THE FIRST

100

IUGS GEOLOGICAL HERITAGE SITES

IUGS 60TH
ANNIVERSARY

THE FIRST 100 IUGS GEOLOGICAL HERITAGE SITES

60 IUGS

First Published in Spain, October 2022

EDITED & PUBLISHED BY IUGS
(International Union of
Geological Sciences)
EMAIL iugs.globalgeosites@igme.es
ISBN: 978-1-7923-9975-6
D.L.: LG D 01086-2022

DESIGN & LAYOUT BY DOSGES
PRINTED BY GRÁFICAS ULZAMA

"An IUGS Geological Heritage Site is a key place with geological elements and/or processes of international scientific relevance, used as a reference, and/or with a substantial contribution to the development of geological sciences through history"

IUGS. Zumaia 2021

Credits

THE FIRST 100 IUGS GEOLOGICAL HERITAGE SITES has been developed in the framework of the International Geosciences Program.
IGCP 731 (2021 – 2023)

THE FIRST 100 IUGS GEOLOGICAL HERITAGE SITES PARTICIPANTS

NATIONAL REPRESENTATIVES

EUROPE

France
Nicolas Charles. BRGM. Service Géologique National.
Benjamin van Wyk de Vries. Université Clermont Auvergne.
Guy Martini. Haute Provence UGGp

Greece
Charalampos Fassoulas. Psiloritis UGGp / University of Crete

Germany
Marie-Luise Frey. Welterbe Grube Messel World Heritage

Italy
Cristina Giovagnoli. Geological Survey of Italy

Lithuania
Jonas Satkūnas. Lithuanian Geological Survey

Norway
Kristin Rangnes. Gea Norvegica UGGp

Poland
Stanisław Wołkowicz and Jacek Kozma. Geological Survey of Poland

Portugal
João Carlos Carreiro Nunes. University of Azores.
Artur Sá. Arouca UGGp / Universidade de Trás-os-Montes e Alto Douro.
José Brilha and **Paulo Pereira.** University of Minho

Rumania
Alexandru Andrasanu. Hateg Country UGGp / University of Bucharest

Slovenia
Matevz NovaK. Geological Survey of Slovenia

Spain
Juana Vegas, Gonzalo Lozano, Enrique Díaz Martínez and **Luis Carcavilla.** Instituto Geológico y Minero de España (IGME), CSIC
Asier Hilario. Basque Coast UGGp
Pedro Castiñeiras. Universidad Complutense de Madrid

Sweden
Sven Lundqvist. Geological Survey of Sweden

U.K
Kirstin Lemon. British Geological Survey

AMERICA

Argentina
Fernando Miranda. Servicio Geológico Minero Argentino

Brasil
Joana Sanchez. Federal University of Goiás

Canada
John Calder. Cliffs of Fundy UGGp

Chile
Manuel Arenas Abarca. Servicio Nacional de Geología y Minería
Manuel E. Schilling Danyau. Kütralkura UGGp

Colombia
Marcela Gómez Pérez. Servicio Geológico Colombiano

Cuba
Enrique Castellanos. Servicio Geológico de Cuba

Jamaica
Sherene Jones Williams. University of West Indies

México
José Luis Palacio-Prieto. Universidad Nacional Autónoma de México / Mixteca Alta UGGp
Emmaline M. Rosado-González. Mixteca Alta UGGP

Peru
Bilberto Zavala. Instituto Geológico, Minero y Metalúrgico de Perú

USA
Stanley Finney. California State University
David Mogk. Montana State University

ASIA - PACIFIC / MIDDLE EAST

Australia
Margaret Brocx. Murdoch University

China
JIN Xiaochi. Chinese Academy of Geological Sciences
Jianping Zhang. China University of Geosciences

India
Satish C. Tripathi. Society of Earth Scientist

Iran
Alireza Amrikazemi. Qeshm Island UGGp

Japan
Setsuya Nakada. National Research Institute of Earth Science and Disaster Resilience.

Malasya
Ibrahim Komoo. University Kebangsaan / Langkawi UGGp

Pacific islands (Samoa, Vanuatu, Luavu)
Gary Lee. Geotecnical adviser

Turkey
Nizamettin Kazanci. Ankara University

AFRICA

Bostwana
Asfawossen Asrat. Botswana International University of Science and Technology

Cameroon
Ghislain Zangmo Tefogoum. University of Maroua

Madagascar
Julie Kapoma and **Voahanginiaina Saholiarimanana.** Geological Survey of Madagascar

Mozambique
Nelson Nhamutole. Mational Museum of Geology

Namibia
Kombada Mhopjeni and **Helke Mocke.** Geological Survey of Namibia

Tanzania
Ramadhani Khatibu and **Joshua Mwankunda.** Ngorongoro Conservation Area Authotity

INTERNATIONAL ORGANIZATIONS

Global Geoparks Network
Nickolas Zouros. President

ProGeo
Lars Erikstad. President

IUGS – International Commission on Stratigraphy (ICS)
David Harper. Chair
Laia Alegret. Chair, Subcommission on Paleogene

International Association of Geomorphologist (IAG)
Mauro Soldati. President
Piotr Migon. Member

International Paleontological association (IPA)
Sylvie Crasquin. President
Tatsuo Oji. Vice-president
Isabelle Rouget. Member

Commission on the History of Geology (INHGEO)
Ezio Angelo Vaccari. Chair

IUGS TC-Task
Enrique Gomez Rivas. Chair
Lorenzo Gemignani. Secretary General

International Mineralogical Association (IMA)
Hans-Peter Schertl. President

Scientific Committee on Antartic Research (SCAR)
Jerónimo López. President

International association of Volcanology and Chemistry of the Earth's interior (IAVCEI)
Karoly Nemeth. Volcano Geoheritage and Protected Volcanics Landscapes
Jazzmine Scarlett. Member

UNESCO International Research Centre on Karst (IRCK)
Mary Luo. Deputy Secretary General
Cao Jianhua. Executive Deputy Director

UNESCO - IGCP
Ozlem Adiyaman.IGCP

IUGS COORDINATION

Stanley Finney. Secretary General, IUGS
Asier Hilario. Chair, IUGS – International Commission on Geoheritage (IUGS-ICG)
Jianping Zhang. Vice-chair, IUGS-ICG
Benjamin Van Wyk de Vries. Chair, IUGS Sub-commission on Sites
Juana Vegas. Secretary General, IUGS-ICG

Secretariat
Gonzalo Lozano. Instituto Geológico y Minero de España (IGME), CSIC.

DEFINITION AND MAIN STANDARDS

Asier Hilario, Spain. **Asfawossen Asrat,** Bostwana. **Babbis Fassoulas,** Greece. **Benjamin van Wyk de Vries,** France. **Enrique Díaz,** Spain. **Fernando Miranda,** Argentina. **Helke Mocke,** Namibia. **Jianping Zhang,** China. **Joana Sanchez,** Brazil. **José Brilha,** Portugal. **Juana Vegas,** Spain. **Kirstin Lemon,** UK. **Luis Carcavilla,** Spain. **Manuel Arenas,** Chile. **Margaret Brocx,** Australia. **Nicolas Charles,** France. **Paulo Pereira,** Portugal. **Stanley Finney,** USA.

EVALUATORS / VOTING MEMBERS

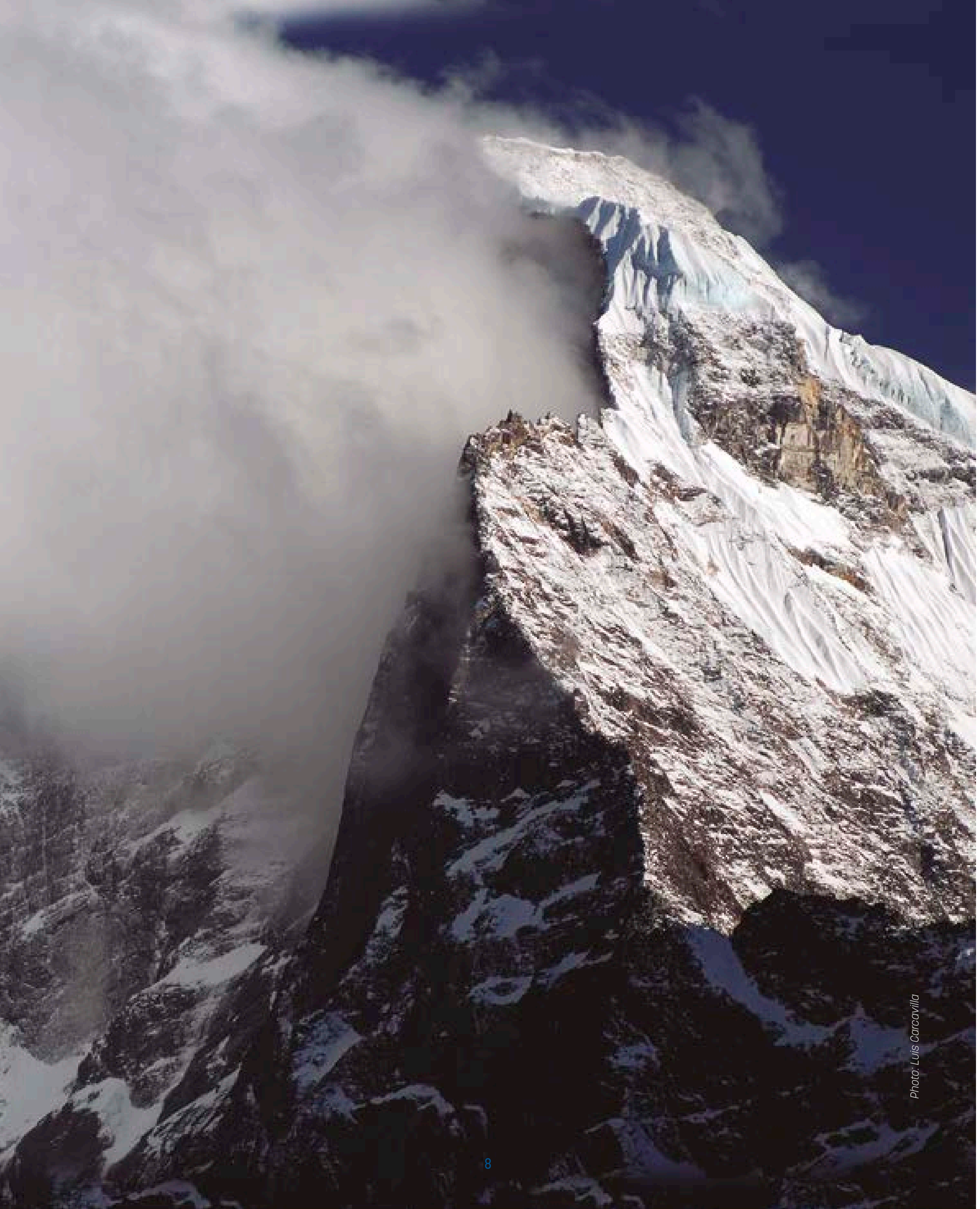
Alireza Amrikazemi, Iran. **Arthur Sá**, Portugal. **Asfawossen Asrat**, Bostwana. **Cao Jianhua**, China. **David Harper**, USA. **David Mogk**, USA. **Enrique Castellanos**, Cuba. **Enrique Díaz**, Spain. **Enrique Gomez**, Spain. **Ezzio Vacarri**, Italy. **Helke Mocke**, Namibia. **Ibrahim Komoo**, Malasya. **Isabelle Rouget**, France. **Jazzmine Scarlett**, UK. **Jin Xiaochi**, China. **Joana Sanchez**, Brazil. **Jose Brilha**, Portugal. **Juana Vegas**, Spain. **Kristin Lemon**, UK. **Laia Alegret**, Spain. **Lorenzo Gemignani**, Germany. **Mahar Lagmay**, Phillipines. **Marcela Gomez**, Colombia. **Margaret Brocx**, Australia. **Mauro Soldati**, Italy. **Nizamettin Kazanci**, Turkey. **Pedro Castiñeira**, Spain. **Piotr Miorn**, Poland. **Sharad Master**, South Africa. **Stanley Finney**, USA. **Sylvie Crasquin**, France. **Tatsuo Oji**, Japan. **Zhang Jianping**, China.

THE FIRTS 100 BOOK EDITORS

Asier Hilario, Spain. **Asfawossen Asrat**, Bostwana. **Benjamin van Wyk de Vries**, France. **David Mogk**, USA. **Gonzalo Lozano**, Spain. **Jianping Zhang**, China. **José Brilha**, Portugal. **Juana Vegas**, Spain. **Kirstin Lemon**, UK. **Luis Carcavilla**, Spain. **Stanley Finney**, USA.

SCIENTIFIC PARTNERS:

SECRETARIAT:



The International Union of Geological Sciences, 60 years old

It is a pleasure to see this volume on the Earth's 100 geological heritage sites, and I thank the many contributors to its production.

The IUGS is the global voice of the geological sciences and brings together more than 1 million geologists world-wide in more than 100 countries. It was created 60 years ago in response to the need to correlate global geological successions and a shared common understanding of the history of the Earth. The IUGS stratigraphic chart is the global standard and underpins many significant geological findings and the economic development of the planet - we continue to improve this. However, the creation of the IUGS was prior to the advent of digital technology, which now means that information can be shared much more readily and that IUGS must now also be able to respond to one of the most important challenges for geoscientists at the present time - mitigating the effects of climate change.

The selection of the *first* 100 geological heritage sites of course means that there are many more, and I thank the jury for their work in making the selection. Included are geological sites where the fundamental tenets of geology were defined, notably Siccar Point in Scotland where James Hutton defined how the earth has been eroded and created unconformities, and questioned the existing theories of the age of the Earth. The Burgess shale of Canada records the explosion of life on Earth and poses questions as to why and how such an explosion occurred. Not only do these sites go back into the pre-3-billion-year-old Earth, but they also include the arrival of human-kind on the Earth in the Olduvai George in Tanzania.

However, as well as spectacular, geology also underpins life on Earth in many ways through maintaining groundwater and by creating economic deposits of salt, hydrocarbons, metals, and material for construction. Geologists are trained in our universities to respond to these needs, and the geological heritage sites selected include mineralised systems – some, such as the giant mercury deposit in Spain, remind us of the need for careful planning and rehabilitation. Geologists need to focus on how the subsurface will help us attain net zero carbon production while sustainably using resources.

Then of course the Earth is dynamic and destructive, and some of the sites relate to large volcanic system such as Yellowstone in USA or ignimbrite flows in Peru. Others relate to external forces from meteorite impacts.

These geological features and rocks react differently when eroded, creating outstanding coastlines such as in Zumaia and features such as the Sugarloaf in Brazil, the Grand Canyon of Arizona, active landslides and earthquake scars.

I do hope you enjoy the geological beauty in this book and reflect on the practical role of the geosciences in underpinning humankind on Earth, which we hope to be able to maintain into the future.

Professor John Ludden, CBE
President of the IUGS.


Photo: Luis Carcavilla

Geological Heritage Sites: standards, procedures, and value of IUGS recognition

The announcement on October 28, 2022, of the "First 100" Geological Heritage Sites recognized by the International Union of Geological Sciences follows a 60-year tradition of the IUGS establishing globally recognized geostandards through international collaborations. The chronostratigraphic units and GSSPs, the IUGS Classification of Igneous Rocks and the Global Geochemical Reference Network represent good examples of these global standards.

IUGS ratified geostandards have authority. They are of the highest importance to the practice of geology and, thus, receive international recognition. Their legitimacy derives from the well established, transparent, deliberative process by which decisions are made and proposals are approved often by consensus or unanimously by the voting members of a subcommission, who are experts and internationally diverse. The proposals must then be analyzed and approved at the Commission level, and finally the IUGS EC must vote to approve the proposal. It is then ratified as an international geostandard.

The Commission on Geoheritage was reorganized recently with the immediate objectives of recognizing Geological Heritage Sites, strengthening the recognition of Global Heritage Stone Resources, and establishing a group to recognize Geocollections. For IUGS Geological Heritage Sites, a first group of 20 international experts on geoheritage from 13 different countries developed the high standards for recognition. An open process of identification was open among more than 40 participant of the IGCP 731 project. 181 candidates from 56 countries were proposed and were evaluated by 33 international experts. The result of this international collaboration between IUGS and more than 10 commissions and affiliated organization is the selection of the "First 100" presented in this book. The First 100 IUGS Geological Heritage Sites is a great milestone that will inspire the work of this ambitious program. There will be more IUGS Geological Sites recognized in the coming years.

IUGS recognition of Geological Heritage Sites gives visibility to those sites. It identifies them as being of the highest scientific value. They are sites that served to develop the science of geology, particularly its early history. They are the world's best demonstrations of geologic features and processes. They are the sites of fabulous discoveries of the Earth and its history.

Their visibility is greatly enhanced by IUGS recognition. Some of the sites are classic and known to almost all geologists, but few geologists know most of the sites because of their diverse types and geographic settings. The announcement of the "First 100" and the attractive book and webpage will lead to many of the sites becoming known for the first time to large numbers of geologists and the public. Interest in individual sites will increase as will geo-visitors. Many of the "First 100" are well protected in national parks, geoparks, and natural reserves, but many are not. Recognition and visibility of the "First 100" IUGS Geological Heritage Sites can lead to their further appreciation, to their use as educational resources, and, most importantly, to their preservation.

Stanley Finney
IUGS Secretary General.

Asier Hilario
Chair. IUGS Commission on Geoheritage.

Geological Heritages sustaining local communities

I would like to express in the name of the Global Geoparks Network our warmest congratulations to the International Union of Geological Sciences (IUGS) for the initiative of the first 100 IUGS Geological Heritage Sites and to all contributors of this excellent book.

The Global Geoparks Network (GGN) established in 2004 in collaboration with UNESCO, is the international association of the Global Geoparks and the Global Geoparks professionals, and represents a growing network of collaboration and sharing of good practices on Geoparks operation and management. Since 2015 the GGN is the official partner of UNESCO for the operation of the UNESCO Global Geoparks programme. The Global Geoparks Network is collaborating with IUGS and IUCN to ensure quality criteria for abiotic and biotic natural heritage assessment in Geoparks.

Today the GGN comprises of 177 UNESCO Global Geoparks located in 46 countries working together to protect geological heritage and promote local sustainable development. The Global Geoparks Network's mission is to influence, encourage and assist local communities all over the world to conserve the integrity and diversity of their geological heritage and to support economic and cultural development through the valorization of their territorial heritage and identity.

Geoparks can be considered as natural laboratories to practice geoscientific knowledge and to enhance public awareness on Planet Earth, natural phenomena and geodynamic processes in order to benefit properly from its sources and avoid its disasters. Through various activities Geoparks are developing, experimenting and enhancing innovative methodologies for preserving the geological heritage and supporting the development of scientific research in the various disciplines of Earth Sciences.

Geoparks promote the links between geological heritage and all other aspects of the area's natural and cultural heritage, clearly demonstrating that geodiversity is the foundation of modern ecosystems and the basis of human interaction with the landscape.

UNESCO Global Geoparks encourage awareness of the story of the planet as read in the rocks and landscape and are committed to the conservation, management and communication to society of the Earth heritage as an integral part of the world's natural and cultural heritage.

The GGN endorsed and supported the new initiate of IUGS for the nomination of IUGS Geological Heritage Sites. The selection of the first 100 IUGS Geological Heritage Sites was not an easy task and we have to congratulate all the members of the jury for their hard and professional work. These sites, landscapes and geological formations are key witnesses to the geological structure and processes of Earth's crust and evolution of life on our planet. We are very proud that many of them lay within UNESCO Global Geoparks, proving the high standards of the selection criteria used for the evaluation of territories to become UNESCO Global Geoparks.

This publication is an excellent tool to communicate the first 100 IUGS Geological Heritage Sites, to interpret geological features and landscapes for the general public, to support awareness raising activities and promote the values of the geological heritage of our planet as tools for the regeneration of rural communities around the globe through the development of geo-tourism. The informative, easy to read and scientifically accurate text accompanied by fascinating pictures in this publication enhance the values of emblematic geo-sites of international significance.

Nickolas Zouros
President of the Global Geoparks Network.

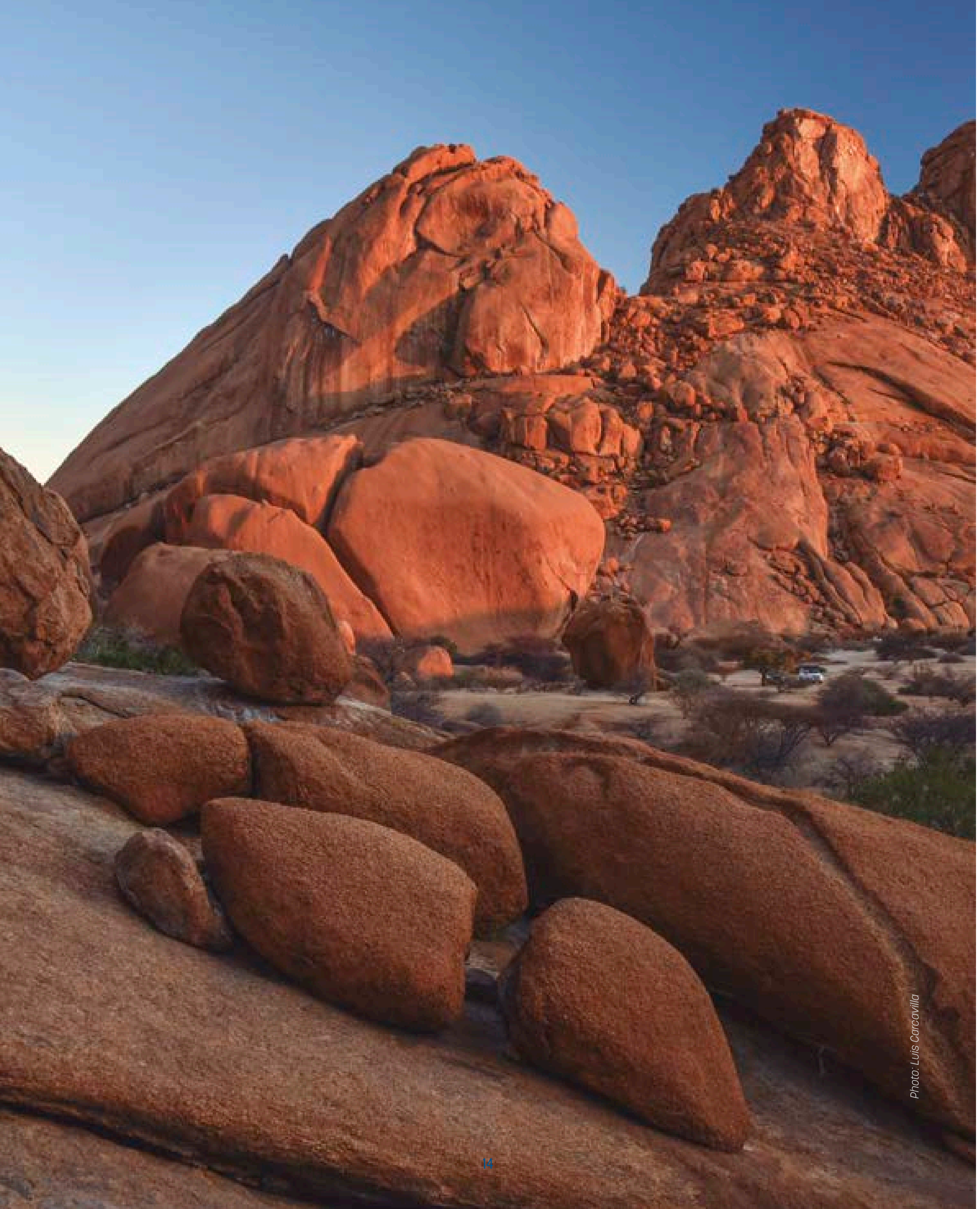


Photo: Luis Carcavilla

The conservation of geological heritage

It can be discussed when nature conservation really started, but in the mid-1800's and onwards the American National Park movement had a huge international impact on conservation. During the second half of the 1900's, geoconservation activities going on in many countries, but it was soon realised that there was a need for international cooperation, change of experiences and support for national geoconservation efforts. In 1988 a working group was established in Europe to fill this need, and in 1993 the group evolved into the European association ProGEO. In 2021 ProGEO expanded into a global association.

One of the early issues raised by ProGEO was the need for a global listing of international scientific valuable sites. The Geosite project started in 1995 under the IUGS-umbrella but even if this project was terminated a few years later, it lived in ProGEO and has resulted in methodological approaches and many national inventories and geoconservation programmes within Europe. ProGEO welcomes the new and revised initiative from IUGS, and we are convinced that active work on geoheritage projects under a IUGS umbrella will be an important step forward for international geoconservation.

One of the most important meetings in ProGEO history was the first international symposium on geoconservation held in Digne-les-Bains, France in 1991. This was when the "Declaration of the Rights of the Memory of the Earth" was born, a statement which has worked as a foundation for ProGEO and the geopark movement. This demonstrates both the common origin for these two initiatives and serves as a reminder that international cooperation is the way forward to achieve results.

ProGEO has been active within the international nature conservation movement. As a member of IUCN, members of ProGEO have attended all world congresses since 2008 and in cooperation with other organisations promoted several motions which have been accepted as IUCN resolutions. This contributes to a growing acceptance for geodiversity as a term on par with biodiversity, raising the awareness of geoheritage and geoconservation as a natural and important part of nature conservation. Today ProGEO is working within in the Geoheritage Specialist Group under the IUCN's World Commission of Protected Areas.

For future success in international geoconservation, it is vital to establish a close cooperation between all existent international initiatives involved with the recognition of geosites of international significance, such as the "IUGS Geological Heritage Sites" or the UNESCO's Global Geoparks and World Heritage as well as other national and international designations. We need these initiatives to work in synergy, not in competition to each other, and it will be a constant ProGEO task to be a reminder about the importance of cooperation as the main prerequisite for success.

The International Geodiversity Day recently proclaimed by UNESCO will play an important role to remind that geodiversity should work on par with biodiversity to assure natural qualities globally and to secure all geo- and ecosystem services that we depend on. Let this book be an inspiration for us all in this work!

Lars Erikstad
President of ProGEO

1

HISTORY OF GEOSCIENCES

SITE 001 - SITE 011

Ezio Vaccari
Università degli Studi dell'Insubria. Italy.
President, International Commission on the History of Geological Sciences (INHIGEO) - IUGS / IUHPST.
IUGS Geological Heritage Sites voting member.

Kirstin Lemon
Geological Survey of Northern Ireland. UK.
IUGS Geological Heritage Sites voting member.

The reconnaissance of geosites of historical relevance is of great importance, as it allows us to recognize the foundation, the development and consequently the scientific potential of the geological sciences, as well as their role in human society. The history of geosciences, is based not only on archival documents and printed material, but also on places, routes and landscapes which have been described and studied by scholars and scientists since the origins of the geological sciences, in particular with the increase of scientific travels and the emergence of fieldwork from the 18th century to the present day.

Each geological heritage site has its own history, because it was discovered or identified on a certain date and has also been the subject of a number of scientific investigations throughout time. However, an historical geosite is not just a site with a history, but a site that has made history in the field of the geological sciences: a place where the observation of some specific features determined new ideas, theories and interpretations which have changed human understanding of the geological phenomena and of the history of the Earth. An historical geosite is a landmark for the history of science, as well as a milestone for modern geology.

For this reason, most of the classic sites for the history of geosciences are also regarded as iconic sites for contemporary research within the Earth sciences and present remarkable interdisciplinary features.

This is the case regarding all the geosites presented in this section, as well as some others that are included under different thematic chapters within this book. The historical value of important sites for modern volcanology, such as the Phlegrean Fields and Puy-de-Dôme, is determined by significant 18^{th}-19^{th} century fieldwork, which allowed the understanding of the dynamics of volcanic phenomena (in order to identify their potential hazard) and the recognition of the existence of extinct volcanoes. The early studies on Taburiente volcanic caldera in La Palma island and later on Capelinhos volcano contributed to the development of volcanology from the first half of the 19^{th} century to the present day. Moreover, the 18^{th} and 19^{th} century geological debates expressed important theories strictly linked to specific sites: the Giant's Causeway proved the theory of the origin of the extrusive igneous rocks such as basalt; in Genbudo Cave basalts were studied for geomagnetism since the beginning of the 19^{th} century; Siccar Point was the fundamental site for the establishment of the theory of unconformity and the idea of 'deep time' in geology, expressed by James Hutton in the late 18^{th} century. Also the Moine Thrust zone (included in chapter 6) is certainly a classic site for modern tectonics research, but also an iconic area for the studies on the origins of mountains since the 19^{th} century.

Other sites can be considered landmarks of the development of the geological sciences during the 20^{th} century: Funafuti Atoll is the site were Charles Darwin's subsidence theory of atoll formation was first tested in 1904; the site of Gros Morne was at the heart of the debate on the revolutionary theory of plate tectonics; the site in Ragunda is essential for the advancement of geochronology, while at Klonk Hill the first global boundary stratotype section and point was established.


Quaternary glacial varves of Ragunda
SWEDEN
Siccar Point Hutton's Unconformity
UK
Mohorovičić discontinuity at Gros Morne N.P.
CANADA
The Paleocene volcanic rocks of the Giant's Causeway and Causeway coast
UK
The Holocene Puy-de-Dôme and Petit-Puy-de-Dôme volcanoes
FRANCE
GSSP for the Silurian-Devonian boundary at Klonk Hill
CZECH REPUBLIC
Capelinhos Volcano
PORTUGAL
The Quaternary Phlegrean Fields volcanic complex
ITALY
Genbudo cave
JAPAN
Taburiente Volcanic Caldera
SPAIN
Funafuti Atoll
TUVALU

SICCAR POINT HUTTON'S UNCONFORMITY

UNITED KINGDOM

Hutton's Unconformity at Siccar Point with a geotourist for scale. The figure is standing on shallowly dipping Devonian rocks that rest unconformably upon steeply dipping Silurian-aged rocks beneath (Photo: Colin MacFadyen/NatureScot).

AN ICONIC AND IMPORTANT SITE WHERE JAMES HUTTON RECOGNIZED THE SIGNIFICANCE OF UNCONFORMITIES AND THE POSSIBILITY FOR "DEEP TIME" IN GEOSCIENCE.

James Hutton (1726–1797) envisaged in his Theory of the Earth (1795) not only processes that weather and destroy rocks, and thus ruin a perfectly created world, but also processes capable of regenerating the Earth. This led Hutton to propose the existence of continual, cyclical Earth processes which could drive change over long timescales. The spectacle of the unconformable relationship between the two different rock sequences at Siccar Point provided Hutton the empirical evidence for previous cycles of his Earth machine. Hutton used the location to demonstrate the existence of cycles of deposition, folding, and further deposition of rocks that which the unconformity represents. He understood the implication of unconformities in the evidence they provided for the enormity of geological time and the antiquity of the Earth.

SITE 001

GEOLOGICAL PERIOD	Lower Silurian - Upper Devonian
LOCATION	Cockburnspath, Berwickshire, Scottish Borders, Scotland, UK. 55° 59' 15" N 002° 24' 24" W
MAIN GEOLOGICAL INTEREST	History of geosciences Stratigraphy and sedimentology

An aerial view of Hutton's unconformity at the coastal promontory of Siccar Point in the Scottish Borders. (Photo Source: UKRI© British Geological Survey (P1020257).

Geological Description

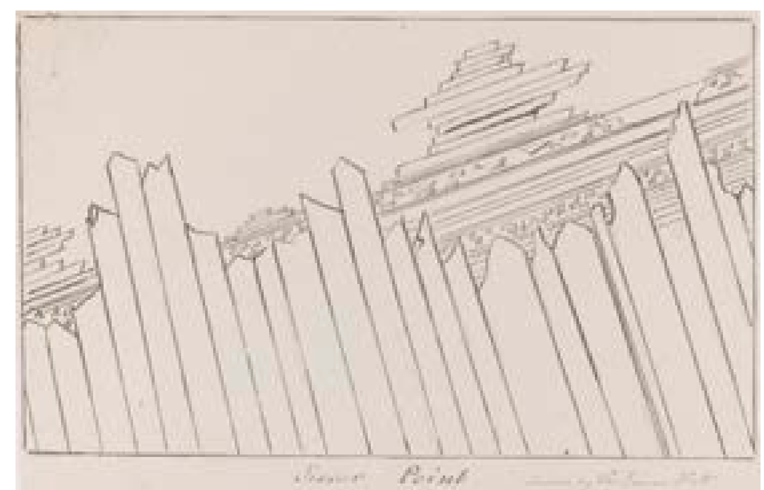
Siccar Point is a coastal promontory that beautifully displays in three dimensions the spectacular angular unconformity with Upper Devonian beds resting discordantly on folded, near vertical, Lower Palaeozoic strata.

The Lower Palaeozoic beds are turbiditic dark grey, fine grained wacke sandstone and interbedded finely laminated, fissile mudstone of the Gala Group, of early Silurian (Llandovery Epoch) age (Browne and Barclay, 2005). These rocks were strongly deformed, being folded and cleaved, during the Caledonian Orogeny. Subsequent erosion, pre-Late Devonian times, formed an irregular surface with considerable palaeorelief through differential rates of weathering and erosion of individual beds in the Silurian succession; beds of wacke sandstone standing up more sharply and prominently than others (Greig, 1988; Treagus, 1992). Upon the sharp angular unconformity there rests Upper Devonian strata, comprising reddish brown breccia and conglomerate, of the Redheugh Mudstone Formation of the Stratheden Group. In marked contrast to the underlying Silurian strata the Upper Devonian beds have only a gentle inclination produced during the later, here less intense, Variscan Orogeny.

The unconformity played a key role in James Hutton's insight that geological processes are not just "destructive" but also capable of restoring thus leading to a rock cycle of indefinite duration so "that we find no vestige of a beginning, – no prospect of an end" (Hutton, 1788: 304).

Scientific research and tradition

Siccar Point is of great historical importance in the development of geoscience as evidence supporting James Hutton's celebrated Theory of the Earth that in its final form proposed a cycle of geological processes (Dean, 1992). The locality also became the celebrated nexus for empirical argument concerning the great age of the Earth.



A sketch by Sir James Hall which records the observations made by James Hutton of the unconformity at Siccar Point. (Photo reproduced with the permission of Sir Robert Clerk of Penicuik Bt.).

THE QUATERNARY PHLEGREAN FIELDS VOLCANIC COMPLEX

ITALY

Map of the Gulf of Pozzuoli, with a part of the Phlegrean Fields, drawn by Pietro and Francesco La Vega in 1778, printed by Perrier in 1780 (Carte du Golfe de Pouzzoles: avec une partie des champs phlégréens).

A CLASSIC AREA FOR THE STUDY OF VOLCANIC ACTIVITIES AND VOLCANIC HAZARD ASSESSMENT SINCE THE 18TH CENTURY.

The site had a major role in the European debates that created the modern science of geology in the 18th and 19th centuries. Naturalists were attracted to the area to record evidence directly in the field regarding both active and extinct volcanoes and their products preserved in the landscape. The Phlegraean Fields is one of the very few volcanoes in the world considered capable of producing a colossal eruption of level VEI 8 (Orsi *et al.,* 2004), which had already occurred during its volcanological history with the emplacement of the Campanian Ignimbrite that supposedly caused the near disappearance of Neanderthals (39ka).

SITE 002

GEOLOGICAL PERIOD	Upper Pleistocene – Holocene
LOCATION	Campania, Naples. Italy. 40° 49' 37" N 014° 08' 20" E
MAIN GEOLOGICAL INTEREST	History of Geosciences Volcanology

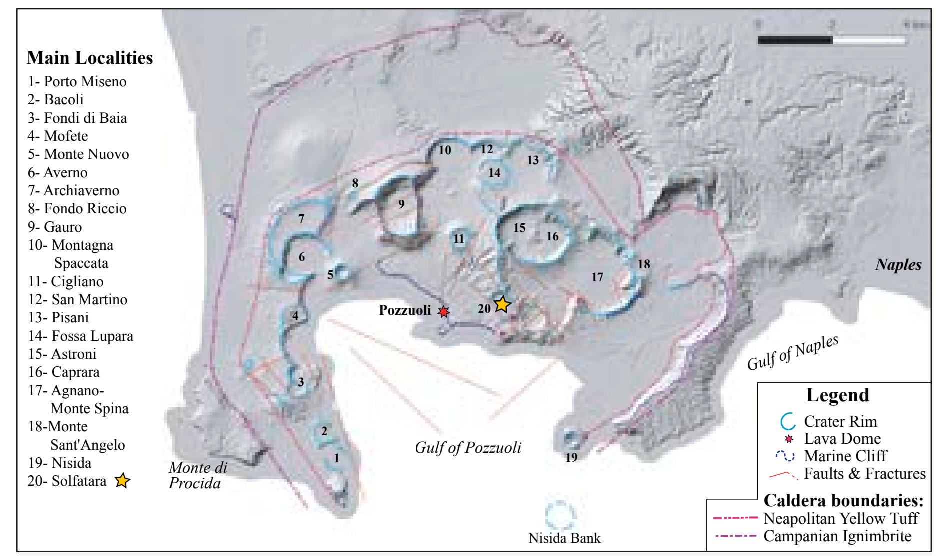
Diffuse hydrothermal fumaroles discharge at Solfatara crater. The yellow-orange colours are deposits of Sulfur. (Photo courtesy of Roberto Bonomo).

Geological Description

The Phlegrean Fields volcanic complex is a 13 km wide nested volcanic caldera complex located west of Naples, near Vesuvius, famous for the iconic Temple of Serapis, with evidence of vertical ground movements since the Roman period. The volcanic complex started its activity c.80 ka BP. That activity ranged from phreatomagmatic-magmatic explosions to effusive eruptions. The present volcanic structure results from major collapses related to the Campanian Ignimbrite (39 ka) and the Neapolitan Yellow Tuff (15 ka) emplacement. During the last 12 ka volcanism has been concentrated within the former area forming tuff cones and rings, minor scoria cones, and lava domes. Intense ground deformation generated by uplift and subsidence phenomena indicates the presence of an active volcanic system associated with hydrothermal fluid inflation-deflation processes. In the famous locations of Solfatara and Pozzuoli this activity is particularly evident. The Solfatara crater is characterized by high temperature hydrothermal fluid discharge, boiling pools, and diffuse CO_2 emissions. In recent decades Pozzuoli has undergone several episodes of bradyseism, raising the coastline by c.4.5m. Today, the area is highly monitored as a rapid release of magmatic gases or new magma intrusion could trigger a significant eruption at anytime (Sbrana *et al.,* 2021; Orsi *et al.,* 2022).

Scientific research and tradition

The site is one of the most intensively studied volcanic area in the world, ranging from the observations by Ray (17th century), to Spallanzani and Lyell in the 18th and 19th centuries (Dean, 1998). A focal point in this research, based on fieldwork, was the work of William Hamilton (1776-79).



Phlegrean Fields DTM map showing the main volcanological and structural features (modified after Isaia et al., 2019 and Di Vito et al., 1999). The principal localities are listed. The red and yellow stars indicate Pozzuoli town and Solfatara crater, respectively.

MOHOROVIČIĆ DISCONTINUITY AT GROS MORNE NATIONAL PARK
CANADA

UNESCO World Heritage Site

Rocks of the Moho exposed on the tablelands of Gros Morne. (Photo: John Waldron, University of Calgary).

ONE OF THE WORLD'S BEST EXPOSURES OF THE MOHO, THE BOUNDARY BETWEEN OCEANIC CRUST AND MANTLE ROCKS, PRESERVED AT THE EARTH'S SURFACE IN A DRAMATIC GLACIAL LANDSCAPE.

Gros Morne was inscribed on the list of the World's Heritage as an exceptional illustration of seldom seen plate tectonic processes and of a glacially modified coastal landscape of deep fjords and 'tabletop' highlands. It allows visitors to stand on the 'Moho', a boundary that is normally buried 5 to 70 km beneath the Earth's surface. Gros Morne played a seminal role in the development of plate tectonic theory and the understanding of processes involved in building mountain belts.

SITE 003

GEOLOGICAL PERIOD	Cambrian - Ordovician
LOCATION	Gros Morne National Park Newfoundland, Canada. 49° 27' 56" N 058° 02' 22" W
MAIN GEOLOGICAL INTEREST	History of geoscience Tectonics

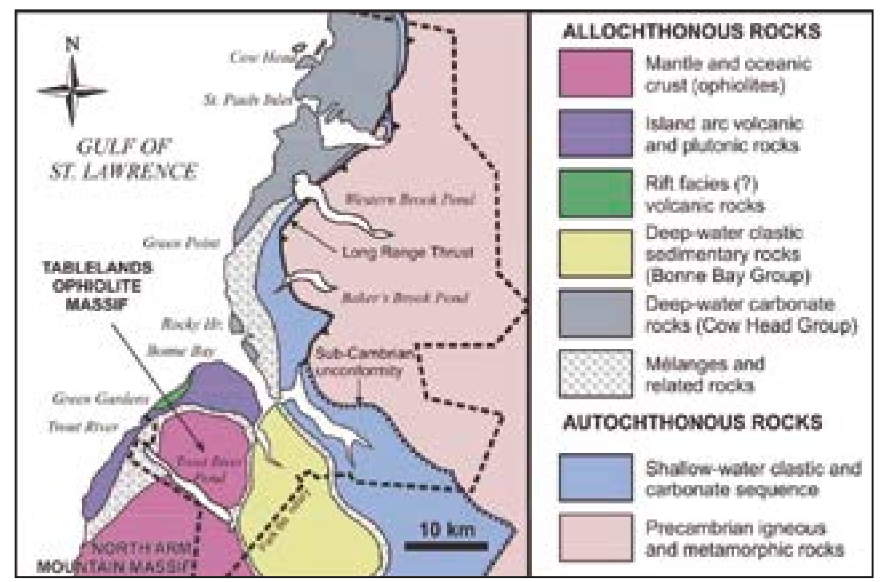
Closeup of structures produced during mid-ocean ridge deformation of hot magmatic rocks at Gros Morne. (Photo: John Waldron, University of Alberta).

Geological Description

The deep fjords and barren plateaux of Gros Morne National Park in western Newfoundland expose rare examples of rocks from the Earth's deep ocean crust and mantle, and their contact, the 'Moho' or Mohorovičić discontinuity. These oceanic rocks – ophiolites – are exposed here due to exceptional tectonic events that obducted deep, seldom seen mantle rocks toward the Earth's surface approximately 470 million years ago as plate tectonics closed the Iapetus Ocean and gave birth to the Appalachian mountain belt. Exposed to view by glacial erosion, the ultramafic rocks are geochemically inhospitable to most plant life, resulting in the barren, otherworldly landscape known as the 'Tablelands'. Gros Morne was at the heart of the great revolutionary theory of plate tectonics in the 20th century, leading to concepts of how ancient oceans closed and how ancient orogenic systems – mountain belts – formed.

Scientific research and tradition

The geology of Gros Morne and the Bay of Islands ophiolite has played a key role in our understanding of the formation both the continental and oceanic crust through the processes of plate tectonics. Gros Morne is one of the world's most profound examples of plate tectonics writ large in the rock record.



Geological map of the Gros Morne ophiolite complex. (Andrew Kerr, Geoscience Canada dsg).

THE HOLOCENE PUY-DE-DÔME AND PETIT-PUY-DE-DÔME VOLCANOES

FRANCE

UNESCO World Heritage Site

Oblique aerial view of the Petit-Puy-de-Dôme and Puy-de-Dôme from the NE (van Wyk de Vries et al., 2014).

A WORLD ICONIC RIFT-RELATED TRACHYTE LAVA DOME AND THE CLASSIC AREA FOR RECOGNITION OF EXTINCT VOLCANOES IN HISTORICAL GEOLOGICAL DEBATES.

This site was the first in which physical features were recognised as unambiguously volcanic in origin with demonstrable sequence of volcanic eruptions, depositional and erosional processes, all of which had evidently acted on a vast timescale. The site received attention during studies of physics and atmospheric scienes, and it is used as a geophysical standard. The site continues to be an exceptional locality for worldwide volcanological and geomorphological study, even after more than 250 years of research, and it is a type example of intrusion related uplift, and accompanying erupted edifice, which itself has been tilted by the bulging. The site is included in the Chaîne des Puys - Limagne fault tectonic arena UNESCO World Heritage.

SITE 004

GEOLOGICAL PERIOD	Holocene
LOCATION	Auvergne, France. 45° 46' 20'' N 002° 57' 52'' E
MAIN GEOLOGICAL INTEREST	History of geosciences Volcanology

Puy de Dôme summit trachyte spines with slabs and fractures of foliated lava. The dome is tilted ~15° southwards by the Petit Puy de Dôme bulge.

Geological Description

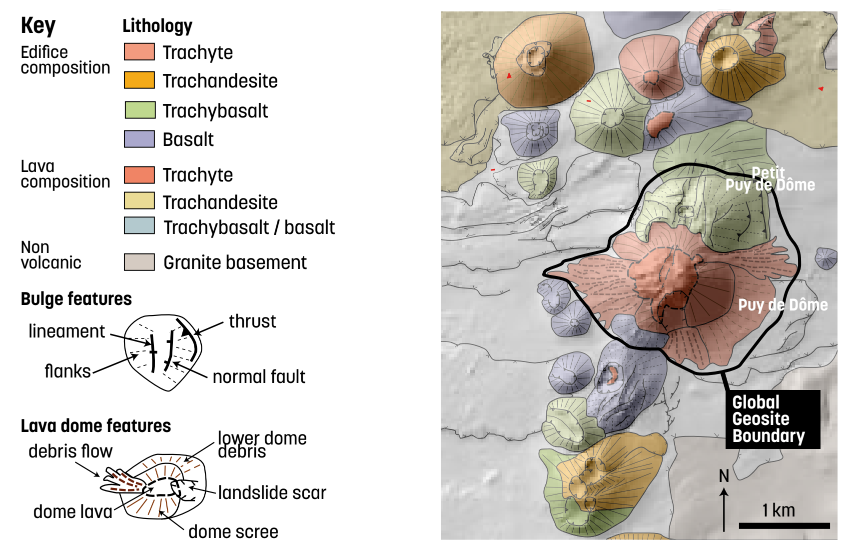
The Puy-de-Dôme and Petit-Puy-de-Dôme constitute a volcano-tectonic landform occupying the central part of the Chaîne des Puys-Limagne Fault UNESCO World Heritage site. It is a Grand Site de France located in the Auvergne Volcanoes Regional Nature Park, and it is listed in the French National Geoheritage inventory.

The Petit-Puy-de-Dôme is a classic bulged uplift created by the intrusion and inflation of trachyte magma within pre-existing monogenetic scoria cones (van Wyk de Vries *et al.*, 2014). The bulge has steep sides, clear faults with a central graben and a late stage minor explosion crater.

The Puy-de-Dôme is probably the result of extrusion from the Petit-Puy-de-Dôme, and was subsequently tilted, as the bulge continued to inflate (Petronis *et al.*, 2019). The dome had two eruptions separated by several hundred years, the main dome-forming phase and a final ash eruption. It also has a complex magmatic assembly indicating multiple intrusion phases (Deniel *et al.*, 2020).

Emblematic site studied since the 18th century (e.g. Guettard, 1752; Desmarest, 1771), both volcanoes formed about 11,000 years ago (Miallier *et al.*, 2010), and they are now evolving slowly as active processes, including occasinal rock falls and lahars, naturally modify their forms.

Detailed map with the Global Heritage Site boundary, defined a line just outside the outer limit of the deposits, or structures of the two elements (Petronis et al., 2019).



Scientific research and tradition

This site was at the centre of 18th and 19th century volcanological debates and was studied by many major scientists such as Desmarest, von Buch, Scrope, Lyell and others (Taylor, 2007). Nowadays, this World Heritage Site continues to be used as a reference for geoscientific, physics and atmosphere research.

THE PALEOCENE VOLCANIC ROCKS OF THE GIANT'S CAUSEWAY AND CAUSEWAY COAST

UNITED KINGDOM

UNESCO World Heritage Site

The Giant's Causeway is made up of some 40,000 columns of tholeiitic basalt that extend out into the Atlantic Ocean like a pavement. Their characteristic shape was a key factor in determining the origin of extrusive igneous rocks in the 18th century. (© National Trust).

ONE OF THE BEST EXAMPLES OF COLUMNAR BASALT IN THE WORLD AND A KEY SITE IN PROVING THE ORIGIN OF EXTRUSIVE IGNEOUS ROCKS DATING BACK TO THE 18TH CENTURY.

The Giant's Causeway was at the centre of a fierce debate since the late 18th century disputing the origin of basalt (Wyse Jackson, 2000). The Neptunists, led by Abraham Werner and locally by Rev. William Richardson, argued that basalt precipitated from seawater (Richardson, 1805) while the other side, the Vulcanists, led by Rev. William Hamilton and John Playfair, argued that basalt was volcanic in origin (Hamilton, 1786) a theory initially proposed by Nicholas Desmarest. The basalt columns at the Giant's Causeway provided the evidence to support the "Vulcanist" theory for the origin of extrusive igneous rocks.

SITE 005

GEOLOGICAL PERIOD	Paleogene
LOCATION	County Antrim, Northern Ireland, United Kingdom 55° 14' 27" N 006° 30' 42" W
MAIN GEOLOGICAL INTEREST	History of geosciences Volcanology

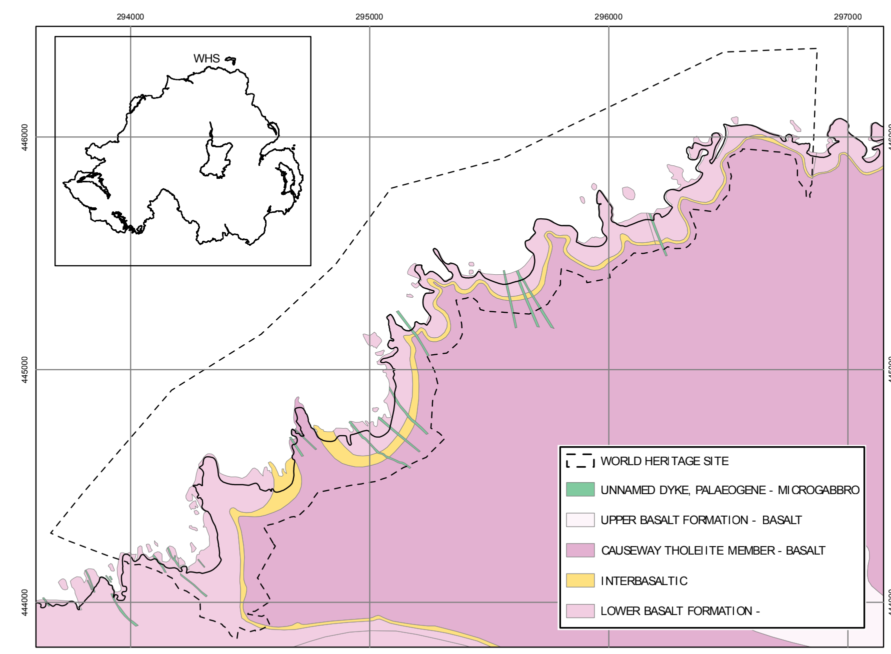
The cliffs of the Causeway Coast are made up of a succession of basaltic lava flows interspersed with lateritic (iron-rich) interbasaltic horizons formed during a sequence of events associated with volcanic activity in the Paleocene. (© National Trust).

Geological Description

The Giant's Causeway and Causeway Coast World Heritage Site, located along a 4km stretch of the northern County Antrim, exposes the coast basalts of the Antrim Lava Group (Simms, 2021). This site contains an exposure of over 40,000 tholeiitic basalt columns forming a pavement, regarded as one of the finest examples of columnar basalt in the world, including exceptional cliff exposures of columnar and massive basalt. The prismatic columns formed due to slow cooling of lava that had ponded in a palaeovalley. On the Causeway coastline three lava flows are present: the Lower Basalt, the Causeway lava, and the Upper Basalt as well as two interbasaltic laterite horizons, formed through weathering of the upper levels of the first two flows. The Antrim basalts extend through much of north-east Ireland and are the western extent of the British and Irish Igneous Province formed during the opening of the North Atlantic Ocean approximately 50 million years ago (Lyle and Preston, 1993). Distributed within the basalts is a diverse assemblage of zeolite minerals that reflects a temperate gradient present during their formation.

Scientific research and tradition

The Giant's Causeway is a site of significant historical importance in the development of geoscience and since the 1600s has attracted scientific investigations which continue to the present time. These studies have included research into volcanic processes, petrology and mineralogy of the basalts and fossil faunas contained in the laterites.



Giant's Causeway and Causeway Coast World Heritage Site.

FUNAFUTI ATOLL

TUVALU

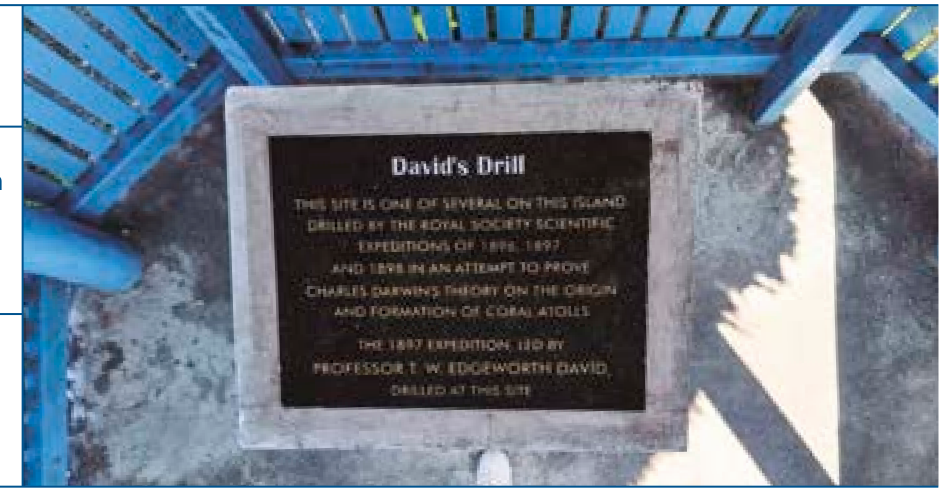
Aerial image of Fongafale Islet (main islet of Funafuti Atoll), looking southwest.

THE SITE WHERE CHARLES DARWIN'S SUBSIDENCE THEORY OF ATOLL FORMATION WAS FIRST TESTED.

Funafuti Atoll is an internationally significant site with substantial contributions to the geological sciences, through the rich history associated with the first drilling experiment to test Darwin's subsidence theory of atoll formation (Armstrong *et al.*, 1904). This internationally significant drilling site reflects interaction between atoll carbonate sedimentation, dolomite formation, tectonic subsidence and eustatic sea-level change (Ohde *et al.*, 2002). The site is proudly conserved as 'Te Vili O Tavita' ('David's Drill'), named after the geologist Sir Edgeworth David who led the 1897-expedition. Additionally, Funafuti has the oldest, most comprehensive geological maps of any atoll globally, that provide a unique dataset for on-going contributions to the geological sciences.

SITE 006

GEOLOGICAL PERIOD	Pliocene - Holocene
LOCATION	South-West Pacific Region Funafuti Atoll, Tuvalu. 08° 30' 56" S 179° 12' 03" E
MAIN GEOLOGICAL INTEREST	History of geosciences



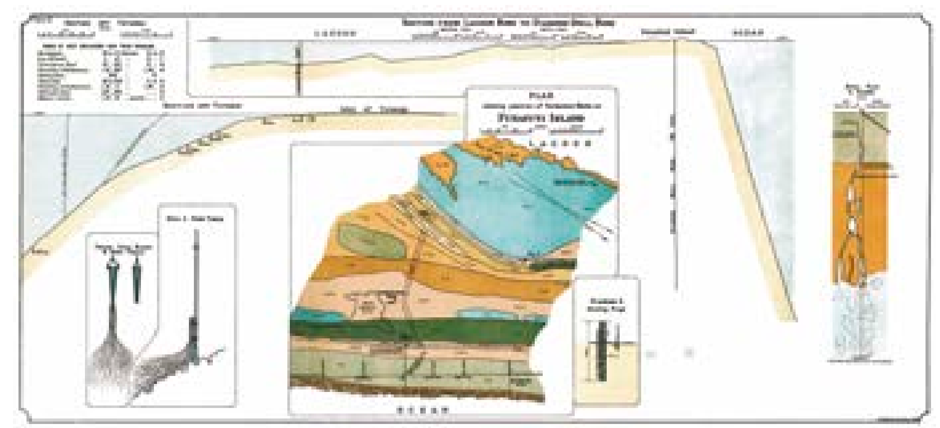
Commemorative plaque installed at the location of 'David's Drill', which reached a depth of 1114 ft in 1898.

Geological Description

The origin of atolls was a mystery to science and source of great debate since the pioneering days of modern geoscience. Following observations made during the voyage of HMS Beagle, Charles Darwin proposed a revolutionary theory that atolls formed as the result of oceanic volcanic islands undergoing prolonged subsidence, together with upward growth of reef-constructing coral formation (Darwin, 1842; Armstrong *et al.*, 1904). To test this theory, the Royal Society sponsored three expeditions to Funafuti Atoll between 1896-1898 and completed a drilling experiment which sampled the subsurface geology of the atoll (Armstrong *et al.*, 1904). The deepest core recovered over 300m of shallow-water carbonates, which provided sufficient evidence to satisfy the principal of Darwin's theory (Armstrong *et al.*, 1904; Ohde *et al.*, 2002). Analysis of the core suggested a subsidence rate of 30m/Ma, with the Pleistocene-Pliocene boundary at a depth of ca 200m and the deepest dolomite with 2.3 Ma. Subsequent seismic reflection and bathymetric interpretation indicates the underlying volcanic basement is approximately 600m below sea level and the crustal age under Funafuti is estimated ca 110 Ma (Gaskell and Swallow, 1953; Krüger, 2008). During the 1897 expedition the team also produced the most detailed geological maps and cross sections of any atoll (Armstrong *et al.*, 1904). The maps remain an internationally unparalleled baseline dataset to study atoll morphological changes resulting from coastal processes, anthropogenic influences, and climate change.

Scientific research and tradition

Darwin first proposed his subsidence theory of atoll formation in the book Structure and Distribution of Coral Reefs (Darwin, 1842). He outlined an experiment to test his theory which was carried out on Funafuti Atoll between 1896-1898 (Armstrong *et al.*, 1904). His theory has since been recognized globally and further developed by works from other notable scholars (Gaskell and Swallow, 1953; Stoddart, 1969; Ohde *et al.*, 2002; Krüger, 2008).



One of the first detailed geological maps of an atoll ever produced, showing the position and cross section of David's Drill (Diamond Drill Bore) and other boring sites.

CAPELINHOS VOLCANO
PORTUGAL

UNESCO Global Geopark

Picture taken on the early phase of the 1957-58 Capelinhos eruption, with the typical phreatomagmatic eruptions "cypress tree-like" ash jets and steam clouds.

A HISTORIC, SMALL SUBMARINE VOLCANO THAT CHANGED THE WORLD OF VOLCANOLOGY.

The eruption of Capelinhos Volcano attracted the world's attention due to its geological characteristics, location and study. It was the first submarine eruption in the world to be fully monitored and properly documented throughout its activity. Being so close to the shore and arousing the international scientific community's curiosity (Tazieff, 1959; Waters and Fisher, 1971; Cole *et al.*, 2001), Capelinhos became one of the best-documented phreatomagmatic volcanoes of the World (Sigurdsson *et al.*, 2000). Those studies allowed new knowledge and opened a new page in the understanding of submarine volcanoes. The site is located in the Azores UNESCO Global Geopark.

SITE 007

GEOLOGICAL PERIOD	Holocene. 1957/58
LOCATION	Faial island, Azores Geopark, Portugal. 38° 36' 05" N 028° 49' 53" W
MAIN GEOLOGICAL INTEREST	History of geosciences Volcanology

Capelinhos landscape today, about 65 years after the eruption. The old sea shore line and its lighthouse, and the subaerial and the submarine cones of Capelinhos eruption (on the background) can be recognized.

Geological Description

This newly-born site results from a submarine volcanic eruption that started on 27 September 1957 and continued for the next 13 months, only 1 km away from Faial Island (Zbyszewski, 1960; Machado *et al.*, 1962). It is the most recent of about 20 small monogenetic volcanoes along a tectonic alignment that contributed to the island's formation and shape. The basaltic eruption started with the projection of volcanic ash accompanied by a large column of steam and volcanic gases. The accumulation of the tephra created a small islet that eventually connected to the island of Faial. The eruption then evolved to a subaerial style with the emission of scoria and lava flows. This eruption was accompanied by intense seismic activity that strongly affected the surrounding area. During the eruption, the volcano expelled around 174000000 m^3 of volcanic material, covering the agricultural fields and adding 2.4 km^2 to Faial Island – with only a fourth of this area remaining today due to sea erosion. The marks of this eruption remain, not only in the landscape but also in a cultural, social and economic frame. With the memory of the eruption, this surtseyan-type born tuff cone tells us the story of how volcanic islands are created.

Sketch of the westernmost sea shore cliff of Faial Island (e.g. Costado da Nau - CN) before Capelinhos Volcano (CV) eruption, with their tuff and scoria (sc) deposits and lava flows (lf). Scree slope deposits (sd) and Costado da Nau volcano main conduit (including feeding dykes and sill) are outlined. ©J.C. Nunes.

Scientific research and tradition

During the eruption, scientists from all over the world travelled to the Azores, resulting in innumerous scientific publications on the eruption. Today, this site is still a hotspot for research in various areas, used as a key example of submarine eruptions in books, and being a worldwide iconic geosite for surtseyan-type eruptions.

TABURIENTE VOLCANIC CALDERA IN LA PALMA ISLAND

SPAIN

Caldera de Taburiente seen from the crater top to the South of La Palma Island.

THE VOLCANIC LANDFORM KNOWN WORLDWIDE AS CALDERA WAS NAMED AFTER THE FIRST USE OF THIS LOCAL TERM IN THIS SITE IN THE BEGINNING OF THE 19TH CENTURY.

Taburiente Caldera contributes to the development of volcanology since the 19th century, not only for the contribution to the 'Theory of elevation craters' (von Buch, 1825) but also for being the most complete record of the evolution of an oceanic volcanic island. In this Caldera has been possible to study the Pliocene submarine basal complex, the metamorphism originated by the magmatic intrusion, the building of a Quaternary volcanic edifice, and giant landslides and intense erosion that defines its final morphology (Lyell, 1865; Gagel, 1908; Hausen, 1969; de la Nuez, 1983; Staudigel and Schmincke, 1984; Carracedo *et al.*, 2001).

SITE 008

GEOLOGICAL PERIOD	Pliocene - Quaternary
LOCATION	La Palma Island Canary Islands, Spain. 28° 42' 60" N 017° 52' 34" W
MAIN GEOLOGICAL INTEREST	History of geosciences Volcanology

Caldera de Taburiente seen from inside the crater to the North wall. This big circular and deep volcanic morphology of La Palma Island served as a model for volcanic craters that are called 'Caldera'. This local name is used in Geology since the 19th century by geologist who studied Taburiente and 'caldera' is used worldwide as a volcanic term.

Geological Description

This large volcanic structure that forms a crater 8 km in diameter and more than 2000 m deep has been the model for defining large volcanic craters from the local name of 'Caldera'. This local term, which comes from the aborigines of the island, is used to define this circular volcanic morphology of large diameter, almost vertical inner walls, which stands out and its great depth.

Nowadays, Taburiente is one of the best examples of a deep erosive volcanic caldera that records great erosive processes that predominate in an oceanic volcanic environment. Giant landslides and the deep fluvial incision of the Las Angustias gorge has connected the Caldera with the Atlantic Ocean throughout the Late Pleistocene and Holocene (Carracedo *et al.,* 2001). Precisely because of these intense erosional and tectonic processes, it is possible to observe the interior of the island from the early submarine stages of Pliocene age and the intense magmatic and dyke intrusion triggered metamorphic processes in the primitive seamount, which uplifted it up to 1500 m asl (de la Nuez, 1983 Staudigel and Schmincke, 1984). The subaerial volcanic reactivation continued during the initial stages and Pleistocene volcanic activity was dominated by superimposed volcanoes.

Reproduction of the physical map made by Leopold von Buch in 1814 showing the Taburiente Caldera as one of the main volcanic features of the La Palma Island (Canary Islands, Spain).

Scientific research and tradition

Taburiente Caldera is linked to renowned naturalists of the nineteenth and twentieth century worldwide. L. von Buch (1825) traveled to the Canary Islands on the express recommendation of A. von Humboldt. But it was Lyell and Hartung, who make specific reference to the Spanish term "caldera" in Taburiente to refer to this great volcanic morphology. During the 20th century, scientific expeditions continued with the researchers as Gagel, Jeremine, Middlemost, Schmincke, Staudigel, Hernández-Pacheco, de la Nuez, Carracedo, among others.

QUATERNARY GLACIAL VARVES OF RAGUNDA

SWEDEN

Historical photo of Storedan – De Geer's actual sample area in Ragunda. The area is today overgrown as river regulation has allowed vegetation to cover the banks. (Photo: Hans W:son Ahlmann, in Ahlmann. 1915).

A KEY SITE FOR THE FINAL INTERPRETATION AND COMPLETION OF VARVE CHRONOLOGY BY GERARD DE GEER.

Gerhard De Geer invented the first absolute geochronology method and system. The glacial clay varve chronology is the result of sampling covering a huge area in Sweden, but the final correlation could be made from samples from the bottom layers of the pre-existing Ragundasjön lake. While the age of the ice recession in Sweden was the original scientific target, the system and method has proven to be of global importance, as it allowed the geological science to take its primary step from relative to absolute dating.

SITE 009

GEOLOGICAL PERIOD	Quaternary / Holocene
LOCATION	Sweden, Jämtland County, Ragunda. 63° 07' 10'' N 016° 21' 27'' E
MAIN GEOLOGICAL INTEREST	History of geosciences

Detail of the varves at a geosite at Remmarna in the Ragunda area, where De Geer finalised his geochronology work. (Photo: Geopark Indalsälven/Peter Ladan).

Geological Description

De Geer built up a varve chronology from Skåne to Jämtland in central Sweden, a year-by-year chronology of glacial retreat for the Late-glacial period (De Geer, 1912). This chronology was not only the most precise and accurate geological timescale of its day, it was the first absolute time-scale, showing the exact record of the end of the last ice age. His research showed that it took 1073 years for the land-ice to retreat from Stockholm to Ragunda in central Sweden, a distance of 500 km. Later, in 1940, he published his major and classic scientific paper, the Geochronologia Suecica Principles, in which he presented the full Swedish Time Scale, a floating varve chronology for ice recession from Skåne to Jämtland.

As varves as such are found in many geological environments, the varve chronology system has with time proven to be of wider use and importance. Along with new dating methods, like radiocarbon dating, the system has during the twentieth century been both challenged and improved. The full plethora of De Geer's ideas on varve chronology for global correlation have not stood the test of time, but the essence of the method has proven a solid tool for modern geological science.

Gerard De Geer. As it appeared in the obituary by Madsen, V. (1943).

Scientific research and tradition

Since the construction of the varve chronology by De Geer, there have been revisions as new sites are discovered, and old ones are reassessed. At present, the Swedish varve chronology encompasses thousands of sites and covers about 14,000 varve years. International application and use have followed.

GENBUDO CAVE
JAPAN

UNESCO Global Geopark

Genbudo and two caves, which are the remnants of digging, where rocks were used for construction against natural disasters but are now preserved as a monument. (Photo: Noritaka Matsubara).

LOCATION WHERE GEOMAGNETIC REVERSED POLARITY WAS FIRST PROPOSED THROUGH STUDYING BASALTS.

Around 100 years ago, Motonori Matuyama first proposed geomagnetic reversal in Genbudo. This discovery greatly contributed to the subsequent advancement of earth science; for example, ocean-floor paleomagnetic stripes based on magnetic normal and reversed polarity intervals advanced model of plate tectonics in the late 1960s (Vine and Mattherws, 1963).

The age of the basalt was determined in 1966, and their geological mapping was completed in 1991. Good exposures in Genbudo Park are quarries worked before the designation of the natural monument. Hexagonal disks of their columns of basalt were used for river banks, fire walls, and house fences. Such findings are useful for educational purposes.

SITE 010

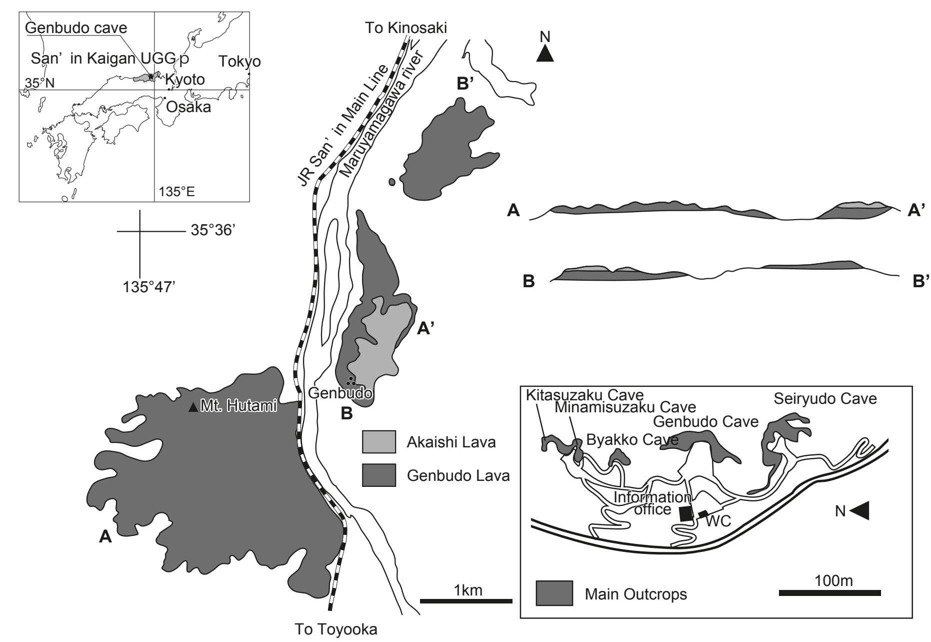
GEOLOGICAL PERIOD	Quaternary / Pleistocene
LOCATION	San'in Kaigan Geopark. Hyogo Prefecture. Japan. 35° 35' 17" N 134° 48' 18" E
MAIN GEOLOGICAL INTEREST	History of geosciences

Seiryudo Cave in the Genbudo Cave park, with its regularly but complexly oriented columnar jointing, is an excellent site for scientific research, education, and sightseeing. (Photo: Noritaka Matsubara).

Geological Description

Genbudo is one of the Quaternary Monogenic Basalt volcanoes in central Japan. The lava of Genbudo Cave is 1.61-Ma alkaline basalt (Genbudo Research Group, 1991; Kawai and Hirooka, 1966). It exhibits spectacular columnar jointing reflecting its complex cooling history. In 1926, Dr. Motonori Matuyama discovered that the basalt of Genbudo Cave exhibited magnetic polarity opposite to the present geomagnetic field. This discovery led to the recognition of the presence of a period of the earth's magnetic field opposite to the present, and in 1929, he proposed "geomagnetic reversal polarity" (Matuyama, 1929). The geomagnetically reversed period, including the age of Genbudo, was named "Matuyama Reversed Chron" in the 1960s, whose start corresponds to the beginning of Quaternary.

Ritsuzan Shibano, a Confucian scholar, visited Genbudo Cave in 1807 and named it Genbudo because he compared the outcrop's irregularly oriented columnar joints to a Chinese legendary animal, Genbu (black tortoise). In 1884, Koto Bunjiro named the basalt "Genbugan" in Japanese from Genbudo, whose Chinese characters are used also in China. In 1931, Genbudo Caves were designated as a national natural monument. Since then, they have been preserved and managed as educational sites, accessible only for research.



Geological Map around the Genbudo Cave Park. Five caves in the Genbudo Cave Park are the ruins of quarries.

Scientific research and tradition

Matuyama proposed the first geomagnetic reversal polarity approximately 100 years ago. The 2.58–0.774-Ma period was adopted as "Matuyama Reversed Chron" in the 1960s (Cox *et al.,* 1964). The Matuyama Reversal was established as the start of Quaternary (Head *et al.,* 2008).

GSSP FOR THE SILURIAN-DEVONIAN BOUNDARY AT KLONK HILL

CZECH REPUBLIC

A view of the monument in front of the Klonk hill near Suchomasty B –The GSSP section. The yellow line marks the Silurian-Devonian boundary.

THE FIRST GLOBAL BOUNDARY STRATOTYPE SECTION AND POINT (GSSP).

During the second half of the 20th century the International Commission on Stratigraphy (ICS) and the International Union of Geological Sciences (IUGS) developed criteria and procedures for approval and formal ratification of GSSPs. This lead to the first GSSP at Klonk, what was ratiifed at the 24th International Geological Congress in Montreal 1972 . Since then, 77 more GSSPs have been ratified for the system, series, and stages of the ICS International Chronostratigraphic Chart – Geologic Time Scale. The GSSP for the Silurian-Devonian boundary at Klonk was the first achievement in the most successful multi-decadal, international endeavor of the International Commission on Stratigraphy.

SITE 011

GEOLOGICAL PERIOD	Silurian - Devonian
LOCATION	Suchomasty village Central Bohemia Czech Republic. 49° 54' 03'' N 014° 03' 40'' E
MAIN GEOLOGICAL INTEREST	History of geosciences Stratigraphy and sedimentology

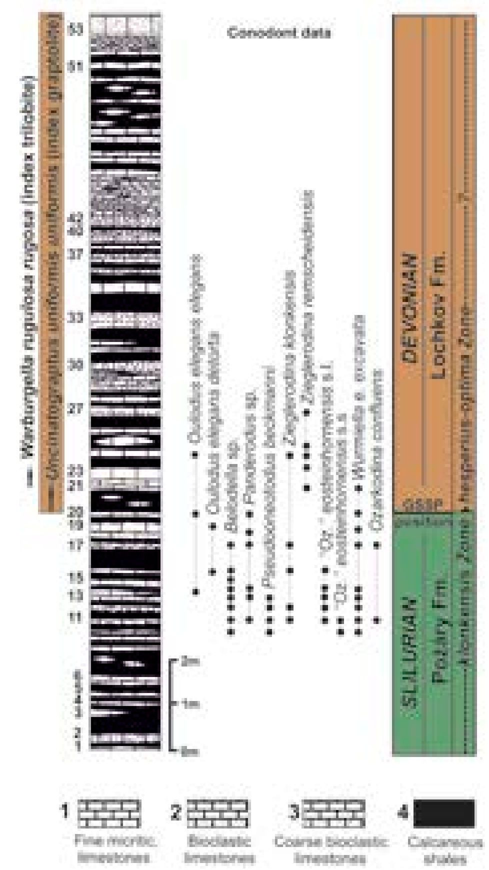
A close-up view of the boundary interval, the base of the Devonian is in the upper part of Bed 20.

Geological Description

The Klonk section is situated in the southwestern part of the Prague Synform, which is a part of Teplá-Barrandian Unit (Bohemian Massif, Czech Republic). In its present form, the central part of the Prague Synform is an asymmetrical elliptical structural depression, which represents an erosional relic of Lower Paleozoic volcanosedimentary successions (Knížek *et al.,* 2010). The stratotype section itself is a large natural escarpment exposed on western slope of the Klonk hill. The GSSP boundary interval consists of a well bedded uppermost Silurian (Přídolí) and lowermost Devonian (Lochkovian) sequence formed by alternation of fine-grained, mostly dark grey limestone layers and dark calcareous shale layers. The first rock types correspond mostly to distal calciturbidite and current-related drifted sediment, and the latter have a significant proportion of pelagic material that was dissolved and condensed in early stages of lithification (Chlupáč *et al.,* 1972; Chlupáč and Vacek, 2003, and Hladil, 1991). The S/D boundary level is in the upper part of bed No. 20 with no marked change in lithology where the index graptolite *Uncinatograptus uniformis uniformis* (Přibyl) first appears. Beside the base of the Devonian System, this level defines also the base of the Lower Devonian Series and the Lochkovian Stage.

Scientific research and tradition

The problem of the Silurian-Devonian boundary had been controversial since the second half of the 19th century. It is known in literature as "The Hercynian Question". Accordingly, the Klonk section since its first description (Chlupáč *et al.,* 1972) attracted many specialists and more than 50 research articles appeared.



Biostratigraphic data from the section (conodonts, graptolites and trilobites) in relation to the GSSP, modified according to Slavík (2017) and Slavík and Hladil (2020).

2

STRATIGRAPHY AND SEDIMENTOLOGY

SITE 012 - SITE 023

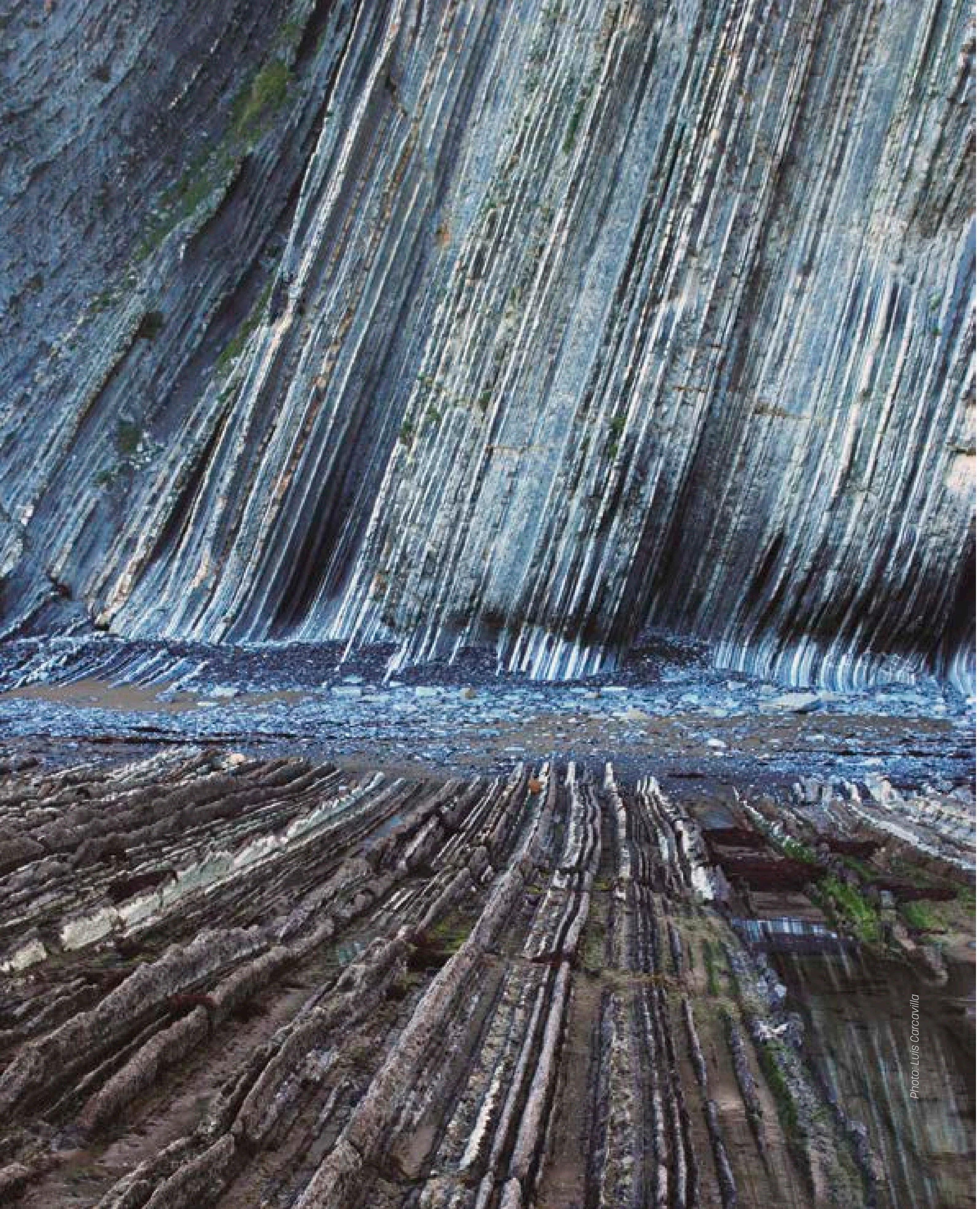


Photo: Luis Carcavilla

David A.T. Harper
Durham University. Durham. UK.
Chair. IUGS International Commission on Stratigraphy (ICS).
IUGS Geological Heritage Sites voting member.

Jin Xiaochi
Chinese academy of Geological Sciences. China.
IUGS Geological Heritage Sites voting member.

Stratigraphy is the oldest of the disciplines in the earth science, providing a framework to chart the passage of time, from the origin of the Earth to the present, and understand the biological and geological evolution of our planet. Scientists, such as Leonardo da Vinci (1452-1519), began to study the order and sequence of geological events during the Renaissance when artists rediscovered and applied perspective to landscapes. The Danish polymath Nicolaus Steno (1638-1686) developed the concept of superposition and illustrated the lateral continuity of strata in sedimentary basins. Whereas a century later Giovanni Arduino (1714-1795) building on the work of Johann Lehmann (1719-1767) had already applied superposition to mountain belts, mapping primary, secondary and tertiary successions. William Smith (1769-1839) added an essential part of the stratigrapher's toolkit by introducing the law of 'Correlation by Fossils' during his research in England and Wales culminating in the first geological map, published in 1815. The dimension of deep time was added by James Hutton (1726-1797) whose understanding of the significance of unconformities, at the Scottish localities of Siccar Point, Arran and Jedburgh, suggested that there was 'no vestige of a beginning, no prospect of an end'. The Earth was thus very old.

Stratigraphy has a number of key components. Lithostratigraphy is the establishment of rock-based units. Biostratigraphy, using zone fossils, forms the basis for correlation, and it can now be investigated using a range of quantitative techniques. Chronostratigraphy, global standard stratigraphy, is the division of geological time into workable intervals with reference to type sections in the field including Global Stratotype Sections and Points (GSSPs). Cyclostratigraphy links rhythmic changes in the chemical and physical properties in rock successions with Milankovitch cycles. Sequence stratigraphy can also provide more refined frameworks that can also help understand biological and geological change. Geochronometry is based on absolute time. This together with orbital-tuning calibrate chronostratigraphy; the dates deliver rates of biological and geological processes through deep time.

This section documents nearly 30 spectacular geological sites that each illustrate a unique event in the history of our planet. Many of these events changed the course of Earth history. Evidence of early life in the Archean Barberton Mountains, the legacy of the Great Oxygenation Event, the Ediacara Biota, the Cambrian Explosion in the remote mountains of Peary Land or the Great Unconformity in the Grand Canyon are among the oldest sites presented.

Three global stratotypes are illustrated in the next three vignettes: The base of the Devonian System was the first ratified GSSP; the GSSPs for the base of the Triassic System together with that for the Changhsingian Stage (Permian) have been the focus for research on the end Permian extinctions or the 'Great Dying'. The highest GSSP, for the Meghalayan Stage, is defined in the unusual medium of a stalagmite, coincident with a near-global drought that ravaged civilizations.

The iconic angular unconformity between Upper Carboniferous and Upper Triassic strata, exposed along the Portuguese coast, the most complete Early Cretaceous record of marine reptiles in Colombia and the Bottaccione Gorge section through the K/Pg boundary in Italy are among the sites selected for the Mesozoic Era. Later, during the Neogene massive eruptions of Miocene ignimbrites on and within rivers and lakes with mammal faunas formed a unique landscape of Fairy-Chimneys in Capadoccia. The Badain Jaran Desert is characterized by the largest megadunes on the planet. The megadune-lake environments are spectacular, and a unique region to research contemporary climate change in the monsoon transition zone.


The Cambrian Explosion in Sirius Passet
GREENLAND
Cretaceous – Paleogene stratigraphic section of Zumaia
SPAIN
Cretaceous to Paleogene stratigraphic section of Bottaccione Gorge
ITALY
The Ordovician rocks of Mount Everest
NEPAL
CHINA
The Great Unconformity at Grand Canyon
USA
Carboniferous-Triassic Unconformity in Telheiro
PORTUGAL
Permian-triassic extinction and GSSPs of Meishan
CHINA
GSSP of the Meghalayan Stage in the Mawmluh Cave
INDIA
Glacial record of the Marinoan snowball Earth
NAMIBIA
Paleoproterozoic Banded Iron Formation of the Quadrilátero Ferrífero
BRAZIL
Archaean Barberton Greenstone Belt
SOUTH AFRICA
Cretaceous-Paleogene transition at Seymour (Marambio) Island
ANTARCTICA

ARCHEAN BARBERTON GREENSTONE BELT

SOUTH AFRICA

UNESCO World Heritage Site

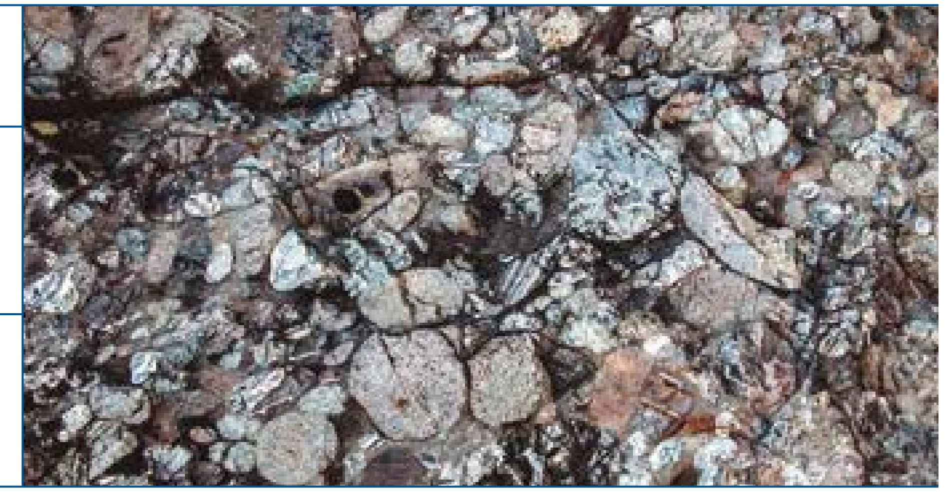
General view of the Barberton Makhonjwa Mountains, where part of the Barberton Greenstone Belt is exposed.

UNIQUE REMNANT OF ANCIENT EARTH'S CRUST, CONTAINING AMONG THE OLDEST, AND THE BEST-PRESERVED SEQUENCE OF VOLCANIC AND SEDIMENTARY ROCKS ON EARTH.

The outcrops of the Barberton Greenstone Belt, designated as Barbeton Makhonjwa Mountains UNESCO World Heritage Site in 2008, have "provided a globally unique source of information about the earliest measurable conditions of the Earth's gradually solidifying oceanic crust 3.5 billion years ago." (UNESCO World Heritage Documents, 2018). It shows evidence of the Earth's earliest life forms such as photosynthetic microbial mats (Homann, 2019), the earliest continent-forming processes, and the earliest large meteorite impact events. It is 'type-locality' of the distinctive komatiite volcanic rocks and pillow lavas, and it contains the oldest migmatites at the Greenstone Belt margins.

SITE 012

GEOLOGICAL PERIOD	Hadean / Eoarchean (4.3 – 3.8 Ga)
LOCATION	South Africa, Mpumalanga Province, and Eswantini. 25° 30' 00" S 030° 30' 00" E
MAIN GEOLOGICAL INTEREST	Stratigraphy and sedimentology Paleontology



Moodies Group polymict conglomerate pebbles and granitic material (dated at ca. 3500 Ma) from the base of the Eureka Syncline northeast of Barberton. The conglomerate is largely undeformed but have been intensely flattened (Photo Credit: Carl Anhaeusser).

Geological Description

The Barberton Greenstone Belt is a rugged mountain terrain of substantially untransformed Archaean rocks (Armstrong *et al.*, 1990; de Wit *et al.*, 1994; Lowe, 1994; Homann, 2019). The BGB contain the best-preserved, oldest, and most diverse sequence of volcanic and sedimentary rocks on Earth that has not been affected by subduction (and metamorphism) and erosion. The BGB is a complex of volcanic, sedimentary, and shallow intrusive rocks ranging in age from 3.6 to 3.25 Ga, and it is 15 km thick (Lowe and Byerly, 2007; Homann, 2019). The BGB is divided into three main lithostratigraphic units: from base to top:

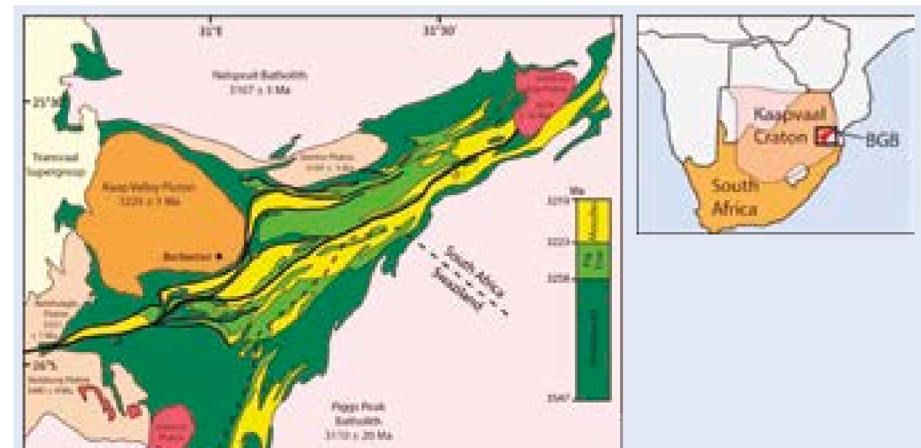
The Onverwacht, Fig Tree, and Moodies Groups. The Onverwacht Group (3.6-3.26 Ga), which exceeds 10 km in stratigraphic thickness, is composed largely of mafic and ultramafic volcanic rocks with subordinate felsic volcanic flow units and tuffs and thin interbedded impure cherts. Ultramafic and mafic rocks of 3.33 to 3.24 Ga age and ~1000 m thick bound the western and northern edge of the belt.

The Fig Tree Group (3.26-3.225 Ga), ~1800m thick, is a transitional unit composed of interlayered volcaniclastic strata and terrigenous clastic units eroded from uplifted portions of the underlying greenstone succession.

The Moodies Group (post 3.225 Ga) is composed of up to 3000m of coarse, quartzose and feldspathic sandstone and chert-clast conglomerate derived by erosion of underlying greenstone units and uplifted plutonic rocks (Lowe and Byerly, 2007).

Scientific research and tradition

The Barberton Greenstone Belt is a well-researched terrain since mostly the 1960s by researchers from all over the world particularly South African Universities. From these rocks, more has been learned than from anywhere else about the surface processes at work as the Earth cooled from a molten body to the creation of the primitive biosphere and lithosphere.



Geological map of the Barberton Greenstone Belt (Source: Homann, 2019)

PALEOPROTEROZOIC BANDED IRON FORMATION OF THE QUADRILÁTERO FERRÍFERO

BRAZIL

Aerial view of Pico do Itabirito formed by a compacted hematite monolith surrounded by an open pit iron ore mine in BIF.

ONE OF THE MOST IMPORTANT RECORDS OF PALEOPROTEROZOIC BIF ON EARTH AND PLACE OF FERRUGINOUS CAVES.

The Banded Iron Formation (BIF) in the Quadrilatero Ferrifero is a Lake Superior-type iron deposit formed at the beginning of the Great Oxygenation Event. During the Cenozoic the wetter climate favored weathering that enriched iron minerals, which produced economically significant iron ore bodies.

Duricrust is formed by iron oxide and hydroxide (ferricrete) close to the top of weathering profiles in the BIF. These capstone deposits, named regionally as canga, are resistant to erosion and are host to small caves that are the first to have been described in detail in ferruginous rocks (Auler *et al.,* 2014; Simmons, 1963).

SITE 013

GEOLOGICAL PERIOD	Paleoproterozoic
LOCATION	State of Minas Gerais, Brazil. 20° 14' 25'' S 043° 52' 01'' W
MAIN GEOLOGICAL INTEREST	Stratigraphy and sedimentology Geomorphology and active geological processes

Outcrop of folded metamorphic BIF in Serra da Piedade Protected Area.

