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A global framework for the Earth: putting geological sciences in context

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ABSTRACT

We propose a global framework for the Earth system to facilitate communication between the geoscience community, the public and policy makers. Geoscience research aims to understand the history and evolution of the Earth system. This combines the non-living and living parts of the Earth, especially through interactions of the lithosphere, biosphere and atmosphere as well as the other parts of the system, such as the asthenosphere, core and extraterrestrial influences. Such research considers a system that spans scales from microscopic (micrometer scale) to megascopic (many 1000 s of km scale), and from milliseconds to millions of years. To connect different parts of this immense system, we habitually use a wide range of ad hoc geological frameworks, systems and geological environment models, where different processes and features operate and combine. In consequence, one way to judge the significance of our work, and to increase its value, is to assess how the elements studied are integrated within the whole Earth system. This allows us to see what implications any study has for this greater Earth system. To do this successfully, our research needs a standard global framework to assess a study's relevance. However, such a global framework does not formally exist, and so this article looks at existing examples and proposes one that can systematically place research into a global geological context. This proposed framework has the advantage of being useful for communicating geological processes to other disciplines, and can be used for any type of Earth (or planetary) environment. This framework is a fundamental tool for geoscience communication and for outreach, especially through geological heritage (geoheritage). Geoheritage concerns the valuing and protection of geoscience and geological sites, and is a vital tool for communicating geoscience. It can be used to communicate our knowledge of global change, providing, through landscapes and outcrops, a story that renders the concepts and advances of geoscience accessible. Like our basic research, the concept of geoheritage evolves as our understanding of the Earth progresses, and these dual changes can be explained with the global framework. Geoheritage is a global activity and it needs a global framework to put sites into context. A revision of the UNESCO geological thematic studies was called for by the World Heritage Committee in 2014 (decision: 38 COM 8B.11), and this can be done with the input from the full geoscience community using this global geological framework.

Thus, for research, geoscience policy and for geoheritage, a global framework is now needed. The proposed framework can place any site in its geological environment, related to its lithospheric plate tectonic setting and

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its history. The framework has a solid-earth bias (lithosphere), but includes all other spheres, such as the biosphere and anthropogenic activity. Extraterrestrial influences, like solar variations and metorite impacts are included. The framework is phenomenological, due to the necessity of grouping the features that we see, but these phenomena provide evidence of processes that we cannot see. The basic format is a table, a sketch of the Earth and a system diagram, three complementary and most powerful ways of depicting a system. A timeline, or stratigraphic column can be included, to show the evolution of geological history, and the table can be used as a 'game board' where one site migrates across from one set of conditions to another over time. The global framework allows any research site, area or subject to be set in the Earth's system, in a way that gives it context, allows comparisons and provides significance. We suggest that it can be a template for an internationally accepted version used to consolidate the necessary geoscience – geoheritage link and promote outreach.

1. Introduction

In the context of global and planetary systems, the lithosphere has a major role as the interface between the inside and the outside. It is the geological environment that controls what happens between the inner asthenosphere and the core of the Earth and the outer hydrosphere-atmosphere-biosphere where we live (Fig. 1). The evolution of the lithospheric part of the system has also been affected by changes in life on Earth, which have had major effects on sedimentary environments, and the atmosphere/hydrosphere. For example, carbonate production and CO_2, production of oxygen, terrestrial vegetation development, organic material production are all biological processes that have radically changed parts and processes in the lithosphere. Through subduction, these biological changes have affected the asthenosphere as well.

Two analogies for this are:

a. Our own human bodies, where the lithosphere would be the skin that separates the inner organism from the outer environment, and which gives the organism its boundaries and allows it to interact and live; or.
b. A fruit like a peach, where the skin (lithosphere again) is the interface between the soft inner part (asthenosphere and core), and the outside.

Both of these are metaphors for the Earth, that help imagine something much larger than most people can grasp, and each works more or less well, depending on the individual. The use of several analogies is better than one single one, as the difference between them can also raise awareness of the actual state of the Earth.

When we use the term 'geological environment', we mean any part of the geological setting or system, e.g. orogenic or rift environment, lithosphere - asthenosphere boundary, not just surface environment. An environment can be localised, such as a karst cave, or a volcanic vent, but it will be part of a greater environment. This broader context is at the origin of the local environment. For example, a karst cave cannot form unless the limestone is formed on a stable continental shelf, nor without suitable plate tectonic and hydrological history to form the feature, and it will not survive if the conditions change.

This last point is very important. Plate tectonics is *the* overall global process that has shaped our planet, including its climate and biosphere over the last at least 3 million years. All surface phenomena are ultimately based on plate tectonics and its interaction with other parts of the system. A simple thought experiment shows this: if plate tectonics stopped, there would be limited surface movement (that allows, say, a karst limestone to change from sea bed to mountain range). Without plate tectonics there would be no recycling of water into the mantle, or expelled into the atmosphere. CO_2 would not be recycled-released through volcanoes, possibly leading to global cooling and the development of a snowball Earth. On a longer time scale heat would not be liberated, leading to greater hot spot magmatism (e.g. Silver and Behn, 2008).

Geological environments are systems that can be considered at a very small scale, e.g. the size of a crystal, a river bed, or a karst doline, but they can also be large, such as a lithospheric fault or a mantle plume. The small systems form parts of larger systems, and the large ones are an amalgamation of smaller systems. This scale change is something that geoscientists and other scientists habitually navigate, in both space and time, but is not often considered in other spheres of activity, even if it is present (e.g. the behaviour of an individual or a crowd, or a nation).

The importance of the lithosphere as the Earth's skin was underlined in the original definition of the biosphere by Suess (1885), who considered the latter as part of the Earth's particular geological system:

> *'One thing seems to be foreign on this large celestial body [Earth] consisting of spheres, namely, organic life. But this life is limited to a determined zone at the surface of the lithosphere. The plant, whose deep roots plunge into the soil to feed, and which at the same time rises into the air to breathe, is a good illustration of organic life in the region of interaction between the upper sphere and the lithosphere, and on the surface of continents it is possible to single out an independent biosphere.'*

For some researchers, such as Vernadsky (1926) the biosphere itself was also but an organic part of geological processes. Vernadsky went further to suggest 'noosphere', the sphere of thought that can be considered as an element of the anthroposphere, which has developed with the expansion of humans on planet Earth, and is now reaching other solar system bodies through space exploration.

The Anthropocene (or for some the Anthropogene), the geological Era into which we may be moving is the geological time scale reflection of this (Gerasimov, 1979; Waters et al., 2014).

1.1. Background to the proposed framework

In the recent International Lithosphere Program (ILP) meeting in

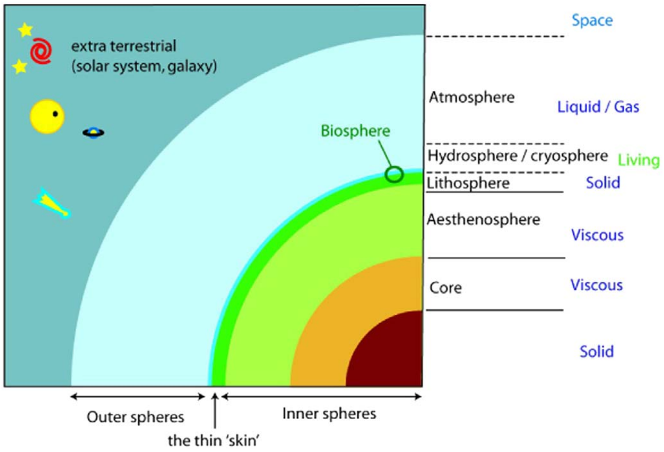


Fig. 1. Different characterisations of the lithosphere, and Earth processes **A.** A highly simplified diagram of the Earth's system, seen though a cross section with the different rheology spheres. This is a geo-centric viewpoint with the hydrosphere and lithosphere thickened.

Clermont-Ferrand (3–7 October 2016), we discussed the place of the lithosphere in a global geoscience framework, especially with regard to the link between deep and surface processes. We also considered ways that geoscience research in this domain could be transmitted out of our scientific confines to have greater impact and assure that its relevance is valued internationally. This reflects a continued discussion about how to present the lithosphere in the Earth's system, in order to communicate its importance to a broad public, including UNESCO.

The discussion has been ongoing at geoheritage and geodiversity sessions at the Geological Society of America meeting, Denver 2013, and Baltimore 2015, the European Geosciences Union general meeting in 2016, and the American Geophysical Union fall meeting in 2017. The long author list of this paper and acknowledgement list reflects the broad input of the geoscience community into this idea. During these meetings we discussed a large body of textbook and classic geology text descriptions of the Earth system dating from the present day back to the 18th Century, and this provides the background for the text presented below (Figs. 2, 3, 4 and 5).

This article thus provides the fruit of nearly nine years of growing international discussion about the Earth's system and about ways of providing a global framework that can be used in thinking about the larger consequences of our research, as well as a tool for communication and outreach.

If we had such a broadly agreed global geological framework, there would be the potential to place any site within the context of the whole Earth system, and this would allow its significance to be fully appreciated.

1.2. Relevance of a global geological framework

If our science has a significance to global change and to humanity as a whole (*as it is clear to us scientists that it does*), then this importance has to be transmitted, and the implications of our research need to be integrated into government policy from a global to local scale.

One problem in the actual post-trust and post-modernist world (e.g. Keyes, 2004) is that facts are not often used as the basis for important decisions related to large-scale Earth systems (climate change, natural disasters and resource management). This is perhaps partly because the whole Earth system is not often taken into consideration, and this is where a template global geological framework has a role in placing facts into a structure that can be referred to, accepted, and understood by the various actors.

The main problem to be solved is to get actors and users outside geosciences to think in terms of this domain when they are considering global topics like environmental change, risk reduction, and the use or protection of natural resources and the environment. For this, a global framework for geology needs to be available, understandable, agreed on and promoted. It has to be understandable to users outside geosciences, which requires the use of simple language, clear concepts and dedicated education about the main concepts, as they are not universally understood.

For example, geoscience concepts and terms like ‘the lithosphere’ are not well known or understood by the general public, or policy-makers. Thus, for example, ‘Atmosphere’ is known by everybody, but the ‘Litho’ is enough to cause mystification.