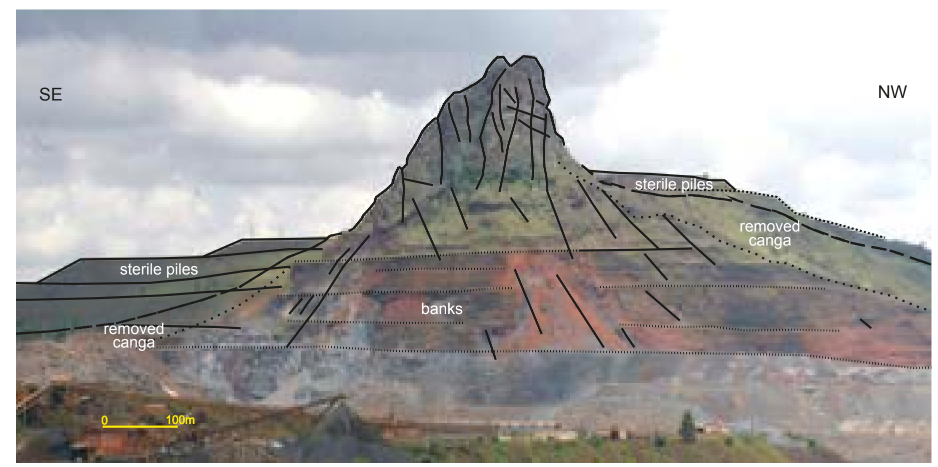
Geological Description

The most conspicuous Banded Iron Formation in Quadrilátero Ferrifero, together with marbles, dolomites and hematitic and dolomitic phyllites, constitute the Cauê Formation of the Supergroup Minas. These rocks are Paleoproterozoic in age, up to 350 m thick, 2.42-2.58 GA, and deposited in a shallow marine ocean (Spier *et al.,* 2003). They are capped by dolomitic BIF and dolomites of the Gandarela Formation, which exhibit biogenetic structures such as stromatolities and algal mats. These rocks have been deformed in two Proterozoic orogenies.

The Cenozoic climate favored weathering, which leached silicious and carbonate minerals of the the BIF and enriched iron minerals. This porcess has produced bodies of iron ore thaty have up to 75% FeO. These deposits are of global significance. Iron mines in the region produced more than 3.0 billion tons of iron in the last 20 years. The weathering profile is the oldest and most continuous known (Spier *et al.,* 2006). The leasching at the tip of the BIF produced duricrust, which is formed by iron oxide and hydroxide (ferricrete). The Duricrust prevents erosion and is regionally called canga.

Scientific research and tradition

The BIF oucrops were landmarks for European and African populations in the region since the 18th century, and decribed by scientists in the 19th century. These deposits have been the subject of geochemical and tectonic investigations, as well as studies on the genesis of duricrusts and related cave formation.



Reconstitution of Pico do Itabirito, drawn on current photography. Designed based on 19th century paintings and on Rosiere et al. (2009)

GLACIAL RECORD OF THE MARINOAN SNOWBALL EARTH

NAMIBIA

Abrupt contact between terminal ice-rafted carbonate debris and postglacial cap dolomite, western terminus of Fransfontein Ridge near Narachaams se Pos. (Photo: Luis Carcavilla)

STRATIGRAPHIC RECORD OF A SNOWBALL EARTH FROM ONSET TO TERMINATION ON THE FORESLOPE OF A WARMWATER MARINE CARBONATE PLATFORM.

During snowball Earth, ice sheets covered most continents causing large sea- level falls. This, combined with thick shelf ice, shifted sediment accumulations from continental shelves to slopes. Slopes were relatively narrow and the probability of fortuitous exposure 635 million years later is low. Snowball Earths are rare, occupying only 1.5% of Earth history. Evidence of glaciated carbonate platforms is critical because, due to saturation chemistry, they represent the warmest parts of the ocean. If they were glaciated, colder regions were frozen also. This was the first line of evidence for snowball Earth, much later supported by many independent lines of evidence.

SITE 014

GEOLOGICAL PERIOD	Upper Cryogenian – Early Ediacaran
LOCATION	Fransfontein Ridge Kunene Region, Namibia 20° 11' 51" S 015° 01' 11" E
MAIN GEOLOGICAL INTEREST	Stratigraphy and sedimentology

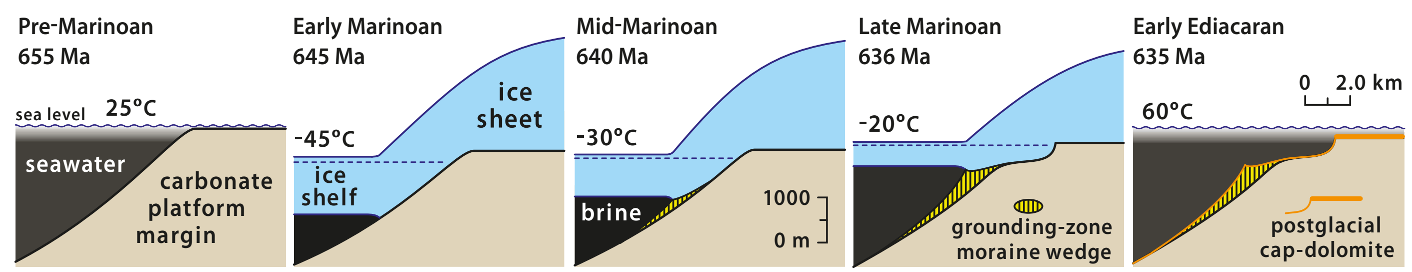
Ice-rafted dropstone (oolitic limestone) in proglacial carbonate turbidites, illustrating impact structures including an ejected flap below the 2 cm coin on the first post-impact layer.

Geological Description

On Fransfontein Ridge, the margin of an ancient warmwater marine carbonate platform is exposed in oblique cross-section, allowing its construction to be examined in detail (Hoffman *et al.*, 2021). During its growth, Earth experienced a 6–16 million-year panglacial epoch when the world ocean was covered by an unbroken ice shelf hundreds of metres thick (Hoffman *et al.*, 2017). A grounded ice sheet formed on the carbonate platform, fed by sublimation off the tropical ice shelf. Its motion was slow, because cold air holds little moisture, but its longevity caused cumulative glacial erosion and deposition that reshaped the platform margin. Headwall erosion at the top of the foreslope produced a bench 0.4 km vertically below the top of the platform (Hoffman, 2022). On the slope below the bench is a composite moraine, ≤0.6 km thick, marking the grounding zone of the ice shelf (Domack and Hoffman, 2011). The moraine rests on a glacial erosion surface to ≥0.6 km paleodepth below the bench, reflecting initial ice-shelf thickness and sea-level fall. During snowball Earth meltdown, the entire platform and margin were covered by a 'cap dolomite' (Hoffman, 2011) that occurs globally and defines the base of the Ediacaran Period.

Scientific research and tradition

Stratigraphic, sedimentologic, isotopic and radiometric evidence from Fransfontein Ridge was critical in the framing and broad acceptance of the snowball Earth hypothesis for Cryogenian glaciations (Hoffman *et al.*, 1998). Stratigraphic sections logged over the past 30 years are currently being stitched together with the aid of high-resolution drone-based imagery.



Schematic reconstructions of the south-facing Otavi Group platform margin before, during and after the Marinoan snowball Earth, based on stratigraphic relations exposed on Fransfontein Ridge.

THE CAMBRIAN EXPLOSION IN SIRIUS PASSET

GREENLAND

The main section in Sirius Passet, showing the white carbonate rocks of the Portfjeld Formation, faulted against the dark, metamorphosed muddy siltstones of the Buen Formation; the main section is in the brown strata in the centre of the photograph (Photo: Paul Smith).

THE MOST REMOTE AND CURRENTLY LEAST WELL-KNOWN OF THE 'CAMBRIAN EXPLOSION' SITES, YIELDING EXCEPTIONALLY-PRESERVED FOSSILS.

The setting in the mountains of North Greenland is spectacular; the completely exposed section indicates the relationship between the Upper Precambrian (white) rocks and the lower Cambrian (dark) strata (photo above) containing an abundant and diverse fauna, dominated by arthropods (photo next page) with soft-part preservation of gut contents, muscles and nervous systems within a remote but accessible section.

Most of the animals have not been transported and represent a living community in relatively deep-water environment. The fauna provides a unique insight into some of the first complex ecosystems, dominated by animals, positioned in a more modern structured food chain (Harper *et al.*, 2019).

SITE 015

GEOLOGICAL PERIOD	Upper Neoproterozoic
LOCATION	Peary Land, North Greenland. 82° 47' 35" N 042° 13' 32" W
MAIN GEOLOGICAL INTEREST	Stratigraphy and sedimentology Paleontology

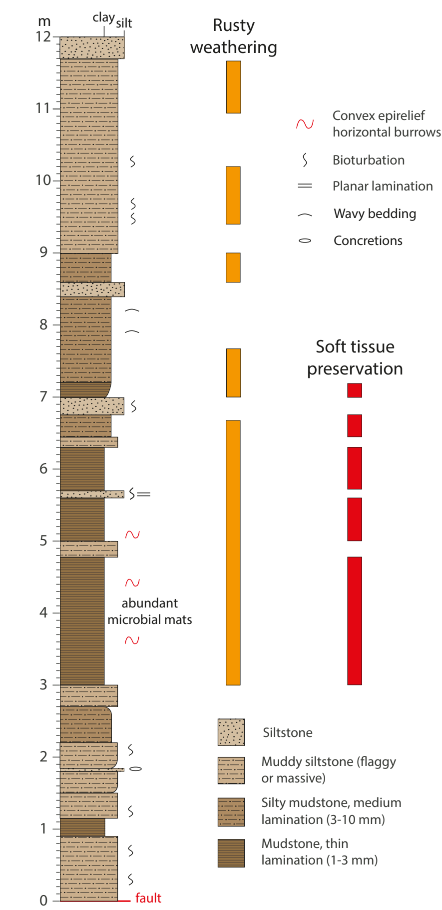
Beautifully preserved stem-group trilobitomorph, Arthroaspis (left); specimen approximately 200 mm in length, photo taken in the field under low Arctic light (Photo by David Harper). Pelagic predator Isoxys (right); scale bar 5 mm. (Photo by Arne Thorshøj Nielsen).

Geological Description

The site, in the Franklinian Basin, was discovered serendipitously by geologists in 1984 during regional mapping with the Geological Survey of Greenland. The first fossils turned out to be a Cambrian sponge and trilobites, and blocks from the site later revealed a partly sclerotized fauna with similarities to the much better-known Burgess Shale fauna from the Canadian Rockies. Subsequent expeditions have established large collections of fossils, and taxonomic work has already proved significant in understanding the origins and early evolution of animal phyla. The key properties of the site are the abundance and diversity together with the exceptional preservation of these early animals (Topper *et al.*, 2018); strata are correlated with middle to upper Cambrian Stage 3. Moreover, the environment can be identified as relatively deep-water, at the shelf–slope break, in low-oxygen conditions (Hammarlund *et al.*, 2019). Particularly exciting are the diverse arthropods and related forms (many are predators), some preserving guts, gut contents (Strang *et al.*, 2016) and muscles together with brains and nervous systems (Park *et al.*, 2018). Many new data are available to assess the ecology and taxonomy of individual animals, their phylogeny (Vinther *et al.*, 2014) and the communities in which they lived.

Scientific research and tradition

The site was discovered by the Geological Survey of Greenland in 1984 (Conway Morris *et al.*, 1987). Expeditions led by Peel (Geological Survey of Greenland), Harper (Natural History Museum of Denmark) and more recently Park (Korea Polar Research Institute) collected large numbers of fossils, significant in understanding the early evolution of animal phyla.



Geological section through the exposure of the Buen Formation in Sirius Passet (From Harper et al. 2019).

THE GREAT UNCONFORMITY AT GRAND CANYON

USA

UNESCO World Heritage Site

Two major unconformities of the Great Unconformity: 500 million years are "missing" below the Unkar Group (green arrow) and up to 1.3 billion years are "missing" where Cambrian strata overlie Vishnu Basement rocks. (Photo: Michael Quinn, NPS).

ONE OF THE MOST PROFOUND UNCONFORMITIES ON EARTH, WITH UP TO 1.3 BILLION YEARS OF EARTH'S HISTORY REMOVED BY EROSION

The Great Unconformity has multiple erosion surfaces, two shown in the photo above: a nonconformity where 1.25 Ga rocks of the Unkar Group rest on the 1.75 Ga igneous and metamorphic rocks of the Vishnu Basement (green arrow) with 500 million years of Earth's history "missing" (not recorded); and an angular unconformity where flat-lying 500 Ma Cambrian strata overlie tilted 1.25 to 0.73 Ga strata (red arrow, see Figure at lower right on opposite page). Important concepts for public science education: unconformities are the missing rock record that frames the rock record to provide an understanding of geologic time (Karlstrom and Crossey, 2019). The site is part of the Grand Canyon National Park UNESCO World Heritage Site.

SITE 016

GEOLOGICAL PERIOD	Mesoproterozoic, Neoproterozoic and Cambrian
LOCATION	Grand Canyon National Park in Arizona, USA. 36° 05' 13" N 112° 07' 07" W
MAIN GEOLOGICAL INTEREST	Stratigraphy and sedimentology

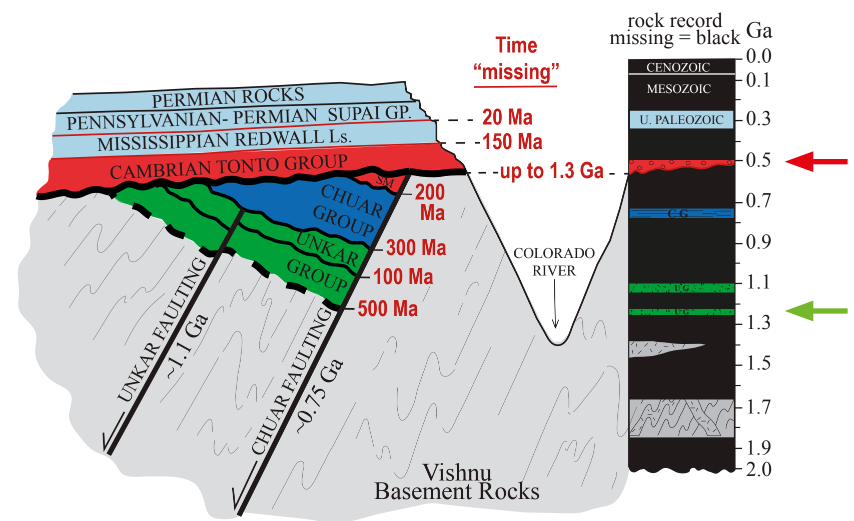
Geologist's hand spans 1.3 billion years of missing rock record across the erosional contact called the Great Unconformity: 1.84 Ga Vishnu Basement rocks below and 0.5 Ga Cambrian strata above. (Photo: Laura Crossey).

Geological Description

The vertical mile of rock revealed in Grand Canyon looks like a spectacularly complete rock record (and it is), but more time is missing than is preserved. Grand Canyon is the type location for a profound unconformity, found on many continents, that has Paleozoic sedimentary strata overlying the unroofed igneous and metaphoric core of ancient mountain belts (a nonconformity). Across this contact at Grand Canyon, up to 1.3 billion years of Earth History has been removed by erosion in several stages. As noted by Grand Canyon's preeminent stratigrapher and former park naturalist Eddie McKee (1969), this unconformity is a composite erosion surface. McKee summarized: "These unconformities were discussed by Powell (1875), who pointed out that each represents a sequence of events of tremendous importance in Earth history, including the formation of mountains by tectonic forces, the erosion of these mountains to a condition of base level, and finally, the burial of the erosion surface by sediments of advancing seas".

Scientific research and tradition

Recognition of great unconformities by John Wesley Powell led Clarence Dutton (1882) to name the Great Unconformity and identify Grand Canyon as its type area. This geologic feature remains of research importance as new geochronological and thermochronological tools are developed to quantify timing, magnitude, and causes of deep basement erosion (Karlstrom *et al.*, 2018).



Grand Canyon has one of the world's most complete geologic records, yet more time is missing (black) than preserved in the rock column at right. Red letters are approximate numeric ages for the time "missing" (not recorded) along each unconformity.

THE ORDOVICIAN ROCKS OF MOUNT EVEREST

CHINA AND NEPAL

The majestic slopes and summit of Mount Everest viewed from Gokyo Ri at 5.350m Above the sandstones of the Yellow Band, pale grey limestones here on the summit, and elsewhere have yielded Middle Ordovician (Darriwilian fossils). (Photo: Luis Carcavilla).

NOW LOCATED ON THE ROOF OF THE WORLD, THE HIGHEST ROCKS IN THE PLANET ARE FOSSILIFEROUS, MARINE LIMESTONE.

Mount Everest (Qomolangma) is the highest point on the Earth's crust, an iconic symbol of beauty and human achievement. Commonly known as the Roof of the World, or the Third Pole, the Himalayan plateau supports a unique ecosystem but also captures the evidence for the evolution of the best-known of the planet's tectonic belts (Myrow *et al.,* 2019). The summit of the mountain is a tropical Middle Ordovician limestone with abundant and diverse marine fossils that formed part of an ancient seafloor long before the collision of India with the Asian continent, which started about 55 million years ago.

SITE 017

GEOLOGICAL PERIOD	Middle Ordovician (Darriwilian)
LOCATION	Everest Range, Nepal and Tibet, China 27° 59' 17" N 086° 55' 30" E
MAIN GEOLOGICAL INTEREST	Stratigraphy and sedimentology Paleontology

Climbers cross the the pale grey and light brown limestones near the summit at 8500m, exhibiting cycles of shelf limestones and peritidal dolomites. (Photo: Luis Carcavilla).

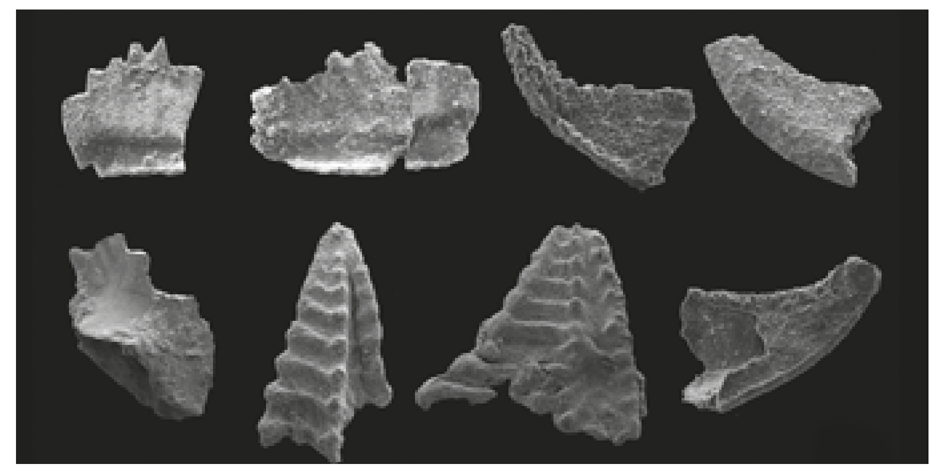
Geological Description

The highest rocks on Earth, marking the summit of Mount Everest, are Ordovician limestones, deposited in a warm, shallow-water sea some 450 million years ago. More remarkably, these rocks still contain the fossils of marine animals such as brachiopods, conodonts and crinoids that occupied tropical habitats during one of the most important intervals in Earth history, the Great Ordovician Biodiversification Event (GOBE). These rocks, deposited in an ancient Tethyan Ocean were thrust and uplifted into their present commanding position when Indian collided with the Asian continent some 55 million years ago.

Strata at lower altitudes, equivalent to those of the summit of Everest, have yielded new shallow-water faunas dominated by brachiopods and crinoids (Harper *et al.,* 2011) The shallow-water shelly faunas were dominated by suspension feeders including orthide and strophomenide brachiopods (Zhan *et al.,* 2014), and a robust pentameride crinoid, 'Pentagonopentagonalis' (col.) sp. (Donovan *et al.,* 2012). New conodont data precisely correlate part of the succession with the P. serra conodont Zone (upper Darriwilian); the Colour Alteration Index of the conodonts indicate a finite temperature of 350°C to 550°C (Stouge *et al.,* 2021). This fauna was part of the Toquima-Table Head Realm, a circum-equatorial province during the late Middle Ordovician.

Scientific research and tradition

An Ordovician age for the summit was established in the 1970s. The Ordovician also crops out at Jiacun, adjacent to the Lhasa - Kathmandu highway, north of Nyalam, at some 4.5 km altitude. Research continues on the sedimentology, tectonics and other aspects of the diverse faunas to piece together the geological history of this iconic part of the Earth's crust (Zhen *et al.,* 2021).



Key conodont species from the Chiatsun Group, providing a Middle Ordovician (middle-late Darriwilian) age for the summit of Mount Everest (From Stouge et al. 2021).

PERMIAN-TRIASSIC GREAT EXTINCTION AND GSSPs OF MEISHAN

CHINA

Photograph showing the Changhsingian Stage defined between Induan GSSP (left arrow) and Changhsingian GSSP (right arrow). This section has been intensively-studied containing several high-precision geochronology and lithostratigraphy points.

ONE OF THE MOST DETAILED AND DOCUMENTED RECORDS OF THE GREATEST PHANEROZOIC MASS EXTINCTION.

The Meishan D section is a unique section in containing two GSSPs including the base of the Triassic (thus the base of Mesozoic) (Yin *et al.,* 2001) and the base of the Changhsingian Stage (Jin et al., 2006). High-precision geochronology from multiple ash beds has provided a precise calibration for Earth's biggest mass extinction as well as rates of biodiversity, geochemical and paleoclimatic changes. The ash beds of the Meishan sections have been used as a natural laboratory for refining high-precision geochronologic dating, since the results of Bowring *et al.,* (1998). Magnetic polarity zones and astronomical cycles are also used for inter-continental correlation between marine and terrestrial successions around the Permian-Triassic boundary.

SITE 018

GEOLOGICAL PERIOD	Permian - Triassic
LOCATION	Changxing County, Zhejiang Province, southeast China. 31° 04' 51" N 119° 42' 22" E
MAIN GEOLOGICAL INTEREST	Stratigraphy and sedimentology Paleontology

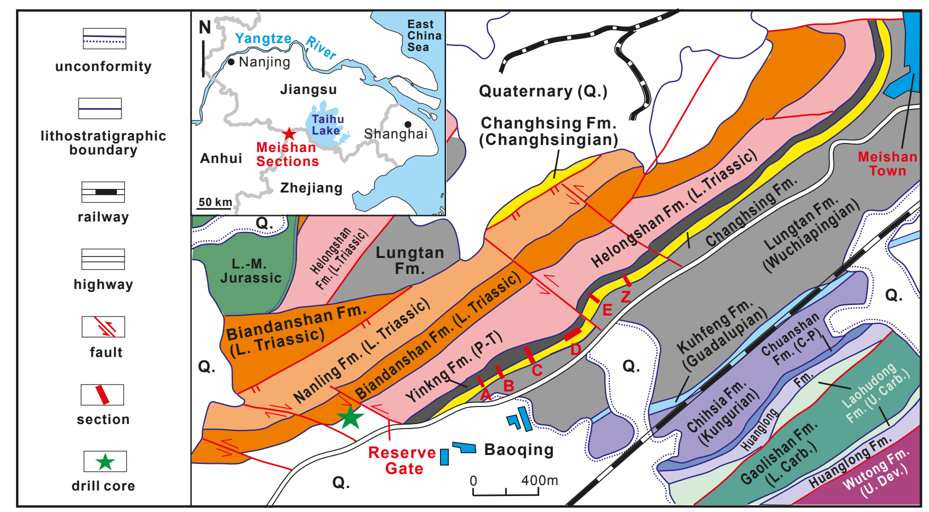
The end-Permian mass extinction interval and the Permian-Triassic boundary at the Meishan section C.

Geological Description

These Meishan GSSP sections are the most intensively-studied Lopingian (Upper Permian) and Permian-Triassic boundary sections in the world. The Permian strata contain a highly diverse tropical marine fauna, which includes more than 330 species belonging to 15 different fossil groups (Jin *et al.,* 2000). These sections possess the best record of the end-Permian mass extinction that occurred 251.94 million years ago when more than 81% (formerly ~96%) marine species became extinct within a time interval <61±48 kyr (Burgess *et al.,* 2014). Multiple geochemical records including C, O, Sr, S, Li, Zn, Hg and Ca isotopes have provided proxies for environmental deterioration leading to the extinction. These include a rapid 10°C temperature rise, euxinia and ocean acidification. The sections are correlated using high-resolution conodont and ammonoid biostratigraphic zones and geochronology. More than 30 volcanic ash beds have yielded eight high-precision CA-ID-TIMS dates. Detailed magnetostratigraphy and astronomical cyclostratigraphy also aid correlation. For many decades, the Meishan sections have been widely recognized as the premier location for world-wide correlation of the Permian-Triassic boundary (Yin *et al.,* 2001) and for understanding the biggest Phanerozoic biotic mass extinction (Jin *et al.,* 2000; Shen *et al.,* 2011).

Scientific research and tradition

The Meishan sections include excellent quarry exposures of the Permian-Triassic boundary and the entire Changhsingian Stage, and the reserve covers an area of 2.3 km². More than 200 articles and books were published including 11 in Science and Nature since Grabau first mentioned the site in 1932. The sections have been protected since 1981, and the site was named as the National Geoheritage Reserve of China in 2005.



Geological map of the Meishan area. A-E, Z refer to the sections (modified from Jin et al., 2006).

CARBONIFEROUS-TRIASSIC UNCONFORMITY IN TELHEIRO

PORTUGAL

General view of the Telheiro angular unconformity between upper Carboniferous metasedimentary rocks (flysch turbidites) and Upper Triassic red sandstones (Vila do Bispo, Portugal). (Photo: Diamantino Pereira).

ONE OF THE MOST ICONIC ANGULAR UNCONFORMITY IN THE WORLD.

This site is internationally known for being a very well exposed angular unconformity between Upper Carboniferous metamorphic rocks and Upper Triassic metasedimentary rocks.

This site is representative of four geological frameworks that supports the Portuguese inventory of geological heritage with national and international scientific value. It is also recognized for its scenic value created by the occurrence of rocks with different colors and structural feature. A photo of this site is on the cover of "Geoheritage in Europe and its conservation", edited by ProGEO in 2012, and "The Geology of Iberia: A Geodynamic Approach, Vol. 2 The Variscan Cycle", edited by Springer in 2019.

SITE 019

GEOLOGICAL PERIOD	Upper Carboniferous - Upper Triassic
LOCATION	Vila do Bispo, Algarve, Portugal. 37° 02' 59" N 008° 58' 48" W
MAIN GEOLOGICAL INTEREST	Stratigraphy and sedimentology Tectonics

Detail of the Telheiro angular unconformity between upper Carboniferous metasedimentary rocks and Upper Triassic red sandstones (Vila do Bispo, Portugal). (Photo: Filipe da Palma).

Geological Description

The outcrop of the Tehlheiro Unconformity located on the southwest coast of Portugal testifies the late phase of Pangea as a supercontinent and its initial break-up.

The most striking geological characteristics of this cliff are:

a. A flattened surface at the top of the cliff with preserved gravel beds corresponding to a Quaternary raised beach;

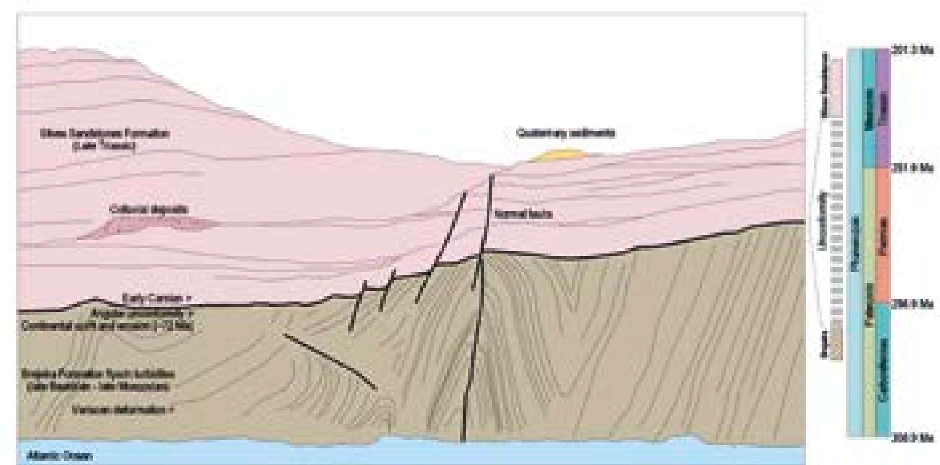
b. The Silves Sandstone Formation (Upper Triassic) is composed of reddish sandstone and siltstone beds, with thin intercalations of conglomerate. The beds exposed in the cliff correspond to the lower part of the formation. Its reddish color and the sedimentary structures like cross bedding suggest deposition in the middle part of continental alluvial fans under an arid climate. These strata represent the first stage of Pangea breakup (Gama *et al.,* 2021).

c. Angular unconformity between the Silves Formation on the top and the Upper Paleozoic flysch turbidites metasedimentary rocks of the Brejeira Formation at the bottom, encompassing ~72 Ma. During this period a basement uplift and erosion of a significant part of the Variscan Chain took place.

d. Brejeira Formation [Bashkirian (320 Ma) - Moscovian (307 Ma)] is composed of a thick (>1000m) turbidite sequence formed by shale and graywacke alternations that exhibit clear sedimentary structures (Oliveira, 1990; Jorge *et al.,* 2013). This formation was affected by the Variscan orogeny, that produced subvertical fols and shistose cleavage (Ribeiro *et al.,* 2007).

e. At the bottom of the cliff the current marine abrasion platform is visible.

Interpretation of the Telheiro angular unconformity.



Scientific research and tradition

The Silves Sandstone Formation was described for the first time in 1887 by Paul Choffat, a Swiss geologist working for the Portuguese Geological Survey. A detailed study of this formation was done by Palain (1976). The Carboniferous flysch of Southern Portugal has been studied extensively since mid-20th century (Oliveira *et al.,* 2019 and included references).

CRETACEOUS TO PALEOGENE STRATIGRAPHIC SECTION OF BOTTACCIONE GORGE, GUBBIO

ITALY

Upper part of the Bottaccione Gorge section, showing the Campanian and Maastrichtian part of the section. A medieval aqueduct is also seen. (Photo by Birger Schmitz).

ONE OF THE MOST COMPLETE CRETACEOUS TO PALEOGENE PELAGIC LIMESTONE SECTIONS KNOWN, AND WHERE THE K-PG IRIDIUM ANOMALY WAS FIRST FOUND.

The section is a global reference succession for bio-and magnetostratigraphy across the Cretaceous and Paleogene, including the K-Pg boundary. Here pelagic limestones were first dated with foraminifera in thin section, long-section magnetic polarity-reversal stratigraphy was first established, and the K-Pg iridium anomaly was first detected. Reconstructions have also been made of Earth's orbital cycles and variations in flux of extraterrestrial matter from different regions of the solar system. Every year the section is visited by hundreds of geologists. Many students learn here the basics of reading Earth's history from its stratigraphic record.

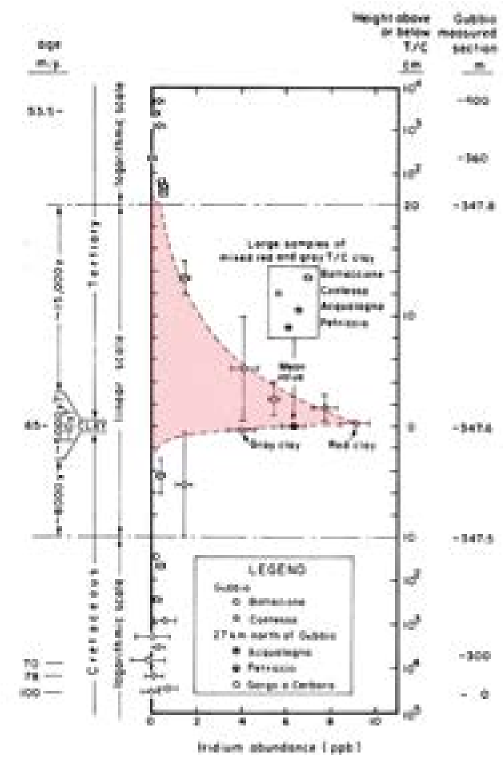
SITE 020

GEOLOGICAL PERIOD	Cretaceous - Paleogene
LOCATION	Umbria, Italy. 43° 21' 55" N 012° 34' 57" E
MAIN GEOLOGICAL INTEREST	Stratigraphy and sedimentology History of geosciences

Cretaceous-Paleogene boundary interval at the Bottaccione section. (Photo: Marco Menichetti).

Geological Description

The Bottaccione Gorge at Gubbio was the first major outcrop of pelagic limestone ever studied. Here the identification of planktonic foraminifera in thin section was first applied to hard rocks from which isolated foraminifera could not be extracted (Renz, 1936; Luterbacher and Premoli Silva, 1962). Anomalous levels of iridium were first reported from the K-Pg boundary at this and nearby localities (Alvarez *et al.*, 1980). Iridium is present in meteorites but essentially absent in Earth's sediments, which led to the theory that a large comet or asteroid impacted the Earth, triggering the K-Pg mass extinction. This theory was later confirmed by the discovery of the 150-km diameter Chicxulub structure in the subsurface of the Yucatán Peninsula of Mexico, the largest impact crater known from the last billion years of Earth history. Magnetic polarity reversal stratigraphy of limestones was first done in the Bottaccione Gorge, with the foraminiferal biostratigraphy making possible the dating of the magnetic polarity stripes on the ocean floor, and in turn the dating of the opening of the Atlantic Ocean by sea-floor spreading (Lowrie and Alvarez, 1981). Lately, a high-resolution cyclostratigraphic framework has been established at the section. For a review see e.g., Galeotti *et al.* (2015).



The iridium profile across the Cretaceous-Paleogene boundary from samples collected in several Scaglia Rossa sections throughout the Umbria-Marche basin, as reproduced from fig. 5 in Alvarez et al. (1980). Note the linear scale (in cm) in the 15 cm interval bracketing the boundary interval (from Montanari and Coccioni, 2019).

Scientific research and tradition

The section has been the subject of scientific research since the pioneering work of Renz in 1936. During the '60s and '70s, the analysis of the section contributed to an integration of bio- and magnetostratigraphy. The section is visited by hundreds of geologists from all over the world every year.

CRETACEOUS-PALEOGENE TRANSITION AT SEYMOUR (MARAMBIO) ISLAND

ANTARCTICA

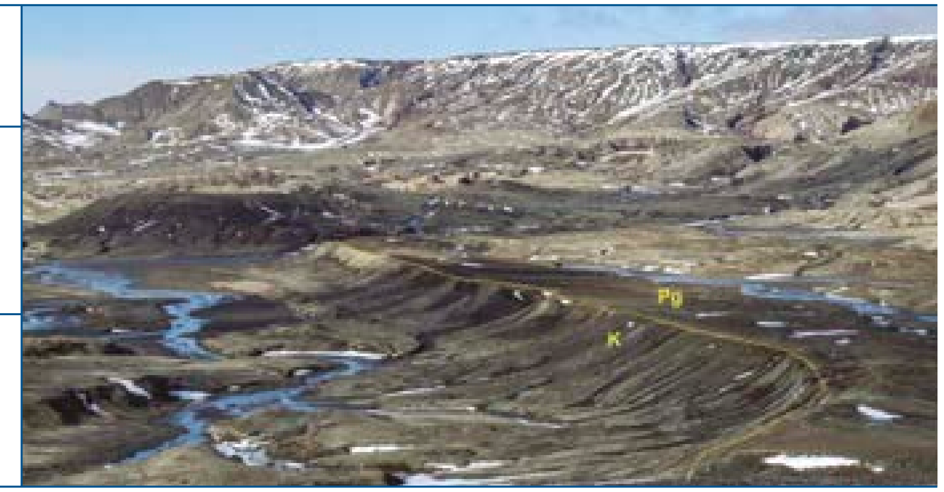
Photograph showing the K-Pg boundary at the site of the iridium anomaly identification.

THE MOST REPRESENTATIVE HIGH LATITUDE K-PG BOUNDARY LOCATION AND ONE OF THE MOST SIGNIFICANT AND BEST EXPOSED GLOBALLY.

The location represents one of the best sites globally for the study of the K-Pg global mass extinction event. The exposure is exceptional and continuous. The site has been subject to substantial international research. It is a key southern hemisphere site for the study of palaeontology, biostratigraphy, geochemistry and magnetostratigraphy. The location contains evidence that the K-Pg extinction in the high latitudes was just as extensive as in lower latitude sites closer to the asteroid impact site. Extensive geological mapping and many books and research articles have been published in scientific journals (Feldmann and Woodburne, 1988; Francis *et al.,* 2006).

SITE 021

GEOLOGICAL PERIOD	Cretaceous-Paleogene (K-Pg) transition
LOCATION	North-eastern Antarctic Peninsula region, Antarctica. 64° 17' 15" S 056° 44' 07" W
MAIN GEOLOGICAL INTEREST	Stratigraphy and sedimentology Paleontology



The Cretaceous (K)-Paleogene (Pg) boundary at the northern end of its area of outcrop on Seymour (Marambio) Island.

Geological Description

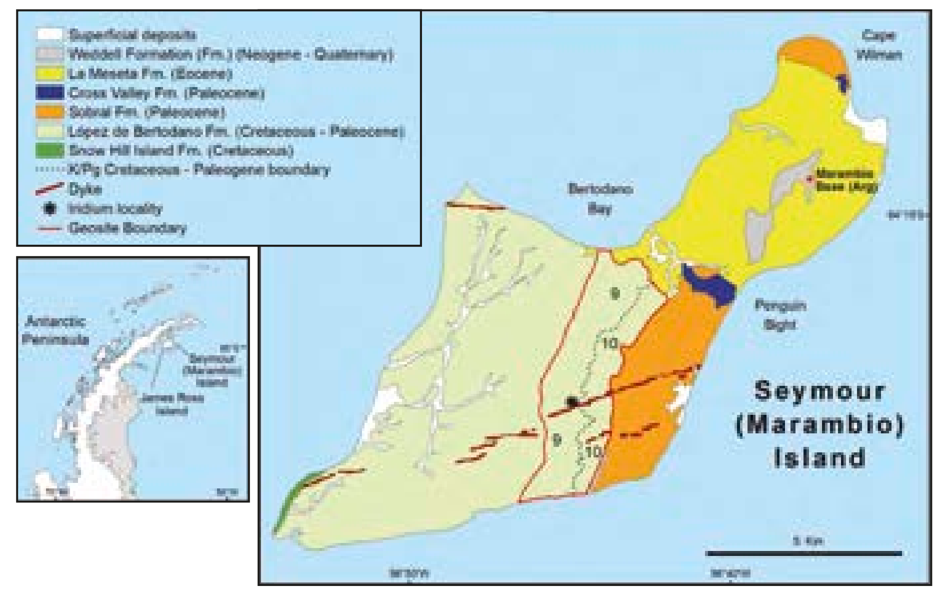
The Site encompasses the K-Pg boundary and the upper part of the López de Bertodano Formation, Seymour Island Group (late Maastrichtian-early Danian age). The boundary zone considered for this Geosite is c. 7 km long and c. 1.8 km wide (c. 13 km^2).

The well documented stratigraphic section where the iridium anomaly was first identified (Elliot *et al.,* 1994) is located adjacent to Blackrock Ridge (Filo Negro) (coordinates: 64° 17′ 24″ S; 56° 44′ 30″ W). The glauconite-bearing sandstone interval is easily recognized across the southwestern part of the island. Visibility of the site is excellent, and it is easily identified in the field because of the adjacent basalt dyke.

In the northern sector of the K-Pg boundary is where the boundary was first defined palaeontologically (coordinates: 64° 16′ 07″ S; 56° 42′ 37″ W). There is an exceptional three-dimensional exposure, with little surface cover and ice-free, lateral continuity over several kilometres and including a rare combination of fossils from many different groups (invertebrates, vertebrates, plants, microfossils, etc.) (Acosta Hospitaleche *et al.,* 2019, Montes *et al.,* 2019).

Scientific research and tradition

This is the only confirmed onshore locality showing an extensive K-Pg transition in Antarctica. It contains the first locality where the iridium anomaly was identified in Antarctica and is a locality for key reference fossil collections.



Simplified geological map of Seymour (Marambio) Island showing the Geosite boundary outlined in red. The K-Pg boundary and mapping units 9 and 10 are shown.

CRETACEOUS - PALEOGENE STRATIGRAPHIC SECTION OF ZUMAIA

SPAIN

UNESCO Global Geopark

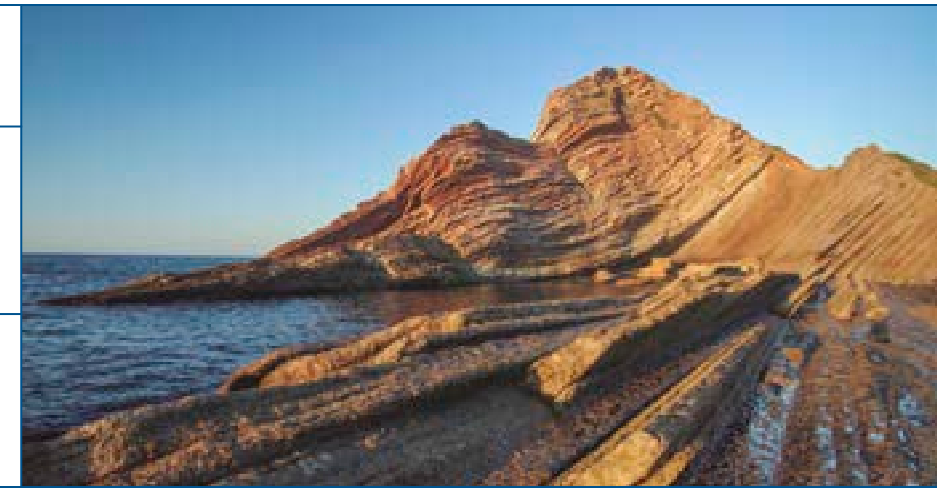
Eocene turbiditic system in Zumaia, which was the cover of the classic book "Atlas and Glossary of Primary Sedimentary Structures" (F.J Pettijhon and P.E Potter, Springer –Verlag 1964). (Photo: M. A. Langa).

ONE OF THE BEST EXPOSED, MOST CONTINUOUS AND HIGHLY STUDIED OUTCROPS OF DEEP MARINE SEDIMENTS IN THE WORLD.

Zumaia section provides critical information about climate and biosphere evolution through critical intervals of geological time. The integrated bio-, magneto- and cyclostratigraphic records helped to reconstruct the K/Pg mass extinction (Gilabert V. *et al.,* 2021) and the impact of the PETM global warming in the oceans and the subsequent recovery, and to define the GSSPs for the bases of the Selandian and Thanetian stages. The concentration of these major events marking key chronostratigraphic boundaries in a continuous section makes Zumaia one of the most studied and referenced stratigraphic outcrops of the World. Zumaia is also a key location for study of deep marine trace fossils.

SITE 022

GEOLOGICAL PERIOD	Cretaceous- Paleogene
LOCATION	Zumaia, Basque Coast Geopark, Spain. 43° 17' 59" N 002° 15' 41" W
MAIN GEOLOGICAL INTEREST	Stratigraphy and sedimentology Paleontology



Maastrichtian deep marine hemi pelagic sediments and K/Pg boundary in Zumaia.

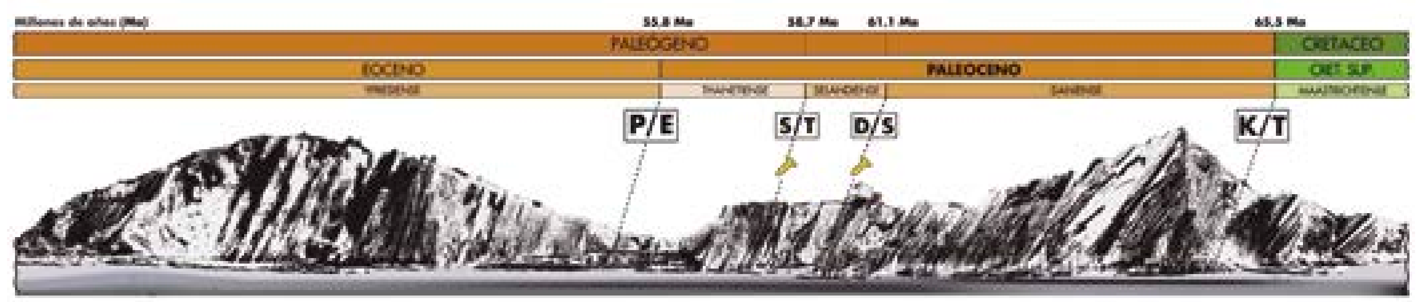
Geological Description

The Cretaceous - Paleogene stratigraphic section of Zumaia is magnificently and continuously exposed along 10 km of beautiful sea cliffs on the Basque coast. This deep marine succession, brought to the surface during the Pyrenean orogeny, comprises hemipelagic marl/limestone alternations and intercalated turbidites. One of the early models of deep-water submarine fans were partly based on Eocene deposits from Zumaia (Kruit C. *et al.,* 1972). The two major events bracketing the Paleocene Epoch, i.e. the mass extinction at the Cretaceous/Paleogene (K/Pg) boundary and the global warming across the Paleocene Eocene Thermal Maximum (PETM) had dramatic environmental and evolutionary consequences and are exceptionally well recorded at Zumaia (Ward PD, *et al.,* 1991) Extensive analyses of greatly preserved foraminifera and calcareous nannofossils have helped to refine the biostratigraphic scales and to infer the paleoenvironmental consequences of these global events (Alegret *et al.,* 2009). Additionally, detailed magneto and cyclostratigraphic studies made Zumaia a key reference section for the Maastrichtian and Paleocene astrochronological timescale (Dinnares-Turell J. *et al.,* 2014). Not surprisingly, Zumaia was unanimously selected to place the GSSPs for the bases of the Selandian and Thanetian stages, turning into one of the very few outcrops containing two IUGS Global stratotypes in the World (Schmitz *et al.,* 1972).

Scientific research and tradition

Zumaia has long attracted Geologists' interest. Since 1946 more than 120 research articles appeared in refereed journals and more than 10 PhD Theses are partly, or entirely, based on the section. Photos of Zumaia have been used as the front cover of many publications, including Pettijonh and Potter's, 1964, Atlas of Sedimentary Structures.

Location of the main chronostratigraphic boundaries of Zumaia section. The total stratigraphic thickness of the section is more than 5000 m, and the section, extending from the Albian to the Ypresian, is exposed continuously along 10 kilometers of sea cliffs.



GSSP OF THE MEGHALAYAN STAGE IN THE MAWMLUH CAVE

INDIA

Hanging Garden: Mawmluh cave stalagmites and stalactites, Meghalaya, India. (Photo: Gerald Samuel Duia).

THE GSSP OF YOUNGEST UNIT OF THE GEOLOGIC TIME SCALE ASSOCIATED WITH DRAMATIC CLIMATE CHANGES WITH IMPLICATIONS ON HUMAN CIVILIZATION.

The site is the GSSP for the Meghalayan Stage of Holocene Series. The stalagmite sample of Mawmluh cave has shown that they were not subjected to diagenesis and erosion and that they are suitable for preserving chemical signatures. The stalagmite has preserved a very high-resolution record of Holocene palaeoclimate and palaeomonsoon. Intensive Oxygen Isotope analyses revealed that around 4,200 yr BP, there was a mega-draught event that devastated many civilizations. The more intense period of weakened monsoon occurred from 4071 to 3888 yr BP and marked as nearly a Global event.

SITE 023

GEOLOGICAL PERIOD	Holocene Meghalayan Stage
LOCATION	Mawmluh, East Khasi Hills District, Meghalaya, India. 25° 15' 30" N 091° 42' 57" E
MAIN GEOLOGICAL INTEREST	Stratigraphy and sedimentology

Speleothem KM-A from Mawmluh Cave, Meghalaya, northeast India. The speleothem is ~308 mm long (repository: Birbal Sahni Institute of Palaeosciences, Lucknow, India).

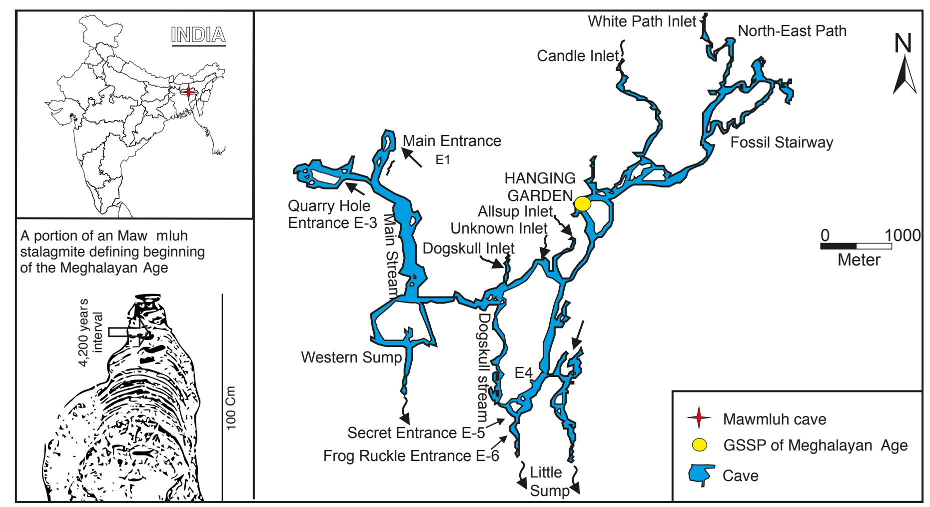
Geological Description

The Mawmluh Cave is formed along the contact between Early Eocene Lakadong dolomite of Sylhet Limestone Formation and the Therria Sandstone Formation (Gogoi *et al.,* 2009). At present, the cave is 7.2 Km long maze with many openings and decorated with stalactites, stalagmites, columns, drapes and moon milk.

The Meghalayan Stage is the newest entrant in the geologic history of the Earth and; latest of three subdivisions of the Holocene Epoch. The International Commission on Stratigraphy officially ratified it along with the earlier Greenlandian and Northgrippian Stages (Walker *et al.,* 2018). The lower boundary of the Meghalayan Stage is defined at a specific level in a stalagmite of Mawmluh Cave. The uranium series dated Upper Pleistocene to Upper Holocene stable isotope profile shows a marked shift to heavier isotopic values at ~4.2 ka, reflecting an abrupt reduction in precipitation due to a weakening of the monsoon across the Indian sub-continent and southeast Asia (Berkelhammer et al 2012). Due to abrupt mega-drought, the agriculture-based society were nearly collapsed. The 4.2 ka event was global or near global in nature and constitutes a timestratigraphic marker (Walker *et al.,* 2018).

Scientific research and tradition

Speleothems of Mawmluh Cave, Meghalaya has been extensively studied by many researchers. The Working Group of The Subcommission on Quaternary Stratigraphy (SQS) of the International Commission on Stratigraphy (ICS) proposed the subdivision of the Holocene Series and later IUGS formally ratified and accepted the three fold classification with youngest Stage 'Meghalayan' in the year 2018.

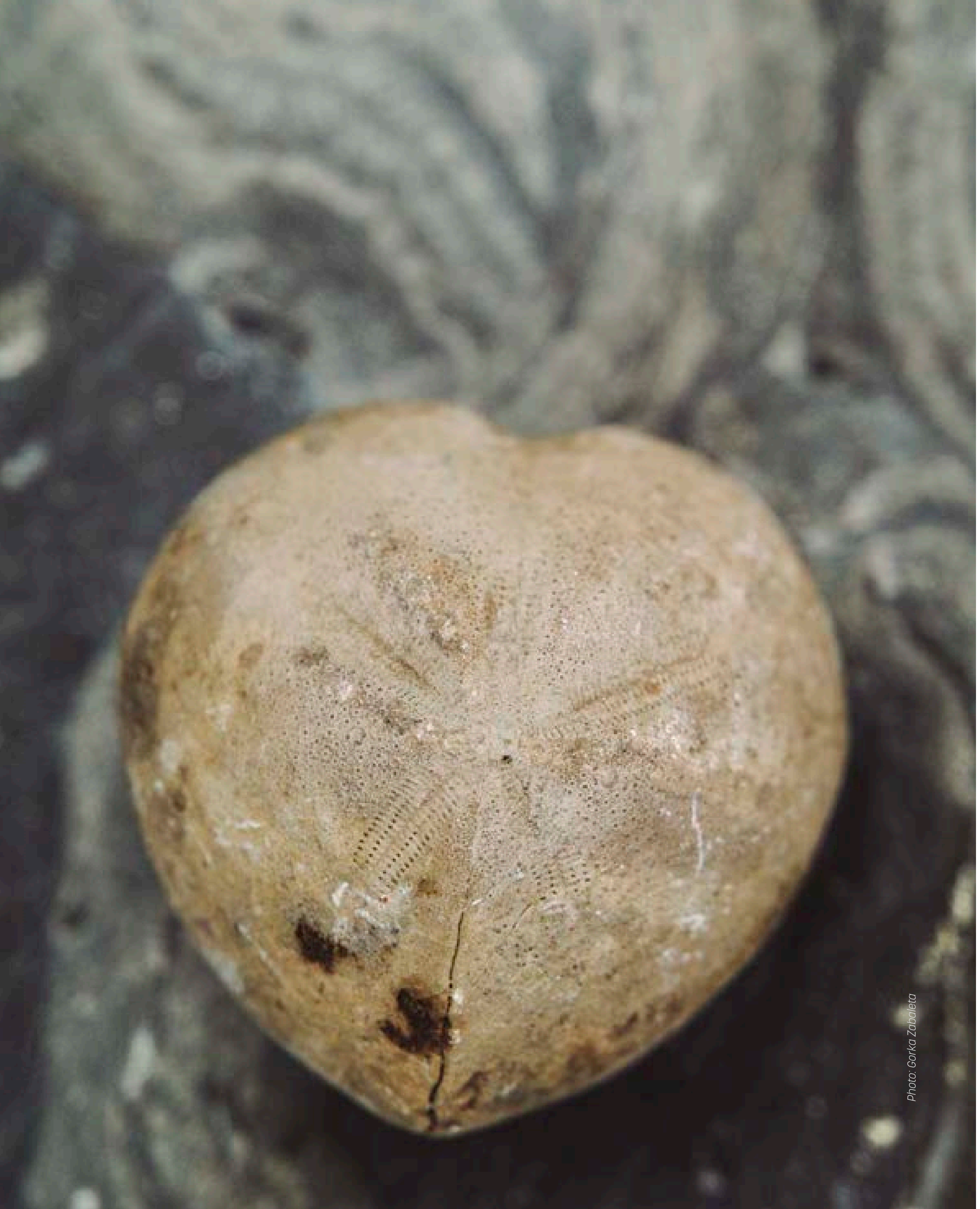


Mawmluh cave system, Meghalaya, India.

3

PALEONTOLOGY

SITE 024 - SITE 042



Sylvie Crasquin
Sorbonne Université. Paris, France.
President of the International Palaeontological Association (IPA).
IUGS Geological Heritage Sites voting member.

Marcela Gómez
Servicio Geológico Colombiano. Bogota, Colombia
IUGS Geological Heritage Sites voting member.

Palaeontology is a natural science at the crossroads of biology, geology, chemistry and physics. Palaeontologists study the traces of life, fossils, preserved in the sedimentary rock record. Fossils can be the remains of animal or plants, fungi or bacteria, with sizes ranging over many orders of magnitude, from the tiny nanometre scale organisms up to giants several tens of meters in length. These fossils can be parts of organisms or the traces of their activities. These vestiges of living things from deep time allow us to take numerous approaches to their study.

Firstly, fossils are the building blocks used to reconstruct, step by step, the history of life since its first appearance, highlighting Earths ever changing biodiversity. Secondly, fossils also document how evolution has modified living things to continue to thrive on our mutable planet, as well as how life has recovered from the crises of mass extinctions. Thirdly, the variable succession of fossils through time lets us date sedimentary rocks by establishing a non-repeating biostratigraphy. Fourthly, the fossil record provides the essential information needed to reconstruct past environments, from the oxygenation of the atmosphere to the natural cycles of climate change, and assemblages of organisms indicate the fluctuating limits between sea and land.

The term "Palaeontology" appeared in 1922, 100 years ago. To celebrate this anniversary, 17 of the most impressive palaeontological sites in the world are presented in this chapter. They illustrate the diversity of past life on our planet since its explosion more than 635 million years ago (Ma) to the recently extinct Pleistocene megafauna that once roamed on almost every continent. Each fossil site is exceptional, containing unique and beautiful fossils that were once witnesses to exceptional moments in the evolution of life on Earth.

We will travel through deep time, beginning with some of the very first metazoan (multicellular) organisms of the Ediacaran period at Mistaken Point in Newfoundland, Canada (580 Ma) and gradually make our way up to just 60 000 years ago with fossils preserved in the asphalt seeps of Rancho La Brea in California, USA. The explosion of life during the Cambrian and Ordovician is illustrated by the Chengjiang biota (518 Ma) from Yunnan in the Peoples Republic of China, by the Burgess Shale biota (505 Ma) in British Columbia, Canada, by the Fezouata biota (485 Ma) of Jbeltizgzaouine, Morocco, and by the Canelas Quarry (467 Ma) in Portugal. The Late Palaeozoic is exemplified by the Devonian (393 Ma) of Holy Cross Mountains in Poland, by the Coal Age deposits of Joggins (310 Ma) in Nova Scotia, Canada, and by the Late Permian Tete forest (259 Ma) of Mozambique. Emblematic fossils from the Mesozoic are to be encountered here, with an ammonite slab (199 Ma) from Dignes les Bains, France, the justifiably famous ‘first bird’ Archaeopteryx (156 Ma) from Solnhofen, Germany, a lower Cretaceous marine reptile Lagerstätte (122 Ma) from Boyacá, Colombia, and a series of rudist bivalve reefs (70 Ma) from Jamaica. More recent periods of time are represented by the exceptional Messel Pit site (56 Ma) in Germany, the Napak volcanic area (23 Ma) of Uganda, the Lesvos Petrified Forest (21 Ma) of Greece, and the Laetoli-Olduvai Gorge complex (5.3 Ma) of Tanzania.

Burgess Shale Cambrian palaeontological record
CANADA
Dinosaur provincial Park
CANADA
Ediacaran fossil site of Mistaken Point
CANADA
Eocene paleontological record of messel pit fossil site
GERMANY
Jurassic Solnhofen-Eichstätt Archaeopteryx serial site
GERMANY
Devonian tetrapod trackways of Holy Cross Mountains
POLAND
Lesvos Early Miocene Petrified Forest
GREECE
"Coal Age" Joggins Fossil Cliffs
CANADA
Late Quaternary asphalt seeps and paleontological site of La Brea Tar Pits
USA
Middle Ordovician giant trilobites of Canelas quarry
PORTUGAL
The Ammonite Slab of Digne-les-Bains
FRANCE
Late Cretaceous rudist bivalves of the Caribbean Province
JAMAICA
Cambrian Chengjiang Fossil Site and Lagerstätte
CHINA
Ordovician Fezouata Shale fossil site at JbelTizagzaouine
MOROCCO
Miocene primates palaeontological site of Napak
UGANDA
Marine Reptile Lagerstätte from the Lower Cretaceous of the Ricaurte Alto
COLOMBIA
Palaeoanthropological Sites of Human Evolution of Laetoli – Olduvai Gorge
TANZANIA
Late Permian Tete fossil forest
MOZAMBIQUE
Ediacaran fossils in the Ediacra Hills
AUSTRALIA

EDIACARAN FOSSIL SITE OF MISTAKEN POINT

CANADA

UNESCO World Heritage Site

The Ediacaran fossil site of Mistaken Point, Newfoundland, Canada, an exceptional record in the history of life on Earth. (Image credit: Barrett and MacKay Photography, Mistaken Point Ambassadors).

THE BEST EXAMPLE ON THE WORLD OF AN EDIACARAN FOSSIL COMMUNITY, WHERE LIFE "FIRST GOT BIG".

Mistaken Point was inscribed on the list of the World's Heritage as the best site in the world to witness the first complex communities of large metazoan lifeforms in the history of life on planet Earth (Narbonne and Gehling, 2003; Narbonne, 2005, 2011). More than 10,000 fossil impressions, ranging from a few centimetres to nearly 2 metres in length, are readily visible for scientific study and supervised viewing along the coastline of Mistaken Point. These fossils range in age from 580 to 560 million years and illustrate a critical watershed in the early history of life on Earth: the appearance of large, biologically complex organisms, including the first ancentral animals.

SITE 024

GEOLOGICAL PERIOD	Ediacaran Period (Neoproterozoic)
LOCATION	Newfoundland, Canada. 46° 38' 06" N 053° 12' 40" W
MAIN GEOLOGICAL INTEREST	Paleontology

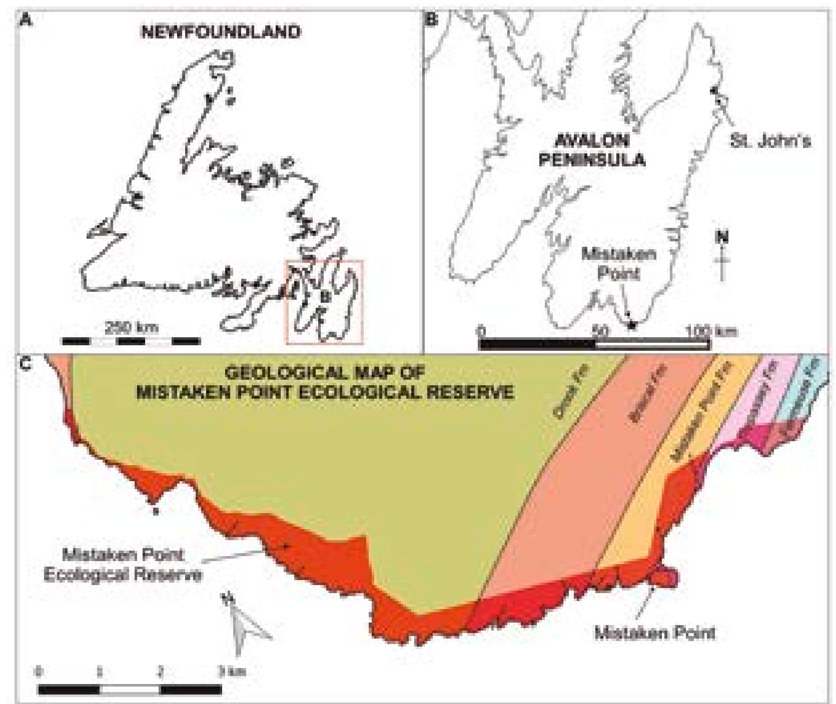
Ediacaran fossils at Mistaken Point represent the first time in Earth history that "life got big". (Photo: Alex Liu).

Geological Description

Mistaken Point illustrates better than anywhere the critical milestone in the history of Life on Earth when, after almost 3 billion years of microbe-dominated evolution, "life got big" and metazoan communities bloomed (Narbonne, 2011). The enigmatic lifeforms preserved at Mistaken Point (Anderson and Misra, 1968; Morris, 1989) are early experiments in the evolution of complex life on Earth, dating to 580-560 million years before present. Here at Mistaken Point are found the oldest known examples of architecturally complex organisms up to 2 m in length, soft bodied organisms known as rangeomorphs and others, including forms interpreted as ancestral animals. The exceptional preservation at Mistaken Point is a consequence of sudden and repeated burial beneath fine volcanic ash layers gently dispersed in the marine waters. Preserved are the oldest and most diverse examples of deep sea Ediacaran communities, with evidence of tiering and ecological succession. The sedimentary succession at Mistaken Point (Williams *et al.*, 1985) records 20 million years of this pivotal watershed in evolution.

Scientific research and tradition

The significance of the Mistaken Point fossil record is key to writing the evolution of life from simple single celled life to complex metazoan life forms that became recognizable as plants and animals (Narbonne, 2005, 2011). These enigmatic lifeforms challenge NASA astrobiologists to consider the possibilities of extraterrestrial life.



Map of the Mistaken Point fossil site.

EDIACARAN FOSSILS IN THE EDIACRA HILLS, FLINDERS RANGES
AUSTRALIA

Dicksonia, an Ediacaran fossil (image from Alamy).

ICONIC AND INTERNATIONALLY SIGNIFICANT PRECAMBRIAN FOSSIL LOCALITY PRESERVING EARLY MULTICELLULAR LIFE AND IS NAMESAKE OF THE EDIACARAN PERIOD.

The Ediacra Hills was the locality where well preserved Precambrian fossils of multicellular life were first found globally (Sprigg, 2007). At this location the Precambrian fossil life forms exhibit diversity (Coutts *et al.,* 2016) with over 20 species of fossils recorded including Parvancorina, Rugoconites, Spriggina, Dickinsonia, Tribrachidium, Kimberella, Charniodiscus and Yorgia. In addition to being the type section for the newly established Ediacaran Period, the Ediacra Hills contains one of the best-exposed and most complete successions of Neoproterozoic to early Paleozoic rocks in the world.

SITE 025

GEOLOGICAL PERIOD	Ediacaran
LOCATION	Enorama Creek, South Australia 31° 19' 52" S 138° 38' 07" E
MAIN GEOLOGICAL INTEREST	Paleontology Stratigraphy and sedimentology

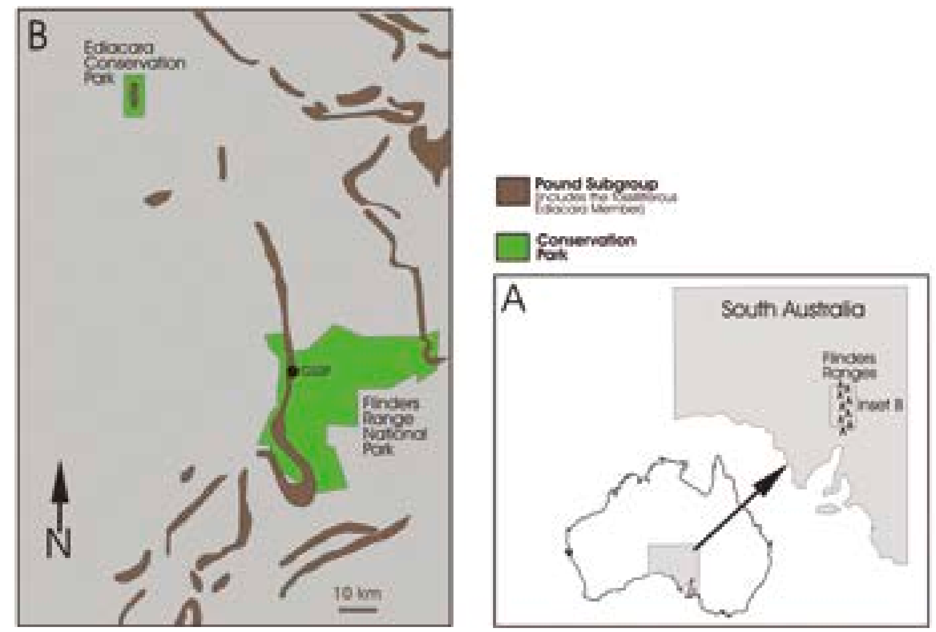
Location of the 'Golden Spike' in lower part of photograph showing the lower boundary of newly recognised Ediacaran Period (image courtesy Peter Neaum and Geological Survey of South Australia).

Geological Description

The Ediacra Hills is an iconic and internationally significant fossil locality preserving early (Precambrian) soft-bodied multicellular life (Sprigg, 2007) and is namesake of the Ediacaran period. The area contains a Global Boundary Stratotype Section and Point (GSSP), defined by IUGS International Commission on Stratigraphy (ICS) as an internationally agreed upon reference point on a stratigraphic section which defines the lower boundary of a stage on the geologic time scale - this boundary is marked by a 'Golden Spike'. The GSSP in the Flinders Ranges, located in Enorama Creek within the Flinders Ranges National Park, was ratified by the ICS in 2004 and pinpoints the lower boundary of the then newly recognised Ediacaran System (Period). The base of the Ediacaran System (Period) is defined by a Golden Spike at the base of the Nuccaleena Formation cap carbonate composed of laminated to well-bedded dolomicrite (Dalgarno and Johnson, 1964) directly above glacial diamictites and associated facies. The new Ediacaran Period encompasses a distinctive interval of Earth history that is bounded both above and below by equally distinctive intervals. The history of this site, fossil studies, and the GSSP selection process for the site are outlined in more detail by Preiss (2005) and Knoll *et al.* (2006).

Scientific research and tradition

From their first discovery in 1946 (Sprigg, 2007), Precambrian fossils of this locality have been researched to investigate the origins of Life, the diversity of Life in the Precambrian, and aspects of its palaeoecology. Enorama Creek also is a Global Boundary Stratotype Section and Point (GSSP) ratified in 2004.



Map of Flinders Ranges region showing outcrop of Pound Subgroup (containing the Ediacara Member), and location of the GSSP (map modified after Coutts et al. 2016).

CAMBRIAN CHENGJIANG FOSSIL SITE AND LAGERSTÄTTE

CHINA

UNESCO World Heritage Site

Innovatiocaris maotianshanensis (ELRC 20001), a nearly complete anomalocaridid specimen, represents the Cambrian giant predator. (Scale bar = 10 mm)..

REVEALS A SPECTACULAR, FASCINATING, AND DIVERSE BIOTA THAT RECORDS THE EARLY CAMBRIAN EXPLOSION.

The fossil site presents an exceptional record of the diversification of life on Earth during the early Cambrian, when almost all the major groups of animals appeared in the stratigraphic record for the first time. It is also recognized as the globally outstanding example of a major stage in the history of life, representing a palaeobiological window of great significance (Hou *et al.,* 2017). The fossils were recognized to be of the highest quality of preservation and convey the earliest record of a complex marine ecosystem (Chen *et al.,* 1994; Zhao *et al.,* 2010).

SITE 026

GEOLOGICAL PERIOD	Cambrian Epoch 2, Age 3 (Approximately 518 million years ago)
LOCATION	Chengjiang City, Yunnan Province, China. 24° 40' 08'' N 102° 58' 38'' E
MAIN GEOLOGICAL INTEREST	Paleontology

The Maotianshan, the site of the initial discovery of Chengjiang fossils, is the core area of the UNESCO World Heritage Chengjiang Fossil Site.

Geological Description

The Chengjiang fossils represent an unparalleled record of the fundamentally important rapid diversification of metazoan life in the early Cambrian (Cambrian explosion) and the primary establishment of a complex marine ecosystem.

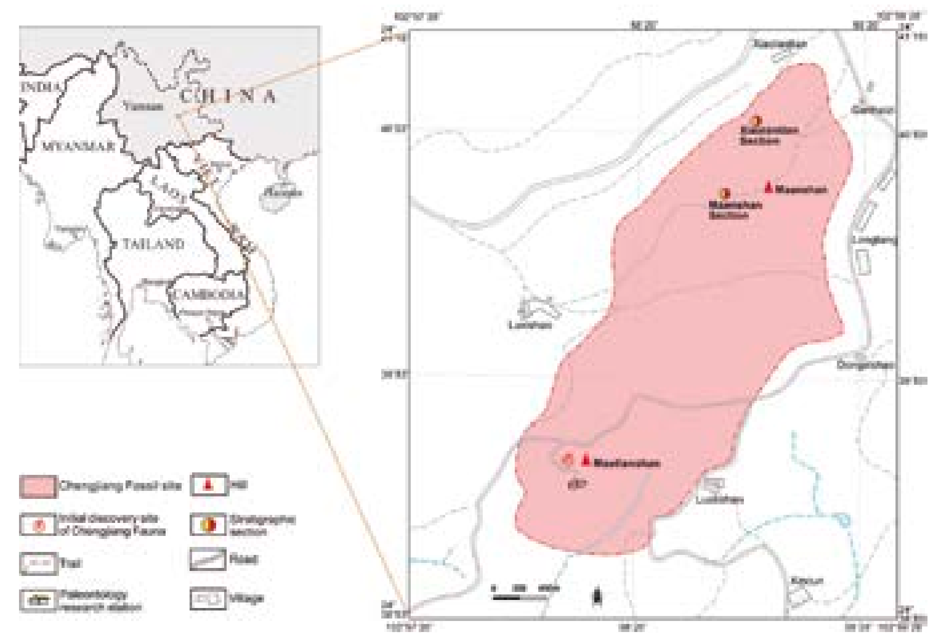
The fossils and rocks of the site provide direct evidence for the roots of animal biodiversity. Over 300 representing more than 20 phyla have been reported. They display a great diversity of metazoan body plans, many comparable with those of living groups. These fossils bear upon fundamental questions regarding the design of animal body plans and the genetic generation of evolutionary novelty. The diverse vertebrates, representing the "missing" history between an amphioxus-like ancestor and craniate vertebrates, provide an important understanding of the early evolution of the vertebrates (Chen *et al.,* 1995, 1999; Shu *et al.,* 1999).

It is one of the earliest records of a complex marine ecosystem with food webs capped by sophisticated predators (Chen *et al.,* 1994).

The exceptional fossils display the anatomy of hard and soft tissues of a great variety of organisms in exquisite detail (Hou *et al.,* 2017). The mode of preservation imparts an extraordinary and rare beauty to the fossils, extending their value from the scientific to the aesthetic.

Scientific research and tradition

The Chenjiang Fossil Site was discovered in 1984. More than thirty years of intensive study have made this fossil fauna one of the best known in the geological column. The site has been well protected. It became a national Geopark in 2001 and a World Natural Heritage site in 2012.



Location and detailed map of Chengjiang Fossil Site.

BURGESS SHALE CAMBRIAN PALAEONTOLOGICAL RECORD

CANADA

UNESCO World Heritage Site

Anomalocaris canadensis from the Burgess Shale, an extinct arthropod and the top Cambrian predator. ROMIP 51211. (© Royal Ontario Museum 2021 - Image J.-B. Caron).

CHARACTERIZED BY EXCEPTIONAL SOFT-TISSUE PRESERVATION, CONTAINS THE MOST COMPLETE FOSSIL RECORD OF CAMBRIAN (WULIUAN) MARINE ECOSYSTEMS.

The Walcott Quarry in Yoho National Park is the best-known and most visited Burgess Shale site. Together with the nearby Trilobite Beds on Mount Stephen, it was designated a UNESCO World Heritage Site in 1980 because "the Burgess Shale fossils provide key evidence of the history and early evolution of most animal groups known today, and yield a more complete view of life in the sea than any other site for that time period". It is a key global reference for Cambrian sites exhibiting similar taphonomic characteristics that are referred to as "Burgess Shale-type" deposits (Gaines, 2014).

SITE 027

GEOLOGICAL PERIOD	Cambrian / Miaolingian
LOCATION	Yoho and Kootenay National Parks, British Columbia, Canada. 51° 26' 18" N 116° 28' 20" W
MAIN GEOLOGICAL INTEREST	Paleontology

Parks Canada guide with visitors on a Burgess Shale interpretive hike at the Walcott Quarry, Yoho National Park. (© Parks Canada / Ryan Creary).

Geological Description

The Burgess Shale has proved critical to the scientific understanding of the Cambrian explosion, an event that marked the first appearance of recognizable animals in the fossil record. Characterized by exceptional preservation of soft-bodied organisms, the Burgess Shale yields an extraordinary diversity of marine animals that lived along or near the Cambrian seafloor, including sponges, ctenophores, cnidarians, echinoderms, hemichordates, chordates, chaetognaths, molluscs, annelids, priapulids and arthropods, in addition to cyanobacteria and algae. This site provides a wealth of information for a range of paleoecological and evolutionary studies, including research into some of our deepest relatives (eg. Morris and Caron 2013), and also provides the basis for large scale quantitative palaeocommunity studies due to the abundance of specimens preserved at multiple sites (eg. Nanglu *et al.,* 2020).

Burgess Shale fossils are found at several locations within the regional Stephen Formation clastic sedimentary sequence in Yoho National Park and Kootenay National Park. The Stephen Formation is divided into "thin" and "thick" expressions representing platformal and basinal facies respectively (Aitken and Fritz, 1968). Burgess Shale fossils occur mainly in the thick Stephen Formation where it consists of a succession of thin-bedded mudstones, claystone, and carbonate up to 300m thick.

Scientific research and tradition

Discovered by Charles Walcott in 1909, the Burgess Shale experienced a resurgence of research in the latter half of the 20th century (Morris, 1998). Since 1975, the Royal Ontario Museum has been conducting ongoing research on the Burgess Shale resulting in significant new discoveries (eg. Caron *et al.,* 2014).

Burgess Shale localities within part of the Canadian Rocky Mountain Parks World Heritage Site. © As the Crow Flies cARTography.

ORDOVICIAN FEZOUATA SHALE FOSSIL SITE AT JBELTIZAGZAOUINE

MOROCCO

Soft-bodied Furca sp. marrellomorph fossil arthropod, one of the most iconic Burgess Shale-type fossils from the Fezouata Shale.

EXCEPTIONAL FOSSIL PRESERVATION BRIDGING THE CAMBRIAN EXPLOSION AND THE GREAT ORDOVICIAN BIODIVERSIFICATION.

The biodiversity, abundance and quality of the fossils preserved at the Fezouata Shale, particularly the assemblage at JbelTizagzaouine, offer a unique window into one of the most important evolutionary transitions in the history of Life on Earth and the establishment of the ecologically-modern marine biosphere. The geology and paleontology of the Fezouata Shale has produced landmark contributions across multiple disciplines, including taphonomy, stratigraphy, and evolutionary biology, all made possible thanks to the long history of geological research on the Anti-Atlas region and sustained efforts to characterize the fossil richness of the Fezouata Biota over the last two decades (Destombes, 1962; Saleh *et al.*, 2021).

SITE 028

GEOLOGICAL PERIOD	Ordovician (485.4 ± 1.9 to 443.8 ± 1.5 Ma)
LOCATION	Drâa-Tafilalet Region, Zagora Province, Ternata Plain, Morocco 30° 31' 57" N 005° 49' 58" W
MAIN GEOLOGICAL INTEREST	Paleontology

General view looking towards the north of the hill of JbelTizagzaouine (in the foreground) and the Ternata Plain.

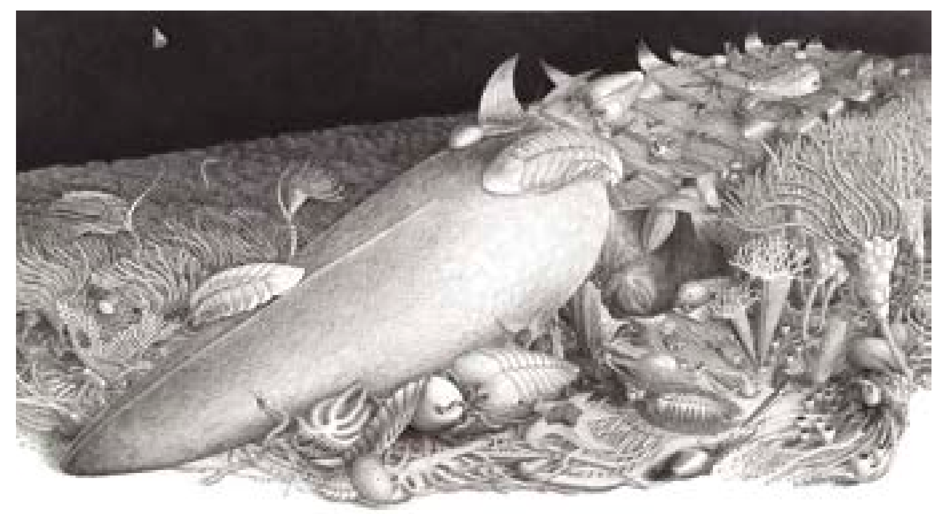
Geological Description

The Fezouata Biota represents the only major Konservat-Lagerstätte that reflects an open marine Ordovician fauna, and critically documents the earliest stages of the Great Ordovician Biodiversification. It bridges a major gap in our understanding of marine ecosystems between the middle Cambrian and the Silurian (Van Roy *et al.*, 2010; Van Roy *et al.*, 2015b). Among the 185+ taxa identified, some belong to typical post-Cambrian groups (e.g. asterozoans, bivalves, cephalopods, crinoids), while others are icons of exceptionally preserved Cambrian Burgess Shale-type biotas (e.g. lobopodians, radiodonts, sachitids), providing pivotal insight into the origin and evolution of major animal clades (Destombes, 1962; Van Roy *et al.*, 2015b). Furthermore, several Fezouata species (e.g. *chelonielliids, phyllodocids*, various *chelicerates*) represent the oldest occurrences of their groups. The sedimentology, stratigraphy, paleoenvironment and geological history of the Fezouata Shale have been characterized in detail, and analyses of Fezouata sediments have significantly refined our understanding of soft-tissue taphonomy (Saleh *et al.*, 2021). JbelTigzazaouine represents one of the most complete and easily accessible sections through the main interval of exceptional preservation in the Fezouata Shale, and is the site of some of the most important discoveries. Its sedimentology is typical for the intermediate bathymetry at which the Fezouata Biota lived, and the hill offers an excellent vantage point, overlooking all major geological features of the area.

Scientific research and tradition

Abundant and diverse shelly faunas have been described from this open marine locality since the 1950s (Destombes, 1962), but the first exceptionally preserved soft-bodied fossils were discovered in the early 2000s. Since then, studies on the biological diversity, depositional environment, geological age, and taphonomy have characterized this locality in detail (Van Roy *et al.*, 2010; Saleh *et al.*, 2021).

Artistic reconstruction of an Early Ordovician sea floor typical of the Fezouata Biota.



MIDDLE ORDOVICIAN GIANT TRILOBITES OF CANELAS QUARRY

PORTUGAL

UNESCO Global Geopark

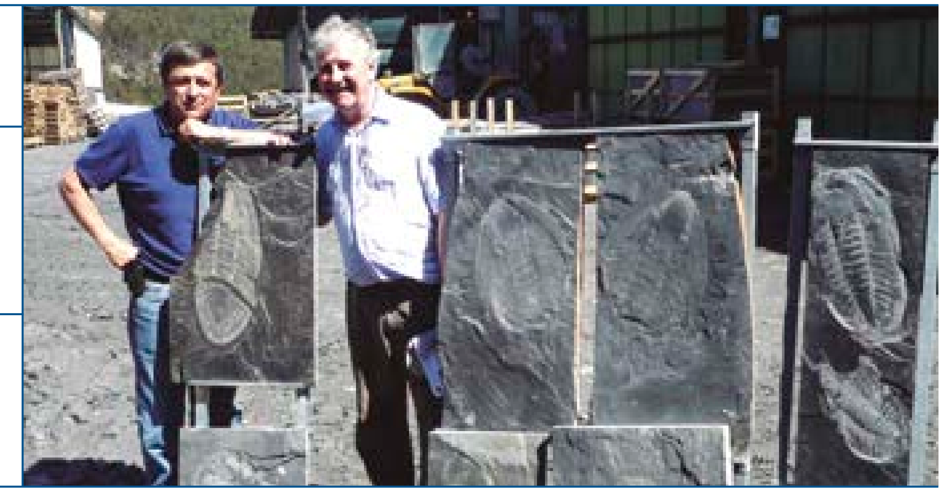
Monospecific association of Ogyginus forteyi (Rábano, 1989) from Canelas quarry, probably fossilized during the ecdysis process (external and internal molds). Scale bar = 10 cm.

FOSSILS OF THE LARGEST TRILOBITES EVER FOUND, DEMONSTRATING A VERY ACTIVE SOCIAL LIFE.

The fossil trilobites provide unique, valuable information on gigantism and social behavior among some species, as well as their interactions with other invertebrates preserved with the trilobites. Furthermore, the on-site museum is an extensively used educational resource, and development of the site serves as an example of cooperation between extractive industry, education, science, and sustainable development.

SITE 029

GEOLOGICAL PERIOD	Darriwilian – Middle Ordovician
LOCATION	Arouca Geopark, Portugal. 40° 57' 55" N 008° 13' 04" W
MAIN GEOLOGICAL INTEREST	Paleontology



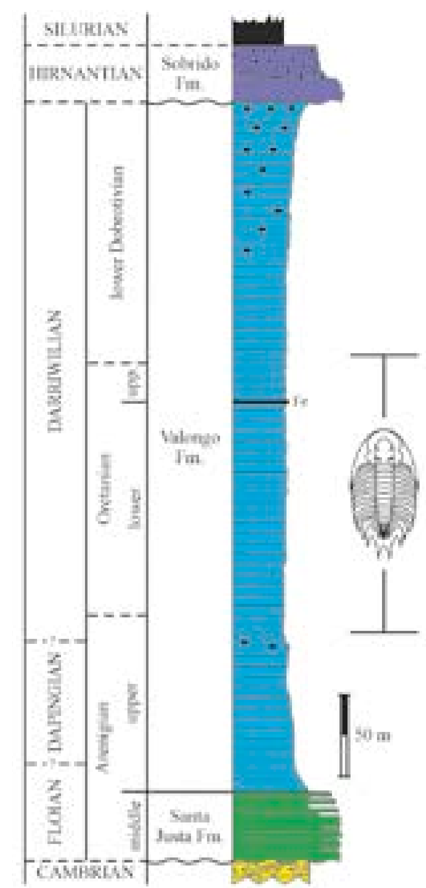
The palaeontologists Juan Carlos Gutiérrez-Marco (left) and Richard Fortey (right) pose with some Darriwilian (Middle Ordovician) giant trilobites from the Canelas quarry.

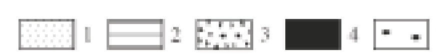
Geological Description

The Canelas Quarry exposes large surfaces of roofing slate in the village of Canelas, in the Arouca UNESCO Global Geopark (northern Portugal). These rocks were formed under oxygen-depleted conditions and have yielded a unique Ordovician fossil lagerstätte, which during the research made in the last two decades brought new information on the social behavior of trilobites. Besides that, it provides several of the world's largest trilobite specimens (some reaching 80 cm), showing evidence of possible polar gigantism in some species, as well as numerous examples of monotaxic and polytaxic size-segregated autochthonous trilobite clusters, some of which contain as many as 1000 specimens. These reveal a very diverse social behavior, which includes temporary refuge from predation and synchronous molting and reproduction. Added to this is a diverse invertebrate fauna, which includes cephalopods, graptolites, hyolithids, conularids, gastropods, bivalves, rostroconchs, brachiopods, and echinoderms, as well as an assorted set of ichnofossils (Gutiérrez-Marco *et al.*, 2009; Sá and Gutiérrez-Marco, 2006, 2008, 2015; Sá *et al.*, 2021).

Scientific research and tradition

Known since the mid-19th century, the giant trilobites of Canelas were the motive that inspired the creation of the Arouca UNESCO Global Geopark. This geosite is nowadays a scientific and tourist attraction worldwide recognised, already visited by palaeontologists and geologists during international congresses of trilobites and of Ordovician, among others.





Stratigraphic log of the Ordovician of Arouca region, showing the vertical distribution of trilobites. 1, sandstones and quartzites; 2, shales and slates; 3, glaciomarine diamictites; 4, black shales; 5, nodules.

DEVONIAN TETRAPOD TRACKWAYS OF HOLY CROSS MOUNTAINS

POLAND

Surface of dolomite bed with preserved tetrapod's footprints in Zachelmie Quarry (Photo: Hodbod M.).

THE OLDEST KNOWN FOSSIL TETRAPOD TRACKS ON LAND.

The earliest known tetrapods body fossils date to the Late Devonian. Well-preserved and securely dated tetrapod tracks of early Middle Devonian rocks have been found in Zachelmie Quarry (Poland). These tetrapod tracks are the oldest in the world and suggest that tetrapods evolved 18 million years earlier than indicated by the oldest body fossils. The site documents the transition of life from water to land – a momentous turning point in evolution, and it provides the oldest reliably dated evidence of tetrapods moving over land during the early Eifelian.

SITE 030

GEOLOGICAL PERIOD	Middle Devonian
LOCATION	Zachelmie Quarry, Holy Cross Mountains, Poland. 50° 58' 10" N 020° 41' 27" E
MAIN GEOLOGICAL INTEREST	Paleontology

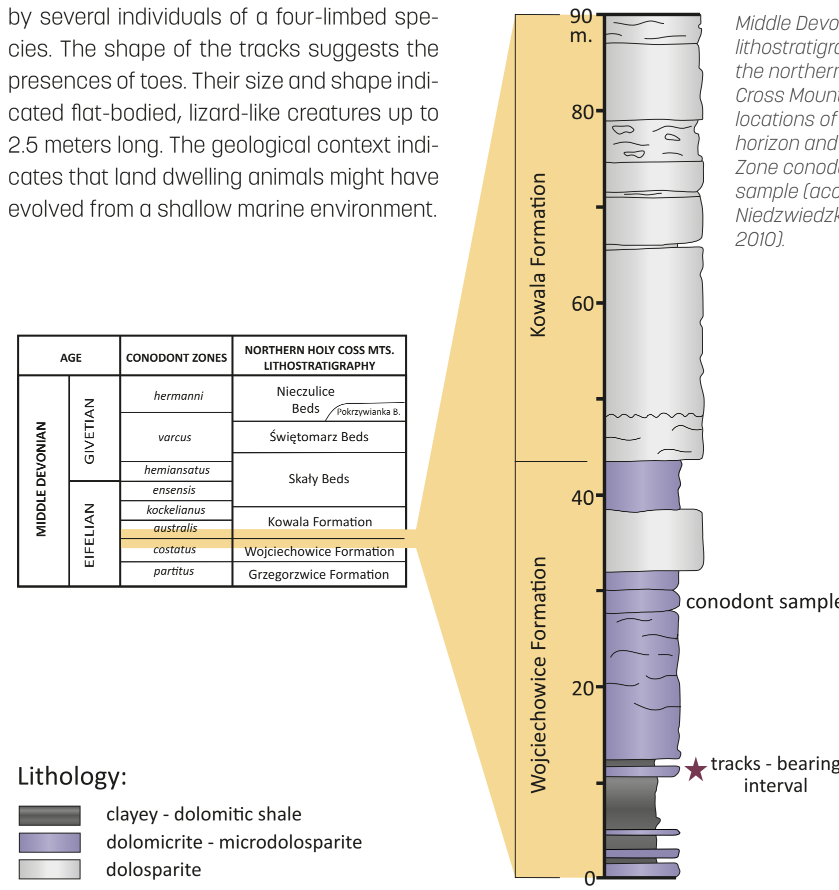
View of the Zachełmie Quarry - since 2013 has been declared a Nature Reserve "Zachelmie". (Photo: Szrek P.).

Geological Description

The Middle Devonian Wojciechowice Formation crops out in Zachelmie quarry in the Holy Cross Mountains. It is a dolomite that was deposited in a transitional lacustrine to marginal-marine environment in a broad shallow carbonate platform. A set of tracks, interpreted as those of tetrapods, occur on bedding planes in the dolomite (Niedzwiedzki *et al.,* 2010). Conodonts of the costatus Zone are evidence that the trackway bed in the Wojciechowice Formation correlates with the lowest Eifelian Stage (Niedzwiedzki and Szrek, 2020), indicating that the tetrapod tracks were made approximately 18 million years earlier than the oldest known body fossils of tetrapods. The tracks were made by several individuals of a four-limbed species. The shape of the tracks suggests the presences of toes. Their size and shape indicated flat-bodied, lizard-like creatures up to 2.5 meters long. The geological context indicates that land dwelling animals might have evolved from a shallow marine environment.

Scientific research and tradition

The trackways were first described in Nature in 2010 (Niedzwiedzki *et al.,* 2010). After the discovery new results of research on the local sedimentation environment have been presented in several new publications (Narkiewicz *et al.,* 2015; Jaworska, 2017; Niedzwiedzki and Szrek, 2020).



Middle Devonian lithostratigraphy of the northern Holy Cross Mountains, locations of trackway horizon and costatus Zone conodont sample (according to Niedzwiedzki et al., 2010).

"COAL AGE" JOGGINS FOSSIL CLIFFS

CANADA

UNESCO World Heritage Site

One of the standing fossil trees for which Joggins is famous, in which are found fossils of the world's earliest reptiles. (Photo: Andrew MacRae).

THE WORLD'S BEST EXAMPLE OF 'COAL AGE' TROPICAL FORESTS AND SITE OF OLDEST KNOWN REPTILES.

This IUGS Geological Heritage site was inscribed on the UNESCO list of the World Heritage as the most outstanding example in the world of terrestrial life in the Pennsylvanian 'Coal Age'. It includes the iconic elements of this period of Earth history - the Coal Age forest ecosystem that gave rise to the coal deposits of Europe and North America and in which evolved the earliest reptiles and first amniotes in the history of Life. From the 'Origin of Species' to current research, Joggins has played a seminal role in the development of geology and evolutionary science.

SITE 031

GEOLOGICAL PERIOD	Carboniferous
LOCATION	Nova Scotia, Canada. 45° 23' 15" N 064° 02' 54" W
MAIN GEOLOGICAL INTEREST	Paleontology History of geoscience

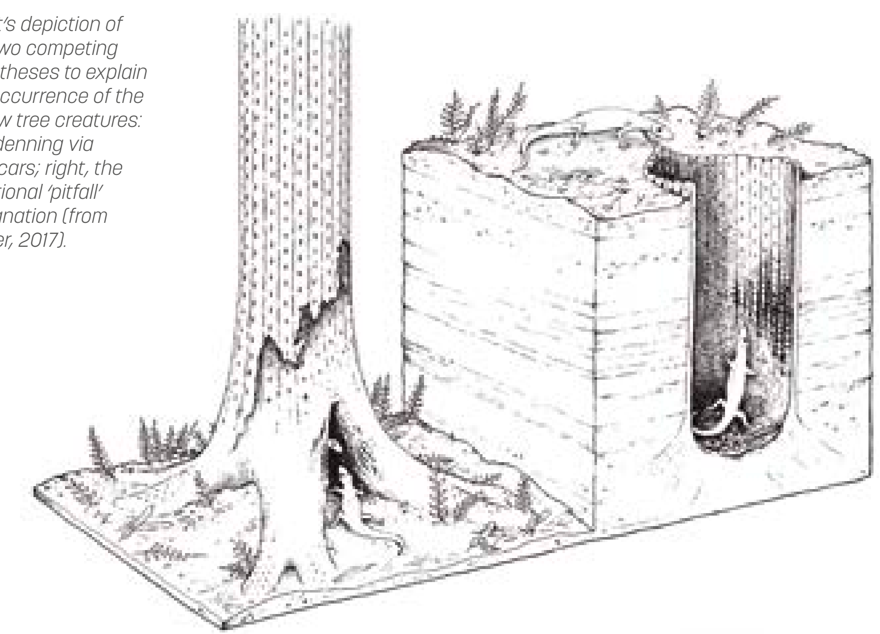
Delegates to the International Geological Congress of 1912 dining on their field stop at Joggins.

Geological Description

The coastal cliffs of Joggins, hewn by the highest tides in the world, expose anew fossil trees of the great tropical forest swamps that gave rise to the coal deposits of Europe and North America (Calder *et al.,* 2006). Visited and studied by Sir Charles Lyell and Sir William Dawson in the Nineteenth Century (Lyell and Dawson, 1853), the cliffs were cited as the best possible exposure of the fossil record by Charles Darwin in his seminal work 'On the Origin of Species' (Darwin, 1859).

The standing trees have captured the imagination of scientists and citizen scientists alike because of the fossils contained in their once hollow trunks. These fossils include the earliest reptile and amniote in the fossil record, *Hylonomus lyelli* (Carroll, 1964). Over 100 individual tetrapods (amphibians and reptiles) have been discovered within the trees of Joggins, historically ascribed to having fallen victim to open pitfalls. More recent analysis suggests that these tetrapods, along with millipedes and the earliest land snails, denned inside the tree hollows (Calder, 2017).

Examples of life in these tropical swamp forests include trackways of one of the largest terrestrial myriapods Arthropleura, scorpions, whip spiders, footprints of tetrapods, aquatic fauna in beds that derive from basinwide flood events, and foliage and stems of the tropical forests themselves.



Artist's depiction of the two competing hypotheses to explain the occurrence of the hollow tree creatures: left, denning via fire scars; right, the traditional 'pitfall' explanation (from Calder, 2017).

Scientific research and tradition

Scientists have been drawn to the Joggins cliffs for more than two centuries to ponder the record of standing fossil forests and life here, and even earlier to mine coal formed from the primeval peatlands (Calder, 2017). The importance of Joggins in unravelling the evolution of reptiles continues today, with continuing discoveries (Mann *et al.,* 2020).

LATE PERMIAN TETE FOSSIL FOREST

MOZAMBIQUE

Petrified wood lying in the ground and some scattered trunks over the fossil forest from Nhambando site.

THE MOST EXTENSIVE LARGEST FOSSIL FOREST EVER FOUND IN AFRICA.

The paleontological site extends over an area of 1482 km². Fossil wood at Tete Fossil Forest is very well preserved, allowing the study of internal structures including tree fossil hollows (Araújo *et al.,* 2018). Some woods already identified from TFF are *Australoxylon teixeirae* (new specie, Marguerier, 1973), *Zalesskioxylon zambesiensis* (new specie, Bajpai and Maheshwari, 1986), *Agathoxylon Karoensis, Agathoxylon africanum, Cupressinoxlyon sp. nov* (new specie) and *Prototaxoxylon uniseriale* (Nhamutole *et al.,* 2021). These woods belonged to conifer trees that flourished in the area some 250 Ma (late Permian), representing a snapshot for the study of the flora of the worldwide Permian-Triassic Mass Extinction. In addition, this fossil wood has provided new scientific genera and species (Nhamutole *et al.,* 2021).

SITE 032

GEOLOGICAL PERIOD	Late Permian
LOCATION	Tete Province, Mozambique. 15° 43' 31" S 032° 18' 15" E
MAIN GEOLOGICAL INTEREST	Paleontology

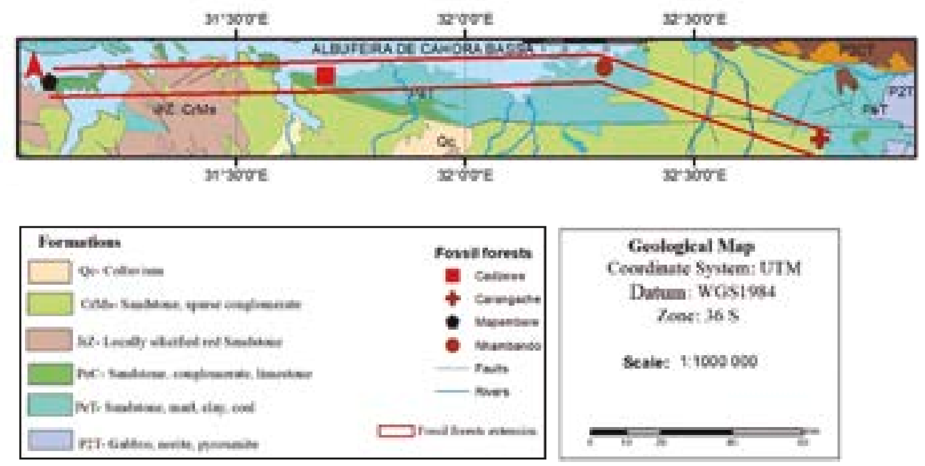
Fossil woods from the Nhambando site, Tete province laying in the ground.

Geological Description

The Tete Fossil Forest has a high density of petrified wood stems, both in situ and ex-situ, with the most remarkable trunk reaching 25 meters in length. Geologically, the Tete province is represented by the Vúzi and Moatize Formations, which are made up of glacial and fluvio-lacustrine deposits, tilites, carbonaceous schists, siltstones intercalated with coal beds. The overlying Late Permian to Early Triassic Formation is the Matinde Formation, which consists of cross-bedded sandstone, siltstones and coal beds. This formation contains large exposures of petrified woods within the terrains of the Karoo Vulcano-sedimentary Province. The exposures extend from the Carangache site to Mapembera locality, which represents a continuation of the same fossil forest (Nhamutole *et al.,* 2021). In its turn, the Matinde Formation (Late Permian) which the Tete Fossil Forest is found is overlain by the following units in a stratigraphic order: the late Triassic Cadzi Formation, the Early Jurassic Zumbo Formation and other igneous formations.

Scientific research and tradition

Many scientific papers have been published about the Tete fossil Forest, covering a wide range of topics. These include the systematic identification of plant types which have yielded important new wood species diversity, fossil leaves, external wood structures including tree hollows, and the need for preservation of this remarkable Late Palaeozoic flora. The list of publication are listed in the section for references, however some of the pioneering researchs in the area are from Silva *et al.,* 1967; Marguerier, 1973; Bajpai and Maheshwari, 1986.



Geological map/diagram of Tete Fossilized Forests (red lines represents the approximate area covered by the Fossil Forest).

THE AMMONITE SLAB OF DIGNE-LES-BAINS

FRANCE

UNESCO Global Geopark

View of the exceptional concentration of ammonites with in situ specimens of Coroniceras multicostatum. The largest are up to 70 cm in diameter. (©Haute-Provence Global Geopark).

WORLD FAMOUS AND OUTSTANDING ACCUMULATION OF FOSSILS FROM A LOWER JURASSIC MARINE ENVIRONMENT.

The site is a spectacular concentration of fossil ammonites, and offers the best exposure for the Coroniceras multicostatum biohorizon (Lower Sinemurian, top of Bucklandi Zone) in Europe allowing for new palaeontological analyses. Thus, this site constitutes an international reference for this stratigraphic level and is emblematic of the creation of UNESCO Global Geoparks. This designation coincided with the "International Declaration of the Rights of the Memory of the Earth" written in Digne-les-Bains in 1991. These scientific, aesthetic and historical aspects contribute to the worldwide reputation of this site.

SITE 033

GEOLOGICAL PERIOD	Lower Jurassic, Sinemurian
LOCATION	Haute-Provence Geopark, France. 44° 07' 10" N 006° 14' 03" E
MAIN GEOLOGICAL INTEREST	Paleontology Stratigraphy and sedimentology

Drone view showing the site facilities: visitors' path, mediation area, footbridge accessible to people with reduced mobility, and observation platform. (©Haute-Provence Global Geopark).

Geological Description

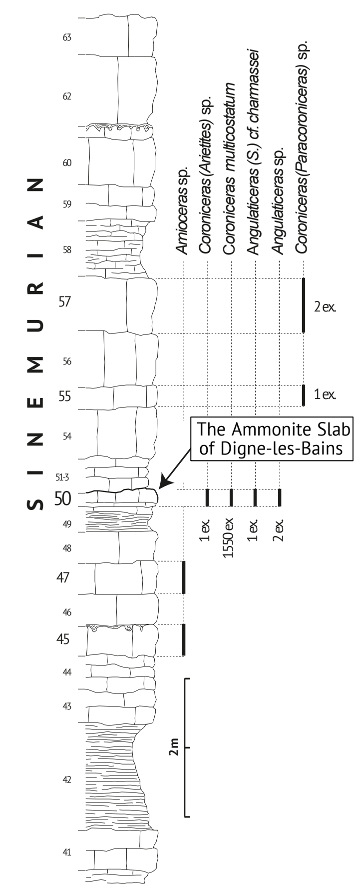
The slab belongs to the Subalpine Basin marly-limestone Lower Jurassic sequence and is part of the Nappe de Digne, a top-to-the-South allochthonous unit. The Lower Jurassic strata record the early history of the Southeast Basin in the Alpine Tethys Ocean during its rifting.

The slab (ca. 320 m²) bears more than 1,550 cephalopods (some nautilus and many ammonites), up to 70 cm in diameter, and a benthic fauna composed of bivalves and crinoids (Corna *et al.,* 1990). One of the distinctive features is that the ammonites are 99% represented by a single species *(Coroniceras multicostatum)*. It characterises a well-known stratigraphic biohorizon in Western Europe, but the Digne slab is the only well-exposed outcrop presenting such a concentration of fossils and constitutes an international reference for this stratigraphic level (Dommergues and Meister, 1991; Bert and Pagès, 2021). No preferential orientation indicates that no dominant current guided the shells deposition.

Field surveys, completed by a drill hole, confirmed the extension of the fossiliferous level under the surface, over several thousand square metres. The site is in the French Geoheritage Inventory, the National Geological Nature Reserve of Haute-Provence (Martini, 1979) and the Haute-Provence UNESCO Global Geopark (Neige *et al.,* 2021).

Scientific research and tradition

This world-renowned site exposes a reliable biostratigraphic marker for establishing correlations with the faunas of the Mediterranean Tethys. It is the first place where intraspecific variability of a large Lower Jurassic ammonite species was studied using 3D-Scan. The site hosts more than 20,000 visitors a year.



Stratigraphic log of the Isnards section (Corna et al., 1990) including the ammonite slab (top of bed 50). Details of the ammonites and bivalves distribution.

JURASSIC SOLNHOFEN-EICHSTÄTT ARCHAEOPTERYX SERIAL SITE
GERMANY

The "Eichstätt specimen" of Archaeopteryx, found in 1951. The original fossil is displayed in the "Jura-Museum" in the town of Eichstätt (LfU, Erwin Geiß).

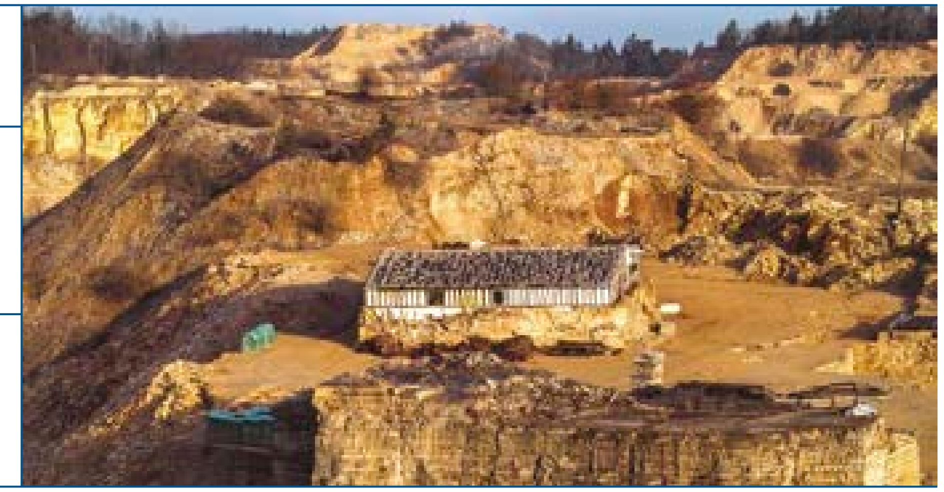
A FIRST-CLASS PALEONTOLOGICAL SITE DISPLAYING HIGH-QUALITY REFERENCE MATERIAL FOR SCIENTISTS WORLDWIDE, INCLUDING ALL KNOWN SPECIMENS OF *ARCHAEOPTERYX*.

Due to the special sedimentation conditions fossils from Solnhofen-Eichstätt are exceptionally well preserved. So far, 12 specimens of *Archaeopteryx* are known, and all of them have been found in the area. Together with the numerous other species described scientifically, this fossil Lagerstätte is one of the world`s most significant windows to the past.

In the region there are numerous quarries, some of them serving as official sites for visitors searching for fossils. Several thematic hiking pathes and several museums enable the serial geological heritage site to be experienced by local residents and visitors.

SITE 034

GEOLOGICAL PERIOD	Upper Jurassic
LOCATION	Altmühltal Nature Park / Bavaria, Germany 48° 53' 25'' N 010° 58' 05'' E
MAIN GEOLOGICAL INTEREST	Paleontology History of geosciences



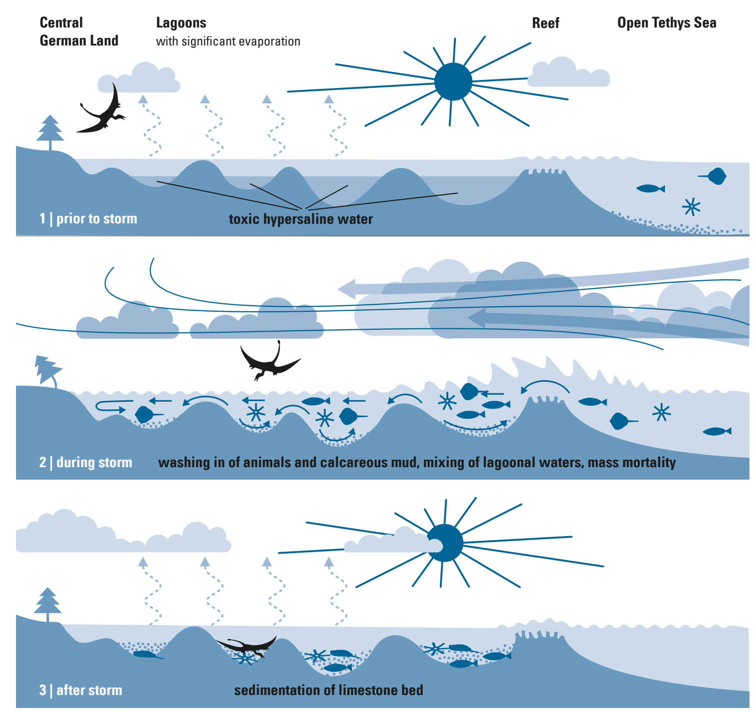
Panoramic view of a quarry near Solnhofen. In the lower part the fine bedding of the platy limestones is visible (LfU, Stefan Glaser).

Geological Description

The area around the municipalities of Solnhofen and Eichstätt is the only occurrence of Tithonian platy limestones of the Altmühltal Formation worldwide. These rocks developed from material washed into lagoons of the "Solnhofen Archipelago" during occasional storms. As there was no life present at the bottom of these toxic hypersaline lagoons, the sediment remained undisturbed. Due to this, fossils of marine as well as land living animals and plants, which were deposited in the lagoons, are exceptionally well preserved. The early bird *Archaeopteryx*, found for the first time in 1861 (Meyer, 1862), is the most iconic of them. All of the known 12 specimens of *Archaeopteryx* originate from the Solnhofen-Eichstätt area. They are a matter of research up to now (e.g. Foth *et al.,* 2014). Additionally there have been found a lot of other famous fossils like pterosaurs and small land-living carnivorous dinosaurs besides numerous other species (Arratia *et al.,* 2015). The platy limestones have been quarried for hundreds of years as roofing material, decoration stone and for lithographical printing. Therefore the number of good outcrops is comparatively high, which leads to the finding of new fossils up to now.

Scientific research and tradition

Early records of Solnhofen-Eichstätt fossils in the literature go back to the 16th century. Archaeopteryx fossils have been the matter of debate in the scientific dispute about the theory of evolution (e.g. Owen, 1863; Darwin, 1866; Huxley, 1868). Research on Solnhofen fossils is still in progress.



Geological processes leading to sedimentation of the platy limestones of the Altmühltal Formation with their exceptionally well preserved fossils (LfU)

MARINE REPTILE LAGERSTÄTTE FROM THE LOWER CRETACEOUS OF THE RICAURTE ALTO

COLOMBIA

The exquisitely preserved "El Fósil" (*Monquirasaurus boyacensis*), an iconic seven-meter-long Early Cretaceous marine megapredator, with a 2.8-meter-long skull and 30 cm teeth, from Ricuarte Alto.

THE WORLD'S MOST COMPLETE RECORD OF LOWER CRETACEOUS MARINE REPTILES AND ASSOCIATED FAUNA.

The Ricaurte Alto preserves a unique marine fauna that opens an exceptional window into the marine reptile and associated fauna and flora of an equatorial Early Cretaceous epicontinental seaway, located between the northern and southern hemispheres and bordering the proto-Pacific Ocean and Tethyian realms. Exquisite preservation is characterized by very high levels of skeletal completeness and articulation of pliosaurs, plesiosaurs, ichthyosaurs, and marine turtles, which is critical for understanding the evolutionary history of these groups. The associated three-dimensionally preserved fish, exceptionally rich ammonite fauna, terrestrial plants, and dinosaur remains are also outstandingly important. The site also comprises a remarkably complete Hauterivian to lower Aptian sedimentary sequence, incorporating evidence for Cretaceous oceanic anoxic events (Noè and Gómez-Pérez, 2020).

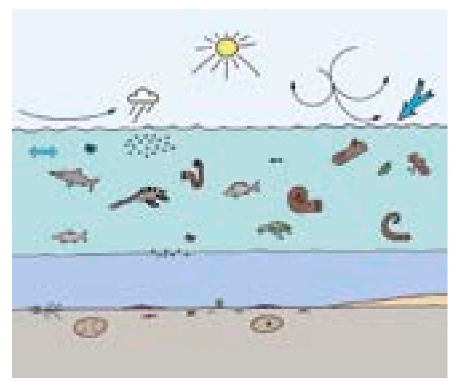
SITE 035

GEOLOGICAL PERIOD	Lower Cretaceous
LOCATION	Ricaurte Alto Province, Boyacá, Colombia. 05° 37' 48" N 073° 33' 00" W
MAIN GEOLOGICAL INTEREST	Paleontology Stratigraphy and sedimentology

Panoramic view of La Yesera Hill, one the most iconic and best studied sections of the region, which includes the lower boundary of the Barremian stage.

Geological Description

The Paja Formation crops out almost continuously in the Alto Ricaurte region in the municipalities of Villa de Leyva, Sáchica and Sutamarchán. These deposits are mainly black shale with abundant calcareous concretions and the abundance of organic carbon. Deposition of the Paja Formation in the Alto Ricaurte took place during the Hauteriveran to Aptian in a world with high global sea levels, warm and equitable global temperatures. The "calcite seas" were dominated by marine reptiles, fish, and ammonites, which are now beautifully preserved. This preservation is strong evidence for rapid burial and other exceptional diagenetic conditions. The dysoxic–anoxic bottom waters precluded scavenging fish and cephalopods, severely reduced epibiont encrustation, and minimized the possibility of scavenging by air–breathing marine reptiles. The diversity of the marine reptile fauna is exemplified by the various groups such as pliosaurs, plesiosaurs, marine turtles, and ichthyosaurs. Marine reptiles of the Lower Cretaceous are scarce around the world, but in this area are abundant, with at least 12 species and genera, many undescribed (Noè and Gómez-Pérez, 2020).



Model of the Paja Sea based upon analysis of sedimentology, stratigraphy, and palaeobiology. The sea floor fauna is poor, but surface waters teem with life.

Scientific research and tradition

The Ricaurte Alto has long been recognized as an exceptional fossiliferous deposit and has been studied by generations of national and international researchers and students. Commencing in the 1930s and 40s, the Ricaurte Alto strata were explored for their biostratigraphic importance and potential for hydrocarbon generation. During this time, the first marine reptiles (two articulated plesiosaurs, now *Callawayasaurus colombiensis*) were discovered and subsequently described (Welles, 1962). Commencing in the 1960s, considerable research effort has been undertaken on the strata, invertebrate (ammonite) fauna (Etayo-Serna, 1968), and flora of the Ricaurte Alto. Since the 1980s, an increasing number of exceptionally preserved marine reptiles have been described (Cadena and Parham, 2015; Cortes *et al.*, 2021; Gomez-Perez and Noè, 2017). The site is now recognized as both a Lagerstätte and as globally important 'Lower Cretaceous Gap' deposits (Noè and Gómez-Pérez, 2020). Many marine reptiles and other taxa are awaiting formal description.

DINOSAUR PROVINCIAL PARK
CANADA

UNESCO World Heritage Site

Articulated skeleton of the theropod Gorgosaurus from Dinosaur Provincial Park, at the Royal Tyrell Museum of Palaeontology. (Photo: Royal Tyrell Museum of Palaeontology).

WORLD'S MOST ABUNDANT AND DIVERSE DINOSAUR LOCALITY, YIELDING MORE THAN 166 VERTEBRATE TAXA, INCLUDING 51 SPECIES OF NON-AVIAN DINOSAURS.

This IUGS Geological Heritage site provides exquisitely preserved evidence of the tremendous diversity of organisms on the North American continent in a relatively short (2.4 Ma) interval of late Cretaceous time. It is the richest and most diverse dinosaur site in the world. Fifty-one species of dinosaur have been identified so far, more than 500 specimens have been excavated and placed on display in museums around the world, and exposed dinosaur bones are so numerous as to be uncountable. The enormous diversity of the complete fossil assemblage is the reason it was designated a UNESCO World Heritage Site in 1979.

SITE 036

GEOLOGICAL PERIOD	Late Cretaceous (Campanian)
LOCATION	Drumheller Alberta, Canada. 50° 46' 04" N 113° 39' 15" W
MAIN GEOLOGICAL INTEREST	Paleontology

Paleontologists of the Royal Tyrell Museum of Palaeontology conducting field work in Dinosaur Provincial Park. (Photo: Royal Tyrell Museum of Palaeontology).

Geological Description

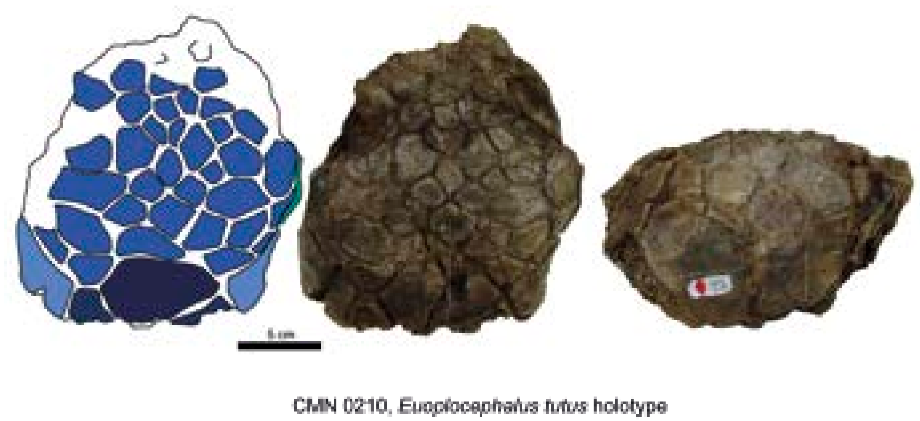
Dinosaur Provincial Park comprises 80 km^2 of badlands consisting of alluvial to coastal plain strata of the Campanian-age Belly River Group. Strata accumulated in alluvial to coastal regions west of the Bearpaw seaway. Based on U-Pb (TIMS) dating, the strata are 76.72 to 74.30 million years old, and coincide with the "zenith" of global dinosaur diversity. Two formations are present, including a portion of the alluvial Oldman Formation, and the entire alluvial-to-paralic Dinosaur Park Formation. The latter is uniquely rich in the remains of large dinosaurs (hadrosaurs, ceratopsians, theropods) preserved as fully-to-partially articulated skeletons, skeletal parts (limbs, skulls, and vertebrae), and football-field size bonebeds.

Many bonebeds contain remains from hundreds of individuals from single taxa of herbivorous dinosaurs *(Centrosaurus, Coronosaurus, Styracosaurus)*. Apart from the staggering impact they have on visitors, these bonebeds provided the first published evidence of gregarious behavior in dinosaurs (late 1970s). More than 110 years of collecting has yielded more than 166 species of vertebrates (including 51 species of dinosaur), and assemblages of plants and invertebrates. Dinosaurs from the Park are displayed around the world, but are showcased at the Royal Tyrell Museum of Palaeontology in Drumheller, Alberta.

Scientific research and tradition

The first dinosaur fossil in Alberta was found in 1884 by Joseph Tyrrell (Geological Survey of Canada). Many scientists were attracted to the area in search of dinosaur remains in the nineteenth and twentieth centuries and the Royal Tyrell Museum of Palaeontology continues to make new discoveries to this day.

Specimen CMN 0210, holotype of Euoplocephalus tutus, skull in dorsal and left lateral views with interpretive dorsal view diagram (Arbour and Currie, 2013). It was collected by Lawrence M. Lambe in 1897 East side of Red Deer River at mouth of Berry Creek.© 2013 Arbour, Currie



LATE CRETACEOUS RUDIST BIVALVES OF THE CARIBBEAN PROVINCE

JAMAICA

The barrel-shaped rudist bivalve Macgilavryia nicholasi in growth position (lower) and as toppled specimens in the Guinea Corn Formation of the Rio Minho.

THE MOST DIVERSE AND THICKEST LIMESTONE SUCCESSION WITH ABUNDANT RUDIST BIVALVES WITHIN THE CARIBBEAN FAUNAL PROVINCE.

Different assemblages of rudist bivalves developed in the Americas and the Tethys (Mediterranean, western Asia, and northern Africa) during the Late Cretaceous. The best studied and most diverse assemblages of late Maastrichtian rudists in the Americas is in Jamaica, specially those from Rio Minho. The rudists of Rio Minho have been extensively studied in terms of their taxonomy, their palaeoecology and their sedimentology. The different assemblages indicate that different rudists were adapted to different microenvironments across the carbonate platform in terms of their size, their growth morphology and their substrate preferences.

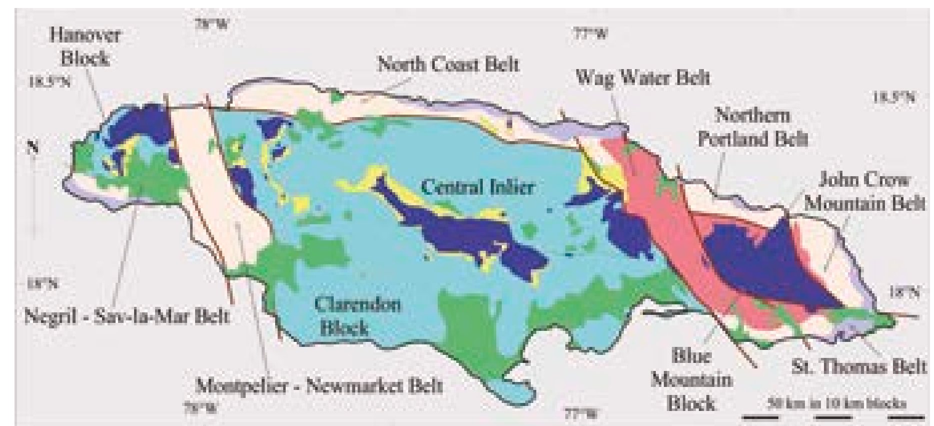
SITE 037

GEOLOGICAL PERIOD	Cretaceous / Late Maastrichtian
LOCATION	Rio Minho, parish of Clarendon, central Jamaica 18° 09' 18" N 077° 23' 12" W
MAIN GEOLOGICAL INTEREST	Paleontology Stratigraphy and sedimentology

The giant rudist bivalve Titanosarcolites sp. from the Guinea Corn Formation (Rio Minho); certainly amongst the largest bivalves that ever lived.

Geological Description

The 200-m thick Guinea Corn Formation forms the marine portion of a 1,000 m thick transgressive-regressive tectonic cycle (Kellits Synthem). The complete Guinea Corn succession is exposed in the bed and banks of the Rio Minho, and the alternations of limestone, shale, mudstone, and sandstone, form small-scale cycles, which can be correlated from section to section along the river. Rudist bivalves occur throughout the limestone and also in some of the shale, with specimens preserved in growth position, toppled, or reworked. A highly diverse assemblage of rudist bivalves is present including at least 34 species belonging to 18 genera. Distinct assemblages are present including: 1, very small radiolitids *(Trechmannites)*; 2, small radiolitids *(Parabournonia, Guanacastea and Thyrastylon)* and antillocaprinids *(Antillocaprinia, Rotacaprina)*, 3, larger radiolitids *(Chiapasella)*; 4, giant radiolitids *(Macgillavryia)* and hippruitids *(Praebarrettia)*; and 5, various antillocaprind associations. The barrel-shaped *Macgillavryia* and *Praebarrettia* reach sizes of 43 cm and 35 cm high, respectively, whereas the giant *Titansoarcolites* can reach up to 1.3 m across (making it amongst the largest bivalves that every lived). This high-diversity rudist fauna occurs in uppermost Maastrichtian strata and is restircted to the American biogeoprovince. The bivalve community was likely terminated by the K-Pg extinction event.



Geological map showing divisions in the Guinea Corn Formation (see Mitchell, 2002) along the Rio Minho in the vicinity of Cabbage Hill.

Scientific research and tradition

Rudist bivalves were discovered in northern Clarendon during the first official geological survey of Jamaica (Sawkins, 1969) and subsequently monographed by Whitfield (1897), Chubb (1971), and Mitchell (2013). Their age has been constrained (Steuber *et al.*, 2002) and their sedimentology, palaeoecology and depositional environment have been investigated (Mitchell, 2002).

EOCENE PALEONTOLOGICAL RECORD OF MESSEL PIT FOSSIL SITE

GERMANY

UNESCO World Heritage Site
UNESCO Global Geopark

The darkling beetle Ceropria messelense with 48 million year old structural colours and a petal on one elytron. (Photo: Senckenberg).

THE RICHEST GEOSITE IN THE WORLD FOR UNDERSTANDING THE LIVING ENVIRONMENT OF THE EOCENE, AS IT INCLUDES EXCEPTIONALLY WELL-PRESERVED FOSSILS.

An inventory of more than 50.000 fossils (e.g. incl. > 45 mammal species, > 100 plant families, ca. 50 bird species and > than 80 insect species) exists. Complete fossils of animals provide a unique insight into an early stage of mammal evolution and diversification. For interpreting mammals, insects, plants and other organisms in "paratropical" ecosystems and in other (esp. holarctic) floras and faunas the Messel fossils are uniquely important. They allow the reconstruction of the behaviour and interactions of organisms and comprise a large number of holotypes. The UNESCO World Heritage Site Messel Pit is a flagship in geoscience popularization and in collaboration with Global Geoparks Network partners. Situated in the northern part of UNESCO Global Geopark Bergstrasse-Odenwald, both institutions collaborate since 2003 and by this are a best practice example of synergies across the UNESCO programme designations.

SITE 038

GEOLOGICAL PERIOD	Paleogene / Eocene (Ypresian – Lutetian)
LOCATION	Geopark Bergstrass-Odenwald, Hesse, Germany. 49° 54' 46'' N 008° 45' 15'' E
MAIN GEOLOGICAL INTEREST	Paleontology Stratigraphy and sedimentology

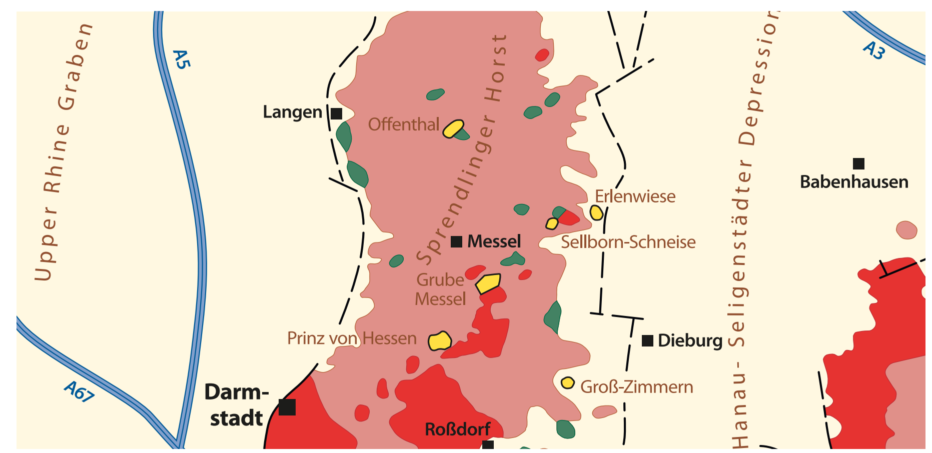
View from the visitor platform into the Messel Pit WHS, Germany, with its dark, fossiliferous oilshale. (Photo: Welterbe Grub Messel gGmbH).

Geological Description

The Eocene was an epoch in the evolution of life on earth, when mammals became firmly established in all the principal land ecosystems and took to the air (Vianey-Liaud *et al.,* 2019; Schaal, 2020). The Messel Pit provides the single best site which contributes to the understanding of this period (Smith *et al.,* 2018). The pre-eminence of Messel thus derives from its universal importance as a record of the development of the vertebrates. Messel is also exceptional in the quality, quantity and diversity of fossils. While most fossil vertebrate remains yield only fragments of bones, Messel offers fully articulated skeletons, the outline of the entire body as well as feathers, hairs and stomach contents (Wappler *et al.,* 2015). Significant scientific discoveries have and are being made at Messel. Sauropsids, fishes, insects and plants all contribute to an extraordinary fossil assemblage. The finds cover the entire spectrum of the organisms in a biodiversity and quality hitherto unmatched by any other site. Furthermore, Messel is also the only fossil site of this status which remains truly preservable. The Messel Pit is a best practice example of collaboration between UNESCO entities in the long term (McKeever *et al.,* 2014; Frey 2018).

Scientific research and tradition

The first scientific publication about the Messel Pit was published in the year 1876. Nearly a hundred years later, in 1975 the first popular scientific publication was made. Regular and continous scientific investigations started in 1965 by the Hesse State Museum in Darmstadt, followed from 1975 onwards by the Senckenberg Society for Nature Research, Frankfurt am Main, Germany. Scientific publications since 1968 started to skyrocket. The institutions continue their scientific investigations until now.



Oil shale deposits (Eocene)
Volcanic rock (Tertiary)
Odenwald crystalline rocks (Carboniferous)
Rotliegendes (Permian)

Geological map of Messel Pit (Grube Messel) in the middle of Sprendlinger Horst in the north-eastern Upper Rhine Graben (Photo: Grube Messel gGmbH)

MIOCENE PRIMATES PALEONTOLOGICAL SITE OF NAPAK

UGANDA

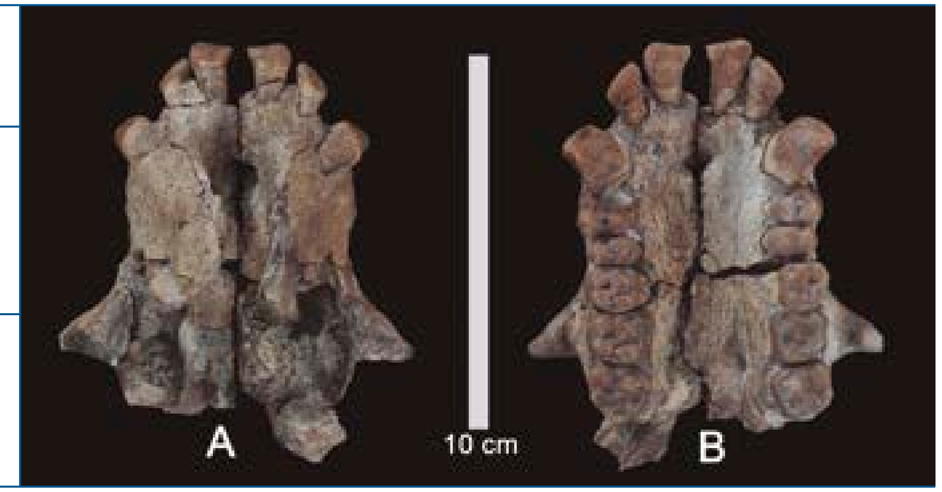
Alekilek in the foreground with Akisim in the background.

ONE OF THE RICHEST UNIVERSAL SOURCES OF EARLY MIOCENE WELL-PRESERVED PRIMATES ASSOCIATED WITH AN AMAZING FOSSIL FAUNA AND FLORA.

Napak is one of the few volcanoes in Africa that exposes its innards as well as parts of the edifice and the central plug. It is thus a natural choice for an IUGS Geological Heritage Site. The volcanic ashes and palaeosols preserve a diverse flora and fauna (including 15 taxa of primates ranging in size from bushbaby to gorilla) adding to its scientific value. These fossils permit the reconstruction of the Early Miocene palaeoenvironment, dominated by forest growing on the slopes of the nascent volcano, with open grassy patches. Given its volcanic, geomorphological and fossil resources Napak is a reference for African geosciences.

SITE 039

GEOLOGICAL PERIOD	Miocene
LOCATION	District of Napak Iriri Sub-County, UGANDA 02° 08' 30" N 034° 16' 44" E
MAIN GEOLOGICAL INTEREST	Paleontology Volcanology



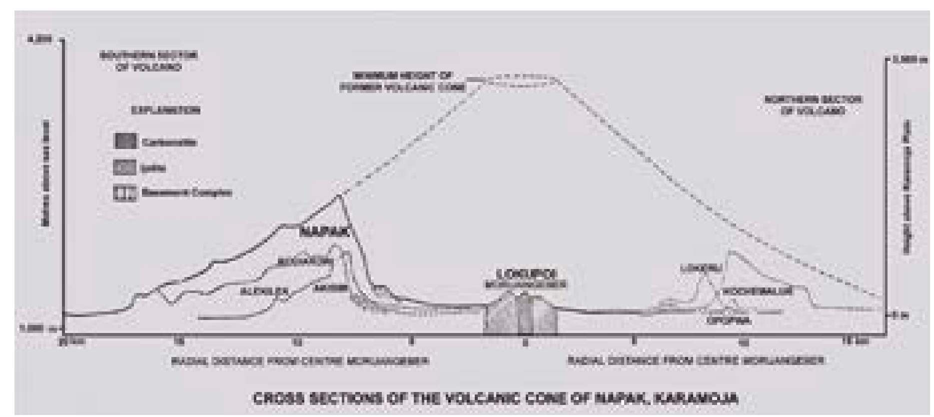
Skull of Ugandapithcus major.

Geological Description

Napak is a deeply dissected Carbonatite-Nephelinite Volcano of Early Miocene age (20.5 – 19 Ma) in northeastern Uganda, posed impressively on the rigorously flat Karamoja Plains beneath. The total edifice is 40 kms in diameter, leaving some remnants. It is of great scientific interest for several reasons. It is one of a series of alkaline volcanoes that erupted along the margins of the Great Rift Valley. Napak is also of the greatest interest to volcanologists, in that it provides a rare opportunity to see the insides of a volcano. In effect, erosion has dissected the edifice of the volcano, exposing its flanks in several magnificent cliffs, and its vent. In addition, the volcanic rocks preserve patches of the African Erosion Surface at several outcrops. In most of East Africa, evidence of this geomorphological surface has been destroyed by erosion. Napak thus forms an irreplaceable anchor for geomorphologists interested in the evolution of the African interior since the Oligocene (25 m.y. ago). The volcano-sedimentary deposits yielded a very rich, amazing palaeobiodiversity (fauna and flora) preserved in volcanic ash and palaeosols derived from the carbonate-rich ash which yield evidence about past climates.

Scientific research and tradition

Following initial geological observations in the 1920's by E.J. Wayland, B.C. King (1949) mapped the mountains and established their carbonatite–nephelinitic affinities. Fossil discoveries by J. Wilson (1958 unpublished) were followed by Bishop's collections (1958-1964). Fieldwork ceased in 1964 due to security issues, but was resumed in 1985 by a Franco-Ugandan collaborative project (see Senut, 2014 and Pickford *et al.,* 2021).



Cross section of the volcanic cone of Napak, Karamoja.

LESVOS EARLY MIOCENE PETRIFIED FOREST

GREECE

UNESCO Global Geopark

The largest standing trunk of a petrified tree known so far in the world belongs to a conifer tree (Taxodioxylon albertense), an ancestor of the modern sequoias.

ONE OF MOST COMPLETE EARLY MIOCENE FOREST ECOSYSTEM RECORDS OF THE WORLD.

The Lesvos Petrified Forest is one of the best preserved fossil forest sites in the world, well protected and conserved as a Natural Monument. Its creation is linked with the Early Miocene volcanism of the Aegean area. It is a historic site related with the early steps of Earth Sciences because of the first reference to the fossilisation process by the philosopher Theophrastus (371BC-287BC) . It is one of the first four areas recognised as geoparks in Europe in 2000. It is a flag site for geoeducation and raising awareness on geological heritage nationally and internationally.

SITE 040

GEOLOGICAL PERIOD	Lower Miocene
LOCATION	Lesvos Island Geopark, North Aegean Region, Greece. 39° 12' 32'' N 025° 53' 50'' E
MAIN GEOLOGICAL INTEREST	Paleontology Volcanology History of geosciences

Petrified tree trunk revealed due to the natural weathering of the volcanic rocks which surrounded it.

Geological Description

The Lesvos Petrified Forest is a protected natural monument (Presidential Decree 433/1985). It represents successive subtropical forests fossilized in situ due to the intense volcanic activity during Lower Miocene (21 - 16.5 Ma.).

It covers an area of 15,000 ha with pyroclastic formations both on Lesvos island and the marine area along its western coast. The trees were petrified in their original growing position.

Lesvos is part of a belt of late Oligocene to middle Miocene calc-alcaline to shoshonitic volcanism of the northern and central Aegean Sea and western Anatolia. The fossilized flora of the Lesvos Petrified Forest consists of pteridophytes, conifers, and angiosperms. The conifers are represented by the families of Protopinaceae, Pinaceae, Cupressaceae, Taxodiaceae, Gingoales. Of the monocotyledons, various types of palms have been identified while of the broadleaves (angiosperm-dicotyledona), species of poplar, laurel, cinnamon, plane, oak, lime, beech, alder and maple have been found. The composition of the petrified flora indicates that the Petrified Forest developed in a subtropical climate. This changed suddenly into a continental climate with plants characteristic of the subtropics of Southeast Asia and America.

Scientific research and tradition

First references to Lesvos fossils were made by Theophrastus (371-287 BC). F. Unger (1844) describe Lesvos fossil trees. Systematic scientific study started in 1978. Scientific research and excavations have been carried out by the Natural History Museum of the Lesvos Petrified Forest since 1997. During the last years rescue excavations revealed thousands of petrified trees and fossil leaves in the area.

The Petrified Forest of Lesvos is one of the four founding members of the European Geoparks Network in 2000 and among the initial members of the Global Geoparks Network in 2004. It is a flag geological heritage site used for decades by schools and universities in earth sciences and environmental education and recently on geohazards and climate change educational activities.

Map of Lesvos Island UNESCO Global Geopark. Marked is the protected area of the Lesvos Petrified Forest.

PALAEOANTHROPOLOGICAL SITES OF HUMAN EVOLUTION OF LAETOLI-OLDUVAI GORGE

TANZANIA

UNESCO World Heritage Site

Olduvai Gorge. Deposition sequence of pyroclastic material at Olduvai Gorge.

THE PALAEOANTHROPOLOGICAL SITES INDICATING EARLY HOMININ DEVELOPMENT AND ACTIVITIES.

Laetoli and Olduvai Gorge are the two important paleoanthropological sites, which depict the direct evidences of early hominin development and activities. These sites are rich in hominin fossils, artifacts, and tracks. At Laetoli, fossil footprints occur in a 27 m long track. They are dated at 3.6 Ma and are associated with the earliest hominids known as Australopithecus afarensis. These footprints provide well-accepted evidence that hominins were bipedal as early as several million years ago. Hominid fossils from Olduvai Gorge include remans of Zinjanthropus boisei (1.848 Ma), Homo habilis (1.848–1.832 Ma), Homo erectus, earliest modern humans *(Homo sapiens)* and numerous stone tools, which suggest that there was co-existence of multiple species of hominids in Olduvai.

SITE 041

GEOLOGICAL PERIOD	Pliocene - Holocene
LOCATION	Ngorongoro Conservation Area, Arusha, Tanzania. 03° 13' 32" S 035° 11' 32" E
MAIN GEOLOGICAL INTEREST	Paleontology

A 3.6 million years fossilized footprints at Laetoli site reveal that hominins were walking upright.

Geological Description

The stratigraphic sequence of both Laetoli and Olduvai gorge are associated with volcanic eruptions from the Ngorongoro Volcanic Highlands, which generated vast amounts of volcanic ash and pumice (pyroclastic material) that accumulated in the east of the Serengeti Plains. The depositional sequences are divided into a number of beds in which the footprints and hominid fossils were discovered.

The Laetoli Beds are subdivided into a Lower Unit (4.3 Ma) and Upper Unit, both composed of eolian and air-fall tuff. The lower unit is characterized by rain-printed surface and few fossils. The upper unit, dated at 3.8 Ma, is 60m thick and contains the fossils and footprints.

The Olduvai Gorge is 48Km long and 100m deep and extends to the east into the Olbalbal depression cutting through numerous layers of volcanic ash and pumice. Its stratigraphic succession is nearly 100 m thick and divided into seven formations that overlie Neoproterozoic basement rocks of the Mozambique Belt. The formations represent deposition in volcanic, alluvial fan, fluvial, aeolian, and lacustrine settings.

Three million years prior to the formation of the gorge, the region was a low area periodically occupied by a large, saline lake. During this time, the lake and surrounding areas were home to earliest hominid ancestors.

Laetoli Early life. Prehistoric people migrating during Ngorongoro Volcanics eruption

Scientific research and tradition

From the early 1900s, the area has attracted the world and scientific community attention as many discoveries of the important hominid fossils and artifacts that explain in details the human evolution. In 1960s, the leakey family establish a research camp, which still operates. A number of research papers and PhD's have been published.

LATE QUATERNARY ASPHALT SEEPS AND PALEONTOLOGICAL SITE OF LA BREA TAR PITS

USA

Mass of Late Quaternary fossils preserved in an asphaltic deposit at Rancho La Brea exposed during 2017 excavations. (©Natural History Museum of Los Angeles County).

THE RICHEST PALEONTOLOGICAL SITE ON EARTH FOR TERRESTRIAL FOSSILS OF LATE QUATERNARY AGE.

Long recognized as one of the most important fossil localities in the world, the asphaltic deposits collectively known as the La Brea Tar Pits have been the subject of intensive research on geology, paleontology, and archaeology for over 150 years. In 1951 this locality was designated as the type locality for the Rancholabrean North American Land Mammal Age (NALMA). The site was formally recognized by the United States National Parks Service as a National Natural Landmark in 1963.

SITE 042

GEOLOGICAL PERIOD	Late Pleistocene - Holocene
LOCATION	Los Angeles, California, United States 34° 03' 50" N 118° 21' 20" W
MAIN GEOLOGICAL INTEREST	Paleontology

NHMLAC excavation of Pits 61 and 67 in 1915 looking NNE across the Salt Lake Oil Field towards the Santa Monica Mountains. RLB-327. (©Natural History Museum of Los Angeles County).

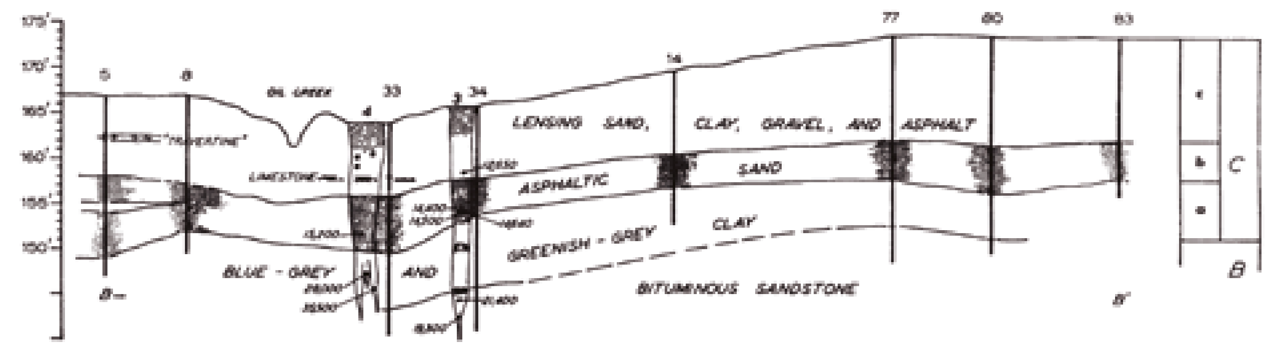
Geological Description

Los Angeles, California, sits atop a sedimentary basin bounded by the Transverse and Peninsular ranges. On the northern part of the basin lies an alluvial plain shed from the Santa Monica Mountains during the Pleistocene. In the vicinity of La Brea Tar Pits (Rancho La Brea), 45 meters of this alluvium, referred to as the Palos Verdes Sand, rests upon Middle Pleistocene shallow marine strata and thick, oil-rich Middle Miocene deep-marine deposits. Through multiple intervals of uplift and faulting, crude petroleum has seeped to the surface over the last ~60,000 years, forming shallow pools that have entrapped and preserved millions of fossils representing hundreds of species of plants, invertebrates, and vertebrates. These fossil remains, ranging from *Mammuthus*, *Smilodon*, and entire *Juniperus* trunks to seeds, insects and songbirds, form a continuous record of ecosystem structure and change across major climatic and geological boundaries. The asphaltic fossil preservation is so exquisite that original biotic materials including collagen, cellulose, and chitin are preserved, allowing geochemical analyses including radiocarbon dating and studies of stable isotopic signatures. The Rancho La Brea Lagerstätte therefore represents a unique opportunity to study the impacts of Earth processes like climate change on ecosystem dynamics, species adaptations, and extinction.

Scientific research and tradition

More than four million fossil specimens have been excavated since the site's discovery in 1875. These collections, and the locality itself, have been the subject of more than 400 scientific publications. Ongoing excavations, a growing collection, and evolving research techniques continue to yield new insights about Late Quaternary ecosystems.

Geological cross-section of Palos Verdes Sand showing stratigraphic placement of asphaltic deposits where fossils are concentrated ("Pits" 5, 8, etc.) and radiocarbon dates obtained on in situ Smilodon bones. Source: Woodard and Marcus, 1973, Journal of Paleontology, v. 47, p. 60.



4

IGNEOUS AND METAMORPHIC PETROLOGY

SITE 043 - SITE 050

Photo: Luis Carcavilla

Igneous petrology is the field of study of rocks that form by crystallization from magmas. Magmatic rocks that are intrusive into pre-existing rocks and cool slowly within the crust are known as plutonic rocks, and those that are eruptive or effusive at the surface of the Earth occur as volcanic rocks. Metamorphic petrology is the study of rocks that form through solid-state transformations that usually occur deep in the Earth due to changes in pressure and temperature, and may be related to intense deformational processes. Through careful study of field relations (with scales of observation ranging from regional geologic mapping to hand sample scale descriptions of outcrops), chemical and isotopic composition of rocks and minerals, and the structures and textures that have developed in these rocks, it is possible to determine their origins and occurrences, environments of formation, rock-forming processes, and geologic history. Igneous and metamorphic rocks are important components of the global rock cycle, and provide essential evidence for interpreting environments and processes related to plate tectonics. Igneous and metamorphic rocks are important to humanity with regard to geohazards such as volcanic eruptions and Earth resources such as metallic ore deposits and sources for building stones.

Igneous and metamorphic petrology as the core of the geological sciences is key to understanding the origin and evolution of the Earth. The Earth is a dynamic planet, and igneous and metamorphic rocks attest to the tremendous forces at work in creating and transforming Earth's crust throughout geologic time. Many geoheritage sites on crystalline rocks could be used to study the basic concepts and processes of igneous and metamorphic petrology. In this chapter, iconic sites of crystalline rocks are explored through geologic space and time. Some of the oldest crystalline rocks on Earth, formed 3.5-3.0 Ga with a second magmatic event dated at 2.8 Ga, are described in the Beartooth Mountains, MT USA, including crust-forming processes that occur 20-30 km below the Earth's surface. Related magmatic rocks of the 2.7 Ga, layered mafic/ultramafic Stillwater Complex, MT USA, demonstrate processes that occur in magma chambers and ore-forming processes for Cr, Cu-Ni, and Pt-Pd deposits. More recent examples of intrusive rocks include the Richat Structure, Mauritania, that occurs as a ring dike structure that formed at 99-86 Ma as multiple intrusions of basalts, kimberlites, and alkalic volcanic rocks into Late Proterozoic to Ordovician sedimentary rocks. The Miocene Torres Del Paine Intrusive Complex, 12.5 Ma, demonstrates the structural control of magmas emplaced at shallow crustal levels. The Mount Kinabalu granitic intrusion of Malaysia, dated at 8-7 Ma, is one of the youngest exposures of plutonic rocks in the world. Eruptive rocks include the 165 Ma old ignimbrite (pyroclastic flow) deposits of Sillar de Arequipa, Anashuayco Quarry site, Peru; these rocks demonstrate the important relation with hot gasses that alter and cement the rocks that provided rock resources for artisan to modern quarrying of building stones. The early Cretaceous rhyolite deposits of Hong Kong, China, have produced ~1300 km^3 of volcanic ash deposited in sheets that have cooled to form spectacular columnar joints. An example of crustal deformation is exhibited in the Miocene, 16-17 Ma, metamorphic core complex of the northern Snake Range, Nevada USA, where extensional faulting has thinned the deforming rocks to as much as 10% of their original thickness.

David Mogk
Montana State University. USA.
IUGS Geological Heritage Sites voting member.

Asfawossen Asrat
Botswana International University of Science and Technology. Botswana.
IUGS Geological Heritage Sites voting member.


Archean Rocks of the Eastern Beartooth Mountains
USA
The Stillwater Complex
USA
The Hadean to Eoarchean Nuvvuagittuq greenstone belt
CANADA
Early Cretaceous Rhyolitic Columnar Rock Formation of Hong kong
CHINA
Richat Structure, a Cretaceous Alkaline Complex
MAURITANIA
Mount Kinabalu Neogene Granite
MALAYSIA
Archean Zircons of Erawondoo Hill
AUSTRALIA
The miocene Torres del Paine intrusive complex
CHILE

ARCHEAN ZIRCONS OF ERAWONDOO HILL

AUSTRALIA

Erawondoo Hill, a resistant outcrop of Archaean sandstone and conglomerate.

LIKE A WINDOW INTO THE ORIGINS OF THE EARTH, IT IS HOST TO DETRITAL ZIRCONS WITH AGES 4.4-4.0 GA PRESERVING THE OLDEST REMNANTS OF EARTH'S PRIMORDAL CRUST.

Erawondoo Hill is the largest in situ repository of the oldest terrestrial crystals known to exist on Earth. It is one of the world's most important sites for ongoing research into the origin and evolution of the Earth.

Using modern analogues, the sedimentary structures, grain sizes, and sequence of graded bedding and lithologies of the sandstone and conglomerate suggest the deposits formed in braided river environments and fan deltas. As such, they provide a unique and important window to the processes and landscape of the Earth's surface in this part of the globe in very ancient times.

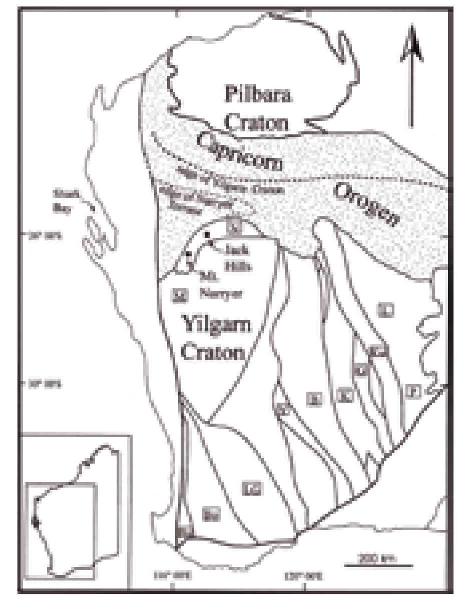
SITE 043

GEOLOGICAL PERIOD	Archaean (Hadean)
LOCATION	Erawondoo Hill (Jack Hills) Murchison District, Western Australia. 26° 10' 58'' S 116° 55' 57'' E
MAIN GEOLOGICAL INTEREST	Petrology Geochronology

Archaean layered conglomerate of quartz pebbles in a sandy matrix cropping out on Erawondoo Hill – the zircons are within the quartz pebbles.

Geological Description

Erawondoo Hill, part of the Jack Hills Range, is located in the Murchison District of Western Australia. Geologically, it is in the northern part of the Yilgarn Craton in a structural/metamorphic terrane known as the Narryer Terrane, a northeast-trending belt of folded and metamorphosed supracrustal rocks between 3.1-3.2 billion years old. The Jack Hills range is comprised of vertically-dipping Precambrian rocks and the detrital zircons over 4 billion years old occur within pebble conglomerates therein. Locally are interlayered sheets of massive sandstone and cross-bedded sandstone. Hard and heat-resistant, zircon is capable of persisting even after the primary features of the host or parent rock have been destroyed. These ancient zircon crystals provide the only geological evidence to provide insight into this time period. In fact, these zircons being older than the sedimentary rocks in which they occur represent rocks that no longer exist or can no longer be identified. The exact age of deposition of the pebble conglomerate in which the crystals are found is still unknown and is one of the unresolved questions surrounding this ancient fragment of Earth's early crust in this part of Western Australia.



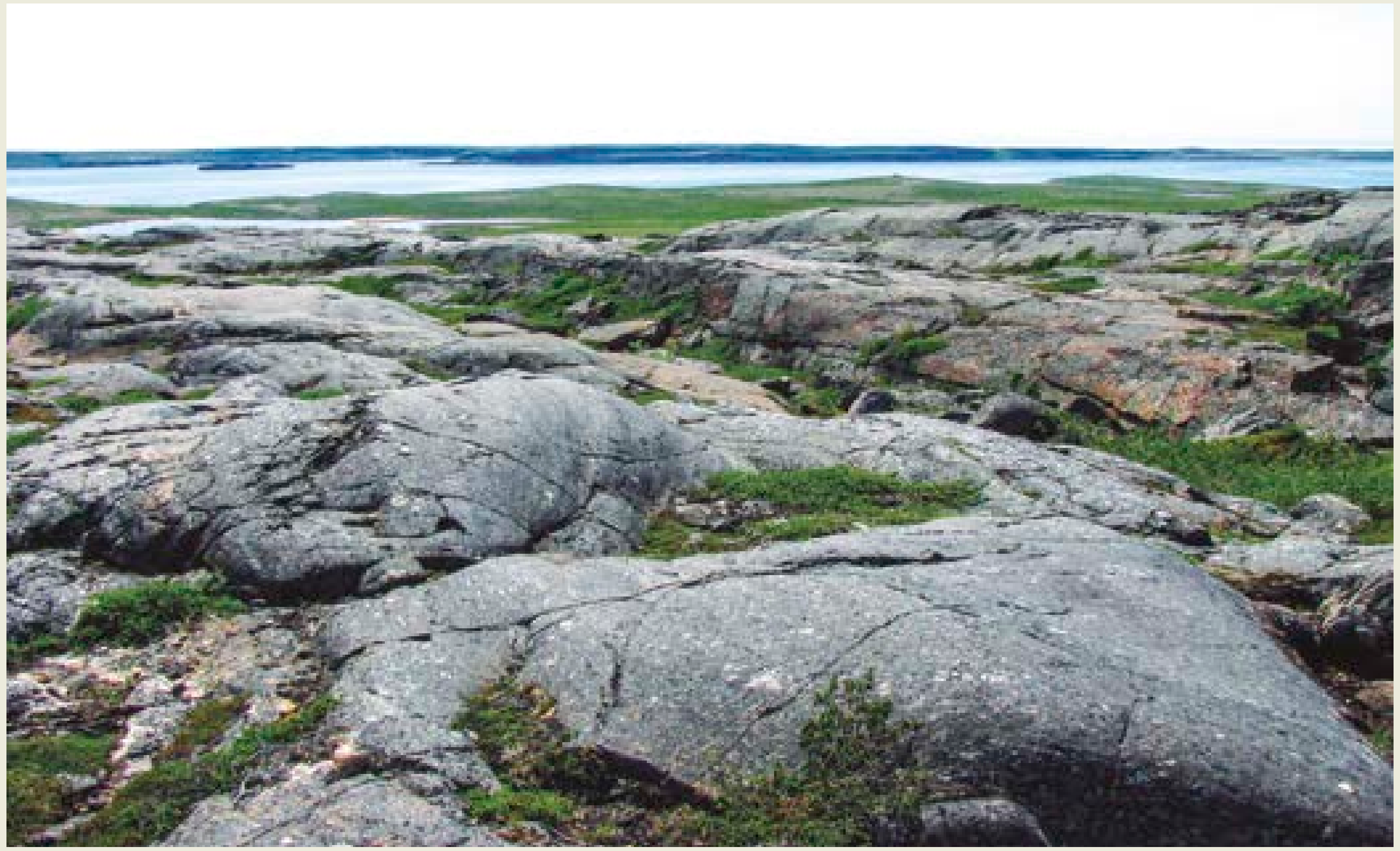
Simplified geological map of mid to southern Western Australia showing terranes of Precambrian rocks and location of Jack Hills. Nomenclature of terranes in the Yilgarn Craton after Wilde et al. (1996).

Scientific research and tradition

The zircons from Erawondoo Hill have been important to science in that they have provided insights into early crustal evolution of the Earth. More detailed geochemical studies with technological advancements have provided further information on early Earth water, oxygen, rare Earth elements, Lithium, and other elements, and their relationship to crustal evolution.

THE HADEAN TO EOARCHEAN NUVVUAGITTUQ GREENSTONE BELT

CANADA



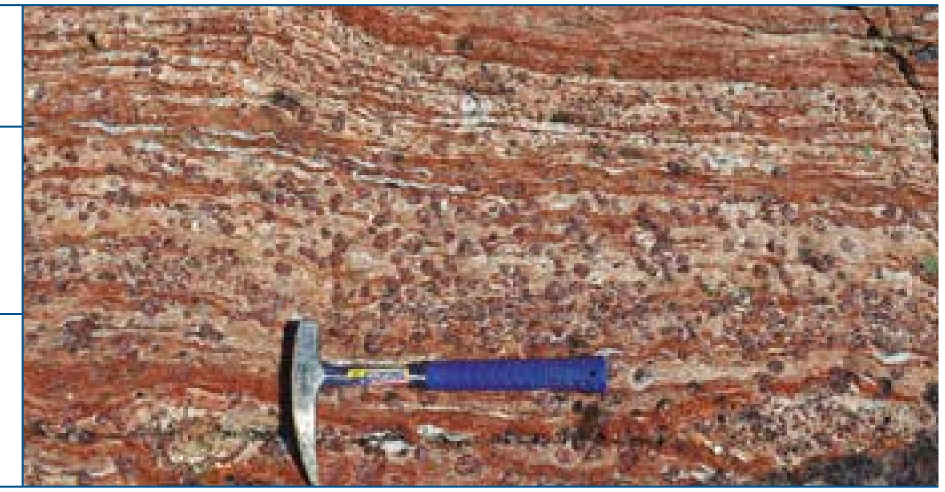
View (looking South) from the Nuvvuagittuq greenstone belt. Outcropping rocks are believed to be as old as 4.3 billion-years-old. (Jonathan O'Neil).

SOME OF THE OLDEST, IF NOT THE OLDEST ROCKS ON EARTH, WITH POTENTIALLY EARLIEST TRACES OF LIFE.

With a likely age of 4.3 billion years old (O'Neil *et al.,* 2008), the Nuvvuagittuq greenstone belt may represent the only known rocks formed within the Hadean eon. This remnant of ancient oceanic crust offers a unique window into Earth's earliest times. It can help to shed light on important and broad scientific questions ranging from understanding how Earth's first crust formed, elucidating early tectonic regimes, to establishing the geological environments (early atmosphere, presence of liquid water, temperature of the earliest oceans, etc.) where early life could have arisen on Earth.

SITE 044

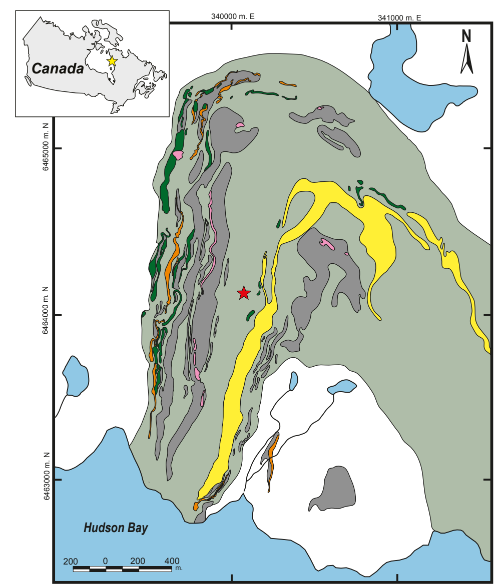
GEOLOGICAL PERIOD	Hadean / Eoarchean (4.3 – 3.8 Ga)
LOCATION	Nunavik, Quebec, Canada. 58° 17' 31" N 077° 43' 53" W
MAIN GEOLOGICAL INTEREST	Igneous and metamorphic petrology Paleontology Geochronology



Close-up view of the mafic volcanic rocks dated at 4.3 billion-years-old. Metamorphic mineral assemblage mainly consists of cummingtonite-plagioclase-biotite-garnet-quartz. Location shown on the map. (Jonathan O'Neil).

Geological Description

The Nuvvuagittuq greenstone belt is a volcano-sedimentary sequence located in northeastern Canada, mostly composed of metamorphosed mafic volcanic rocks and chemical sedimentary rocks such as banded iron formation (O'Neil *et al.,* 2019). The Nuvvuagittuq greenstone belt includes some of the oldest, if not the oldest rocks, preserved on our planet. The exact age of the Nuvvuagittuq greenstone belt has been debated in the scientific community (Cates *et al.,* 2013; O'Neil *et al.,* 2019), but it is at least 3.75 billion-years-old (Cates and Mojzsis, 2007). However, variation in the isotope tracer 142Nd measured in the dominant volcanic rocks supports an age of 4.3 billion-years-old, making them the oldest rocks known on Earth (O'Neil *et al.,* 2008). The petrology and geochemistry of the Nuvvuagittuq rocks suggest it represents a remnant of hydrothermally altered oceanic crust, perhaps formed in short-lived subduction-like settings (O'Neil *et al.,* 2019). This would represent the earliest evidence on Earth of a geodynamic regime resembling modern-day plate tectonic. The Nuvvuagittuq greenstone belt includes jasper-bearing banded iron formations displaying micrometer-scale hematite tubes and filaments with morphologies and mineral assemblages consistent with formation via biological activity (Dodd *et al.,* 2017). This would constitute the earliest evidence of life on Earth.



Simplified geological map of the Nuvvuagittuq greenstone belt. Location in Canada is shown by the yellow star. Red star shows the location of the photo above.

Scientific research and tradition

The Nuvvuagittuq greenstone belt became a region of interest for research after 3.8 billion-years-old rocks were discovered (Simard *et al.,* 2003). O'Neil *et al.* (2008) later proposed that it included 4.3 billion-years-old rocks, representing the oldest rocks on Earth. It has since been the object of multiple scientific publications.

ARCHEAN ROCKS OF THE EASTERN BEARTOOTH MOUNTAINS

USA

Interlayered 3.5-3.0 Ga TTG gneiss and metasupracrustal rocks (ridge in foreground) as a km-scale pendant in voluminous 2.8 Ga calc-alkaline magmatic rocks seen on the skyline, Hellroaring Plateau.

ARCHEAN ROCKS OF THE EASTERN BEARTOOTH MOUNTAINS RECORD EARLY CRUSTAL GENESIS AND EVOLUTION.

Archean crustal genesis and evolution are revealed: a) separation of mafic crust from the mantle in a plume-dominated tectonic environment (4.0-3.6 Ga); b) partial melting of mafic crust to produce the first tonalite-trondhjemite-granodiorite (TTG) continental nuclei (3.6-3.1 Ga; Mueller *et al.,* 2014); c) stable platform sedimentation followed by convergent margin tectonics (2.8 Ga) produced calc-alkaline magmatic rocks by subduction processes comparable to a modern continental arc (Mueller *et al.,* 2014; Mogk *et al.,* 2020). The "granite controversy" is addressed in the gneiss which was originally interpreted as solid-state transformations ("granitization"; Eckelmann and Poldervaart, 1957) vs. magmatic processes (Mueller *et al.,* 2010).

SITE 045

GEOLOGICAL PERIOD	Paleo- to Mesoarchean
LOCATION	20 Km south of Red Lodge, Montana, USA. 45° 01' 45" N 109° 24' 57" W
MAIN GEOLOGICAL INTEREST	Igneous and metamorphic petrology

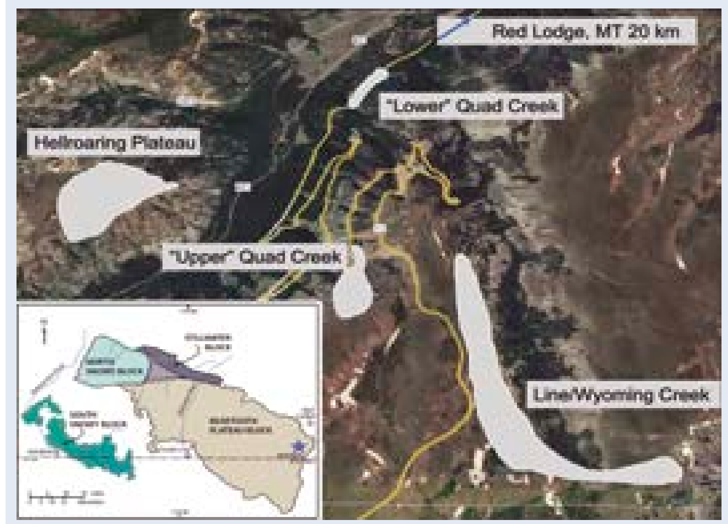
Tectonically interleaved Paleoarchean TTG gneiss (gray), quartzite (white), and amphibolite (dark, upper left) in the upper Quad Creek area exposed on the Beartooth Highway. Scale: yellow hammer is 1 meter.

Geological Description

The eastern Beartooth Mountains contain pendants of Paleo-Mesoarchean high-grade gneiss intruded by voluminous Neoarchean calc-alkaline rocks (Mogk *et al.,* 2020). The oldest gneiss is dominantly of the TTG suite in composition and crystallized 3.5-3.1 Ga based on U-Pb zircon geochronology (Mueller *et al.,* 2014). This rock is ion bi-modal association with amphibolite and are tectonically interleaved with metasupracrustal rocks (Henry *et al.,* 1982). Detrital zircons in quartzite reveal crust-forming events at ~4.0, 3.7, and 3.5 Ga with a major crust forming event at 3.3-3.2 Ga; the latest deposition occurred at ~3.0-3.1 Ga (Mueller and Wooden, 2012). The metasupracrustal rocks were deposited in tectonically quiescent environments and were subsequently tectonically mixed with bodies of gneiss and metamorphosed between 3.0 and 2.8 Ga at pressure-temperature conditions of ~680-750°C and 6-8 Kbar (20-25 km depth of burial). The deep burial of the supracrustal sequence results from crustal thickening via horizontal tectonics (Henry *et al.,* 1982). The Neoarchean magmatic cycle occurred over a restricted time interval (2.83-2.79 Ga) and produced large volumes of rocks of intermediate and tonalitic composition, along with the first major occurrence of true granite (Mueller *et al.,* 2010). The Neoarchean rocks are interpreted as the products of subduction analogous to a modern-day continental arc setting.

Scientific research and tradition

The eastern Beartooth Mountains have been extensively studied for over 60 years, starting with detailed field studies (Eckelmann and Poldervaart, 1957) and continuing with modern analytical studies including major and trace element geochemistry, geochronology (U-Pb and Lu-Hf zircon, Nd-Sm, and Rb-Sr methods), isotopic tracers, and quantitative geothermobarometry (Mueller *et al.,* 2014).



Exposures of Paleo-Mesoarchean enclaves (shaded gray), Beartooth Highway (yellow trace), and reference map of the Beartooth Mountains showing site location (blue star).

THE STILLWATER COMPLEX
USA

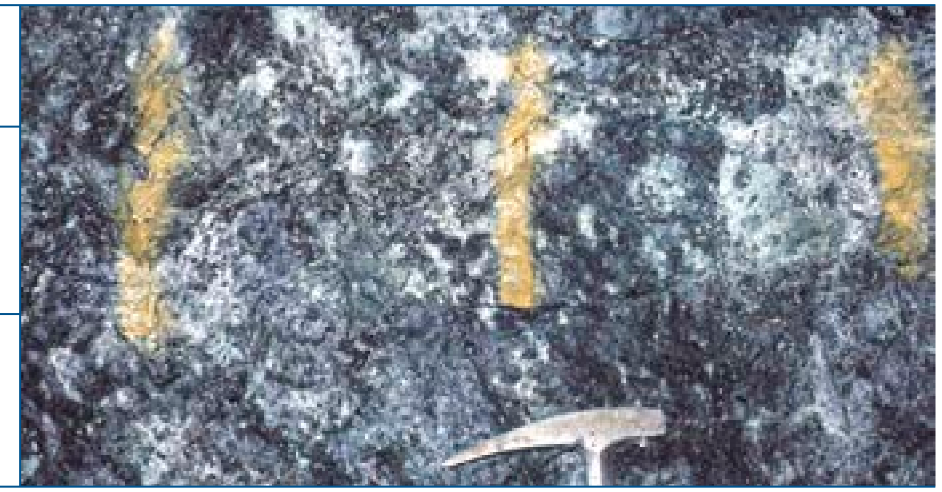
Outcrop of "inch-scale doublets" tilted to vertical; original stratigraphic "up" is to the right. (Photo courtesy Brian O'Driscoll).

ONE OF THE WORLD'S OLDEST LAYERED INTRUSIONS, CONTAINING THE WORLD'S HIGHEST-GRADE PLATINUM-GROUP ELEMENT DEPOSIT.

The Stillwater Complex has been an important laboratory for understanding a host of igneous processes and magmatic ore deposit models. These include the use of the thick Stillwater anorthosites as analogues for understanding the origin of lunar anorthosites (Salpas *et al.,* 1983). More recently, investigations have centered on role of high-temperature hydrothermal processes vs. conventional magmatic precipitation mechanisms for the concentration of Cr and platinum-group element deposits in layered intrusions (Boudreau *et al.,* 2020). This includes debate if the reappearance of olivine in the stratigraphy is the result of conventional magmatic mixing schemes or is instead the result of incongruent melting owing to volatile fluxing.

SITE 046

GEOLOGICAL PERIOD	Neoarchean
LOCATION	Montana, USA centered at approximately 45° 25' 00" N 110° 00' 00" W
MAIN GEOLOGICAL INTEREST	Igneous and metamorphic petrology



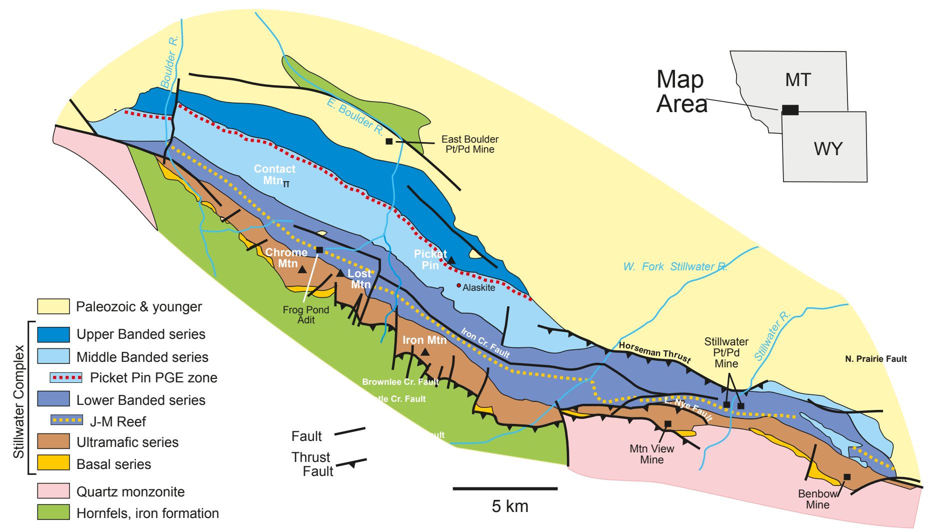
Coarse grained olivine-rich host rock of the platiniferous J-M Reef.

Geological Description

The 2.7 Ga age Stillwater Complex is a large layered intrusion, with a ~5.5 km thick section exposed for ~50 km along the northern front of the Beartooth Mountains in south-central Montana. Starting from its lower contact, it is divided into the Basal series (composed of norite and orthopyroxenite), the Ultra-mafic series (composed of dunite, harzburgite, and orthopyroxenite), and the Banded series (composed of norite, gabbronorite, troctolite, and anorthosite). The upper part was eroded and covered in the late Pre-cambrian-early Proterozoic.

The outcrop of "inch-scale doublets" (Photo, previous page) is unique to the complex, and photos of it are found in many petrology text-books as an example of pattern formation during magmatic crystallization (Boudreau, añadir coma 1995). Ni- and Cu-rich sulfide occur in the lower part of the complex and into the underlying hornfels. Chromite-rich seams associated with peridotite of the Ultramafic series were mined under government contract sporadically between 1940's the early 1960's (Jackson, 1961). In the 1970's the J-M Reef in the Lower Banded series was discovered. It is a world-class platinum-group element deposit that is the highest-grade deposit of its type and is the only significant source for these elements in the United States (Zientek *et al.*, 2002).

Geologic map of the Stillwater Complex showing major stratigraphic sub-divisions. Modified after Zientek and Parks (2014) USGS public domain.



Scientific research and tradition

Zientek and Park (2014) note that there are over 600 Stillwater-related publications dating back to the late 1800's, with many from researchers based around the world. In addition, it has been the focus of numerous scientific conferences and published field trip guides.

EARLY CRETACEOUS RHYOLITIC COLUMNAR ROCK FORMATION OF HONG KONG

CHINA

UNESCO Global Geopark

Photograph showing the typical geomorphological feature of the High Island Formation.

ONE OF THE MOST SPECTACULAR RHYOLITIC COLUMNAR ROCK FORMATIONS IN THE WORLD.

The High Island Formation is the relic of an early Cretaceous supervolcano, which had produced a massive amount of 1,300km^3 volcanic ash (Sewell *et al.*, 2019). Columnar joints were developed by thermal contraction in the ash deposited within the caldera. The rock formation is different from mafic volcanic rock columns found elsewhere in the world. It was developed from felsic rhyolitic rock with up to 76% SiO^2 content (Strange *et al.*, 1990). The entire formation displays an extremely high degree of homogeneity in lithology, petrology and geochemistry (Strange *et al.*, 1990). And this formation is integrated with diverse coastal erosion and deposition landforms, such as sea cliffs, sea notches, sea caves, sea arches, sandy and pebble beaches. The site presents a rare geomorphological landscape.

SITE 047

GEOLOGICAL PERIOD	Early Cretaceous
LOCATION	Sai Kung, Hong Kong, China. 22° 21' 21" N 114° 22' 13" E
MAIN GEOLOGICAL INTEREST	Igneous and metamorphic petrology Volcanology

Photograph showing deformation structure, and a mafic dyke intrusion (white arrow) cutting the deformed rhyolitic columns.

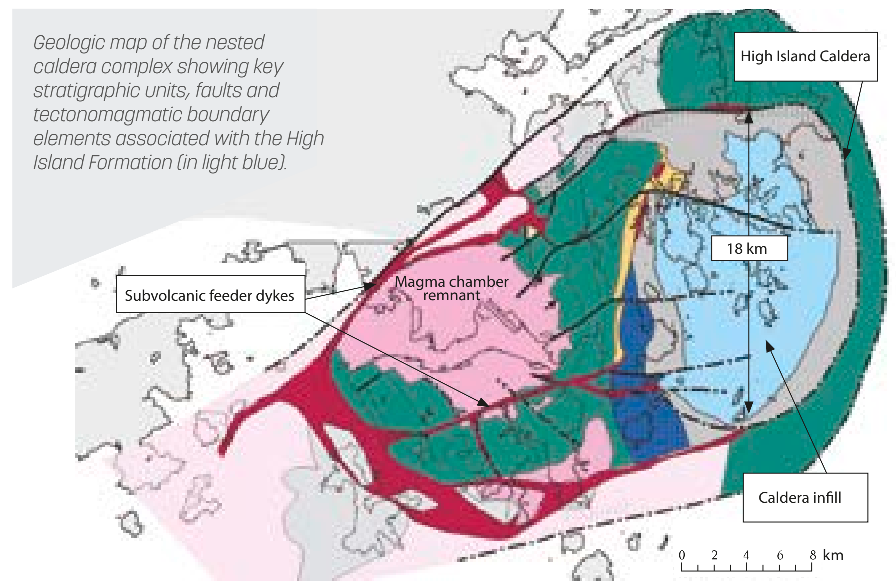
Geological Description

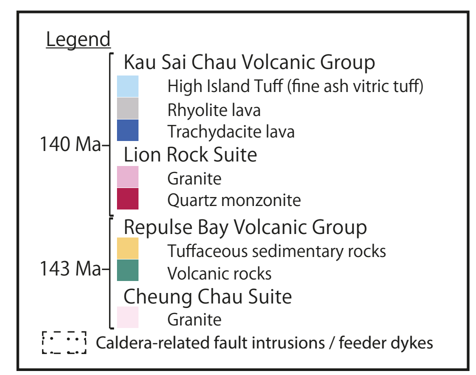
The columnar rock formation (140-141 Ma.), called the High Island Formation, is widely exposed along the coast, cliffs and numerous islands in Sai Kung, Hong Kong. The formation occurs as a wide-spread sheet of about 100km^2 and up to 400m in thickness (Strange *et al.*, 1990) in a giant caldera complex (Sewell *et al.*, 2012). The average column diameter is 1.2m, with the largest specimens measuring 3m. Sai Kung is characterised by long meandering coastlines and numerous islands. In this setting, the hexagonal rock columns are well exposed. The shores are rimmed with steep sea cliffs; at some points, the columns stand up to 100m above sea level. It is the most iconic and globally rare geological heritage of the Hong Kong UNESCO Global Geopark.

Scientific research and tradition

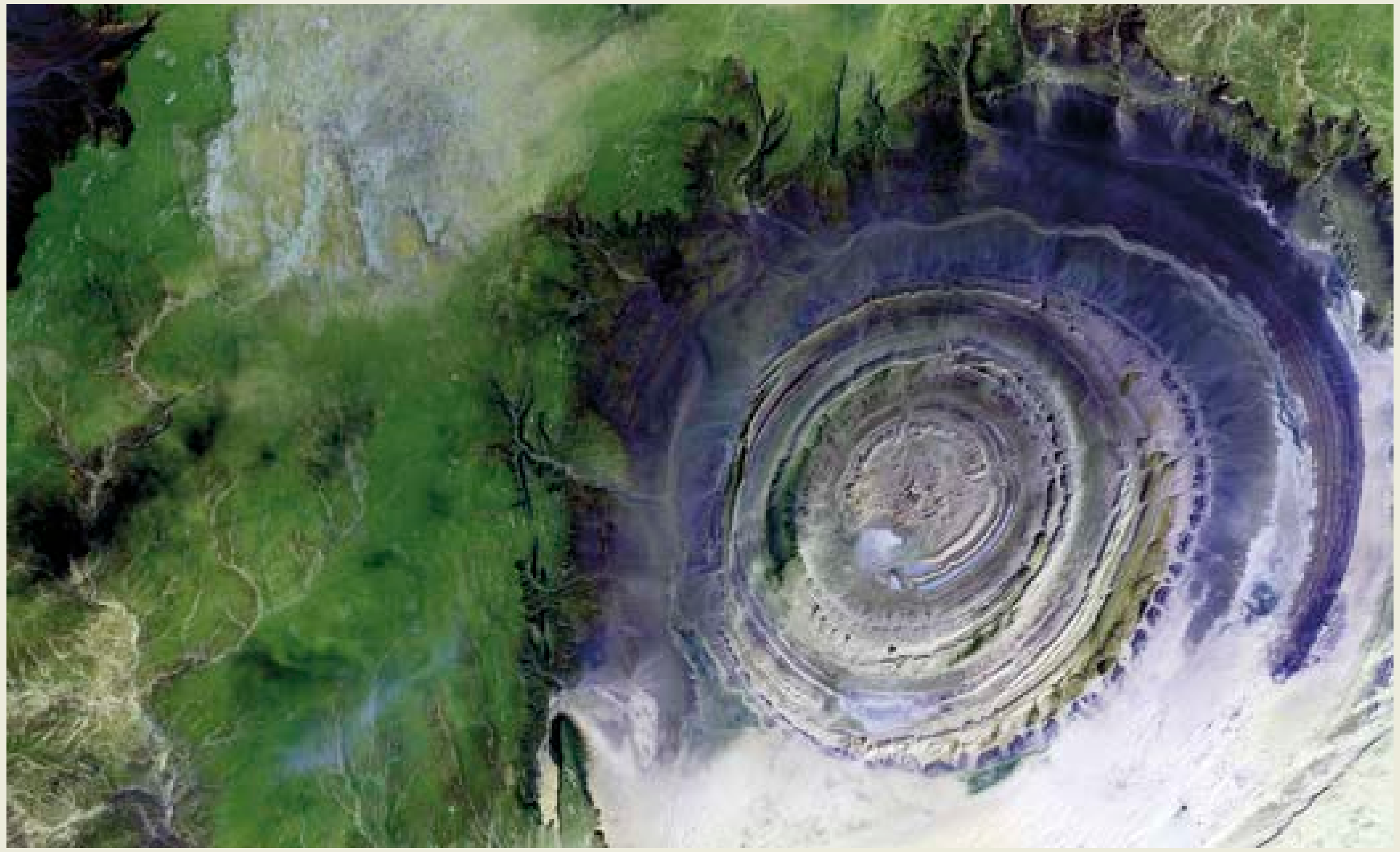
Comprehensive studies on this rock formation started as early as 1926 and continue at the present. Geologists have reconstructed remarkable details about the eruption history and the geometry of the nested caldera complex, making this rock formation the most significant geological heritage in Hong Kong and the most well studied formation of its kind in the world. The formation has been a part of Hong Kong UNESCO Global Geopark since 2009.

Geologic map of the nested caldera complex showing key stratigraphic units, faults and tectonomagmatic boundary elements associated with the High Island Formation (in light blue).





RICHAT STRUCTURE, A CRETACEOUS ALKALINE COMPLEX
MAURITANIA



Aerial view of the Richat structure. (Photo: USGS en Unsplash).

THE "EYE OF AFRICA" RICHAT STRUCTURE IN THE SAHARAN DESERT IS A SPECTACULAR EXAMPLE OF A MAGMATIC CONCENTRIC ALKALINE COMPLEX.

The Richat structure has been a case of scientific debate about the origin of ring structures in the world. There have been several studies to define whether it was an impact structure or intrusive feature. It is a case in point that shows serious scientific inquiry can lead to definite answers.

It is one of the most spectacular examples of magma-induced ring structures in the world.
It is aesthetically beautiful and unique geological feature whose outline is pronounced by the contrasting landscape of the wider Sahara Desert.

SITE 048

GEOLOGICAL PERIOD	Late Proterozoic - Ordovician
LOCATION	Taoudeni basin, Mauritanian Adrar plateaus. 21° 00' 00'' N 011° 31' 12'' W
MAIN GEOLOGICAL INTEREST	Igneous and metamorphic petrology Volcanology

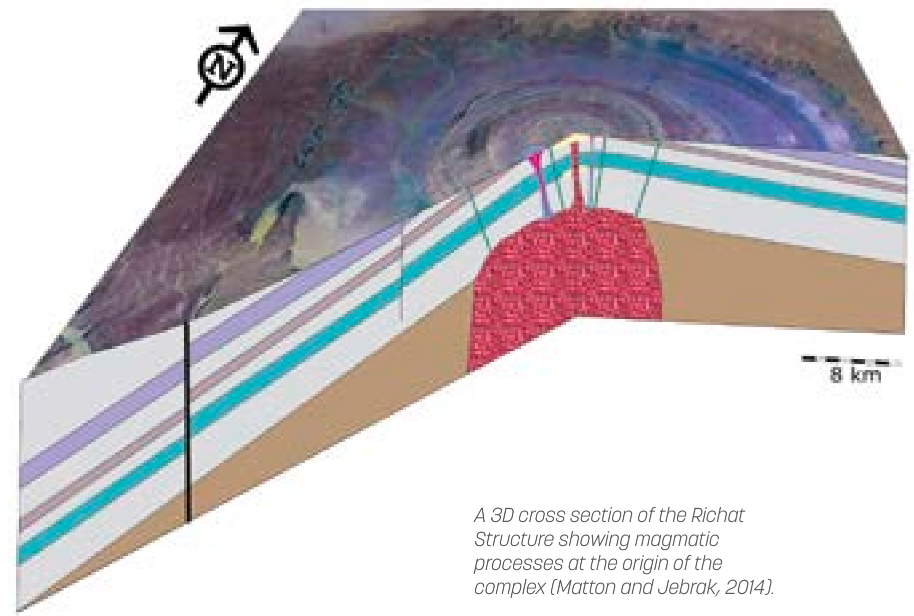
Photograph showing the very central section (Ombilic) of Richat Structure. (Photo: Michel Jebrak).

Geological Description

The circular structure of Richat is located in the northwestern part of the Taoudeni basin, in the central part of the Mauritanian Adrar plateaus, where it is expressed at the surface as a slightly elliptical depression, about 40 km in diameter, marked by concentric ridges of Proterozoic-Lower Paleozoic strata (O'Connor *et al.,* 2004; Abdeina *et al.,* 2021; Hamoud *et al.,* 2021). The Richat structure appears as a large dome within a Late Proterozoic to Ordovician sequence, with circular cuestas represented by three nested rings dipping outward from the structure. The center of the structure consists of a limestone-dolomite shelf that encloses a kilometer-scale siliceous mega-breccia and is intruded by basaltic (gabbroic) ring dikes, kimberlitic intrusions, and alkaline volcanic rocks (Matton *et al.,* 2005). Its origin has been enigmatic and debated with some suggesting that it was a meteoritic impact crater, which has been disproved in favour of an intrusion theory (Faudli 1969). The Richat is the superposition of a bimodal tholeiitic suite crosscut by carbonatitic (85 ± 5 Ma and 99 ± 5 Ma) and kimberlitic magmatic rocks (Matton and Jebrak, 2014). According to Abdeina *et al.* (2021) the gabbroic ring dykes represent deep magmatic structures connected to a large intrusive magmatic body.

Scientific research and tradition

The Richat circular structure has been studied since the 1950s when it was first identified from aerial photos with most of the debate focused on its origin. Recent works have ascertained its magmatic/ intrusive origin through various geological and geophysical studies including field-based investigations.



A 3D cross section of the Richat Structure showing magmatic processes at the origin of the complex (Matton and Jebrak, 2014).

THE MIOCENE TORRES DEL PAINE INTRUSIVE COMPLEX
CHILE

General view of Torres del Paine peaks, formed by intrusive granitic rocks. (Photo: Lorenzo Albertini).