However, there is a general appreciation of landscape, and concern through emotive topics like ‘the environment’, ‘global warming’, and ‘climate change’, or heritage (Fig. 2). There is also an ever increasing ability to see geological landscapes through utilities like Google Earth, social media, virtual reality. So a combination of natural sites and complementary media can now be brought together to increase public understanding and to communicate science (e.g. Rapprich et al., 2016).

In this context, geological heritage, ‘geoheritage’ is expanding through local and national sites, and in protected areas of all types. Geoheritage involves the description, classification, protection and exploitation of the geodiversity for scientific and educational purposes, as well as for tourism, risk and resources. Geodiversity is a term to describe the whole range of different geological elements in an area, and is the equivalent of biodiversity. High geodiversity often goes hand in hand with high biodiversity, and a change in the former leads to changes in the latter.

Geoheritage began to become an internationally accepted way of managing and protecting geological resources in the 1990s (e.g. Wimbledon, 1999), through the Global Indicative List of Geological Sites (GILGES), which was set up by the International Union of Geological Sciences (IUGS), UNESCO and the International Union for the Conservation of Nature (IUCN). The lists' criteria were based on the UNESCO World Heritage definition of Geological criteria, given in Table 1B (Cowie and Wimbledon, 1994). This was replaced by ‘Global Geosites’ in 1995, and since that time, the slow process of cataloguing the world's geosites has been undertaken by essentially by national bodies (Gray, 2013).

The most recent development, in 2016, has been the establishment of an International Union of Geological Sciences (IUGS) Commission on Geoheritage, with a Heritage Sites and Collections Subcommission (HSCS) that is working to establish scientific criteria through which applications for new UNESCO geoparks can be assessed (Page and de Wever, 2017).

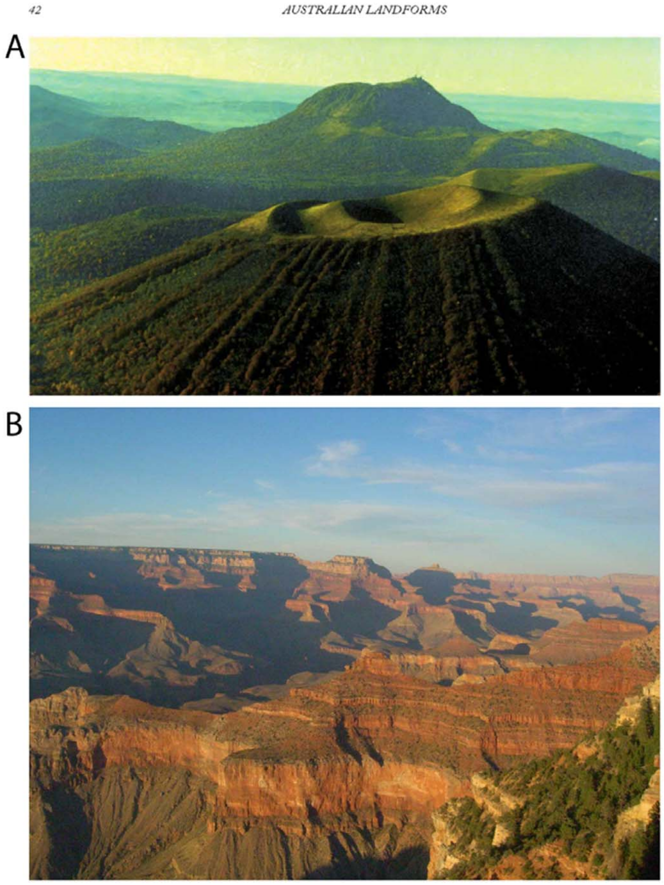


Fig. 2. Landscapes are clear expressions of geological processes. **A**. Image of the Chaîne des Puys volcanoes (Massif Central of France) used in ‘Australian Landforms’ (Twidale and Campbell, 2005). This is a fine example of using one site in its global context to illustrate a landform on the other side of the world. **B**. Image of Grand Canyon, showing the globally-known view from the south rim of the Canyon. Most people can appreciate the layers of rock, and the process of erosion by the Colorado River, however they remain unaware of the significance of the flat skyline of the uplifted plateau, caused by the probable delamination of underlying lithosphere. The Chaîne des Puys image, in this context can be used to remind people that the Colorado plateau and the Massif Central both share similar tectonic elements related to delamination and that both the Chaîne and the Canyon volcanoes are manifestations of broader tectonic processes in contrasting geological environments.

Table 1
Extracts from the UNESCO World Heritage Convention, defining Natural and Geological Heritage. **A**. Article 2of the World Heritage Convention (http://whc.unesco.org/en/convention/); **B**. the World Heritage Natural Criteria (http://whc.unesco.org/en/criteria/). Note that *all* natural criteria (including ix and x) could be gathered under Suess's (1885) and Vernadsky's (1926) definition of geological processes. C. Decision 38 COM 8B.11. From the UNESCO World Heritage meeting at Doha in 2014.

A. UNESCO World Heritage convention	**Article 2** For the purposes of this Convention, the following shall be considered as "natural heritage": **Natural features** consisting of physical and biological formations or groups of such formations, which are of outstanding universal value from the aesthetic or scientific point of view; **Geological and physiographical formations** and precisely delineated areas which constitute the habitat of threatened species of animals and plants of outstanding universal value from the point of view of science or conservation; **Natural sites** or precisely delineated natural areas of outstanding universal value from the point of view of science, conservation or natural beauty.
B. UNESCO Natural Criteria	(viii) to contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance; (ix) to be outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features; (x) to be outstanding examples representing significant on-going ecological and biological processes in the evolution and development of terrestrial, fresh water, coastal and marine ecosystems and communities of plants and animals; (xi) to contain the most important and significant natural habitats for in-situ conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation.
Decision: 38 COM 8B.11	Recalling Decision **37 COM 8B.15** adopted at its 37th session (Phnom Penh, 2013), reiterates its request to IUCN to revisit and update its thematic study on "World Heritage Volcanoes" to clearly articulate a short and appropriately balanced list of the strongest remaining volcanic sites with potential for inscription on the World Heritage List, and also requests IUCN to revise its thematic study on geological sites, the "Geological World Heritage: A Global Framework" (2005) to refine the proposed 13 themes, articulate the threshold of Outstanding Universal Value, and clarify the difference between the criterion (viii) of the World Heritage and Geoparks status.

Geoheritage sites include natural landscapes, but also mine and quarry exhibitions, and urban geosites. A 'geosite' is a site with geological features, and is close to the German-sourced term geotope. Geotope is the geological equivalent of an ecotope, or typical geological feature such as a distinct landform element like a mountain, or an outcrop, or even a stone wall that displays geological features. The geosite then, can contain one or more geotopes, collected into a meaningful entity, such as a set of outcrops that show a feature.

The many internationally important protected areas are linked through UNESCO programmes of Global Geoparks and World Heritage sites. The former are sites of important geological interest that are protected in a sustainable manner, integrating tourism and economic activity. There are many other types of protected area around the world that preserve and value geoheritage, such as national geoparks, national parks, national monuments, private reserves, each depending on their local or national status. The geoheritage of protected areas is beginning to be used as a tool for organising territories for sustainable practices and risk reduction (Gray, 2013; Rose and van Wyk de Vries, 2016; Leven et al., 2017).

The World Heritage site accreditation is based on the concept of 'Outstanding Universal Value' (OUV). This 'OUV' is defined as being a site that is so significant that it is of global importance. It also has to have solid management and protection (see Table 1 for the full definitions).

Outstanding Universal Value for natural sites is defined by the UNESCO World Heritage convention as 'being from the point of view of science' (Table 1), and because of this the geoscience community has an important role in defining the OUV. The global framework for geology would be a major step forward in consolidating how this OUV is defined from the conventional requirement of 'the view of science' (Table 1).

Before going into how this has been defined up to present, it is worth looking at geological frameworks, geological environments and systems in the scientific literature. This overview is not designed to be a complete history of the study of whole Earth systems (that is a huge subject), but is aimed at providing the most relevant examples.

1.3. Global Geological systems in the literature

Discussion of global systems, that goes further than religious-based doctrines, has gone on since at least ancient Greek times. However, for the purposes of this study we start with the beginnings of modern geological investigation. Buffon (1778), was an early proponent of a science-based Earth system, based on a solar system with planets that gradually cooled, and he calculated an age of 75,000 years for the Earth.

The Wernian Neptunist ideas, so well championed by Jameson (1809) gave another view: a primordial ocean with precipitation of granites and basalts before the later 'transition', 'secondary' and 'tertiary' rocks, finishing with a smattering of volcanoes produced from coal burning. Davy (1980) concluded that alkaline metal combustion caused volcanoes, and proposed a hollow Earth. He provided much of the basis of the material for Journey to the Centre of the Earth (Verne, 1864). The contrasting theory of Plutonism, came in with the Plutonists, who saw the Earth's internal heat as creating molten magma that formed the igneous rocks of the Earth.

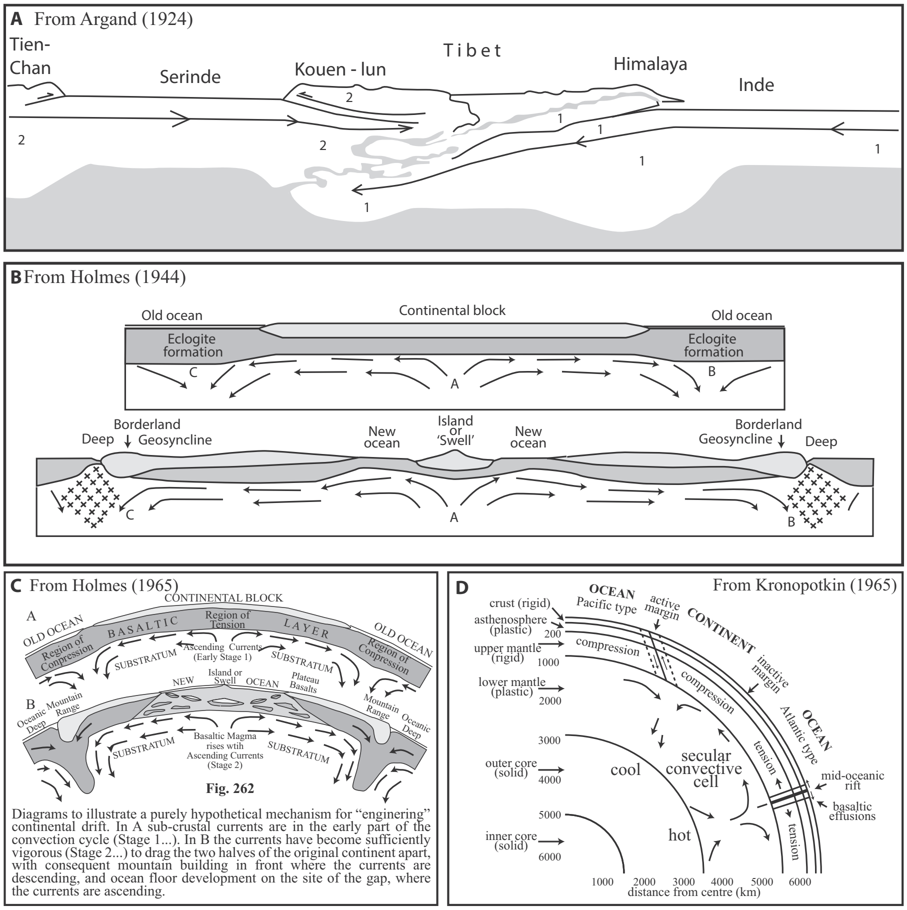
Thus, different, but more modern familiar Earth systems came in with Hutton (1788), whose principles were succinctly described by Playfair (1802). Hutton's theory of uniformitarianism is based on an idea of an Earth system, where the processes acting at present are the same as those in the past, and will be the same in the future. The ideas rely on a global framework, in which surface processes and deep processes are linked.

Such ideas were taken up by Scrope (1825) in his description of volcanoes, and by Lyell (1830) in his 'Principles of Geology', and by this time the idea of describing the whole Earth as a system, which included the atmosphere, oceans and extraterrestrial effects, was being developed. These ideas were taken a step further by von Humbolt (1845), who attempted to place the Earth in a unified theory of the universe in 'Kosmos'. Suess (1885) stared to develop ideas that sea level could change globally from time to time and that continents changed in shape, with oceans flooding the gaps. He also developed the idea of the biosphere as part of the Earth's geological system.

Wegener (1912), du Toit (1937), and Holmes (1944) and others suggested that continents could move on the Earth's surface, and from this time Earth systems ideas slowly developed towards plate tectonics.

There have been other alternative Earth systems along the way, like Van Bemmelen's (1954) theory of vertical movements, which was a forerunner of delamination (e.g. Bird, 1979). The theory of the expanding Earth was also proposed (Carey, 1958).

Wilson (1966) proposed a theory, now called the 'Wilson Cycle', of ocean opening and closure and the development of continental drift/plate tectonics can be seen in the successive editions of Holmes (1944, 1965), and in the collection of papers in Runcorn (1962) 'A symposium on Continental Drift' (Figs. 3 and 4).



Diagrams to illustrate a purely hypothetical mechanism for "enginering" continental drift. In A sub-crustal currents are in the early part of the convection cycle (Stage 1...). In B the currents have become sufficiently vigorous (Stage 2...) to drag the two halves of the original continent apart, with consequent mountain building in front where the currents are descending, and ocean floor development on the site of the gap, where the currents are ascending.

Fig. 3. Some old Earth systems. **A.** An early diagram of the Himalayas showing lithospheric subduction from Argand (1924). **B.** and **C.** successive models from Holmes (1944) and Holmes (1965), providing a model framework of the Earth, that approaches that of plate tectonics. **D.** Pre-Plate-tectonic diagram of the Earth from Kronopotkin (1965). This shows that the spheres of the Earth were known by 1965, and that convection in the 'plastic' mantle was becoming accepted, but there is no concept of subduction and no clear idea of the formation of lithosphere at ridges.

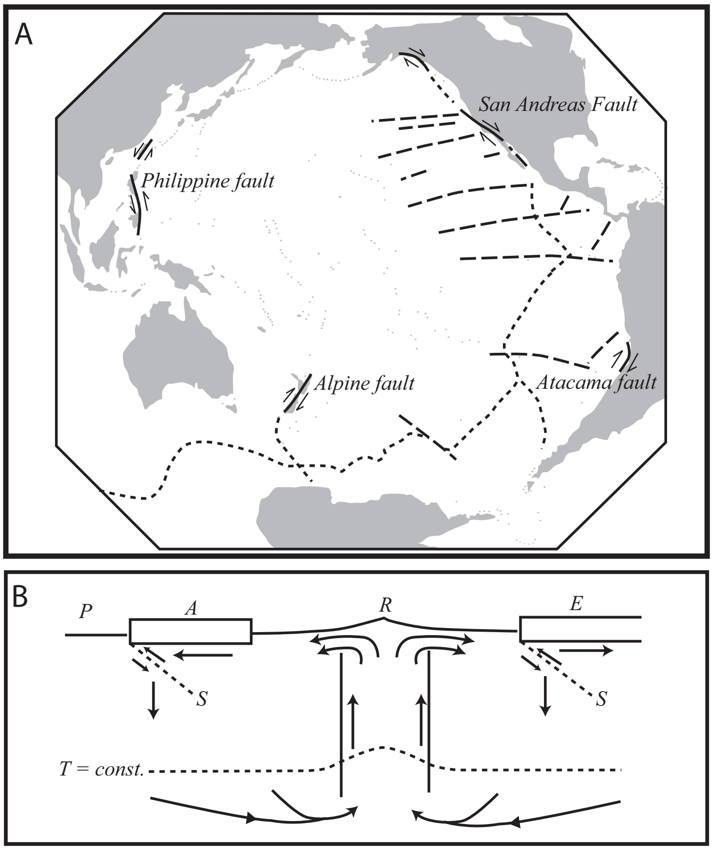


Fig. 4. Images from the symposium on Continental Drift edited by Blackett et al. (1965). **A.** Map of transcurrent faults and mid-ocean ridges around the Pacific taken from Allen (1965). Note that no subduction zone is shown. That lack of subduction zones fed for a while the model of the expanding Earth (e.g. Carey, 1958) **B.** From Orowan (1965) showing his Fig. 6, schematic of convection and the rift-subduction system.

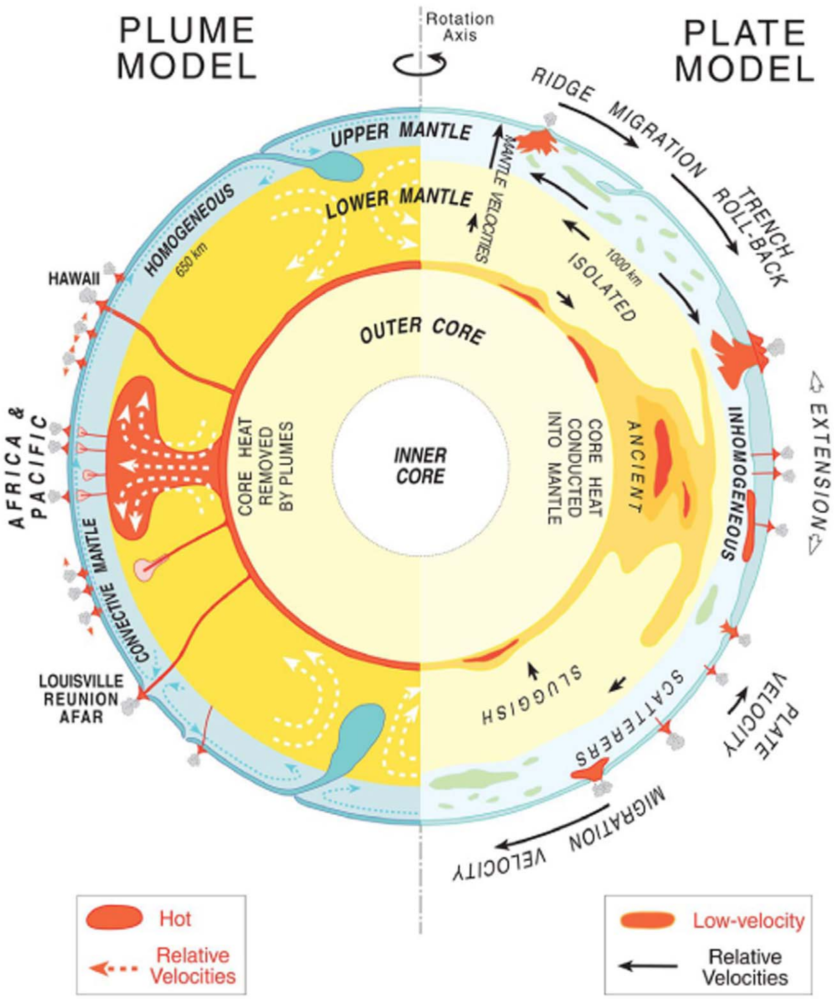


Fig. 5. The Foulger (2010) diagram adapted from Courtillot et al. (2003) for the plume model, and Anderson (2005), for the plate model.

Interestingly, the 1965 symposium contains the ideas of rifting and transform faulting, but subduction had not yet been fully described, However, subduction of continental roots had already been suggested in the 1920s (Anglard 1920) (Fig. 3A).

Recent geology text books such as Foulger (2010) suggest revisions of plate tectonics and challenge some aspects of plate tectonics, suggesting that while we have at present much data about the working of the inner Earth, the complexity of it does not allow one single system proposition to account for all observations. However, a single framework can be used with the accepted and agreed elements to illustrate differences of scientific opinion and communicate the problem (e.g. Fig. 5). Thus, a geological framework is useful for not just comparing facts, but comparing competing theories.

The practical use of a geological system, seen as a Earth system has been demonstrated by Griffiths and Stokes (2008). Their systems approach to geomorphological descriptions of areas for engineering works has a close parallel to the approach here, and provides a complementary, surface orientated way of looking at the Earth system.

1.4. Geological systems in geoheritage

In the last few years attempts have been made to define geological frameworks for geoheritage purposes based on geological systems. Much of this has been done through the idea of geodiversity – the diversity of geological features and processes that necessarily requires a framework for it to be appreciated. The first edition of ‘Geodiversity’ sets out in Chapter 2 a description of the Earth as a system (Gray, 2004). This is a complete overview of most types of geological environment, although the description stops short of providing a global tectonic framework for each environment, or ‘setting’. The second edition of Gray (2013) he remarks that the first four chapters deal with describing and putting in place the framework for geodiversity.

Brocx and Semeniuk (2007) reviewed geoheritage and provided several examples of sites seen through their idea of geological systems and tectonic context, while pointing out that a full framework for global geoheritage did not yet exist.