A WORLD CLASS SITE FOR THE STUDY OF STRUCTURALLY CONTROLLED EMPLACEMENT AND CONSTRUCTION OF SHALLOW BIMODAL LACCOLITHS.

The Torres del Paine Intrusive Complex is a world class site for the study of the emplacement and construction of shallow (upper crustal) layered laccoliths. It crops out extensively (it can be appreciated from base to top) thanks to tectonic uplifting and erosion (mostly glacial), allowing for the study and divulgation of one of the most important processes in geology: mountain building. Detailed geochronological studies have shown that this complex reveals unique clues for understanding the evolution of magmatic chambers and the upwelling of magma towards shallow levels of the upper crust.

SITE 049

GEOLOGICAL PERIOD	Miocene
LOCATION	Región de Magallanes y de la Antárctica Chilena, Chile. 50° 58' 21" S 073° 00' 00" W
MAIN GEOLOGICAL INTEREST	Igneous and metamorphic petrology

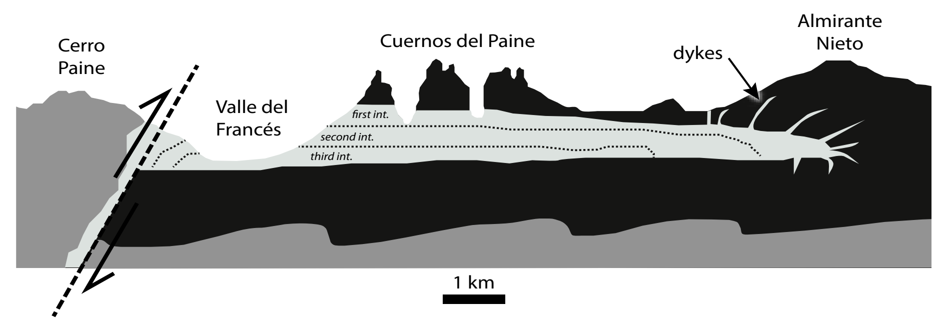
General view of the Cuernos del Paine peaks. Light color Miocene (12,5 Ma) granitic rocks of the Torres del Paine Intrusive Complex were emplaced (while molten) into older (Cretaceous, 98-86 Ma), dark color sedimentary country rocks. (Photo: Marcos Aguilar).

Geological Description

The Miocene Torres del Paine Intrusive Complex (12.5 Ma; Michel *et al.*, 2008) is formed by a subhorizontal granitic laccolithic that intruded on top of a mafic body. It extends for more than 12 km with a maximum thickness of 2.5 km. The laccolith is emplaced along a shallow to subhorizontal thrust fault, which is associated with internal folding and faulting developed during an early, pre-intrusion, thin-skinned tectonic phase that deformed the Cretaceous country rock (Halpern, 1973; Michael, 1991). Where the intrusion is thickest, it connects downwards with a subvertical feeder dyke emplaced along an old high-angle reverse fault, thought to be related with a period of thick-skinned tectonic shortening that caused a several kilometer uplift to the western block and consequent erosion of the stratigraphic cover (Skarmeta and Castelli, 1997). The granite intruded as a series of three sheets, each one underplating the previous sheet along the top of the basal Paine Mafic Complex. High-precision U-Pb geochronology in single zircon defines a time frame of 90 ± 30 k.y. for the emplacement of the >2000-m-thick granite laccolith (12.593±0.009 Ma to12.431±0.006 Ma respectively, for the first and last sheet of the laccolith; average growth rate: 0.0005 km^3_{y}, total volume: ~88 km^3; Leuthold *et al.*, 2012). These results permit identification of the pulses in a 20 k.y. range, which is markedly lower and much more precise than previous data for crustal magma chambers infill.

Scientific research and tradition

This intrusive complex is an extraordinary example of an upper crust mafic and granitic intrusive system that has been studied since early '70. Recent investigations applied forefront dating analytics to unveil its characteristics regarding the time scale of magmatic pulses and the construction of a shallow laccolith.



Schematic W-E section showing the intrusive relations between the Paine Intrusive Complex (light grey) and the country rocks (black and dark grey, Cerro Toro and Punta Barrosa Formations, respectively). The magma that formed the laccolith ascended through the earth´s crust taking advantage of a preexisting thrust fault, to the west (segmented line). Arrows indicate the relative the sense of movement of the rock blocks. Int.: intrusive granite. Scale in the figure. Modified from Skarmeta and Castelli (1997).

MOUNT KINABALU NEOGENE GRANITE

MALAYSIA

Granitic pluton of Mount Kinabalu seen from Kundasang. The hilly foreground is made up of sedimentary rocks of the Crocker Formation; the flat area in front is made up of glacial deposits of the Pinousuk Gravels.

ONE OF THE YOUNGEST GRANITIC INTRUSIONS EXPOSED ON EARTH AND THE SITE OF SPECTACULAR TROPICAL GLACIAL LANDSCAPES.

Mount Kinabalu Neogene Granite is the youngest granitic pluton in the world. Its age dating indicates that the cooling of the magma ranged from 8 to 7 million years ago. The igneous intrusion into the accreted ophiolitic and sedimentary rocks may be related to the subduction of the Proto South China Sea plate under southeast Borneo. The glacial processes on top of Mount Kinabalu during the last Ice Age created the most spectacular glacial landscape in the tropics. At the foothills of Mount Kinabalu, on the Pinousuk Plain, are the most extensive tilloid deposits in Southeast Asia, as young as 10,000 years old.

SITE 050

GEOLOGICAL PERIOD	Late Miocene - Pliocene
LOCATION	Mount Kinabalu is located in the state of Sabah, Malaysia. 06° 04' 31" N 116° 33' 32" E
MAIN GEOLOGICAL INTEREST	Igneous and metamorphic petrology Geomorphology and active geologic processes

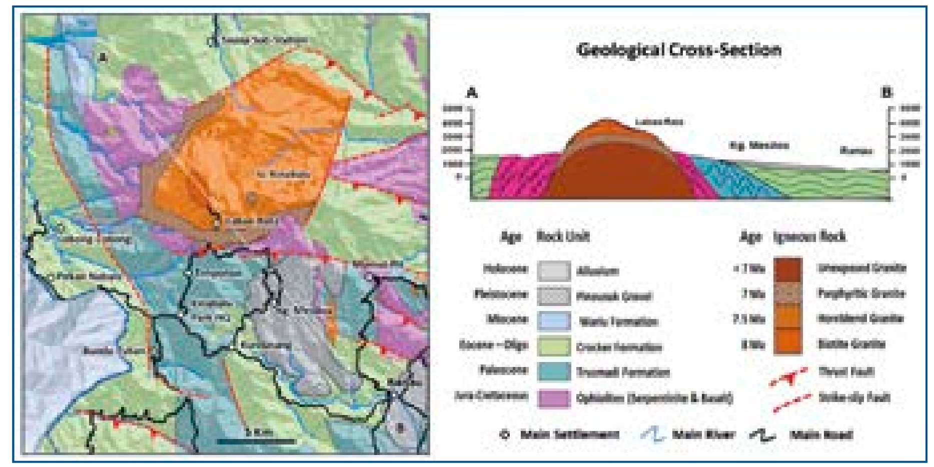
Glacial erosion landforms at the Mount Kinabalu plateau include cirque, remnant peaks and striated surfaces.

Geological Description

Mount Kinabalu is the youngest granitoid intrusion in Southeast Asia. U–Pb ages from zircon ranged between 8 and 7 million years (Cottam *et al.,* 2010). The granitic body intrudes ultrabasic rocks and sedimentary rocks of the Trusmadi and Crocker Formations. It was emplaced in a regional extension setting (Burton-Johnson *et al.,* 2017) after the ultrabasic basement and sedimentary rocks were accreted (Hall, 2013). Igneous thermochronometry gave an upper to mid-crustal emplacement depth of 7–12 km (Cottam et al. 2013). The plutonic body is exposed at an elevation of around 4000 m. The rapid uplift of the area is thought to be associated with the removal of a dense lithospheric root under Sabah about 8 million years ago (Hall et al., 2009). The pluton has two phases: the outer part consists of coarse-grained porphyritic granite, whereas the main body consists of finer-grained hornblende granite and biotite granite. The landscape of Mount Kinabalu was shaped by glacial processes during the Quaternary (Koopmans and Stauffer, 1967). Rocks eroded from the mountain were deposited as the Pinousuk Gravels at Mesilou Plain. The erosion created the east and west plateaus and peaks such as Low's Peak (4,101 m) and St. John's Peak (4,098 m).

Scientific research and tradition

Mount Kinabalu has been the focus of scientific research since the 1960s. Geological studies were mostly carried out by the Geological Survey of Malaysia (North Borneo). Systematic mapping of geoheritage sites started in 1996. To date, over 300 projects by researchers from all over the world have been conducted here.



A geological map of the Mount Kinabalu area showing the distribution of rock units and major tectonic structures. The granite pluton intrudes into the accreted Mesozoic ophiolitic basement rock and overlying Paleogene turbidite sediments. Tilloid deposits of the Pinousuk Gravel occur on the southeastern part of the mountain.

5

VOLCANOLOGY

SITE 051 - SITE 067

Volcanoes are fundamental phenomena of the Earth's active system, and are features found on all rocky planets and moons in our solar system. Volcanoes provide essential exchange of materials from the interior of the Earth to the surface and atmosphere, providing environments for the biosphere, and importantly for humanity they are a resource, a cultural influence and at times a hazard. Volcanic landforms and rocks are highly diverse and seamlessly integrate though their environments into other aspects covered in the IUGS Global Geosites, including but not restricted to tectonics, stratigraphy, geomorphology and history of geology.

The representative sites for the first 100 IUGS Geosites have a broad and well distributed geographic spread, spanning the globe. Due to the huge possible number of sites, areas and types, many volcanic regions and highly significant sites have not yet been included (such as Antarctica, Indonesia or the Caribbean), and will surely be integrated in the following years. A major effort is needed to study and characterise the global geodiversity in volcanology, and should be a major effort in the coming years for the International Association of Volcanology and of the Earth's Interior (IAVCEI) and it's commission for geoheritage.

In the first 100 there are some volcanic sites not grouped in the volcanology section, e.g. in the historical and geomorphological sections, which underline the diversity and inseparable interlinking of volcanoes and other geological systems. Volcanoes beautifully reflect their lithospheric and biospheric environments and can be considered as ambassadors for other Earth systems, drawing attention to the interconnectedness of our planet and the need to consider holistically our environment and our place within it.

Volcano geosites are thus vital ambassadors for this human – Earth link, and all of the geosites in the first 100 illustrate this to a high degree. Either they have been sites of major catastrophes, such as Santorini, Huaynaputina, or Nevado del Ruiz, or major impacts and tell stories of adaptive resilience of local populations such as Matavanu. Some show geosites where local populations are constantly adapting and living with their changing environments, such as La Isla de Ometepe and Yasur-Yenkahe. All geosites can tell the important story of humans integrating within volcanic environments and the pitfalls of ignoring geological and environmental change.

Some sites are iconic in their place as protection of natural spaces, such as Yellowstone. The Phlegrean Fields are steeped in classical European history, and Cotacachi-Cuicocha and the Sillar of Arequipa represent a possible site of future or past super-eruptions. On the other hand, Cameroon volcano, Jabal Qidr or Cappadoccia are steeped in diverse global cultural contexts. All these not only show high geological importance, but also integrate into humanity's place on the planet.

The scale of the geosites varies enormously from broad regions, such as the Danakil, to whole volcanoes (including some of the largest, such as Kilimanjaro or Poás), to small features such as the Ulmen Maar. Some geosites are specific volcanic features (calderas are a large and highly diverse group), are integrated with tectonic settings, or associated with major hydrothermal systems, such as El Tatio, and a few are individual deposits from ancient and historic eruptions, such as from Huaynaputina.

In all, the first 100 volcanology sites are representative of the huge volcanic geodiversity and provide an example of where the future IUGS global Geosites should go.

Benjamin van Wyk de Vries
Université Clermont Auvergne. France.
Chair. IUGS Sub-Commission on Sites.
IUGS Geological Heritage Sites voting member.

Jazmin Scarlett
University of East Anglia. UK.
International Association of Volcanology and Chemistry of the Earth's iInterior. IAVCEI.
IUGS Geological Heritage Sites voting member.

The Yellowstone volcanic and hydrothermal system
USA
The Holocene Ulmen maar
GERMANY
The Quaternary Santorini Caldera
GREECE
The Miocene Cappadocian Ignimbrites sequence
TURKEY
The historic scoria cone of the Jabal Qidr
SAUDI ARABIA
La Isla de Ometepe: Quaternary volcanoes in the Lake Nicaragua sedimentary basin
NICARAGUA
The Nevado del Ruiz Quaternary Volcanic Complex
COLOMBIA
The Poás Volcano
COSTA RICA
The Cotacachi - Cuicocha volcanic complex
ECUADOR
The 1905-1911 Matavanu volcanic eruption
SAMOA
The vapor phase ignimbrites of Sillar in the Añashuayco Quarries of Arequipa
PERU
El Tatio geothermal field
CHILE
The pyroclastic deposits from the Huaynaputina volcano eruption 1600 CE
PERU
The Quaternary Cameroon Volcano
CAMEROON
The Danakil Rift depression and its volcanism
ETHIOPIA
ERITREA
The Pleistocene Kilimanjaro Volcano
TANZANIA
The active Yasur–Yenkahe volcanic complex
VANUATU

THE DANAKIL RIFT DEPRESSION AND ITS VOLCANISM

ETHIOPIA AND ERITREA

Dallol acidic brines. Dried sulfur mounds are at the center of the acidic brines (Copyright: Olivier Grunewald).

THE ONGOING BIRTH OF AN OCEAN WITNESSED THROUGH TECTONICS AND VOLCANISM IN AN EXTREME EVAPORITE ARID ENVIRONMENT.

A site where the birth of a new ocean is happening and new oceanic crust is forming can be observed at the surface in the Danakil Depression. The region boasts several iconic and spectacular geological sites: Ert'ale volcano with an active lava lake, the Dallol geothermal area with uniquely important polyextreme environment (brines, active geysers, and other hydro-thermal and saline systems), and several salt lakes

Despite being an extreme environment, the salt has been mined for centuries by traditional miners and continues to date

It is a major tourist destination with geosites as attractions (Dalol, the salt caravans, and the Ert'ale volcano).

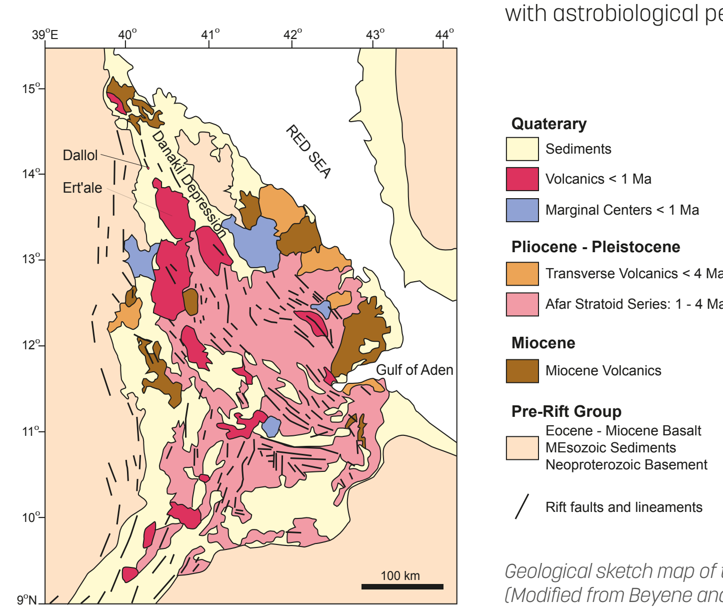
SITE 051

GEOLOGICAL PERIOD	Miocene - Quaternary
LOCATION	Ethiopia and Eritrea, Northern Afar. 12° 45' 00" N 040° 00' 00" E
MAIN GEOLOGICAL INTEREST	Volcanology Tectonics

Ert'ale lava lake (Copyright: Olivier Grunewald).

Geological Description

The Danakil Depression (also known as the Afar Depression) is a segment of just-formed oceanic crust, a young ocean rift (Makaris and Ginzburg, 1987), where rift floor is 120m below sea level. The floor is cut by faults and dotted with many and diverse shield volcanoes (Varet, 1978; Asrat, 2016). The Danakil Depression shows considerable diversity of geological formations ranging from Miocene volcanoes to Holocene sedimentary and volcanic units (Varet, 1978; Beyene and Abelsalam, 2005). The Afar Stratoid Series of mostly Pliocene flood basalts (4-1 Ma) covers two thirds of the Afar depression (Varet, 1978; Beyene and Abelsalam, 2005). Recent volcanic eruptions (<1 Ma) at rift-axial volcanic ranges are characterized by fissure eruptions and shield volcanoes with basaltic flows and with alkaline and per-alkaline silicic rocks occur along northwest-southeast trending narrow volcano-tectonic rift zones (Wright *et al.*, 2006). The axial volcanic shields include Erta'Ale, Tat'Ale and Alayta volcanic shield complex, the Alayta-and Manda-Hararo range, the spectacular Dallol geothermal area, and the Alid volcano, a unique 'crater of elevation'. The floor of the Danakil depression is underlain by Pliocene sedimentary rocks (succession of gypsiferous clastic and carbonate rocks including coral reefs, thick salt Quaternary sediments (evaporitic to marine sediments with coral and oyster beds). The depression floor is covered by several salt lakes and thick salt formations.



Geological sketch map of the Afar Rift (Modified from Beyene and Abdelsalam, 2005).

Scientific research and tradition

The Afar region, particularly the Afar Depression has been the subject of intensive geological and geophysical investigation since the 1960s and mostly since the 1990s in order to understand its unique geological setting as a natural laboratory for active seismic, volcanic, and seismo-volcanic processes. Recently the polyextreme environment of Dallol has been investigated with astrobiological perspectives.

THE QUATERNARY CAMEROON VOLCANO

CAMEROON

Picture of pyroclastic cones on upper slopes of Cameroon Volcano. (Photo: Michal Szymanski / Shutterstock).

ONE OF THE FEW VOLCANOES IN THE WORLD LOCATED AT THE OCEAN-CONTINENT BOUNDARY IN A PASSIVE TECTONIC MARGIN.

Cameroon Volcano (CV) is one of the few volcanoes in the world located at the ocean-continent boundary in passive margin. It contains 140 adventive craters, reflecting its high degree of fracturing. CV is one of Africa's largest and most active volcanoes with eight major eruptions (effusive, explosive and hydromagmatic) recorded in the last century (1909, 1922, 1925, 1954, 1959, 1982, 1999, and 2000). These events were accompanied by high intensity (VI-VII) seismic events (200/24hours during the 1999 eruptions) associated with catastrophic landslides and lahars.

SITE 052

GEOLOGICAL PERIOD	Quaternary
LOCATION	South West Region, Cameroon. 04° 12' 55" N 009° 10' 28" E
MAIN GEOLOGICAL INTEREST	Volcanology

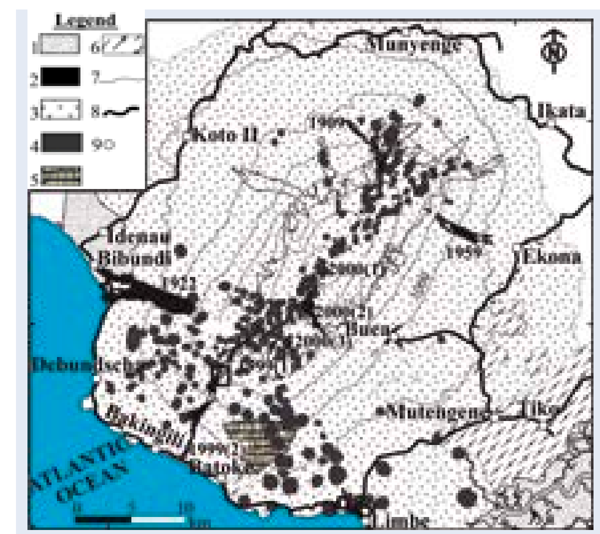
Picture of the aa-type lava from Cameroon Volcano's 1999 eruptions (Copyright Jacques-Marie Bardintzeff).

Geological Description

Cameroon Volcano (CV) is a large elliptical (50x35 km wide) stratovolcano elongated in the SW-NE direction, built on a Pan-African granito-gneissic basement covered by Cretaceous to Quaternary strata (Suh *et al.,* 2003; Tsafack *et al.,* 2009). It culminates at 4095 m with a volume of ~1,200 km³ and includes several geological features: (1) ashes, cinders and, scoriaceous lapilli, blocks and bombs whose accumulation constructed nearly 140 cones. These cones, mainly broken, have high slopes (25-43°); (2) aa-type mafic lava emitted at the base of cones with variable widths of 30 to ~120 m, the length from 3 km (SW flanks) to ~9 km (NE flanks) and a distal front of 15 m high (Déruelle *et al.,* 2000; Suh *et al.,* 2003). These lavas belong to a typical alkaline series, weakly differentiated (basanite, alkaline basalt, hawaiite, and mugearite), characteristic of the interior of plates. Basanite and basalt in places possess xenoliths (1-5 x 0.5-4 cm) of dunite, wehrlite and clinopyroxenite (Tsafack, 2009); (3) Mount Etindé that is located on the southwestern flanks of CV. It culminates at 1713 m and is exceptionally composed entirely of silica-undersaturated rocks called nephelinite (Mama *et al.,* 2021); (4) two maars (Debundscha and Bomana) respectively located at the SW and the NW slopes (Tsafack, 2009); (5) several tectonic fractures due to the alignment of cones and several vents and, rifts.

Scientific research and tradition

Volcanic and tectonic processes coupled with natural hazards give the Cameroon Volcano unique characteristics that have aroused great curiosity on a national and international scale for over half a century. The pioneering geological and geomorphological research were from Gèze (1941, 1953). They have been followed by several works that led to the publication scientific papers till nowadays. Moreover, CV is a nature laboratory for outdoor training programs.



Geological map of the Cameroon Volcano (Wantim et al., 2013, modified): 1. Sediments; 2. Recent lavas; 3. Basalts (Old Lavas); 4. Pyroclastic cones; 5. Nephelinites; 6. Lahars; 7. Contour lines; 8. Major roads; 9. Settlements.

THE HISTORIC SCORIA CONE OF THE JABAL QIDR

SAUDI ARABIA

Jabal Qidr crater from the air. Jebel Abyad rhyolitic tuff ring in the background surrounded by basaltic pahoehoe lava flow field from Jabal Qidr.

THE LARGEST HISTORIC BASALTIC VOLCANIC CONE IN INTRACONTINENTAL SETTINGS WITHIN A PLEISTOCENE RHYOLITIC TUFF RING AND LAVA DOME FIELD.

Jabal Qidr and its volcanic environment is a global type of example for the full spectrum of volcanic geoforms, volcanic deposits, and interaction of active volcanism with early human civilizations of a long-lived (mature) small-volume (monogenetic) volcanic field. The variations from rhyolitic to basaltic intraplate magmatism and the dramatic changes of eruption styles from phreatomagmatic to violent Strombolian within a geologically short time frame provides a type of site to explore the breadth of type of volcanism we can face within intracontinental settings.

SITE 053

GEOLOGICAL PERIOD	Holocene (Pleistocene)
LOCATION	Harrat Khaybar, Arabian Peninsula (Kingdom of Saudi Arabia) 25° 43' 13'' N 039° 56' 36'' E
MAIN GEOLOGICAL INTEREST	Volcanology

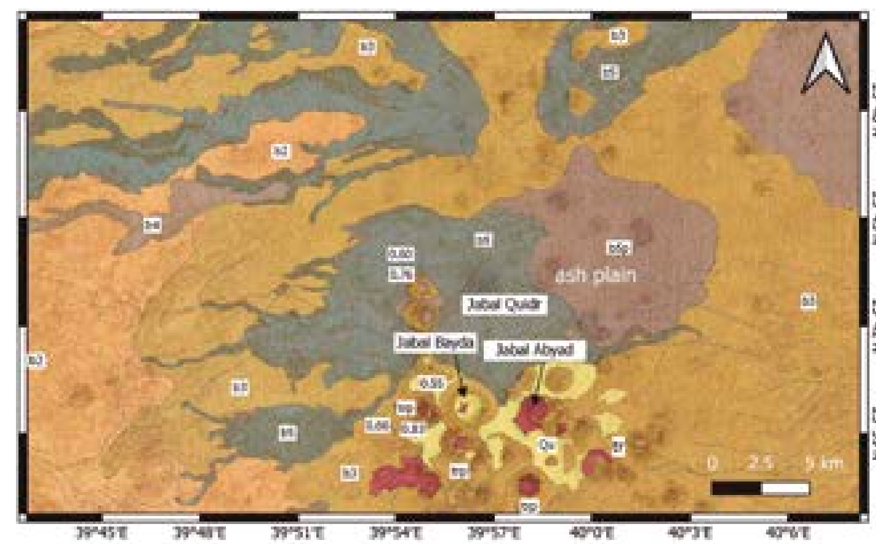
Jabal Abyad rhyolitic tuff ring with erosional gullies in the Jabal Qidr basaltic pahoehoe lava flow field.

Geological Description

Jabal Qidr is the youngest volcanic eruption within the largest intracontinental bimodal volcanic field in the Arabian Peninsula (Camp *et al.*, 1991). It is a large volcanic cone with a relative elevation of about 400 meters. Its part of a roughly N-S trending fissure that emitted large volume of basaltic pahoehoe tube-fed lava flows that reached Bronze Age (~5000 years) occupation sites of the so called "desert kites" (Kempe and Al-Malabeh, 2013; Kennedy et al., 2021). The eruption is inferred to have reached sub-Plinian explosive intensity and produced thick ash plain through a violent Strombolian style eruption that reached at least 20 km from the central vent (Németh and Moufti, 2017). The crater of Jabal Qidr is a spectacular ~200-meter-deep and 300-meter-wide depression showing evidence of violent explosive processes and pit collapses due to lava flow drainage through the feeder fissure system. The lava flows have superb pahoehoe lava flow surface textures following early Holocene stream networks occupied by early human civilizations. Jabal Qidr erupted in volcanic field dominated by monogenetic rhyolite that generated tuff rings forming spectacular white lava domes and tuff rings such as Jebel Abyad and Jebel Bayda respectively (Moufti and Németh, 2014). This site demonstrates the volcanic geodiversity of mature, small-volume intracontinental volcanic field (Moufti and Németh, 2016; Németh and Moufti, 2017).

Scientific research and tradition

The remoteness and the closed societal aspects of the region until recent years prevented prevented access for research in the region. This has changed in the last decade resulting in an accelerated rate of global research within volcanology, archaeology and volcanic geoheritage studies.



The Jabal Qidr region geological map based on the Geological Map of the Khaybar Quadrangle, Sheet 25D, Kingdom of Saudi Arabia (Compiled by R Dhellemmes & J Delfour 1979) on an ALOS-PALSAR 12.5 DEM-generated contour map. Labels: b2 = basalt 3-9 My; b3 = basalt 0.3-3 My; tr – trachyte/benmoreit/commendaite 0.2-4.5 My; trp = trachyte pyroclastics; b4 = basalt 30 – 300 ky; b5 = recent basalt <30 ky; b5p = recent pyroclastics, e.g., ash plains. Numbers refer to measured radiometric ages in My.

THE PLEISTOCENE KILIMANJARO VOLCANO

TANZANIA

Aerial view looking west of the Kibo inner cone with central ash pit and collapsed rim (centre right), known as the Western Breach. Note the glaciation around the edges leading up to the Uhuru summit ridge (back right) (Photo credit G. Pearson).

UNESCO World Heritage Site

THE HIGHEST STRATOVOLCANO OF THE EAST AFRICAN RIFT THAT MAINTAINS A GLACIER ON ITS SUMMIT.

It is a spectacular landscape whose snow-capped summits and the majestic volcanic landscape forms a strong contrast with the surrounding plains. The Kilimanjaro region is World Heritage site registered by UNESCO in 1987.

Its highly alkaline volcanic products and the later lahar deposits due to the interaction of the glaciers with the erupting volcanoes from its summit craters form a particular suite of rocks (phonolites, tephri-phonolites, phono-tephrites and tephrites).

The rapidly retreating glaciers and the snows capping the summit are unique phenomenon as they occur near the equator (Kaser *et al.,* 2004); these glaciers provided a unique opportunity to investigate the climate of the late Pleistocene; in addition, the various archives (lake deposits, pit bogs, glaciers) at pristine locations at high altitudes provided important climate records (Barker *et al.,* 2010; Courtney Mustaphi *et al.,* 2021).

SITE 054

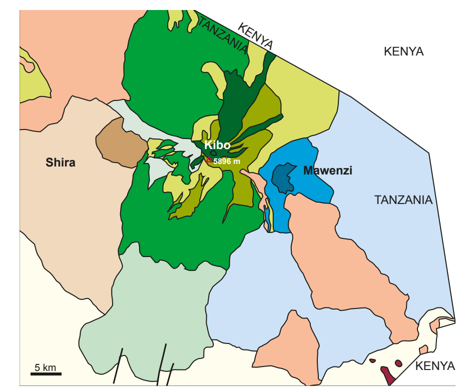
GEOLOGICAL PERIOD	Quaternary
LOCATION	Tanzania. 02° 45' 00" S 037° 00' 00" E
MAIN GEOLOGICAL INTEREST	Volcanology Geomorphology and active geological processes

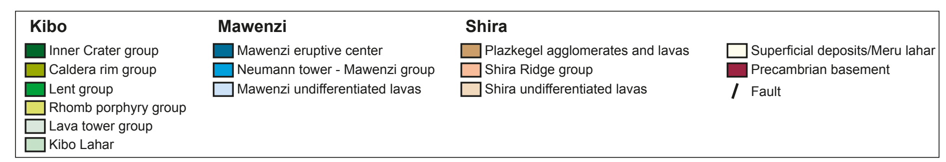
Resistant lava flows with associated ash layers, viewed from the Kibo Barranco on the southern edge of the mountain (Photo credit G. Pearson).

Geological Description

Mt. Kilimanjaro is the highest mountain in Africa (5895m a.s.l. at its peak). It is a 40×60 km elliptic volcanic edifice with three centres/peaks (Shira, Kibo, and Mawenzi from West to East) equally spaced along a N110°E-striking axis (Kent, 1944). It is a polyphased volcano successively built since ~2.5 Ma years ago. According to Nonnotte *et al.* (2008) the oldest phases of volcanic activity begun at ~2.5 Ma in the Shira vent while the latest important phases occurred around 1.9 Ma, before the collapse of the Northern part of the edifice. Magmatic activity then shifted eastwards in the Mawenzi and Kibo twin centres where initial volcanism is dated at ~1 Ma. the most recent Mawenzi rocks (492 ka and 448 ka) close to the present summit, are linked to the final stage of edification for this centre. The present cone at Kibo was built at 274 to 170 ka ago (Nonnotte *et al.,* 2008). However, volcanism might have continued until 150 ka. The volcanic products are highly alkaline (mostly phonolites, tephri-phonolites, phono-tephrites and tephrites, with few trachy-basalts). The summit of Kilimanjaro is covered by a rapidly retreating glaciers, whose age might date back to the late Pleistocene (Nonnotte *et al.,* 2008; Cullen *et al.,* 2013).

Geological map of Mt. Kilimanjaro (Modified from Nonnotte et al., 2008).





Scientific research and tradition

Mount Kilimanjaro has been investigated since the 1950s. Its geology and particularly the glaciers at the summit have been a subject of continued investigation. The climate archives at the summit and high-altitude ranges of the volcano have also been well researched.

THE HOLOCENE ULMEN MAAR

GERMANY

UNESCO Global Geopark

Aerial view of Ulmen Maar with preserved tephra ring (background) and highly eroded Jungferweiher maar (foreground).

YOUNGEST VOLCANO IN CENTRAL EUROPE, SITUATED IN VULKANEIFEL, THE VOLCANIC REGION WHERE THE MODEL OF FORMATION OF MAARS BY PHREATOMAGMATIC ERUPTIONS WAS ESTABLISHED.

The IUGS Geological Heritage Site Ulmen Maar represents a key site for four geologically important processes that are of international relevance: (1) The maar allows introduction into the youngest volcanic activity in Central Europe. (2) It clearly shows the consequences of multiple explosive magma-water-interactions leading to phreatomagmatic eruptions. (3) The Ulmen maar is part of a maar-rich volcanic field. Here, essential arguments for the formation of maar volcanoes were developed. (4) Its postvolcanic crater lake presents a paramount insight into lake sediments and their interpretation with respect to the local weather and the climate during the maar's lake history.

SITE 055

GEOLOGICAL PERIOD	Quaternary / Holocene
LOCATION	Vulkaneifel Geopark, Rhineland-Palatinate, Germany. 50° 12' 37" N 006° 58' 58" E
MAIN GEOLOGICAL INTEREST	Volcanology

Tephra outcrop in the tunnel connecting the Ulmen and Jungferweiher Maar.

Geological Description

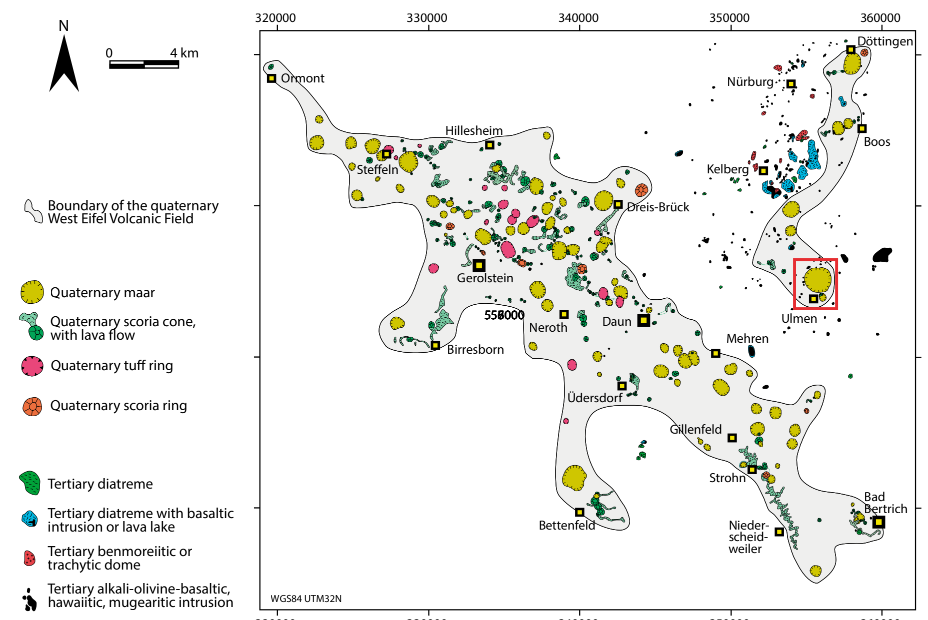
The 11,000 years old Ulmen Maar is Central Europe's youngest volcano. Its maximum crater diameter is 470 m; its depth is 72 m including the 39 m deep crater lake. The 30 m thick tephra ring consists of ash and block-bearing lapilli-tuffs, which display characteristic features of explosive magma water interaction and phreatomagmatic eruptions. The magma involved had a hauyne melilite nephelinite composition.

The Ulmen Maar was formed in the youngest southeastern part of the West Eifel volcanic field. An amazing number of maars have formed here. 80 of the total 260 eruption centers in the West Eifel consist of maar volcanoes. Most of them are concentrated in the northwestern part (mainly old) and in the southeastern part (mainly young) of the volcanic field, where there is not very much groundwater. In the central part there are many scoria cones with an initial maar phase.

Just north of the Ulmen Maar the 136,000 old Jungferweiher maar has a diameter of 2000 m and a depth of only 30 m. Its crater contains most of the altered and eroded debris of its catchment area. A 140 m deep drill hole gives evidence of the climate evolution during the past 119,000 years.

Scientific research and tradition

Scientific research on maar volcanism has been carried out by numerous international researchers for more than 200 years. The young and old crater topography of the Ulmen and Jungferweiher maars and their lake sediments serve as records of the youngest volcanism in the West Eifel and indicate where future volcanism might occur.



Volcanological map of the West Eifel Volcanic Field

THE 1905-1911 MATAVANU VOLCANIC ERUPTION

SAMOA

Pahoehoe lava flow from the 1905-11 Matavanu eruption inside the ruins of the London Missionary Society Church of Saleaula. (Samoa Tourism Authority).

ONE OF THE BEST EXAMPLES IN THE SW PACIFIC OF AN OCEANIC HOT SPOT AND ITS EARLY 20TH-CENTURY ERUPTION.

The Matavanu 1905 – 1911 eruption is the youngest volcanic eruption in Samoa and as such it is a global example of oceanic hot spot volcanism and of a Pacific Island chain.
This eruption destroyed a local village and originated an extensive lava flow field that expanded the landmass of Savai'i Island.
The Matavanu volcano and near-by faults associated with the slumping of northern Savai'i Island are related to the volcano-tectonics of the island.

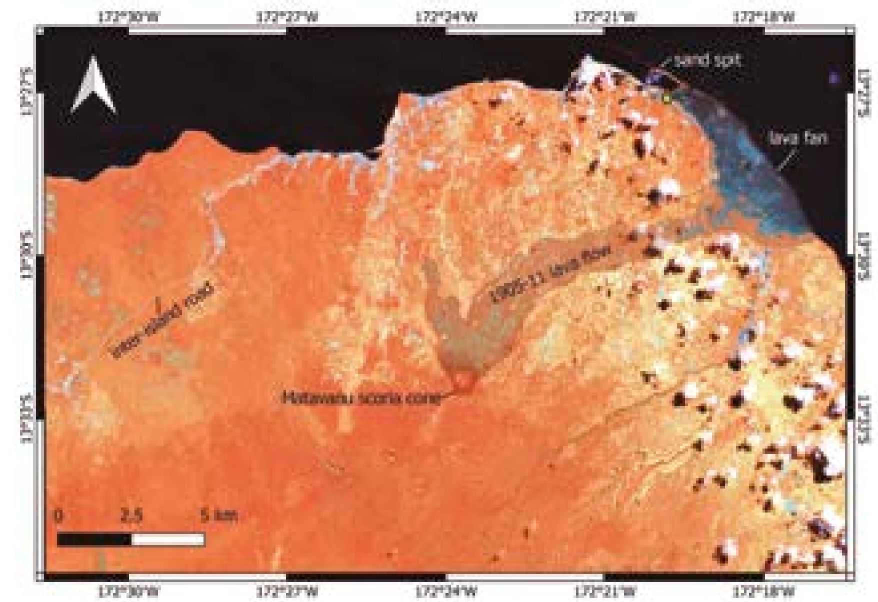
SITE 056

GEOLOGICAL PERIOD	Holocene
LOCATION	Matavanu, Savai'i island. Samoa, SW Pacific. 13° 32' 17" S 172° 23' 38" W
MAIN GEOLOGICAL INTEREST	Volcanology

Post-eruption volcaniclastic-carbonate sand spit NW of the Matavanu 1905-11 eruption lava field.

Geological Description

The Samoan Islands have a record of ~2 million years of hot spot volcanism (Kear and Wood, 1959), culminating in historic eruptions at both the east and western ends of the volcanic island chain, including a major lava- producing episode in Savai'i Island during the 1905–1911 Matavanu eruption (Anderson, 1910). This eruption covered large coastal plains in NE Savai'i, beginning on 4 August 1905 with ash emission from a scoria cone, followed by lava flows that reached the sea producing steam explosions at the flow front in early 1906 (Anderson, 1910). With the development of the lava field, much of the lava flowed through tubes. Several lava benches collapsed into the sea generating local tsunamis with 2–2.5 m waves in late 1906 and throughout 1907. Four settlements and one major village (Sale'aula) were destroyed by lava. The walls and upper parts of two stone churches are the sole remnants. Displaced communities were relocated to a new village called Salamumu (meaning "fire punishment") (Fepuleai *et al.,* 2017). The eruption was a significant event in Samoan history and is a powerful reminder of potential volcanic hazards in Savai'I (Fepuleai *et al.,* 2021). Numerous textbook features are conserved and easily accessible, including craters, pahoehoe and aa flows, tumulus, lava tubes (with associated blowholes) and a post-eruption volcaniclastic-carbonate spit (Németh and Cronin 2009; Németh *et al.,* 2017).



Satellite image of the 1905-11 Matavanu eruption site (Sentinel-2 L2A Geology - Band 8,11,12). The lava flow is outlined, and the yellow dot marks the ruins of the London Missionary Society Church of Sale'aula.

Scientific research and tradition

Scientific literature is scarce but recent interest in geoconservation and establishing a geopark ignited a new wave of volcanology and geocultural research.

THE ACTIVE YASUR–YENKAHE VOLCANIC COMPLEX
VANUATU

Yasur volcano within the Siwi caldera. The caldera margin marked as an escarpment north of Yasur. Left of Yasur resurgent lava domes form a ridge.

ERUPTING FOR MORE THAN 800 YEARS, IT IS "THE LIGHTHOUSE OF THE PACIFIC"!

The Yasur–Yenkahe volcanic complex within the Siwi caldera is an excellent active site to study the diversity of volcanic processes and their eruptive products associated with a near-sea level mafic-intermediate arc volcano. The location provides graphic examples of welded to non-welded mafic ignimbrites and their proximal to distal facies variations. The Strombolian-style and phreatomagmatic explosive eruptions of Yasur can be observed with ease and safely. The caldera hosts a rapidly uplifting resurgent block and a fast-filling caldera demonstrating the dynamic processes associated with a modern caldera volcano.

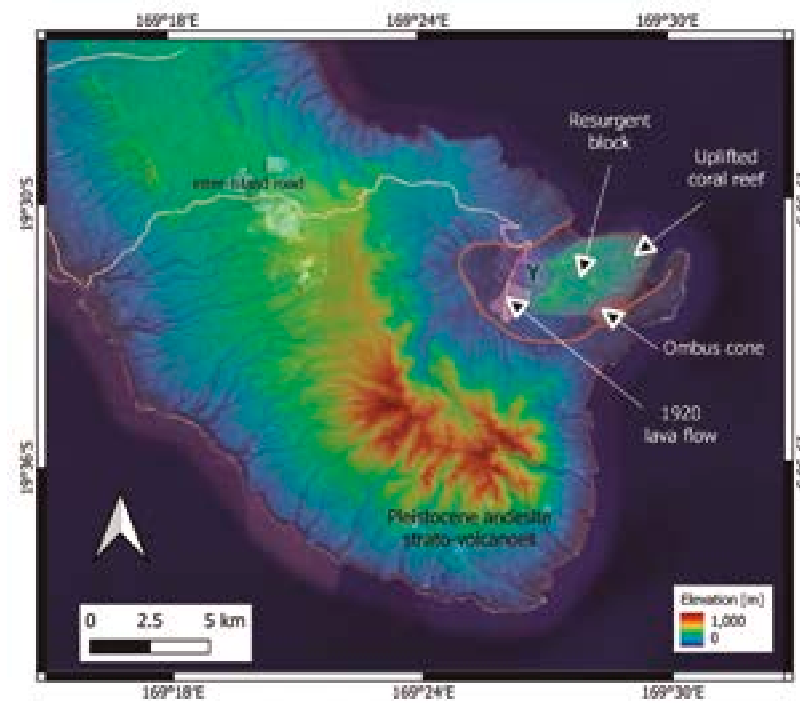
SITE 057

GEOLOGICAL PERIOD	Holocene
LOCATION	Tanna Island, Vanuatu. SW Pacific. 19° 31' 45" S 169° 26' 50" E
MAIN GEOLOGICAL INTEREST	Volcanology

Typical Strombolian-style explosive eruption observed during night from the crater rim of Yasur. (Copyright, Olivier Grunewald).

Geological Description

The Yasur–Yenkahe volcanic complex is hosted within the Siwi caldera in the SE sector of Tanna Island, which is part of the central volcanic chain of Vanuatu (Allen, 2004). The Siwi caldera (9×4 km) is delimited by the "Siwi Ring Fracture" (Allen, 2004). The resurgent intra-caldera Yenkahe block (6×3 km) is composed of up to 20,000 year old magmatic intrusions (Brothelande *et al.,* 2016; Firth *et al.,* 2021). Coral reef terraces dated at 1000 years BP are found today at altitudes more than 150 m high, which implies a mean uplift rate of 156 mm/year over the last millennium. Hence, this site is one of the faster caldera floor resurgences in the world. Yasur is a persistently active basaltic trachy-andesite volcano (361 m high and 1500 m wide) located within the Siwi caldera (Spina *et al.,* 2016). In a near-constant state of eruption for approximately 800 years, giving the site its nickname "the lighthouse of the Pacific". It has a 400 m wide crater, with three active vents located at the summit. Explosions described at Yasur suggest the occurrence of Strombolian-type eruptions with intermittent phreatomagmatic events (Woitischek *et al.,* 2020).



Digital Elevation Model of SE Tanna over a GoogleEarth satellite image, showing the Yasur cone (Y) and its 1920 lava flow within the Siwi caldera (orange line). Note the resurgent block, uplifted Holocene coral reef, and Ombus cone also marked within the caldera.

Scientific research and tradition

Due to its easy access, Yasur volcano is a subject of volcanology research for over two decades and provides an excellent study site where theories can be tested by direct measurements and observations.

LA ISLA DE OMETEPE
QUATERNARY VOLCANOES IN THE LAKE NICARAGUA
NICARAGUA

The different shapes of Concepcion and Maderas: Maderas plunges directly into a trough, but Concepcion is ringed by anticlinal hills, clearly seen on the left.

A TYPE EXAMPLE OF VOLCANO SPREADING AND VOLCANO-TECTONIC INTERACTIONS IN THE VOLCANIC ARC SEDIMENTARY BASIN OF LAKE NICARAGUA.

Isla de Ometepe is a globally significant site for interactions between plate tectonics, gravity tectonics, and magmatic - volcanic process, all combined with the external environment, which has fashioned human culture and resilience. The island's geomorphology, seen as a tectonic and volcanic landscape, allows the interface between geosphere, biosphere, archaeology, history and present day activity to be understood. The island's location in an inland sea, which has been the point of concentration of cultures for thousands of years, has attracted scientists for intensive and ongoing research.

SITE 058

GEOLOGICAL PERIOD	Quaternary
LOCATION	Lake Nicaragua, Nicaragua. 11° 30' 10'' N 085° 34' 15'' W
MAIN GEOLOGICAL INTEREST	Volcanology Tectonics

A view over a block of uplifted lake sediments toward the deeply forested Maderas, where two fault scraps can bee seen bracketing the summit crater.

Geological Description

Isla de Ometepe, Lake Nicaragua is a landscape of ongoing interactions between gravity, tectonics and volcanism in a lacustrine environment on a convergent plate boundary (Borgia and van Wyk de Vries 2003; Saballos *et al.,* 2013). The island has two stratovolcanoes, Concepción and Maderas, displaying active geodynamics interacting with environment and biosphere.

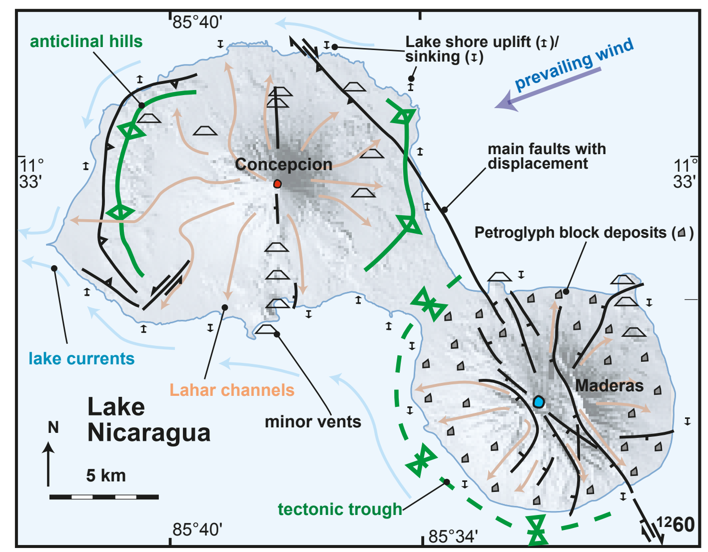
Maderas (Mathieu *et al.,* 2011; Kapelanczyk *et al.,* 2012) is long dormant and is cut by impressive faults reflecting strike-slip regional and gravity tectonics. An abundance of lahar boulders have inspired hundreds of pre-colombian petroglyph carvings.

Concepcion is an active cone, fashioned by historical eruptions, and is surrounded by uplifted pre-volcano lake sediments to heights of over 200 m, in a range of rolling anticlinal hills. Regional tectonics, magmatic pressure and gravitational stresses have created folds and faults. A complete eruptive sequence of the whole volcano history is exposed. Pre-colombian artifacts are found within the tephra sequence (Haberland 1986). The 40,000 inhabitants also come together in an impressive example of community resilience to disaster risk.

Isla de Ometepe reflects the conjunction of multiple processes in a volcanic arc setting (Funk *et al.,* 2009), geologically combining plate tectonics, gravity tectonics and volcanism surface processes in one perfect figure of eight.

Scientific research and tradition

Isla de Ometepe has been continually in scientific literature since the 19th Century. Concepcion volcano has been intensively studied, and Maderas volcano is one of the best dated volcanoes in Central America. Both are used as type examples of volcano spreading and of arc volcano-tectonic interactions.



Isla de Ometepe with Concepcion with its annular anticlinal hills and constructional cone; Maderas with its faulted and eroded cone, block fields and trough.

THE POÁS VOLCANO

COSTA RICA

Aerial view of Poás volcano looking into the main active crater lake, the central manifestation of its permanently active hydrothermal system.

AN ICONIC AND TYPE EXAMPLE OF AN ARC SHIELD-LIKE MASSIVE STRATOVOLCANO AND TYPE EXAMPLE OF AN ACTIVE CRATER LAKE COMPLEX.

Poás volcano is a huge arc volcano-tectonic massif, large enough to deform gravitationally under its own weight (Borgia *et al.,* 1990). It is also a globally important example of a persistently active magmatic-hydrothermal crater lake system, with attendant important geosphere-biosphere interactions. Because of this and its central location as a 'drive in' volcano, Poás is not only one of the most studied volcanoes in Central America, but also a global tourist attraction. The continuity of scientific studies at Poás from the 19th Century to present show that this is a globally important site for geosciences.

SITE 059

GEOLOGICAL PERIOD	Quaternary – Holocene
LOCATION	Central Volcanic Range. Costa Rica, Central America. 10° 11' 47" N 084° 13' 54" W
MAIN GEOLOGICAL INTEREST	Volcanology Geomorphology and active geological processes

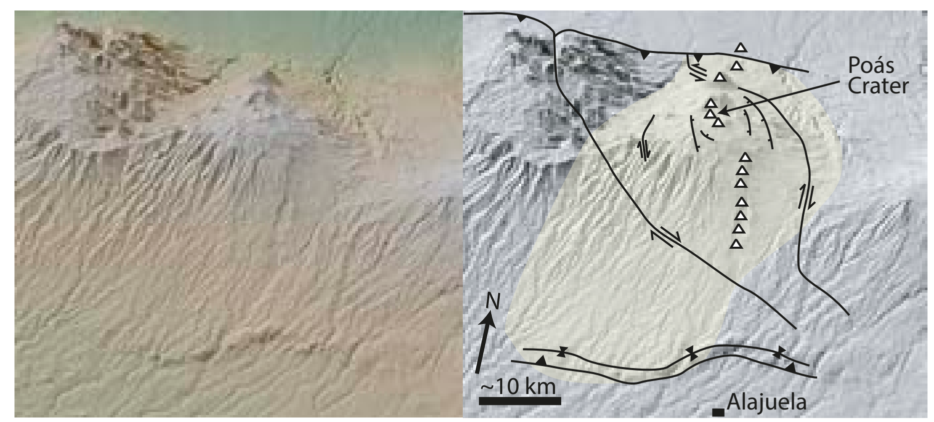
Aerial view over the inactive Botos Crater lake, to the active Poás crater, which have formed in the summit graben of the volcano.

Geological Description

Poás volcano is a composite stratovolcano with an irregular complex form and a basal area of about 400 km^2 (Alvarado, 2021). It has been an object of close study from the 19th Century, especially due to its permanently active crater lake, which with Raupehu, New Zealand, and Kelud, Indonesia, form a global group of key examples of this highly hazardous, but scientifically intriguing phenomena (Francis *et al.,* 1980). The whole Poás volcanic complex is proposed as an IUGS geosite, because the entire structure is one unique volcano-tectonic entity with its own gravitational and magmatic tectonics, including large basal thrust faults and a summit rift (Borgia *et al.,* 1990; Montero *et al.,* 2009; Ruiz *et al.,* 2019). It also has a specific geological ecosystem individuality, founded on the edifice form and the interactions between the crater lake system and the environment (Pérez-Umaña *et al.,* 2019). Its north-south alignment of vents also reflects the ongoing regional strike-slip tectonic situation of subduction close to an oceanic ridge.

It is composed of basalt and andesite and lesser dacite. Its prehistoric activity ranges from lava flows, lahars, plinian to strombolian eruptions as well as phreatic to phreatomagmatic. The historical activity is presented from 1828 to the present (Alvarado, 2021).

Oblique image showing the whole shield-like stratovolcano shape of Poás. The faults and vents (triangles) related to regional, gravitational and volcano tectonics are indicated.



Scientific research and tradition

Poás volcano has been studied from its volcanology, tectonics, and geomorphology from the 19th century (references in Borgia et al 1990), and continues to be studied intensely (Alvarado, 2021; Ruiz *et al.,* 2019), including by geo - ecological studies and geoheritage outputs (Pérez-Umaña *et al.,* 2019).

THE NEVADO DEL RUIZ QUATERNARY VOLCANIC COMPLEX

COLOMBIA

The iconic "Crater Arenas" and surrounding ice cap of the Nevado del Ruiz Volcanic Complex stratovolcano.

ONE OF THE MOST EMBLEMATIC AND BEST-STUDIED VOLCANOES IN THE WORLD, A MODEL FOR VOLCANIC RISK MANAGEMENT.

The Nevado del Ruiz expelled an estimated 3.5x1010 kg of mixed andesite and dacite tephra on November 13, 1985 (Melson *et al.,* 1990). This small plinian explosion melted 10% of approximately 19 km^2 of glacier ice (Pierson *et al.,* 1990), generating a lahar that claimed at least 25,000 human lives (Naranjo *et al.,* 1986). The eruption was classified as the second largest disaster of volcanic origin in the 20^{th} Century, leaving a lesson of the importance of promoting community awareness of, and involvement in, volcanic hazard management (Voight, 1990. In addition, it promoted the creation of several volcanological observatories around the world.

SITE 060

GEOLOGICAL PERIOD	Pleistocene-Holocene
LOCATION	Caldas and Tolima departments, Colombia. 4° 53′ 43" N 75° 19′ 21" W
MAIN GEOLOGICAL INTEREST	Volcanology

Ash emission from the Nevado del Ruiz volcano during May 2017.

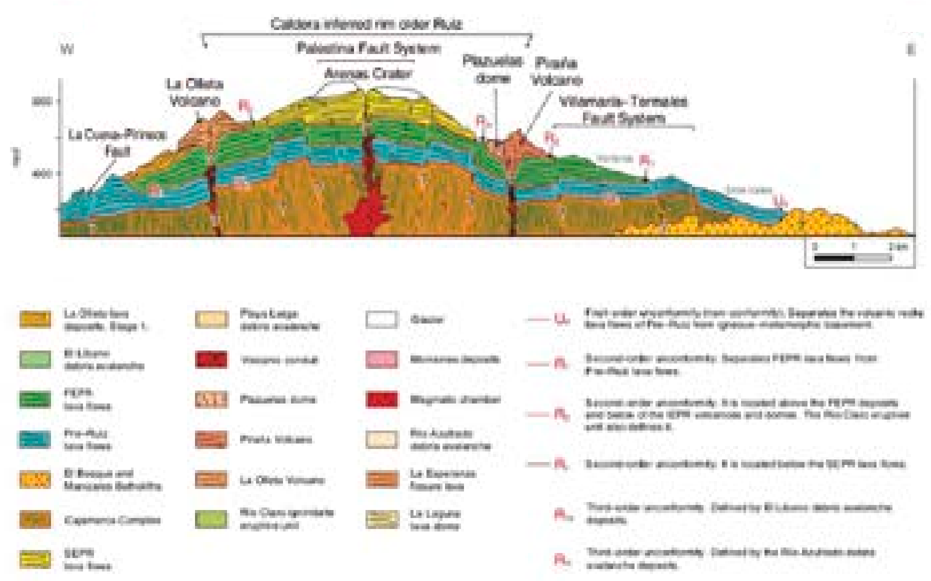
Geological Description

Nevado del Ruiz is a stratovolcano of andesitic composition and with a height of 5,321 meters above sea level, of andesitic composition. It is 66,000 years old, and during the last 13,000 years its activity has been mainly explosive with the generation of at least 14 subplinian-style eruptions and the occurrence of recurring eruptive phenomena of pyroclastic density currents, lahars, pyroclastic falls, and non-magmatic debris avalanches. The main crater, which is 750 m in diameter and 200 m deep, is called "Cráter Arenas" (Ceballos *et al.,* 2020). Currently, the volcano has an ice cap covering 8.37 km^2. It activity is manifested by its record of seismicity, emission of gases and ash, and the presence of hot springs.

This volcano is part of the so-called "Nevado del Ruiz Volcanic Complex". It corresponds to a series of structures and volcanic deposits genetically related to each other within the framework of a history of construction and destruction of 1.8 Ma. Four eruptive periods have left a record of lava flows, domes, pyroclastic density sucrrents, falls of balits, wind projection, debris avalanches, and lahars (Ceballos *et al.,* 2020).

Scientific research and tradition

The first geoscientific description of the Nevado del Ruiz volcanic activity was made by Joaquin Acosta (1846). Later, as a result of the eruption on November 13, 1985, the formal beginning of vulcanology in Colombia took place (in 1986). Since then, Nevado del Ruiz has been kept under constant monitoring by the Volcanic Network of the Colombian Geological Survey, with the participation of national and international researchers. Their investigations have produced 130 publications in scientific journals.



THE COTACACHI - CUICOCHA VOLCANIC COMPLEX

ECUADOR

UNESCO Global Geopark

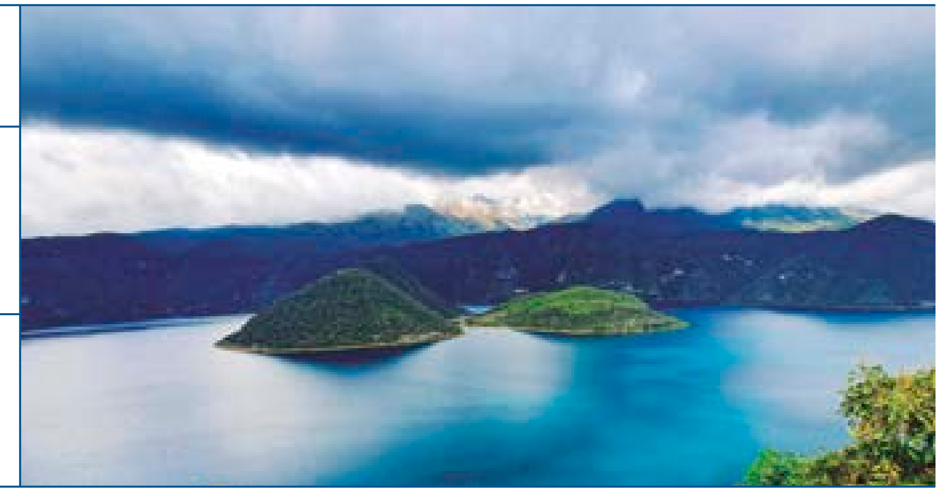
The more recent active volcanic domes of Wolf (right) and Yerovi (left) islands emerge in the middle of Cuicocha caldera lake. Photo taken from the south flank of Cotacachi volcano.

VOLCANIC COMPLEX WITH A SPECTACULAR 3 KM WIDE ACTIVE VOLCANIC CALDERA, WITH MANY DOCUMENTED RECORDS OF VIOLENT HISTORICAL ERUPTIONS.

The Cotacachi-Cuicochoa volcanic complex (CCVC) is one of the most powerful volcanoes in Ecuador. Its activity during the last 3100 years includes the destruction of a pre-caldera dome due to violent eruptions with pyroclastic waves. After the formation of the caldera, there was a lava extrusion that formed the two islands that are visible today within the caldera and its accumulation of glacial water, forming Lake Cuicocha. It is currently the most visited tourist attraction offered by the Global Geopark Imbabura UNESCO with around 200,000 visitors a year due to its easy access and beauty.

SITE 061

GEOLOGICAL PERIOD	Cuaternary / Pleistocene
LOCATION	Cotacachi, Imbabura Geopark. Imbabura, Ecuador. 00° 17' 32'' N 078° 21' 27'' W
MAIN GEOLOGICAL INTEREST	Volcanology Geomorphology and active geological processes



Partially covered by clouds, in the background Cotacachi volcano is visualized.

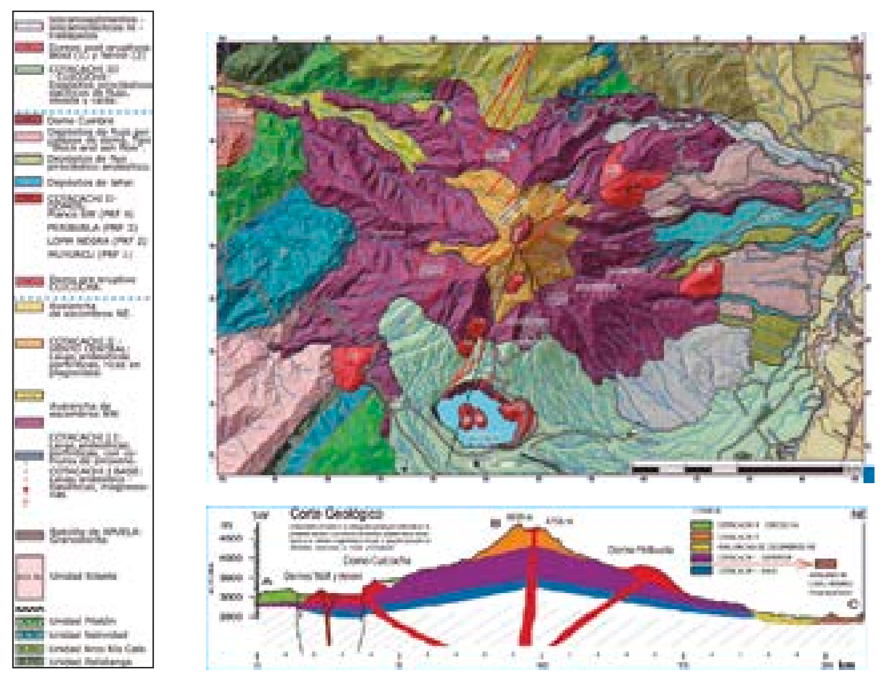
Geological Description

The Cotacachi – Cuicocha volcanic complex is a Geosite of the Imbabura UNESCO Global Geopark with a base area of approximately 268 km². The CVCC consists of a central building (Cotacachi volcano; maximum summit= 4939 m a.s.l.), four satellite domes (Cuicocha, Muyurcu, Loma Negra and Piribuela) and a volcanic caldera (Cuicocha caldera).

The Cotacachi Volcano is an extinct stratum-volcano, and two large avalanches of debris are evidenced of its evolution. The first is associated with the closure of the formation of the first volcanic building that occurred between 162 and 108 thousand years BP.

According to the stratigraphic position, it is estimated that the second avalanche of rubble occurred between 102 and 65 thousand years BP, being part of the development of the second volcanic building. The closure of Cotacachi II is marked by a sequence of lava flows that fill the crater. It is considered that satellite domes began to form from 44 thousand BP years.

The Cuicocha caldera, wich represents the most recent phase of the complex, has presented at least two phases of activity in 3100 and 2900 years BP (Hillebrant, 1989), which makes it a potentially active volcano.



Geological map and cross-section of the Cotacachi-Cuicocha Volcanic Complex (Imbabura UGGp).

Scientific research and tradition

Since 2011, the EPN Geophysical Institute has been constantly monitoring the volcano, and since 2016 it has published annual reports. Since 2019 it has been producing quarterly reports of CO_2 and seismic activity, showing its importance in risk management. Many universities use Cuicocha to conduct geological, biological and risk management research.

THE QUATERNARY SANTORINI CALDERA

GREECE

Dafni crater on Nea Kameni and view of the cliffs of caldera. (Photo: A. Argyrou).

ONE OF THE LARGEST CALDERAS IN THE MEDITERRANEAN SEA FORMED BY PLINIAN ERUPTIONS IN A VOLCANIC ARC TECTONIC FRAMEWORK.

The caldera is the result of one of the most destructive and the most famous of the eruptions that have impacted ancient civilizations, the iconic Minoan Eruption which occurred approximately 3600 years before present. This eruption may has contributed to the fall of the Great Minoan Civilization, leaving its imprint on Greek mythology (Atlantis), archaeology and volcanology in general (McCoy F. and Heiken G., 2000; Nomikou *et al.,* 2016). It is also outstanding that the stratigraphy of the volcanic rocks of multiple eruptive episodes is evident in the caldera walls. The entire area of the caldera features outstanding geological and natural characteristics, thus making it a living laboratory for earth sciences, volcanic risk monitoring and study (Pyle and Elliott, 2006).

SITE 062

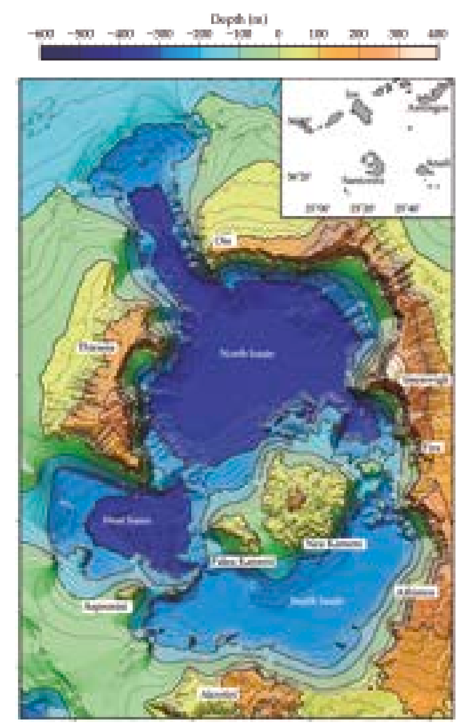
GEOLOGICAL PERIOD	Middle Pleistocene-Holocene
LOCATION	Thira Island, Region of South Aegean, Cyclades, Greece. 36° 24' 38" N 025° 23' 33" E
MAIN GEOLOGICAL INTEREST	Volcanology

Part of the majestic Santorini caldera with view to the north. (Photo: A. Argirou).

Geological Description

With dimensions of 8 x 11 km, it is one of the largest calderas globally, a result of many Plinian eruptions that have occurred from different eruptive centers during the volcanic history of the region (650-0 Ky) (Druitt, Francaviglia, 1992). Its steep and imposing walls portray layers of explosive products including lavas and pumice, intercalated by paleosols that represent a cease of activity. Unique volcanic landforms, including lava tubes and veins that fill tectonic structures, offer a glimpse of the interior of past volcanic centers and can be found on many areas along the caldera walls. Santorini is part of a broader volcanic field that has been active for more than half a million years, and offers a perfect natural laboratory for studying arc volcanism. It has undergone twelve powerful Plinian eruptions over the past 350.000 years, at least four of which caused a caldera collapse (Druitt, 2014). These voluminous eruptions are fed by reassembling magma chambers located at approximately 4-8 km depth, which are refilled with magma from a deeper sub-caldera reservoir (McVey *et al.,* 2020). Plinian eruptions are estimated to occur every 10 – 30 thousand years and are separated by Sub - Plinian periods, which are characterized by effusion of lavas that build shields, accompanied by weaker explosive activity.

Onshore-Offshore morphology of Santorini Caldera with the main islets and the new volcanic cones of Palea and Nea Kameni (From Nomikou et al., 2014, GeoResJ, 1-2, pp.8.)



Scientific research and tradition

Existing onland volcanological research, sea floor mapping, shallow coring and dredge sampling, combined with a dense network of seismic profiles, a 3D marine-land active-source seismic dataset and the pioneering IODP Ocean Drilling (Exp 398) make Santorini caldera one of the most well-known studied areas in the world.

THE VAPOR PHASE IGNIMBRITES OF SILLAR IN THE AÑASHUAYCO QUARRIES OF AREQUIPA

PERU

View of the left bank of the "Añashuayco quarry" where the Arequipa Airport ignimbrite is seen with white unit and pink unit.

THE GLOBAL TYPE LOCALITY FOR 'SILLAR' VAPOR PHASE IGNIMBRITE, FORMED BY A LARGE EXPLOSIVE ERUPTION 1.65 MA AGO IN SOUTHERN PERU.

The Añashuayco quarry is the global type locality for vapor phase ignimbrites, providing this important facies with its name, 'Sillar'. The Añashuayco quarry is also a globally recognized site connected to the UNESCO World Heritage designation for Arequipa, and for Peruvian intangible heritage. The Añashuayco sillar quarry is a global site for the communication, through geoheritage, of the origin of ignimbrite and carries a vital global and local message about natural hazards and community resilience. It is a perfect site to showcase science working for, and within, society.

SITE 063

GEOLOGICAL PERIOD	Pleistocene / Calabrian
LOCATION	The Añashuayco quarries, South America. 16° 21' 35" S 071° 36' 23" W
MAIN GEOLOGICAL INTEREST	Volcanology Igneous and metamorphic petrology

A "Cantero (quarryman)" working to extract sillar in the quarry.

Geological Description

Sillar is a specific type of ignimbrite deposit, where hot gasses alter and cement the pumice into a strong coherent mass. It was first described in what is today called the Arequipa Airport Ignimbrite by (Hatch, 1885-1886) and fully described by Fenner (1948). The Ignimbrite represents a large caldera forming eruption, dated at c. 1.65 Ma (Paquereau-Lebti *et al.,* 2006), generating pyroclastic density currents that filled the Arequipa tectonic depression which is a pull-apart basin. This ignimbrite is divided into a lower white and compact unit covered by an upper unconsolidated pink unit. The composition of magmas is rhyolitic. The geographic location of the Arequipa Airport Ignimbrite source is suggested to be buried by Chachani Volcano Cluster (Paquereau-Lebti *et al.,* 2008; Aguilar *et al.,* 2022).

The classic locality for the Sillar is in the Añashuayco Quarries (e.g. Fenner 1948), where natural exposures and quarries surfaces give an unparalleled view into the ignimbrite. The Sillar stone itself is the building block for the UNESCO World Heritage Centre of Arequipa, and the traditional artisan extraction techniques are Peru Intangible Heritage. As well as being the global scientific type site for Sillar, the Añashuayco Quarries are a global tourist site (Negro, 2015).

Image of a cross section in the "Quebrada Añashuayco". Note that the Arequipa Airport ignimbrite made up of two cooling units: an underlying white unit and an overlying weakly consolidated pink unit.

Scientific research and tradition

Sillar has become the facies name and Añashuayco the type locality for vapor phase ignimbrite, especially over discussions of the origin of the Ten Thousand Smokes Valley eruption in Alaska 1912 (Fenner, 1948). References for studies of ignimbrites in the Andes and other places are Paquereau-Lebti *et al.* (2006; 2008), and Aguilar *et al.* (2022) determined its age and composition.

THE PYROCLASTIC DEPOSITS FROM THE HUAYNAPUTINA VOLCANO ERUPTION 1600 CE

PERU

Pyroclastic density current and tephra deposits from the 1600 CE Huaynaputina eruption in the area of the Calicanto geosite, southeast edge of the Quebrada (valley) del Volcan.

THE PYROCLASTIC DEPOSITS OF THE LARGEST HISTORICAL VOLCANIC ERUPTION IN SOUTH AMERICA PRESERVED IN THE INCA VILLAGE OF CALICANTO.

The 1600 CE eruption of Huaynaputina is considered the most voluminous (VEI 6) that occurred in historical times in South America and one of the largest in the world over the past 1,500 years. The eruption had an impact on the global climate, as it triggered a temperature drop of -1.13 °C in 1601 in the northern hemisphere (Stoffel *et al.,* 2015). At the more regional scale, this eruption buried at least a dozen Inca villages, causing perhaps 1,500 fatalities, and disrupting the early Colonial economy in Peru for years. The Calicanto geosite is therefore a geological and cultural reference.

SITE 064

GEOLOGICAL PERIOD	Late Holocene
LOCATION	Department of Moquegua, Southern Peru. 16° 44' 07" S 070° 51' 38" W
MAIN GEOLOGICAL INTEREST	Volcanology Geoarchaeology

Structures buried by the 1.70 m-thick Plinian tephra fall in Calicanto. The upper structure was knocked down by the surge and flow pyroclastic deposits.

Geological Description

Huaynaputina, southern Peru, is an active volcano of the Central Andean Volcanic Zone. Huaynaputina is built of two edifices: a stratovolcano (Pleistocene) overlain by a dome cluster and a group of vents (Late Pleistocene-Holocene) within a horse-hoed-shaped scar.

The 1600 CE explosive eruption of the Huaynaputina volcano produced a range of pyroclastic deposits with an average thickness of ~3 m at the geosite. The pyroclastic sequence shows five units: a Plinian tephra fall deposit (U1), Vulcanian ashfall deposits (U2), Pyroclastic density current deposits (U3), Crystal-rich ashfall deposit (U4) and Ash flow deposit (U5) (Thouret *et al.,* 2002; Prival *et al.,* 2020). Tephrostratigraphy conducted at this geosite and its surroundings allowed the eruptive processes to be reconstructed and Plinian eruptions to be better understood.

The Inca Calicanto town, located 13 km south of Huaynaputina near the village of Quinistaquillas, was one of a dozen of villages buried by this event. Study of the ruins and damage on the structures help understand the impact of the pyroclastic deposits on houses and Inca cultivated terraces. In an approximate area of 50,000 m², we identified about 20 edifice walls and 21 Inca terraces mantled by pyroclastic deposits (Mariño *et al.,* 2021; Arias, 2021; INGEMMET, 2021).

Scientific research and tradition

The first investigation period (1995-2002) dealt with the tephrostratigraphy and the analysis of chronicles, aiming at reconstructing the evolution of the 1600 CE eruption. From 2015 to the present, multi-disciplinary studies (mapping, geophysical surveys, etc.) have examined the impacts of the eruption and have studied the geo-heritage in Calicanto and other sites (Arias, 2021; Marino *et al.,* 2021).

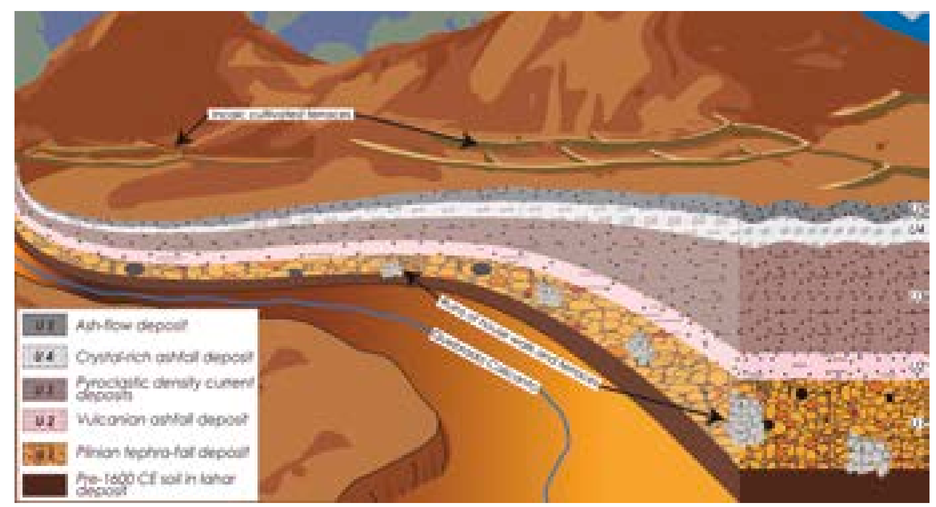


Diagram showing the ruins of walls and pyroclastic deposits from the eruption of Huaynaputina, 1600 CE mantling the Inca town village of Calicanto.

THE MIOCENE CAPPADOCIAN IGNIMBRITES SEQUENCE
TURKEY

UNESCO World Heritage Site

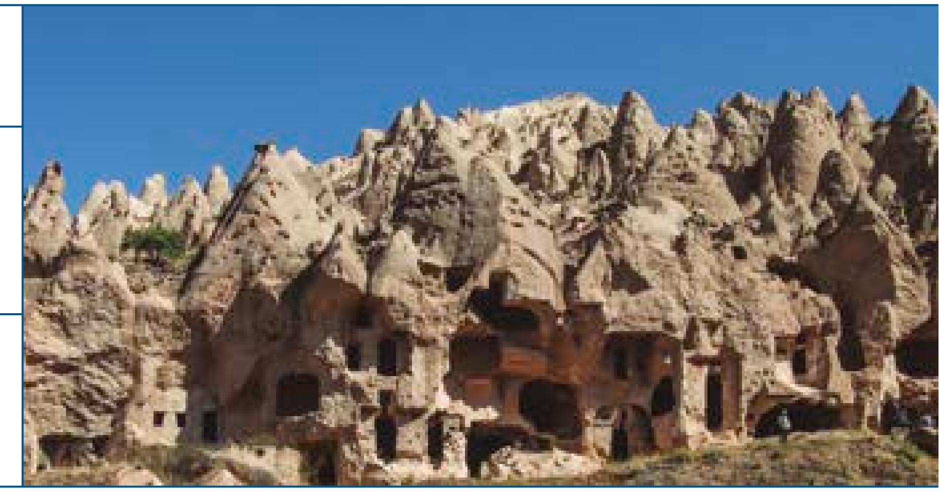
A general view of Cappadocian volcanic plateau (Photo: Ali İhsan Gökçen).

VOLUMINOUS ERUPTION DEPOSITS IN A FLUVIO-LACUSTRINE SEQUENCE WITH 'FAIRY-CHIMNEY' DEVELOPMENT PRODUCED BY UPLIFT AND EROSION.

Cappadocian Volcanic Province is a good example of coeval activity of sedimentation, volcanism and faulting. Emplacement of voluminous ignimbrites is interstratified with sedimentary rocks of the same basin. Nine ignimbrites were identified, mapped, dated and studied in detail. The thickness of the sequence is more than 430 m. Several primary sedimentological structures related to the fluctuation of the basin level were formed during emplacement of the ignimbrites. The presence of fossil mammals provide the opportunity to calibrate the paleontological record with absolute dates.

SITE 065

GEOLOGICAL PERIOD	10-5 MA (Miocene)
LOCATION	Cappadocia plateau, Turkey. 38° 40' 36'' N 034° 51' 16'' E
MAIN GEOLOGICAL INTEREST	Volcanology Geomorphology and active geological processes

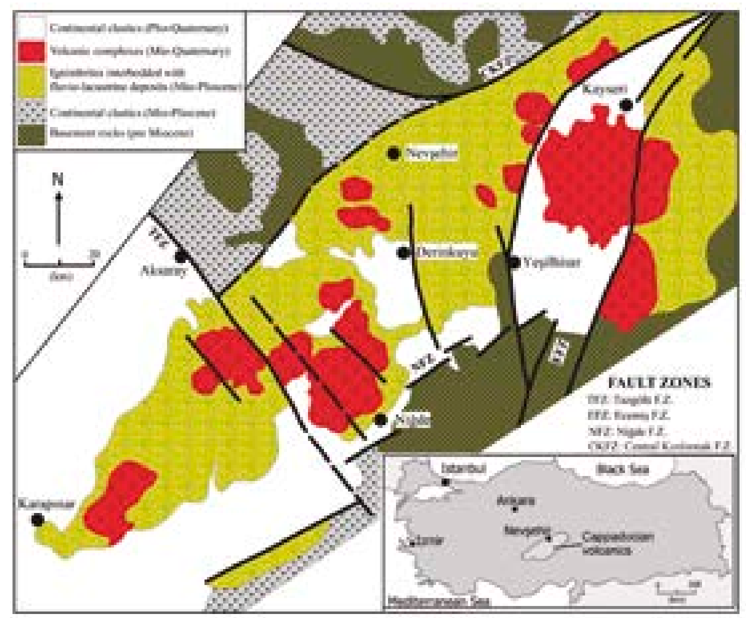


Fairy chimneys with ancient rock-hewn settlements in Zelve ignimbrite (Photo: Vedat Toprak).

Geological Description

Cappadocian Volcanic Province (CVP) is a Neogene-Quaternary volcanic field located in the central Turkey that extends in NE–SW direction for a length of 300 km and a width of 20–50 km. Formation of CVP is attributed to the convergence between Afro-Arabian and Eurasian continents (Le Pennec *et al.,* 2005 and references therein). The most prominent feature of the CVP is the presence of several thick and widespread voluminous ignimbrites interstratified with fluvio-lacustrine strata. This sequence was deposited in a basin that developed under the control of faults, which were coeval with volcanic activity and sedimentation (Toprak, 1998). The source of the ignimbrites, which are large calderas, are buried today (Froger *et al.,* 1998). All ignimbrites are well-studied in terms of petrography, geochemistry, age and stratigraphy (Schumacher and Mues-Schumacher, 1997; Temel et al., 1998; Le Pennec *et al.,* 2005). Maars and maar volcanism were sometimes associated with tectonism in the area (Gevrek and Kazancı, 2000). "Fairy-chimneys" are a typical and unique product of CVP, which are formed by subsequent uplift and erosion of ignimbrites. These structures are developed in the form of cones under certain thickness, welding and topographic slope conditions of ignimbrites.

Simplified geological map of Cappadocian Volcanic Province (Toprak, 1998).



Scientific research and tradition

The area has been attractive for studies of volcanology, tectonism and sedimentology as it includes diverse features. Formation of systematic "fairy chimneys" draw the attention of geomorphology and engineering geology. Numerous rock-cut settlements carved into the ignimbrites also should be noted for their cultural heritage.

EL TATIO GEOTHERMAL FIELD
CHILE

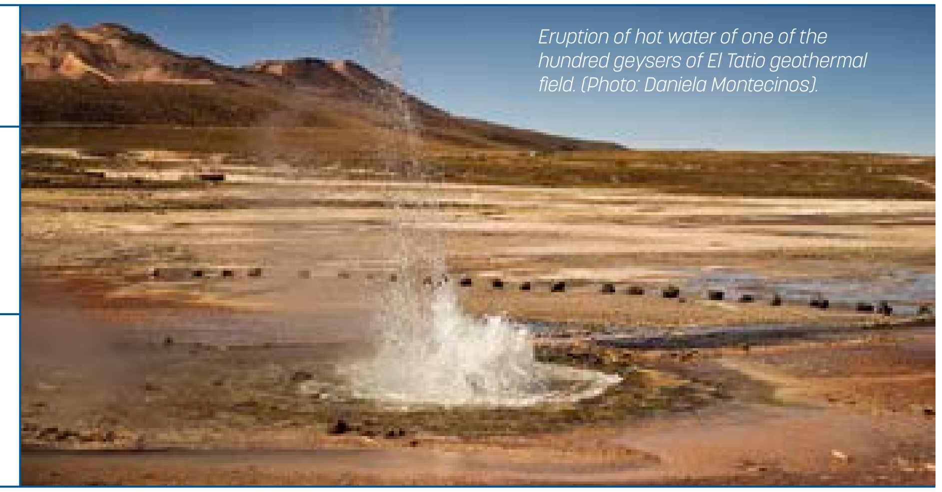
View to the East to the geysers of El Tatio geothermal field. (Photo: Daniela Montecinos).

THE LARGEST AND MOST DIVERSE GEOTHERMAL FIELD IN THE SOUTHERN HEMISPHERE WITH MORE THAN A HUNDRED VARIED MAJOR SURFACE MANIFESTATIONS.

El Tatio, one of the world's highest geyser fields (~4300 m a.s.l.), is a unique environment compared to other hydrotherml localities. Its provides an analouge to conditions of the early Earth and Mars (Phoenix *et al.,* 2006). These conditions are extreme aridity, strong winds, low atmospheric pressure, high UV radiation and daily temperature variations, lower water boiling point (88°C), plus high toxic water concentrations (Wilmeth *et al.,* 2021). The geyser field has one of the highest silica precipitation rates found in the world (Nicolau *et al.,* 2014).

SITE 066

GEOLOGICAL PERIOD	Upper Miocene - Holocene
LOCATION	Antofagasta Region, Chile. 22° 20' 06" S 068° 00' 47" W
MAIN GEOLOGICAL INTEREST	Volcanology Geothermal, Geobiology

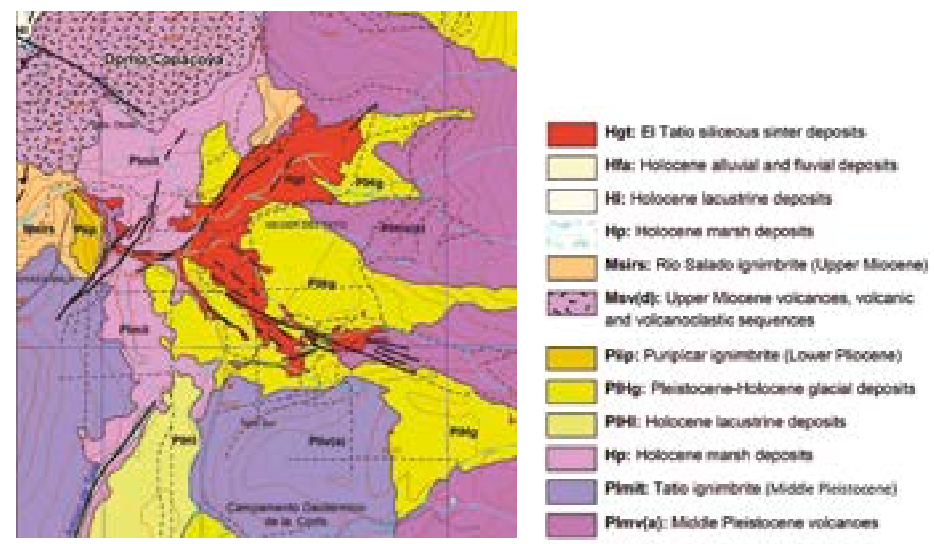


Eruption of hot water of one of the hundred geysers of El Tatio geothermal field. (Photo: Daniela Montecinos).

Geological Description

El Tatio is situated in the Altiplano–Puna Volcanic Complex. Surface thermal manifestations (fumaroles, hot springs, sinter cones, perpetual spouters, mud volcanoes and sinter terraces) are located on the upper levels in a Pliocene graben ~4 km wide and 6 km long. The western flank of the graben is the Serranía de Tucle–Loma Lucero horst, and the eastern flank is an alignment of andesitic stratovolcanoes and rhyolitic domes that form the summit of the Andes mountains at this latitude (Fernández-Turiel *et al.,* 2005). The geothermal field is contained in ignimbrites and lavas of the upper Cenozoic that overlies a basement of Mesozoic sedimentary rocks (Glenon and Paff, 2003).

According to geochemical and structural data, the water comes from precipitation in an area located at 12–20 km to the E–SE of El Tatio, and it is heated by volcanic complexes (Pastos Grandes and Cerro Guacha caldera systems) located east of the field (Glenon and Paff, 2003). Hydrothermal manifestations occur over a 30 km² area, divided into three basins, with most hydrothermal activity concentrated in the Upper Basin of 10 km². The hot water is mainly confined to two aquifers, which are overlain by volcanic formations (Tucle tuffs and Tatio ignimbrite). The El Tatio episodic hot springs eruptions have a maximum discharge that ranges between 250 to 500 lts/second, depending on seasonal changes; with a mean erupting column height of two meters and a maximum heigth of 8 meters. (Glenon and Paff, 2003; Fernández-Turiel *et al.,* 2005).



Geological simplified map of El Tatio.

Scientific research and tradition

While remote and with harsh environment, El Tatio was first mentioned in 1885 then 1909, and since 1921 hundred publications, studies and technical reports has been released about El Tatio geothermal field, by scientist around the world related to different aspects (Bertrand, 1885; Nicolau *et al.,* 2014; Wilmeth *et al.,* 2021). Nevertheless, still many questions remain, and numerous research possibilities exist for El Tatio geothermal field, the least known major geothermal system.

THE YELLOWSTONE VOLCANIC AND HYDROTHERMAL SYSTEM

USA

UNESCO World Heritage Site

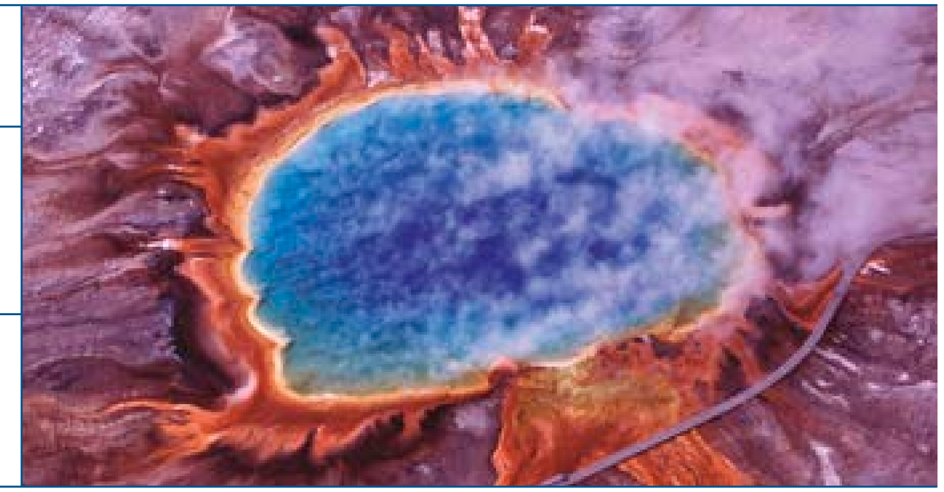
Silex Spring, located in the Lower Geyser Basin, is one of over 10,000 hydrothermal features in Yellowstone National Park, which contains some of the highest concentrations of hydrothermal features in the world. (Copyright Olivier Grunewald).

WELL-KNOWN FOR ITS PAST EXPLOSIVE VOLCANIC ERUPTIONS AND LAVA FLOWS AS WELL FOR ITS WORLD CLASS HYDROTHERMAL SYSTEM.

The Yellowstone area fits most, if not all, the definitions and standards for an IUGS Geological Heritage Site. It is protected, with most of it within Yellowstone National Park; it has world-class geological deposits that are accessible to the over 4 million annual visitors It is scientifically valuable to a host of disciplines, including but not limited to tectonics, petrology, seismology, volcanology, minerology, geomorphology, biology, ecology, and medicine. Also, it is unique on Earth, hosting world-famous geysers such as Old Faithful and Steamboat. Given the dynamic nature of Yellowstone, it is a superb natural laboratory for biological, ecological, and geological processes.

SITE 067

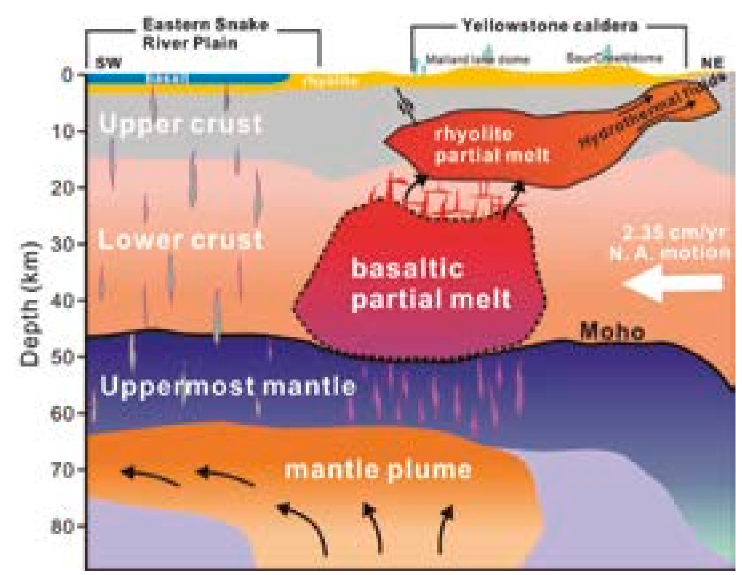
GEOLOGICAL PERIOD	Quaternary
LOCATION	Northwest corner of Wyoming with small portions in Idaho and Montana, USA. 44° 36' 00" N 110° 36' 00" W
MAIN GEOLOGICAL INTEREST	Volcanology Tectonics



Aerial view of Grand Prismatic Spring (one of the largest hot springs in the world) in the Midway Geyser Basin of Yellowstone National Park, USA.