On a slightly more focussed level, Sengor and Natal'in (2011) provided a review of ‘Rifts of the World’, that began to place them into a global tectonic framework. Merle (2011) went further in describing rifts and provided a simplified global framework classification for rift systems. The figure proposed by Merle (2011) gives a simple system diagram that contains most rift environments and their genetic evolution (Fig. 6). This is a good example of how a simple visual representation of a system can be very useful for communicating concepts and processes which can otherwise be difficult to grasp, allowing geological landscapes to be put into context.

Note the term used by Merle ‘mountain chain rift’ has been challenged. Possibly ‘orogenic’ is a more appropriate term, although mountain range is currently more understandable to the general public (unless the term ‘orogenic’ became common use, e.g. by introduction into school curricula). The opposite problem occurs with rifts, where the term rift is commonly understood, but an equivalent term to orogen, ‘taphrogen’, despite its correctness, has never been adopted, even in academic circles (Sengor and Natal'in, 2011).

In 2015, van Wyk de Vries proposed an simple framework to integrate tectonics with volcanoes that could be applied to any other

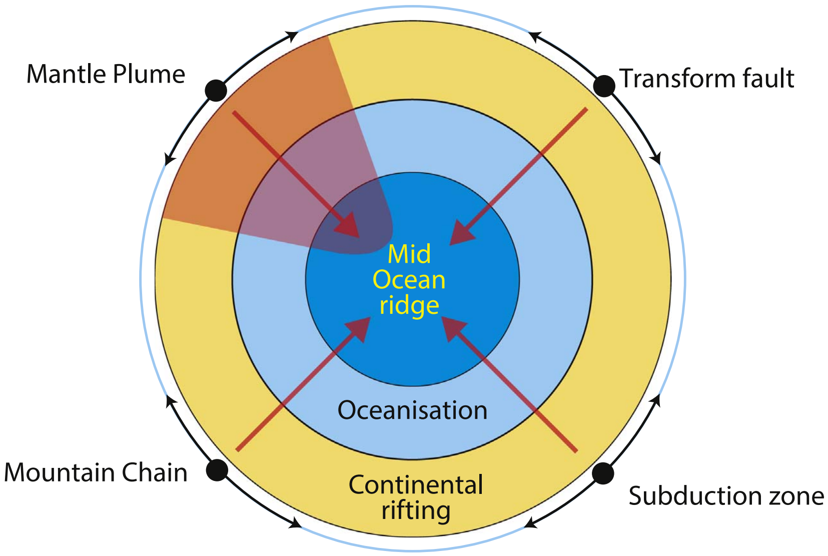


Fig. 6. A diagram for the simple classification of rifts from Merle (2011). This simple system, takes four possible rift environments, which can all evolve, if they keep developing, into oceanic ridges. The four rift environments here are; mantle plume, transform fault, subduction zone and mountain chain (the latter could be termed 'orogen' for correctness, but this is a term less understandable to lay people, as discussed in the text. Note that some rifts, such as the Baikal or Basin and Range do not fit in either end member, but are combinations of two nodes. So Baikal may have opened as subduction roll-back from the Japanese arc, but also from pull from the Himalayas; or The Basin and Range was probably generated by ridge subduction and orogenic collapse.

geological system (Fig. 7). Tormey et al. (2016) also proposed that geological elements like volcanoes should be considered through their geological tectonic environment, and used the Perfit and Davidson (2000) diagram (Fig. 8). These authors are revising the volcanoes thematic study for the IUCN (International Union of the Conservation of Nature) based on geological systems (Tormey et al., 2016).

1.5. Evolution of global geological frameworks at UNESCO

Both the Geoparks and the World Heritage are UNESCO programmes that deal with global geological heritage, and are in many ways the geopolitical face of geosciences. These programmes' sites have developed without a clearly adopted framework for geological heritage (Gray, 2004).

For example, the first World Heritage sites, such as the Galapagos and Yellowstone were inscribed with no clear statement of their significance in a global context. Their place in a science-based Earth system was not explored, even though one of the most fundamental tenets of the World Heritage Convention is that natural heritage should be science based (Table 1). Other sites with clear geological significance were inscribed, but not for geological reasons. Gray (2004) described the situation at that time:

> *'The IUCN has undertaken a review of the geological World Heritage Sites* (UNESCO, 2002) *and concludes that "it appears that the current system of World Heritage sites goes a long way in representing the geological history, features and processes that support life on earth". Even ignoring this biocentric view of the role of geology, an analysis of the list would lead many geologists to reach a different conclusion. Firstly, there are some sites that are of limited geological or geomorphological importance and would not appear on any geologists' list of the world's 39 most important sites. Secondly, there are several examples of mountain landscapes, karst topography and volcanoes while numerous aspects of*

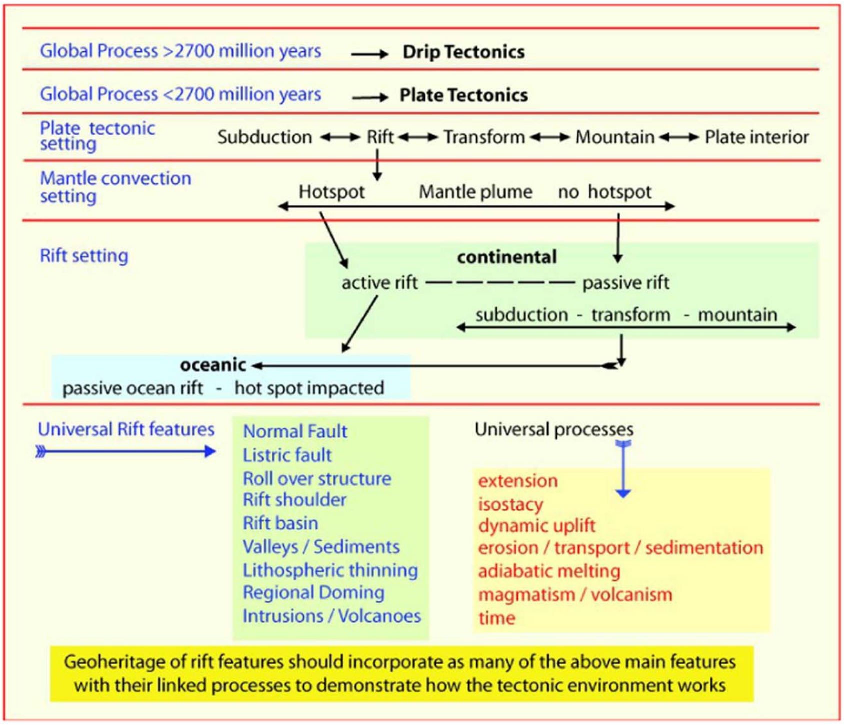


Fig. 7. Tectonic classification diagram modified from that proposed at the Geological Society of America fall meeting in 2015 (van Wyk de Vries, 2015). This diagram is concentrating in placing rift features in their global context. Thus, the lower part of the diagram deals with the features found on all rift faults. Higher in the diagram, the reader climbs to a more global context. The change over the time history of the Earth is taken into account with the possible switch from plate tectonics to drip tectonics at about 2700 Ma. Note the original diagram omitted regional doming and dynamic uplift, that are included here on a reviewer's request. Other processes could be added, but at the cost of making the diagram too complicated. This illustrates that a balance between completeness and comprehensibility is required, and sub-system boundaries are necessary to render the Earth system intelligible in detail.

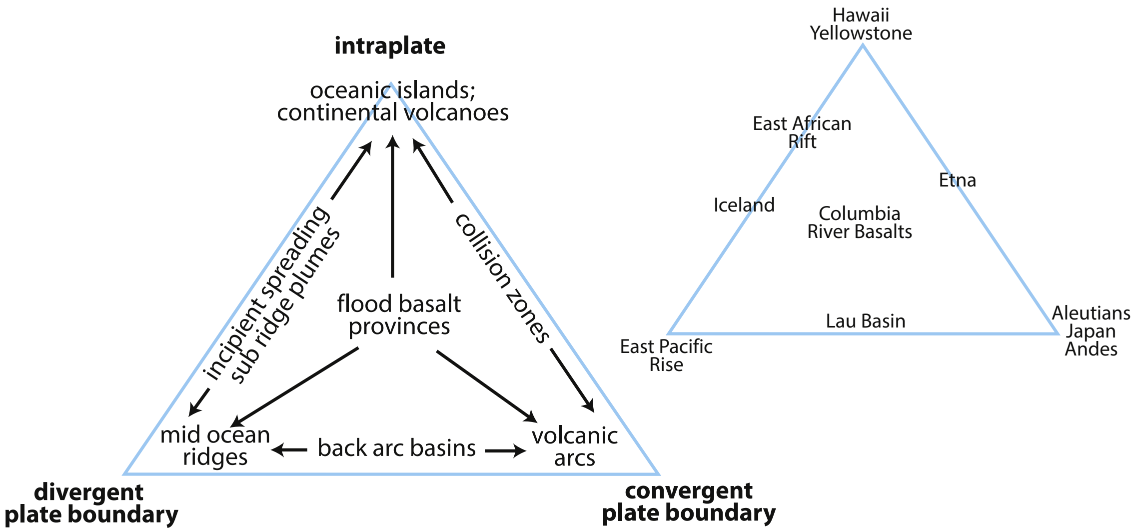


Fig. 8. The Perfit and Davidson (2000), classification framework for volcanism in relation to tectonics, in Encyclopedia of Volcanoes. This elegant triangular representation, shows the most tectonic environments (except transform ones), and provides some examples of individual areas.

> *geodiversity are absent. Thus, the list by no means adequately represents global geodiversity. Thirdly, it is clear that a review of site classifications is needed since some WHS are clearly geologically important but lack an N (i) class. For example, Uluru (Ayers Rock) in Australia is listed only as a cultural site. There are also some hidden gems. The Canadian Rocky Mountain Parks WHS, for example, contains the famous Burgess Shale Cambrian fossil site* (Coppold and Powell, 2000) (Fig. 5.4) *and Ujung Kulon National Park WHS in Indonesia, contains the remnants of the Krakatoa volcano. Greater proactivity from UNESCO, IUGS, IUCN and others would be useful in ensuring that global geodiversity is more fully represented in the list.'*
>
> (*Gray, 2004, p 185*)

This need for a more coherent approach was recognised by UNESCO, and an IUCN report responded suggesting a 13-themed framework to cover global geological heritage (Dingwall et al., 2005). It has been noted that this recognition has led to a general improvement, e.g.

> *'In a sense therefore, we can say that UNESCO and the IUCN are attempting to make the list more representative in both a chronostratigraphic and thematic sense,* i.e. *the List is aiming to represent the world's outstanding geodiversity'* (Gray, 2013, p277).

However in 2014, the UNESCO World Heritage committee made a request for the geological criterion of World Heritage to be reviewed, the 13 proposed themes to be refined and the Outstanding Universal Value threshold to be articulated (Table 3, UNESCO Decision: 38 COM 8B.11). Thus, from the UNESCO committee, itself, there is a request to improve on the global framework. We note that Gray (2004) called for there to be more proactivity from the International Union of Geological Sciences (IUGS), amongst others, in this matter. It is clearly up to the geoscience community to ensure that any global framework used is fully representative of the Earth system.

The origin for this lack of scientific base within the World Heritage system is most probably due to the lack of outreach from the geoscience community especially from the 1970s to 1990s, and is something that requires a certain amount of effort to set right. The first review of a global framework of geological heritage from within the World Heritage organisation, thematic study of Dingwall et al. (2005), came forty years after the beginning of Natural World Heritage.

The Dingwall et al. (2005) document provides a few pages of geological description and the thirteen-class global framework proposed is thematic and phenomenological, based on a mix of features: 'fossil sites, karst, glaciers and ice caps', and concepts 'ice ages', and processes 'coastal development, mountain systems'. In this study, the Earth is not presented as a system, nor is there an attempt to link different features. However, the study does indicate that the:

> *'Assessment framework for this criterion [viii geology] is global, reflecting both the global distribution of geomorphological features and the world-wide perspective required to encompass the representation of the 4.6 billion years of Earth History, address the evolution of life on Earth as well as the changes in the geography of the planet'* (Dingwall et al., 2005, p 41).

This implies that the authors consider that a global framework is necessary, although the statement does not include mention of the geological processes, which are part of the geological criterion for UNESCO World Heritage (Table 1).

There have subsequently been several more detailed thematic studies from the IUCN, such as for volcanoes (Wood, 2009), karst systems (Williams, 2008) and desert systems (Goudie and Seely, 2011). These, as noted by Gray (2013), attempt to make progress in the representation of global geodiversity on the World Heritage List, although they are still not integrated into a coherent global framework. Wood (2009) considered that a full classification scheme was beyond his study's scope (Wood, 2009, p. 19), while Williams (2008) suggested that karst systems should be placed in their geographic and geological context, but did not take this idea further. Goudie and Seely (2011) go further than the previous studies and initially place the world's deserts in their plate tectonic context. Their approach is the closest to a global framework and our proposed framework fits best with the direction that these authors are following, and which Gray (2013) also suggests should be taken.

The above IUCN thematic reports are internal, non peer-reviewed reports, and there is a need for greater involvement of the geoscience community with peer-reviewed studies, and much wider discussion within the geoscience community to guide institutions like UNESCO and the IUCN to strengthen the geological criterion.

The earlier lack of geoscience community input has been partly redressed by work such as Brocx and Semeniuk (2007), Gray (2004, 2013), and Brilha (2016). Geoheritage sessions have begun to appear in international meetings, the largest being at the European Geophysical Union Meeting at Vienna (2012 onwards) and at the International Association of Geomorphologists (e.g. Paris 2014, New Delhi 2017), or Cities on Volcanoes 9 in 2016.

Specialist meetings, such as the Global Geopark conferences, ProGEO, VOLCANPARK, also push for geoheritage within the geoscience community. However, so far at meetings such as the Geological Society of America, or the American Geophysical Union (AGU) the presence has been minimal, and awareness needs to be raised within the community, one way is through 'geosystem services'.

To assess the value of nature to humanity and to understand its use and protection requires the concept of 'ecosystem services' to be developed. The equivalent concept of 'geosystem services' has been fully described by Gray (2013). Geosystem services underpin the ecosystem services, as geology is the foundation for the evolution and maintenance of life on Earth. This relationship has often been overlooked and there is an ongoing campaign by geoheritage commissions such as that of the International Union of Geological Sciences, Or ProGEO (European association for the conservation of the geological heritage), for a correct inclusion of the importance of geosystem services in the recent Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) global consultation on behalf of the IUCN (International Union for the Conservation of Nature). The framework proposed here would be an excellent tool for describing the geosystem interrelationships with ecosystem services.

2. The global geological framework

The framework of global geology needs to contain all spheres of the Earth from the core to the exosphere (outer part of atmosphere), and must include extra-terrestrial inputs (such as energy from the sun, cosmic particles and solid particles). The framework must include some spheres that exist within one or more spheres, such as the magnetosphere and the biosphere. For each sphere, the framework must include the most important features related to the environments and processes that operate within and between them. These elements are set out in Table 2**,** which includes a non-exclusive list of the main parts of the system, and the processes, all of which need to be included.

Such an inclusive classification needs to be presented in a list or table form to be sure of containing all the elements, although the simple list of Table 1 is not enough, because it does not show the connections and interactions. To show these a more connected table is required that is developed through Tables 2, 3 and 4A, 4B. Such a table can be likened to the Periodic Table of Elements, which is more than a list, as it also describes the systematic arrangement of elements related to their atomic number.

Table 3
The basic framework for global tectonics and geological environments, presented and discussed informally at the American Geophysical Union fall meeting in 2016.

Tectonic environment	Stable	Divergent	Convergent	Transverse
Lithosphere environment				
OCEANIC	Abyssal plain	Mid ocean ridge	Oceanic subduction arc (+ obduction)	Oceanic transform
OCEANIC-CONTINETAL MARGIN	Passive margin	Extensional margin	Continental subduction (+ obduction)	Coastal transform
CONTINENTAL	Craton/ shield Continental interior	Continental rift	Orogenic mountain belt	Strike-slip zone
Earth system interactions, Environments and processes	Boyancy Mantle Plume - Oceanic Subduction - Lithosperic Subduction - dynamic support/underplating Ocean–cryosphere–atmosphere *Surface processes* *Biosphere - anthroposphere interactions*			

At the same time, on one hand, such a representation is not necessarily the best way, nor the only way, to communicate relationships and the working of the system, so schematic diagrams and systems diagrams need to be added to illustrate and develop the workings (for a description of such systems diagrams refer to Hugget, 1985. On the other hand, these schematics alone, due to their abstraction, are not capable of setting out the whole system, so a combination is needed, which includes the basic table of information. So to continue the analogy with the periodic table, this cannot show all the physical-chemical working of the elements (e.g. radioactive decay, molecules, nor sub-atomic particles) and other systems descriptions are needed as well.

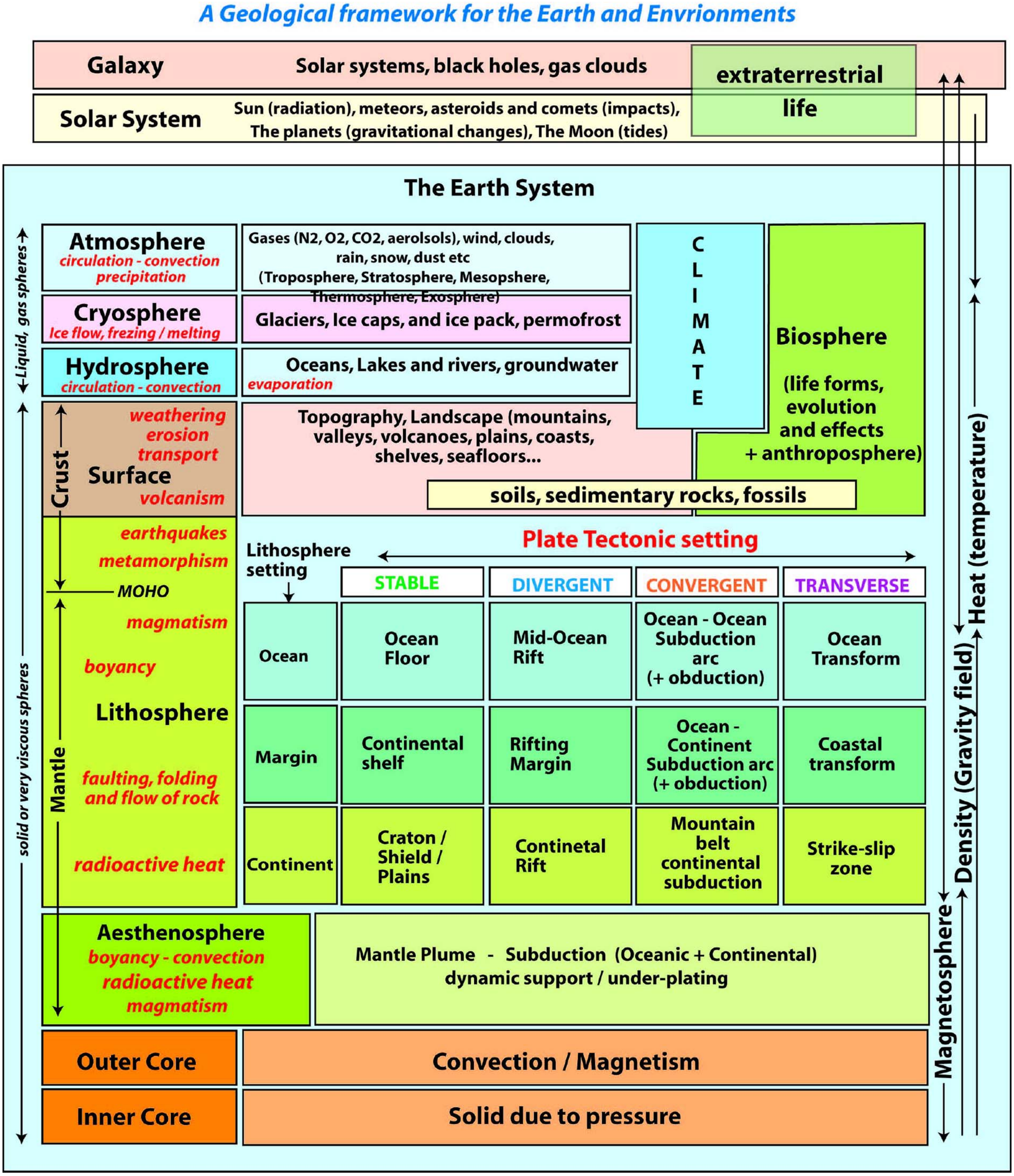
Thus, the global framework must contain all the features of the

Table 2
The list of all features and processes to be included in the whole Earth geological system.