Geological Description

Yellowstone is home to half the world's active geysers, including Old Faithful and Steamboat (the world's tallest at ~100m) geysers, as well as over 10,000 individual hydrothermal features. This volcano provides the opportunity to study the Earth on multiple scales, from imaging the mantle fueling the volcanic system down to an individual extremophile. This renowned hydrothermal system is not only visually stunning but is home to thermophile organisms that provide insight into biological processes and even the origin of life on this planet (Brock, 1985). The Yellowstone area is one of the most seismically active areas in the U.S. Intermountain West. The 1959 M7.3 Hebgen Lake earthuake was the largest earthquake to occur in the region in historical times (Pierce and Morgan, 1992; Smith and Braile, 1994). In addition, Yellowstone is a living, breathing volcanic system with the caldera uplifting and subsiding on decadal time scales. The igneous rock record in Yellowstone is world class, preserving ash-flow tuffs from multiple caldera-forming explosive eruptions as well as rhyolitic and basaltic lava flows that are a testament to the size and character of underlying magma reservoirs (Christiansen, 2001; Huang et al., 2015). All of these volcanic deposits are overlain on the extensional tectonics of the Basin and Range province, providing the rare opportunity to study magmatic-tectonic interactions.



The Yellowstone magmatic system showing the relationship between the mantle plume (below), the lower-crustal magma reservoir (middle), and the upper-crustal magma reservoir (top). Modified from Huang et al., 2015.

Scientific research and tradition

From the first colonialist expeditions to Yellowstone in the 1800s to the present, Yellowstone has been home and host to numerous curious researchers, resulting in several seminal works and foundational understandings in the earth sciences.

6

TECTONICS

SITE 068 - SITE 074

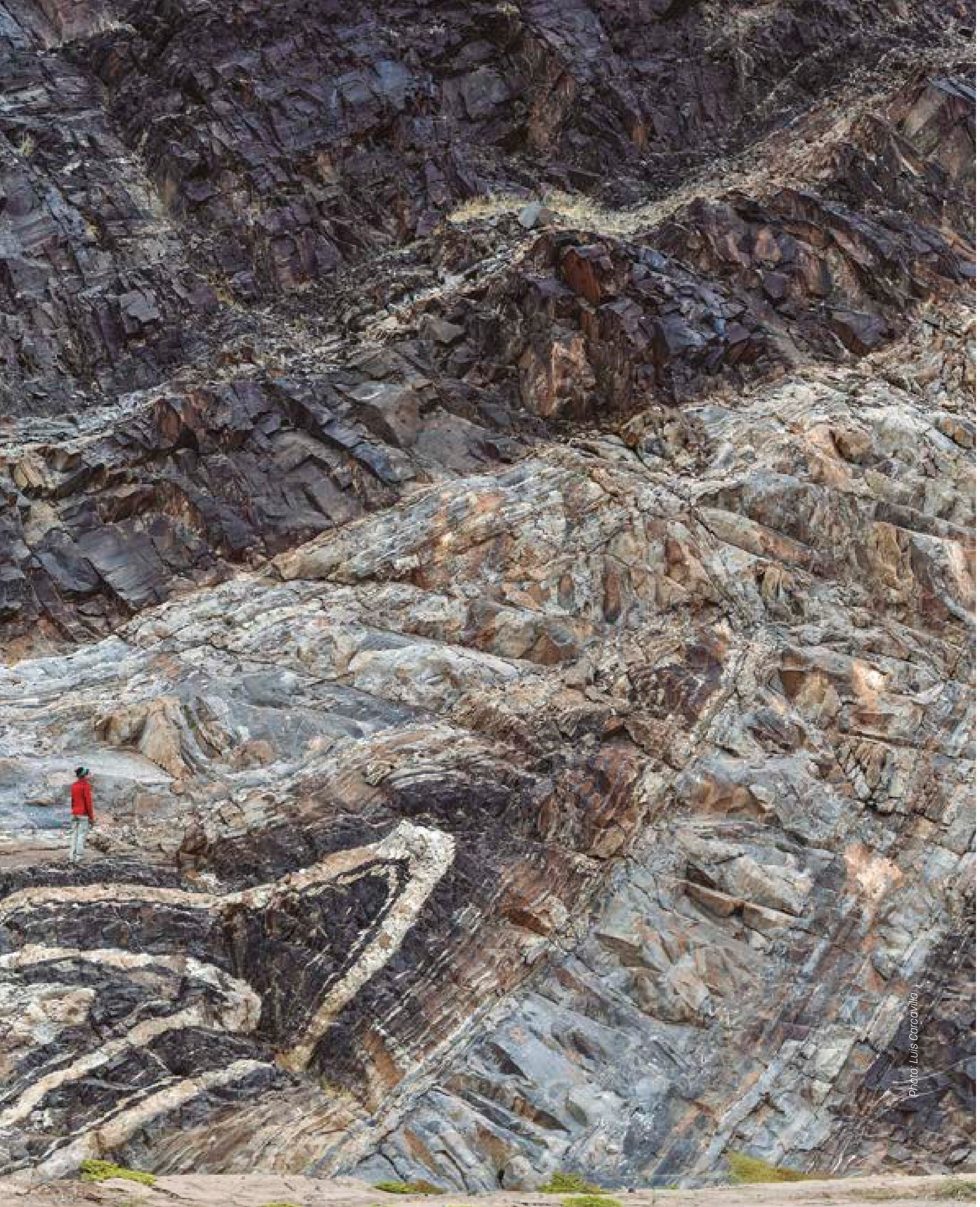


Photo: Luis Carcavilla

Enrique Gomez-Rivas
Universitat de Barcelona. Spain.
President, The IUGS Commission on Tectonics and Structural Geology (TecTask).
IUGS Geological Heritage Sites voting member.

Lorenzo Gemignani
Free University of Berlin. Germany.
The IUGS Commission on Tectonics and Structural Geology (TecTask).
IUGS Geological Heritage Sites voting member.

Tectonics investigates the evolution of the lithosphere and the forces that cause its deformation. Our understanding of the Earth's evolution has drastically improved by studying plate tectonic processes and their interaction with surface processes. Stated simply, plate tectonics allows us to unravel fundamental controls on sedimentary basin formation, mountain building, metamorphism and magmatism, earthquakes, and their effect on the Earth's surface through time. Yet, plate tectonics has founded the modern concept of Earth Sciences by bridging the geological disciplines upfront in the understanding of our planet's evolution as a dynamic rather than a static system. Tectonic processes strongly influence the Earth's surface, where most human activities take place, and knowing them is therefore essential for the exploration of energy and mineral resources, and to mitigate natural hazards.

To our eyes, the movement of tectonic plates may seem episodic, such as earthquakes or volcanic eruptions, or incredibly slow, such as relief formation. However, plates evolve at the same rate as how our nails grow. On the million years' time scale, the Earth's lithosphere has changed drastically. Yet, if we could look at a short film of the evolution of the Earth over millions of years, we would see a very dynamic and complex system which has cyclically changed the fate of its submerged lands. The exposed rocks preserve the record of the dynamic interplay among tectonics and landscape formation, forming the present-day archive of processes which took place through the Earth's history. Linking the evolution of lithospheric processes with climate and speciation has become an increasingly important research goal among the scientific community and public. The latter has become of great interest for the 100 IUGS Geological Heritage sites initiative, which can help the public and the research community to experience and protect the evidence that has been used to formulate and consolidate the theoretical framework of tectonic disciplines.

This section documents seven spectacular geological sites that collectively allow exploration of key tectonic processes in three different continents, and that expose outstanding tectonic structures. The Moine Thrust Zone in the Scottish Highlands led to the establishment of the plate tectonics theory and to the understanding of compressional tectonics. The South Tibetan Detachment System in the Rongbuk Valley in China is an excellent example of extension in an orogen, which allowed the exhumation of deep metamorphic rocks. Another site in which metamorphic rocks are exhumed because of a relatively young detachment fault system is the Northern Snake Range metamorphic core complex in the USA, which exposes spectacular ductile deformation structures. In other very different geodynamic contexts, a world-class ophiolite complex in a back-arc spreading ridge (La Désirade Island, Caribbean) and a Neoproterozoic-Cambrian mélange (Ynys Llanddwyn, UK) are presented. Finally, examples of structures produced by Quaternary earthquakes can be visualised in the Nojima fault in Japan, and the effects of subsurface salt flow can be examined in the spectacular Namakdan Salt Cave in Iran.


The Moine
Thrust Zone
UK
Ynys
Llanddwyn late
Neoproterozoic-
Cambrian Mélange
UK
Northern Snake
Range metamorphic
core complex
USA
The South Tibetan
Detachment
System in the
Rongbuk Valley
CHINA
Nojima
Fault
JAPAN
Namakdan
Salt Cave
IRAN
Upper Jurassic
ophiolitic sequence in
La Désirade Island
FRANCE

YNYS LLANDDWYN LATE NEOPROTEROZOIC-CAMBRIAN MÉLANGE

UNITED KINGDOM

UNESCO Global Geopark

Late Neoproterozoic-Cambrian mélange at the southwest tip of Ynys Llanddwyn. (Photo: Stewart Campbell).

SPECTACULAR, ACCESSIBLE AND WELL-PRESERVED EXPOSURES OF LATE NEOPROTEROZOIC-CAMBRIAN MÉLANGE WITH MORE THAN 200 YEARS OF GEOLOGICAL STUDY.

Ynys Llanddwyn is globally significant as an historical reference site for mélange (Greenly, 1919) and for testing geological paradigms on the formation of mélange-type deposits. The MORB pillow lavas are globally significant as some of the oldest and best preserved - including finely crystalline chilled margins and cracked and pitted cooling surfaces. The site has a history of more than 200 years of geological research and has been used as critical evidence in numerous important regional and transcontinental geological syntheses and detailed studies (e.g. Gibbons and Horák, 1996; Schofield *et al.*, 2020).

SITE 068

GEOLOGICAL PERIOD	Late Neoproterozoic - Cambrian
LOCATION	Anglesey Geopark North Wales, UK 53° 08' 19" N 004° 24' 39" W
MAIN GEOLOGICAL INTEREST	Tectonics History of geosciences Igneous and metamorphic petrology

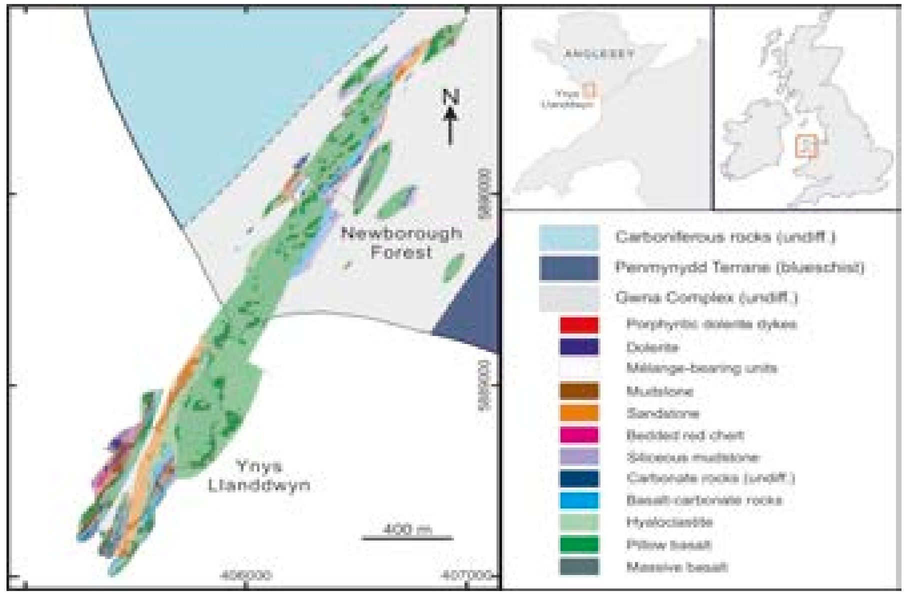
Late Neoproterozoic/Cambrian rocks are exposed in coastal sections and outcrops on Ynys Llanddwyn. (Crown copyright reproduced with permission (000574/1) of Royal Commission on the Ancient and Historical Monuments of Wales, under delegated authority from The Keeper of Public Records).

Geological Description

Ynys Llanddwyn featured in one of the first geological investigations and mapping exercises in the world (Henslow, 1822), and the term 'mélange' was first coined by Greenly (1919) for the mixture of rocks found on the western tip of the island. Rock exposures on and around Ynys Llanddwyn showcase some of the UK's most important geology. Late Neoproterozoic-Cambrian rocks of both continental and oceanic settings belong to the Gwna Group (now the Bodorgan Formation (Schofield *et al.*, 2020) and include pillow and massive basalt, hyaloclastite, carbonate and basalt-carbonate, chert, sandstone, mudstone and mélange-bearing units. These rocks are superbly exposed in coastal sections and outcrops that extend northeast from the southern tip of Ynys Llanddwyn across a tidal causeway into Newborough Forest. The assemblage is one of several mélanges preserved on Anglesey and northwest Llŷn, which are of controversial origin and of considerable ongoing research value. Debate continues as to whether these mélanges were formed entirely by tectonic emplacement, as part of an accretionary wedge or prism in a subduction zone, or if gravity slide or mass flow, mobilised by a catastrophic event such as continental shelf collapse, was a contributory process (Maruyama *et al.*, 2010; Groome, 2022).

Scientific research and tradition

Ynys Llanddwyn was studied by Henslow (1822) and was critical to Greenly's (1919) pioneering work on Anglesey. Featuring in long-running Japanese-British and BGS mapping/research programmes (Maruyama *et al.*, 2010; Schofield *et al.*, 2020), it continues to attract field parties and international researchers testing new geological paradigms.



The geology of Ynys Llanddwyn: principal lithological units and structures (from Groome, 2022).

NAMAKDAN SALT CAVE

IRAN

UNESCO Global Geopark

One of the big halls of Namakdan Cave with untouched stalactites. (Photo: Philippe Crochet).

ONE OF THE WORLD'S LONGEST SALT CAVES INSIDE AN AMAZING SALT DOME, INCLUDING THE HISTORICAL AND CULTURAL BACKGROUND.

This is one of the most unique salt caves in the world. It is 6.580m long and up to 40m wide. The discovered part of the cave is the longest salt cave known in the world. This Cave is considered the "key geosite" in Qeshm Island UNESCO Global Geopark. The remnants of historical sulphur and salt mining and trading are among the cultural values of this site.

Namakdan is also on the tentative list of World Heritage Sites. For these reasons, the cave is under strict protection and preservation strictly.

SITE 069

GEOLOGICAL PERIOD	Cambrian
LOCATION	Qeshm Island UNESCO Global Geopark / Hormozgan Province, Iran. 26° 37' 31" N 55° 31' 00" E
MAIN GEOLOGICAL INTEREST	Tectonics Geomorphology and active geological processes

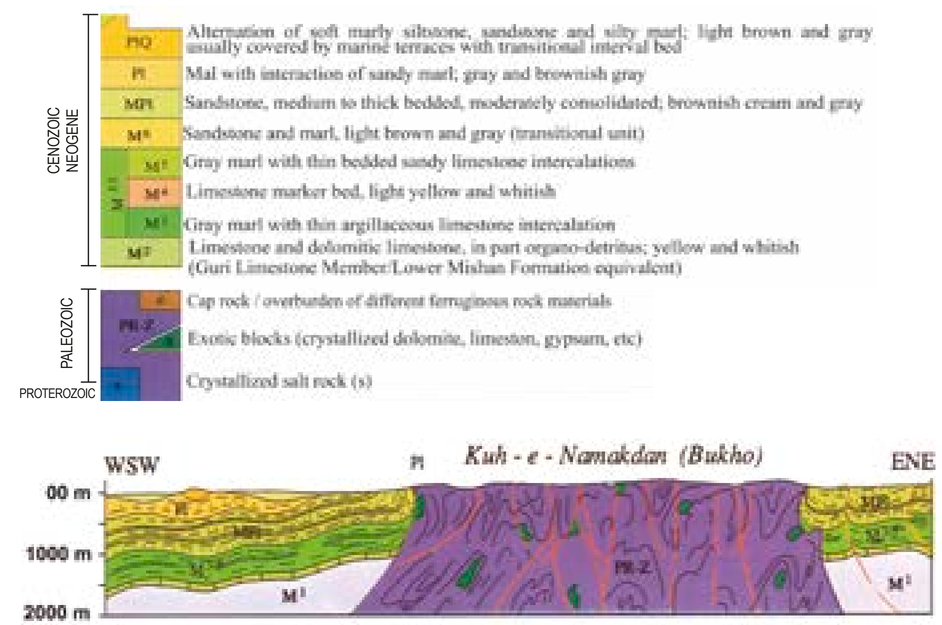
Namakdan Salt Cave in Salt Dome, 3N Entrance. (Photo: Phillippe Crochet).

Geological Description

The sedimentary succession of the Persian Gulf basin is warped and pierced by numerous salt diapirs of the basal Late Proterozoic Hormuz Series that was deposited in intracratonic basins formed during Late Proterozoic transtensional events after the Precambrian basement accretion. Namakdan salt diaper is among the most fascinating salt diapers (out of more than 250) in Iran. This diapir is composed of massive rock salt, anhydrite, fetid limestone, dark cherty dolomite, red sandstone, shale, and volcanic rocks. Marine, fluvial cave sediments and karst phenomena were studied and dated by 14C, U-series, and OSL methods to determine the evolution of the Namakdan diapir during the Holocene and the Last Glacial Period. Sea-level oscillations, the uplift rate of the diapir and its surroundings, and erosion are the main factors influencing the diapir morphology. Namakdan Salt Dome has a round shape with an area of about 38 km^2 on the surface. Based on new geophysical data, the root of the salt dome originates at a depth of 20 km. This dome is located in the western part of the Salakh Anticline, and it has affected the western nose of the anticline. During uplift igneous, metamorphic, and sedimentary rocks have come up along with the salt as exotic blocks. Some features such as radial faults and rim syncline have been formed around the Namakdan Salt Dome.

Scientific research and tradition

The salt karst of the southern east of Iran (Zagros Mountains) was surveyed in the Namak Project (means salt in Farsi) by Czech-Iranian researchers. The project has two phases and the first research phase was done in 1998-2000 and continued in the period 2005-2017. During this project, the salt dome of Qeshm Island was surveyed and mapped.



THE MOINE THRUST ZONE

UNITED KINGDOM

UNESCO Global Geopark

View of the thrust front at Beinn Aird da Loch with basement gneiss thrusted onto younger metasedimentary rocks along the Glencoul Thrust (see cross-section).

THE CLASSIC OROGENIC FRONT OF SIGNIFICANT IMPORTANCE IN BOTH MODERN AND HISTORICAL TECTONICS RESEARCH.

Debate on the origins of mountain belts raged in the 19th and early 20th centuries (e.g. Lapworth, 1885). An emerging recognition of thrust tectonics marked a monumental shift in understanding how our planet works, ultimately leading to the establishment of the theory of plate tectonics (e.g. Dewey and Kidd, 1974).

The Moine Thrust Zone is a key locality enabling this transition, and many fundamental concepts in structural geology, such as mylonites (Lapworth, 1885), were established there. Its excellent exposure and the beautiful Scottish Highlands setting continue to attract students, professionals and amateur geologists.

SITE 070

GEOLOGICAL PERIOD	Archaean - Devonian
LOCATION	North West Highlands Geopark, Scotland, UK. 58° 02' 02'' N 005° 04' 16'' W
MAIN GEOLOGICAL INTEREST	Tectonics History of geosciences Igneous and metamorphic petrology

Close-up of the thrust plane, exposed near the geological trail at Knockan Crag Visitor Centre.

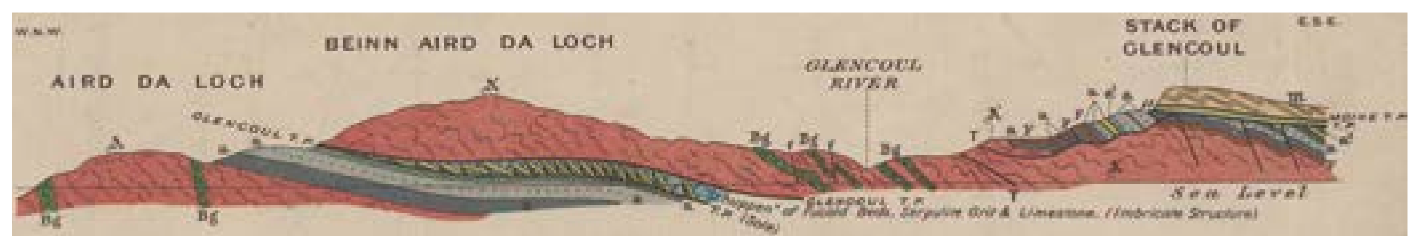
Geological Description

The Moine Thrust Zone in NW Scotland is over 200 km long, extending from Tongue area in the north to the Sleat Peninsula on the Isle of Skye (Murchison and Geikie, 1862; Peach *et al.*, 1907; Law *et al.*, 2010). The thrust zone is one of the best exposed orogenic fronts in the world, representing a geological history of >2 billion years. The Precambrian basement gneiss (up to c 3.0 Ga) are unconformably overlain by Meso- to Neoproterozoic (c. 900-1000 Ma) sandstone and conglomerate; these are in turn overlain by Cambro-Ordovician (c. 500 Ma) sandstone, shale and limestone. During the Silurian (c. 320 Ma), the Scandian phase of the Caledonian Orogeny thrusted the Precambrian gneiss onto the younger sedimentary rocks. This entire package is in turn overthrusted by the Neoproterozoic metasedimentary rocks of the Moine Supergroup. The thrust zone geometry and the deformation within the foreland sediments is very variable in 3D, ranging from single thrust surfaces to networks of splays, including up to 100 m-scale imbricate packages. Much of the thrust zone is within the NW Highlands Geopark, easily accessible at the Knockan Crag visitor centre, with other good viewpoints e.g. around Loch Glencoul, Kylesku.

Scientific research and tradition

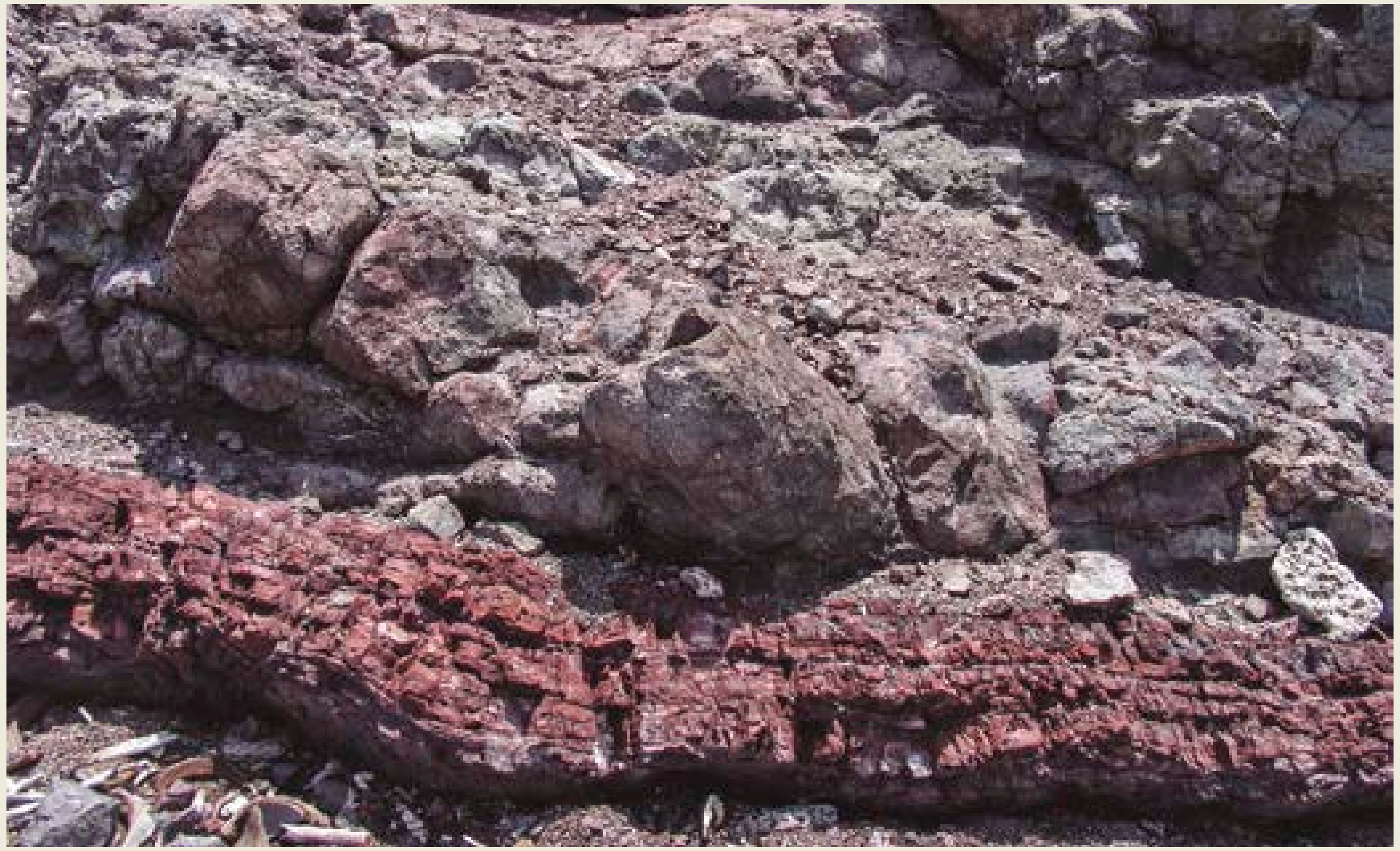
Research along the Moine Thrust Zone was sparked by 19th century debates on the origins of mountain belts, culminating in the seminal publication of Peach *et al.* (1907). The variety of structures along the thrust zone continues to inspire research, exemplified by Law *et al.* (2010).

Cross section along Loch Glencoul, published in the original 1923 Assynt District geological map.



UPPER JURASSIC OPHIOLITIC SEQUENCE IN LA DÉSIRADE ISLAND

FRANCE



Devant-y-Bon inlet cliffs with Tithonian ophiolitic sequence made of red radiolarian chert and pillow-lava, La Désirade Island (©BRGM).

THE OLDEST WITNESS OF BACK-ARC SPREADING RIDGE OF THE EASTERN CARIBBEAN PLATE.

La Désirade Island represents the unique exposure of the oldest rocks in the Lesser Antilles arc and eastern Caribbean plate and, thus, constitutes a compelling example of the geodynamic evolution of sedimentation, volcanism and tectonism in Caribbean. This geosite is a real open-air laboratory where international geoscientists carry out various research on ophiolitic rocks (radiolarian cherts and pillow-lava) and their deformation. Outcrops are a must-see for students and are part of the French national inventory of geoheritage with a national and international interest.

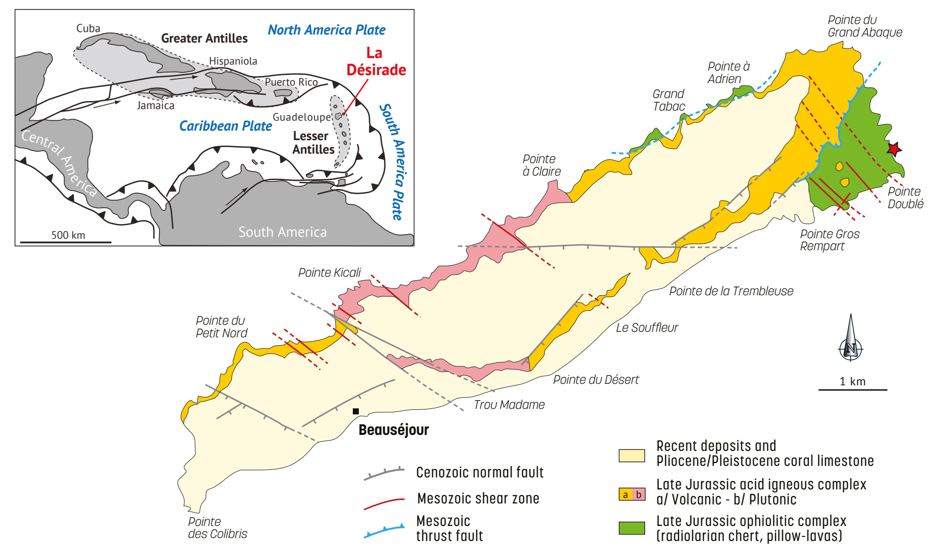
SITE 071

GEOLOGICAL PERIOD	Upper Jurassic (Tithonian)
LOCATION	La Désirade Island, Guadeloupe archipelago, Lesser Antilles, France. 16° 20' 11'' N 061° 00' 13'' W
MAIN GEOLOGICAL INTEREST	Tectonics

Outstanding outcrop of Late Jurassic pillow-lava flows, oldest witness of back-arc spreading ridge of the eastern Caribbean plate (©BRGM).

Geological Description

Rocks consist in an Upper Jurassic ophiolitic complex with basaltic pillow-lava flows and interbedded radiolarites, well visible in the Devant-y-Bon inlet cliffs, along the northeastern coast. Red radiolarian chert layers are linked to an origin in the Pacific Ocean and were deposited during Tithonian, coevally to outstanding basaltic pillow-lavas emplacement (Mattinson *et al.*, 1973, 2008; Neill *et al.*, 2010). This sequence represents a part of the exhumed base of the Cenozoic to present-day active Lesser Antilles volcanic arc. The interpretation of the ophiolitic complex is debated, and authors propose an ophiolite-type oceanic crust or a back-arc spreading ridge model, the latter being overwhelmingly favored. The geosite is also a perfect place to observe important tectonics (faults, folds and thrusts) allowing the reconstruction of the geodynamics evolution of the Caribbean plate (Corsini *et al.*, 2011). Indeed, La Désirade Island is a key-site, which recorded the subduction polarity reversal (between Caribbean, North and South America plates), from eastward to westward during the Late Jurassic to Early Cretaceous. Upper Pleistocene - Holocene coral limestone overlies the ophiolite complex, reflecting the recent uplift of the island and the sea-level variations during the Quaternary Period (Léticée *et al.*, 2019).



Geological map of La Désirade Island and location of the Global Geosite. Modified after Westercamp (1980) and Corsini et al. (2011). Red star: IUGS-Geological Heritage Site.

Scientific research and tradition

Pioneering studies date back to 1960s. Geologists demonstrated La Désirade Island is a crucial element for understanding the proto Pacific-Caribbean margin and Caribbean plate geodynamics and the current tectonic setting of the Lesser Antilles arc through numerous scientific papers. This geosite benefits from a National Natural Reserve label since 2011.

THE SOUTH TIBETAN DETACHMENT SYSTEM IN THE RONGBUK VALLEY

CHINA

The STDS (White arrow just above the withish rocks corresponding to deformed Miocene leucogranite) dipping to the North (top-down-to-the North sense of shear), Rongbuk valley. Upper part of the photo: Tethyan Sedimentary rocks; Lower part of the photo: high-grade metamorphic rocks belonging to the Greater Himalaya.

THE PLACE WHERE THE HIGHEST REGIONAL SCALE LOW-ANGLE NORMAL FAULT OF THE EARTH CAN BE DIRECTLY OBSERVED.

The discovery during the 1980's of orogen-perpendicular extension in the Himalayas along the South Tibetan Detachment System (STDS) coeval with compression revolutionized models of orogenic belts (Burg *et al.*, 1984) and improved considerably understanding of their tectonic-metamorphic evolution. The exhumation of deeply seated metamorphic rocks in the core of the Himalayan belt was made possibly by displacement on the STDS. Rongbuk Valley is of scientific importance because in this location the complex STDS architecture, with brittle and ductile branches, was described and formalized (Carosi *et al.*, 1998). Moreover, here the lower ductile structure was identified as the major extensional feature.

SITE 072

GEOLOGICAL PERIOD	Miocene
LOCATION	Rongbuk Valley, southern Tibet. China. 28° 16' 02" N 086° 48' 36" E
MAIN GEOLOGICAL INTEREST	Tectonics

The STDS getting in contact low-grade Ordovician (meta-) limestone of the Tethyan strata (upper part) with sillimanite-bearing gneiss of the Greater Himalayan (lower part).

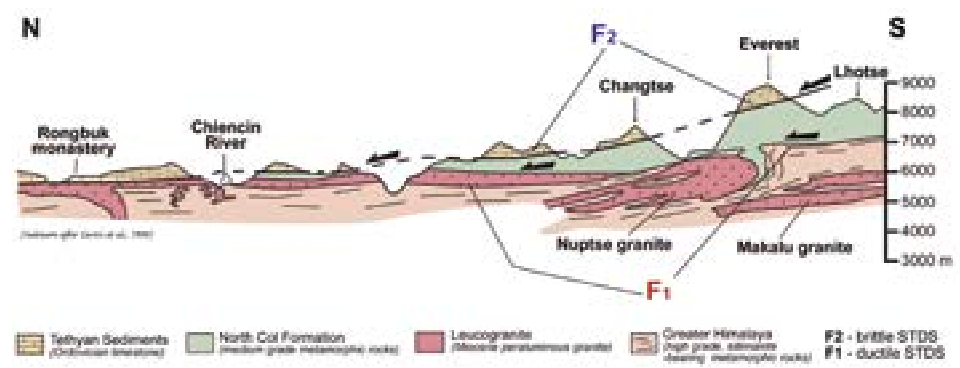
Geological Description

The recognition of syn-collisional extensional structures, referred as the South Tibetan Detachment System (STDS), in the Himalaya deeply influenced Plate Tectonics since the 1980's. STDS is a set of orogen-parallel normal-sense faults and shear zones, traced along the entire strike length (c. 2000 km) of the Himalaya. This structure, exposed on the Everest summit, is the highest fault on the earth. Along the Rongbuk valley (S Tibet), the STDS is easily accessible and nicely exposed, where a complex architecture is documented by the occurrence of two major fault zones showing top-to-NE normal kinematics. The lower one is a wide ductile shear zone, more than 1 km thick, juxtaposing medium grade rocks (North Col Formation, NCF) with high grade metamorphic rocks of the Greater Himalayan Sequence. More than 5 km of vertical displacement is accommodated along this ductile branch. The upper fault is instead a low-angle brittle fault zone characterized by a metric thick cataclasites, accommodating at least 1600 m of vertical displacement. Along this brittle structure slightly metamorphosed Ordovician limestone is juxtaposed against the NCF. In this place, it was demonstrated that the lower ductile shear must be considered the main extensional feature of the STDS.

Scientific research and tradition

Because of its importance in understanding the tectonic evolution of the Himalaya, the The South Tibetan Detachment System in Rongbuk Valley has been subject to many investigations over the last 35 years. The initial description is that of Burg *et al.* (1984). Subsequent investigations are those of Burchfiel *et al.*, 1992; Carosi *et al.*, 1998; Searle *et al.*, 2003; Corthouts *et al.*, 2016; and Waters *et al.*, 2019.

Cross-section showing the STDS along the Rongbuk valley from Mt Everest to the Rongbuk monastery. The complex STDS architecture consisting of a brittle upper fault (F2) and a lower km-tick ductile shear zone (F1) is observed (modified from Carosi et al., 1998).



NORTHERN SNAKE RANGE METAMORPHIC CORE COMPLEX

USA

View north of the Northern Snake Range. Stretched lower plate quartzite and schist units (subhoriontal) visible in Hendry's Creek, SE flank of the Range. High peak is Mt. Moriah.

A CENOZOIC EXTENSIONAL METAMORPHIC CORE COMPLEX WHERE NEOPROTEROZOIC-LOWER PALEOZOIC STRATA ARE TECTONICALLY THINNED TO AS MUCH AS ~10% OF THEIR ORIGINAL THICKNESSES.

The definition of mylonites was closely linked to their discovery and study in extensional metamorphic core complexes of the Cordillera. The Northern Snake Range is distinguished from other metamorphic core complexes because of its remarkable stratigraphy of units in both upper and lower plates allowing for semi-quantitative measures of strain (Miller *et al.*, 1983). Lower plate rocks record an extraordinary strain gradient from ~165% to ~ 650% extension from west to east with an associated progression in quartz micro- and mesoscopic structures and petrofabrics from pure to simple shear deformation (see cross-section) (Lee *et al.*, 1987; 2017).

SITE 073

GEOLOGICAL PERIOD	Cenozoic, Oligocene to Miocene
LOCATION	East Central Nevada, USA. 39° 12' 30" N 114° 04' 33" W
MAIN GEOLOGICAL INTEREST	Tectonics

Flaggy quartz mylonite in Precambrian-Cambr an Prospect Mountain Quartzite, Hendry's Creek, exhibiting strong E-W trending stretching lineations. (Photo was a gift to authors from Richard Hatch, quarry owner, in 1982).

Geological Description

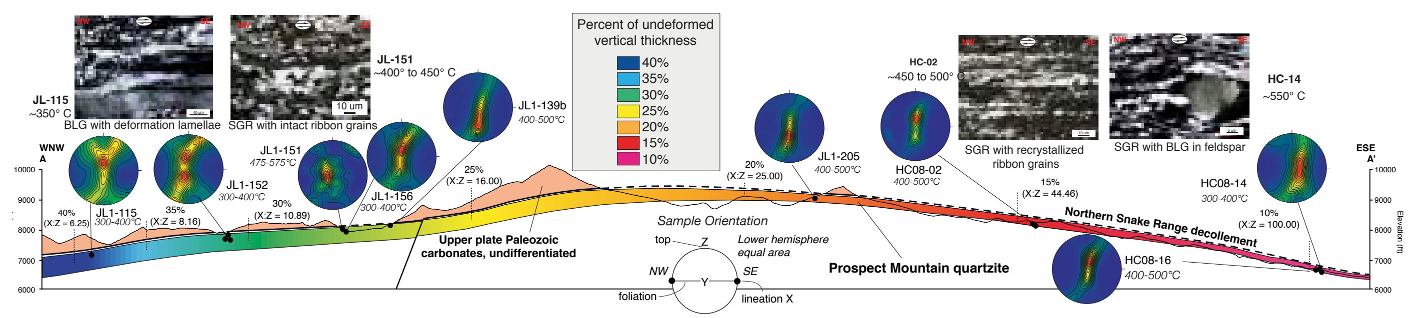
Metamorphic core complexes and their detachment faults were enigmatic structures interpreted in pre-plate tectonic times as basal detachments for gravitationally driven thrust faults exposed to the east in the Mesozoic Sevier fold-thrust belt. Recognition that Cenozoic rocks were involved in detachment faulting in the 1970s was key to their interpretation as younger extensional fault systems.

Rock units near Hendry's Creek in the Northern Snake Range include Precambrian to Cambrian quartzite and schist (lower plate) and highly faulted Cambrian to Permian strata in an upper plate position above the Snake Range detachment (SRD) (cross-section below). Ductile deformation produced flaggy lineated quartz mylonites in the lower plate (photo above); this deformation is kinematically coordinated to upper plate extension by faulting (Miller *et al.*, 1983; Lee *et al.*, 1987). U-Pb zircon ages of dikes bracket lower plate strain to between late Eocene and early Miocene (Lee *et al.*, 2017). Miocene strata are cut and tilted by upper plate faults along the flanks of the range (Miller *et al.*, 1999) and apatite fission track data indicate likely continued mylonitization and rapid cooling of lower plate rocks to near surface conditions in the Miocene, ca. 15-17 Ma (Miller *et al.*, 1999).

Scientific research and tradition

The Northern Snake Range provides a natural laboratory for modern studies on the tectonic processes that form metamorphic core complexes and the deformational processes that form mylonites. Geologic mapping and work to date has provided the foundation for decades of continuing research and teaching efforts; yet many unresolved questions remain.

Cross-section showing strain and contoured quartz C-axes for select samples (Lee et al., 1987; 2017; author's data).



NOJIMA FAULT

JAPAN

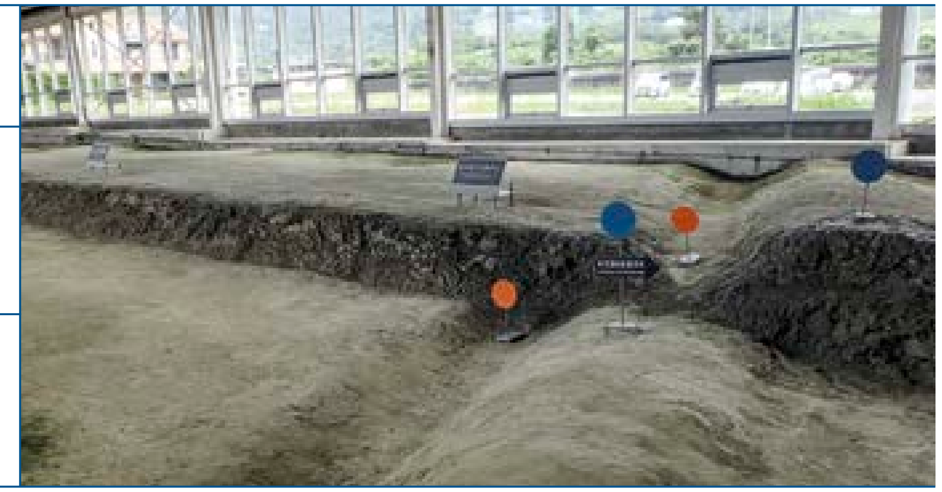
Northeastern section of the earthquake fault trench inside the Nojima Fault Preservation Pavilion in the Hokudan Earthquake Memorial Park. (Shigehiro Kato)

THE FAULT THAT CAUSED THE 1995 KOBE EARTHQUAKE.

"Earthquake fault" is a surface displacement that is important evidence of both the earthquake and the resultant disaster. The preservation of earthquake faults is extremely rare because they are soon flattened by landowners to recover their livelihoods in addition to the difficulty in conservation techniques and management. Fortunately, immediately after the Kobe Earthquake, the Nojima Fault was preserved for educational and research purposes, and the topography and damaged condition of this fault were preserved in the best way possible (Katoh, 2020). As in Taiwan, the technique and management methods developed here have become the standard for fault conservation.

SITE 074

GEOLOGICAL PERIOD	Quaternary Modern (1995)
LOCATION	Awaji City, Hyogo Prefecture, Japan 34° 32' 60" N 134° 56' 16" E
MAIN GEOLOGICAL INTEREST	Tectonics Geomorphology and active geological processes



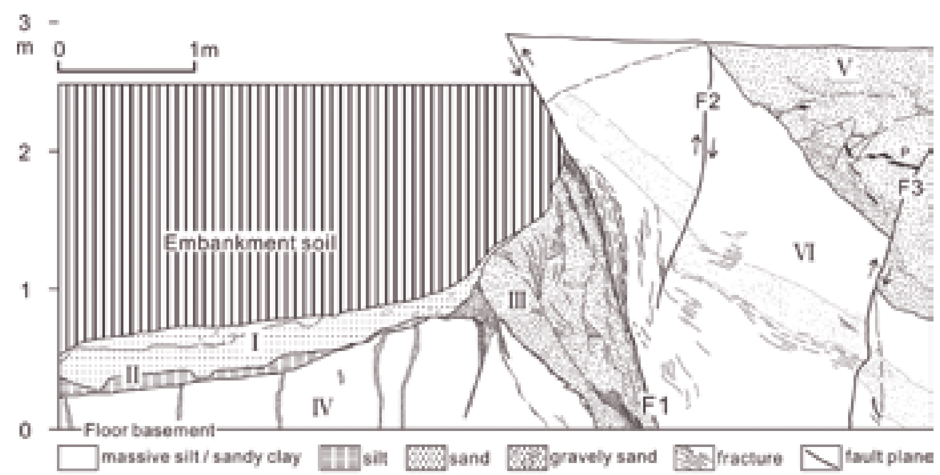
Right-lateral displacement of the earthquake fault in the Nojima Fault Preservation Pavilion. (Shigehiro Kato).

Geological Description

The Nojima Fault is an active fault that generated the "Hyogo-ken Nambu Earthquake" (Kobe Earthquake) (M7.3), which hit the southern part of Hyogo Prefecture, central Japan, on January 17, 1995, killing approximately 6,400 people (Ando *et al.,* 2001; Awata *et al.,* 1996). The fault extends northeastward, intermittently traceable on the surface, for a total length of approximately 9 km from Hokudan to Ichinomiya towns (both now Awaji City) in the northern part of Awaji Island. This is a reverse fault with a right-lateral strike-slip component, showing the maximum horizontal and vertical displacements of 2.1 and 1.2 m, respectively (Lin and Uda, 1996). The Nojima Fault is typically exposed for approximately 185-m long in Hokudan Town, with approximately four-fifths of it preserved in the building, Nojima Fault Preservation Pavilion of Awaji City, which is open to the public. A trench inside the building exhibits the cross section of the fault, which has a vertical displacement of 0.2–0.5 m that uplifted the southeast side with a right-lateral displacement of 0.7–1.5 m (Takemura *et al.,* 1998). The main fault and parallel-extending bifurcated fault with destroyed paved roads, displaced ridges, drainage channels, and forest hedges are preserved.

Scientific research and tradition

Rupture propagation along the Nojima Fault is discussed from detailed along-fault distributions of vertical and horizontal displacements. Based on trenching surveys and analysis of nearby drilling cores, the fault was reactivated many times during the late Quaternary with a recurrence interval of approximately 2000 years (Lin and Nishiwaki, 2019).



I and II: Late Pleistocene slope deposits, III: Liquefied sand, IV–VI: Early Pleistocene Osaka Group, F1: Earthquake fault plane and fracture zone, F2 and F3: Secondary fault planes. P: Peaty clay layer.

Sketch of the northeastern section of the earthquake trench inside the preservation pavilion.

7

MINERALOGY

SITE 075 - SITE 077

Mineralogy primarily refers to the study of minerals that formed on Earth and delivered from other planets as meteorites. It is one of the oldest branches of Science. On Earth, minerals are essentially formed in sedimentary, igneous and metamorphic environments, and about 6000 species are formally recognized by the International Mineralogical Association (IMA). Annually more than 100 new species are still being discovered. Today mineralogy not only includes classical studies on geochemical, crystallographical, petrological and geochronological topics, it is closely linked to material and environmental sciences, geology, geophysics, physics and chemistry and even archaeology. Thus it developed into a global science on various questions concerning the entire Earth system.

Minerals are also intimately linked to the development of humanity and social progress. Their possession and use have resulted in many conflicts and thus have changed the course of history. Undoubtedly the knowledge of large mineral deposits and the exploration even in remote areas such as the ocean floor have created an enormous technological innovation that was achieved in the XXI century. Knowing and recognizing mineral deposits of international relevance and their ecological and considerate exploitation is a major duty of the IUGS. Minerals are the key to geological sciences, and their research opens new frontiers of knowledge from the sub-atomic level to their physical and chemical properties. They allow us to use them in the industries where their applications are innumerable from food, health, energy, construction, beauty, agriculture, aerospace to jewelry, among many others. In addition mineralogy allows us to unravel the composition of terrestrial rocks, to characterize endogenous and exogenous processes, to date geological events and to build robust numerical chronologies on which to anchor the Earth's history. For this reason, mineralogy is of vital relevance for other disciplines in geoscience.

With respect to our geological heritage it is necessary to make an effort to include more unique mineralogical sites worldwide, which are known for their outstanding scientific value. In this first stage, three unique mineral deposits have been declared as IUGS Geological Heritage Sites. These are (1) the Los Catalanes Gemological District in Uruguay well known for its world-class amethyst and agate occurrences, (2) the Tsumeb ore deposit in Namibia, a polymetallic (Copper-Lead-Arsenic-Zinc-Silver-Germanium-Molybdenum) deposit that contains one of the most diverse examples of mineralogical parageneses observed within a single mineral deposit, and (3) the giant Almadén syncline ore deposit with occurences of cinnabar and mercury, which is hosted in the Lower Silurian Criadero Quartzite, Spain, and that represents the largest mercury geochemical cluster on Earth, having produced one third of the total world mercury.

Hans-Peter Schertl
Ruhr-University Bochum. Germany.
President, International Mineralogical Assocciation (IMA).
IUGS Geological Heritage Sites voting member.

Juana Vegas
Geological Survey of Spain, CSIC.
IUGS Geological Heritage Sites voting member.


The giant mercury deposit of the Almadén syncline
SPAIN
Deposits of Amethyst of Los Catalanes Gemological District
URUGUAY
Tsumeb Ore Deposit
NAMIBIA

TSUMEB ORE DEPOSIT
NAMIBIA

Tsumeb Mine 1936. From left to right: Old Shaft No.1 Headframe, Steigerhaus, New Shaft No. 1 Headframe, Powerplant Hall and Ore processing.

ONE OF THE RICHEST ORE DEPOSITS WITH RESPECT TO VARIETY, RARITY AND AESTHETICS OF MINERALS IN THE WORLD.

The Tsumeb polymetallic (Copper-Lead-Arsenic-Zinc-Silver-Germanium-Molybdenum) deposit contains one of the most diverse examples of mineralogical paragenesis observed within a single mineral deposit (Keller, 1977). The unique hydrothermal processes provided oxidizing waters to lower parts of the deposit causing the formation of a variety of minerals with increasing depth of the ore body. This provided special conditions for the development of secondary minerals of extreme beauty with respect to form and habit (Bowell and Mocke, 2018). In addition, the detection and occurrence of extremely rare elements in the deposit like Germanium and Gallium led to the development of extremely rare minerals.

SITE 075

GEOLOGICAL PERIOD	Palaeozoic Era, Early Cambrian Period
LOCATION	Otjikoto Region, Namibia. 19° 13' 00" S 017° 42' 00" E
MAIN GEOLOGICAL INTEREST	Mineralogy History of geosciences

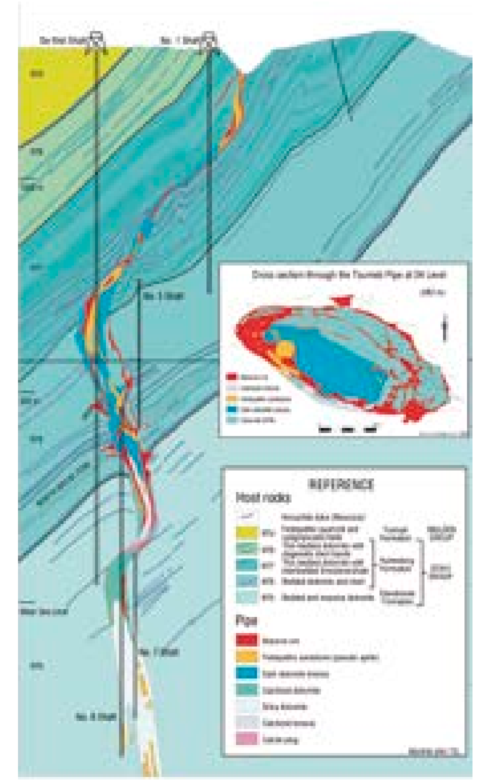
Mottramite, Calcite and Duftite, an example of the many minerals of the Tsumeb Polymetallic deposit.

Geological Description

The Tsumeb ore deposit lies in the upper part of the Neoproterozoic Otavi Group that comprises limestone and dolomite. This polymetallic Tsumeb-type deposit has an age of 530 ± 11 Ma (Kamona and Günzel, 2007) and takes on the structure of a pipe that is infilled by feldspar-rich sandstone and sandstone breccia of the overlying Mulden Group, which have undergone various degrees of hydrothermal alteration fueled by karstification processes (Lombaard *et al.*, 1986). The pipe has approximate dimensions of 120 by 15 m in cross section. It is steeply dipping and extends from the surface to a depth of approximately 1 700 m. It hosts a polymetallic (Copper-Lead-Arsenic-Zinc-Silver-Germanium-Molybdenum) deposit with three oxidation zones, which contain a great diversity of ore minerals of lead, copper, zinc, silver, arsenic, antimony, cadmium, cobalt, germanium, gallium, gold, iron, mercury, molybdenum, nickel, tin, vanadium and tungsten. Three vertical zones of oxidation in the mineralised pipe structure enabled the development of extensive assemblages of secondary mineral species such as tsumebite, arsentsumebite, schneiderhöhnite, ludlockite and leiteite. The deposit hosts approximately 489 minerals of which 72 minerals were first described from the deposit and more than 25 minerals are known only from the Tsumeb ore deposit.

Scientific research and tradition

In 1906 Otto Schneider of the Berlin Mining Academy detected the mineral Otavite. Hans Schneiderhöhn of the University of Freiburg investigated the ore minerals. Hugo Strunz from the Berlin Institute of Technology, Bruno Geier and Gerhard Söhnge from Tsumeb Corporation Limited described the rare minerals stottite and söhngeite.



Longitudinal and cross sections through the Tsumeb ore pipe after Lombaard et al. 1986 and from the original sketch by P. G. Soehnge in the 1960s, used with permission from the Geological Survey of Namibia. The red indicates massive ore, yellow is feldspathic sandstone, light blue is dark dolomite breccia, aqua represents calcitized dolomite, white is silica dolomite, light purple is calcitized breccia and pink is a calcite plug.

THE GIANT MERCURY DEPOSIT OF THE ALMADÉN SYNCLINE
SPAIN

UNESCO World Heritage Site

Cinnabar crystals on quartz from Almadén. (Photo: Luis Carcavilla Urquí).

THE LARGEST KNOWN MERCURY DEPOSIT IN THE EARTH AND WITH A LONGEST PRODUCTIVE HISTORY DATING BACK TO THE 3RD CENTURY BCE.

The exceptionality of this ore deposit lies in the unique geological characteristics that led to the high concentrations and large accumulations of mercury, which constitutes its own metallogenetic model (Saupé, 1990; Ortega Gironés and Hernández Sobrino, 1992; Palero-Fernández *et al.*, 2015).
The mining and metallurgical complex, together with part of the rest of the museum facilities, currently constitute the Almaden Mining Park, which is open to the public since 2008. The park includes a Visitor Center, the Mining Interpretation Center, and the Mercury Museum. It offers tours in real tunnels in the 16th-century inner mine. Almadén is included into the World Heritage List.

SITE 076

GEOLOGICAL PERIOD	Upper Ordovician - Lower Silurian
LOCATION	Castilla-La Mancha, Spain. 38° 46' 30" N 004° 50' 30" W
MAIN GEOLOGICAL INTEREST	Mineralogy History of geosciences

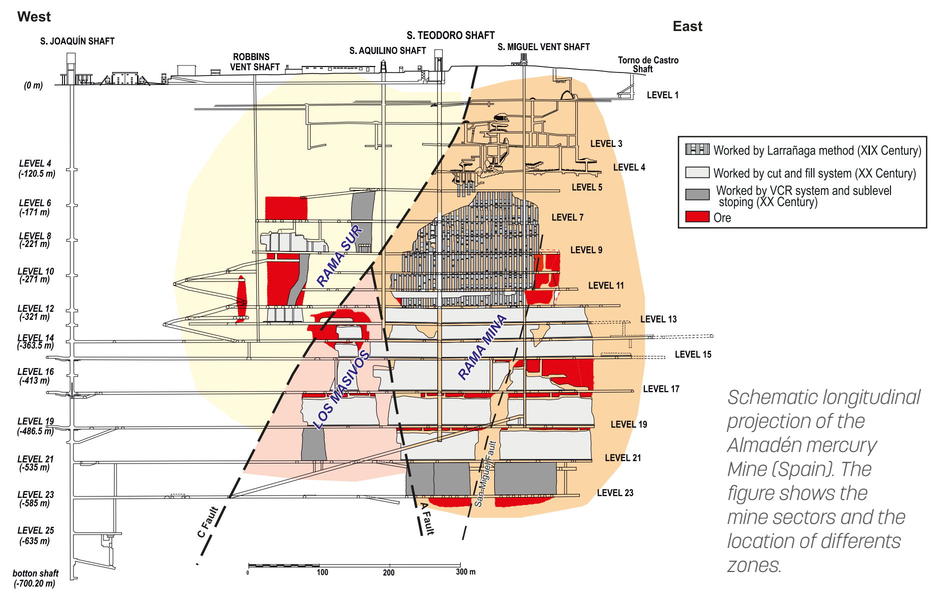
General view of the town of Almadén, Spain, in the foreground are the mercury mining facilities located to the west of the town and in which the main shaft and their metallurgical fence stand out.

Geological Description

The giant Almadén mercury deposit is hosted in the Lower Silurian Criadero Quartzite; in turn this ore-bearing rock unit is cross-cut by the so-called Frailesca unit, a diatreme body of basaltic composition. The Almadén district is the largest mercury geochemical cluster on Earth, having produced one third of the total world mercury. It is a stratabound mineral deposit and is composed of three mineralized levels in the "Cuarcita del Criadero". Formation that correlates with the Upper Ordovician to lower Silurian. The Silurian intraplate alkaline volcanism developed in submarine conditions, which triggered widespread hydrothermal activity resulting in Hg ore formation and pervasive alteration to carbonates.

The deposit consists of impregnated and infilled joints with cinnabar in siliceous sandstone beds. It appears to be linked to the presence of explosive volcanic tuffs (Roca Frailesca). It is located on the southern limb of the Almadén syncline where it appears in a vertical position and with an E-W strike. In addition, the good outcrops of the mine tunnels allow excellent observations of the sedimentology, volcanic petrology, and Variscan tectonic structures, and are classic sites for fossil occurrences, particularly Silurian graptolites.

The Almaden deposit has mined out about 7,000,000 flasks (= 241.500 Tm) with an average grade of 3.5% Hg. This is about a third part of all the mercury consumed by humanity.



Schematic longitudinal projection of the Almadén mercury Mine (Spain). The figure shows the mine sectors and the location of differents zones.

Scientific research and tradition

There are many studies of the Almadén ore deposit dating back in time. The mining history began some 2000 years ago when Romans use cinnabar as a vermilion red pigment (Hernández *et al.*, 1999). When the arabs invaded, they gave this locality its name of Almaden. However, the 'modern' history of Almadén and mercury begins in 1555 when Bartolomé de Medina discovered the use of mercury in silver processing (Higueras *et al.*, 2013).

DEPOSITS OF AMETHYSTS OF LOS CATALANES GEMOLOGICAL DISTRICT

URUGUAY

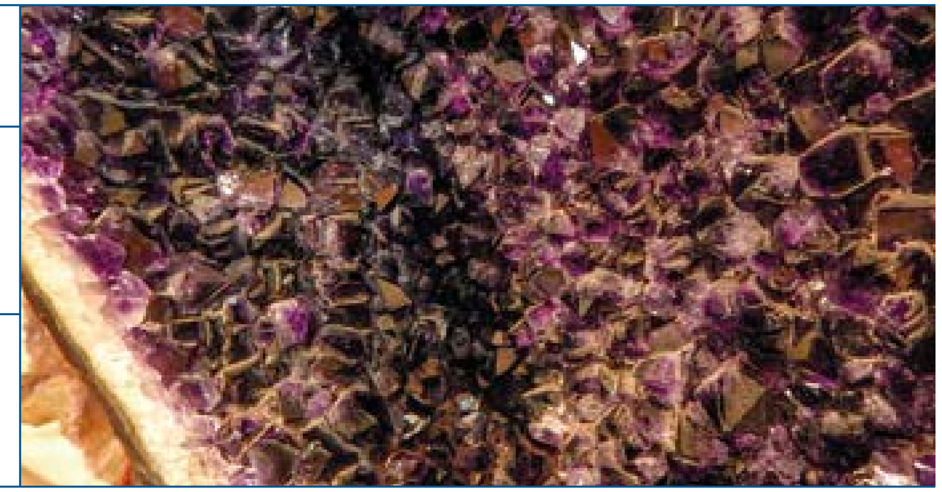
Amethyst-filled giant geodes discovered in an underground mine in Los Catalanes Gemological District. Shiny crystals of amethyst, in contrast to the opaque basalt that surrounds them, create an arrangement reminiscent of a starry night. (Photo: Santiago Guerrero).

THE SITE OF WORLD-CLASS AMETHYST DEPOSITS, WHERE THE LARGEST AMETHYST-FILLED GIANT GEODES WERE EVER FOUND.

Amethyst deposits in Uruguay are unique due to the concentration of mega-geodes, their enormous reserves, their gemstone quality and variations in size and forms, and by the abundance of giant geodes. Although amethysts occur in very different geological environments, the most important amethyst mineralization and mining are located in the areas of southern Brazil and northern Uruguay. Although geodic cavities filled with quartz are abundance in the Pararna basalt, the best amethyst deposits are in the lower-middle basin of the Catalan Grande stream. Achieving a understanding of the genesis of this mineralization and the origin of its intense purple color have motivated national and international investigations.

SITE 077

GEOLOGICAL PERIOD	Early Cretaceous
LOCATION	Artigas Department, northern Uruguay 30° 47' 34" S 056° 16' 13" W
MAIN GEOLOGICAL INTEREST	Mineralogy



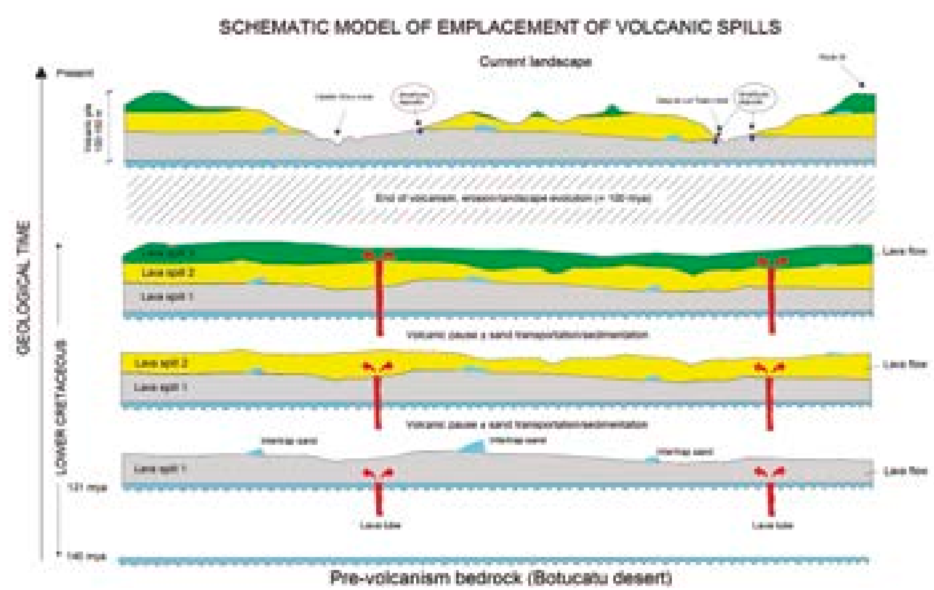
Amethyst crystals in detail grown inside a geode in basalt.

Geological Description

The amethyst-filled geodic cavities are housed in the Paraná flood basalt that comprises the large igneous province of Paraná-Etendeka traps. With an area of 1.5 million square kilometers and a volume of more than 2 million cubic kilometers, it is one of the largest igneous provinces in the world. The effusive magmatic event was associated with the break up of the supercontinent Gondwana and the opening of the South Atlantic Ocean during the Early Cretaceous (138-128 Mya). The extrusion of lava through multiple fissures occured in pulses (more than 25), which formed a volcanic pile more than 1 km thick. The basalt is composed of a succession of tabular bodies called spills or lava flows. Three different types of spills were identified: pahoehoe, aa and massive lava flows. The cylindrical, prolate geodes in pahoehoe lavas are up to 4 m tall, whereas the more irregular-shaped, oblate geodes in aa lavas are up to 5 m wide and weigh up to 20 tons. The understanding of the processes related to the generation of the geodes in the volcanic rocks of the large continental Paraná volcanic province is a major issue in volcanic and ore deposit geology.

Scientific research and tradition

Amethyst deposits along the Catalan stream have been known since 1750, during the period of the Spanish rule. Numerous scientific works have been carried out on the site in the last two decades. In 2007, the Geological Survey of Uruguay published the first detailed study in the area, defining The Catalanes Gemological District. This is a region with a mining tradition of more than a century. Currently, several mining companies employing hundreds of workers are producing very high quality amethysts, and some abandoned mines support a geotouristic entrepreneurship.



8

GEOMORPHOLOGY AND ACTIVE GEOLOGICAL PROCESSES

SITE 078 - SITE 099

Mauro Soldati
Università degli Studi di Modena e Reggio Emilia. Italy.
President, International Association of Geomorphologists (IAG).
IUGS Geological Heritage Sites voting member.

Margaret Brocx
Murdoch University. Australia.
IUGS Geological Heritage Sites voting member.

Geomorphology focuses on the study of landforms and their evolution as a result of Earth surface processes. The origin and development of landforms can be related to endogenous and exogenous processes. Biogenic activity may also play an important role in shaping landforms, as well as human action. Landforms are generally classified according to their genesis, geometry, the geomorphic factors that control them, and the climate system in which they originate and develop.

The origin and evolution of landforms can be related to ongoing processes acting in a region. However, relict, or inherited landforms – shaped under environmental conditions or tectonic regimes different from present ones – often characterize landscapes making them extremely spectacular and attractive for non-specialists. In this respect, it should be emphasized that Geomorphology is also defined as the Science of Scenery and can significantly contribute to geotourism and geoheritage study initiatives.

Geomorphology developed as a branch of Physical Geography and has its origin in the 19th century being the first studies focused primarily of fluvial processes and landforms. An important contribution to the understanding the changes occurring on the Earth surface was provided by William Morris Davis who introduced the 'cycle of erosion' in 1899, which describes mountain denudation through a sequence of stages resulting in peneplanation, and eventually followed relief 'rejuvenation' caused by uplift. This was the first attempt to look at landscapes with a process-based dynamic approach and, besides any criticism inherent in the theory, it became a milestone for future generations of geomorphologists.

In the past few decades, geomorphological studies have increasingly shown societal implications including (i) the analysis and prediction of frequency and magnitude of geomorphic processes, which are of paramount importance in the context of climate change; (ii) the assessment of impacts of the ongoing global environmental change and human activities on landscapes and Earth surface processes, with special emphasis on geohazards and geoheritage.

This chapter shows an amazing collection of very diverse geosites which reflect the powerful action of geological processes and geomorphic agents that generated and controlled the development of outstanding landforms at different temporal and spatial scales. Highly scenic landforms, like the Uluru inselberg (Australia) and the Sugar Loaf monolith of Rio de Janeiro (Brazil) reflect the importance of rock control on landscape evolution. The same applies to the subaerial Shilin Karst (China), the Bemaraha Tsingy (Madagascar), the underground Slovenia Classical Karst, and the Sac Actun cave system (Mexico). As a result of intense river incision and differential erosion, highly scenic landscapes can be observed at the Grand Canyon (USA), Iguazú (Argentina/Brazil), and the Victoria waterfalls (Zambia/Zimbabwe). The Namib Sand Sea (Namibia) and the Lut Desert (Iran) are undoubtedly geosites of world importance in showing the long-lasting effects of aeolian processes in arid areas. Other geosites included in this chapter are linked to the combined action of other geomorphic agents, such as ice (Perito Moreno glacier, Argentina; Engadine rock glaciers, Switzerland), gravity (Vajont landslide, Italy; La Puerta del Diablo, El Salvador), and running waters (Okavango Delta, Botswana). The effects of chemical processes are demonstrated through examples of intriguing geomorphological features in Chile, Cuba and Turkey. Finally, landforms related to catastrophic glacial outburst floods are exemplified by the Channeled Scabland (USA) and the Jutulhogget Canyon (Norway).


Jutulhogget Canyon
NORWAY
Rockglaciers of the Engadine
SWITZERLAND
Škocjan Caves in the Classical Karst
SLOVENIA
Bilutu megadunes and lakes in the Badain Jaran Desert
CHINA
Dry Falls and the Channeled Scabland
USA
Vajont landslide
ITALY
Yardang (Kalut) in the Lut Desert
IRAN
Sac Actun Underwater Cave System
MEXICO
The Grand Canyon
USA
Pamukkale Travertines
TURKEY
Shilin Karst
CHINA
Quaternary interglacial coral and marine uplifted terraces of Maisí
CUBA
La Puerta del Diablo inverted relief
EL SALVADOR
Mosi-oa-Tunya Victoria Falls
ZAMBIA
ZIMBABWE
The Sugar Loaf monolith of Rio de Janeiro
BRAZIL
Puquios of the Llamara salt flat
CHILE
Tsingy of Bemaraha
MADAGASCAR
Uluru inselberg
AUSTRALIA
Iguazú / Iguaçu waterfalls
ARGENTINA
BRAZIL
Namib Sand Sea
NAMIBIA
The Okavango Delta
BOTSWANA
Perito Moreno Glacier
ARGENTINA

ULURU INSELBERG
AUSTRALIA

UNESCO World Heritage Site

Massive sandstone inselberg (a prominent isolated residual knob that rises abruptly from and surrounded by extensive flat lowlands). (Image credit: Andy Selinger / Alamy Stock Photo).

THE MOST WELL-KNOWN MASSIVE SANDSTONE MONOLITH/INSELBERG IN THE WORLD CONSTITUTING A FUNDAMENTAL LANDFORM IN THE TRADITIONAL BELIEF OF ABORIGINAL PEOPLE.

Uluru, as part of the Uluru-Kata-Tjuta National Park, was added to the UNESCO World Heritage List in 1987. Uluru is one of the largest and best known inselbergs in the world. Unlike many other inselbergs that are erosionally developed from cratons and composed of granite or gneiss or both, Uluru is composed of vertically dipping bedded arkose (feldspathic sandstone). In 1994, UNESCO recognised the cultural landscape and the unique relationship between the natural environment and the belief system of Anangu people (one of the oldest human societies on Earth). Uluru is globally unique because of its size and shape, combined with its composition.

SITE 078

GEOLOGICAL PERIOD	Precambrian (Ediacaran)
LOCATION	Uluru-Kata Tjuta National Park World Heritage site. Northern Australia. 25° 20' 40" S 131° 02' 08" E
MAIN GEOLOGICAL INTEREST	Geomorphology and active geological processes

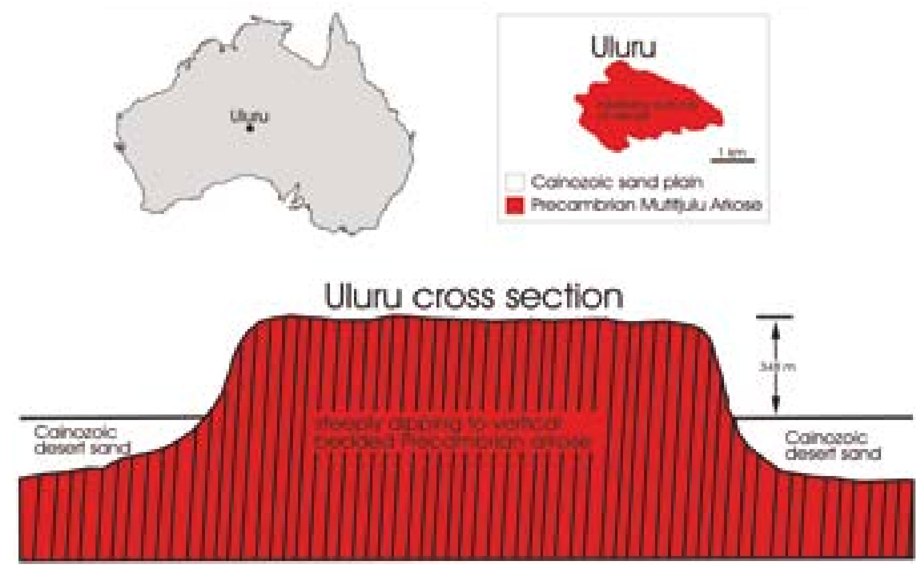
Oblique aerial view of Uluru showing prominent vertically dipping strata. (Image credit: Nature Picture Library / Alamy Stock Photo).

Geological Description

Uluru (Pitjantjatjara: Uluru, also known as Ayers Rock (Sweet and Crick, 1994; Twidale and Bourne, 2012), is a large sandstone formation in the centre of Australia. It is in the southern part of the arid Northern Territory. Uluru, a massive inselberg or 'island mountain' of bedded sandstone referred to the Mutitjulu Arkose, is a prominent isolated residual knob that rises abruptly from and surrounded by extensive flat lowlands. The remarkable feature of Uluru is its lack of jointing and parting at bedding surfaces, leading to the lack of scree slopes and soil (Figures 2 and 3). Uluru is dominantly composed of coarse-grained arkose (a sandstone characterised by abundant feldspar) and some conglomerate, and is Precambrian, some 550 million years old. The minerals present suggest derivation predominantly from a granite source. Weathering of iron-bearing minerals gives the outer surface layer of rock a red-brown rusty colour. Sedimentary features within the sandstone include cross-bedding and ripples, analysis of which indicates deposition from broad shallow high energy fluvial channels and sheet flooding (Young *et al.,* 2002).

Scientific research and tradition

From an Aboriginal perspective, Uluru was created at the beginning of time by spirit people (Isaacs, 1980). Early investigators interpreted Uluru as the residual after long-distance scarp retreat or scouring by the elements. More recent investigators, largely by Twidale, found that the inselberg developed by the lowering of the surrounding plains (Sweet and Crick, 1994; Twidale and Bourne, 2012).



Geology of Uluru showing its location in Australia, its plan form, and cross-section bordered by Cainozoic desert sand plain.

THE SUGAR LOAF MONOLITH OF RIO DE JANEIRO

BRAZIL

UNESCO World Heritage Site

It is the ideal lookout for a stunning 360-degree view, giving the place invaluable educational importance for understanding landscape evolution (Alexandre Macieira | Riotur).

ONE OF THE MOST ICONIC ROCK MONOLITHS IN THE WORLD IN AN URBAN LANDSCAPE.

Although more than 50 mountains are named "Sugar Loaf" (New Webster's Dictionary and Thesaurus. Lexicon Publications, Danbury, Connecticut, 1993), the Sugar Loaf monolith is the world reference for this type of landform. The top of this outstanding pinnacle, easily reached by cable car, is the ideal lookout for the unique geomorphology of Rio de Janeiro (Silva and Ramos 2002) and the Serra do Mar range more to the north. It is also a cultural landmark because it has been a symbol of Brazil and of Rio de Janeiro in paintings and reports since the colonial period (Castro *et al.*, 2021). It is part of a UNESCO World Heritage Site.

SITE 079

GEOLOGICAL PERIOD	Neoproterozoic / Ediacaran
LOCATION	Rio de Janeiro City, Rio de Janeiro State, Brazil. 22° 56' 59" S 043° 09' 23" W
MAIN GEOLOGICAL INTEREST	Geomorphology and active geological processes Tectonics

The type example of near-conical granite domes or bornhardts. Although accessible by difficult climbing routes, the summit is easely reachable by cable car.

Geological Description

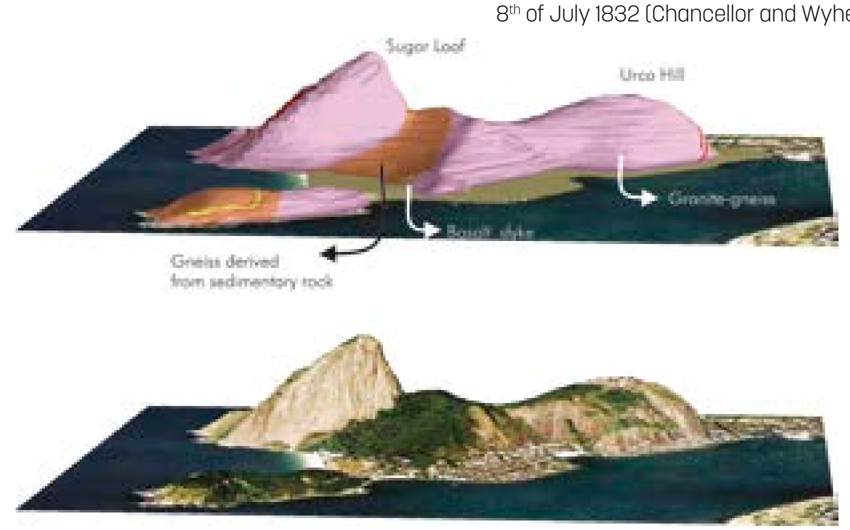
The Sugar Loaf (Pão de Açúcar, in Portuguese) is an outstanding 396 m high near-conical gneiss monolith located at the entrance of the Guanabara Bay, in Rio de Janeiro, SE Brazil.

The Sugar Loaf is composed of an augen gneiss referred in local literature as the "Phacoid Gneiss" (from the Greek word for lens shaped). This gneiss is the product of metamorphism and deformation of a K-feldspar granite during the main collisional phase of the Ribeira orogenic belt at ca. 560 Ma (Ediacaran Period). Several isoclinal folds can be seen in the northern, southern and western sub-vertical faces (Valeriano *et al.*, 2012).

Considering the geomorphological evolution of Sugar Loaf, the role of chemical alteration under the rainy tropical climate is evident. The metasedimentary gneiss was preferentially weathered and eroded, leaving the fresher augen gneiss making up the higher local relief. Steep ENE vertical fractures that affected the area during the Paleogene also control erosive processes that formed the sub-vertical south and north walls. At the southern wall a rock pillar, still attached to the main body, is a remnant of rockfall processes that shaped the monolith. Around the bottom of this pillar, an impressive boulder deposit represents debris from past rockfall events (Valeriano and Magalhães, 1984).

Scientific research and tradition

The Sugar Loaf is represented in maps as early as the 16th century when Europeans arrived in Brazil. One of the earliest map is from Jean de Léry (The singularities of the Antarctic France, 1572), where it was named "Pot de Beurre" by the French sailors, serving as the main reference for the entrance of the Guanabara Bay and Rio de Janeiro. In his famous voyage aboard the Beagle, Charles Darwin also pointed out the imposing presence of Sugar Loaf when he left Rio de Janeiro on the 8th of July 1832 (Chancellor and Wyhe, 2009).



Chemical alteration has preferentially weathered and eroded away the biotite-rich metasedimentary gneiss (forested area), leaving the fresher augen-gneiss making up the higher local relief.

SHILIN KARST

CHINA

Pinnacle karst occurring on Middle Permian dolomitic limestone.

UNESCO World Heritage Site

UNESCO Global Geopark

THE BEST SITE WORLDWIDE PRESERVING AND DISPLAYING VARIOUS PINNACLE KARST LANDFORMS.

Shilin karst is a site of plateau karst, outstanding for the limestone pinnacles decorated with deep, sharp karren, which is the result of karst processes. The limestone is overlain by red Paleogene sandstone and Permian basalt. Shilin exhibits pinnacle shaped karst and other representative karst landforms such as doline, karst cave, depression, karst lake, natural bridge and waterfall, which not only enrich the aesthetic characteristics and values of karst in southern China, but also show the complex evolution history of karst landscape in southern China.

SITE 080

GEOLOGICAL PERIOD	Devonian, Carboniferous, Permian
LOCATION	Shilin Geopark, Shilin county, Yunnan province, China. 24° 47' 30" N 103° 16' 30" E
MAIN GEOLOGICAL INTEREST	Geomorphology and active geological processes Stratigraphy and sedimentology

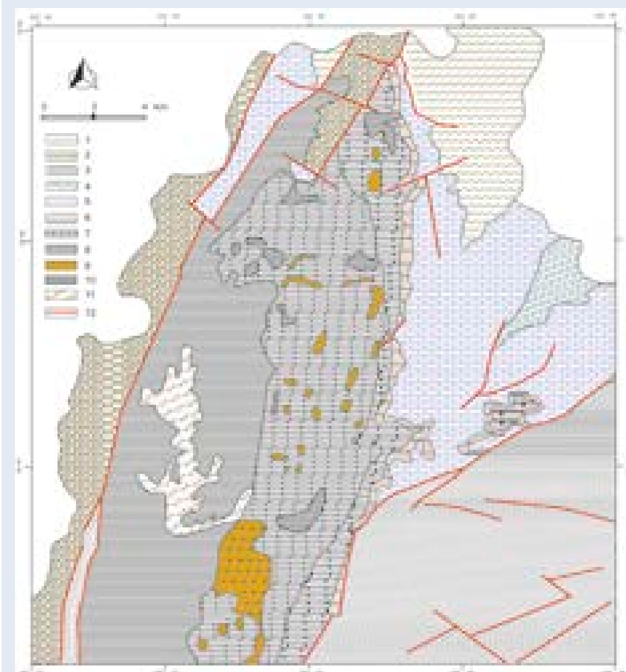
Pinnacle karst arising from a lake.

Geological Description

Diverse karst landforms in Shilin provide an valuable record of the regional geological history. Marine sedimentation ended in the Permian and was followed by terrestrial evolution until the present as represented by overlying basalt and lacustrine red beds. Shilin karst has been preserved and re-exposed repeatedly. Shilin is, therefore, the only site int he world that preserves the oldest stone forest, and it relfects over 200 million years of successive formation of karst landforms. Abundant marine fossil contained in the Middle Permian carbonate rocks (Qixia and Maokou Formations) and terrestrial fossils in the Eocene and Oligocene red beds are of great significance in regional stratigraphical correlation, particularly in southern China. Shilin preserves and displays various pinnacle karst landforms. Almost all existing pinnacle karst landforms, such as spire and pinnacle, can be found within the area. Therefore, it is regarded as the "Museum of Stone Forest Karst". The Karst landforms and karstification mechanism are of great geomorphologic significance. "Stone Forest" is a term describing a distinctive karst landform and the term is now widely known.

Scientific research and tradition

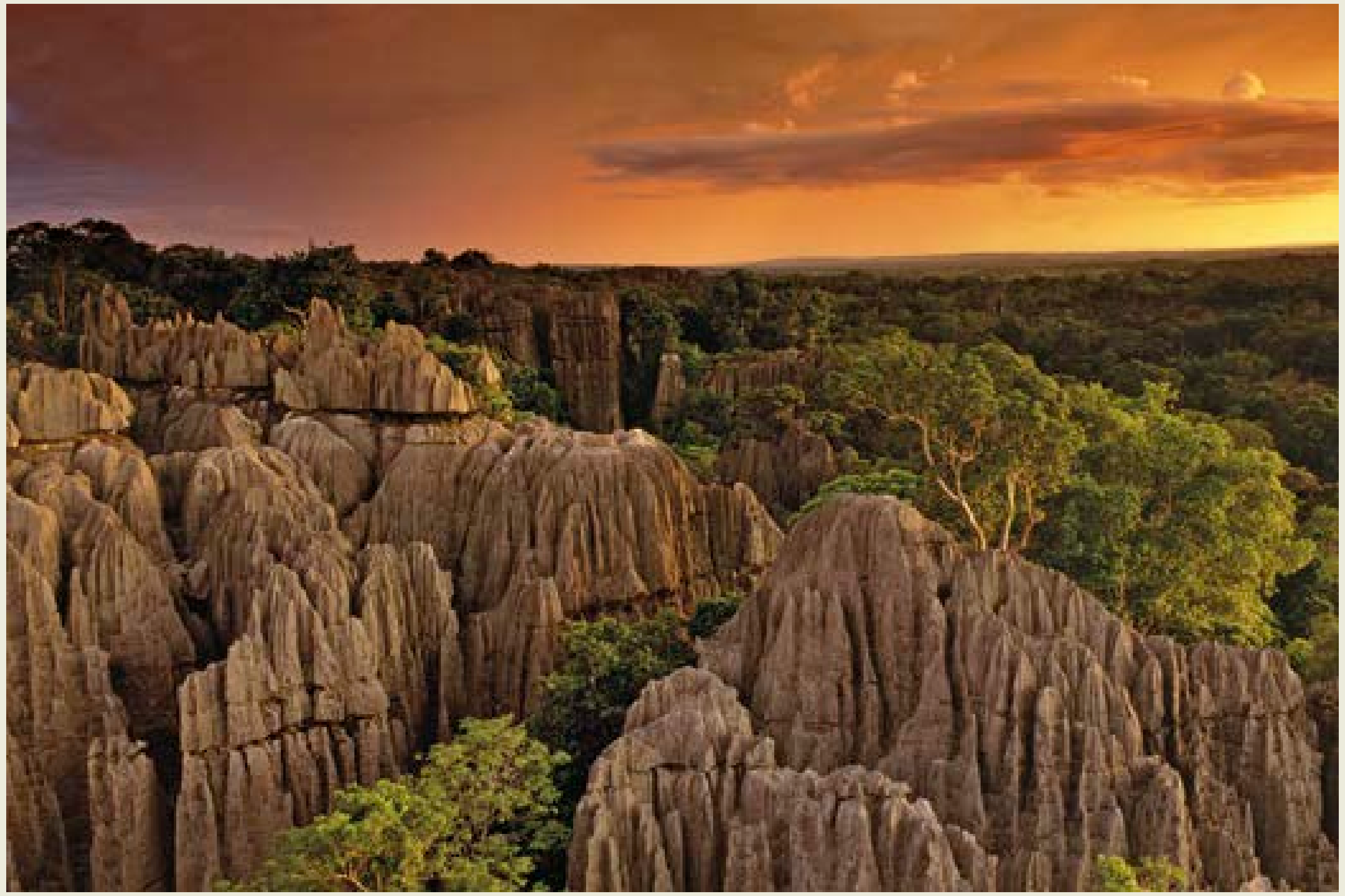
Shilin contains a wider range of pinnacle shapes than other karst landscapes with pinnacle, attracting geologists' interest. More than 150 articles and books have been published. The site has been well protected and was inscribed as Global Geopark in 2004 and World Natural Heritage site in 2007.



Geological map of Shilin area.

TSINGY OF BEMARAHA

MADAGASCAR



UNESCO World Heritage Site

The spectacular limestone landscape of Bemahara is formed by sharp pinnacles, known in Malagasy language as Tsingy. (Copyright, Olivier Grunewald).

THE KARSTIC LANDSCAPE WITH"FOREST OF SHAPE STONES" OF EXCEPTIONAL BEAUTY THAT GIVES ITS NAME TO THIS GEOLOGICAL FEATURE.

The Bemaraha Tsingy represents rare and remarkable geological phenomena and are of exceptional beauty. The landscape is impressive. It is characterized by karst developed on a highly dissected limestone massif, which is crossed by a deep gorge. It is a spectacular expression of karstification and forms a "forest of sharp stones" with high limestone peaks rising 100 meters, forming veritable cathedrals and offering a grandiose, spectacular natural landscape. Further, "the Tsingy" of the limestone plateau forms an unusual feature of outstanding beauty, unique in the world, universally recognized by the effect created by the shades of forest green on metallic reflections of the grey karst "bristles".

SITE 081

GEOLOGICAL PERIOD	Pliocene - Holocene
LOCATION	District d'Atsalova Région Melaky/ Madagascar. 18° 12' 00" S 044° 34' 00" E
MAIN GEOLOGICAL INTEREST	Geomorphology and active geological processes

The top of the limestone massif shaped by centuries of erosion is made up of pungent and sharp rocks. (Copyright, Olivier Grunewald).

Geological Description

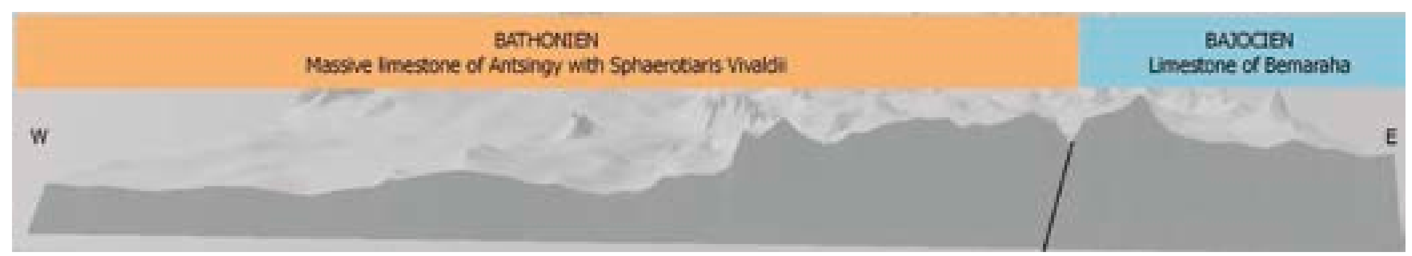
The Bemaraha Tsingy constitue a hill type karst developed on the surface of a 300-500m thick Mesozoic Era, Middle Jurassic, Bajocian-Bathonian limestone sequence (Bésairies and Collignon, 1972). It relief varies from 100 m in the west to 600 m in the east, where it then drops 300-500 m to the Betsiriry Valley. The limestone is crossed by several large rivers, the Tsierbinia and manambolo. The latte has eroded a canyon 300 m deep (Dobrilla *et al.,* 2006). The BemarahaTsingy is presented as a true cathedral of limestone. It is characterized by a dense network of faults, by crevasses, and by surfaces of limestone sculpted into blades and sharp needles. The limestone formed as a deposit of fossil corals during the Middle Jurassic. The dissolution of carbonate rocks creates dolines and avens which act as a refuge for the green vegetation in the dry forest of the West.

The limestone has a complex karst hydrology with the Tsingy servince as a water tower for the region of Antsalova.

Scientific research and tradition

The Bemaraha Tsingy has been studied the past 50 years. Investigations have focused on the caves and grikes. The Bemaraha Tsingy strict Nature reserve was listed as a UNESCO World Heritage Site in 1990.

Geological sketch or diagram showing the age and the formation in the Tsingy.



LA PUERTA DEL DIABLO INVERTED RELIEF

EL SALVADOR

Aerial view of Puerta del Diablo showing the large volcanic landslide mega blocks forming the inverted relief ridge and tectonic viewpoint.

A TYPE INVERTED VOLCANIC LANDSLIDE MEGABLOCK DEPOSIT WITH AN OVERVIEW OF THE CENTRAL AMERICAN VOLCANIC ARC'S TECTONIC, VOLCANIC AND GEOMORPHOLOGIC EVOLUTION.

La Puerta del Diablo is a type locality for volcanic landslide blocks and matrix, where the major textural and structural elements are well exposed and accessible in a small area, allowing the kinematics of such huge events to be observed in detail. In addition, Puerta el Diablo is a prime example of volcanic inverted topography, a valley-confined landslide that has become a ridge. The dominating topography in turn allows a wide overview of the highly diverse surrounding volcano-tectonic geomorphology, where the plate tectonic evolution of Central American Volcanic Arc can be read clearly in the landscape.

SITE 082

GEOLOGICAL PERIOD	Lower Pliocene - Recent
LOCATION	El Salvador, Central America. 13° 37' 26" N 089° 11' 24" W
MAIN GEOLOGICAL INTEREST	Geomorphology and active geological processes Volcanology Tectonics

Close up view of outcrop (6m across) of the volcanic landslide block and matrix facies contacts, with injected breccia in one large lava megablock.

Geological Description

La Puerta del Diablo is a debris avalanche deposit with megablocks. The 100 m wide blocks stand out as cliffs surrounded by weaker landslide matrix. The blocks, their structures and their mechanical interaction with the matrix are well exposed in roadcuts and natural outcrops, providing a type example of the interior textures and structure of a volcanic landslide, with classic breccias, jig-saw crack textures, and block interactions.

The resistant deposit forms a high inverted relief ridge perched above the heavily faulted and eroded Pleistocene Panchimalco Caldera. The landslide lies on a full stratovolcano sequence of the coastal El Bálsamo range of volcanoes.

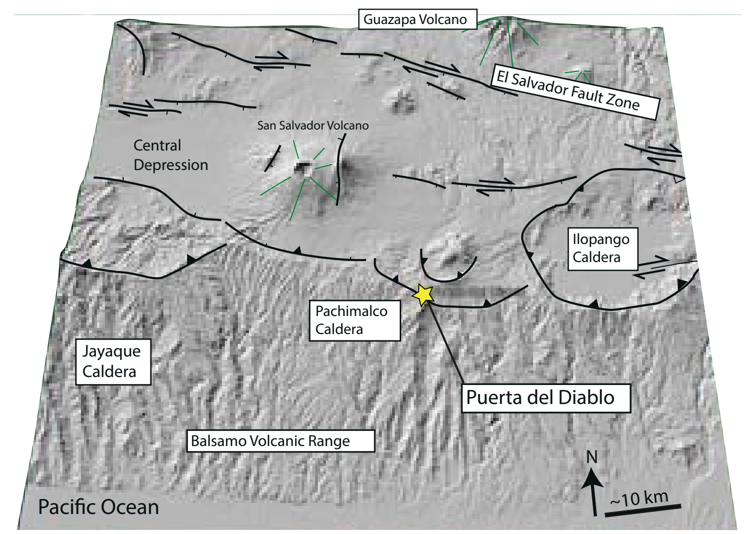
The high ridge afford a 360 degree panorama of the tectonics, volcanism, and geomorphology of the Central American volcanic arc. This includes the Pacific volcanic slope, the southern and northern rims of the central rift, rifted calderas (e.g., Jayaque, Panchimalco, La Carbonera, Ilopango) (Lexa *et al.*, 2011, Hernández and Jicha, 2019; Jicha and Hernández, 2022) and faulted volcanoes (e.g.. San Salvador). The landscape displays the effects of subduction steepening followed by strike-slip tectonics.

Poet Raúl Contreras named Puerta del Diablo in 1951, although it was known in 1762 for seismic and rain triggered-collapse of some megablocks (Lardé and Larín, 2000).

Scientific research and tradition

Conditions in El Salvador have not allowed research until recently. The outcrops of the landslide blocks are exemplary, and their formation and setting are highly significant. In addition, the viewpoint has been long used for geodynamic overviews of the Central American arc (Sapper, 1937; Williams and Mayer-Abich, 1955).

Oblique view of the Puerta del Diablo vistas, showing the central depression, calderas, faults and coastal ranges of the volcanic arc in El Salvador.



QUATERNARY INTERGLACIAL CORAL AND MARINE UPLIFTED TERRACES OF MAISÍ

CUBA

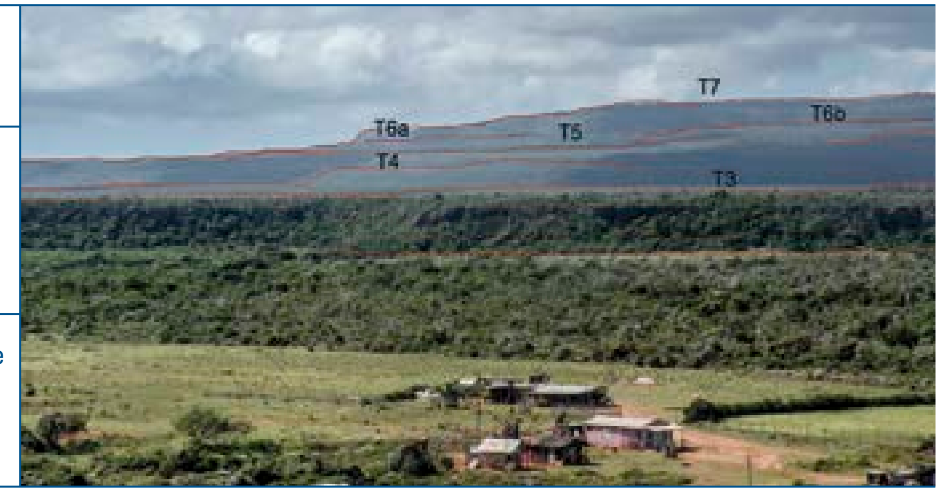
General view of coral and marine uplifted terraces at south of Maisí municipality, eastern of Guantánamo province, Cuba.

ONE OF THE BEST PRESERVED MARINE AND CORAL UPLIFTED TERRACES SEQUENCES IN THE WORLD BY INTERACTION OF GLOBAL SEA LEVEL AND TECTONICS.

The marine and coral uplifted terraces of Maisí are a very important source of information to reveal the tectonics of the Greater Antilles within the Caribbean domain during the Quaternary Period. As a result of multiple investigations, marine terraces are known in Haiti, in Lesser Antilles and other parts of the world is known. The marine terraces in Cuba can be correlated with global sea-level changes in the Quaternary. In addition to being in an area regularly impacted by hurricanes, this area is important for studying wave energy during these meteorological events.

SITE 083

GEOLOGICAL PERIOD	Quaternary
LOCATION	Punta de Maisí, Guantánamo province, Cuba. 20° 08' 10" N 074° 13' 59" W
MAIN GEOLOGICAL INTEREST	Geomorphology and active geological processes Stratigraphy and sedimentology



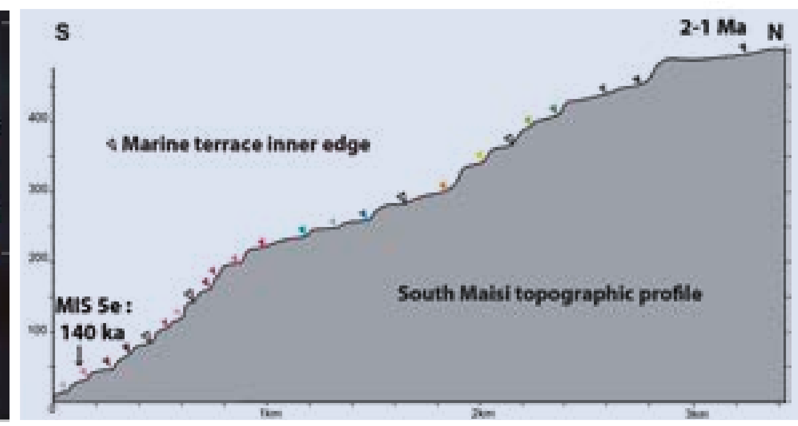
Terraces levels marked on a sector. Some terrace levels can be traced across the area, but others have more limited extent (T6a and T6b).

Geological Description

The marine and coral terraces are made up of coral and shelly limestone with abundant fossils. They are underlain by the Jaimanitas Formation of Late Pleistocene age (MIS 5e, 122 ± 6 ka) (Toscano *et al.*, 1999) and older, underlying Pleistocene strata. About 28 terrace levels are observed, with an elevation up to 560 ± 10 m. Most of the terraces are very well preserved where fossil tidal notches, caverns and other karst features are present. These represent the record of approximately 2 Ma of sea level fluctuations. The area is tectonically linked to the Oriente transform fault zone in eastern Cuba, which is the boundary between the North American and Caribbean plates, where block uplifts of 0.33 ± 0.01 mm/yr are recorded (Peñalver *et al.*, 2021). Geomorphologically, the area is a large ring of about 75 km long covering the eastern coastal zone of Cuba as a staircase being narrow at north and south, and wider in the east corner. Steps are cut by rivers forming gorges with large transversal outcrops. Due to the active tectonics, predominantly tilting and folding, in some places the same step has different altitude at both sides of the gorge. The lower terrace has blocks overturned from the sea by hurricanes and landslide features like crowns are observed.

Scientific research and tradition

These terraces were described as early as 1898 (Hersey, 1898), and investigations have continued to the present day (Muhs *et al.*, 2017). Recent radioisotopic dating was carried out to investigate relationships between erosion of terraces and tectonics and climate.



Shadowed relief overlapped over satellite image where marine terraces are observed. Topographic profile showing the inner edge of each terrace level of Maisí area, Guantánamo, Cuba.

THE GRAND CANYON

USA

UNESCO World Heritage Site

View from the South Rim near Yavapai Point looking across the inner gorge (in shadow) to the North Rim. Sunset lighting accentuates the horizontal Paleozoic strata. (Photo Credit: Michael Quinn, NPS).

EARTH'S ICONIC CANYON PROVIDES AN ARCHIVE OF TWO BILLION YEARS OF EARTH'S HISTORY AND A GLOBALLY IMPORTANT LABORATORY FOR RESEARCH AND EDUCATION.

Grand Canyon is one of the most visited of the USA's National Parks. Its geologic record spans seven geologic eras and much of Earth's biologic evolution history with well exposed sedimentary rocks containing rich fossil assemblages. Its stunning landscape includes a 1.6-kilometer-deep gorge that ranges in width from 500 m to 30 km and twists and turns for a length of 445 km. The canyon formed in the past 6 million years by the erosional power of the Colorado River and its tributaries, deepening older paleocanyon segments (Karlstrom *et al.,* 2014) and carving through an uplifting Colorado Plateau. Geoscience education efforts (Karlstrom and Crossey, 2019) also have global reverberations in terms of understanding how human and geologic timescales interact.

SITE 084

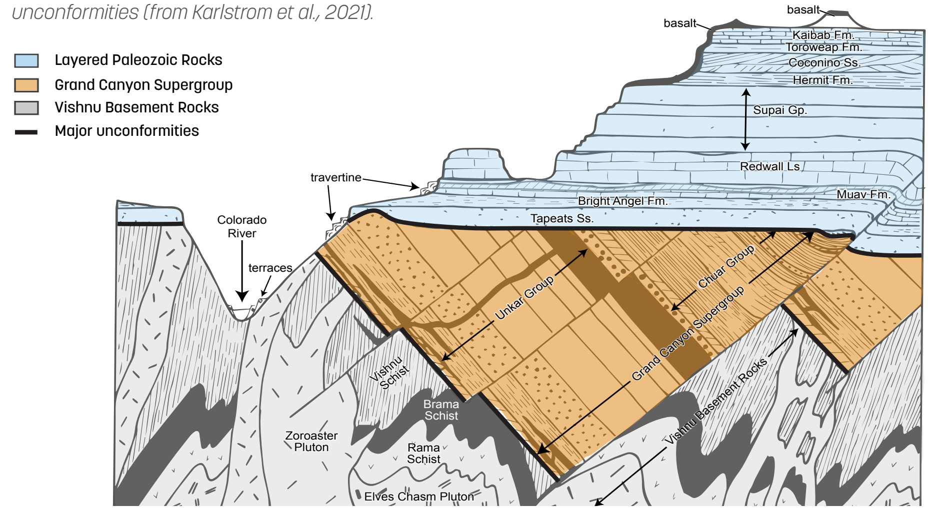
GEOLOGICAL PERIOD	Pliocene and Pleistocene
LOCATION	Colorado Plateau region of the USA. 36° 03' 56" N 112° 07' 04" W
MAIN GEOLOGICAL INTEREST	Geomorphology and active geological processes

Vishnu basement rocks deep in the inner gorge record the assembly of this part of the North American continent. (Photo Credit Ron Chappell).

Geological Description

Grand Canyon is 1.6-km-deep and is being carved into the uplifting Colorado Plateau by the erosional power of the Colorado River and its tributaries (Karlstrom *et al.,* 2022). It exposes an exceptionally complete rock record of 1.84 billion years (about 40%) of Earth's history. A visit to the rims, a hike into the canyon, or a river trip through its 445-km length are awe-inspiring experiences. They motivate >6 million annual visitors to ponder the depths of geologic time and how humans are part of Earth's history and processes. Vishnu basement rocks, exhumed from 25 km depths, formed via collisions of volcanic island chains between 1,840 and 1,375 million years ago. Grand Canyon Supergroup records basins within the continent that responded to assembly and breakup of an early supercontinent of Rodinia between 1,250 and 729 million years ago, a time dominated by single-celled life. The flat-lying layered Paleozoic rocks encode stories, layer by layer, of dramatic environmental changes and the evolution of animal life between 530 and 270 million years ago. The iconic landscapes of the region are dynamic and provide a key laboratory for understanding interactions among geomorphic, volcanic, tectonic, and anthropogenic processes.

Stratigraphic column of the three sets of rocks and major unconformities (from Karlstrom et al., 2021).



Scientific research and tradition

Building on scientific research extending back to the 1850s (Karlstrom and Crossey, 2019), there is ongoing research on most rock units and many aspects of geomorphology. Hot topics include middle crustal processes, evolving Precambrian Earth systems, the Cambrian explosion (Karlstrom *et al.,* 2020), age and integration of the Colorado River (Crow *et al.,* 2021), rates and processes of canyon carving, and arid land hydrogeology.

IGUAZÚ / IGUAÇU WATERFALLS

ARGENTINA AND BRAZIL

UNESCO World Heritage Site

General view of an area of the Iguazú falls and the basaltic mantles. (Photo: Luis Carcavilla).

ONE OF THE MOST ICONIC AND OUTSTANDING WATERFALLS IN THE WORLD.

Iguazú/Iguaçu is one of the major world references in what concerns waterfalls, which is one the reasons why it was designated as a UNESCO's World Heritage site. The great accessibility and infrastructure of the area make Iguazú/Iguaçu a place with educational potential in relation to a very clear example of regressive fluvial erosion. In addition (Ardolimo and Miranda, 2008), the coexistence with large and extensive basaltic outcrops originated during the fragmentation of the primitive Gondwana continent, allow addressing issues related to global tectonics.

SITE 085

GEOLOGICAL PERIOD	Quaternary / Holocene
LOCATION	Argentina: Puerto Iguazú / Misiones Province Brazil: Foz do Iguaçu / Paraná. 25° 41' 44" S 054° 26' 13" W
MAIN GEOLOGICAL INTEREST	Geomorphology and active geological processes Volcanology

Garganta del Diablo (Devil's throat). (Photo: Luis Carcavillla).

Geological Description

The Iguazú/Iguaçu waterfalls constitute a set of 275 falls with an average height of 75 meters distributed along a front of almost 2,700 meters. These discharge an average of 1,800,000 l/s into the narrow and deep canyon of the Iguazú river (Salamuni *et al.,* 1998). The "Garganta del Diablo" (Devil's Throat), the most important fall, is the culmination of this canyon that begins in the Paraná river, on the border between Argentina, Brazil and Paraguay, 18 km downstream from the falls. Fissural basaltic volcanic rocks that spread over the surface some 125 to 115 Ma ago (Lower Cretaceous) dominate the region (Ardolino and Miranda, 2008). These lava flows covered an area of 1,200,000 km² and accumulated thicknesses of up to 1,500 meters, constituting the largest basaltic lava flow recorded on the planet's continental crust. Its origin is synchronous with the fragmentation of Gondwana, for which these rocks are also recognized in the western sector of Africa, an intercontinental group known as the Parana-Etendeka volcanic province (Llambías, 2023). In South America, these lavas are known as the Serra Geral Formation. The region is a high, flat plateau that is crossed and incised by several rivers. The channel of some of them, like part of the Paran and the final section of the Iguazu are probably structurally controlled (Ardolino and Miranda, 2008).

Scientific research and tradition

Since the waterfalls are located on the border between Argentina and Brazil and constitute the most imposing feature within the homonymous National Parks, there is profuse international research on active geomorphological processes, petrological and volcanological aspects, as well as numerous publications that contemplate biotic factors.

Iguazú/Iguaçu waterfalls are a very clear example of an active geological process of regressive fluvial erosion.

MOSI-OA-TUNYA VICTORIA FALLS
ZAMBIA AND ZIMBABWE

UNESCO World Heritage Site

Clear evidence of the tectonic control in the norrowly incised gorges with basalt exposition.

THE "THE SMOKE THAT THUNDERS" FORMING THE LARGEST SHEET OF FALLING WATER IN THE WORLD.

The Victoria Falls represent an outstanding example of the interplay between fluvial geomorphology, tectonics, and active erosive processes (active geomorphological and land formation processes).
The Victoria Falls, Mosi-oa-Tunya [the smoke that thunders], has an outstanding beauty attributed to the falls, which raise an iridescent mist that can be seen more than 20 km away.
The site exhibits erosive processes that cut back the basalt and thus caused migration of the Falls upstream.

SITE 086

GEOLOGICAL PERIOD	Quaternary
LOCATION	Zambia and Zimbabwe 17° 55' 30" S 025° 51' 30" E
MAIN GEOLOGICAL INTEREST	Geomorphology and active geological processes Tectonics

The Devil's cataract showing the sheer basalt cliff. (Photo credit: Darrel Plowes, provided by Andy Moore).

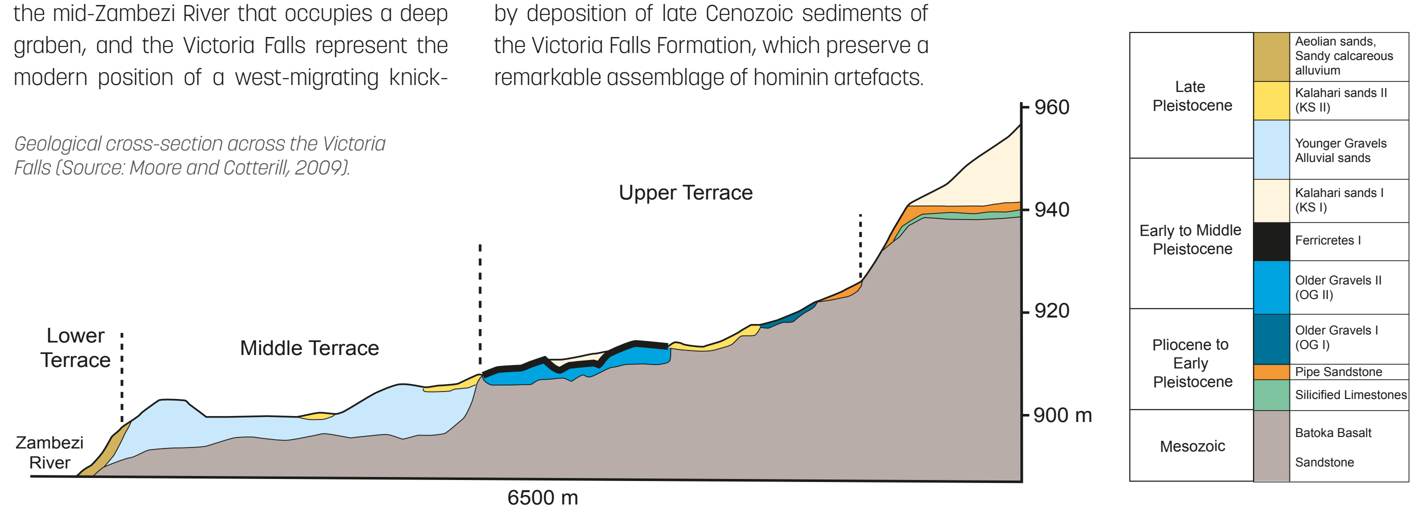
Geological Description

The Victoria Falls are located on the Zambezi River, forming the boundary between Zambia and Zimbabwe. The Falls form the world's largest sheet of falling water with a maximum vertical drop of 108 m, and a length of 1,700 m, in full flood (Moore and Cotterill, 2009). The Falls represent a major geomorphological break between low gradient of the up to 2km wide channel upstream and the steep gradient of the norrowly incised gorges downstream. The Falls are a culmination of a long geomorphological process initiated by diversion of drainage off the Kalahari plateau into the mid-Zambezi River that occupies a deep graben, and the Victoria Falls represent the modern position of a west-migrating knickpoint that incised the lower gorges into Jurassic layered basalts that form the bedrock (Derricourt, 1976; Lamplugh, 1907; Maufe, 1936; Nugent, 1990; Moore and Cotterill, 2009). The Victoria Falls and associated eight steep sided downstream gorges have been formed through the changing waterfall positions over an extended geological time. The gorges are an outstanding example of river capture in a tectonic basin. The erosive forces of the water continue to carve the hard basalt (UNESCO World Heritage Document, 1989). Evolution of the Falls and lower gorges was accompanied by deposition of late Cenozoic sediments of the Victoria Falls Formation, which preserve a remarkable assemblage of hominin artefacts.

Scientific research and tradition

The Zambezi River including the Victoria Falls and the gorges and cataracts downstream have been a subject of geological, geomorphological and geographic research since the beginning of the 20th century, and hundreds of publications have been produced about it. Owing to the nature of the terrain more studies have been on fluvial geomorphology than the bedrock and the archaeological sediments deposited downstream. The Victoria Falls has also been used as an example for many high school geography students all around the world and featured in many textbooks.

Geological cross-section across the Victoria Falls (Source: Moore and Cotterill, 2009).



DRY FALLS AND THE CHANNELED SCABLAND

USA

A panoramic view of the 400-foot (122-meter) high cliffs and waterfall plunge pools of Dry Falls from the state park visitor center.

THE DRY REMNANTS OF ICE AGE WATERFALLS THAT MAKE UP ONE OF THE LARGEST CATARACTS ON THE PLANET.

The debate surrounding the origin of Dry Falls and the Channeled Scabland has had a significant impact on our understanding of basic geologic principles. When J Harlan Bretz first proposed in 1923 that huge floods had shaped the landscape of eastern Washington, his hypothesis was rejected as not conforming to the current assumptions of uniformitarianism. This principle assumes that geologic processes have occurred gradually in the past, just as they do in the present. As evidence continued to build for a glacial flood origin, the scientific community eventually accepted that catastrophic events can punctuate periods of slower geologic evolution.

SITE 087

GEOLOGICAL PERIOD	Pleistocene
LOCATION	Columbia Basin / Washington State, USA. 47° 36' 23" N 119° 21' 53" W
MAIN GEOLOGICAL INTEREST	Geomorphology and active geological processes

An aerial view of Dry Falls, showing the steep cliffs of the cataract and the waterfall plunge pools now filled with groundwater.

Geological Description

Dry Falls, the main feature in a series of huge cataracts known as the "great cataract group", sits at the heart of Washington's Channeled Scabland, a vast landscape of dry canyons scoured out by glacial outburst floods at the end of the last ice age. Tall cliffs and plunge pools tell the story of this waterfall estimated to have been several times larger than Niagara Falls and a key piece of evidence that massive floods had scoured this area. The history of the Channeled Scabland starts in the late Pleistocene, as ice sheets in the Columbia River Basin began to melt. The ice dam holding back glacial Lake Missoula in northern Idaho and western Montana collapsed and released a cataclysmic surge of water estimated to have been ten times the flow of all the rivers in the world. The floodwaters carved out deep canyons, known as coulees, into the thick stacks of Miocene basaltic lava flows that cover nearly one third of Washington. These lava flows, known as the Columbia River Basalt Group, are riddled with cooling cracks and crumbly flow tops. These properties made it possible for the huge floods to erode the rocks into this unique landscape.

Scientific research and tradition

Research on the origins of the Channeled Scabland has been going on for almost a century, starting with the fundamental work of J Harlan Bretz in the 1920s. The debate has resulted in hundreds of publications on the topic, both in the scientific literature and in popular science.

Map of the Missoula floods at their maximum extent, highlighting the vast Channeled Scabland terrain, with its network of coulees eroded into basaltic lava flows.

JUTULHOGGET CANYON

NORWAY

Jutulhogget ("cut by trolls") canyon was incised in the Precambrian sandstone as flood waters drained from Østerdalen valley to Rendalen valley during a glacial lake outburst flood. View towards Østerdalen in the west. Note the people on the left hand side of the image.

A LARGE CANYON CREATED BY A DRAMATIC ICE AGE FLOOD.

The site has been subject to research since 1880s and is a reference area for understanding glacial retreat and glaciofluvial processes. Early scientific discussions debated different explanations not only about the canyon but also on former shorelines and moraines. Ongoing research is revealing new knowledge and understanding of the complexity in such processes especially based upon deposition in the areas connected to the glacial lake and the catchment area. Besides, the area is easily accessible for visitors – to admire and learn.

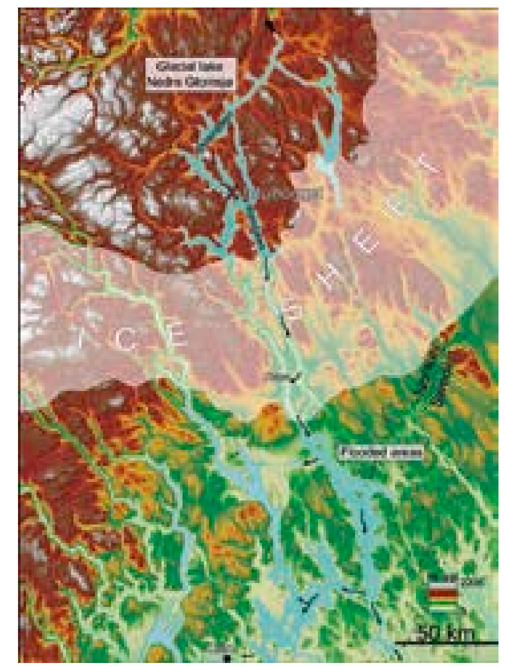
SITE 088

GEOLOGICAL PERIOD	Quaternary / Holocene
LOCATION	Alvdal and Rendalen municipalities, Innlandet Country, Norway. 61° 59' 59" N 010° 54' 27" E
MAIN GEOLOGICAL INTEREST	Geomorphology and active geological processes

The steep walls along the Jutulhogget canyon are unstable, and the canyon floor is draped by a thick layer of scree material. The canyon walls are now home for rare types of lichens.

Geological Description

Jutulhogget canyon, 2.5 km long, 150-300 meters wide and up to 240 meters deep, is an impressive and striking landscape feature. It is the result of a dramatic event during the final demise of the Scandinavian Ice Sheet at the end of the last Ice Age. As the ice sheet retreated across the main drainage divide, meltwater was dammed between local spillways and the receding ice margin. A big glacial lake – "Nedre Glomsjø" – formed in Østerdalen valley, covering a 1350 km² large area, holding 140 km³ of water (about three times the size of Norway's largest lake Mjøsa). When the glacier dam broke a catastrophic outburst flood (jökulhlaup) funneled southward beneath the remnant ice sheet. As the ice-dam collapse occurred in Rendalen, a large amount of water had to drain eastward from Østerdalen, leading to vast erosion and formation of the huge Jutulhogget canyon over a short period of time. The basement rock of Precambrian sandstone forms a huge thrust sheet related to the Caledonian orogeny. Weakened by old tectonic stress, it broke apart and was transported and re-deposited far downstream by the outburst flood. The gigantic boulders located downstream of the canyon tells a tale of the extreme energy involved during such outburst floods.



Map showing the location of Jutulhogget canyon; extent of glacial lake Nedre Glomsjø, the remnant ice sheet and areas south of the ice sheet inundated during the outburst flood.

Scientific research and tradition

The first scientific publications, mainly in Norwegian publications created a strong debate on the mechanisms and processes able to create such features. New tools, such as LIDAR, now provide a new understanding of the complexity of the processes and the depositions connected to the lake, the jökulhlaup and the depositions.

PERITO MORENO GLACIER
ARGENTINA

UNESCO World Heritage Site

Panoramic view of the Perito Moreno Glacier. (Photo courtesy of Leonardo Escosteguy).

AN AMAZING GLACIER FRONT AND A STABLE GLACIER IN THE FACE OF GLOBAL WARMING.

The Perito Moreno Glacier is an iconic site in the Patagonia Argentina included in the Los Glaciares National Park, declared as World Heritage Site by UNESCO in 1981. It has well-defined limits (Aniya and Skvarca, 1992), great accessibility and infrastructure (you can even walk on it) that gives the area educational potential. Besides the anomalous and periodic unique behavior of this glacier (Skvarca *et al.,* 2004), the area offers an excellent example of the significant process of glaciation, as well as of geological, geomorphic and physiographic phenomena caused by the advance and retreat of the glaciations, which took place during the Pleistocene Epoch (Pasquini and Depetris, 2011).

SITE 089

GEOLOGICAL PERIOD	Pleistocene-Holocene
LOCATION	Santa Cruz province / Argentina. 50° 28' 45'' S 073° 03' 58'' W
MAIN GEOLOGICAL INTEREST	Geomorphology and active geological processes

Walking towards the glacier. The front of the glacier is 5 km long and its walls reach 60 meters in height.

Geological Description

The Perito Moreno is one of the most important glaciers that break off from the Southern Patagonian Ice Field located in the southern chain of the Andes (Argentina and Chile). This icefield is the last reliect of the greatest glacial expansions that occurred form the late Miocene to the late Pleistocene. This glacier is approximately 30 km long. Its front is 5 km long and has walls up to 60 m high (Aniya and Skvarca, 1992; Stuefer *et al.,* 2007). The glacier penetrates Argentino Lake, but its base maintains contact with the rocky substratum. It´s a temperate or humid base glacier with a unique dynamic behavior. In this sense, its front presents a condition of stability (Stuefer *et al.,* 2007; Ciappa *et al.,* 2010), with brief oscillations (advances) that, when colliding with the western end of the Magallanes Peninsula, periodically causes the temporary blockage of Brazo Rico (as a dam), raising its water level. This situation generates differential stresses at the end of the glacier and causes the progressive transfer of water to the Argentino lake through a tunnel excavated in the ice. The roof of the tunnel collapsed in 1995, which was a spectacular event that made the glacier famous internationally (Del Valle *et al.,* 1995).

Scientific research and tradition

Perito Moreno is one of the few glaciers in the Southern Patagonian Ice Field that have not retreated during the last 50 years (Ciappa *et al.,* 2010).This makes it something special in the face of global warming, which has motivated numerous investigations (e.g. Pasquini and Depetri, 2011). Likewise, for greater attractiveness, the ice terminus periodically reaches the Magallanes Peninsula, generating an "ice dam" that finally collapses due to the pressure of the water (Del Valle *et al.,* 1995).

Perito Moreno Glacier image and detail of the collision against the Magallanes Peninsula during periodical advances of the ice body.

ROCKGLACIERS OF THE ENGADINE
SWITZERLAND

View of Val dall'Acqua rockglacier from drone. (Photo: A. Cicoira, autumn 2019).

DUE TO CONTINENTAL CLIMATE CONDITIONS, HIGH ELEVATION AND HIGH WEATHERING RATES, THE ENGADINE IS ONE OF THE ROCKGLACIER HOTSPOTS IN THE WORLD AND THE HOME OF RESEARCH ON ROCKGLACIERS.

The Engadine is a reference place for mountain permafrost research, in particular rockglaciers. The Val da l'Acqua and Val Sassa rockglaciers movements have been investigated for nearly one century (Chaix, 1923). Movement rates – quantified by repeated measurements of painted stone lines – were described for the first time in 1923. Murtèl/Corvatsch is a key locality where the internal structure of rockglaciers and permafrost creeping have been investigated since the mid-1970s. Several drilling and intensive geophysical surveys in both Murtèl/Corvatsch and Muragl rockglaciers make them key localities for mountain permafrost research and long-term monitoring.

SITE 090

GEOLOGICAL PERIOD	Quaternary / Holocene
LOCATION	Engadine / Canton Graubünden, Switzerland. 46° 25' 43" N 009° 49' 20" E
MAIN GEOLOGICAL INTEREST	Geomorphology and active geological processes

The Muragl rockglacier. (Photo: I. Gärtner-Roer, August 2020).

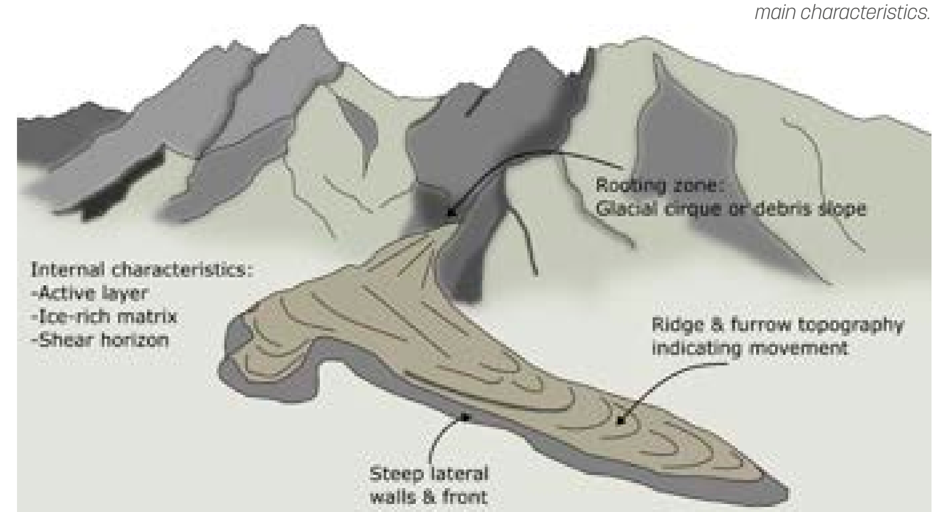
Geological Description

The Engadine is one of the rockglacier hotspots in the European Alps with a large number of rockglaciers in all states of activity (active, inactive, relict), indicating the former and present occurrence of discountinuous permafrost (Gärtner-Roer and Hoelzle, 2021). The proposed geosite is made of four specific rockglaciers representing various features of permafrost creeping: the Val Sassa and the Val da l'Acqua rockglaciers, in the core of the Swiss National Park, emblematic of valley bottom rockglaciers, and the Muragl and Murtèl/Corvatsch rockglaciers, typical of rockglaciers developed in formerly glaciated cirques. The two latter are part of the Permafrost Monitoring Network Switzerland PERMOS, created in 2000, which is one of the longest monitoring networks in the World. The findings from rockglacier research in the Engadine improved knowledge on high-mountain permafrost, in particular on permafrost distribution, rockglacier internal structure and kinematics (Haeberli, 1985; Vonder Mühll *et al.*, 1998; Springmann *et al.*, 2012), and sediment transfer (Gärtner-Roer, 2012). They indicate warming permafrost conditions and related process changes, such as increased horizontal velocities and degradation of certain landforms.

Scientific research and tradition

The rockglaciers Val da l'Acqua and Val Sassa were the first rockglaciers described and investigated systematically. The Val Sassa rockglacier is surveyed by photogrammetric and geophysical investigations since the 1950s. The Murtèl/Corvatsch rockglacier was the first rockglacier drilled in 1987, which allowed continuous thermal monitoring until today, the longest series in the World.

Schematic sketch of a rockglacier showing it's main characteristics.



THE OKAVANGO DELTA
BOTSWANA

UNESCO World Heritage Site

Aerial view of the Okavango delta. (Photo: Wynand Uys / Unsplash).

AFRICA'S LARGEST INLAND ALLUVIAL FAN AND AN EXCEPTIONAL EXAMPLE OF THE INTERACTION BETWEEN CLIMATIC, HYDROLOGICAL AND BIOLOGICAL PROCESSES.

Okavango Delta has been registered as a World Heritage Site by UNESCO in 2014 for its exceptionally intact wetland system and its rich and diverse biodiversity. However, the delta is mainly a geological phenomenon, and it should be recognized as an important geological feature.

The climatic-hydrological system is a unique feature. The annual flood cycle which happens during the dry season in Botswana is critical to revitalization of the wetlands ecosystem.

The Okavango Delta is a vast wetland system with spectacular scenery and rich biodiversity, which includes the largest elephant population in Africa and serves as a core refuge of Africa's mega-fauna.

The Okavango Delta provides vital ecosystem services and is an important source of fresh water in a largely arid region.

SITE 091

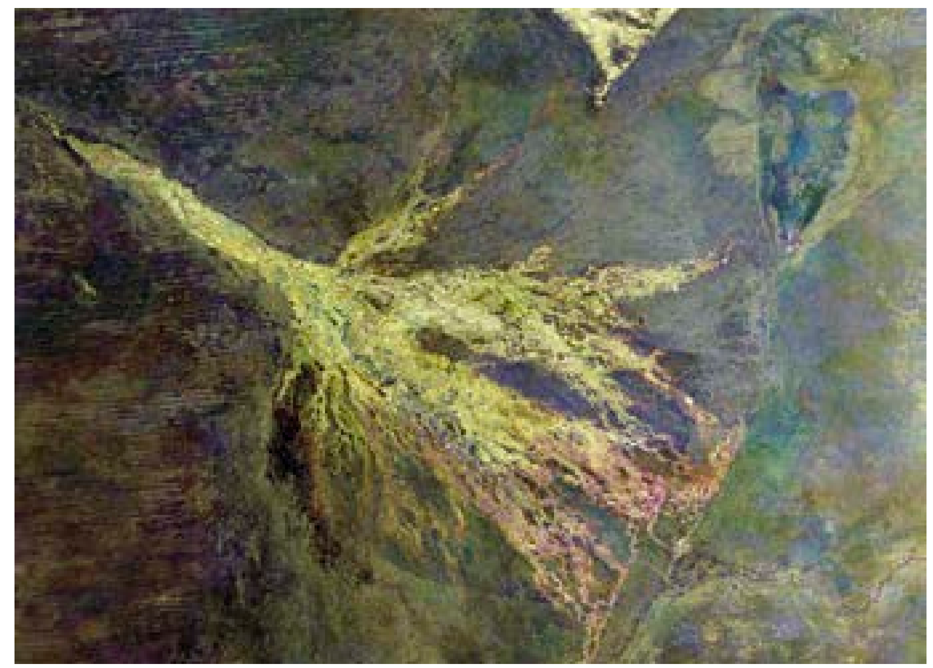
GEOLOGICAL PERIOD	Miocene – Quaternary
LOCATION	Okavango, Northwest, Botswana, UNESCO World Heritage Site. 19° 17' 00" S 022° 54' 00" E
MAIN GEOLOGICAL INTEREST	Geomorphology and active geological processes Stratigraphy and sedimentology

The Okavango River at its terminus, showing the ubiquitous fan grassland and water lilies on the shallow water. (Photo credit: Asfawossen Asrat).

Geological Description

The Okavango Delta, situated in northern Botswana, is a large alluvial fan (40,000 km^2) lying within grabens of the southern extension of the East African Rift system (Scholtz, 1975). The Okavango Delta is situated within two major grabens, one containing the Panhandle and the other the Delta itself (McCarthy *et al.*, 1998). The delta is located at the terminus of the Okavango River and is a terminal depository for the Okavango River system, which drains central Angola (McCarthy and Metcalfe, 1990; McCarthy, 2013). Topographic gradients on the fan are low, and at the fan the Okavango River forms a system of anastomosing channels flanked by perennial and seasonal swamps (McCarthy and Metcalfe, 1990). The river discharges about 10 km^3 of water onto the fan each year, augmented by about 6 km^3 of rainfall, which sustains about 2500 km^2 of permanent wetland and up to 8000 km^2 of seasonal wetland (McCarthy, 2006). The Okavango is a large low gradient Inland delta and is Africa's largest endorheic delta and the third biggest alluvial fan in Arica. It is largely untransformed wetland system, with uniquely adapted biota timed with the arrival of flood water in the dry, winter season of Botswana (World Heritage Nomination Dossier, 2013).

The Okavango River empties into the inland Okavango Delta in northern Botswana (Photo: © ESA, CC BY-SA 3.0 IGO. Compilation of three images from Envisat's radar; Source: European Space Agency, 2013).



Scientific research and tradition

The Okavango Delta has been a subject of fascination since the 1920s. Serious scientific research on its geology and hydrology has been conducted since the 1980s, as can be evidenced by the rich scientific literature about the Delta.

YARDANG (KALUT) IN THE LUT DESERT

IRAN

UNESCO World Heritage Site

Yardangs (Kaluts) with Stunning Parallel Ridges in the Lut Desert. (Photo: Mehran Maghsoudi).

THE HIGHEST, LONGEST, AND MOST CONTINUOUS YARDANGS (KALUTS) OF THE WORLD.

The Lut Desert was added to the UNESCO World Heritage List as the first natural (geological) heritage site of Iran in 2016. One of the main criteria for the recognition of the Lut Desert was the outstanding universal values of the yardangs, which cover about 32% of the core zone of the Lut Desert World Heritage Site (State Party of Iran, 2015). Therefore, the yardangs are one of the main geological elements of the Lut Desert World Heritage Site for which geo-conservation measures have been taken and are being developed (by the Lut Desert World Heritage Base, on behalf of the government). The IUCN assessed its conservation status as "good" in 2020 (IUCN, 2020).

SITE 092

GEOLOGICAL PERIOD	Pliocene – Pleistocene
LOCATION	Lut desert Shahdad region, Kerman province, Iran. 30° 31' 48'' N 058° 13' 19'' E
MAIN GEOLOGICAL INTEREST	Geomorphology and active geological processes Stratigraphy and sedimentology

General Area of Yardangs (Kaluts): the northwestern part of Yardangs (Kaluts) that is intended for general visits. (Photo from Lut Desert World Heritage Base Archive).

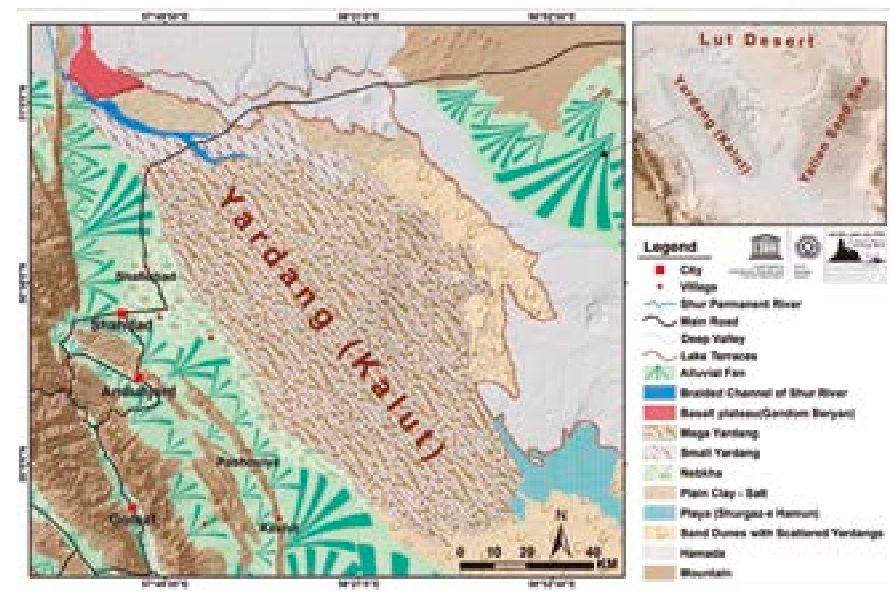
Geological Description

In the Lut Desert, yardangs (kaluts) have been formed by the action of hydro-aeolian processes in lacustrine strata consisting of silt, clay and silty clay with intercalation of salt and gypsum (called Lut Formation in Iran). During the Pliocene, the current location of the yardangs was a lake. The lake dried up due to climate change. The initial rills and gullies were then created by surface runoff caused by seasonal rains. Finally, aeolian processes (by continuous 120-days long, strong and uniform wind known as Sistan) have dominated, and yardangs have expanded and developed (Maghsoudi, 2021). These yardangs, classified by size, include mega-yardang, meso-yardang, and micro-yardang. Each type exhibits considerable morphological diversity. Currently, the highest yardangs in the world with a height of more than 225 meters, the longest yardangs in the world with a length of more than 40 km and the most continuous yardangs in the world with an area of ~7185 square kilometers are located in the west of the Lut Desert (State Party of Iran, 2015; Maghsoudi *et al.*, 2019). Also, the flow of the permanent Shur River in the northern part of the yardangs and the hottest recorded place on Earth (80.83 ÐC - Azarderakhsh *et al.*, 2020) in the southern part of yardangs are extraordinary features of this geological heritage. Because of good access, these yardangs have potential for scientific, educational and geotourism uses (Maghsoudi *et al.*, 2019).

Scientific research and tradition

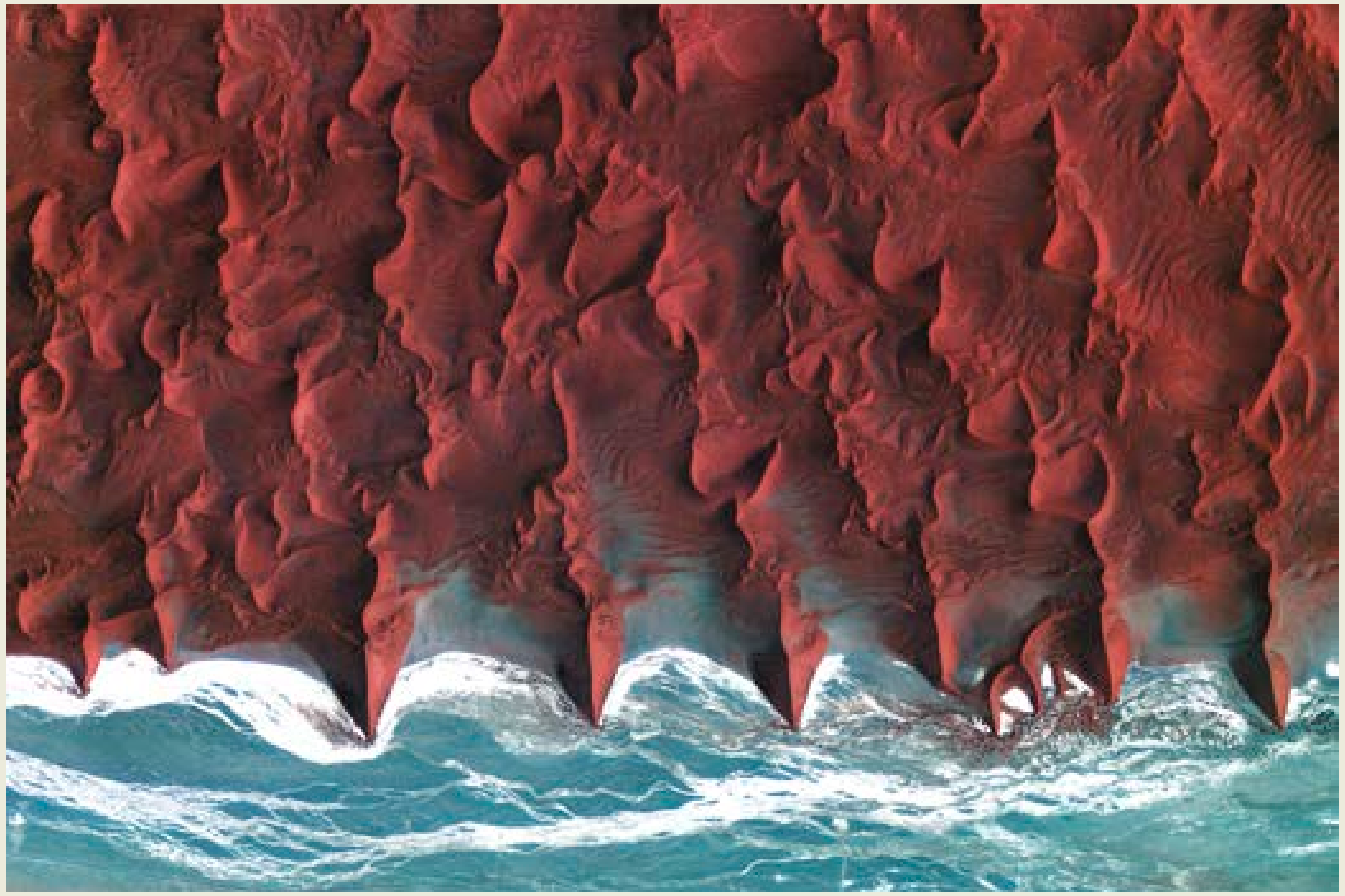
There are scientific reports from the early 1900s (Gabriel, 1938). The focused researches began in 1970 by a scientific group from Iran and France. Since then, various reports, books and papers have been published on the yardangs (kaluts).

Geomorphological map: yardangs (kaluts) fields and significant surrounding geodiversity in the western part of the Lut Desert. The area of both Mega-Yardang and Meso-Yardang is the proposed boundary for the geoheritage of yardang (kalut) in the Lut Desert (after Maghsoudi et al., 2019).



NAMIB SAND SEA

NAMIBIA



UNESCO World Heritage Site

View from the International Space Station of the north-south linear dunes and star dunes along the Tsauchab River Valley. (Courtesy of KARI/ESA).

THE HIGHEST DIVERSITY OF DUNE TYPES IN A COASTAL DESERT INFLUENCED BY FOG.

The Namib Sand Sea is an active geological-geomorphological phenomenon that is a spectacular example of the evolution of a desert landscape.
The Namib Sand Sea, a UNESCO World Heritage Site since 2013, is a well conserved part of the Namib Desert offering a spectacular landscape formed by an interplay of geological, geomorphological, and atmospheric processes.

Dunes of the Namib Sand Sea, developed over an older dune system, exhibit the highest diversity of types and form an unparalleled aeolian geomorphological landscape.
The Namib Sand Sea presents a spectacular and fascinating desert scenery with red hued majestic sand dunes.

SITE 093

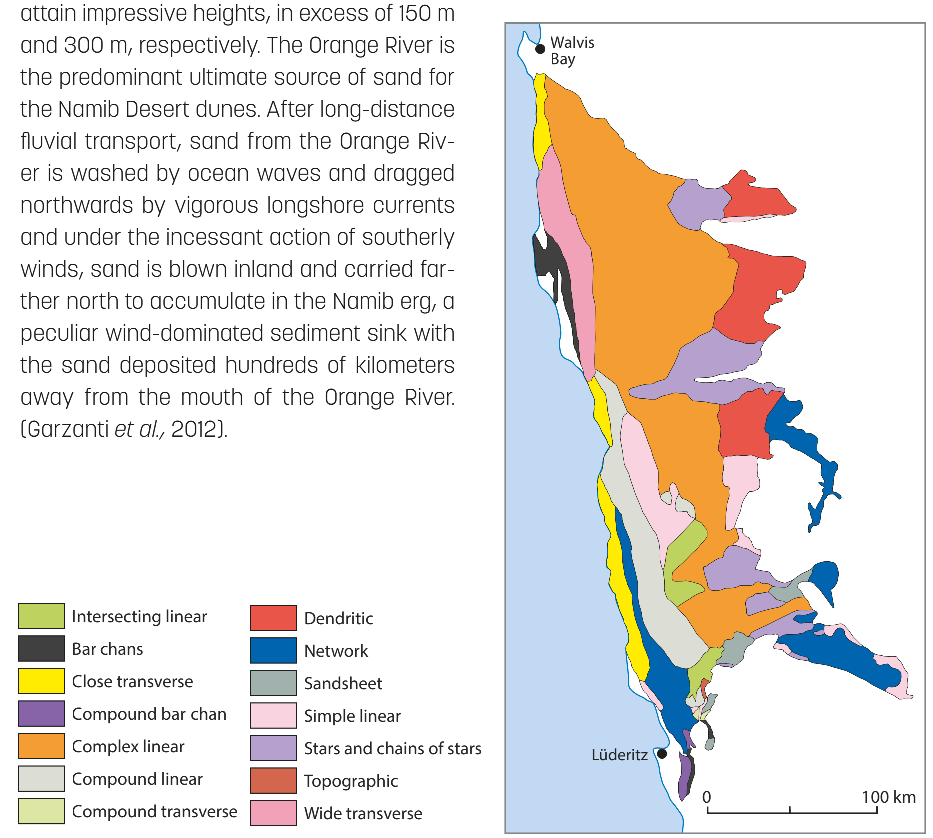
GEOLOGICAL PERIOD	Quaternary / Holocene
LOCATION	Namibia, West. 22° 55' 00" S 015° 09' 00" E
MAIN GEOLOGICAL INTEREST	Geomorphology and active geological processes Stratigraphy and sedimentology

Red star dunes and white playa at Sossus Vlei. (Copyright Olivier Grunewald).

Geological Description

The Namib Sand Sea (the Sossus Sand Formation) is a major physiographic feature of the Namib Desert, covering a 50–160 km wide region of the coast between Lüderitz and Walvis Bay and covering an area of ~34,000 km^2 (Stone, 2013). It is bordered by the southern Atlantic Ocean to the west and by the Great Escarpment of southern Africa to east. New age control from cosmogenic dating indicates that the sand sea is more than a million years old (Vermeesch *et al.,* 2010; Stone, 2013). The sand sea overlies a Neogene age fossil desert (the Tsondab Sandstone Formation). The sandy desert is dominated by large linear dunes and has areas of star-shaped dunes on its eastern margin and a belt of simple and compound transverse and barchanoid dunes along the coast (Livingstone, 2013). Linear and star dunes attain impressive heights, in excess of 150 m and 300 m, respectively. The Orange River is the predominant ultimate source of sand for the Namib Desert dunes. After long-distance fluvial transport, sand from the Orange River is washed by ocean waves and dragged northwards by vigorous longshore currents and under the incessant action of southerly winds, sand is blown inland and carried further north to accumulate in the Namib erg, a peculiar wind-dominated sediment sink with the sand deposited hundreds of kilometers away from the mouth of the Orange River. (Garzanti *et al.,* 2012).

Distribution of different dune types in the Namib Sand Sea after (Livingston et al., 2010).



Scientific research and tradition

The Namib Sand Sea has been studied over the past 50 years since the establishment of the research station at Gobabeb, which served as a base for geoscientific work by a considerable number of scientists. Numerous papers including in top journals have been published about the geology and geomorphology of the Namib Sand Sea.

BILUTU MEGADUNES AND LAKES IN THE BADAIN JARAN DESERT

CHINA

UNESCO Global Geopark

Bilutu Sand Peak and interdune lake.

THE LARGEST MEGADUNES IN THE WORLD AND A UNIQUE MEGADUNE-LAKE SYSTEM.

The unique megadune-lake system and the largest dunes in the world are the product of Asian inland aridity, and directly and objectively reflect the history and process in this area. The site, located in the west wind and monsoon transition zone and north-east edge of Qinghai-Xizang Plateau, is an ideal area to study late Quaternary climate change along with the uplift of Qinghai-Tibet Plateau, and water resources in the arid area of aeolian landform. It is also of great practical significance for studying people's livelihood-related matters, such as aeolian sand control.

SITE 094

GEOLOGICAL PERIOD	Late Quaternary
LOCATION	Alxa Desert Geopark, Inner Mongolia Autonomous Region, China. 39° 32' 00" N 102° 05' 00" E
MAIN GEOLOGICAL INTEREST	Geomorphology and active geological processes

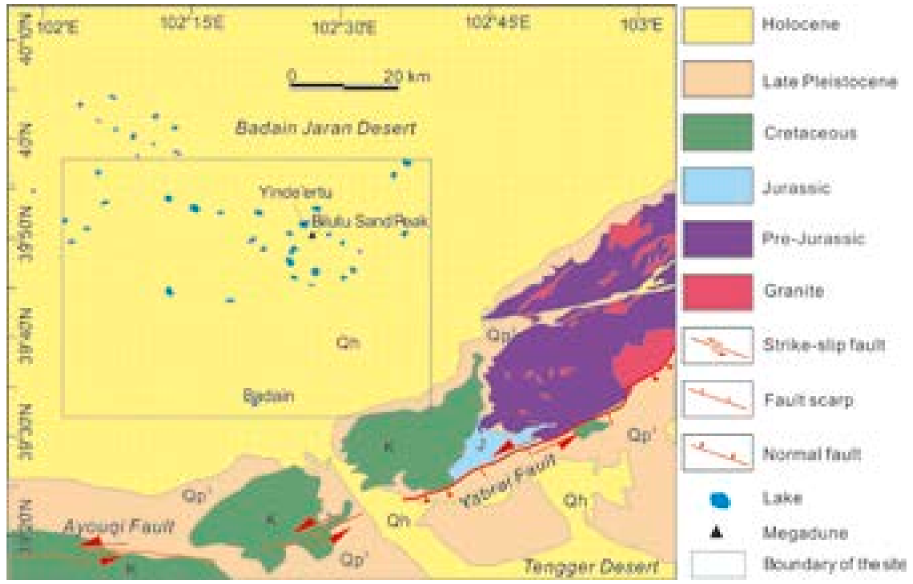
Megadunes and interdune lakes in the Badain Jaran Desert.

Geological Description

The Badain Jaran Desert (BJD) hosts the largest megadunes in the world and the unique megadune-lake system (Chen *et al.,* 2019). Most of the megadunes are over 300m high, with the highest, the Bilutu Sand Peak, a compound transverse dune, of 450m (Dong *et al.,* 2004). Currently, there are more than 100 lakes in the site, mostly smaller than 1km². The bottom age of the desert is ca. 1100 ka. The site is located in the transitional zone between the Asian summer monsoon and the Westerlies, and it is west of the Yabrai Fault. The climate changes and tectonic evolution of Yabrai Fault play important roles in the formation and maintenance of the unique megadune-lake system in the BJD. During the humid periods since MIS 15, extensive lakes developed. Climate changes led to fixation, reactivation and ultimate formation of megadunes. Uplift of the Yabrai Mountains formed a topographic barrier, which suppresses and enhances sand transport by affecting climate, wind and water circulation (Wang *et al.,* 2015; Du *et al.,* 2019). The megadunes in the BJD are becoming higher and steeper because of the upward migration and accumulation of sands that originate from the lake basin (wang *et al.,* 2019).

Scientific research and tradition

The early scientific study of the site dates to 1927. Systematical and in-depth investigation and research of the BJD began in the 1960s, and more than 150 papers have been published. This site has been well managed and protected within the Alxa Desert UNESCO Global Geopark since 2009.



Geological map of the site (Du et al., 2021).

VAJONT LANDSLIDE

ITALY

The extensive scarp and the huge body of the Vajont landslide detached from Mt. Toc. (Drone photo courtesy Monica Ghirotti).

ONE OF THE MOST EMBLEMATIC AND BEST RESEARCHED LARGE LANDSLIDES WORLDWIDE KNOWN FOR ITS PECULIAR DYNAMICS AND CATASTROPHIC EFFECT.

The Vajont is one of the best researched landslide localities globally, and it has received regular attention from the scientific community during the last 60 years. It has a unique scientific importance, as the complex geology and mechanism of the landslide have been debated since the occurrence of the event, which was a turning point in the scientific knowledge of landslides. The wide scar and the enormous landslide body are still visible in their entire extent, and they indelibly mark the landscape of the valley. The site is easily accessible to visitors, who can also visit a memorial museum in Longarone, the first village to be destroyed. The Vajont can be considered an excellent example of a site of landslide geomorphology (Morino *et al.*, 2022).

SITE 095

GEOLOGICAL PERIOD	Quaternary / Holocene
LOCATION	Vajont valley (Eastern Italian Alps). Friuli Venezia Giulia, Italy. 46° 15' 30'' N 012° 20' 31'' E
MAIN GEOLOGICAL INTEREST	Geomorphology and active geological processes Engineering Geology

Panoramic view of the Vajont valley and of the residual lake located upstream of the landslide. (Photo: Mauro Soldati).

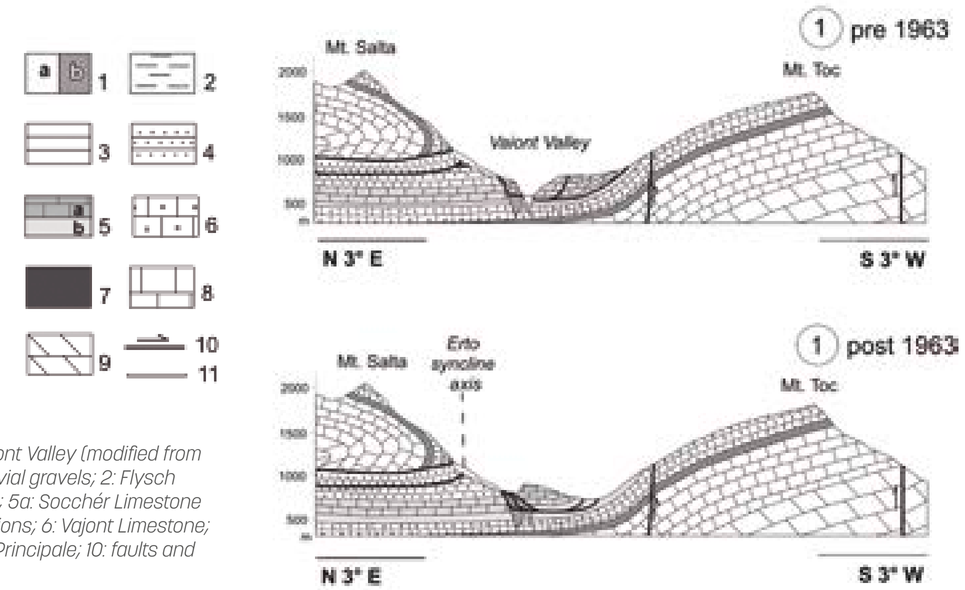
Geological Description

The Vajont landslide is a vast compound rock slide of approximately 270 million m^3 of rock and debris detached from Mount Toc in 1963. It collapsed into a reservoir created by a 262 m high double curved arch dam built across the Vajont valley (Ghirotti, 2012). The movement mainly involved jointed limestone and marl of Jurassic and Cretaceous age, and it occurred along a M-shaped failure surface, which corresponds to a paleo-sliding surface (Semenza and Ghirotti, 2010). The impressive landslide body filled the reservoir in a few tens of seconds, causing the overflow of the dam and a 50 million m^3 displacement wave that destroyed seven villages in the Piave River Valley, killing almost 2000 people.

The dynamics of the initial stages of movement and of the final collapse are complex and still under debate (Selli *et al.*, 1964; Hendron and Patton, 1985; Paronuzzi and Bolla, 2012), but the groundwater variations related to the reservoir water filling operation are considered as the most important triggering factors.

Scientific research and tradition

The Vajont is one of the best-studied landslides in the world. The site is visited and studied by many scientists, and hundreds of articles have been published. A dedicated museum and many scientific and educational projects have been promoted in order to preserve the memory of the deadliest landslide event in Europe in recorded history.



Pre-1963 and post-1963 geological sections of the Vajont Valley (modified from Ghirotti, 2012). Legend: 1a: Quaternary; 1b: stratified alluvial gravels; 2: Flysch Formation; 3: Marls of Erto; 4: Scaglia Rossa Formation; 5a: Socchér Limestone Formation; 5b: Ammonitico Rosso and Fonzaso formations; 6: Vajont Limestone; 7: Igne Formation; 8: Soverzene Formation; 9: Dolomia Principale; 10: faults and overthrusts; 11: failure surface of the 1963 landslide.

PAMUKKALE TRAVERTINES

TURKEY

UNESCO World Heritage Site

Terrace pools at sunset in Pamukkale, (Photo from Archive of Ministry of Culture and Tourism).

A GLOBALLY OUTSTANDING TYPE SITE WITH A HIGH DIVERSITY OF TRAVERTINE FEATURES AND PROCESSES ON AN ACTIVE FAULT.

The Pamukkale travertines are a key location for 'travitonics' embracing all aspects of travertine tectonics. This region includes five of six morphologies suggested for travertine deposits accompanied with active faults; these include terrace-mound, fissure-ridge, range-front, eroded-sheet and self-built channel travertine (Hancock *et al.,* 1999). The dateable character of travertines by the U-series method allows the determination of ancient tectonic activity such as the destruction of the ancient city of Hierapolis. The travertines reveal how seismicity affected the ancient Hellenistic to Byzantine civilizations, and modern urban develoments (Kumsar *et al.,* 2016).

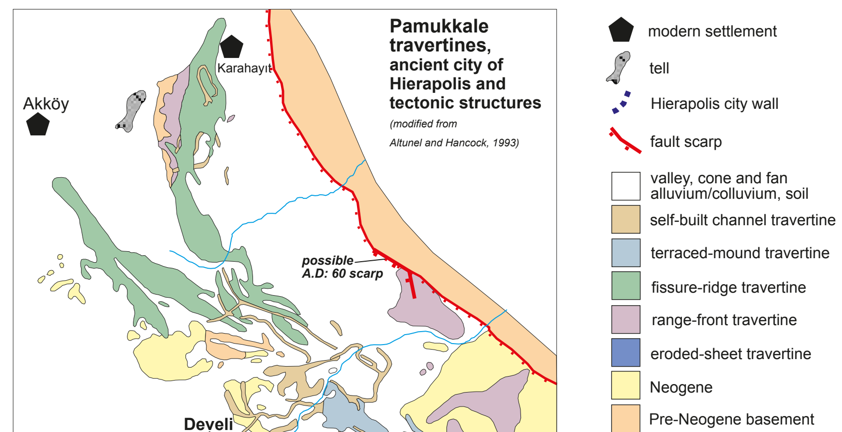
SITE 096

GEOLOGICAL PERIOD	Middle Pleistocene - Holocene
LOCATION	Pamukkale, Denizli, Turkey. 37° 55' 25" N 029° 07' 15" E
MAIN GEOLOGICAL INTEREST	Geomorphology and active geological processes Stratigraphy and sedimentology

Self-built channel formed by flowing thermal waters and, Çukurbağ Fissure ridge at the background. (Photo: Mehmet Özkul).

Geological Description

Pamukkale is a globally important type locality for travertine (Altunel and Hancock, 1993; Altunel and D'Andria, 2019). Pamukkale means "cotton castle" in Turkish for its snow-white colored travertine terraces. Calcium-carbonate-laden geothermal waters with temperatures higher than 35 °C sourced from a fault scarp have, since the middle Pleistocene, created an outstanding natural landscape. The groundwater circulation through limestone bedrock is a key component in the supersaturation of hot waters with calcite (Kele *et al.,* 2011). There is a high diversity of step-like terraces with pools (terrace-mounds), fissure ridges, and individual channel-type travertine formations and related hot springs (Hancock *et al.,* 1999). These have attracted different civilizations over thousands of years, and as a result, while the ancient city of Hierapolis was established next to it, the Pamukkale travertine is still the most visited international destination point in Turkey (Scoon, 2021). Several destructive earthquakes damaged ancient structures in Hierapolis by rupturing along an active fault, and there is a long record of historical seismicity in the area (Kumsar *et al.,* 2016). Therefore, it is long-time voiced that the Hierapolis ancient city can provide a broad basis to realize the relationship between seismic damage and active faulting.



Main travertine types in Pamukkale (modified from Altunel and Hancock 1993)

Scientific research and tradition

Pamukkale has been the subject of much research into travertine formation and paleoseismicity, and of many documentaries. Its photos are used for publication covers in many disciplines; its cultural heritage has been linked to the unique travertine deposits.

PUQUIOS OF THE LLAMARA SALT FLAT
CHILE

The Puquios are natural depressions where subterranean water come to the surface at the western part of Atacama desert, the most arid of the world. (Photo: Sernageomin).

MICROBIAL MATS ON THE BRINE LAGOONS OF THE ATACAMA DESERT SIMILAR TO THE FIRST ORGANISMS INHABITING THE EARTH.

The Puquios de Llamara is one of the driest and most irradiated environments of Earth, and from the biodiversity studies it has been proposed as analogous to the primitive Earth (Gutiérrez-Preciado *et al.,* 2018). The microbial mats, evaporitic domes and their metabolic transitions recapitulate what happened during the great oxygenation event, that is, when cyanobacteria began to produce oxygen 2.5 billion years ago (Gutiérrez-Preciado *et al.,* 2018). These poly-extreme environments open a universe of possibilities to elucidate these ancient metabolic pathways that provide critical information about early life in extreme environments (Farías *et al.,* 2017).

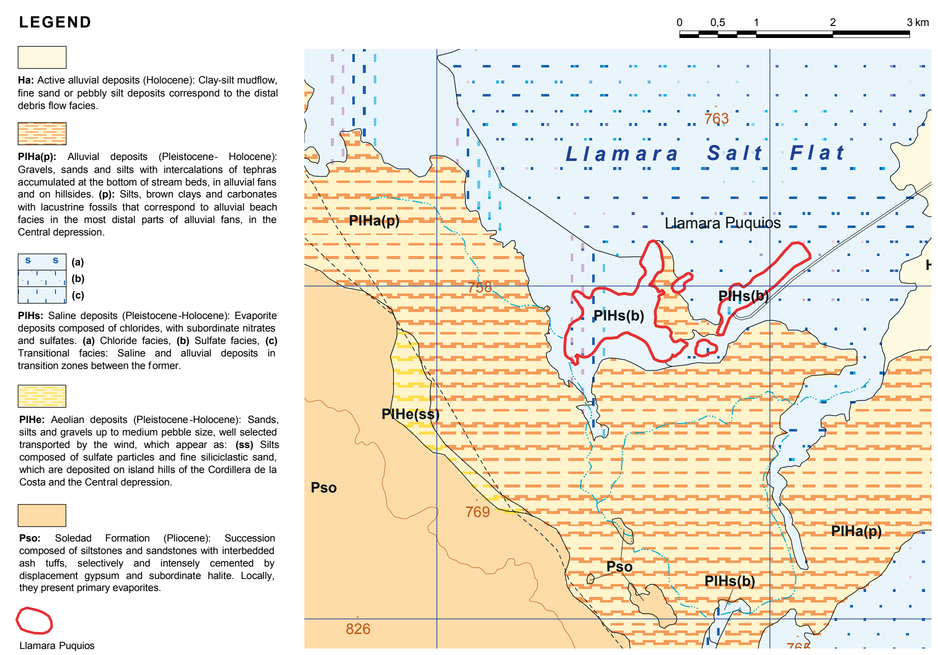
SITE 097

GEOLOGICAL PERIOD	Pleistocene-Holocene
LOCATION	Tarapacá Region, Chile. 20° 37' 19" S 069° 39' 44" W
MAIN GEOLOGICAL INTEREST	Geomorphology and active geological processes Geobiology

Subaquatic photo of microbial mats of cyanobacteria and sulphate minerals creating evaporitic domes within the ponds. (Photo: Sernageomin).

Geological Description

The Llamara salt flat is made up of salt crusts and smaller amounts of fine sediment. Among the most common salts are sulfates (gypsum, anhydrite), carbonates, nitrates and halides (common salt) that form a superficial crust (Vásquez *et al.,* 2018), associated with deep groundwater, from the Pampa del Tamarugal aquifer. In the Puquios, the chemical analysis of these waters shows that there is a predominance of sulfates and dissolved sodium in them, although in some sectors chlorine or bicarbonate, and magnesium or calcium also predominate, especially towards the southwest of the salt flat (López *et al.,* 2017). Geological and climatic conditions have allowed the development of microbial mats of cyanobacteria and other organisms and of microbial structures like evaporitic domes (stromatolites). Microbial mats are laminated structures, which are controlled by environmental factors such as light, temperature, salinity, dissolved oxygen, and the presence of sulfides. These laminations have different colorations as a result of the development of photosynthetic bacteria that contain photosynthetic pigments and, therefore, different patterns of available light (Farías *et al.,* 2017). The evaporitic domes occur where microorganisms form aggregates occupying the pore spaces inside halite, where microbial interactions occur (Farías *et al.,* 2017).



Extract of the Guanillos of the north and Llamara salt flat geological map (modified of Vásquez et al., 2018).

Scientific research and tradition

The Puquios of the Llamara salt flat has been studied by various specialists in geology, hydrogeology, salt deposits, mineral resources (saline deposits) and biology.

ŠKOCJAN CAVES IN THE CLASSICAL KARST

SLOVENIA

UNESCO World Heritage Site

Underground canyon of Škocjan Caves which is about 100 m high and 3 km long.

AN OUTSTANDING KARST SYSTEM IN THE CLASSICAL KARST WITH ONE OF THE LARGEST KNOWN UNDERGROUND CANYONS IN THE WORLD.

Škocjan caves, with their numerous remarkable speleological, hydrological and morphological karst features, are unique in their appearance and size. They are one of the most spectacular examples of contact karst formed by a torrential sinking river at the contact of impermeable flysch and permeable limestone. Textbook examples of sinkholes, natural bridges, gorges, potholes, collapse dolines, abysses, an underground canyon, springs, and passages covered with flowstone deposits give this small area worldwide significance in the study of karst features and processes. Due to their geological and aesthetic importance, Škocjan Caves have been on the UNESCO World Heritage List since 1986.

SITE 098

GEOLOGICAL PERIOD	Neogene - Holocene
LOCATION	Kras (Karst). Škocjan Caves UNESCO World Heritage, Slovenia. 45° 39' 47" N 013° 59' 21" E
MAIN GEOLOGICAL INTEREST	Geomorphology and active geological processes

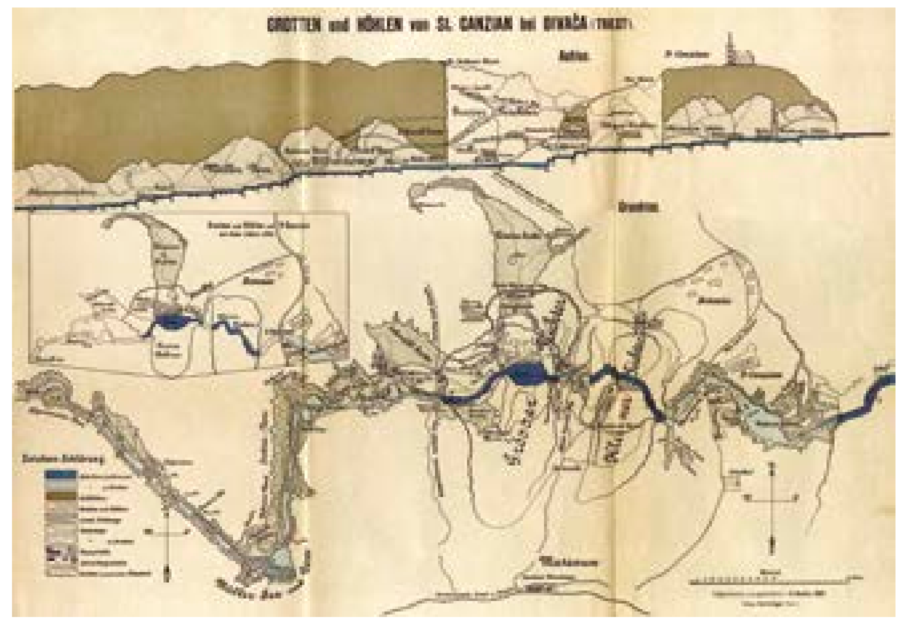
A view of the Big and the Little Collapse Doline with the River Reka flowing at the bottom.

Geological Description

The Škocjan Caves are an approximately 6 km long cave system formed by sinking Reka river which flows from impermeable Eocene flysch rocks into the mostly well bedded Upper Cretaceous limestone of the Kras Plateau. The area is extremely rich in surface karst formations, caves, and especially collapse dolines and unroofed caves, the latter being described for the first time in this area. Rock stratification and tectonic deformation have significantly influenced the formation and spatial distribution of the passages. The main cave passage is impressive with a canyon about 100 m high, where the river flows, and one of the largest cave chambers in the world with a volume of 2.5 million m^3. Due to the torrential nature of the Reka river, the water level in the cave rises up to 130 m during occasional floods. In the sediments, brought by the river into the caves from the surface to the ponors, about 5 million years of karst and cave evolution is written. When describing collapse dolines, karstologists based their writing on Velika and Mala dolina and the term collapse dolines is currently used in the international karstic terminology (Boegan, 1924; Oedl, 1924; Aljančič *et al.*, 1998; Kranjc, 2002).

Scientific research and tradition

In the 19th century, this geosite in the heart of Classical Karst, contributed to the emergence and development of karstology, speleology and speleobiology as scientific disciplines (Müller, 1890). Due to the distinctive relief forms, local terms for karst phenomena, such as kras (karst) itself, entered the international scientific terminology.



Plan of Škocjan Caves by A. Hanke in 1888 (Müller F 1890; Archive of the Department for Karst and Cave Studies, Natural History Museum in Vienna).

SAC ACTUN UNDERWATER CAVE SYSTEM
MEXICO

Heaven's gate. One of the most popular places of the cenote Nohoch Nah Chich part of the Sac Aktun system. (Photo: Álvaro Herrero. Mekanphotography).

THE LONGEST UNDERWATER CAVE SYSTEM IN THE WORLD.

The extensive cave systems under the Yucatan Peninsula have been a guardian of hidden and invaluable treasures to learn from our history. Remains of Pleistocene animals and humans that date from a time long before the occupation by the Mayan civilization have been found within submerged passages and galleries (de Azevedo *et al.,* 2015). Being underwater, these caves provide a unique environment for the preservation of human and animal remains linked to a fascinating and unique geological and geomorphological history (Collins *et al.,* 2015), and they provide evidence of the Holocene paleoclimate (van Hengstum *et al.,* 2010).

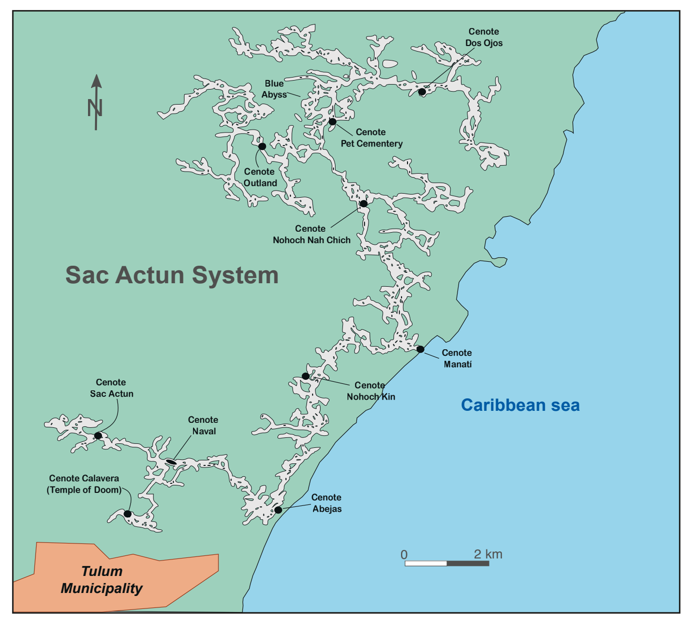
SITE 099

GEOLOGICAL PERIOD	Pleistocene
LOCATION	Yucatán Peninsula / Quintana Roo State – Mexico. 20° 14' 47" N 087° 27' 51" W
MAIN GEOLOGICAL INTEREST	Geomorphology and active geological processes

The Blue Abyss is an underwater shaft of 71 m in depth part of the Sac Actun System. (Photo: Álvaro Herrero. Mekanphotography).

Geological Description

The Sac Actun cave is 368 km long, making it the longest underwater cave system in the world and the second longest cave in the world after Mammoth Cave in Kentucky, USA. This system is in the Yucatan Peninsula in Mexico and formed on a sedimentary platform of Mesozoic and Cenozoic rocks with a thickness of up to 3500 meters (Kambesis and Coke, 2016). The most extensive rocks belong to the Carrillo Puerto Formation with ages ranging from Miocene to Pliocene. They accumulated in a shallow marine environment affected by constant sea level variations with constant emersions and submersion as evidenced by at least three "caliches" levels recorded in situ (Collins *et al.,* 2015). It is important to note that the Yucatan Platform has been stable since the Cretaceous, and the karst development is the result of the dynamics of the mixing zone (halocline). The mixing zone was affected by sea-level changes, which allow for paleoenvironmental interpretations (Gabriel *et al.,* 2009). More than 7000 sinkholes (cenotes) exist in the Yucatan Peninsula. These are deep sinkholes, and most of them occur in the region of the Sac Actun System (Smart *et al.,* 2016) (Kambesis and Coke IV, 2016).



Sac Actun system. Underwater cartography is a very slow, expensive, and risky work. Every year divers survey for new sections of the Sac Actun system, and the information is compiled by the Quintana Roo Speleological Survey in a volunteer effort.

Scientific research and tradition

The Sac Actun underwater cave system has been extensively studied for knowledge of its geology and karst geomorphology, the paleoclimatic and paleoenvironmental evolution of the Yucatan Peninsula, ecosystem services of the underground system, and preserved archives of archaeological, anthropological, and paleontological evidence of occupation in different periods.

9

IMPACT STRUCTURES AND EXTRATERRESTRIAL ROCKS

SITE 100

Meteorite impacts record the history of collisions between celestial bodies resulting from the evolution of the solar system. Our planet Earth is no less: it also suffered many large-size collisions during its early history. Since then, it has received multiple impacts from asteroids and comets, and it is still continuously colliding with the remaining smaller bodies in the form of "shooting stars" and meteorites. How do we know about this earlier evolution? Because of the geological evidence left behind. The evidence includes typical circular structures, rocks and minerals permanently deformed by impact-related shock waves and rocks formed as a result of the impact, called impactites. Sometimes, even the geochemical signature of the impactor is preserved in the geological record. The size of the crater and its internal morphology depend on the mass, composition and velocity of the bolide, as well as on the characteristics of the substrate where it collided. Furthermore, chronostratigraphic and geochronological dating allow the age of collision to be constrained, providing useful information to relate it with other events, such as mass extinctions, relevant to understand the history of our planet and the evolution of life. Thus, meteorite impact sites allow scientists to understand many different aspects of Earth's evolution. In fact, the fundamental basic components needed by human society (air, water, mineral deposits, even life itself) were greatly conditioned by cosmic collisions that led to the current Earth.

This chapter only includes one meteorite impact location as IUGS Geological Heritage Site: the Araguainha impact site, a complex-type impact structure 40 km in diameter. This scarcity is only transitory, as there are many other meteorite impact structures on Earth. In fact, even with active geological processes rapidly erasing impact structures from the geological record, we now know of ca. 200 confirmed impact sites (Earth Impact Database, University of New Brunswick, Canada), and the list keeps slowly growing. The majority of these structures have diameters between 5 and 20 km, but there are some below 1 km diameter and three above 100 km. Hence, the possibility to include more impact sites on the list in coming years is evident. Hopefully, they will represent the different ages, sizes, depths, tectonic features and mineralogy that characterize the record of meteorite impacts on Earth.

Joana P. Sánchez
Federal University of Goiás (UFG). Brazil.
IUGS Geological Heritage Sites voting member.

Álvaro P. Crósta
State University of Campinas (UNICAMP). Brazil
IUGS Geological Heritage Sites voting member.

Enrique Díaz-Martínez
IGME-CSIC, Spain.
IUGS Geological Heritage Sites voting member.


Domo de
Araguainha
Impact
Structure
BRAZIL

DOMO DE ARAGUAINHA IMPACT STRUCTURE
BRAZIL

View of the central uplift of Araguainha Dome. The hills comprise Furnas sandstone and impact breccia. The scene in the background is close to 3 km across. (Photo: J. Sanchez).

THE LARGEST (~40 KM) AND BEST EXPOSED IMPACT STRUCTURE IN SOUTH AMERICA WITH EXAMPLES OF IMPACTITES AND SHOCK DEFORMATION FEATURES.

The structure boasts spectacular scenery and is easily accessible. A diversity of impact lithologies, such as polymictic impact breccia and impact melt rocks, together with abundant shock deformation features such as shatter cones and a variety of microscopic shock deformation features, make the Araguainha Dome a fantastic natural laboratory to understand impact cratering and planetary processes. It has even been suggested that this impact could have been involved, directly or indirectly, with the major mass extinctions at the Permian-Triassic boundary. Textbook examples of impactites and shock deformation features make Araguainha an ideal location for developing geotourism, geoheritage and geoconservation-related, as well as educational, activities.

SITE 100

GEOLOGICAL PERIOD	Permian-Triassic boundary
LOCATION	States of Mato Grosso and Goiás, central Brazil. 16° 48' 00" S 052° 59' 00" W
MAIN GEOLOGICAL INTEREST	Impact structures and extraterrestrial rocks Stratigraphy and sedimentology

Prominent shatter cones in phyllites of the crystalline basement. Pen for scale is 14 cm long. (Photo: A. P. Crósta).

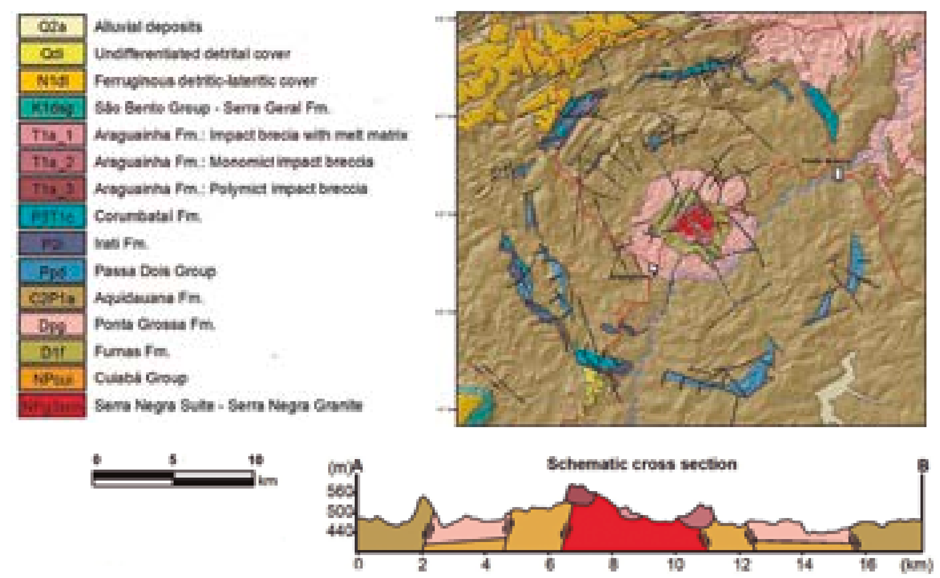
Geological Description

The Domo de Araguainha (Araguainha Dome) exhibits a large diversity of rock types and impact features exposed in its >1.3 thousand km² area, including Neoproterozoic and Paleozoic crystalline rocks at the center of the structure that are surrounded by Silurian to Permian sedimentary strata of the intracratonic Paraná Basin. The impact structure is cut by the Araguaia River that drains into the Amazon River basin. The structure exhibits an annular, concentric structure with a central uplift where the Neoproterozoic to Cambrian crystalline basement is well exposed. The central uplift is surrounded by sedimentary sequences of the Paraná Basin including, from the base to the top, the Rio Ivaí (Silurian), Paraná (Devonian), Itararé (Carboniferous), and Passa Dois (Permian) groups. The sedimentary strata are arranged in a bull´s eye pattern around the central crystalline core, forming a formidable geological scenario. Impactites, namely polymict impact breccia and various types of impact melt rock, occur abundantly in the central portion of the structure.

Scientific research and tradition

Brazilian and foreign scientific investigations have been conducted at Araguainha since the 1960s, and results have been widely published. Excursions have been conducted as part of international conferences, such as an International Geological Congress, Annual Meeting of the Meteoritical Society, Large Meteorite Impacts and Planetary Evolution VI conference.

Geological map and cross section for the Araguainha Dome (CPRM/Brazilian Geological Survey); inset: location of the structure in the Paraná Basin (dark grey).



REFERENCES

I. HISTORY OF GEOSCIENCE

1. Siccar Point (Hutton's Unconformity)

Browne, M.A.E. and Barclay, W.J. (2005) 'Siccar Point to Hawk's Heugh, Scottish Borders', in *The Old Red Sandstone of Great Britain*. Barclay, W.J., Browne, M.A.E., McMillan, A.A., Pickett, E.A., Stone, P. and Wilby P.R. Peterborough: Joint Nature Conservation Committee (Geological Conservation Review Series, 31), pp. 181–187.

Dean, D. (1992) *James Hutton and the History of Geology*. Cornell University Press: Ithaca.

Greig, D.C. (1988) *Geology of the Eyemouth District*. Sheet 34 (Scotland). London: HMSO, p. 78.

Hutton, J. (1788) 'Theory of the Earth; or an investigation of the laws observable in the composition, dissolution, and restoration of land upon the Globe', in *Transactions of the Royal Society of Edinburg*. (1), pp. 209–304.

Hutton, J. (1795) *Theory of the Earth. With Proofs and Illustrations* (I and II). Cadell & Davies, London; William Creech, Edimburg.

Treagus, J.E. (1992) 'Siccar Point', in *Caledonian Structures in Britain South of the Midland Valley*. Treagus, J.E. Peterborough: Joint Nature Conservation Committee (Geological Conservation Review Series, 27), pp. 17–19.

2. The Quaternary Phlegrean Fields volcanic complex

Dean, D. (1998) 'Italian volcanoes and English observers', in Volcanoes and History: Proceedings of the 20th INHIGEO Symposium, Napoli-Eolie-Catania (Italy) , 19-25 September 1995. Genova: Brigati, pp. 99–122.

Di Vito, M.A. *et al*. (1999) 'Volcanism and deformation since 12,000 years at the Campi Flegrei caldera (Italy)', Journal of Volcanology and Geothermal Research, 91(2), pp. 221–246. Available at: https://doi.org/10.1016/S0377-0273(99)00037-2.

Hamilton, W. (1776) Campi Phlegraei. Observations on the Volcanos of the two Sicilies as they have been communicated to the Royal Society of London. Naples: Fabris.

Isaia, R. *et al*. (2019) 'High-resolution geological investigations to reconstruct the long-term ground movements in the last 15 kyr at Campi Flegrei caldera (southern Italy)', Journal of Volcanology and Geothermal Research, 385, pp. 143–158. Available at: https://doi.org/10.1016/j.jvolgeores.2019.07.012.

Orsi, G., D'Antonio, M. and Civetta, L. (eds) (2022) Campi Flegrei: A Restless Caldera in a Densely Populated Area. Berlin Heidelberg: Springer Book Series (Active Volcanoes of the World).

Orsi, G., Di Vito, M.A. and Isaia, R. (2004) 'Volcanic hazard assessment at the restless Campi Flegrei caldera', Bulletin of Volcanology, 66(6), pp. 514–530. Available at: https://doi.org/10.1007/s00445-003-0336-4.

Sbrana, A., Marianelli, P. and Pasquini, G. (2021) 'The phlegrean fields volcanological evolution', Journal of Maps, 17, pp. 545–558. Available at: https://doi.org/10.1080/17445647.2021.1982033.

3. Mohorovičić discontinuity at Gros Morne National Park

Church, W.R. and Stevens, R.K. (1971) 'Early Paleozoic ophiolite complexes of the Newfoundland Appalachians as mantle-oceanic crust sequences', Journal of Geophysical Research (1896-1977), 76(5), pp. 1460–1466. Available at: https://doi.org/10.1029/JB076i005p01460.

Dewey, J.F. and Bird, J.M. (1971) 'Origin and emplacement of the ophiolite suite: Appalachian ophiolites in Newfoundland', Journal of Geophysical Research (1896-1977), 76(14), pp. 3179–3206. Available at: https://doi.org/10.1029/JB076i014p03179.

Dewey, J.F. and Casey, J.F. (2013) 'The sole of an ophiolite: the Ordovician Bay of Islands Complex, Newfoundland', Journal of the Geological Society, 170(5), pp. 715–722. Available at: https://doi.org/10.1144/jgs2013-017.

Hess, H.H. (1938) 'A Primary Peridotite Magma', American Journal of Science, 35, pp. 321–344.

Kerr, A. (2019) 'Classic Rock Tours 2. Exploring a Famous Ophiolite: A Guide to the Bay of Islands Igneous Complex in Gros Morne National Park, Western Newfoundland, Canada', Geoscience Canada, pp. 101–136. Available at: https://doi.org/10.12789/geocanj.2019.46.149.

Williams, H. (1979) 'Appalachian Orogen in Canada', Canadian Journal of Earth Sciences, 16(3), pp. 792–807. Available at: https://doi.org/10.1139/e79-070.

4. The Holocene Puy-de-Dôme and Petit-Puy-de-Dôme volcanoes

Deniel, C. *et al*. (2020) 'Multi-stage growth of the trachytic lava dome of the Puy de Dôme (Chaîne des Puys, France). Field, geomorphological and petro-geochemical evidence', Journal of Volcanology and Geothermal Research, 396, p. 106749. Available at: https://doi.org/10.1016/j.jvolgeores.2019.106749.

Desmarest, N. (1771) 'Mémoire sur l'origine et la nature du basalte à grandes colonnes polygones, déterminées par l'histoire naturelle de cette pierre, observée en Auvergne', in Histoire et mémoires de l'Académie Royale des Sciences. Paris, pp. 705–775.

Guettard, J.-É. (1752) 'Sur quelques montagnes de France qui ont été des volcans', in Mémoire lu à l'Académie Royale des Sciences. Paris.

Miallier, D. *et al*. (2010) 'The ultimate summit eruption of Puy de Dôme volcano (Chaîne des Puys, French Massif Central) about 10,700 years ago', Comptes Rendus Geoscience, 342(11), pp. 847–854. Available at: https://doi.org/10.1016/j.crte.2010.09.004.

Petronis, M.S., van Wyk de Vries, B. and Garza, D. (2019) 'The Leaning Puy de Dôme (Auvergne, France) tilted by shallow intrusions', Volcanica, 2(2), pp. 161–186. Available at: https://doi.org/10.30909/vol.02.02.161186.

Taylor, K.L. (2007) 'Geological travellers in Auvergne, 1751–1800', Geological Society, London, Special Publications, 287(1), pp. 73–96.

van Wyk de Vries, B. *et al*. (2014) 'Craters of elevation revisited: forced-folds, bulging and uplift of volcanoes', Bulletin of Volcanology, 76(11), p. 875. Available at: https://doi.org/10.1007/s00445-014-0875-x.

5. The Paleocene volcanic rocks of the Giant's Causeway and Causeway coast

Hamilton, W. (1786) Letters concerning the northern coast of the county of Antrim. Containing a natural history of its basaltes: with an account of such circumstances as a worthy of notice representing the antiquities, manners and customs of that country. London: Printed by G. Robinson and Co.

Lyle, P. and Preston, J. (1993) 'The geochemistry and volcanology of the Tertiary basalts of the Giant's Causeway area, Northern Ireland', Journal of the Geological Society of London, (149), pp. 109–120.

Richardson, W. (1805) Inquiry into the origin of the opinion that basalt is a volcanic production, with the motives that induced the author to publish it, and the modes adopted by its advocates to obtain it credit, with the facts and arguments adduced by different writers in its support: and also, the arguments and facts from the Giant's Causeway and its vicinity, by which this opinion is proved to be precipitately adopted, and totally unfounded. Dublin: Graisberry and Campbell.

Simms, M.J. (2021) 'Subsidence, not erosion: Revisiting the emplacement environment of the Giant's Causeway, Northern Ireland', Proceedings of the Geologists' Association, 132(5), pp. 537–548. Available at: https://doi.org/10.1016/j.pgeola.2021.07.001.

Tomkeieff, S.I. (1940) 'The basalt lavas of the Giant's Causeway district of Northern Ireland', Bulletin of Volcanology, 6(1), pp. 89–143. Available at: https://doi.org/10.1007/BF02994875.

Wyse Jackson, P. (2000) 'Tumultuous times: geology in Ireland and the debate on the nature of basalt and other rocks of north-east Ireland between 1740 and 1816', in Science and Engineering in Ireland in 1798: a time of revolution. Dublin: Royal Irish Academy, p. viii+81, pp. 35–49.

6. Funafuti Atoll

Armstrong, H.E. *et al*. (1904) The atoll of Funafuti; borings into a coral reef and the results, being the report of the Coral Reef Committee of the Royal Society. London, The Royal Society of London. Available at: http://archive.org/details/atolloffunafutib00roya (Accessed: 22 July 2022).