Elements	Features	Processes
The extraterrestrial system		
Galaxy	Stars, black holes, gas clouds, the Sun, planets, the Moon	radiation and cosmic particles, gravity and electromagnetic effects
Solar system		Asteroids, meteorites, comets cosmic dust. Tides
Exo biosphere?		External life?
The Earth system		
Gravity field	All density effects	Capture of extraterrestrial objects (impacts), holding to Earth of atmo- and hydrosphere. Weather Erosion and transport, plumes and subduction, rise of magma.
Magnetosphere	Aurora Borealis, north and south	Preservation of atmosphere, protection from radiation…
Heat field	Convection, state of matter (solid vs liquid vs gas)	(partial) Melting, solidification, flow and fracture. Ocean and atmosphere circulation, Lithosphere deformation, asthenosphere circulation
Atmosphere, exosphere, stratosphere, mesosphere	Climate, weather, life supporting environment	Circulation, convection, atmospheric chemistry and physics… erosion and transport.
Cryosphere/hydrosphere	Oceans, lakes rivers, groundwater, glaciers, ice sheets, sea ice, permafrost.	Circulation, convection, water chemistry and physics… erosion and transport.
Biosphere	Ecosystems, Flora, fauna (including humans and anthrophosphere)	Ecosystem interactions, environmental changes evolution.
Surface	Topography, landscape, soils (surface + biosphere + hydrosphere),	Uplift, sinking, eruption, lateral movement, weathering, erosion, transport, deposition
Lithosphere	Lithosphere setting (Oceanic, Marginal, Continental) Crust, Mantle, Igneous (volcanoes), metamorphic and sedimentary rocks, Earthquakes	surface processes (as above), sedimentary processes, diagenesis, metamorphism, deformation, igneous processes. Subduction, delamination, obduction
Asthenosphere	Plume (Hot Spot), convection, advection and flow, magmas	Convection and advection, partial melting convection, conduction, electromagnetic field
Outer and inner core	Dense NI-Fe, electromagnetic field	

Table 4A

The basic framework for global tectonics and geological environments cast into the whole Earth system, and extending into the solar system, out to the galaxy.



A Geological framework for the Earth and Envrionments

Galaxy – Solar systems, black holes, gas clouds

Solar System – Sun (radiation), meteors, asteroids and comets (impacts), The planets (gravitational changes), The Moon (tides)

extraterrestrial life

The Earth System

Atmosphere circulation - convection precipitation	Gases (N2, O2, CO2, aerolsols), wind, clouds, rain, snow, dust etc (Troposphere, Stratosphere, Mesosphere, Thermosphere, Exosphere)	CLIMATE
Cryosphere Ice flow, frezing / melting	Glaciers, Ice caps, and ice pack, permofrost	CLIMATE
Hydrosphere circulation - convection	Oceans, Lakes and rivers, groundwater evaporation	CLIMATE
Crust – **Surface** weathering erosion transport volcanism	Topography, Landscape (mountains, valleys, volcanoes, plains, coasts, shelves, seafloors...) soils, sedimentary rocks, fossils	**Biosphere** (life forms, evolution and effects + anthroposphere)

Plate Tectonic setting

Lithosphere earthquakes, metamorphism, MOHO, magmatism, boyancy, faulting, folding and flow of rock, radioactive heat	Lithosphere setting	STABLE	DIVERGENT	CONVERGENT	TRANSVERSE
	Ocean	Ocean Floor	Mid-Ocean Rift	Ocean - Ocean Subduction arc (+ obduction)	Ocean Transform
	Margin	Continental shelf	Rifting Margin	Ocean - Continent Subduction arc (+ obduction)	Coastal transform
	Continent	Craton / Shield / Plains	Continetal Rift	Mountain belt continental subduction	Strike-slip zone

Aesthenosphere – boyancy - convection, radioactive heat, magmatism – Mantle Plume - Subduction (Oceanic + Continental) dynamic support / under-plating

Outer Core – Convection / Magnetism

Inner Core – Solid due to pressure

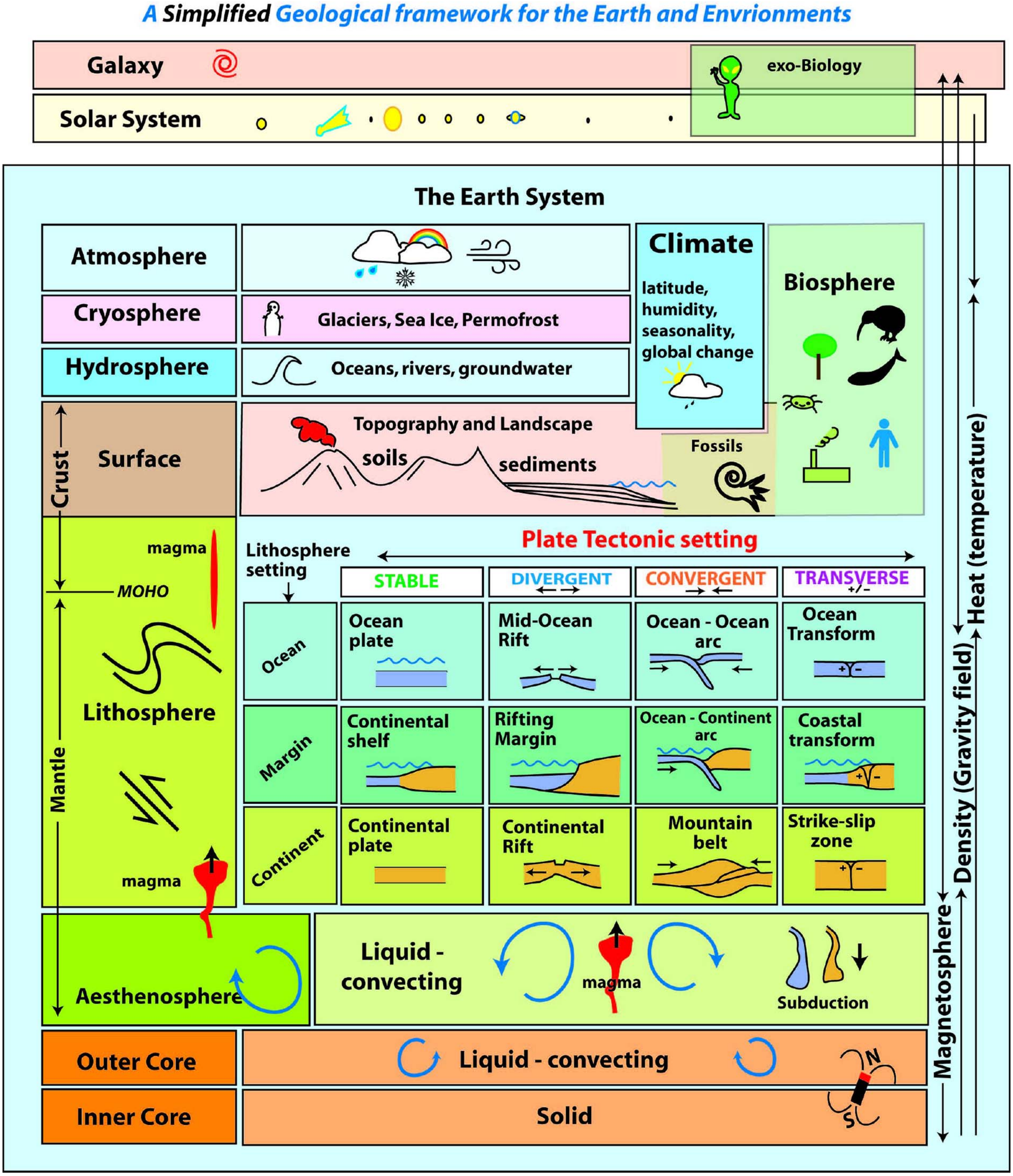
whole Earth system (Table 2), and also show how these elements are related and interact through the processes that operate in the Earth. This representation must also be useful to both specialist and non-specialist users, to allow for efficient communication of ideas and concepts, and to demonstrate how parts of the Earth system work.

To use an example for a small part of the Earth system, Merle's (2011) simplified rift classification provides a reductive graphical description of a set of features, phenomena and processes in a plate tectonic context. It is a sparse and abstracted systems diagram (Fig. 6). It has the advantage of being simple and conveying a simplified message. To do this it has defined limits (only rifts), although some outside elements (hot spot, mountain range) are included. It is, however, limited by being highly simplified, and many interactions with the rest of the system are not included. This type of diagram is not possible for the whole Earth because of the complexity of the entire system (e.g. Sparks, 1983). This is nicely illustrated by the global system for anthropogenic activities described by Forrester (1971) and reproduced by Hugget (1985), which is complete, but difficult to navigate round.

There are examples of other types of diagram that describe parts of the Earth system, such as the Perfit and Davidson (2000) tectonic setting diagram for volcanism (Fig. 8), also used in Tormey et al. (2016).

The framework can thus be cast in different ways, and we suggest

Table 4B
The simplified and pictogram adapted basic framework for global tectonics and geological environments, cast into the whole Earth system, and extending into the Solar system, and galaxy.



that combining table, schematic and system flow diagrams is best.

1. Table form

A table can show different tectonic settings and lithospheric settings, set in the whole Earth system. A first example is based on a general list of features and processes (Table 2), and is given in Table 3. This starts by setting out and defining the tectonic environment (Stable, Collision, Divergent, Transform) and the lithospheric setting (Oceanic, Marginal, Continental). Below in the table are buoyancy and convection processes of the asthenosphere, including lithosphere - asthenosphere interactions, such as delamination (subduction included). In this draft, other parts of the Earth system were drawn up below this, so that the interactions with the hydrosphere-atmosphere-biosphere etc. could be included. The core is also placed at the base of the table. This first table was prepared after the International Lithosphere Program meeting in September 2016 and passed around for discussion at the AGU 2016 fall meeting.