Darwin, C. (1842) The Structure and Distribution of Coral Reefs: Being the First Part of the Geology of the Voyage of the Beagle, under the Command of Capt. Fitzroy, R.N. during the Years 1832 to 1836. London: Smith, Elder and Co (Cambridge Library Collection - Earth Science). Available at: https://doi.org/10.1017/CBO9781107325098.

Gaskell, T.F. and Swallow, M.A. (1953) Seismic experiments on two Pacific atolls. F.J. Milner (Occasional papers of the Challenger Society, 3).

Krüger, J. (2008) High-Resolution Bathymetric Survey of Tuvalu. Suva: Pacific Islands Applied Geoscience Commission.

Ohde, S. *et al*. (2002) 'The chronology of Funafuti Atoll: revisiting an old friend', Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences, 458(2025), pp. 2289–2306. Available at: https://doi.org/10.1098/rspa.2002.0978.

Stoddart, D.R. (1969) 'Ecology and Morphology of Recent Coral Reefs', Biological Reviews, 44(4), pp. 433–498. Available at: https://doi.org/10.1111/j.1469-185X.1969.tb00609.x.

7. Capelinhos volcano

Cole, P.D. *et al*. (2001) 'Capelinhos 1957–1958, Faial, Azores: deposits formed by an emergent surtseyan eruption', *Bulletin of Volcanology*, 63(2), p. 204. Available at: https://doi.org/10.1007/s004450100136.

Machado, F. *et al*. (1962) 'Capelinhos Eruption of Fayal Volcano, Azores, 1957-1958', *Journal of Geophysical Research*, 67, pp. 3519–3529. Available at: https://doi.org/10.1029/JZ067i009p03519.

Sigurdsson, H. *et al*. (2000) *Encyclopedia of volcanoes*. San Diego: Academic Press.

Tazieff, H. (1958) 'L'eruption de 1957-1958 et la tectonique de Faial (Açores)', *Bulletin de la Societé belge de la géologie*, LXVII, pp. 13–49.

Waters, A.C. and Fisher, R.V. (1971) 'Base surges and their deposits: Capelinhos and Taal Volcanoes', *Journal of Geophysical Research*, 76(23), pp. 5596–5614. Available at: https://doi.org/10.1029/JB076i023p05596.

Zbyszewski, G. (1960) 'L'éruption du Volcan de Capelinhos (Ile de Faial, Açores)', *Bulletin Volcanologique*, 23(1), pp. 77–100. Available at: https://doi.org/10.1007/BF02596633.

8. Taburiente volcanic Caldera in La Palma Island

von Buch, L. (1825) Physicalische Beschreibung Der Canarischen Inseln. Berlin: Hofdruckerei von Königlichen Akademie.

Carracedo, J.C. *et al*. (2001) 'Geology and volcanology of La Palma and El Hierro, Western Canaries', Estudios Geológicos, 57(5–6), pp. 175–273. Available at: https://doi.org/10.3989/egeol.01575-6134.

Gagel, C. (1908) Die Caldera von La Palma. Berlin: Zeitschr. D. Ges. für Erdk.

Hausen, H. (1969) Some contributions to the geology of La Palma, Canary Islands. Helsinki: Societas Scientiarum Fennica (Com. Phys. Math., 35).

Lyell, C. (1865) Elements of Geology. 6th edn. London.

de la Nuez, J. (1983) El complejo intrusivo subvolcánico de la Caldera de Taburiente: La Palma, Canarias. Available at: https://www.semanticscholar.org/paper/El-complejo-intrusivo-subvolc%C3%A1nico-de-la-Caldera-de-Pestana/0b3086a513ef55b221e25ec783d427184ca63a8f.

Staudigel, H. and Schmincke, H.-U. (1984) 'The Pliocene seamount series of La Palma/Canary Islands', Journal of Geophysical Research: Solid Earth, 89(B13), pp. 11195–11215. Available at: https://doi.org/10.1029/JB089iB13p11195.

9. Quaternary glacial varves of Ragunda

Ahlmann, H.J.K.W. (1915) Ragundasjöns geomorfologi. Stockholm: Sveriges Geologiska Undersökning (Ser. Ca, 12).

Bergström, R. (1968) Stratigrafi och isrecession i södra Västerbotten. Stockholm: Sveriges Geologiska Undersökning (Ser C, 634).

De Geer, G.J. (1912) 'A geochronology of the last 12,000 years', in Compte Rendus XI Session du Congree Geologique International. Stockholm, pp. 241–253.

De Geer, G.J. (1940) 'Geochronologia Suecica Principles', Kungliga Svenska Vetenskapsakademiens Handlingar, 18(6), pp. 1–360.

Mörner, N.-A. (2014) 'Varve Chronology', in Geochronology – Methods and Case Studies. Mörner, N.A. London: IntechOpen. Available at: https://doi.org/10.5772/58630.

Strömberg, B. (1989) Late Weichselian deglaciation and clay varve chronology in east-central Sweden. Uppsala : Stockholm: Sveriges Geologiska Undersökning (Ser. Ca, nr. 73).

10. Genbudo Cave

Cox, A., Doell, R.R. and Dalrymple, G.B. (1964) 'Reversals of the Earth's Magnetic Field', *Science*, 144(3626), pp. 1537–1543. Available at: https://doi.org/10.1126/science.144.3626.1537.

Genbudo Research Group (1991) 'Geology and petrology of Quaternary volcanic rocks from the Genbudo area, northern Hyogo Prefecture, southwest Japan', *Chikyukagaku*, 45, pp. 131–144.

Head, M.J., Gibbard, P. and Salvador, A. (2008) 'The Quaternary: Its character and definition', *Episodes*, 31(2), pp. 234–238. Available at: https://doi.org/10.18814/epiiugs/2008/v31i2/009.

Kawai, N. and Hirooka, K. (1966) 'Some age dating results of Cenozoic volcanic rocks in the southwest Japan', in *Annual Meeting Geological Society of Japan*. 30.

Matuyama, M. (1929) 'On the Direction of Magnetisation of Basalt in Japan, Tyôsen and Manchuria', in *Proceedings of the Imperial Academy*. Tokyo, pp. 203–205. Available at: https://doi.org/10.2183/PJAB1912.5.203.

Vine, F.J. and Matthews, D.H. (1963) 'Magnetic Anomalies over Oceanic Ridges', *Nature*, 199, pp. 947–949. Available at: https://doi.org/10.1038/199947a0.

11. GSSP for the Silurian-Devonian boundary at Klonk Hill

Chlupáč, I., Jaeger, H. and Zikmundová, J. (1972) 'The Silurian-Devonian Boundary in the Barrandian', Bulletin of the Canadian petroleum Geology, 20(1), pp. 104–174. Available at: https://doi.org/10.35767/GSCPGBULL.20.1.104.

Chlupáč, I. and Vacek, F. (2003) 'Thirty years of the first international stratotype: The Silurian-Devonian boundary at Klonk and its present status', Episodes Journal of International Geoscience, 26(1), pp. 10–15. Available at: https://doi.org/10.18814/epiiugs/2003/v26i1/002.

Hladil, J. (1991) 'Evaluation of the sedimentary record in the Silurian/Devonian boundary stratotype at Klonk (Barrandian area, Czechoslovakia)', Newsletters on Stratigraphy, 25(2), pp. 115–125. Available at: https://doi.org/10.1127/nos/25/1991/115.

Slavík, L. (2017) 'Summary of conodont data from the GSSP of the Silurian-Devonian boundary at Klonk near Suchomasty', in International Conodont Symposium 4: Progress on Conodont investigation, Field Guide Book. Suttner, T.J., Valenzuela-Ríos, J.I., Liao, J.-C., Corradini, C. & Slavík, L. Berichte des Institutes für Erdwissenschaften, Karl-Franzens-Universität Graz, pp. 192–197.

Slavík, L. and Hladil, J. (2020) 'Early Devonian (Lochkovian – early Emsian) bioevents and conodont response in the Prague Synform (Czech Republic)', Palaeogeography, Palaeoclimatology, Palaeoecology, 549, p. 109148. Available at: https://doi.org/10.1016/j.palaeo.2019.04.004.

II. STRATIGRAPHY AND SEDIMENTOLOGY

12. Archean Barberton Greenstone Belt

Anhaeusser, C. (2016) 'The Barberton-Makhonjwa Mountainland', in Africa's Top Geological Sites. Anhaeusser, C. R., Viljoen, M. J., Viljoen, R. P. Cape Town: Struik Nature, pp. 189–196.

Armstrong, R.A. *et al.* (1990) 'The stratigraphy of the 3.5-3.2 Ga Barberton Greenstone Belt revisited: A single zircon ion microprobe study', Earth and Planetary Science Letters, 101(1), pp. 90–106. Available at: https://doi.org/10.1016/0012-821X(90)90127-J.

Homann, M. (2019) 'Earliest life on Earth: Evidence from the Barberton Greenstone Belt, South Africa', Earth-Science Reviews, 196, p. 102888. Available at: https://doi.org/10.1016/j.earscirev.2019.102888.

Lowe, D. and Byerly, G. (2007) 'An Overview of the Geology of the Barberton Greenstone Belt and Vicinity: Implications for Early Crustal Development', in Developments in Precambrian Geology, pp. 481–526. Available at: https://doi.org/10.1016/S0166-2635(07)15053-2.

Lowe, D.R. (1994) 'Accretionary history of the Archean Barberton Greenstone Belt (3.55-3.22 Ga), southern Africa', Geology, 22(12), pp. 1099–1102. Available at: https://doi.org/10.1130/0091-7613(1994)022<1099:AHOTAB>2.3.CO;2.

UNESCO World Heritage Documents (2018) Barberton Makhonjwa Mountains, UNESCO World Heritage Centre. Available at: https://whc.unesco.org/en/list/1575/.

de Wit, M.J., Furnes, H. and Robins, B. (2011) 'Geology and tectonostratigraphy of the Onverwacht Suite, Barberton Greenstone Belt, South Africa', Precambrian Research, 186(1), pp. 1–27. Available at: https://doi.org/10.1016/j.precamres.2010.12.007.

13. Paleoproterozoic Banded Iron Formation of the Quadrilátero Ferrífero

Auler, A. *et al.* (2014) 'Hypogene Cave Patterns in Iron Ore Caves: Convergence of Forms or Processes', in *Hypogene Cave Morphologies*. Alexander Klimchouk; Ira D. Sasowsky; John Mylroie; Scott A. Engel; Annette Summers Engel. Lewisburg: Karst Waters Institute, pp. 15–19.

Rosière, C. *et al.* (2005) 'Pico de Itabira, MG Marco estrutural, histórico e geográfico do Quadrilátero Ferrífero', in *Sítios Geológicos e Paleontológicos do Brasil*. Winge, M. *et al.* Brasília: CPRM, pp. 193–202.

Simmons, G.C. (1963) 'Canga caves in the Quadrilátero Ferrífero, Minas Gerais, Brazil', *The National Speleological Society Bulletin*, 25, pp. 66–92.

Spier, C.A., de Oliveira, S.M.B. and Rosière, C.A. (2003) 'Geology and geochemistry of the Águas Claras and Pico Iron Mines, Quadrilátero Ferrífero, Minas Gerais, Brazil', *Mineralium Deposita*, 38(6), pp. 751–774. Available at: https://doi.org/10.1007/s00126-003-0371-2.

Spier, C.A., Vasconcelos, P.M. and Oliviera, S.M.B. (2006) '40Ar/39Ar geochronological constraints on the evolution of lateritic iron deposits in the Quadrilátero Ferrífero, Minas Gerais, Brazil', *Chemical Geology*, 234(1), pp. 79–104. Available at: https://doi.org/10.1016/j.chemgeo.2006.04.006.

14. Glacial record of the Marinoan snowball Earth

Domack, E.W. and Hoffman, P.F. (2011) 'An ice grounding-line wedge from the Ghaub glaciation (635 Ma) on the distal foreslope of the Otavi carbonate platform, Namibia, and its bearing on the snowball Earth hypothesis', *GSA Bulletin*, 123(7–8), pp. 1448–1477. Available at: https://doi.org/10.1130/B30217.1.

Hoffman, P.F. *et al.* (1998) 'A Neoproterozoic Snowball Earth', *Science*, 281(5381), pp. 1342–1346. Available at: https://doi.org/10.1126/science.281.5381.1342.

Hoffman, P.F. (2011) 'Strange bedfellows: glacial diamictite and cap carbonate from the Marinoan (635 Ma) glaciation in Namibia', *Sedimentology*, 58(1), pp. 57–119. Available at: https://doi.org/10.1111/j.1365-3091.2010.01206.x.

Hoffman, P.F. *et al.* (2017) 'Snowball Earth climate dynamics and Cryogenian geology-geobiology', *Science Advances*, 3(11), p. e1600983. Available at: https://doi.org/10.1126/sciadv.1600983.

Hoffman, P.F. *et al.* (2021) 'Snowballs in Africa: sectioning a long-lived Neoproterozoic carbonate platform and its bathyal foreslope (NW Namibia)', *Earth-Science Reviews*, 219, p. 103616. Available at: https://doi.org/10.1016/j.earscirev.2021.103616.

Hoffman, P.F. (2022) 'Glacial erosion on snowball Earth: testing for bias in flux balance, geographic setting, and tectonic regime', *Canadian Journal of Earth Sciences* [Preprint]. Available at: https://doi.org/10.1139/cjes-2022-0004.

15. The Cambrian Explosion in Sirius Passet

Hammarlund, E.U. *et al.* (2019) 'The Sirius Passet Lagerstätte of North Greenland—A geochemical window on early Cambrian low-oxygen environments and ecosystems', Geobiology, 17(1), pp. 12–26. Available at: https://doi.org/10.1111/gbi.12315.

Harper, D.A.T. *et al.* (2019) 'The Sirius Passet Lagerstätte of North Greenland: a remote window on the Cambrian Explosion', Journal of the Geological Society, 176(6), pp. 1023–1037. Available at: https://doi.org/10.1144/jgs2019-043.

Morris, S.C. *et al.* (1987) 'A Burgess shale-like fauna from the Lower Cambrian of North Greenland', Nature, 326(6109), pp. 181–183. Available at: https://doi.org/10.1038/326181a0.

Park, T.-Y.S. *et al.* (2018) 'Brain and eyes of Kerygmachela reveal protocerebral ancestry of the panarthropod head', Nature Communications, 9(1), p. 1019. Available at: https://doi.org/10.1038/s41467-018-03464-w.

Strang, K.M., Armstrong, H.A. and Harper, D. a. T. (no date) 'Minerals in the gut: scoping a Cambrian digestive system', Royal Society Open Science, 3(11), p. 160420. Available at: https://doi.org/10.1098/rsos.160420.

Topper, T.P. *et al.* (2018) 'Characterization of kerogenous films and taphonomic modes of the Sirius Passet Lagerstätte, Greenland', Geology, 46(4), pp. 359–362. Available at: https://doi.org/10.1130/G39930.1.

Vinther, J. *et al.* (2014) 'A suspension-feeding anomalocarid from the Early Cambrian', Nature, 507(7493), pp. 496–499. Available at: https://doi.org/10.1038/nature13010.

16. The Great Unconformity at Grand Canyon

Dutton, C.E. (1882) *Tertiary history of the Grand Canyon District, with atlas*. Volume II: 263. Department of the Interior, p. Atlas, 23 Sheets. Available at: https://doi.org/10.3133/m2.

Karlstrom, K. *et al.* (2018) 'Cambrian Sauk transgression in the Grand Canyon region redefined by detrital zircons', *Nature Geoscience*, 11(6), pp. 438–443. Available at: https://doi.org/10.1038/s41561-018-0131-7.

Karlstrom, K. and Crossey, L. (2019) *The Grand Canyon Trail of Time Companion: Geology essentials for your canyon adventure*. Albuquerque, NM: Trail of Time Press.

Karlstrom, K.E. and Timmons, J.M. (2013) 'Many unconformities make one "Great Unconformity"', in *Grand Canyon Geology: 2 Billion Years of Earth History*. Timmons, J.M., and Karlstrom, K.E. Geological Society of America Special Paper, pp. 73–80. Available at: https://pubs.geoscienceworld.org/gsa/books/book/647/chapter/3806403/Many-unconformities-make-one-Great-Unconformity (Accessed: 22 July 2022).

McKee, E.D. (1969) *Stratified rocks of the Grand Canyon*. USGS Numbered Series 669-B. Washington, D.C.: U.S. Government Printing Office, p. 2358. Available at: http://pubs.er.usgs.gov/publication/pp669B.

Powell, J.W. (1875) *Exploration of the Colorado River of the West and its tributaries*. USGS Unnumbered Series. Washington, D.C.: Government Printing Office, p. 368. Available at: http://pubs.er.usgs.gov/publication/70039238.

17. The Ordovician rocks of the Mount Everest

Donovan, S.K. *et al.* (2012) 'A primitive cladid crinoid from the Jiacun Group, Tibet (Darriwilian, Middle Ordovician)', Geological Journal, 47(6), pp. 653–660. Available at: https://doi.org/10.1002/gj.2436.

Harper, D. *et al.* (2011) 'Ordovician on the roof of the world: macro-and microfaunas from tropical carbonates in Tibet', Publicaciones del Instituto Geológico y Minero de España. Serie: Cuadernos del Museo Geominero, 14, pp. 215–220.

Myrow, P.M., Hughes, N.C. and McKenzie, N.R. (2019) 'Reconstructing the Himalayan margin prior to collision with Asia: Proterozoic and lower Paleozoic geology and its implications for Cenozoic tectonics', Geological Society, London, Special Publications, 483(1), pp. 39–64. Available at: https://doi.org/10.1144/SP483.10.

Stouge, S. *et al.* (2021) 'Middle Ordovician (Darriwilian) conodonts from southern Tibet, the Indian passive margin: implications for the age and correlation of the roof of the world', Geological Magazine, 158(6), pp. 1010–1034. Available at: https://doi.org/10.1017/S0016756820001077.

Zhan, R. *et al.* (2014) 'Middle Ordovician Aporthophyla brachiopod fauna from the roof of the World, southern Tibet', Palaeontology, 57(1), pp. 141–170. Available at: https://doi.org/10.1111/pala.12058.

Zhen, Y.Y. *et al.* (2020) 'Ordovician successions in southern-central Xizang (Tibet), China—Refining the stratigraphy of the Himalayan and Lhasa terranes', Gondwana Research, 83, pp. 372–389. Available at: https://doi.org/10.1016/j.gr.2020.01.023.

18. Permian-Triassic great extinction and GSSPs of Meishan

Bowring, S.A. *et al.* (1998) 'U/Pb zircon geochronology and tempo of the end-permian mass extinction', Science, 280(5366), pp. 1039–1045. Available at: https://doi.org/10.1126/science.280.5366.1039.

Burgess, S.D., Bowring, S. and Shen, S. (2014) 'High-precision timeline for Earth's most severe extinction', Proceedings of the National Academy of Sciences, 111(9), pp. 3316–3321. Available at: https://doi.org/10.1073/pnas.1317692111.

Jin, Y. *et al.* (2006) 'The Global Boundary Stratotype Section and Point (GSSP) for the base of Changhsingian Stage (Upper Permian)', Episodes, 29(3), pp. 175–182. Available at: https://doi.org/10.18814/epiiugs/2006/v29i3/003.

Jin, Y.G. *et al.* (2000) 'Pattern of marine mass extinction near the Permian-Triassic boundary in South China', Science, 289(5478), pp. 432–436. Available at: https://doi.org/10.1126/science.289.5478.432.

Shen, S.Z. *et al.* (2011) 'Calibrating the end-Permian mass extinction', Science, 334(6061), pp. 1367–1372. Available at: https://doi.org/10.1126/science.1213454.

Yin, H. *et al.* (2001) 'The Global Stratotype Section and Point (GSSP) of the Permian-Triassic boundary', Episodes, 24(4), pp. 102–114. Available at: https://doi.org/10.18814/EPIIUGS/2001/V24I2/004.

19. Carboniferous – Triassic Unconformity in Telheiro

Gama, C. *et al.* (2021) 'Detrital zircon provenance of Triassic sandstone of the Algarve Basin (SW Iberia): evidence of Gondwanan- and Laurussian-type sources of sediment', Geological Magazine, 158(2), pp. 311–329. Available at: https://doi.org/10.1017/S0016756820000370.

Jorge, R.C.G.S. *et al.* (2013) 'Geochemistry and provenance of the Carboniferous Baixo Alentejo Flysch Group, South Portuguese Zone', Sedimentary geology, 284–285, pp. 133–148. Available at: https://doi.org/10.1016/j.sedgeo.2012.12.005.

Oliveira, J.T. (1990) 'Stratigraphy and Synsedimentary Tectonism', in R.D. Dallmeyer and E.M. Garcia (eds) Pre-Mesozoic Geology of Iberia. Berlin, Heidelberg: Springer (IGCP-Project 233), pp. 334–347. Available at: https://doi.org/10.1007/978-3-642-83980-1_23.

Oliveira, J.T. *et al.* (2019) 'South Portuguese Terrane: A Continental Affinity Exotic Unit', in Cecilio Quesada and José Tomás Oliveira (eds) The Geology of Iberia: A Geodynamic Approach: Volume 2: The Variscan Cycle. Cham: Springer International Publishing (Regional Geology Reviews), pp. 173–206. Available at: https://doi.org/10.1007/978-3-030-10519-8_6.

Palain, C. (1976) Une série détritique terrigène. Les "Grès de Silves": Trias et Lias inférieur du Portugal. (Memória dos Serviços Geológicos de Portugal, 25).

Ribeiro, A. *et al.* (2007) 'Geodynamic evolution of the SW Europe Variscides', Tectonics, 26(6). Available at: https://doi.org/10.1029/2006TC002058.

20. Cretaceous to Paleogene stratigraphic section of Bottaccione Gorge, Gubbio

Alvarez, L.W. *et al.* (1980) 'Extraterrestrial cause for the cretaceous-tertiary extinction', Science, 208(4448), pp. 1095–1108. Available at: https://doi.org/10.1126/science.208.4448.1095.

Galeotti, S. *et al*. (2015) 'The Bottaccione section at Gubbio, central Italy: a classical Paleocene Tethyan setting revisited', Newsletters on Stratigraphy, pp. 325–339. Available at: https://doi.org/10.1127/nos/2015/0067.

Lowrie, W. and Alvarez, W. (1981) 'One hundred million years of geomagnetic polarity history', Geology, 9(9), pp. 392–397. Available at: https://doi.org/10.1130/0091-7613(1981)9<392:OHMYOG>2.0.CO;2.

Luterbacher, H.P. and Premoli Silva, I. (1962) 'Note préliminaire sur une revision du profil de Gubbio, Italie', Rivista Italiana di Paleontologia e Stratigrafia, 68(2), pp. 253–288.

Montanari, A. and Coccioni, R. (2019) 'The serendipitous discovery of an extraterrestrial iridium anomaly at the Cretaceous-Palaeogene boundary in Gubbio and the rise of a far-reaching theory', Bollettino della Società Paleontologica Italiana, pp. 77–83.

Renz, O. (1936) Stratigraphische und mikropalaeontologische untersuchung der Scaglia (Obere Kreide-Tertiär) im zentralen Apennin. Druck von E. Birkhäuser & cie (Eclogae Geologicae Helvetiae, 29).

21. Cretaceous-Paleogene transition at Seymour (Marambio) Island

Acosta Hospitaleche, C., Gelfo, J.N. and Crame, J.A. (2019) Geology and Paleontology of the James Ross Basin, Antarctic Peninsula. (Advances in Polar Sciences, 30).

Elliot, D.H. *et al*. (1994) 'Iridium and dinocysts at the Cretaceous-Tertiary boundary on Seymour Island, Antarctica: Implications for the K-T event', Geology, 22(8), pp. 675–678. Available at: https://doi.org/10.1130/0091-7613(1994)022<0675:IADATC>2.3.CO;2.

Feldmann, R.M. and Woodburne, M.O. (eds) (1988) 'Geology and Paleontology of Seymour Island Antarctic Peninsula', Geological Society of America Memoir, 169, p. 566. Available at: https://doi.org/10.1130/MEM169.

Francis, J.E., Pirrie, D. and Crame, J.A. (2006) 'Cretaceous–Tertiary High-Latitude Palaeoenvironments, James Ross Basin, Antarctica', Geological Society Special Publication, (258), p. 206. Available at: https://doi.org/10.1017/S0016756807003640.

Montes, M. *et al*. (eds) (2019) Geología y geomorfología de Isla Marambio (Seymour). Acompañado de mapas, E 1:20.000. 1st edition. Madrid-Instituto Geológico y Minero de España; Buenos Aires-Instituto Antártico Argentino (Serie Cartográfica Geocientífica Antártica).

22. Cretaceous – Paleogene stratigraphic section of Zumaia

Alegret, L. *et al*. (2009) 'The Paleocene–Eocene thermal maximum: new data on microfossil turnover at the Zumaia section, Spain', PALAIOS, 24(5), pp. 318–328. Available at: https://doi.org/10.2110/palo.2008.p08-057r.

Dinarès-Turell, J. *et al*. (2014) 'Astronomical calibration of the Danian stage (Early Paleocene) revisited: Settling chronologies of sedimentary records across the Atlantic and Pacific Oceans', Earth and Planetary Science Letters, 405, pp. 119–131. Available at: https://doi.org/10.1016/j.epsl.2014.08.027.

Gilabert, V. *et al*. (2022) 'Contribution of orbital forcing and Deccan volcanism to global climatic and biotic changes across the Cretaceous-Paleogene boundary at Zumaia, Spain', Geology, 50(1), pp. 21–25. Available at: https://doi.org/10.1130/G49214.1.

Kruit, C., Brouwer, J. and Ealey, P. (1972) 'A Deep-water Sand Fan in the Eocene Bay of Biscay', Nature Physical Science, 240(99), pp. 59–61. Available at: https://doi.org/10.1038/physci240059a0.

Schmitz, B. *et al*. (2011) 'The Global Stratotype Sections and Points for the bases of the Selandian (Middle Paleocene) and Thanetian (Upper Paleocene) stages at Zumaia, Spain', Episodes, 34(4), pp. 220–243.

Ward, P.D. *et al*. (1991) 'Ammonite and inoceramid bivalve extinction patterns in Cretaceous/Tertiary boundary sections of the Biscay region (southwestern France, northern Spain)', Geology, 19(12), pp. 1181–1184. Available at: https://doi.org/10.1130/0091-7613(1991)019<1181:AAIBEP>2.3.CO;2.

23. GSSP of the Meghalayan Stage in the Mawmluh Cave

Berkelhammer, M. *et al*. (2012) 'An Abrupt Shift in the Indian Monsoon 4000 Years Ago', in Climates, Landscapes, and Civilizations. American Geophysical Union (AGU) (Geophysical Monographs Series), pp. 75–87. Available at: https://doi.org/10.1029/2012GM001207.

Gogoi, B. *et al*. (2009) 'Foraminiferal biostratigraphy and palaeoenvironment of the Lakadong Limestone of the Mawsynram area, south Shillong Plateau, Meghalaya', Pal. Soc. India, 54, pp. 209–224.

Huguet, C. *et al*. (2018) 'Temperature and Monsoon Tango in a Tropical Stalagmite: Last Glacial-Interglacial Climate Dynamics', Scientific Reports, 8(1), p. 5386. Available at: https://doi.org/10.1038/s41598-018-23606-w.

Walker, M. *et al*. (2018) 'Formal ratification of the subdivision of the Holocene Series/ Epoch (Quaternary System/Period): Two new Global Boundary Stratotype Sections and Points (GSSPs) and three new stages/ subseries', Episodes, 41(4), pp. 213–223. Available at: https://doi.org/10.18814/epiiugs/2018/018016.

III. PALEONTOLOGY

24. Ediacaran fossil site of Mistaken Point

Anderson, M.M. and Misra, S.B. (1968) 'Fossils found in the Pre-Cambrian Conception Group of South-eastern Newfoundland', Nature, 220(5168), pp. 680–681. Available at: https://doi.org/10.1038/220680a0.

Morris, S.C. (1989) 'South-eastern Newfoundland and adjacent areas (Avalon zone)', in The Precambrian-Cambrian Boundary. J.W. Cowie and M.D. Brasier, editors. Oxford: Clarendon Press, pp. 7–39.

Narbonne, G.M. (2005) 'THE EDIACARA BIOTA: Neoproterozoic Origin of Animals and Their Ecosystems', Annual Review of Earth and Planetary Sciences, 33(1), pp. 421–442. Available at: https://doi.org/10.1146/annurev.earth.33.092203.122519.

Narbonne, G.M. (2011) 'When life got big', Nature, 470(7334), pp. 339–340. Available at: https://doi.org/10.1038/470339a.

Narbonne, G.M. and Gehling, J.G. (2003) 'Life after snowball: The oldest complex Ediacaran fossils', Geology, 31(1), pp. 27–30. Available at: https://doi.org/10.1130/0091-7613(2003)031<0027:LASTOC>2.0.CO;2.

Williams, H. *et al*. (1995) 'Avalon Zone – Newfoundland', in Geology of the Appalachian—Caledonian Orogen in Canada and Greenland. H. Williams, editor. Geological Survey of Canada (Geology of Canada, 6), pp. 226–237.

25. Ediacaran fossils in the Ediacra Hills, Flinders Ranges, Australia

Brocx, M. (2019) 'The Role of the International Commission on Stratigraphy (ICS) and the "Golden Spike"', *The Australian Geologist* [Preprint].

Coutts, F.J., Gehling, J.G. and García-Bellido, D.C. (2016) 'How diverse were early animal communities? An example from Ediacara Conservation Park, Flinders Ranges, South Australia', *Alcheringa: An Australasian Journal of Palaeontology*, 40(4), pp. 407–421. Available at: https://doi.org/10.1080/03115518.2016.1206326.

Dalgarno, C.R. and Johnson, J.E. (1964) 'Precambrian rock groups in the Adelaide Geosyncline; a new subdivision - Wilpena Group, Geological Survey of South Australia', *Quarterly Geological Notes*, 9, pp. 12–19.

Knoll, A. *et al*. (2006) 'The Ediacaran Period: a new addition to the geologic time scale', *Lethaia*, 39(1), pp. 13–30. Available at: https://doi.org/10.1080/00241160500409223.

Preiss, W. (2005) 'Global stratotype for the Ediacaran System and Period — the Golden Spike has been placed in South Australia', *MESA Journal*, 37, pp. 20–25.

Sprigg, Reg. (2007) 'On the 1946 Discovery of the Precambrian Ediacabian Fossil Fauna in South Australia.', *Earth Sciences History*, 7(1), pp. 46–51. Available at: https://doi.org/10.17704/eshi.7.1.p13447q-2753jr055.

26. Cambrian Chengjiang Fossil Site and Lagerstätte

Chen, J., Ramsköld, L. and Zhou, G. (1994) 'Evidence for Monophyly and Arthropod Affinity of Cambrian Giant Predators', Science, 264(5163), pp. 1304–1308. Available at: https://doi.org/10.1126/science.264.5163.1304.

Chen, J.-Y. *et al*. (1995) 'A possible Early Cambrian chordate', Nature, 377(6551), pp. 720–722. Available at: https://doi.org/10.1038/377720a0.

Chen, J.-Y., Huang, D.-Y. and Li, C.-W. (1999) 'An early Cambrian craniate-like chordate', Nature, 402(6761), pp. 518–522. Available at: https://doi.org/10.1038/990080.

Hou, X.-G. *et al*. (2017) The Cambrian Fossils of Chengjiang, China: The Flowering of Early Animal Life. Second Edition. Oxford: John Wiley & Sons.

Shu, D.-G. *et al*. (1999) 'Lower Cambrian vertebrates from south China', Nature, 402(6757), pp. 42–46. Available at: https://doi.org/10.1038/46965.

Zhao, F., Zhu, M. and Hu, S. (2010) 'Community structure and composition of the Cambrian Chengjiang biota', Science China Earth Sciences, 53(12), pp. 1784–1799. Available at: https://doi.org/10.1007/s11430-010-4087-8.

27. Burgess Shale Cambrian Palaeontological Record

Aitken, J.D. and Fritz, W.H. (1968) Burgess Shale Project, British Columbia. (82 H-8, (West Half)). 68–1A, pp. 190–192.

Caron, J.-B. *et al*. (2014) 'A new phyllopod bed-like assemblage from the Burgess Shale of the Canadian Rockies', Nature Communications, 5, p. 3210. Available at: https://doi.org/10.1038/ncomms4210.

Gaines, R.R. (2014) 'Burgess Shale-type Preservation and its Distribution in Space and Time', The Paleontological Society Papers, 20, pp. 123–146. Available at: https://doi.org/10.1017/S1089332600002837.

Morris, S.C. (1998) The Crucible of Creation: The Burgess Shale and the Rise of Animals. Oxford University Press.

Morris, S.C. and Caron, J.-B. (2012) 'Pikaia gracilens Walcott, a stem-group chordate from the Middle Cambrian of British Columbia', Biological Reviews, 87(2), pp. 480–512. Available at: https://doi.org/10.1111/j.1469-185X.2012.00220.x.

Nanglu, K., Caron, J.B. and Gaines, R.R. (2020) 'The Burgess Shale paleocommunity with new insights from Marble Canyon, British Columbia', Paleobiology, 46(1), pp. 58–81. Available at: https://doi.org/10.1017/pab.2019.42.

28. Ordovician Fezouata Shale fossil site at JbelTizagzaouine

Destombes, J. (1962) 'Stratigraphie et paleogeographie de l'Ordovicien de l'Anti-Atlas (Maroc): un essai de synthese', Bulletin de la Société Géologique de France, S7-IV(3), pp. 453–460. Available at: https://doi.org/10.2113/gssgfbull.S7-IV.3.453.

Saleh, F. *et al*. (2021) 'Insights into soft-part preservation from the Early Ordovician Fezouata Biota', Earth-Science Reviews, 213, p. 103464. Available at: https://doi.org/10.1016/j.earscirev.2020.103464.

Van Roy, P. *et al*. (2010) 'Ordovician faunas of Burgess Shale type', Nature, 465(7295), pp. 215–218. Available at: https://doi.org/10.1038/nature09038.

Van Roy, P., Briggs, D.E.G. and Gaines, R.R. (2015) 'The Fezouata fossils of Morocco; an extraordinary record of marine life in the Early Ordovician', Journal of the Geological Society, 172(5), pp. 541–549. Available at: https://doi.org/10.1144/jgs2015-017.

Van Roy, P., Daley, A.C. and Briggs, D.E.G. (2015) 'Anomalocaridid trunk limb homology revealed by a giant filter-feeder with paired flaps', Nature, 522(7554), pp. 77–80. Available at: https://doi.org/10.1038/nature14256.

29. Middle Ordovician giant trilobites of Canelas quarry

Gutiérrez-Marco, J.C. *et al*. (2009) 'Giant trilobites and trilobite clusters from the Ordovician of Portugal', Geology, 37(5), pp. 443–446. Available at: https://doi.org/10.1130/G25513A.1.

Sá, A.A. *et al*. (2021) 'Giant trilobites and Other Middle Ordovician Invertebrate Fossils from the Arouca UNESCO Global Geopark, Portugal', Geoconservation Research, 4(1), pp. 121–130. Available at: https://doi.org/10.30486/gcr.2021.1913689.1057.

Sá, A.A. and Gutiérrez-Marco, J.C. (2006) Trilobites gigantes das ardósias de Canelas (Arouca). Ardósias Valério&Figueiredo, Lda.

Sá, A.A. and Gutiérrez-Marco, J.C. (2008) 'Giant Ordovician trilobites from Canelas (Arouca Geopark, northern Portugal)', in Pre-Conference field trip guide. Madrid: Câmara Municipal de Arouca-Museo Geominero, p. 20.

Sá, A.A. and Gutiérrez-Marco, J.C. (2015) 'Aroucaichnus igen. nov. y otros icnofósiles singulares del Ordovícico del Geoparque Arouca (Portugal)', Boletín de la Sociedad Geologica del Peru, 110, pp. 8–23. Available at: https://doi.org/10.13039/501100003329.

30. Devonian Tetrapod Trackways of Holy Cross Mountains

Jaworska, J. (2017) 'Casts of halite crystals in the Devonian dolomites of the Zachełmie Quarry', Salt Review, 13, pp. 135–140.

Narkiewicz, M. *et al*. (2015) 'Palaeoenvironments of the Eifelian dolomites with earliest tetrapod trackways (Holy Cross Mountains, Poland)', Palaeogeography, Palaeoclimatology, Palaeoecology, 420, pp. 173–192. Available at: https://doi.org/10.1016/j.palaeo.2014.12.013.

Niedźwiedzki, G. *et al*. (2010) 'Tetrapod trackways from the early Middle Devonian period of Poland', Nature, 463(7277), pp. 43–48. Available at: https://doi.org/10.1038/nature08623.

Niedźwiedzki, G. and Szrek, P. (2020) 'Non-tetrapod trace fossils from the Middle Devonian tetrapod tracksite at Zachełmie Quarry, Holy Cross Mountains, Poland', Palaeogeography, Palaeoclimatology, Palaeoecology, 553, p. 109763. Available at: https://doi.org/10.1016/j.palaeo.2020.109763.

31. "Coal Age" Joggins Fossil Cliffs

Calder, J. (2017) The Joggins Fossil Cliffs: Coal Age Galapagos. Second Edition. Halifax: Formac Publishing Company.

Calder, J.H. *et al*. (2006) 'A fossil lycopsid forest succession in the classic Joggins section of Nova Scotia: Paleoecology of a disturbance-prone Pennsylvanian wetland', in Wetlands Through Time. S.F. Greb and W.A. DiMichele (editors). (Geological Society of America Special Paper, 399), pp. 169–195. Available at: https://pubs.geoscienceworld.org/gsa/books/book/557/chapter/3802480/A-fossil-lycopsid-forest-succession-in-the-classic.

Carroll, R.L. (1964) 'The earliest reptiles', Journal of the Linnean Society of London, Zoology, 45(304), pp. 61–83. Available at: https://doi.org/10.1111/j.1096-3642.1964.tb00488.x.

Darwin, C. (1859) On the origin of species by means of natural selection, or the preservation of favoured races in the struggle for life. First edition. London: John Murray. Available at: http://archive.org/details/darwin-online_1859_Origin_F373.

Lyell, C. and Dawson, J.W. (1853) 'On the Remains of a Reptile (Dendrerpeton Acadianum, Wyman and Owen) and of a Land Shell discovered in the Interior of an Erect Fossil Tree in the Coal Measures of Nova Scotia', Quarterly Journal of the Geological Society, 9(1–2), pp. 58–67. Available at: https://doi.org/10.1144/GSL.JGS.1853.009.01-02.20.

Mann, A. *et al.* (2020) 'Reassessment of historic "microsaurs" from Joggins, Nova Scotia, reveals hidden diversity in the earliest amniote ecosystem', Papers in Palaeontology, 6(4), pp. 605–625. Available at: https://doi.org/10.1002/spp2.1316.

32. Late Permian Tete Fossil Forest

Araújo, R. *et al.* (2018) 'Fossil tree hollows from a late Permian Forest of the Matinde Formation (Tete, Mozambique)'. Available at: http://wiredspace.wits.ac.za/handle/10539/25916.

Bajpai, U. and Maheshwari, H.K. (1986) 'Two new fossil woods from the Raniganj Formation with remarks on *Zalesskioxylon zambesiensis* from Mozambique', The Palaeobotanist, 35(1), pp. 39–47.

Ferrara, M., Marques, J. and Costa, J. (2002) 'Fossilized Forest in the Tete Province', in. Florence, Italy.

Marguerier, J. (1973) 'Paléoxylologie du Gondwana africain. Etude et affinities du genre Australoxylon', Palaeontologia Africana, 16, pp. 37–58.

Nhamutole, N.E. (2021) Fossil woods from the permian and triassic of Mozambique: taxonomy, palaeocology and geoconservation. Thesis. Available at: http://wiredspace.wits.ac.za/handle/10539/32381.

Silva, G., Barreto, L. and Carvalho, L. (1967) 'Palaeobotanical and petrographical study of a log of a petrified wood, identified as *Dadoxylon nicoli* Seward from the Karroo of Mágoè region, West of Tete', Revista dos Estudos Gerais Universitários de Moçambique, p. 156.

33. The Ammonite Slab of Digne-les-Bains

Bert, D. and Pagès, J.-S. (2021) 'Overview of the Les Isnards Ammonite Slab Geoheritage Site (Digne-les-Bains, Southeastern France)', Geoconservation Research, 4(2), pp. 330–337. Available at: https://doi.org/10.30486/gcr.2021.1917851.1074.

Corna, M. *et al.* (1990) 'Quelques points remarquables dans le Sinémurien des Alpes de Provence (France) : précisions biostratigraphiques et paléontologiques', Géologie Méditerranéenne, 17(1), pp. 3–37. Available at: https://doi.org/10.3406/geolm.1990.1432.

Dommergues, J.-L. and Guiomar, M. (2011) 'La " Dalle à ammonites de Digne " (Réserve Naturelle Géologique de Haute-Provence, France). Étude d'un site fossilifère d'importance patrimoniale.', Revue de Paléobiologie, 30(1), pp. 261–293.

Dommergues, J.-L. and Meister, C. (1991) 'Area of mixed marine faunas between two major paleogeographical realms, exemplified by the Early Jurassic (Late Sinemurian and Pliensbachian) ammonites in the Alps', Palaeogeography, Palaeoclimatology, Palaeoecology, 86(3), pp. 265–282. Available at: https://doi.org/10.1016/0031-0182(91)90085-6.

Martini, G. (1979) Aménagement d'une Réserve géologique dans les Alpes de Haute-Provence. Master degree. Université de Provence.

Neige, P., Dommergues, J.-L. and Guiomar, M. (2021) 'La dalle aux ammonites de Digne-les-Bains : un patrimoine d'âge Sinémurien de réputation mondiale', in Stratotype Sinémurien. Neige, P., Dommergues, J.-L. Muséum National d'Histoire Naturelle, pp. 270–275.

34. Jurassic Solnhofen-Eichstätt Archaeopteryx Serial Site

Arratia, G. *et al.* (eds) (2015) Solnhofen - Ein Fenster in die Jurazeit Vol. 1+2 (2 vol). München: Pfeil-Verlag.

Darwin, C. (1866) On the origin of species by means of natural selection, or the preservation of favoured races in the struggle for life. 4th edition. London: John Murray. Available at: http://darwin-online.org.uk/content/frameset?itemID=F385&viewtype=text&pageseq=1

Foth, C., Tischlinger, H. and Rauhut, O.W.M. (2014) 'New specimen of Archaeopteryx provides insights into the evolution of pennaceous feathers', Nature, 511(7507), pp. 79–82. Available at: https://doi.org/10.1038/nature13467.

Huxley, T.H. (1868) 'On the animals which are most nearly intermediate between birds and reptiles', Annals and magazine of natural history, 2, pp. 66–75.

Meyer, H. von (1862) '*Archaeopteryx lithographica* aus dem lithographischen Schiefer von Solenhofen', Palaeontographica, 10, pp. 53–56.

Owen, R. (1863) 'On the Archeopteryx of Von Meyer, with a Description of the Fossil Remains of a Long-Tailed Species, from the Lithographic Stone of Solenhofen', in. Royal Society of London (Philosophical transactions of the Royal Society, 153). Available at: http://archive.org/details/philtrans08457086

35. Marine Reptile Lagerstätte from the Lower Cretaceous of the Ricaurte Alto

Cadena, E. and Parham, J. (2015) 'Oldest known marine turtle? A new protostegid from the Lower Cretaceous of Colomb', PaleoBios, 32(1), pp. 2–42.

Cortés, D., Maxwell, E.E. and Larsson, H.C.E. (2021) 'Re-appearance of hypercarnivore ichthyosaurs in the Cretaceous with differentiated dentition: revision of *"Platypterygius" sachicarum* (Reptilia: Ichthyosauria, Ophthalmosauridae) from Colombia', Journal of Systematic Palaeontology, 19(14), pp. 969–1002. Available at: https://doi.org/10.1080/14772019.2021.1989507.

Gómez-Pérez, M. and Noè, L.F. (2017) 'Cranial anatomy of a new pliosaurid *Acostasaurus pavachoquensis* from the Lower Cretaceous of Colombia, South America', Palaeontographica Abteilung A, pp. 5–42. Available at: https://doi.org/10.1127/pala/2017/0068.

Noè, L.F. and Gómez-Pérez, M. (2020) 'Plesiosaurs, palaeoenvironments, and the Paja Formation Lagerstätte of central Colombia: An overview.', in The Geology of Colombia. Gomez, J., Pinilla Pachon, A.O. (Eds.). Bogotá: Servicio Geológico Colombiano, Publicaciones Geológicas Especiales (Mesozoic, 36), p. 43. Available at: http://doi.org/10.32685/pub.esp.36.2019.13.

Serna, F.E. (1968) 'El Sistema Cretáceo en la región de Villa de Leiva y zonas próximas', Geología colombiana, 5(1), pp. 5–74.

Welles, S.P. (1962) Elasmosaurid plesiosaurs with description of new material from California and Colorado. Los Angeles: University of California Press (University of California, Berkeley. Memoirs, 13).

36. Dinosaur Provincial Park

Arbour, V.M. and Currie, P.J. (2013) '*Euoplocephalus tutus* and the Diversity of Ankylosaurid Dinosaurs in the Late Cretaceous of Alberta, Canada, and Montana, USA', Plos One, 8(5), p. e62421. Available at: https://doi.org/10.1371/journal.pone.0062421.

Currie, P.J. and Koppelhus, E.B. (eds) (2005) Dinosaur Provincial Park: A Spectacular Ancient Ecosystem Revealed. Bloomington and Indianapolis: Indiana University Press.

Eberth, D.A. (ed.) (2017) Campanian-Maastrichtian dinosaurs and environments at Dinosaur Provincial Park and Drumheller, Alberta, Canada. (Pre-Conference Field Trip Guidebook. Society of Vertebrate Palaeontology, 2017 Annual Meeting, Calgary, Alberta).

37. Late Cretaceous rudist bivalves of the Caribbean Province

Chubb, L.J. (1971) 'Rudists of Jamaica', Palaeontographica Americana, VII(45), pp. 161–257.

Mitchell, S.F. (2002) 'Palaeoecology of corals and rudists in mixed volcaniclastic–carbonate small-scale rhythms (Upper Cretaceous, Jamaica)', Palaeogeography, Palaeoclimatology, Palaeoecology, 186(3), pp. 237–259. Available at: https://doi.org/10.1016/S0031-0182(02)00505-9.

Mitchell, S.F. (2013) 'Revision of the Antillocaprinidae Mac Gillavry (Hippuritida, Bivalvia) and their position within the Caprinoidea d'Orbigny', Geobios, 46(5), pp. 423–446. Available at: https://doi.org/10.1016/j.geobios.2013.07.003.

Sawkins, J.G. (1869) Reports on the Geology of Jamaica; Or, Part II. of the West Indian Survey. London: Longmans, Green and Co. (Memoirs of the Geological Survey).

Steuber, T. *et al.* (2002) 'Catastrophic extinction of Caribbean rudist bivalves at the Cretaceous-Tertiary boundary', Geology, 30(11), pp. 999–1002. Available at: https://doi.org/10.1130/0091-7613(2002)030<0999:CEOCRB>2.0.CO;2.

Whitfield, R.P. (1897) 'Descriptions of species of Rudistae from the Cretaceous rocks of Jamaica, West Indies, collected and presented by Mr. F.C. Nicholas.', Bulletin of the American Museum of Natural History, 9, pp. 185–196.

38. Eocene paleontological record of Messel Pit Fossil Site

Frey, M.-L. (2018) 'Visitor Centre at the Messel Pit World Heritage Site—Platform for the greater public, science and World Heritage', in R. Dornbusch, F. Hansell, and K. Manz (eds) Welterbe Vermitteln—Ein UNESCO Auftrag. Sächsisches Industriemuseum; IWTG/TU Bergakademie Freiberg, UNESCO Commission: Bonn, Germany. (Industrie-Archäologie, 19).

McKeever, P.J., Frey, M.-L. and Weber, J. (2014) 'Global Geoparks and Geological World Heritage—A Case Study from Germany', World Heritage, 70, pp. 34–40.

Schaal, S.F.K. (2020) '25 Jahre UNESCO-Welterbe Messel Pit Fossil Site', in. (Senckenberg - natur forschung museum, 150), pp. 168–174.

Smith, K.T., Schaal, S.F.K. and Habersetzer, J. (2018) 'Messel - An Ancient Greenhouse Ecosystem'. E. Schweizerbart'sche Verlagsbuchhandlung. Available at: https://www.semanticscholar.org/paper/MESSEL-An-Ancient-Greenhouse-Ecosystem-Smith-Schaal/3dc4d4c5d0b3282d23fa15f316e4ba3aff657104.

Vianey-Liaud, M., Marivaux, L. and Lehamnn, T. (2019) 'A Reevaluation of the Taxonomic Status of the Rodent Masillamys Tobien, 1954 from Messel (Germany, Late Early to Early Middle Eocene, 48–47 M.Y.)', Fossil Imprint, 75(3–4), pp. 454–483. Available at: https://doi.org/10.2478/if-2019-0028.

Wappler, T. *et al.* (2015) 'Specialized and Generalized Pollen-Collection Strategies in an Ancient Bee Lineage', Current Biology, 25(23), pp. 3092–3098. Available at: https://doi.org/10.1016/j.cub.2015.09.021.

39. Miocene primates paleontological site of Napak

Bishop, W.W. (1958) 'Miocene Mammalia from the Napak Volcanics, Karamoja, Uganda', Nature, 182(4648), pp. 1480–1482. Available at: https://doi.org/10.1038/1821480a0.

Bishop, W.W. (1962) 'The mammalian fauna and geomorphological relations of the Napak volcanics, Karamoja', Record of Geological Survey of Uganda, (1957–58), pp. 1–18.

King, B.C. (1949) 'The Napak area of southern Karamoja, Uganda: A study of a dissected Late Tertiary volcano', Memoir. Geological Survey of Uganda, (5), p. 57.

Pickford, M. *et al.* (2021) Revision of smaller-bodied anthropoids from Napak, early Miocene, Uganda: 2011-2020 collections. (Münchner Geowissenschaftliche Abhandlungen, Reihe A, Geologie und Paläontologie, 51).

Senut, B. (2015) 'The Miocene Hominoids and the Earliest Putative HominidsHominids', in W. Henke and I. Tattersall (eds) Handbook of Paleoanthropology. W. Henke, I. Tattersall (eds). Berlin, Heidelberg: Springer (Vol. III: Phylogeny of Hominines), pp. 2043–2069. Available at: https://doi.org/10.1007/978-3-642-39979-4_49.

Wayland, E.J. (1921) Geological Survey of Uganda Annual Report. 1919–20. Geological Survey of Uganda, p. 38.

40. Lesvos Early Miocene Petrified Forest

Koufos, G.D., Zouros, N. and Mourouzidou, O. (2003) 'Prodeinotherium bavaricum (Proboscidea, Mammalia) from Lesvos island, Greece; the appearance of deinotheres in the eastern Mediterranean', Geobios, 36(3), pp. 305–315. Available at: https://doi.org/10.1016/S0016-6995(03)00031-7.

Pe-Piper, G. *et al.* (2019) 'Nature of the hydrothermal alteration of the Miocene Sigri Petrified Forest and host pyroclastic rocks, western Lesbos, Greece', Journal of Volcanology and Geothermal Research, 369, pp. 172–187. Available at: https://doi.org/10.1016/j.jvolgeores.2018.11.018.

Süss, H. and Velitzelos, E. (1997) 'Fossile Hölzer der Familie Taxodiaceae aus tertiären Schichten des Versteinerten Waldes von Lesbos, Griechenland', Feddes Repertorium, 108(1–2), pp. 1–30. Available at: https://doi.org/10.1002/fedr.19971080102.

Süss, H. and Velitzelos, E. (2010) 'Lesbosoxylon gen. nov., eine neue Morphogattung mit dem Typus Lesbosoxylon ventricosuradiatum sp. nova aus dem Tertiär der Insel Lesbos, Griechenland', Feddes Repertorium, 121(1–2), pp. 18–26. Available at: https://doi.org/10.1002/fedr.201011124.

Velitzelos, E., Petrescu, I. and Symeonidis, N. (1981) 'Tertiäre Pflanzenreste aus der Ägäis. Die Makroflora der Insel Lesvos (Griechenland)', Ann. Géol. Pays Hellén, 30, pp. 500–514.

Velitzelos, E. and Zouros, N. (1998) 'New results on the petrified forest of Lesvos. Bulletin of the Geological Society of Greece', Bulletin of the Geological Society of Greece, 32(2), pp. 133–142.

41. Palaeoanthropological Sites of Human Evolution of Laetoli – Olduvai Gorge

Ashley, G.M. *et al.* (2010) 'Sedimentary Geology and Human Origins: A Fresh Look at Olduvai Gorge, Tanzania', Journal of Sedimentary Research, 80(8), pp. 703–709. Available at: https://doi.org/10.2110/jsr.2010.066.

Habermann, J. (2016) Pleistocene volcanism of Bed I, Olduvai Gorge, Tanzania: chemostratigraphy, sedimentology, and paleoecology. Thesis. Faculty of Natural Sciences the Friedrich Alexander University.

Hay, R.L. (1976) Geology of the Olduvai Gorge, Geology of the Olduvai Gorge. Berkeley, California: University of California Press. Available at: https://doi.org/10.1525/9780520334229.

Hay, R.L. and Kyser, T.K. (2001) 'Chemical sedimentology and paleoenvironmental history of Lake Olduvai, a Pliocene lake in northern Tanzania', GSA Bulletin, 113(12), pp. 1505–1521. Available at: https://doi.org/10.1130/0016-7606(2001)113<1505:CSAPHO>2.0.CO;2.

Leakey, M.D. and Hay, R.L. (1979) 'Pliocene footprints in the Laetolil Beds at Laetoli, northern Tanzania', Nature, 278(5702), pp. 317–323. Available at: https://doi.org/10.1038/278317a0.

Mollel, G.F. (2007) Petrochemistry and geochronology of Ngorongoro Volcanic Highland Complex (NVHC) and its relationship to Laetoli and Olduvai Gorge, Tanzania. Thesis. Rutgers University - Graduate School. Available at: https://doi.org/10.7282/T32N52NH.

42. Late Quaternary asphalt seeps and paleontological site of La Brea Tar Pits

Merriam, J.C. and Stock, C. (1932) The Felidæ of Rancho La Brea. Washington, D.C.: Carnegie Institution of Washington (Carnegie Institution of Washington Publication, 422).

Mychajliw, A.M. *et al*. (2020) 'Exceptionally preserved asphaltic coprolites expand the spatiotemporal range of a North American paleoecological proxy', Scientific Reports, 10(1), p. 5069. Available at: https://doi.org/10.1038/s41598-020-61996-y.

Stock, C. and Harris, J.M. (1992) Rancho la Brea: A record of Pleistocene life in California. Los Angeles: Natural History Museum of Los Angeles County (Natural History Museum Los Angeles County, Science series, 37).

Ward, J.K. *et al*. (2005) 'Carbon starvation in glacial trees recovered from the La Brea tar pits, southern California', Proceedings of the National Academy of Sciences of the United States of America, 102(3), pp. 690–694. Available at: https://doi.org/10.1073/pnas.0408315102.

Woodard, G.D. and Marcus, L.F. (1973) 'Rancho La Brea Fossil Deposits: A Re-Evaluation from Stratigraphic and Geological Evidence', Journal of Paleontology, 47(1), pp. 54–69.

IV. IGNEOUS AND METAMORPHIC PETROLOGY

43. Archean Zircons of Erawondoo Hill

Reineck, H.E. and Singh, I.B. (1980) *Depositional sedimentary environments*. 2nd Edition. Berlin: Springer-Verlag.

Spaggiari, C.V. (2007) 'The Jack Hills greenstone belt, Western Australia Part 1: Structural and tectonic evolution over >1.5 Ga', *Precambrian Research*, (155), pp. 204–228.

Wilde, S.A. *et al*. (2001) 'Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago', *Letters to Nature*, (409), pp. 175–178.

Wilde, S.A., Middleton, M.F. and Evans, B.J. (1996) 'Terrane accretion in the southwestern Yilgarn Craton: evidence from a deep seismic crustal profile', *Precambrian Research*, (78), pp. 179–196.

Wilde, S.A. and Pidgeon, R.T. (1990) 'Geology of the Jack Hills Metasedimentary Rocks', in *Proceedings of the Third International Archaean Symposium*. Ho, S.E., Glover, J.E., Myers, J.S., Muhling, J.R. Perth, WA: University of Western Australia (Excursion Guidebook), pp. 82–89.

44. The Hadean to Eoarchean Nuvvuagittuq greenstone belt

Cates, N.L. *et al*. (2013) 'Reduced, reused and recycled: Detrital zircons define a maximum age for the Eoarchean (ca. 3750–3780Ma) Nuvvuagittuq Supracrustal Belt, Québec (Canada)', Earth and Planetary Science Letters, 362, pp. 283–293. Available at: https://doi.org/10.1016/j.epsl.2012.11.054.

Cates, N.L. and Mojzsis, S.J. (2007) 'Pre-3750 Ma supracrustal rocks from the Nuvvuagittuq supracrustal belt, northern Québec', Earth and Planetary Science Letters, 255(1), pp. 9–21. Available at: https://doi.org/10.1016/j.epsl.2006.11.034.

Dodd, M.S. *et al*. (2017) 'Evidence for early life in Earth's oldest hydrothermal vent precipitates', Nature, 543(7643), pp. 60–64. Available at: https://doi.org/10.1038/nature21377.

O'Neil, J. *et al*. (2008) 'Neodymium-142 Evidence for Hadean Mafic Crust', Science, 321(5897), pp. 1828–1831. Available at: https://doi.org/10.1126/science.1161925.

O'Neil, J. *et al*. (2019) 'The Nuvvuagittuq Greenstone Belt: A Glimpse of Earth's Earliest Crust', in M. Van Kranendonk, V. Bennett, and E. Hoffmann (eds) Earth's Oldest Rocks. Van Kranendonk, M and Bennett, V and Hoffmann, E. Amsterdam, Netherlands: Elsevier, pp. 349–374. Available at: https://doi.org/10.1016/B978-0-444-63901-1.00016-2.

Simard, M. *et al*. (2003) Géologie de la région de la rivière d'Innuksuac (34K and34L). Quebec: Ministère des Ressources Naturelles.

45. Archean Rocks of the Eastern Beartooth Mountains

Eckelmann, F.D. and Poldervaart, A. (1957) 'Geologic Evolution of the Beartooth Mountains, Montana and Wyoming 1. Archean History of the Quad Creek Area', GSA Bulletin, 68(10), pp. 1225–1262. Available at: https://doi.org/10.1130/0016-7606(1957)68[1225:GEOTBM]2.0.CO;2.

Henry, D. *et al*. (1982) 'Granulite grade supracrustal assemblages of the Quad Creek area, eastern Beartooth Mountains, Montana', Montana Bureau of Mines and Geology, Special Publication, 84, pp. 147–155.

Mogk, D.W., Mueller, P.A. and Henry, D.J. (2020) 'The Archean Geology of Montana', in Geology of Montana. The Montana Bureau of Mines and Geology (MBMG) (Montana Bureau of Mines and Geology Centennial Volume). Available at: https://mbmg.mtech.edu/pubs/GeologyOfMontana/

Mueller, P.A. *et al*. (2010) 'Rapid growth of an Archean continent by arc magmatism', Precambrian Research, 183(1), pp. 70–88. Available at: https://doi.org/10.1016/j.precamres.2010.07.013.

Mueller, P.A. *et al*. (2014) 'The Plume to Plate Transition: Hadean and Archean Crustal Evolution in the Northern Wyoming Province, U.S.A.', in Y. Dilek and H. Furnes (eds) Evolution of Archean Crust and Early Life. Dordrecht: Springer Netherlands (Modern Approaches in Solid Earth Sciences, v. 7), pp. 23–54. Available at: https://doi.org/10.1007/978-94-007-7615-9_2.

Mueller, P.A. and Wooden, J.L. (2012) 'Trace Element and Lu-Hf Systematics in Hadean-Archean Detrital Zircons: Implications for Crustal Evolution', The Journal of Geology, 120(1), pp. 15–29. Available at: https://doi.org/10.1086/662719.

46. The Stillwater Complex

Boudreau, A.E. (1995) 'Crystal aging and the formation of fine-scale igneous layering', Mineralogy and Petrology, 54(1), pp. 55–69. Available at: https://doi.org/10.1007/BF01162758.

Boudreau, A.E. *et al*. (2020) 'Mineral deposits of the Stillwater Complex', in Montana Bureau of Mines and Geology Special Publication. (Geology of Montana, 122).

Jackson, E.D. (1961) Primary textures and mineral associations in the ultramafic zone of the Stillwater complex, Montana, Professional Paper. 358. U. S. Govt. Print. Off., p. 106. Available at: https://doi.org/10.3133/pp358.

Meurer, W.P. and Boudreau, A.E. (1996) 'Petrology and Mineral Compositions of the Middle Banded Series of the Stillwater Complex, Montana', Journal of Petrology, 37(3), pp. 583–607. Available at: https://doi.org/10.1093/petrology/37.3.583.

Salpas, P.A., Haskin, L.A. and McCallum, I.S. (1983) 'Stillwater Anorthosites: A lunar analog?', Journal of Geophysical Research: Solid Earth, 88(S01), pp. B27–B39. Available at: https://doi.org/10.1029/JB088iS01p00B27.

Zientek, M.L. *et al*. (2002) 'Platinum-group element mineralization in the Stillwater Complex, Montana', in The geology, geochemistry, mineralogy and mineral beneficiation of platinum-group elements. Cabri, L.J., ed. (Canadian Institute of Mining and Metallurgy Special Volume, 54), pp. 459–481. Available at: https://pubs.er.usgs.gov/publication/70221813.

Zientek, M.L. and Parks, H.L. (2014) A geologic and mineral exploration spatial database for the Stillwater Complex, Montana, A geologic and mineral exploration spatial database for the Stillwater Complex, Montana. USGS Numbered Series 2014–5183. Reston, VA: U.S. Geological Survey, p. 40. Available at: https://doi.org/10.3133/sir20145183.

47. Early Cretaceous Rhyolitic Columnar Rock Formation of Hong Kong

Sewell, R.J. and Campbell, S.D.G. (1997) 'Geochemistry of coeval Mesozoic plutonic and volcanic suites in Hong Kong', Journal of the Geological Society, 154(6), pp. 1053–1066. Available at: https://doi.org/10.1144/gsjgs.154.6.1053.

Sewell, R.J., Tang, D.L.K. and Campbell, S.D.G. (2012) 'Volcanic-plutonic connections in a tilted nested caldera complex in Hong Kong', Geochemistry, Geophysics, Geosystems, 13(1). Available at: https://doi.org/10.1029/2011GC003865.

Sewell, R.J., Tang, D.L.K. and Sin, Y.M. (no date) Hong Kong's Big Bang - The Discovery of High Island Supervolcano. Hong Kong: Civil Engineering and Development Department, pp. 16, – 18, 21–23, 26–28, 33, 36–40. Available at: https://hkss.cedd.gov.hk/hkss/eng/education/GS/others/HKs Big Bang.pdf.

Strange, P.J., Shaw, R. and Addison, R. (1990) The Geology of Sai Kung and Clear Water Bay. №4. Hong Kong: Geotechnical Control Office, Civil Engineering Services Department, pp. 51–53. Available at: https://www.cedd.gov.hk/eng/publications/geo/hong-kong-geological-survey/memoir_no_4/index.html.

48. Richat Structure, a Cretaceous Alkaline Complex

Abdeina, E.H. *et al*. (2021) 'Geophysical modelling of the deep structure of the Richat magmatic intrusion (northern Mauritania): insights into its kinematics of emplacement', Arabian Journal of Geosciences, 14(22), p. 2315. Available at: https://doi.org/10.1007/s12517-021-08734-4.

Faudli, R.F. (1969) 'Coesite from the Richat Dome, Mauritania: A Misidentification', Science, 166(3902), pp. 228–230. Available at: https://doi.org/10.1126/science.166.3902.228.

Hamoud, A. *et al*. (2021) 'Mauritanian Geological Resources: A Lever for Sustainable Regional Development via Geotourism', International Journal of Geoheritage and Parks, 9, pp. 415–429. Available at: https://doi.org/10.2139/ssrn.3910266.

Matton, G. and Jébrak, M. (2014) 'The "eye of Africa" (Richat dome, Mauritania): An isolated Cretaceous alkaline–hydrothermal complex', Journal of African Earth Sciences, 97, pp. 109–124. Available at: https://doi.org/10.1016/j.jafrearsci.2014.04.006.

Matton, G., Jébrak, M. and Lee, J.K.W. (2005) 'Resolving the Richat enigma: Doming and hydrothermal karstification above an alkaline complex', Geology, 33(8), pp. 665–668. Available at: https://doi.org/10.1130/G21542AR.1.

O'Connor, E.A. *et al*. (2004) Rapport Administratif des cartes géologiques et gîtologiques à 1/200 000 et 1/500 000 du Nord-Ouest de la Mauritanie. Nouakchott: DMG, Ministère des Mines et de l'Industrie, p. 408.

49. The Miocene Torres del Paine intrusive complex

Halpern, M. (1973) 'Regional Geochronology of Chile South of 50° Latitude', GSA Bulletin, 84(7), pp. 2407–2422. Available at: https://doi.org/10.1130/0016-7606(1973)84<2407:RGOCSO>2.0.CO;2.

Leuthold, J. *et al*. (2012) 'Time resolved construction of a bimodal laccolith (Torres del Paine, Patagonia)', Earth and Planetary Science Letters, 325–326, pp. 85–92. Available at: https://doi.org/10.1016/j.epsl.2012.01.032.

Michael, P.J. (1991) 'Intrusion of basaltic magma into a crystallizing granitic magma chamber: The Cordillera del Paine pluton in southern Chile', Contributions to Mineralogy and Petrology, 108(4), pp. 396–418. Available at: https://doi.org/10.1007/BF00303446.

Michel, J. *et al*. (2008) 'Incremental growth of the Patagonian Torres del Paine laccolith over 90 k.y.', Geology, 36(6), pp. 459–462. Available at: https://doi.org/10.1130/G24546A.1.

Skarmeta, J.J. and Castelli, J.C. (1997) 'Intrusión sintectónica del Granito de las Torres del Paine, Andes Patagónicos de Chile', Revista geológica de Chile, 24(1), pp. 55–74.

50. Mount Kinabalu Neogene Granite

Burton-Johnson, A., Macpherson, C.G. and Hall, R. (2017) 'Internal structure and emplacement mechanism of composite plutons: evidence from Mt Kinabalu, Borneo', Journal of the Geological Society, 174(1), pp. 180–191. Available at: https://doi.org/10.1144/jgs2016-041.

Cottam, M. *et al*. (2010) 'Pulsed emplacement of the Mount Kinabalu granite, northern Borneo', Journal of the Geological Society, 167(1), pp. 49–60. Available at: https://doi.org/10.1144/0016-76492009-028.

Cottam, M.A. *et al*. (2013) 'Neogene rock uplift and erosion in northern Borneo: evidence from the Kinabalu granite, Mount Kinabalu', Journal of the Geological Society, 170(5), pp. 805–816. Available at: https://doi.org/10.1144/jgs2011-130.

Hall, R. *et al*. (2009) The geology of Mount Kinabalu. (Sabah Parks Publication, 13).

Hall, R. (2013) 'Contraction and extension in northern Borneo driven by subduction rollback', Journal of Asian Earth Sciences, 76, pp. 399–411. Available at: https://doi.org/10.1016/j.jseaes.2013.04.010.

Koopmans, B.N. and Stauffer, P.H. (1967) 'Glacial phenomena on Mount Kinabalu, Sabah.', Geological Survey of Malaysia, Borneo Region Bulletin, 8, pp. 25–35.

V. VOLCANOLOGY

51. The Danakil Rift depression and its volcanism

Asrat, A. (2016) 'The Danakil Depression', in Africa's Top Geological Sites. Anhaeusser, C. R., Viljoen, M. J., Viljoen, R. P. Cape Town: Struik Nature, pp. 189–196.

Beyene, A. and Abdelsalam, M.G. (2005) 'Tectonics of the Afar Depression: A review and synthesis', Journal of African Earth Sciences, 41(1), pp. 41–59. Available at: https://doi.org/10.1016/j.jafrearsci.2005.03.003.

Makris, J. and Ginzburg, A. (1987) 'The Afar Depression: transition between continental rifting and sea-floor spreading', Tectonophysics, 141(1), pp. 199–214. Available at: https://doi.org/10.1016/0040-1951(87)90186-7.

Varet, J. (1978) Geology of central and southern Afar (Ethiopia and Djibouti Republic), Map and report. Paris: Centre national de la recherche scientifique.

Wright, T.J. *et al*. (2006) 'Magma-maintained rift segmentation at continental rupture in the 2005 Afar dyking episode', Nature, 442(7100), pp. 291–294. Available at: https://doi.org/10.1038/nature04978.

52. The Quaternary Cameroon Volcano

Déruelle, B. *et al*. (2000) 'Éruptions simultanées de basalte alcalin et de hawaiite au mont Cameroun (28 mars–17 avril 1999)', Comptes

Rendus de l'Académie des Sciences - Series IIA - Earth and Planetary Science, 331(8), pp. 525–531. Available at: https://doi.org/10.1016/S1251-8050(00)01454-3.

Gèze, B. (1941) 'Esquisse géographique du Cameroun occidental', Bulletin de l'Association de Géographes Français, 18(134), pp. 11–17. Available at: https://doi.org/10.3406/bagf.1941.7096.

Gèze, B. (1953) 'Les volcans du Cameroun occidental', Bulletin Volcanologique, 13(1), pp. 63–92. Available at: https://doi.org/10.1007/BF02596792.

Mama, N. *et al*. (2021) 'Petrological and Geochemical Studies on the Si-Undersaturated Rocks of the Mount Cameroon: Genesis of the Camptonite and Nephelinite at the Cameroon Hot Line', Open Journal of Geology, 11, pp. 239–252. Available at: https://doi.org/10.4236/ojg.2021.116014.

Suh, C.E. *et al*. (2003) 'The 1999 and 2000 eruptions of Mount Cameroon: eruption behaviour and petrochemistry of lava', Bulletin of Volcanology, 65(4), pp. 267–281. Available at: https://doi.org/10.1007/s00445-002-0257-7.

Tsafack, J.-P.F. *et al*. (2009) 'The Mount Cameroon stratovolcano (Cameroon Volcanic Line, Central Africa): Petrology, geochemistry, isotope and age data', Geochemistry, Mineralogy and Petrology, 47, pp. 65–78.

53. The historic scoria cone of the Jabal Qidr

Camp, V.E., Roobol, M.J. and Hooper, P.R. (1991) 'The Arabian continental alkali basalt province: Part II. Evolution of Harrats Khaybar, Ithnayn, and Kura, Kingdom of Saudi Arabia', GSA Bulletin, 103(3), pp. 363–391. Available at: https://doi.org/10.1130/0016-7606(1991)103<0363:TACABP>2.3.CO;2.

Kempe, S. and Al-Malabeh, A. (2013) 'Desert kites in Jordan and Saudi Arabia: Structure, statistics and function, a Google Earth study', Quaternary International, 297, pp. 126–146. Available at: https://doi.org/10.1016/j.quaint.2013.02.013.

Kennedy, M.A. *et al*. (2021) 'Dating the pendant burials of north-west Arabia: First radiometric results from the Khaybar Oasis, Saudi Arabia', Arabian Archaeology and Epigraphy, 32(S1), pp. 183–197. Available at: https://doi.org/10.1111/aae.12199.

Moufti, M.R. and Németh, K. (2014) 'The White Mountains of Harrat Khaybar, Kingdom of Saudi Arabia', International Journal of Earth Sciences, 103(6), pp. 1641–1643. Available at: https://doi.org/10.1007/s00531-014-1022-9.

Moufti, M.R. and Nemeth, K. (2016) Geoheritage of Volcanic Harrats in Saudi Arabia. Heilderberg: Springer. Available at: https://doi.org/10.1007/978-3-319-33015-0.

Nemeth, K. and Moufti, M.R. (2017) 'Geoheritage Values of a Mature Monogenetic Volcanic Field in Intra-continental Settings: Harrat Khaybar, Kingdom of Saudi Arabia', Geoheritage, 9(3), pp. 311–328. Available at: https://doi.org/10.1007/s12371-017-0243-2.

54. The Pleistocene Kilimanjaro Volcano

Barker, P.A. *et al*. (2011) 'Seasonality in equatorial climate over the past 25 k.y. revealed by oxygen isotope records from Mount Kilimanjaro', Geology, 39(12), pp. 1111–1114. Available at: https://doi.org/10.1130/G32419.1.

Kaser, G. *et al*. (2004) 'Modern glacier retreat on Kilimanjaro as evidence of climate change: observations and facts: GLACIERS AND CLIMATE CHANGE', International Journal of Climatology, 24(3), pp. 329–339. Available at: https://doi.org/10.1002/joc.1008.

Kent, P.E. (1944) 'Kilimanjaro: An Active Volcano', Nature, 153(3885), pp. 454–455. Available at: https://doi.org/10.1038/153454a0.

Mustaphi, C.J.C. *et al*. (2021) 'A 3000-year record of vegetation changes and fire at a high-elevation wetland on Kilimanjaro, Tanzania', Quaternary Research, 99, pp. 34–62. Available at: https://doi.org/10.1017/qua.2020.76.

N.J., C. *et al*. (2013) 'A century of ice retreat on Kilimanjaro: The mapping reloaded', The Cryosphere, 7, pp. 419–431. Available at: https://doi.org/10.5194/tc-7-419-2013.

Nonnotte, P. *et al*. (2008) 'New K–Ar age determinations of Kilimanjaro volcano in the North Tanzanian diverging rift, East Africa', Journal of Volcanology and Geothermal Research, 173(1), pp. 99–112. Available at: https://doi.org/10.1016/j.jvolgeores.2007.12.042.

55. The Holocene Ulmen maar

Büchel, G. (1993) 'Maars of the Westeifel, Germany', in J.F.W. Negendank and B. Zolitschka (eds) Paleolimnology of European Maar Lakes. Berlin, Heidelberg: Springer (Lecture Notes in Earth Sciences, 49), pp. 1–13. Available at: https://doi.org/10.1007/BFb0117585.

Büchel, G., Lorenz, V. and Weiler, H. (1984) 'Das Westeifel-Vulkanfeld: Maare, Schlackenkegel und Hydrogeologie (Exkursion H am 26. und 27. April 1984)', Jahresberichte und Mitteilungen des Oberrheinischen Geologischen Vereins, pp. 107–128. Available at: https://doi.org/10.1127/jmogv/66/1984/107.

Lange, T. *et al*. (2019) 'Neue Aspekte zum Vulkanismus der Westeifel (Exkursion K am 26. April 2019)', Jahresberichte und Mitteilungen des Oberrheinischen Geologischen Vereins, pp. 227–250. Available at: https://doi.org/10.1127/jmogv/101/0010.

Lange, T. and Büchel, G. (2022) 'Zeitliche Abfolge der vulkanischen Ereignisse im SE-Teil des Vulkanfeldes der Westeifel während des Weichsel-Glazials', Jahresberichte und Mitteilungen des Oberrheinischen Geologischen Vereins, pp. 313–365. Available at: https://doi.org/10.1127/jmogv/104/0013.

Lorenz, V. (1986) 'On the growth of maars and diatremes and its relevance to the formation of tuff rings', Bulletin of Volcanology, 48(5), pp. 265–274. Available at: https://doi.org/10.1007/BF01081755.

Steininger, J. (1820) Die erloschenen Vulkane in der Eifel und am Niederrheine: Ein Bericht an die Gesellschaft nützlicher Forschungen zu Trier. - 2; 82. Kupferberg. Available at: http://archive.org/details/dieerloschenenv00steigoog.

56. The 1905-1911 Matavanu volcanic eruption

Anderson, T. (1910) 'The Volcano of Matavanu in Savaii', Quarterly Journal of the Geological Society, 66(1–4), pp. 621–639. Available at: https://doi.org/10.1144/GSL.JGS.1910.066.01-04.30.

Fepuleai, A. *et al*. (2017) 'Eruption Styles of Samoan Volcanoes Represented in Tattooing, Language and Cultural Activities of the Indigenous People', Geoheritage, 9(3), pp. 395–411. Available at: https://doi.org/10.1007/s12371-016-0204-1.

Fepuleai, A., Németh, K. and Muliaina, T. (2021) 'Geopark Impact for the Resilience of Communities in Samoa, SW Pacific', Geoheritage, 13(3), p. 50. Available at: https://doi.org/10.1007/s12371-021-00578-4.

Kear, D. and Wood, B.L. (1959) The Geology and hydrology of Western Samoa. (New Zealand Geological Survey Bulletin, 63).

Németh, K. and Cronin, S.J. (2009) 'Volcanic structures and oral traditions of volcanism of Western Samoa (SW Pacific) and their implications for hazard education', Journal of Volcanology and Geothermal Research, 186(3), pp. 223–237. Available at: https://doi.org/10.1016/j.jvolgeores.2009.06.010.

Nemeth, K., Fepuleai, A. and Muliaina, T. (2017) 'Samoa Geopark Project: a strategic plan to promote the volcanic geoheritage of Savai'i Island, Samoa', in STAR 2017 - The Pacific Islands Science, Technology and Resources Conference. Nadi, Fiji. Available at: https://doi.org/10.13140/RG.2.2.19607.68009.

57. The active Yasur–Yenkahe volcanic complex

Allen, S.R. (2004) 'Complex spatter- and pumice-rich pyroclastic deposits from an andesitic caldera-forming eruption: the Siwi pyroclastic sequence, Tanna, Vanuatu', Bulletin of Volcanology, 67(1), pp. 27–41. Available at: https://doi.org/10.1007/s00445-004-0358-6.

Brothelande, E. *et al*. (2016) 'Insights into the evolution of the Yenkahe resurgent dome (Siwi caldera, Tanna Island, Vanuatu) inferred from aerial high-resolution photogrammetry', Journal of Volcanology and Geothermal Research, 322, pp. 212–224. Available at: https://doi.org/10.1016/j.jvolgeores.2015.07.001.

Firth, C.W. *et al*. (2021) 'Rapid magmatic processes drive persistently active volcanism', Lithos, 380–381, p. 105868. Available at: https://doi.org/10.1016/j.lithos.2020.105868.

Spina, L. *et al*. (2016) 'Explosive volcanic activity at Mt. Yasur: A characterization of the acoustic events (9–12th July 2011)', Journal of Volcanology and Geothermal Research, 322, pp. 175–183. Available at: https://doi.org/10.1016/j.jvolgeores.2015.07.027.

Woitischek, J. *et al*. (2020) 'Strombolian eruptions and dynamics of magma degassing at Yasur Volcano (Vanuatu)', Journal of Volcanology and Geothermal Research, 398, p. 106869. Available at: https://doi.org/10.1016/j.jvolgeores.2020.106869.

58. La Isla de Ometepe: Quaternary volcanoes in the Lake Nicaragua sedimentary basin

Borgia, A. and van Wyk de Vries, B. (2003) 'The volcano-tectonic evolution of Concepción, Nicaragua', Bulletin of Volcanology, 65, pp. 248–266. Available at: https://doi.org/10.1007/s00445-002-0256-8.

Funk, J., Mcintosh, K. and Stephens, J. (2009) 'Cenozoic tectonics of the Nicaraguan depression, Nicaragua, and Median Trough, El Salvador, based on seismic-reflection profiling and remote-sensing data', Geological Society of America Bulletin, 121, pp. 1491–1521. Available at: https://doi.org/10.1130/B26428.1.

Haberland, W. (1986) 'Settlement patterns and cultural history of Ometepe Island, Nicaragua: A preliminary sketch', Journal of the Seward Anthropological Society, 14((1982-1983)), pp. 369–386.

Kapelanczyk, L., Rose, W.I. and Jicha, B. (2012) 'An eruptive history of Maderas volcano using new 40Ar/39Ar ages and geochemical analyses', Bulletin of Volcanology, 74(9), pp. 2007–2021. Available at: https://doi.org/10.1007/s00445-012-0644-7.

Mathieu, L. *et al*. (2011) 'The interaction between volcanoes and strike-slip, transtensional and transpressional fault zones: Analogue models and natural examples', Journal of Structural Geology, 33(5), pp. 898–906. Available at: https://doi.org/10.1016/j.jsg.2011.03.003.

Saballos, J.A. *et al*. (2013) 'Gravity and geodesy of Concepción Volcano, Nicaragua'. Available at: https://doi.org/10.1130/2013.2498(05).

59. The Poás Volcano

Alvarado, G.E. (2021) Costa Rica y sus volcanes. EUNA, EUCR and Editorial Tecnológica de Costa Rica. San José, Costa Rica. Available at: https://ulibros.com/index.php/costa-rica-y-sus-volcanes-vkb1d.html.

Borgia, A. *et al*. (1990) 'Fault propagation folds induced by gravitational failure and slumping of the central Costa Rica Volcanic Range: Implications for large terrestrial and Martian volcanic edifices', Journal of Geophysical Research: Solid Earth, 95(B9), pp. 14357–14382. Available at: https://doi.org/10.1029/JB095iB09p14357.

Francis, P.W. *et al*. (1980) 'Pyroclastic sulphur eruption at Poás Volcano, Costa Rica', Nature, 283, pp. 754–756. Available at: https://doi.org/10.1038/283754a0.

Montero, W. *et al*. (2010) 'División del deslizamiento tectónico y transtensión en el macizo del volcán Poás (Costa Rica), basado en estudios neotectónicos y de sismicidad histórica', Revista Geológica de América Central [Preprint], (43). Available at: https://doi.org/10.15517/rgac.v0i43.3456.

Pérez-Umaña, D. *et al*. (2019) 'Comparative Analysis of Geomorphosites in Volcanoes of Costa Rica, Mexico, and Spain', Geoheritage, 11(2), pp. 545–559. Available at: https://doi.org/10.1007/s12371-018-0313-0.

Ruiz, P. *et al*. (2019) 'Geochemical and Geochronological Characterisation of the Poas Stratovolcano Stratigraphy', in F. Tassi, O. Vaselli, and R.A. Mora Amador (eds) Poás Volcano: The Pulsing Heart of Central America Volcanic Zone. Cham: Springer International Publishing (Active Volcanoes of the World), pp. 13–43. Available at: https://doi.org/10.1007/978-3-319-02156-0_2.

60. The Nevado del Ruiz Quaternary Volcanic Complex

Acosta, J. (1846) 'Relation de l'eruption boueuse sortie du volcán du Ruiz et de la catastrophe de Lagunilla dans la republique de la Nouvelle Grenade', C.R. Acad. Sc. Paris, 2, pp. 709–710.

Ceballos–Hernández, J.A. *et al*. (2020) 'Geological evolution of the Nevado del Ruiz Volcanic Complex', in The Geology of Colombia. Gómez, J. & Pinilla–Pachon, A.O. (eds). Bogotá: Servicio Geológico Colombiano (Publicaciones Geológicas Especiales, 38), pp. 267–296. Available at: https://doi.org/10.32685/pub.esp.38.2019.07.

Melson, W.G. *et al*. (1990) 'Water contents, temperatures and diversity of the magmas of the catastrophic eruption of Nevado del Ruiz, Colombia, November 13, 1985', Journal of Volcanology and Geothermal Research, 41(1), pp. 97–126. Available at: https://doi.org/10.1016/0377-0273(90)90085-T.

Naranjo, J.L. *et al*. (1986) 'Eruption of the Nevado del Ruiz Volcano, Colombia, On 13 November 1985: Tephra Fall and Lahars', Science, 233(4767), pp. 961–963. Available at: https://doi.org/10.1126/science.233.4767.961.

Pierson, T.C. *et al*. (1990) 'Perturbation and melting of snow and ice by the 13 November 1985 eruption of Nevado del Ruiz, Colombia, and consequent mobilization, flow and deposition of lahars', Journal of Volcanology and Geothermal Research, 41(1), pp. 17–66. Available at: https://doi.org/10.1016/0377-0273(90)90082-Q.

Voight, B. (1990) 'The 1985 Nevado del Ruiz volcano catastrophe: anatomy and retrospection', Journal of Volcanology and Geothermal Research, 44(3), pp. 349–386. Available at: https://doi.org/10.1016/0377-0273(90)90027-D.

61. The Cotacachi - Cuicocha volcanic complex

Almeida, M. *et al*. (2019) 'New constraints on the geological and chronological evolution of the Cotacachi-Cuicocha Volcanic Complex (Ecuador)', in 8th International Symposium on Andean Geodynamics (ISAG). Available at: https://hal.archives-ouvertes.fr/hal-02419525.

Gunkel, G. *et al*. (2009) 'Survey and assessment of post volcanic activities of a young caldera lake, Lake Cuicocha, Ecuador', Natural Hazards and Earth System Sciences, 9(3), pp. 699–712.

Hillebrandt, C. (1989) Estudio geovolcanológico del complejo volcánico Cuicocha – Cotacachi y sus aplicaciones, Provincia de Imbabura. Quito. Tesis de Maestría. Escuela Politécnica Nacional.

Melián, G.V. *et al*. (2021) 'Geochemistry of Water and Gas Emissions From Cuicocha and Quilotoa Volcanic Lakes, Ecuador', Frontiers in Earth Science, 9. Available at: https://www.frontiersin.org/articles/10.3389/feart.2021.741528.

Rengel Calvopiña, P.J. (2020) Characterization of pyroclastic density current deposits at Cuicocha caldera volcano, northern ecuadorian Andes. Bachelor's Thesis. Universidad de Investigación de Tecnología Experimetal Yachay. Available at: http://repositorio.yachaytech.edu.ec/handle/123456789/186.

Sierra, D. *et al*. (2021) 'Temporal and spatial variations of CO2 diffuse volcanic degassing on Cuicocha Caldera Lake – Ecuador', Journal of Volcanology and Geothermal Research, 411, p. 107145. Available at: https://doi.org/10.1016/j.jvolgeores.2020.107145.

62. The Quaternary Santorini Caldera

Druitt, T. and Francaviglia, V. (1992) 'Caldera formation on Santorini and the physiography of the islands in the late Bronze Age', Bulletin of Volcanology, 54(6), pp. 484–493. Available at: https://doi.org/10.1007/BF00301394.

Druitt, T.H. (2014) 'New insights into the initiation and venting of the Bronze-Age eruption of Santorini (Greece), from component analysis', Bulletin of Volcanology, 76(2), p. 794. Available at: https://doi.org/10.1007/s00445-014-0794-x.

McCoy, F.W. and Heiken, G. (2000) 'Tsunami Generated by the Late Bronze Age Eruption of Thera (Santorini), Greece', pure and applied geophysics, 157(6), pp. 1227–1256. Available at: https://doi.org/10.1007/s000240050024.

McVey, B.G. *et al*. (2019) 'Magma accumulation beneath Santorini volcano, Greece, from P-wave tomography', Geology, 48(3), pp. 231–235. Available at: https://doi.org/10.1130/G47127.1.

Nomikou, P. *et al*. (2016) 'Post-eruptive flooding of Santorini caldera and implications for tsunami generation', Nature Communications, 7(1), pp. 1–10. Available at: https://doi.org/10.1038/ncomms13332.

Pyle, D.M. and Elliott, J.R. (2006) 'Quantitative morphology, recent evolution, and future activity of the Kameni Islands volcano, Santorini, Greece', Geosphere, 2(5), pp. 253–268. Available at: https://doi.org/10.1130/GES00028.1.

63. The vapor phase ignimbrites of Sillar in the Añashuayco Quarries of Arequipa

Aguilar, R. *et al*. (2022) 'Growth and evolution of long-lived, large volcanic clusters in the Central Andes: The Chachani Volcano Cluster, southern Peru', Journal of Volcanology and Geothermal Research, 426, p. 107539. Available at: https://doi.org/10.1016/j.jvolgeores.2022.107539.

Fenner, C.N. (1948) 'Incandescent tuff flows in southern Peru', GSA Bulletin, 59(9), pp. 879–893. Available at: https://doi.org/10.1130/0016-7606(1948)59[879:ITFISP]2.0.CO;2.

Hatch, F.H. (1885) 'Uber die Gestine der Volkangruppe von Arequipa', Min, Petr. Mitt, 7, pp. 308–360.

Negro, S. (2015) Apreciaciones en torno a la ruta del sillar: Arequipeño. Instituto de Investigación del Patrimonio Cultural.

Paquereau-Lebti, P. *et al*. (2006) 'Neogene and Quaternary ignimbrites in the area of Arequipa, Southern Peru: Stratigraphical and petrological correlations', Journal of Volcanology and Geothermal Research, 154(3), pp. 251–275. Available at: https://doi.org/10.1016/j.jvolgeores.2006.02.014.

Paquereau-Lebti, P. *et al*. (2008) 'Paleomagnetism, magnetic fabric, and 40Ar/39Ar dating of Pliocene and Quaternary ignimbrites in the Arequipa area, southern Peru', Bulletin of Volcanology, 70(8), pp. 977–997. Available at: https://doi.org/10.1007/s00445-007-0181-y.

64. The pyroclastic deposits from the Huaynaputina volcano eruption 1600 CE

Arias Salazar, C.L. (2021) Recursos geoturísticos generados a partir del impacto de la erupción del volcán Huaynaputina del año 1600 d.C. como patrimonio geológico. Thesis. Universidad Nacional del Altiplano. Available at: http://repositorio.unap.edu.pe/handle/UNAP/15619.

Instituto Geológico Minero y Metalúrgico Dirección de Geología Ambiental y Riesgo Geológico (2021) Patrimonio geológico asociado a la erupción del volcán Huaynaputina del año 1600 d.C. en el distrito de Quinistaquillas. Provincia General Sánchez Cerro, departamento Moquegua. Informe técnico N° A7184. Perú: Instituto Geológico Minero y Metalúrgico. Dirección de Geología Ambiental y Riesgo Geológico, p. 57. Available at: https://repositorio.ingemmet.gob.pe/handle/20.500.12544/3306.

Mariño, J. *et al*. (2021) 'Multidisciplinary Study of the Impacts of the 1600 CE Huaynaputina Eruption and a Project for Geosites and Geo-touristic Attractions', Geoheritage, 13, p. 64. Available at: https://doi.org/10.1007/s12371-021-00577-5.

Prival, J.-M. *et al*. (2020) 'New insights into eruption source parameters of the 1600 CE Huaynaputina Plinian eruption, Peru', Bulletin of Volcanology, 82(1), p. 7. Available at: https://doi.org/10.1007/s00445-019-1340-7.

Stoffel, M. *et al*. (2015) 'Estimates of volcanic-induced cooling in the Northern Hemisphere over the past 1,500 years', Nature Geoscience, 8(10), pp. 784–788. Available at: https://doi.org/10.1038/ngeo2526.

Thouret, J.-C. *et al*. (2002) 'Reconstruction of the AD 1600 Huaynaputina eruption based on the correlation of geologic evidence with early Spanish chronicles', Journal of Volcanology and Geothermal Research, 115(3), pp. 529–570. Available at: https://doi.org/10.1016/S0377-0273(01)00323-7.

65. The Miocene Cappadocian Ignimbrites sequence

Froger, J.-L. *et al*. (1998) 'Hidden calderas evidenced by multisource geophysical data; example of Cappadocian Calderas, Central Anatolia', Journal of Volcanology and Geothermal Research, 85(1), pp. 99–128. Available at: https://doi.org/10.1016/S0377-0273(98)00052-3.

Gevrek, A.İ. and Kazanci, N. (2000) 'A Pleistocene, pyroclastic-poor maar from central Anatolia, Turkey: influence of a local fault on a phreatomagmatic eruption', Journal of Volcanology and Geothermal Research, 95(1), pp. 309–317. Available at: https://doi.org/10.1016/S0377-0273(99)00121-3.

Le Pennec, J.-L. *et al*. (2005) 'Stratigraphy and age of the Cappadocia ignimbrites, Turkey: reconciling field constraints with paleontologic, radiochronologic, geochemical and paleomagnetic data', Journal of Volcanology and Geothermal Research, 141(1), pp. 45–64. Available at: https://doi.org/10.1016/j.jvolgeores.2004.09.004.

Schumacher, R. and Mues-Schumacher, U. (1997) 'The pre-ignimbrite (phreato) plinian and phreatomagmatic phases of the Akdag-Zelve ignimbrite eruption in Central Anatolia, Turkey', Journal of Volcanology and Geothermal Research, 78(1), pp. 139–153. Available at: https://doi.org/10.1016/S0377-0273(96)00106-0.

Temel, A. *et al*. (1998) 'Ignimbrites of Cappadocia (Central Anatolia, Turkey): petrology and geochemistry', Journal of Volcanology and Geothermal Research, 85(1), pp. 447–471. Available at: https://doi.org/10.1016/S0377-0273(98)00066-3.