A second version has been elaborated following discussion of the first at the AGU 2016. It was noted that the original one had the drawback of not depicting the global system in a logical order (from inside to outside, and for missing important areas, such as external influences). Table 4A shows this improved table that provides a larger framework, now starting, at its base, with the Earth's core, and proceeding upwards and progressively outwards to the Earth's surface, and then through the outer spheres to include the solar system and galaxy at the top. While writing this we found a remarkably similar framework from 'Earth Science and Society' (National Research Council, 1995). This is sightly different in that it is constructed to depict time scales and research areas, and this shows that the basic framework has the potential for adaptation and being used in many different ways.

The framework can thus include most of the possible interactions and influences into the Earth system. However, not all environments and features can be placed into this, for want of space, so that each box can be considered as a link to an expanded system, or framework for more specific elements. For example a karst system could be drawn up in relation to its local environment (this fits into the table with sedimentary rocks, and hydrosphere/atmosphere), while the geological history of the karst system will be one dominated by limestone deposition/precipitation in a shallow marine setting, probably on a stable continental shelf, or continental interior. Subsequent orogeny may bring the limestones into a new tectonic environment, allowing the development of the particular conditions to promote karst formation. (Below we give the example of some Serbian karst in a World Heritage site that is set in the context of the Dinarides mountain system and the African-Eurasian continental collision).

This example shows that a site's environment may lie in more than one box. This is because a site receives influences from many parts of the whole Earth system and may change over time. For example, a site situated in a stable continental setting at present may have been formed in another setting. Also the geological environment can have its own lithospheric tectonic setting, but also a surface environment setting, and influences from the hydrosphere, atmosphere and the asthenosphere. This is clearly shown in the placement of desert sites in different tectonic settings by Goudie and Seely (2011): desert is a surface environment (climatic) setting, but which depends and is influenced by its tectonic setting.

The table can very easily become complicated, even for the trained eye, and an attempt to simplify it and to make it more visual, and accessible to a non-expert readership is given in Table 4B. This also uses imagery to convey the environments and features. To find out how successful this diagram is at communicating to a wider audience, we need to do a survey of a broad spectrum of people. This will form a subsequent part of this work; here we have to content ourselves with a first presentation that can be discussed amongst the Earth Science community.

2. Physical sketch form

An example for this is given in Fig. 9, where a cross-section of the Earth in cartoon form depicts the Earth system. The Foulger (2010) example in Fig. 5 is another example, as are the more restricted slices in Figs. 1 and 3. This formulation has the advantage of being highly visual, and is probably the most understandable form of showing the Earth system for outreach purposes. However, the sketch form has drawbacks. Firstly, not all elements can be drawn to scale, and not every element or process can be depicted. With this, a more localised sketch can also be provided and linked to the larger one. An on-line version could get over this by allowing different levels to be seen at different magnifications.

Another drawback is that a certain amount of abstraction has to be provided in such a diagram, and it has to be remembered that it is also an interpretation. For example, we do not know (yet) how, or if, plumes rise from the core – mantle boundary, or what is the actual destiny of all the subducted oceanic and delaminated lithosphere, but these features are shown in the cartoon. What is shown is almost an 'artists impression', or perhaps the 'scientists impression'.

The sketch diagram has the advantage of encapsulating ideas, and many geological text books and websites contain similar ones. For example, in Fig. 5 (from Foulger, 2010's Fig. 5) and there is a representation of the different concepts of a plume-dominated and plate-

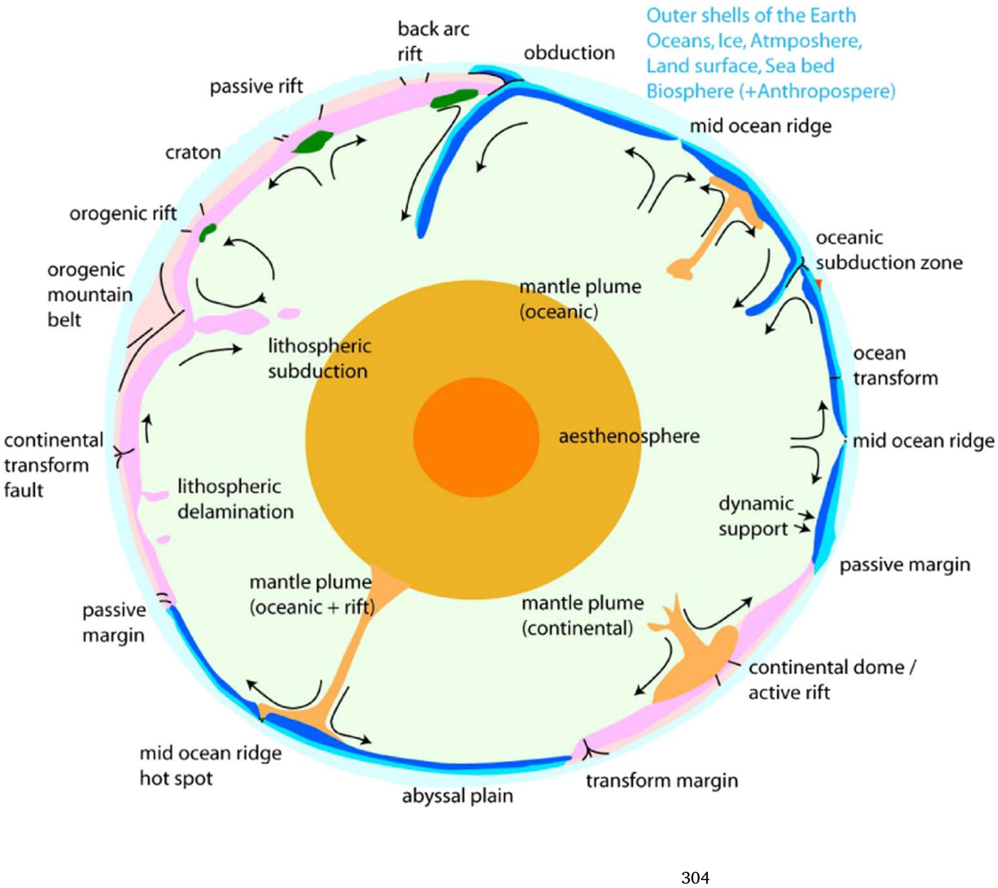


Fig. 9. Sketch of the Earth: this is a simplified and schematic cross section through the globe. It shows hows an abstracted and simplified impression of global processes in plate tectonics and mantle processes. The diagram has the advantage of being immediately visually informative, but also has the drawback of being interpretative and abstracted. Also there is the scale problem of describing the thin lithosphere, crust, surface and outer spheres. This is like the diagram in Fig. 6, but is more inclusive of Earth processes.

dominated Earth system, and many similar ones can be found in the literature (see examples in Figs. 1 to 4).

3. Systems diagram form

The third way of presenting the Earth system is by a systems diagram. Examples are shown in Fig. 10. The first one is an anthropic-centred world model, in which the geological system is included, but not developed. The second is a system for a monogenetic volcano, which concentrates on this subsystem for the Earth's geological system.

This type of diagram is less clear perhaps to the general public, but gives more ability to explore the links in the system, as abstracted elements. It also allows us to see how the table and the diagram elements work and if there are any other links not shown.

Systems and system diagrams are frequently used in geosciences, so often that we are sometimes not aware that we are making them (Dury, 1981; Strahler, 1963; Strahler and Strahler, 1973). Dury's definition is given here:

> *'A system is a structured set of objects (that is components), or a structured set of attributes (characteristics) or a structured set of objects and attributes combined together'* (Dury, 1981, p. 4).

Systems can be drawn for different parts of the whole system. The examples in Fig. 10 show how systems can be complex, and describe either very large systems, such as how all humanity works (Fig. 10A) or more restricted systems, such as a single monogenetic system (Fig. 10B). This latter example takes the restricted system with melting in the Earth's mantle as a starting point through the processes related to the production of monogenetic scoria cones, or maars, and ends with the interface with the external environment. The role of ground water is included to show the two evolutionary paths of a dry magmatic eruption and a wet, hydromagmatic eruption. The system ends with the post eruption environment. Rectangular boxes give properties of the system, diamonds give processes, and rounded boxes are events, or actions. Out of boxes are listed some of the consequences and the landforms relating monogenetic volcanism.

Such a diagram is made by listing properties, parameters and processes and then placing them in the sequence of events (which in this case is also bottom to top). Each element could be made mode complex

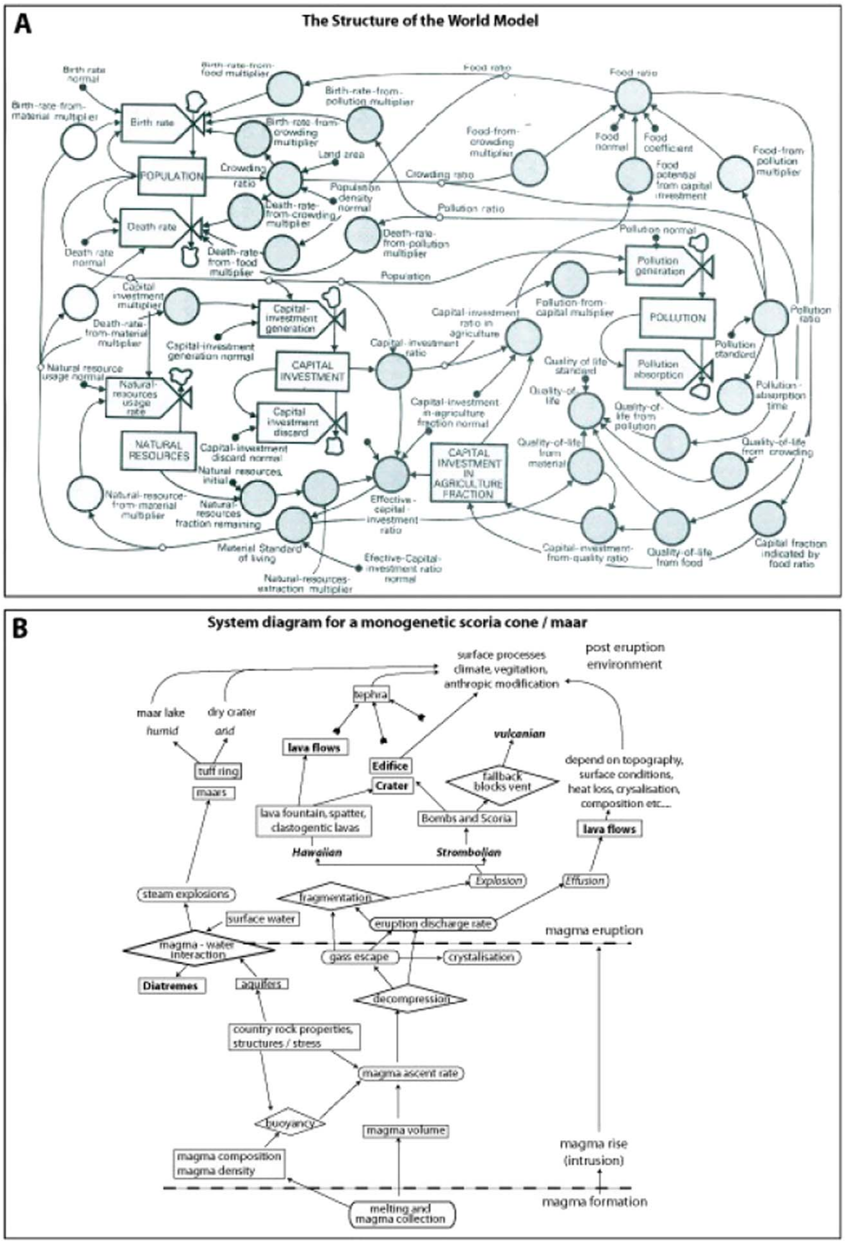


Fig. 10. Systems diagram examples. **A**. A human-focussed example, 'The Structure of the World Model' from Forrester (1971) reproduced in Hugget (1985). and **B**. One created to describe a monogenetic scoria cone or maar.

and, in cases where quantification is possible, mass, element and energy flows could also be entered.