Toprak, V. (1998) 'Vent distribution and its relation to regional tectonics, Cappadocian Volcanics, Turkey', Journal of Volcanology and Geothermal Research, 85(1), pp. 55–67. Available at: https://doi.org/10.1016/S0377-0273(98)00049-3.

66. El Tatio geothermal field

Bertrand, A. (1885) Memoria sobre las cordilleras del desierto de Atacama y regiones limítrofes, presentada al señor ministro del interior. Santiago, Chile: Imprenta Nacional.

Fernández-Turiel, J.L. *et al*. (2005) 'The hot spring and geyser sinters of El Tatio, Northern Chile', Sedimentary Geology, 180(3), pp. 125–147. Available at: https://doi.org/10.1016/j.sedgeo.2005.07.005.

Glennon, A. and Paff, R.M. (2003) 'The extraordinary thermal activity of the El Tatio Geysers, Antofagasta Province, Chile', GOSA Transactions, 8, pp. 31–78.

Nicolau, C., Reich, M. and Lynne, B. (2014) 'Physico-chemical and environmental controls on siliceous sinter formation at the high-altitude El Tatio geothermal field, Chile', Journal of Volcanology and Geothermal Research, 282, pp. 60–76. Available at: https://doi.org/10.1016/j.jvolgeores.2014.06.012.

Phoenix, V.R. *et al*. (2006) 'Chilean high-altitude hot-spring sinters: a model system for UV screening mechanisms by early Precambrian cyanobacteria', Geobiology, 4(1), pp. 15–28. Available at: https://doi.org/10.1111/j.1472-4669.2006.00063.x.

Wilmeth, D.T. *et al*. (2022) 'Evaporative silicification in floating microbial mats: patterns of oxygen production and preservation potential in silica-undersaturated streams, El Tatio, Chile', Geobiology, 20(2), pp. 310–330. Available at: https://doi.org/10.1111/gbi.12476.

67. The Yellowstone volcanic and hydrothermal system

Brock, T.D. (1985) 'Life at High Temperatures', Science, 230(4722), pp. 132–138. Available at: https://doi.org/10.1126/science.230.4722.132.

Christiansen, R.L. (2001) The Quaternary and Pliocene Yellowstone Plateau volcanic field of Wyoming, Idaho, and Montana, The Quaternary and Pliocene Yellowstone Plateau volcanic field of Wyoming, Idaho, and Montana. USGS Numbered Series 729-G. USGS, p. 146. Available at: https://doi.org/10.3133/pp729G.

Huang, H.-H. *et al*. (2015) 'The Yellowstone magmatic system from the mantle plume to the upper crust', Science, 348(6236), pp. 773–776. Available at: https://doi.org/10.1126/science.aaa5648.

Pierce, K.L. and Morgan, L.A. (1992) 'The track of the Yellowstone hot spot: Volcanism, faulting, and uplift', in Regional Geology of Eastern Idaho and Western Wyoming. Link, P.K., Kuntz, M.A., and Platt, L.B., eds. (Geological Society of America Memoir, 179), pp. 1–53. Available at: https://pubs.geoscienceworld.org/gsa/books/book/196/chapter/3793669/Chapter-1-The-track-of-the-Yellowstone-hot-spot

Smith, R.B. and Braile, L.W. (1994) 'The Yellowstone hotspot', Journal of Volcanology and Geothermal Research, 61(3), pp. 121–187. Available at: https://doi.org/10.1016/0377-0273(94)90002-7.

VI. TECTONICS

68. Ynys Llanddwyn late Neoproterozoic-Cambrian Mélange

Gibbons, W. and Horak, J.M. (1996) 'The evolution of the Neoproterozoic Avalonian subduction system: Evidence from the British Isles'. Available at: https://doi.org/10.1130/0-8137-2304-3.269.

Greenly, E. (1919) The geology of Anglesey. London: H.M. Stationery Off.

Groome, N. (2022) Neoproterozoic-Ordovician Evolution of the Monian Subduction Complex, Wales, UK. Unpublished PhD thesis. University of Cardiff.

Henslow, J.S. (1822) Geological Description of Anglesea. (Transactions of the Cambridge Philosophical Society). Available at: http://archive.org/details/Henslow1822TransactionsOfTheCambridgePhilosophi (Accessed: 2 August 2022).

Maruyama, S., Kawai, T. and Windley, B.F. (2010) 'Ocean plate stratigraphy and its imbrication in an accretionary orogen: the Mona Complex, Anglesey–Lleyn, Wales, UK', Geological Society, London, Special Publications, 338(1), pp. 55–75. Available at: https://doi.org/10.1144/SP338.4.

Schofield, D.I. *et al*. (2020) 'Tectonic evolution of Anglesey and adjacent mainland North Wales', Geological Society, London, Special Publications, 503(1), pp. 371–390. Available at: https://doi.org/10.1144/SP503-2020-9.

69. Namakdan Salt Cave

Bruthans, J. *et al*. (2005) 'NAMAK: Czech-Iranian research project in Iranian salt karst (SE Zagros Mts.)', in Czech Speleological Society 2001–2004. P. Bosák and Z. Motyčka. Prague: CSS, pp. 49–53.

Bruthans, J., Filippi, M., *et al*. (2006) '3N Cave (6580 m): Longest salt cave in the world', National Speleological Society, (64), p. 9.

Bruthans, J., Kamas, J., *et al*. (2006) 'Holocene marine terraces on two salt diapirs in the Persian Gulf. Iran: age, depositional history and uplift rate', Journal of quaternary science, 21, pp. 843–857.

Filippi, M. and Bruthans, J. (2009) 'Czech-Iranian research in salt karst (SE Iran, Zagros Mts.): Project NAMAK in the period 2005–2008', in Czech Speleological Society, 2001-2004.

Hassanpour, J. *et al*. (2021) 'Impact of salt layers interaction on the salt flow kinematics and diapirism in the Eastern Persian Gulf, Iran: Constraints from seismic interpretation, sequential restoration, and physical modelling', Tectonophysics, 811, p. 228887. Available at: https://doi.org/10.1016/j.tecto.2021.228887.

Mukherjee, S., Talbot, C.J. and Koyi, H.A. (2010) 'Viscosity estimates of salt in the Hormuz and Namakdan salt diapirs, Persian Gulf', Geological Magazine, 147(4), pp. 497–507. Available at: https://doi.org/10.1017/S001675680999077X.

Shahpasandzadeh, M., Hashemifar, G. and Shafiei Bafti, A. (2016) 'Structural evolution of the Namakdan salt diapir in the Zagros fold-thrust belt: The Persian Gulf, Iran', in EGU General Assembly Conference Abstracts. Geological Research Abstracts, pp. EPSC2016-1226.

70. The Moine Thrust Zone

Dewey, J.F. and Kidd, W.S.F. (1974) 'Continental Collisions in the Appalachian-Caledonian Orogenic Belt: Variations Related to Complete and Incomplete Suturing', Geology, 2(11), pp. 543–546. Available at: https://doi.org/10.1130/0091-7613(1974)2<543:CCITAO>2.0.CO;2.

Lapworth, C. (1885) 'The Highland Controversy in British Geology', Nature, 32, pp. 558–559.

Law, R. *et al*. (2010) Continental Tectonics and Mountain Building: The Legacy of Peach and Horne, Geological Society London Special Publications. Available at: https://doi.org/10.1144/SP335.1.

Murchison, S.R.I. and Geikie, S.A. (1862) First Sketch of a New Geological Map of Scotland with Explanatory Notes. Edinburgh: W. & A.K. Johnston, and W. Blackwood & Sons.

Peach, B.N. *et al*. (1907) The Geological Structure of the NW Highlands of Scotland. Glasgow: HMSO (Memoirs of the Geological Survey of Great Britain).

Peach, B.N. *et al*. (1923) Assynt District Map Sheet. Geological Survey of Scotland.

71. Upper Jurassic ophiolitic sequence in La Désirade Island

Corsini, M. *et al*. (2011) 'Discovery of Lower Cretaceous synmetamorphic thrust tectonics in French Lesser Antilles (La Désirade Island, Guadeloupe): Implications for Caribbean geodynamics', Tectonics, 30(4). Available at: https://doi.org/10.1029/2011TC002875.

Léticée, J.-L. *et al*. (2019) 'Decreasing uplift rates and Pleistocene marine terraces settlement in the central lesser Antilles fore-arc (La Désirade Island, 16°N)', Quaternary International, 508, pp. 43–59. Available at: https://doi.org/10.1016/j.quaint.2018.10.030.

Mattinson, J.M. *et al*. (2008) 'Late Jurassic age of oceanic basement at La Désirade Island, Lesser Antilles arc', in Ophiolites, Arcs, and Batholiths: A Tribute to Cliff Hopson. Wright J. & Shervais J. (eds). (Geological Society of America, Special Paper, 438), pp. 175–190.

Mattinson, J.M., Fink, L.K. and Hopson, C.A. (1973) Age and origin of ophiolitic rocks on La Désirade Island, Lesser Antilles Island arc. (Year Book Carnegie Institute Washington, 72).

Neill, I. *et al*. (2010) 'Origin of the volcanic complexes of La Désirade, Lesser Antilles: Implications for tectonic reconstruction of the Late Jurassic to Cretaceous Pacific-proto Caribbean margin', Lithos, 120(3), pp. 407–420. Available at: https://doi.org/10.1016/j.lithos.2010.08.026.

Westercamp, D. (1980) 'Geological map of La Désirade Island. 1:25,000-scale and explanatory notes'. Ministère de l'industrie, Bureau de recherches géologiques et minières, Service géologique national ; Service géologique régional des Antilles et de la Guyane.

72. The South Tibetan Detachment System in the Rongbuk Valley

Burchfiel, B.C. *et al*. (1992) 'The South Tibetan Detachment System, Himalayan Orogen: Extension Contemporaneous With and Parallel to Shortening in a Collisional Mountain Belt', Geological Society of America Special Paper, 269, p. 41. Available at: https://doi.org/10.1130/SPE269-p1.

Burg, J.P. *et al*. (1984) 'Deformation of leucogranites of the crystalline Main Central Sheet in southern Tibet (China)', Journal of Structural Geology, 6(5), pp. 535–542. Available at: https://doi.org/10.1016/0191-8141(84)90063-4.

Carosi, R. *et al*. (1998) 'The south Tibetan detachment system in the Rongbuk valley, Everest region. Deformation features and geological implications', Journal of Asian Earth Sciences, 16(2), pp. 299–311. Available at: https://doi.org/10.1016/S0743-9547(98)00014-2.

Corthouts, T.L., Lageson, D.R. and Shaw, C.A. (2016) 'Polyphase deformation, dynamic metamorphism, and metasomatism of Mount Everest's summit limestone, east central Himalaya, Nepal/Tibet', Lithosphere, 8(1), pp. 38–57. Available at: https://doi.org/10.1130/L473.1.

Searle, M.P. *et al*. (2003) 'The structural geometry, metamorphic and magmatic evolution of the Everest massif, High Himalaya of Nepal-South Tibet', Journal of the Geological Society, 160(3), pp. 345–366. Available at: https://doi.org/10.1144/0016-764902-126.

Waters, D.J. *et al*. (2019) 'Structural and thermal evolution of the South Tibetan Detachment shear zone in the Mt Everest region, from the 1933 sample collection of L. R. Wager', Geological Society of London Special Publications, 478(1), pp. 335–372. Available at: https://doi.org/10.1144/SP478.17.

73. Northern Snake Range metamorphic core complex

Lee, J., Blackburn, T. and Johnston, S. (2017) 'Timing of mid-crustal ductile extension in the northern Snake Range metamorphic core complex, Nevada: Evidence from U/Pb zircon ages', Geosphere, 13(2), pp. 439–459. Available at: https://doi.org/10.1130/GES01429.1.

Lee, J., Miller, E.L. and Sutter, J.F. (1987) 'Ductile strain and metamorphism in an extensional tectonic setting: a case study from the northern Snake Range, Nevada, USA', Geological Society of London Special Publications, 28, pp. 267–298. Available at: https://doi.org/10.1144/GSL.SP.1987.028.01.18.

Miller, E.L. *et al*. (1999) 'Rapid Miocene slip on the Snake Range–Deep Creek Range fault system, east-central Nevada', GSA Bulletin, 111(6), pp. 886–905. Available at: https://doi.org/10.1130/0016-7606(1999)111<0886:RMSOTS>2.3.CO;2.

Miller, E.L., Gans, P.B. and Garing, J. (1983) 'The Snake Range Décollement: An exhumed Mid-Tertiary ductile-brittle transition', Tectonics, 2(3), pp. 239–263. Available at: https://doi.org/10.1029/TC002i003p00239.

Miller, E.L., Gans, P.B. and Lee, J. (1987) 'The Snake Range decollement, eastern Nevada', in Cordilleran Section, Geological Society of America Centennial Field Guide Vol. 1. Hill, M.L., ed, pp. 77–82.

74. Nojima Fault

Ando, M. (2001) 'Geological and geophysical studies of the Nojima Fault from drilling: An outline of the Nojima Fault Zone Probe', Island Arc, 10(3–4), pp. 206–214. Available at: https://doi.org/10.1111/j.1440-1738.2001.00349.x.

Awata Y. *et al*. (1996) 'Surface Fault Ruptures on the Northwest Coast of Awaji Island Associated with the Hyogo-ken Nanbu Earthquake of 1995, Japan', Zisin (Journal of the Seismological Society of Japan. 2nd ser.), 49(1), pp. 113-124 (in Japanese with English abstract). Available at: https://doi.org/10.4294/zisin1948.49.1_113.

Katoh, S. (2020) 'Preservation and practical use of recent earthquake faults in Japan and Taiwan: the past, present and near future', in New Development in Active Fault Studies – 25 years since the 1995 Kobe earthquake. Hokudan International Symposium on Active Faulting, Okumura, K., Toda, S. and Azuma, T. eds, pp. 48–51.

Lin, A. and Nishiwaki, T. (2019) 'Repeated Seismic Slipping Events Recorded in a Fault Gouge Zone: Evidence From the Nojima Fault Drill Holes, SW Japan', Geophysical Research Letters, 46(3), pp. 1276–1283. Available at: https://doi.org/10.1029/2019GL081927.

Lin, A. and Uda, S. (1996) 'Morphological characteristics of the earthquake surface ruptures on Awaji Island, associated with the 1995 Southern Hyogo Prefecture Earthquake', Island Arc, 5(1), pp. 1–15. Available at: https://doi.org/10.1111/j.1440-1738.1996.tb00008.x.

Takemura K. *et al*. (1998) 'Excavation survey of the 1995 surface rupture in the Nojima Fault Preservation Pavilion at Hokudan Town, Tsuna County, Hyogo Prefecture, Japan', Humans and Nature, (9), pp. 57-72 (in Japanese with English abstract).

VII. MINERALOGY

75. Tsumeb Ore Deposit

Bowell, R. and Mocke, H. (2019) 'Minerals New to Tsumeb', Communications - Geological Survey of Namibia, 19, pp. 20–46.

Kamona, A.F. and Günzel, A. (2007) 'Stratigraphy and base metal mineralization in the Otavi Mountain Land, Northern Namibia—a review and regional interpretation', Gondwana Research, 11(3), pp. 396–413. Available at: https://doi.org/10.1016/j.gr.2006.04.014.

Keller, P. (1977) 'Paragenesis', in W.E. Wilson (ed.) Mineralogical Record. (TSUMEB! (NAMIBIA) SPECIAL ISSUE, 8 (3)), pp. 38–47.

Keller, P. and Innes, J. (1986) 'Neue Mineralfunde aus Tsumeb', Lapis, pp. 28–32.

Lombaard, A.F. *et al*. (1986) 'The Tsumeb lead-copper-zinc-silver deposit, South West Africa/Namibia, 1761-1787', in Mineral deposits of Southern Africa. Anhaeusser, C.R. and Maske, S. (Eds). Johannesburg: Geological Society of South Africa (2), pp. 1021–2335.

76. The giant mercury deposit of the Almadén syncline

Hernández, A. *et al*. (1999) 'The Almadén mercury mining district, Spain', Mineralium Deposita, 34(5), pp. 539–548. Available at: https://doi.org/10.1007/s001260050219.

Higueras, P. *et al*. (2013) 'Intraplate mafic magmatism, degasification, and deposition of mercury: The giant Almadén mercury deposit (Spain) revisited', Ore Geology Reviews, 51, pp. 93–102. Available at: https://doi.org/10.1016/j.oregeorev.2012.12.004.

Ortega Gironés, E. and Hernandez Sobrino, A. (1992) 'The mercury deposits of the Almaden syncline, Spain.', Chronique de la Recherche Miniere, 60(506), pp. 3–24.

Palero-Fernández, F.J. *et al*. (2015) 'Geological context and plumbotectonic evolution of the giant Almadén Mercury Deposit', Ore Geology Reviews, 64, pp. 71–88. Available at: https://doi.org/10.1016/j.oregeorev.2014.06.013.

Saupé, F. (1990) 'Geology of the Almaden mercury deposit, Province of Ciudad Real, Spain', Economic Geology, 85(3), pp. 482–510. Available at: https://doi.org/10.2113/gsecongeo.85.3.482.

UNESCO World Heritage Documents (2012) Heritage of Mercury. Almadén and Idrija, UNESCO World Heritage Centre. Available at: https://whc.unesco.org/en/list/1313/

77. Deposits of Amethyst of Los Catalanes Gemological District

Duarte, L.C. *et al*. (2011) 'Stable isotope and mineralogical investigation of the genesis of amethyst geodes in the Los Catalanes gemological district, Uruguay, southernmost Paraná volcanic province', Mineralium Deposita, 46(3), pp. 239–255. Available at: https://doi.org/10.1007/s00126-010-0323-6.

Hartmann, L.A. (2008) Amethyst geodes formed from hot water in dinosaur times. Gráfica da UFRGS.

Morteani, G. *et al*. (2010) 'The genesis of the amethyst geodes at Artigas (Uruguay) and the paleohydrology of the Guaraní aquifer: structural, geochemical, oxygen, carbon, strontium isotope and fluid inclusion study', International Journal of Earth Sciences, 99(4), pp. 927–947. Available at: https://doi.org/10.1007/s00531-009-0439-z.

Techera, J. (2011) Exploración detallada de los yacimientos de amatista en el Distrito Gemológico Los Catalanes. Proyecto Ágatas y Amatistas - Fase II. Montevideo, Uruguay: DINAMIGE, División Geología.

Techera, J., Loureiro, J. and Spoturno, J. (2007) Estudio geológico, yacimentológico y minero de las piedras semi-preciosas del norte uruguayo. Proyecto Ágatas y Amatistas - Fase I. Montevideo, Uruguay: DINAMIGE, División Geología.

Waichel, B.L. *et al*. (2010) 'Morfologia e estruturas dos derrames da Formação Arapey', in Actas VI Congreso Uruguayo de Geología, pp. 456–461. Available at: https://www.sociedadgeologiauy.org/actas-de-congresos/.

VIII. GEOMORPHOLOGY AND ACTIVE GEOLOGICAL PROCESSES

78. Uluru inselberg

Brocx, M. and Semeniuk, V. (2007) 'Geoheritage and geoconservation - History, definition, scope and scale', Journal of the Royal Society of Western Australia, 90, pp. 53–87.

Isaacs, J. (1980) Australian Dreaming: 40,000 Years of Aboriginal History. Lansdowne Press.

Northern Territory Government (no date) Place Names Register, Place Names Register Extract: Uluru / Ayers Rock. Northern Territory Place Names Register. Available at: http://www.ntlis.nt.gov.au/placenames/view.jsp?id=10532.

Sweet, I.P. and Crick, I.H. (1994) Uluru & Kata Tjuta: a geological history. (Monograph). Canberra: Australian Geological Survey Organisation.

Twidale, C.R. and Bourne, J.A. (2012) 'Contrasted Perceptions of Uluru', Physical Geography, 33(3), pp. 285–302. Available at: https://doi.org/10.2747/0272-3646.33.3.285.

Young, D.N. *et al*. (2002) 'Ayers Rock, Northern Territory, Map Sheet GS52-8 (2nd edition) (Map). 1:250 000'. (Northern Territory Geological Survey. Geological Map Series Explanatory Notes.).

79. The Sugar Loaf monolith of Rio de Janeiro

Castro, N. *et al*. (2021) 'A heritage stone of Rio de Janeiro (Brazil): the Facoidal gneiss', Episodes, 44(1), pp. 59–74. Available at: https://doi.org/10.18814/EPIIUGS/2020/020OS13.

Chancellor, G. and Wyhe, J. van (eds) (2009) Charles Darwin's Notebooks from the Voyage of the Beagle. Illustrated edition. Cambridge: Cambridge University Press. Available at: http://darwin-online.org.uk/content/frameset?itemID=EH88202330&viewtype=text&pageseq=1.

Da Silva, L.C. *et al*. (2003) 'Zircon U-Pb Shrimp dating of the Serra Dos Órgãos and Rio De Janeiro Gneissic Granitic Suites: Implications for the (560 Ma) Brasiliano/Pan-African collage', Revista Brasileira De Geosiencias, 33(2), pp. 237–244.

Silva, L.C.D. and Ramos, A.J.A. (2002) 'Pão de Açúcar, RJ – Cartão Postal Geológico do Brasil', in Sítios Geológicos e Paleontológicos do Brasil. Schobbenhaus C., Campos D.A., Queiroz E.T., Winge M., Berbert-Born M. (eds). Brasília: DNPM/CPRM, Comissão Brasileira de Sítios Geológicos e Paleobiológicos (SIGEP), pp. 263–268. Available at: http://sigep.cprm.gov.br/sitios.htm.

Valeriano, C. de M. *et al*. (2012) Geologia e recursos minerais da folha Baía de Guanabara SF.23-Z-B-IV, estado do Rio de Janeiro, escala 1:100.000. 1. ed. Belo Horizonte. CPRM-Serviço Geológico do Brasil / UERJ- Universidade do Estado do Rio de Janeiro. Available at: http://rigeo.cprm.gov.br/jspui/handle/doc/11375.

Valeriano, C. de M. and Magalhães, A.C. (1984) 'Geologia estrutural de area do Pão de Açucar e adjacências, Rio de Janeiro, Brasil', Anais da Academia Brasileira de Ciências, 56(3), pp. 295–304.

80. Shilin Karst

Group of Stone Forest Study (1997) Study on Lunnan stone forest Karst. Kunming: Yunnan Science and Technology Press.

Knez, M. *et al*. (2011) South China Karst Vol. II, ZRC SAZU, Založba ZRC. Available at: https://doi.org/10.3986/9789610503217.

Linhua, S. *et al*. (1997) 'Stone forest: a jewellery of nature heritage', Beijing: China Environmental Science Press, pp. 10–136.

Shouyue, Z. (1984) 'The development and evolution of Lunan stone forest', Carsologica Sinica, 2, pp. 78–87.

Xiaoping, C. *et al*. (1998) South China Karst Vol. I, ZRC SAZU, Založba ZRC. Available at: https://doi.org/10.3986/9616182684.

81. Tsingy of Bemaraha

Besairie, H. and Collignon, M. (1972) 'Géologie de Madagascarl. Les terrains sédimentaires', Annales Géologiques de Madagascar, p. 463.

Dobrilla, J.C., Colney, F. and Delaty, J.-N. (2006) 'Spéléologie sous les Tsingy de Bemaraha', Spelunca. 5e série [Preprint].

Middleton, G. (1996) 'The 1995 Australo-Anglo-MalagasySpeleo-Ornitho-Malacological Expedition: Tsingy de Bemaraha, Western Madagascar', Journal of the Sydney Speleological Society, 40, pp. 141–158.

Middleton, G. (1998) 'International Speleo-OrnithoGeo-Malacological Expedition: Northern Tsingy de Bemaraha, Western Madagascar', Journal of the Sydney Speleological Society, 42, pp. 231–243.

Veress, M. *et al*. (2008) 'The origin of the Bemaraha tsingy (Madagascar)', International Journal of Speleology, 37(2). Available at: http://dx.doi.org/10.5038/1827-806X.37.2.6.

82. La Puerta del Diablo inverted relief

Hernández, W. and Jicha, B. (2019) Múltiple colapso sectorial del volcán de San Salvador. Universidad Tecnológica de El Salvador. Available at: http://biblioteca.utec.edu.sv:8080/jspui/handle/11298/1105 (Accessed: 3 August 2022).

Jicha, B.R. and Hernández, W. (2022) 'Effusive and explosive eruptive history of the Ilopango caldera complex, El Salvador', Journal of Volcanology and Geothermal Research, 421, p. 107426. Available at: https://doi.org/10.1016/j.jvolgeores.2021.107426.

Lardé y Larín, J. (2000) El Salvador: Inundaciones e incendios, erupciones y terremotos. 2a. ed. San Salvador: Consejo Nacional para la Cultura y el Arte, Dirección de Publicaciones e Impresos (Biblioteca de Historia Salvadoreña, 5).

Lexa, J. *et al*. (2011) 'Geology and volcanic evolution in the southern part of the San Salvador Metropolitan Area', Journal of Geosciences, 56(1), pp. 106–140. Available at: https://doi.org/10.3190/jgeosci.088.

Lexa, J. *et al*. (2021) 'Geología del Área Metropolitana de San Salvador (1:50 000), El Salvador', Revista Geológica de América Central, pp. 1–23. Available at: https://doi.org/10.15517/rgac.v66i0.49972.

Sapper, K. (1937) Mittelamerika. Handbuch der Regionalen Geologie. Winters Universtätsbuchhandlung, Heidelberg.

Williams, H. and Meyer-Abich, H. (1955) Volcanism in the southern part of El Salvador: with particular reference to the collapse basins of Lakes Coatepeque and Ilopango. Berkeley: University of California Press.

83. Quaternary interglacial coral and marine uplifted terraces of Maisí, Cuba

Del Busto, R. (1975) 'Las terrazas marinas de Maisí', in Ciencia. (Serie 7 Geografía, 10), pp. 1–12. Available at: http://repositorio.geotech.cu/jspui/handle/1234/2185 (Accessed: 3 August 2022).

Del Corral, J.I. (1945) 'Terrazas pleistocénicas cubanas', Revista de la Sociedad Cubana de Ingenieros, 40(1), pp. 5–44.

Hershey, O.H. (1898) 'Raised Shore-lines on Cape Maysi, Cuba', Science, 8(189), pp. 179–180. Available at: https://doi.org/10.1126/science.8.189.179.

Muhs, D.R. *et al*. (2017) 'Late Quaternary uplift along the North America-Caribbean plate boundary: Evidence from the sea level record of Guantanamo Bay, Cuba', Quaternary Science Reviews, 178, pp. 54–76. Available at: https://doi.org/10.1016/j.quascirev.2017.10.024.

Peñalver, L. *et al*. (2021) 'The Cuban staircase sequences of coral reef and marine terraces: A forgotten masterpiece of the Caribbean geodynamical puzzle', Marine Geology, 440, p. 106575. Available at: https://doi.org/10.1016/j.margeo.2021.106575.

Toscano, M.A., Rodriguez, E. and Lundberg, J. (1999) 'Geological investigation of the late Pleistocene Jaimanitas Formation: science and society in Castro´s Cuba', in Proceedings of the 9th Symposium on the Geology of the Bahamas and Other Carbonate Regions , San Salvador, Bahamas. Bahamian Field Station.

84. The Grand Canyon

Crow, R.S. *et al*. (2021) 'Redefining the age of the lower Colorado River, southwestern United States', Geology, 49(6), pp. 635–640. Available at: https://doi.org/10.1130/G48080.1.

Karlstrom, K. *et al*. (2021) Telling Time at Grand Canyon National Park 2020 Update Telling Time at Grand Canyon National Park 2020 Update. (Natural Resource Report NPS/GRCA/NRR, 2021/2246). Available at: https://doi.org/10.36967/nrr-2285173.

Karlstrom, K. and Crossey, L. (2019) 'Classic Rock Tours 3. Grand Canyon Geology, One Hundred and Fifty Years after John Wesley Powell: A Geology Guide for Visiting the South Rim of Grand Canyon National Park', Geoscience Canada, pp. 163–193. Available at: https://doi.org/10.12789/geocanj.2019.46.153.

Karlstrom, K.E. *et al*. (2014) 'Formation of the Grand Canyon 5 to 6 million years ago through integration of older palaeocanyons', Nature Geoscience, 7(3), pp. 239–244. Available at: https://doi.org/10.1038/ngeo2065.

Karlstrom, K.E. *et al*. (2020) 'Redefining the Tonto Group of Grand Canyon and recalibrating the Cambrian time scale', Geology, 48(5), pp. 425–430. Available at: https://doi.org/10.1130/G46755.1.

Karlstrom, K.E. *et al*. (2022) 'Tectonics of the Colorado Plateau and Its Margins', Annual Review of Earth and Planetary Sciences, 50(1), pp. 295–322. Available at: https://doi.org/10.1146/annurev-earth-032320-111432.

85. Iguazú/Iguaçu waterfalls

Ardolino, A.A. and Miranda, F. (2008) 'Las Cataratas del Iguazú. El agua grande', Instituto de Geología y Recursos Minerales. Servicio Geológico Minero Argentino, Anales, 46(1), pp. 377–388.

Llambías, E.J. (2003) Geología de los cuerpos ígneos. 2a. ed. Buenos Aires: Asociación Geológica Argentina (Instituto Superior de Correlación Geológica: serie correlación geológica, nro. 15).

Salamuni, R. *et al*. (1998) 'Cataratas de fama mundial', in C. Schobbenhaus *et al*. (eds) Sítios geológicos e paleontológicos do Brasil: volume I. Brasília: DNPM/CPRM, Comissão Brasileira de Sítios Geológicos e Paleobiológicos (SIGEP). Available at: http://rigeo.cprm.gov.br/jspui/handle/doc/19865.

86. Mosi-oa-Tunya/Victoria Falls

Derricourt, R.M. (1976) 'Retrogression rate of the Victoria Falls and the Batoka Gorge', Nature, 264(5581), pp. 23–25. Available at: https://doi.org/10.1038/264023a0.

Lamplugh, G.W. (1907) 'The Geology of the Zambezi Basin around the Batoka Gorge (Rhodesia)', Quarterly Journal of the Geological Society, 63(1–4), pp. 162–216. Available at: https://doi.org/10.1144/GSL.JGS.1907.063.01-04.14.

Maufe, H.B. (1936) 'The Geology of the Victoria Falls', The Journal of the Royal Anthropological Institute of Great Britain and Ireland, 66, pp. 348–368. Available at: https://doi.org/10.2307/2844085.

Moore, A. and Cotterill, F. (Woody) (2010) 'Victoria Falls: Mosi-oa-Tunya – The Smoke That Thunders', in P. Migon (ed.) Geomorphological Landscapes of the World. Dordrecht: Springer Netherlands, pp. 143–153. Available at: https://doi.org/10.1007/978-90-481-3055-9_15.

Nugent, C. (1990) 'The Zambezi River: tectonism, climatic change and drainage evolution', Palaeogeography, Palaeoclimatology, Palaeoecology, 78(1), pp. 55–69. Available at: https://doi.org/10.1016/0031-0182(90)90204-K.

UNESCO World Heritage Documents (1989) Mosi-oa-Tunya / Victoria Falls, UNESCO World Heritage Centre. Available at: https://whc.unesco.org/en/list/509/.

87. Dry Falls and the Channeled Scabland

Baker, V.R. (2009) 'The Channeled Scabland: A Retrospective', Annual Review of Earth and Planetary Sciences, 37(1), pp. 393–411. Available at: https://doi.org/10.1146/annurev.earth.061008.134726.

Bjornstad, B.N. (2021) Ice Age Floodscapes of the Pacific Northwest: A Photographic Exploration. Springer Nature.

Bretz, J.H. (1923) 'The Channeled Scablands of the Columbia Plateau', The Journal of Geology, 31(8), pp. 617–649. Available at: https://doi.org/10.1086/623053.

Bretz, J.H. (1932) The Grand coulee. New York, N.Y: American Geographical Society (American Geographical Society Special Publication, 15). Available at: https://babel.hathitrust.org/cgi/pt?id=mdp.39015035583924.

Bretz, J.H. (1959) 'Washington's channeled scabland.', Washington Division of Mines and Geology Bulletin, 45, p. 59.

U.S. Geological Survey (1973) The channeled scablands of eastern Washington : the geologic story of the Spokane flood. U.S. Geological Survey, p. 23. Available at: https://doi.org/10.3133/70007447.

88. Jutulhogget Canyon

Berthling, I. and Sollid, J.L. (1999) 'The drainage history of glacial lake Nedre Gl msj, southern Central Norway', Norsk Geografisk Tidsskrift - Norwegian Journal of Geography, 53(4), pp. 190–201. Available at: https://doi.org/10.1080/002919599420785.

Høgaas, F. and Longva, O. (2016) 'Mega deposits and erosive features related to the glacial lake Nedre Glomsjø outburst flood, southeastern Norway', Quaternary Science Reviews, 151, pp. 273–291. Available at: https://doi.org/10.1016/j.quascirev.2016.09.015.

Høgaas, F. and Longva, O. (2018) 'The early Holocene ice-dammed lake Nedre Glomsjø in Mid-Norway: an open lake system succeeding an actively retreating ice sheet', Norsk Geologisk Tidsskrift [Preprint]. Available at: https://doi.org/10.17850/njg98-4-08.

Holmsen, G. (1915) Brædæmte sjøer i nordre Østerdalen. Kristiania: Aschehoug (komm.) (Norges geologiske undersøkelse, 99-0119969-7 ; 73).

Longva, O. (1994) Flood Deposits and Erosional Features from the Catastrophic Drainage of Preboreal Glacial Lake Nedre Glåmsjø, SE Norway. PhD Thesis. University of Bergen, Department of Geology.

89. Perito Moreno Glacier

Aniya, M. and Skvarca, P. (1992) 'Characteristics and variations of Upsala and Moreno glaciers, southern Patagonia', Bulletin of Glacier Research, 10, pp. 39–53.

Ciappa, A., Pietranera, L. and Battazza, F. (2010) 'Perito Moreno Glacier (Argentina) flow estimation by COSMO SkyMed sequence of high-resolution SAR-X imagery', Remote Sensing of Environment, 114, pp. 2088–2096. Available at: https://doi.org/10.1016/J.RSE.2010.04.014.

Del Valle, R. *et al*. (1995) 'A preliminary study of sediment cores from Lago Argentino and fluctuations of Moreno Glacier, Patagonia', Bulletin of Glacier Research, 13, pp. 121–126.

Pasquini, A.I. and Depetris, P.J. (2011) 'Southern Patagonia's Perito Moreno Glacier, Lake Argentino, and Santa Cruz River hydrological system: An overview', Journal of Hydrology, 405(1), pp. 48–56. Available at: https://doi.org/10.1016/j.jhydrol.2011.05.009.

Skvarca, P., Naruse, R. and Angelis, H.D. (2004) 'Recent thickening trend of Glaciar Perito Moreno, southern Patagonia', Bulletin of Glaciological Research, 21, pp. 45–48.

Stuefer, M., Rott, H. and Skvarca, P. (2007) 'Glaciar Perito Moreno, Patagonia: climate sensitivities and glacier characteristics preceding the 2003/04 and 2005/06 damming events', Journal of Glaciology, 53(180), pp. 3–16. Available at: https://doi.org/10.3189/172756507781833848.

90. Rockglaciers of the Engadine

Chaix, A. (1923) 'Les coulées de blocs du Parc national suisse d'Engadine (Note préliminaire)', Le Globe. Revue genevoise de géographie, 62(1), pp. 1–35. Available at: https://doi.org/10.3406/globe.1923.5609.

Gärtner-Roer, I. (2012) 'Sediment transfer rates of two active rockglaciers in the Swiss Alps', Geomorphology, 167–168, pp. 45–50. Available at: https://doi.org/10.1016/j.geomorph.2012.04.013.

Gärtner-Roer, I. and Hoelzle, M. (2021) 'Rockglaciers of the Engadine', in E. Reynard (ed.) Landscapes and Landforms of Switzerland. Cham: Springer International Publishing (World Geomorphological Landscapes), pp. 235–248. Available at: https://doi.org/10.1007/978-3-030-43203-4_16.

Haeberli, W. (1985) Creep of mountain permafrost: internal structure and flow of alpine rock glaciers. (Mitteilungen der VAW/ETH Zürich, 77).

Springman, S.M. *et al*. (2012) 'Multidisciplinary investigations on three rock glaciers in the swiss alps: legacies and future perspectives', Geografiska Annaler: Series A, Physical Geography, 94(2), pp. 215–243. Available at: https://doi.org/10.1111/j.1468-0459.2012.00464.x.

Vonder Mühll, D., Stucki, T. and Haeberli, W. (1998) 'Borehole-temperatures in alpine permafrost: a ten-year series', in A.G. Lewkowicz and M. Allard (eds) 7th International Conference on Permafrost, Yellowknife. Proceedings. Centre d'Etudes Nordiques, Université Laval, pp. 1089–1095. Available at: https://www.semanticscholar.org/paper/BOREHOLE-TEMPERATURES-IN-ALPINE-PERMAFROST%3A-A-TEN-Vonder-Stucki/6ed62251a6cd2087112e710d1569f8a70b97a719.

91. The Okavango Delta

McCarthy, T.S. (2006) 'Groundwater in the wetlands of the Okavango Delta, Botswana, and its contribution to the structure and function of the ecosystem', Journal of Hydrology, 320(3), pp. 264–282. Available at: https://doi.org/10.1016/j.jhydrol.2005.07.045.

McCarthy, T.S. (2013) 'The Okavango Delta and its place in the geomorphological evolution of Southern Africa', South African Journal of Geology, 116(1), pp. 1–54. Available at: https://doi.org/10.2113/gssajg.116.1.1.

McCarthy, T.S., Bloem, A. and Larkin, P.A. (1998) 'Observations on the hydrology and geohydrology of the Okavango Delta', South African Journal of Geology, 101(2), pp. 101–117.

McCarthy, T.S. and Metcalfe, J. (1990) 'Chemical sedimentation in the semi-arid environment of the Okavango Delta, Botswana', Chemical Geology, 89(1), pp. 157–178. Available at: https://doi.org/10.1016/0009-2541(90)90065-F.

Scholz, C.H. (1975) Seismicity, Tectonics and Seismic Hazard of the Okavango Delta, Botswana. Final Report to the United Nations Development Programme on the Okavango Delta, Food and Agricultural Organization of UN, and Geological Survey and Mines Department, Botswana. UNDP/FAO BOT/71/506. Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York.

92. Yardang (Kalut) in the Lut Desert

Azarderakhsh, M. *et al*. (2020) 'Satellite-Based Analysis of Extreme Land Surface Temperatures and Diurnal Variability Across the Hottest Place on Earth', IEEE Geoscience and Remote Sensing Letters, 17(12), pp. 2025–2029. Available at: https://doi.org/10.1109/LGRS.2019.2962055.

Gabriel, A. (1938) 'The Southern Lut and Iranian Baluchistan', The Geographical Journal, 92(3), pp. 193–208. Available at: https://doi.org/10.2307/1788828.

IUCN (2020) Lut Desert - 2020 Conservation Outlook Assessment. IUCN World Heritage Outlook (Online). Available at: https://worldheritageoutlook.iucn.org/explore-sites/wdpaid/555622047.

Maghsoudi, M. *et al*. (2019) 'Geotourism Development in World Heritage of the Lut Desert', Geoheritage, 11(2), pp. 501–516. Available at: https://doi.org/10.1007/s12371-018-0303-2.

Maghsoudi, M. (2021) Desert Landscapes and Landforms of Iran. Springer Nature. Available at: https://link.springer.com/book/10.1007/978-3-030-58912-7.

State Party of Iran (2015) Nomination of Lut Desert as a World Heritage site (Online). Tehran, Islamic Republic of Iran: Iranian Cultural Heritage, Handicrafts and Tourism Organization. Available at: https://whc.unesco.org/uploads/nominations/1505.pdf.

93. Namib Sand Sea

Garzanti, E. *et al*. (2012) 'Petrology of the Namib Sand Sea: Long-distance transport and compositional variability in the wind-displaced Orange Delta', Earth-Science Reviews, 112(3), pp. 173–189. Available at: https://doi.org/10.1016/j.earscirev.2012.02.008.

Goudie, A. and Viles, H. (2015) Landscapes and Landforms of Namibia. Dordrecht: Springer Netherlands (World Geomorphological Landscapes). Available at: https://doi.org/10.1007/978-94-017-8020-9.

Lancaster, N. (1985) 'Winds and sand movements in the Namib Sand Sea', Earth Surface Processes and Landforms, 10(6), pp. 607–619. Available at: https://doi.org/10.1002/esp.3290100608.

Livingstone, I. *et al*. (2010) 'The Namib Sand Sea digital database of aeolian dunes and key forcing variables', Aeolian Research, 2(2), pp. 93–104. Available at: https://doi.org/10.1016/j.aeolia.2010.08.001.

Livingstone, I. (2013) 'Aeolian geomorphology of the Namib Sand Sea', Journal of Arid Environments, 93, pp. 30–39. Available at: https://doi.org/10.1016/j.jaridenv.2012.08.005.

Livingstone, I. *et al*. (2014) 'A prospectus for future geomorphological investigation of the Namib Sand Sea', Transactions of the Royal Society of South Africa, 69(3), pp. 151–156. Available at: https://doi.org/10.1080/0035919X.2014.936330.

Stone, A.E.C. (2013) 'Age and dynamics of the Namib Sand Sea: A review of chronological evidence and possible landscape development models', Journal of African Earth Sciences, 82, pp. 70–87. Available at: https://doi.org/10.1016/j.jafrearsci.2013.02.003.

Vermeesch, P. *et al*. (2010) 'Sand residence times of one million years in the Namib Sand Sea from cosmogenic nuclides', Nature Geoscience, 3(12), pp. 862–865. Available at: https://doi.org/10.1038/ngeo985.

94. Bilutu megadunes and lakes in the Badain Jaran Desert

Chen, T. *et al*. (2019) 'Luminescence chronology and palaeoenvironmental significance of limnic relics from the Badain Jaran Desert, northern China', Journal of Asian Earth Sciences, 177, pp. 240–249. Available at: https://doi.org/10.1016/j.jseaes.2019.03.024.

Dong, Z., Wang, T. and Wang, X. (2004) 'Geomorphology of the megadunes in the Badain Jaran Desert', Geomorphology, 60(1), pp. 191–203. Available at: https://doi.org/10.1016/j.geomorph.2003.07.023.

Du, J. *et al*. (2021) 'Cenozoic tectono-geomorphic evolution of Yabrai Mountain and the Badain Jaran Desert (NE Tibetan Plateau margin)', Geomorphology, 389, p. 107857. Available at: https://doi.org/10.1016/j.geomorph.2021.107857.

Wang, F. *et al*. (2015) 'Formation and evolution of the Badain Jaran Desert, North China, as revealed by a drill core from the desert centre and by geological survey', Palaeogeography, Palaeoclimatology, Palaeoecology, 426, pp. 139–158. Available at: https://doi.org/10.1016/j.palaeo.2015.03.011.

Wang, X. *et al*. (2019) 'Optical dating reveals that the height of Earth's tallest megadunes in the Badain Jaran Desert of NW China is increasing', Journal of Asian Earth Sciences, 185, p. 104025. Available at: https://doi.org/10.1016/j.jseaes.2019.104025.

95. Vajont landslide

Ghirotti, M. (2012) 'The 1963 Vaiont landslide, Italy. In: (a cura di): Clague J.J and Stead D., Landslides Types, Mechanisms and Modeling. p. 359-372, Cambridge University Press, ISBN: 9781107002067, doi: 10.1017/CBO9780511740367.030.', in, pp. 359–372. Available at: https://doi.org/10.1017/CBO9780511740367.030.

Hendron, A.J. and Patton, F.D. (1987) 'The vaiont slide — A geotechnical analysis based on new geologic observations of the failure surface', Engineering Geology, 24(1), pp. 475–491. Available at: https://doi.org/10.1016/0013-7952(87)90080-9.

Morino, C., Coratza, P. and Soldati, M. (2022) 'Landslides, a Key Landform in the Global Geological Heritage', Frontiers in Earth Science, 10. Available at: https://www.frontiersin.org/articles/10.3389/feart.2022.864760.

Paronuzzi, P. and Bolla, A. (2012) 'The prehistoric Vajont rockslide: An updated geological model', Geomorphology, 169–170, pp. 165–191. Available at: https://doi.org/10.1016/j.geomorph.2012.04.021.

Selli, R. *et al*. (no date) 'La Frana del Vajont', Giornale di Geologia, 32(1), pp. 1-154 (in Italian).

Semenza, E. and Ghirotti, M. (2000) 'History of the 1963 Vaiont slide: the importance of geological factors', Bulletin of Engineering Geology and the Environment, 59(2), pp. 87–97. Available at: https://doi.org/10.1007/s100640000067.

96. Pamukkale Travertines

Altunel, E. and D'Andria, F. (2019) 'Pamukkale Travertines: A Natural and Cultural Monument in the World Heritage List', in C. Kuzucuoğlu, A. Çiner, and N. Kazancı (eds) Landscapes and Landforms of Turkey. Cham: Springer International Publishing (World Geomorphological Landscapes), pp. 219–229. Available at: https://doi.org/10.1007/978-3-030-03515-0_8.

Altunel, E. and Hancock, P.L. (1993) 'Morphology and structural setting of Quaternary travertines at Pamukkale, Turkey', Geological Journal, 28(3–4), pp. 335–346. Available at: https://doi.org/10.1002/gj.3350280312.

Hancock, P.L. *et al*. (1999) 'Travitonics: using travertines in active fault studies', Journal of Structural Geology, 21(8), pp. 903–916. Available at: https://doi.org/10.1016/S0191-8141(99)00061-9.

Kele, S. *et al*. (2011) 'Stable isotope geochemical study of Pamukkale travertines: New evidences of low-temperature non-equilibrium calcite-water fractionation', Sedimentary Geology, 238(1), pp. 191–212. Available at: https://doi.org/10.1016/j.sedgeo.2011.04.015.

Kumsar, H. *et al*. (2016) 'Historical earthquakes that damaged Hierapolis and Laodikeia antique cities and their implications for earthquake potential of Denizli basin in western Turkey', Bulletin of Engineering Geology and the Environment, 75(2), pp. 519–536. Available at: https://doi.org/10.1007/s10064-015-0791-0.

Scoon, R.N. (2021) 'The Hierapolis-Pamukkale Archaeological and Geosite, Southwest Turkey', in The Geotraveller. Cham, Switzerland: Springer, pp. 301–311. Available at: https://link.springer.com/chapter/10.1007/978-3-030-54693-9_14.

97. Puquios of the Llamara salt flat

Farías, M. (2020) Microbial Ecosystems in Central Andes Extreme Environments Biofilms, Microbial Mats, Microbialites and Endoevaporites. Switzerland: Springer Nature. Available at: https://doi.org/10.1007/978-3-030-36192-1.

Gutiérrez-Preciado, A. *et al*. (2018) 'Functional shifts in microbial mats recapitulate early Earth metabolic transitions', Nature Ecology & Evolution, 2(11), pp. 1700–1708. Available at: https://doi.org/10.1038/s41559-018-0683-3.

López, L. *et al*. (2017) Hydrogeology of the Pampa del Tamarugal Basin, Tarapacá Region. Santiago, Chile: Sernageomin (National Service of Geology and Mining, Geological Chart of Chile, Hydrogeology Series, 6). Available at: https://snia.mop.gob.cl/repositoriodga/handle/20.500.13000/4393.

López, P. *et al*. (1999) 'Geochemical characteristics and evolution patterns of the surface brines of the Salar de Llamara, Chile', Geological Magazine of Chile, pp. 89–108.

Solari, M. (2015) 'The unexplored geobiological heritage of Chile: key to understand the past and future', in Chilean Geological Congress, No. 14, Abstracts 3. La Serena, pp. 388–391.

Vásquez, P. *et al*. (2018) Guanillos del Norte and Salar de Llamara Charts, Regions of Tarapacá and Antofagasta. (SERNAGEOMIN. Geological Chart of Chile, Basic Geology Series, nº195-196 (Original in spanish).

98. Škocjan Caves in the Classical Karst

Aljančič, M. *et al*. (eds) (1998) 'Škocjanske jame - The Škocjanske jame caves. Naše jame', Bulletin of the Speleological Association of Slovenia, 40.

Boegan, E. (1924) Le Grotte di San Canziano, Trieste.

Kranjc, A. (2002) 'Zgodovinski pregled in opis jam (A Historical Overview and Description of the Caves)', in the monograph Park Škocjanske jame (The Škocjan Caves Park). Škocjan Caves Park.

Müller, F. (1890) Die grottenwelt von St. Canzian. Vienna: verlag des Deutschen und oesterreichischen alpenvereins. Available at: http://archive.org/details/bub_gb_QyYEAAAAYAAJ.

Oedl, R. (1924) Der unterirdische Lauf der Reka. Doktordissertation, manuscript.

99. Sac Actun Underwater Cave System

de Azevedo, S. *et al*. (2015) 'Ancient remains and the first peopling of the Americas: Reassessing the Hoyo Negro skull: Reassessing Affinities of the Hoyo Negro Skull', American Journal of Physical Anthropology, 158(3), pp. 514–521. Available at: https://doi.org/10.1002/ajpa.22801.

Collins, S.V. *et al*. (2015) 'Reconstructing water level in Hoyo Negro, Quintana Roo, Mexico, implications for early Paleoamerican and faunal access', Quaternary Science Reviews, 124, pp. 68–83. Available at: https://doi.org/10.1016/j.quascirev.2015.06.024.

Gabriel, J.J. *et al*. (2009) 'Palaeoenvironmental evolution of Cenote Aktun Ha (Carwash) on the Yucatan Peninsula, Mexico and its response to Holocene sea-level rise', Journal of Paleolimnology, 42(2), pp. 199–213. Available at: https://doi.org/10.1007/s10933-008-9271-x.

van Hengstum, P.J. *et al*. (2010) 'Linkages between Holocene paleoclimate and paleohydrogeology preserved in a Yucatan underwater cave', Quaternary Science Reviews, 29(19), pp. 2788–2798. Available at: https://doi.org/10.1016/j.quascirev.2010.06.034.

Kambesis, P.N. and Coke IV, J.G. (2016) 'The Sac Actun System, Quintana Roo, Mexico', Boletín geológico y minero, 127(1), pp. 177–192.

Smart, P.L. *et al*. (2006) 'Cave development on the caribbean coast of the Yucatan Peninsula, Quintana Roo, Mexico', Special Paper of the Geological Society of America, 404, pp. 105–128. Available at: https://doi.org/10.1130/2006.2404(10).

IX. IMPACT STRUCTURES AND EXTRATERRESTRIAL ROCKS

100. Domo de Araguainha Impact Structure

Crósta, A.P. *et al*. (2019) 'Impact cratering: The South American record – Part 1', Geochemistry, 79(1), pp. 1–61. Available at: https://doi.org/10.1016/j.chemer.2018.06.001.

Crósta, A.P., Gaspar, J.C. and Candia, M. (1981) 'Feições de metamorfismo de impacto no Domo de Araguainha', Revista Brasileira de Geociências, 11, pp. 139–146. Available at: https://doi.org/10.5327/RBG.V11I3.219.

Engelhardt, W.V., Matthäi, S.K. and Walzebuck, J. (1992) 'Araguainha impact crater, Brazil. I. The interior part of the uplift', Meteoritics, 27(4), pp. 442–457. Available at: https://doi.org/10.1111/j.1945-5100.1992.tb00226.x.

Hauser, N. *et al*. (2019) 'Linking shock textures revealed by BSE, CL, and EBSD with U-Pb data (LA-ICP-MS and SIMS) from zircon from the Araguainha impact structure, Brazil', Meteoritics & Planetary Science, 54(10), pp. 2286–2311. Available at: https://doi.org/10.1111/maps.13371.

Lana, C. *et al*. (2008) 'Structural evolution of the 40 km wide Araguainha impact structure, central Brazil', Meteoritics & Planetary Science, 43(4), pp. 701–716. Available at: https://doi.org/10.1111/j.1945-5100.2008.tb00679.x.

Tohver, E. *et al*. (2013) 'Shaking a methane fizz: Seismicity from the Araguainha impact event and the Permian–Triassic global carbon isotope record', Palaeogeography, Palaeoclimatology, Palaeoecology, 387, pp. 66–75. Available at: https://doi.org/10.1016/j.palaeo.2013.07.010.

AUTHORS

I. HISTORY OF GEOSCIENCE

1. Siccar Point (Hutton's Unconformity)

Colin MacFadyen. *NatureScot, Scotland's Nature Agency, Scotland, U.K.*

Martina Kölbl-Ebert. *International Commission on the History of Geological Sciences (INHIGEO) & Department of Earth and Environmental Sciences University of Munich, Germany.*

Helen Fallas. *British Geological Survey, Edinburgh, U.K.*

2. The Quaternary Phlegrean Fields volcanic complex

Alessandra Pensa. *Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), Roma, Italy.*

Roberto Bonomo. *Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), Roma, Italy.*

Martin J.S. Rudwick. *International Commission on the History of Geological Sciences (INHIGEO)*

Kathleen Histon. *International Commission on the History of Geological Sciences (INHIGEO)*

3. Mohorovičić discontinuity at Gros Morne National Park

Andrew Kerr. *Department of Earth Sciences, Memorial University, St. John's NL Canada.*

John W.F. Waldron. *Department of Earth Sciences, University of Alberta, Edmonton, AB, Canada.*

John H. Calder. *Cliffs of Fundy UGGp, Canadian Geoparks Network and Saint Mary's University, NS, Canada.*

4. The Holocene Puy-de-Dôme and Petit-Puy-de-Dôme volcanoes

Benjamin van Wyk de Vries. *Université Clermont Auvergne, Laboratoire Magmas et Volcans, OPGC, CNRS et IRD, Clermont Ferrand, France.*

Martin J.S. Rudwick. *International Commission on the History of Geological Sciences (INHIGEO)*

Kathleen Histon. *International Commission on the History of Geological Sciences (INHIGEO)*

Ezio Vaccari. *International Commission on the History of Geological Sciences (INHIGEO) / Università degli Studi dell'Insubria.*

Nicolas Charles. *PhD – BRGM / French Geological Survey.*

5. The Paleocene volcanic rocks of the Giant's Causeway and Causeway coast

Kirstin Lemon. *Geological Survey of Northern Ireland.*

Patrick N. *Wyse Jackson. International Commission on the History of Geological Sciences (INHIGEO) & Trinity College Dublin, Ireland.*

Mark Cooper. *Geological Survey of Northern Ireland.*

Michael Dempster. *Northern Ireland Environment Agency.*

6. Funafuti Atoll

Sapolu Tetoa. *Lands and Survey Department, Office of the Prime Minister, Tuvalu.*

Faatasi Malologa. *Lands and Survey Department, Office of the Prime Minister, Tuvalu.*

Gary Lee. *The Pacific Community (SPC), Fiji.*

Dana Tigarea. *The Pacific Community (SPC), Fiji.*

Roger F. Mclean. *University of New South Wales, Australia.*

Károly Németh. *Massey University, New Zealand; Institute of Earth Physics and Space Science, Hungary and Saudi Geological Survey, Kingdom of Saudi Arabia.*

Benjamin van Wyk de Vries. *Université Clermont Auvergne, Laboratoire Magmas et Volcans, OPGC, CNRS et IRD, Clermont Ferrand, France.*

7. Capelinhos volcano

João Carlos Nunes. *Azores UGGp & Azores University.*

Salomé Meneses. *Azores UGGp.*

Andrea Porteiro. *Azores UGGp.*

8. Taburiente volcanic Caldera in La Palma Island

Juana Vegas Salamanca. *Geological Survey of Spain (IGME), Madrid, Spain.*

Alfredo Hernández Pacheco. *Retired Professor, Complutense University of Madrid, Spain.*

9. Quaternary glacial varves of Ragunda

Sven Lundqvist. *Geological Survey of Sweden.*

10. Genbudo Cave

Noritaka Matsubara. *University of Hyogo/San'in Kaigan Geopark Promotion Council.*

Yuuki Fujihara. *San'in Kaigan Geopark Promotion Council.*

Setsuya Nakada. *The University of Tokyo (presently NIED)*

11. GSSP for the Silurian-Devonian boundary at Klonk Hill

Ladislav SLAVÍK. *Institute of Geology of the Czech Academy of Sciences, v.v.i.*

II. STRATIGRAPHY AND SEDIMENTOLOGY

12. Archean Barberton Greenstone Belt

Asfawossen Asrat. *Botswana International University of Science and Technology, Palapye, Botswana.*

13. Paleoproterozoic Banded Iron Formation of the Quadrilátero Ferrífero

Paulo de Tarso Amorim Castro. *Professor at Universidade Federal de Ouro Preto.*

Úrsula Ruchkys de Azevedo. *Professor at Universidade Federal de Minas Gerais.*

14. Glacial record of the Marinoan snowball Earth

Paul F. Hoffman. *University of Victoria, Canada.*

Daniel J. Condon. *British Geological Survey, Keyworth, U.K.*

Eugene W. Domack. *University of South Florida, USA (†deceased).*

Galen P. Halverson. *McGill University, Montreal, Canada.*

Karl-Heinz Hoffmann. *Private Consultant, Windhoek, Namibia.*

Francis A. Macdonald. *University of California, Santa Barbara, USA.*

Anthony R. Prave. *University of St Andrews, Scotland, UK.*

Ute M. Schreiber. *Geological Survey of Namibia, Windhoek, Namibia.*

Roger Swart. *Private Consultant, Windhoek, Namibia.*

Adrian Tasistro-Hart. *University of California, Santa Barbara, USA.*

Absai Vatuva. *University of Namibia, Keetmanshoop, Namibia.*

14. Glacial record of the Marinoan snowball Earth

Paul F. Hoffman. *University of Victoria, Canada.*

Daniel J. Condon. *British Geological Survey, Keyworth, UK.*

Eugene W. Domack. *University of South Florida, USA (†deceased)*

Galen P. Halverson. *McGill University, Montreal, Canada.*

Karl-Heinz Hoffmann. *Private Consultant, Windhoek, Namibia.*

Francis A. Macdonald. *University of California, Santa Barbara, USA.*

Anthony R. Prave. *University of St Andrews, Scotland, UK.*

Ute M. Schreiber. *Geological Survey of Namibia, Windhoek, Namibia.*

Roger Swart. *Private Consultant, Windhoek, Namibia.*

Adrian Tasistro-Hart. *University of California, Santa Barbara, USA.*

Absai Vatuva. *University of Namibia, Keetmanshoop, Namibia.*

15. The Cambrian Explosion in Sirius Passet

David A.T. Harper. *Department of Earth Sciences, Durham University, Durham, UK.*

M. Paul Smith. *Oxford University Museum of Natural History, Oxford, UK.*

16. The Great Unconformity at Grand Canyon

Karl E. Karlstrom. *Distinguished Professor, Department of Earth and Planetary Sciences, University of New Mexico, USA.*

Laura J. Crossey. *Distinguished Professor, Department of Earth and Planetary Sciences, University of New Mexico, USA.*

17. The Ordovician rocks of the Mount Everest

David A.T. Harper. *Department of Earth Sciences, Durham University, Durham, UK.*

Luis Carcavilla. *Geological Survey of Spain (IGME), Madrid, Spain.*

18. Permian-Triassic great extinction and GSSPs of Meishan

Shuzhong Shen. *School of Earth Sciences and Engineering, Nanjing University, Nanjing, China.*

19. Carboniferous – Triassic Unconformity in Telheiro

José Brilha. *University of Minho, Portugal.*

Paulo Pereira. *University of Minho, Portugal.*

João Matos. *Laboratório Nacional de Energia e Geologia, Portuguese Geological Survey.*

Susana Machado. *Laboratório Nacional de Energia e Geologia, Portuguese Geological Survey.*

20. Cretaceous to Paleogene stratigraphic section of Bottaccione Gorge, Gubbio

Birger Schmitz. *Lund University, Sweden.*

Simonetta Monechi. *Florence University, Italy.*

Walter Alvarez. *University of California, Berkeley, United States.*

Rodolfo Coccioni. *Urbino University, Italy.*

Simone Galeotti. *Urbino University, Italy.*

Alessandro Montanari. *Coldigioco Geological Observatory, Italy.*

21. Cretaceous-Paleogene transition at Seymour (Marambio) Island

Luis Carcavilla. *Geological Survey of Spain (IGME), Madrid, Spain*

Alistair Crame. *British Antarctic Survey, Cambridge, United Kingdom.*

Enrique Díaz-Martínez. *Geological Survey of Spain (IGME), Madrid, Spain.*

David H. Elliot. *Ohio State University, Columbus, United States.*

Jane Francis. *British Antarctic Survey, Cambridge, United Kingdom.*

Kevin A. Hughes. *British Antarctic Survey, Cambridge, United Kingdom.*

Jerónimo López-Martínez. *Universidad Autónoma de Madrid, Spain.*

Manuel Montes. *Geological Survey of Spain (IGME), Madrid, Spain.*

Marcelo Reguero. *Universidad Nacional de La Plata y Instituto Antártico Argentino, Buenos Aires, Argentina.*

22. Cretaceous – Paleogene stratigraphic section of Zumaia

Victoriano Pujalte. *University of the Basque Country.*

Laia Alegret. *University of Zaragoza on behalf of the ISPS-International Subcommission on Paleogene Stratigraph.*

Asier Hilario. *Scientific director of the Basque Coast UNESCO Global Geopark.*

23. GSSP of the Meghalayan Stage in the Mawmluh Cave

Satish C. Tripathi. *The Society of Earth Scientists, Lucknow, India.*

Sabyasachi Shome. *Former Dy. Director General / Geological Survey of India.*

III. PALEONTOLOGY

24. Ediacaran fossil site of Mistaken Point

Guy M. Narbonne. *Department of Geological Sciences and Geological Engineering, Queens University, Kingston, ON Canada.*

John H. Calder. *Cliffs of Fundy UGGp, Canadian Geoparks Network and Saint Mary's University, NS, Canada.*

25. Ediacaran fossils in the Ediacra Hills, Flinders Ranges, Australia

Margaret Brocx. *Adjunct Professor of Research|College of Science, Health, Engineering and Education, Discipline Environmental and Conservation Sciences. Murdoch University, Western Australia, Australia.*

Vic Semeniuk. *Adjunct Professor of Research|College of Science,* Health, Engineering and Education, Discipline Environmental and Conservation Sciences. Murdoch University, Western Australia, Australia.*

26. Cambrian Chengjiang Fossil Site and Lagerstätte

Fangchen Zhao. *Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences.*

Ailin Chen. *Yuxi Normal University, Yunnan, China.*

Renbin Zhan. *Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences.*

27. Burgess Shale Cambrian Palaeontological Record

Todd Keith. *Parks Canada, Yoho National Park, British Columbia, Canada.*

Jean-Bernard Caron. *Richard M. Ivey Curator of Invertebrate Palaeontology, Royal Ontario Museum, Toronto, Ontario, Canada.*

28. Ordovician Fezouata Shale fossil site at JbelTizagzaouine

Khadija El Hariri. *Université Cadi Ayyad, Marrakech, Maroc.*

Bertrand Lefebvre. *Université Lyon 1, Villeurbanne, France.*

Peter Van Roy. *Ghent University, Ghent, Belgium.*

Abderrahmane Soulaimani. *Université Cadi Ayyad, Marrakech, Maroc.*

Ahmid Hafid. *Université Cadi Ayyad, Marrakech, Maroc.*

Ali Bachnou. *Université Cadi Ayyad, Marrakech, Maroc.*

Joseph P. Botting. *Nanjing Institute of Geology and Palaeontology, Nanjing, China & National Museum of Wales, Cardiff, UK.*

Allison C. Daley. *University of Lausanne, Lausanne, Switzerland.*

Juan Carlos Gutiérrez-Marco. *Universidad Complutense de Madrid, Madrid, Spain.*

Farid Saleh. *Yunnan University, Kumning, China.*

29. Middle Ordovician giant trilobites of Canelas quarry

Artur Abreu Sá. *Department of Geology, University of Trás-os-Montes e Alto Douro, 5000-801 Vila Real, Portugal.*

30. Devonian Tetrapod Trackways of Holy Cross Mountains

Izabela Olczak-Dusseldorp. *Department of Environmental Geology - Polish Geological Institute - National Research Institute 4, Warsaw, Poland.*

Szymon Ostrowski. *Department of Engineering Geology - Polish Geological Institute - National Research Institute 4, Warsaw, Poland*

31. "Coal Age" Joggins Fossil Cliffs

John H. Calder. *Cliffs of Fundy UGGp, Canadian Geoparks Network and Saint Mary's University, NS, Canada.*

32. Late Permian Tete Fossil Forest

Nelson Ernesto Nhamutole. *National Museum of Geology, Mozambique & Univesrity of the Witwatersrand, South Africa.*

Marcelino Moiana. *National Museum of Geology, Mozambique.*

Dino Milisse. *National Museum of Geology, Mozambique.*

Zanildo Macungo. *National Museum of Geology, Mozambique.*

Ringo Benjamin. *National Museum of Geology, Mozambique.*

Marion Bamford. *National Museum of Geology, Mozambique.*

Juana Vegas Salamanca. *Geological Survey of Spain (IGME), Madrid, Spain.*

Enrique Díaz-Martínez. *Geological Survey of Spain (IGME), Madrid, Spain.*

33. The Ammonite Slab of Digne-les-Bains

Sylvie Crasquin. *Sorbonne Université-MNHN-CNRS.*

Myette Guiomar. *Haute-Provence National Nature Reserve.*

Guy Martini. *Global Geopark Network*

Jean-Simon Pagès. *Haute-Provence UNESCO Global Geopark.*

Nicolas Charles. *PhD – BRGM / French Geological Survey*

34. Jurassic Solnhofen-Eichstätt Archaeopteryx Serial Site

Georg Loth. *Bavarian Environment Agency (LfU), Department Geological Survey, 95030 Hof, Germany.*

35. Marine Reptile Lagerstätte from the Lower Cretaceous of the Ricaurte Alto

Marcela Gómez-Pérez. *Servicio Geológico Colombiano.*

Leslie F. Noè. *Universidad de los Andes.*

Manuel Gómez Guerrero. *Servicio Geológico Colombiano.*

Marianela Vargas Anaya. *Servicio Geológico Colombiano.*

Edwin Cadena. *Universidad del Rosario.*

36. Dinosaur Provincial Park

David A. Eberth. *Royal Tyrell Museum of Palaeontology (retired), Drumheller, Alberta, Canada.*

Godfrey Nowlan. *Geological Survey of Canada (retired), Calgary, Alberta, Canada.*

37. Late Cretaceous rudist bivalves of the Caribbean Province

Simon F. Mitchell. *University of the West Indies, Mona, Kingston, Jamaica.*

Sherene James-Williamson. *University of the West Indies, Mona, Kingston, Jamaica.*

38. Eocene paleontological record of Messel Pit Fossil Site

Pascal Schmitz. *Welterbe Grube Messel gGmbH, Rossdörferstr. 108, 64409 Messel, www.grube-messel.de*

Marie-Luise Frey. *Welterbe Grube Messel gGmbH, Rossdörferstr. 108, 64409 Messel, www.grube-messel.de*

Anne Koett. *Hessisches Landesamt für Naturschutz, Umwelt und Geologie, Postfach 3209, 65022 Wiesbaden, www.hlnug.hessen.de*

Torsten Wappler. *Hessisches Landesmuseum Darmstadt, Friedensplatz 1, 64283 Darmstadt, www.hlmd.de*

Jutta Weber. *Geo-Naturpark Bergstrasse-Odenwald, Nibelungenstr., 41, 64653 Lorsch, www.geo-naturpark.de*

Sonja Wedmann. *Senckenberg Forschungsstation Grube Messel, Markstr. 35, 64409 Messel, www.senckenberg.de\sonja-wedmann*

39. Miocene primates paleontological site of Napak

Martin Pickford. *Muséum National d'Histoire Naturelle.*

Sarah Musalizi. *Senior Researcher, Department of Museums and Monuments, Ministry of Tourism, Wildlife and Antiquities.*

Jackline Nyiracyiza Besigye. *Assistant Commissioner, Department of Museums and Monuments, Ministry of Tourism, Wildlife and Antiquities, Uganda.*

40. Lesvos Early Miocene Petrified Forest

Nikolaos Zouros. *Director of the Natural History Museum of the Lesvos Petrified Forest, Professor in the Department of Geography, University of the Aegean.*

41. Palaeoanthropological Sites of Human Evolution of Laetoli – Olduvai Gorge

Joshua Mwankunda. *Senior Assistant Conservation Commissioner/ Ngorongoro Lengai UGGp/ Ngorongoro Conservation Area Authority.*

Lightness S. Kyambile. *Cultural Heritage Officer/Ngorongoro Lengai UGGp/ Ngorongoro Conservation Area Authority.*

Ramadhani Khatibu. *Senior Geologist/Ngorongoro Lengai UGGp/ Ngorongoro Conservation Area Authority.*

42. Late Quaternary asphalt seeps and paleontological site of La Brea Tar Pits

Regan E. Dunn. *Assistant Curator, La Brea Tar Pits, Natural History Museum of Los Angeles County*

Emily L. Lindsey. *Associate Curator & Excavation Site Director, La Brea Tar Pits, Natural History Museum of Los Angeles County.*

Luis M. Chiappe. *Senior Vice President, Research & Collections, Gretchen Augustyn Director, Dinosaur Institute, Natural History Museum of Los Angeles County.*

Shana Mathur. *Chief Strategy & External Relations Officer, Marketing & Communications, Natural History Museum of Los Angeles County.*

Yolanda Bustos. *Museum Archivist, Research & Collections, Research Library, Natural History Museum of Los Angeles County.*

Jenn Berger. *Digital Asset Manager, Creative Services, Natural History Museum of Los Angeles County.*

Lori Bettison-Varga. *President and Director, Natural History Museum of Los Angeles County.*

IV. IGNEOUS AND METAMORPHIC PETROLOGY

43. Archean Zircons of Erawondoo Hill

Margaret Brocx. *Adjunct Professor of Research|College of Science, Health, Engineering and Education, Discipline Environmental and Conservation Sciences. Murdoch University, Western Australia, Australia.*

Vic Semeniuk. *Adjunct Professor of Research|College of Science, Health, Engineering and Education, Discipline Environmental and Conservation Sciences. Murdoch University, Western Australia, Australia.*

44. The Hadean to Eoarchean Nuvvuagittuq greenstone belt

Pierre Verpaelst. *Charlevoix Aspiring Geopark, Canadian Geoparks Network, Québec, Canada.*

Jonathan O'Neil. *Ottawa-Carleton Geoscience Centre, department of Earth and Environmental Sciences, University of Ottawa, Canada*

45. Archean Rocks of the Eastern Beartooth Mountains

David W. Mogk. *Dept. Earth Sciences, Montana State University, Bozeman, MT, USA.*

Paul A. Mueller. *Dept. of Geological Sciences, Gainesville, FL, USA.*

Darrell J. Henry. *Dept. of Geology and Geophysics, Baton Rouge, LA, USA.*

46. The Stillwater Complex

Alan Boudreau. *Duke University, North Carolina, USA*

47. Early Cretaceous Rhyolitic Columnar Rock Formation of Hong Kong

CHAN Yu-nam. *Hong Kong UNESCO Global Geopark.*

NG Sin-pan. *Hong Kong UNESCO Global Geopark.*

48. Richat Structure, a Cretaceous Alkaline Complex

Asfawossen Asrat. *Botswana International University of Science and Technology, Palapye, Botswana.*

Michel Jébrak. *UQAM, Montréal, Canada.*

49. The Miocene Torres del Paine intrusive complex

Felipe Espinoza. *Head of the General Geology Department at Chilean Geology and Mining Service- SERNAGEOMIN.*

Manuel Arenas. *National Geological and Mining Service (SERNAGEOMIN), Chile.*

50. Mount Kinabalu Neogene Granite

Ibrahim Komoo. *Emeritus Professor of Engineering Geology at the Institute of Environment and Development (LESTARI), Universiti Kebangsaan Malaysia.*

Felix Tongkul. *Honorary Professor of Geology at the Faculty of Science and Natural Resources, Universiti Malaysia Sabah (UMS).*

Che Aziz Ali. *Professor of Sedimentology, Universiti Kebangsaan Malaysia.*

Norhayati Ahmad. *Professor of Biology at Universiti Kebangsaan Malaysia.*

Maklarin Lakim. *Director of Sabah Parks.*

V. VOLCANOLOGY

51. The Danakil Rift depression and its volcanism

Asfawossen Asrat. *Botswana International University of Science and Technology, Palapye, Botswana.*

52. The Quaternary Cameroon Volcano

Ghislain Zangmo Tefogoum. *Department of Earth Sciences, Faculty of Science, University of Maroua, P.O Box 814 Maroua, Cameroon.*

53. The historic scoria cone of the Jabal Qidr

Károly Németh. *Massey University, New Zealand; Institute of Earth Physics and Space Science, Hungary and Saudi Geological Survey, Kingdom of Saudi Arabia.*

Mohammed Rashad Moufti. *King Abdulaziz University, Jeddah, Kingdom of Saudi Arabia.*

54. The Pleistocene Kilimanjaro Volcano

Asfawossen Asrat. *Botswana International University of Science and Technology, Palapye, Botswana*

55. The Holocene Ulmen maar

Andreas Schüller. *Naturpark und UNESCO Global Geopark Vulkaneifel.*

Georg Büchel. *Universität of Jena, Institute of Geosciences.*

Volker Lorenz. *Universität of Würzburg, Institute of Geography and Geosciences.*

56. The 1905-1911 Matavanu volcanic eruption

Károly Németh. *Massey University, New Zealand; Institute of Earth Physics and Space Science, Hungary and Saudi Geological Survey, Kingdom of Saudi Arabia.*

Lameko Talia. *Ministry Natural Resources and Environment, Samoa.*

Katie Pogi. *Ministry of Natural Resources and Environment, Samoa.*

Aleni Fepuleai. *Blaqsand Enterprise, Samoa.*

Gary Lee. *The Pacific Community (SPC), Fiji.*

Dana Tigarea. *The Pacific Community (SPC), Fiji.*

Benjamin van Wyk de Vries. *Université Clermont Auvergne, Laboratoire Magmas et Volcans, OPGC, CNRS et IRD, Clermont Ferrand, France.*

57. The active Yasur–Yenkahe volcanic complex

Károly Németh. *Massey University, New Zealand; Institute of Earth Physics and Space Science, Hungary and Saudi Geological Survey, Kingdom of Saudi Arabia.*

Gary Lee. *The Pacific Community (SPC), Fiji.*

Dana Tigarea. *The Pacific Community (SPC), Fiji.*

Michel Leodoro. *Ministry of Lands and Natural Resources, Vanuatu.*

Benjamin van Wyk de Vries. *Université Clermont Auvergne, Laboratoire Magmas et Volcans, OPGC, CNRS et IRD, Clermont Ferrand, France.*

58. La Isla de Ometepe: Quaternary volcanoes in the Lake Nicaragua sedimentary basin

Eveling Espinoza. *Dirección de Vulcanología, Dirección General de Geología y Geofísica - INETER, Instituto Nicaragüense de Estudios Territoriales, Managua, Nicaragua.*

Armando Saballos. *INETER, Instituto Nicaragüense de Estudios Territoriales, Managua, Nicaragua.*

David Chavarria. *INETER, Instituto Nicaragüense de Estudios Territoriales, Managua, Nicaragua.*

William Martinez. *INETER, Instituto Nicaragüense de Estudios Territoriales, Managua, Nicaragua.*

Martha Navarro. *Consultora Independiente. Presidenta de Cooperativa de Mujeres Senderos del Cosiguina.*

Benjamin van Wyk de Vries. *Université Clermont Auvergne, Laboratoire Magmas et Volcans, OPGC, CNRS et IRD, Clermont Ferrand, France.*

59. The Poás Volcano

Adolfo Quesada Román. *Laboratorio de Geografía Física, Escuela de Geografía, Universidad de Costa Rica.*

60. The Nevado del Ruiz Quaternary Volcanic Complex

Marcela Gómez-Pérez. *Servicio Geológico Colombiano.*

Manuel Gómez Guerrero. *Servicio Geológico Colombiano.*

Marianela Vargas Anaya. *Servicio Geológico Colombiano.*

Gloria Cortes. *Servicio Geológico Colombiano.*

61. The Cotacachi - Cuicocha volcanic complex

Carlos Merizalde. *Coordinator-Imbabura UNESCO Global Geopark.*

Carlos Ubidia. *Geologist-Imbabura UNESCO Global Geopark.*

Mario Ruiz. *Volcanologist, Geophysical Institute - EPN*

62. The Quaternary Santorini Caldera

Paraskevi Nomikou. *Dept. of Geology and Geoenvironment, NKUA.*

Charalampos Fassoulas. *President of Psiloritis UGGp, Vice Coordinator of EGN.*

Nikolaos Zouros. *Director of the Natural History Museum of the Lesvos Petrified Forest, Professor in the Department of Geography, University of the Aegean*

63. The vapor phase ignimbrites of Sillar in the Añashuayco Quarries of Arequipa

Nélida Victoria Manrique Llerena. *Observatorio Vulcanológico, Instituto Geológico Minero y Metalúrgico (INGEMMET), Arequipa, Perú.*

Benjamin van Wyk de Vries. *Université Clermont Auvergne, Laboratoire Magmas et Volcans, OPGC, CNRS et IRD, Clermont Ferrand, France.*

Rigoberto Aguilar Contreras. *Observatorio Vulcanológico, Instituto Geológico Minero y Metalúrgico (INGEMMET), Arequipa, Perú.*

Carla Jenifer Palacios Nuñez. *Observatorio Vulcanológico, Instituto Geológico Minero y Metalúrgico (INGEMMET), Arequipa, Perú.*

Jersy Mariño Salazar. *Observatorio Vulcanológico, Instituto Geológico Minero y Metalúrgico (INGEMMET), Arequipa, Perú.*

Bilverto Zavala Carrión. *Instituto Geológico Minero y Metalúrgico-INGEMMET.*

Jhonny Pineda Arizaca. *Observatorio Vulcanológico, Instituto Geológico Minero y Metalúrgico (INGEMMET), Arequipa, Perú.*

64. The pyroclastic deposits from the Huaynaputina volcano eruption 1600 CE

Jersy Mariño Salazar. *Observatorio Vulcanológico, Instituto Geológico Minero y Metalúrgico (INGEMMET), Arequipa, Perú.*

Carla Arias Salazar. *Observatorio Vulcanológico, Instituto Geológico Minero y Metalúrgico (INGEMMET), Arequipa, Perú.*

Kevin Cueva Sandoval. *Observatorio Vulcanológico, Instituto Geológico Minero y Metalúrgico (INGEMMET), Arequipa, Perú.*

Jean-Claude Thouret. *Université Clermont Auvergne, Laboratoire Magmas et Volcans, OPGC, CNRS et IRD, Clermont Ferrand, France.*

Bilverto Zavala Carrión. *Instituto Geológico Minero y Metalúrgico-INGEMMET.*

Antony Finizola. *Laboratoire Géosciences Réunion, Université de La Réunion, F 97744 Saint Denis, France & Université de Paris, Institut de Physique du Globe de Paris, CNRS, F 75005 Paris, France.*

Raphael Antoine. *Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement (CEREMA), Rouen, France.*

Eric Delcher. *Laboratoire Géosciences Réunion, Université de La Réunion, F 97744 Saint Denis, France & Université de Paris, Institut de Physique du Globe de Paris, CNRS, F 75005 Paris, France.*

Cyrille Fauchard. *Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement (CEREMA), Rouen, France.*

Franck Donnadieu. *Université Clermont Auvergne, Laboratoire Magmas et Volcans, OPGC, CNRS et IRD, Clermont Ferrand, France.*

Philippe Labazuy. *Université Clermont Auvergne, Laboratoire Magmas et Volcans, OPGC, CNRS et IRD, Clermont Ferrand, France.*

Saida Japura. *Observatorio Vulcanológico, Instituto Geológico Minero y Metalúrgico (INGEMMET), Arequipa, Perú.*

Rachel Gusset. *Laboratoire Géosciences Réunion, Université de La Réunion, F 97744 Saint Denis, France.*

Paola Sanchez. *Observatorio Vulcanológico, Instituto Geológico Minero y Metalúrgico (INGEMMET), Arequipa, Perú*

Domingo Ramos. *Observatorio Vulcanológico, Instituto Geológico Minero y Metalúrgico (INGEMMET), Arequipa, Perú.*

Liliane Thouret. *École Edgar Quinet, Éducation nationale, Clermont Ferrand, France.*

Thibault Saintenoy. *Laboratoire AiHP GEODE, Université des Antilles, 97233 Schoelcher, France & Instituto de Ciencias del Patrimonio, Consejo Superior de Investigaciones Científicas, 15705 Santiago de Compostela, Spain*

Benjamin van Wyk de Vries. *Université Clermont Auvergne, Laboratoire Magmas et Volcans, OPGC, CNRS et IRD, Clermont Ferrand, France.*

Andy Ancalle Quispe. *Observatorio Vulcanológico, Instituto Geológico Minero y Metalúrgico (INGEMMET), Arequipa, Perú.*

65. The Miocene Cappadocian Ignimbrites sequence

Vedat Toprak. *Middle East Technical University, Ankara, Turkey.*

Nizamettin Kazancı. *Ankara University, Ankara, Turkey*

66. El Tatio geothermal field

Manuel Arenas. *National Geological and Mining Service (SERNAGEOMIN), Chile.*

Felipe Cristian Fuentes Carrasco. *Hydrogeology and Geoheritage units. Department of Applied Geology and Geological Resources, National Service of Geology and Mining, Chile.*

67. The Yellowstone volcanic and hydrothermal system

Jamie Farrell. *University of Utah.*

Michael Poland. *U.S. Geological Survey.*

Madison Myers. *Montana State University.*

Robert B. Smith. *University of Utah.*

VI. TECTONICS

68. Ynys Llanddwyn late Neoproterozoic-Cambrian Mélange

Raymond Roberts. *Natural Resources Wales, Chester Road, Buckley, CH7 3AJ.*

Stewart Campbell. *Natural Resources Wales, Chester Road, Buckley, CH7 3AJ.*

Graham Williams. *Natural Resources Wales, Chester Road, Buckley, CH7 3AJ.*

Niall Groome. *School of Earth & Environmental Sciences, Cardiff University, Cardiff, CF10 3AT.*

David Buchs. *School of Earth & Environmental Sciences, Cardiff University, Cardiff, CF10 3AT.*

Alan Holden. *British Geological Survey, Cardiff University, Cardiff, CF10 3AT.*

69. Namakdan Salt Cave

Alireza Amrikazemi. *Director of Qeshm Island UNESCO Global Geopark & Member of the Scientific Committee of Lut Desert World Heritage Base.*

Saeed Afsari fard. *Structural Geologist at National Iranian Oil Company.*

Abdolvahed Pehpouri. *Expert at Qeshm Island UNESCO Global Geopark.*

70. The Moine Thrust Zone

Taija Torvela. *University of Leeds, United Kingdom.*

David Peacock. *University of Göttingen, Germany.*

71. Upper Jurassic ophiolitic sequence in La Désirade Island

Nicolas CHARLES. *PhD – BRGM / French Geological Survey.*

72. The South Tibetan Detachment System in the Rongbuk Valley

Rodolfo Carosi. *Università degli Studi di Torino, Italy.*

Chiara Montomoli. *Università degli Studi di Torino, Italy.*

Salvatore Iaccarino. *Università degli Studi di Torino, Italy.*

73. Northern Snake Range metamorphic core complex

Elizabeth L. Miller. *Department of Geological Sciences, Stanford University, Stanford CA 94305 USA.*

Jeffrey Lee. *Department of Geophysics, Colorado School of Mines, Golden, CO 8040, USA.*

74. Nojima Fault

Tadahiro Shibata. *Agency for Cultural Affairs.*

Shigehiro Kato. *Museum of Nature and Human Activities, Hyogo.*

Setsuya Nakada. *The University of Tokyo (presently NIED)*

VII. MINERALOGY

75. Tsumeb Ore Deposit

Helke Mocke. *Geological Survey of Namibia, Namibia.*

Thomas Böllinghaus. *Federal Institute for Materials, Research and Testing, Germany.*

Rob Bowell. *Queen's University, Canada.*

Gabi Schneider. *Namibia Uranium Institute, Namibia.*

76. The giant mercury deposit of the Almadén syncline

José Luis Gallardo Millán. *Professor at the University of Castilla-La Mancha (Spain)*

Fernando José Palero Fernández. *Consulting Geologist (Spain).*

Saturnino Lorenzo Álvarez. *Professor at the University of Castilla-La Mancha (Spain)*

77. Deposits of Amethyst of Los Catalanes Gemological District

César Goso Aguilar. *Geologist, Professor of Geology at the Geological Sciences Institute of the Faculty of Sciences (University of the Republic, Uruguay)*

Mauricio Faraone. Geologist, Adviser of the Geological Survey of Uruguay National Directorate of Mining and Geology (Ministry of Industry Energy and Mining, Uruguay)

VIII. GEOMORPHOLOGY AND ACTIVE GEOLOGICAL PROCESSES

78. Uluru inselberg

Margaret Brocx. *Adjunct Professor of Research|College of Science, Health, Engineering and Education, Discipline Environmental and Conservation Sciences. Murdoch University, Western Australia, Australia.*

Vic Semeniuk. *Adjunct Professor of Research|College of Science, Health, Engineering and Education, Discipline Environmental and Conservation Sciences. Murdoch University, Western Australia, Australia.*

79. The Sugar Loaf monolith of Rio de Janeiro

Kátia Leite Mansur. *Federal University of Rio de Janeiro (UFRJ)*

Claudio de Morisson Valeriano. *Rio de Janeiro State University (UERJ)*

80. Shilin Karst

Jihong BAO. *Shilin Global Geopark Administrative Bureau, Yunnan, China.*

81. Tsingy of Bemaraha

Voahanginiaina Saholiarimanana. *Geologist Responsible for the Safeguarding of Geological and Mining Heritage at the Ministry of Mines, Madagascar.*

82. La Puerta del Diablo inverted relief

Walter Hernandez. *Universidad de El Salvador, Ciudad Universitaria, San Salvador, El Salvador.*

83. Quaternary interglacial coral and marine uplifted terraces of Maisí, Cuba

Leandro L. Peñalver Hernández. *Institute de Geology y Paleontology/Geological Survey of Cuba.*

Kevin Pedoja. *University of Caen Normandy, France.*

Arelis Nuñez Labañino. *Institute de Geology y Paleontology/ Geological Survey of Cuba.*

Christine Authemayou. *Université de Bretagne Occidentale Plouzané, France.*

Pedro Dunán Ávila. *Université de Bretagne Occidentale Plouzané, France.*

Pedro Benítez Frómeta. *Institute de Geology y Paleontology/ Geological Survey of Cuba.*

Enrique A. Castellanos Abella. *Ministry of Energy and Mines, Cuba.*

84. The Grand Canyon

Karl E. Karlstrom. *Distinguished Professor, Department of Earth and Planetary Sciences, University of New Mexico, USA.*

Laura J. Crossey. *Distinguished Professor, Department of Earth and Planetary Sciences, University of New Mexico, USA.*

85. Iguazú/Iguaçu waterfalls

Alberto Ardolino. *Geological and Mining Survey of Argentina (SEGEMAR)*

Fernando Miranda. *Geological and Mining Survey of Argentina (SEGEMAR)*

86. Mosi-oa-Tunya/Victoria Falls

Asfawossen Asrat. *Botswana International University of Science and Technology, Palapye, Botswana.*

87. Dry Falls and the Channeled Scabland

Susan Schnur. *Washington Geological Survey, Washington State Department of Natural Resources, Washington, USA.*

Ryan Karlson. *Washington State Parks and Recreation Commission, Washington, USA.*

88. Jutulhogget Canyon

Kristin Rangnes. *General manager/Geologist, Gea Norvegica UNESCO Global Geopark.*

Fredrik Høgaas. *Scientist, Geological Survey of Norway.*

Rolv Magne Dahl. *Scientist, Geological Survey of Norway.*

Tom Heldal. *Scientist, Geological Survey of Norway.*

89. Perito Moreno Glacier

Martin Gozalvez. *Geological and Mining Survey of Argentina (SEGEMAR)*

Fernando Miranda. *Geological and Mining Survey of Argentina (SEGEMAR)*

90. Rockglaciers of the Engadine

Emmanuel Reynard. *Institute of Geography and Sustainability and Interdisciplinary Centre for Mountain Research, University of Lausanne, Switzerland, International Association of Geomorphologists.*

Isabelle Gärtner-Roer. *Department of Geography, University of Zurich, Switzerland.*

Martin Hoelzle. *Department of Geosciences, University of Fribourg, Switzerland.*

91. The Okavango Delta

Asfawossen Asrat. *Botswana International University of Science and Technology, Palapye, Botswana.*

92. Yardang (Kalut) in the Lut Desert

Mehran Maghsoudi. *Director of Lut Desert World Heritage Base.*

Alireza Amrikazemi. *Director of Qeshm Island UNESCO Global Geopark & Member of the Scientific Committee of Lut Desert World Heritage Base.*

Anvar Moradi. *Senior Consultant of Lut Desert World Heritage Base.*

93. Namib Sand Sea

Asfawossen Asrat. *Botswana International University of Science and Technology, Palapye, Botswana.*

Piotr Migoń. *Institute of Geography and Regional Development, University of Wrocław, Wrocław, Poland.*

Zbigniew Zwoliński. *Institute of Geoecology and Geoinformation, Adam Mickiewicz University in Poznań, Poland.*

94. Bilutu megadunes and lakes in the Badain Jaran Desert

Tian Mingzhong. *China University of Geosciences (Beijing), China.*

Sun Hongyan. *China University of Geosciences (Beijing), China.*

Tian Nan. *China University of Geosciences (Beijing), China AND Alax Desert UNESCO Global Geopark.*

Humujiletu. *Alax Desert UNESCO Global Geopark, Inner Mongolia, China.*

95. Vajont landslide

Paola Coratza. *Department of Chemical and Geological Sciences, University of Modena and Reggio Emilia -International Association of Geomorphologists.*

96. Pamukkale Travertines

Alper Gürbüz. *Ömerhalisdemir Universitesi, Niğde, Türkiye.*

Mehmet Özkul. *Pamukkale Universitesi, Denizli, Türkiye.*

Nizamettin Kazancı. *Ankara University, Ankara, Turkey.*

Mary Lou. *UNESCO-IRCK.*

97. Puquios of the Llamara salt flat

Felipe Cristian Fuentes Carrasco. *Hydrogeology and Geoheritage units. Department of Applied Geology and Geological Resources, National Service of Geology and Mining, Chile.*

98. Škocjan Caves in the Classical Karst

Nadja Zupan Hajna. *ZRC SAZU Karst Research Institute.*

Andrej Mihevc. *ZRC SAZU Karst Research Institute.*

Borut Peric. *Škocjan Caves Public Service Agency.*

Matevž Novak. *Geological Survey of Slovenia.*

99. Sac Actun Underwater Cave System

Rafael López Martínez. *Institute of Geology, Universidad Nacional Autónoma de México.*

Ricardo Barragán Manzo. *Institute of Geology, Universidad Nacional Autónoma de México.*

Emmaline M. Rosado-González. *Department of Geology/ Geosciences Centre (CGeo), Universidade de Trás-os-Montes e Alto Douro, Portugal.*

IX. IMPACT STRUCTURES AND EXTRATERRESTRIAL ROCKS

100. Domo de Araguainha Impact Structure

Alvaro P. Crósta. *State University of Campinas, Brazil.*

Natalia Hauser. *University of Brasília, Brazil.*

W. Uwe Reimold. *University of Brasília, Brazil.*

Thank you

The IUGS wants to express its most sincere gratitude to all participants and authors that have contributed to this unique announcement.

IUGS recognition identifies these sites as being of the highest scientific value. They are sites that served to develop the science of geology. They are the world's best demonstrations of geologic features and processes. They are the sites of fabulous discoveries of the Earth and its history. Recognition and visibility of the "First 100" IUGS Geological Heritage Sites can lead to their further appreciation, to their use as educational resources, and, most importantly, to their preservation.

Please, do not hesitate to contact us in case you see any error or misspelling. We will be happy to improve future editions.

Contact: iugs.globalgeosites@igme.es

60 IUGS

EUSKADI
BASQUE COUNTRY

SPONSORING

Gipuzkoako Foru Aldundia
Diputación Foral de Gipuzkoa

ETORKIZUNA ORAIN
Es futuro

Euskadi, auzolana, bien común
EUSKO JAURLARITZA GOBIERNO VASCO

unesco
International Geoscience Programme
IGCP731

Geoparkea
Euskal Kostaldea - Costa Vasca

IUGS

SECRETARIAT

CSIC
Consejo Superior de Investigaciones Científicas

IGME
Instituto Geológico y Minero de España

ISBN 978-1-7923-9975-6
90000>
9 781792 399756