This system diagram is one example of many that can be drawn, and each system has to be a summary of the whole system. For example in this case, the complications of magma production and the final post-eruption environment are summarized. Also, for example, inner details like fragmentation could be developed as sub-systems in themselves.

Monogenetic volcanoes and other Earth processes feed into the human world system as they are both hazards and resources, so that both the systems in Fig. 10 could conceivably be put together. However, this would result in an unwieldy and hugely complicated diagram. Thus, the art of systems diagrams is to be inclusive, synthetic to include the necessary, but to avoid getting lost in the complexity. A good example of the very practical use of systems diagrams is the rock cycle system used by Griffiths and Stokes (2008) for geomorphological characterisation of sites for engineering.

3. Casting different environments into their global context

In order to show how the three types of diagram can be used for positioning sites, we give below a number of contrasting examples and cast them into their plate tectonic setting. Some are easily done and plate tectonic features can be directly selected, but there are other parts of the Earth system where it is necessary to work through their local environment first in order to reach out to the broader context. Sometimes the links are not obvious at first, but when they are found and established they can potentially give each site much more meaning.

The first example is a very broad region, the Pannonian Basin and its surrounding mountain belts, chosen to show how a whole region can be described through the framework. This is followed by the much more compact site of the Chaîne des Puys – Limagne fault, and the Dallol area of the Afar rift. This allows us to show how sites with similar tectonic settings can be contrasted (Iceland is also considered as a third).

Following these, we look at the oceanic convergent sites of the Aeolian Islands and Kamchatka. Eight other examples are then taken as listed below:

1. Þingvellir – chosen as it is inscribed on the World Heritage List as a cultural site, which misses its obvious geological qualities.
2. Grand Canyon – A site well known for the physiography and the demonstration of geological time in a stable area, but not well know for its geodynamic origin through lithospheric delamination.
3. Mistaken Point – A fossil site, which can be further appreciated as a record of present and past geological environments.
4. Lut desert - A desert site, inscribed on the World Heritage List for geological values of desert landforms, which also tells a story of lateral movement related to continental collision.
5. Škocjan Caves Karst – A small karst site in the Dinarides mountains. Its geodynamic significance can be understood in the evolution of the Pannonian basin and surrounding regions used in the first

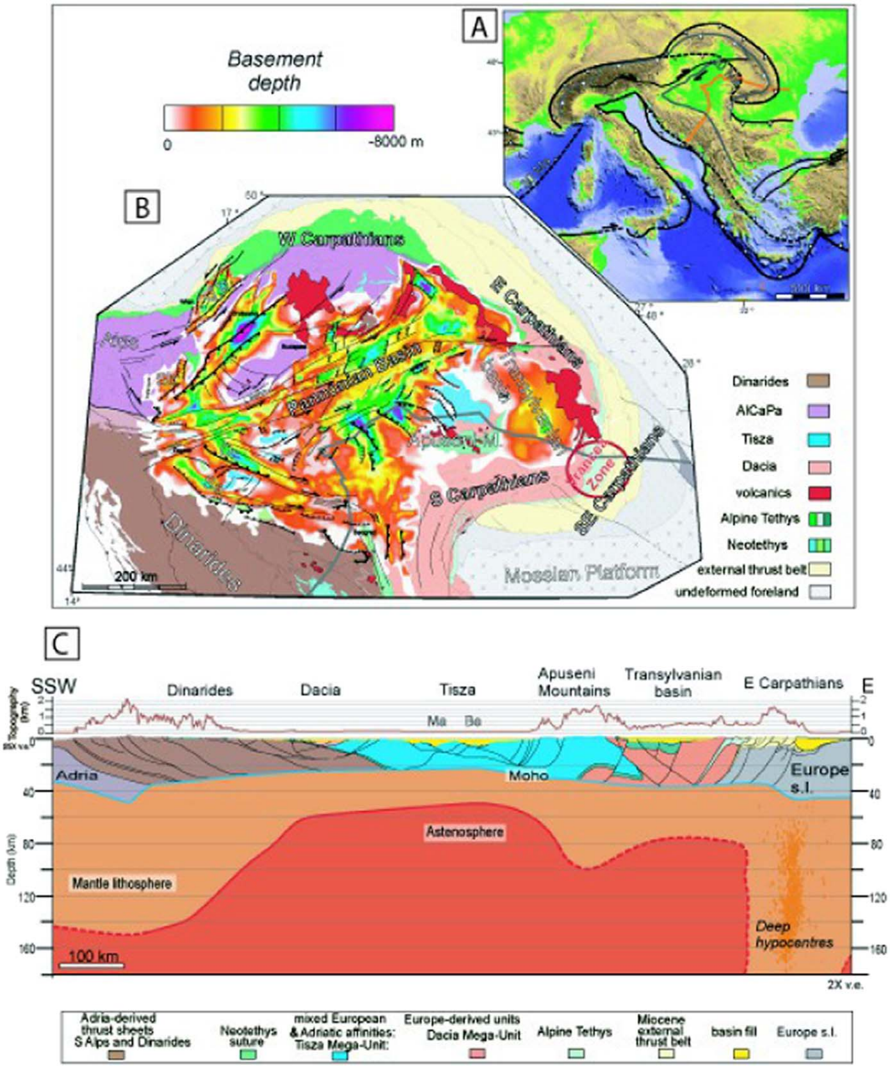


Fig. 11. The Pannonian basin and its geodynamic context in a technical description. **A.** The setting in the African – European convergence, where the basin is part of the broad plate boundary. **B.** Detailed map of the basin and surrounding collisional belts of the Dinarides and Carpathians (and Eastern Alps), with also the ongoing indentation of Adria coming from the south west. **C.** Cross-section of the area to 180 km depth along the line shown in (**A**). This shows the thickened Dinaride lithosphere and the upwelled asthenosphere under the Pannonian, related to the Miocene divergence. Lithosphere thickens under the Apuseni mountains, and then plunges in the Vrancea zone below the Focsani basin.

example. This is an example of a site that might not be at first appreciated for its broader context, but which gains in significance once this has been developed (See also Fig. 20).

6. The Waddon Sea – An example of a coastal environment on a stable continental margin, that owes its existence to the underlying geodynamic context of subsidence late in rifting (Kooi et al., 1991; Kiden, 1995; Vink et al., 2007)
7. Kvarken and the Swedish High Coast – this site in a 'stable' continental interior is interesting as it shows the interaction with climate, (glaciation and de-glaciation), surface processes (moraines) and lithospheric and asthenospheric rheology.
8. The Vredefort Dome – We have chosen the Vredefort dome as an example of an extra-terrestrial influence on Earth processes.
9. Vatnajökull National Park – We come to this example in the final discussion, to show how the geological framework table can be melded with other sketch and system diagram types of representation to give a holistic, and accessible presentation of the geological environment of one area.

This large selection covers a broad range of sites from extensive geological provinces, to small locations displaying one geological feature (e.g. karst, or glacial rebound). In each case the positioning of the site in its geological framework is indicated, and then methods of using the framework in conjunction with sketches and system diagrams is developed in the final part of the paper.

3.1. Pannonian basin and the Carpathian-Dinarides Mountains

The Pannonian basin is surrounded on all sides by mountain chains, and it forms a single geographic entity with great geological and topographic diversity. We start with this example, because of its large scale and complexity, which is shown with a technical description in Fig. 11, and then show how it can be discussed with a popular description in a broader, less technical way using the global geological framework in Fig. 12.

3.1.1. Technical description

The Pannonian's surrounding mountain chains have developed at different times, coming together to produce the present day basin. First, to the SW, the Dinarides Mountains formed in response to the Triassic opening and the subsequent Cretaceous - Paleogene closure of the Neotethys Ocean that was situated between European- and Adriatic-derived continental units (Dimitrijević, 1997; Karamata, 2006; Schmid et al., 2008; Seghedi et al., 2005). Then, the Carpathian Mountains formed in response to the Jurassic opening and subsequent Cretaceous - Miocene closure of a branch of the alpine Tethys Ocean and its adjacent passive continental margins (e.g., Săndulescu, 1988; Schmid et al., 2008; Seghedi et al., 2011). The subsequent uplift of the Alpine - Dinarides mountain chains and their eastward prolongation has separated the Paratethys marine, brackish and lacustrine domain that evolved in a partly endemic and endorheic system starting with Late Eocene - Oligocene times (e.g., Krijgsman et al., 2010; Rögl, 1999; Steininger et al., 1988).

Inside the ring of the Carpathian and Dinarides Mountains, the Pannonian Basin is a typical example of a continental back-arc basin that formed and evolved over the last 20 Ma, driven by the roll-back of an oceanic and continental slab connected with the European continent (e.g. Cloetingh et al., 2006; Horváth et al., 2015). The extensional opening of the basin was controlled by the reactivation of inherited Cretaceous suture zones and nappe stacks in the Carpathians and

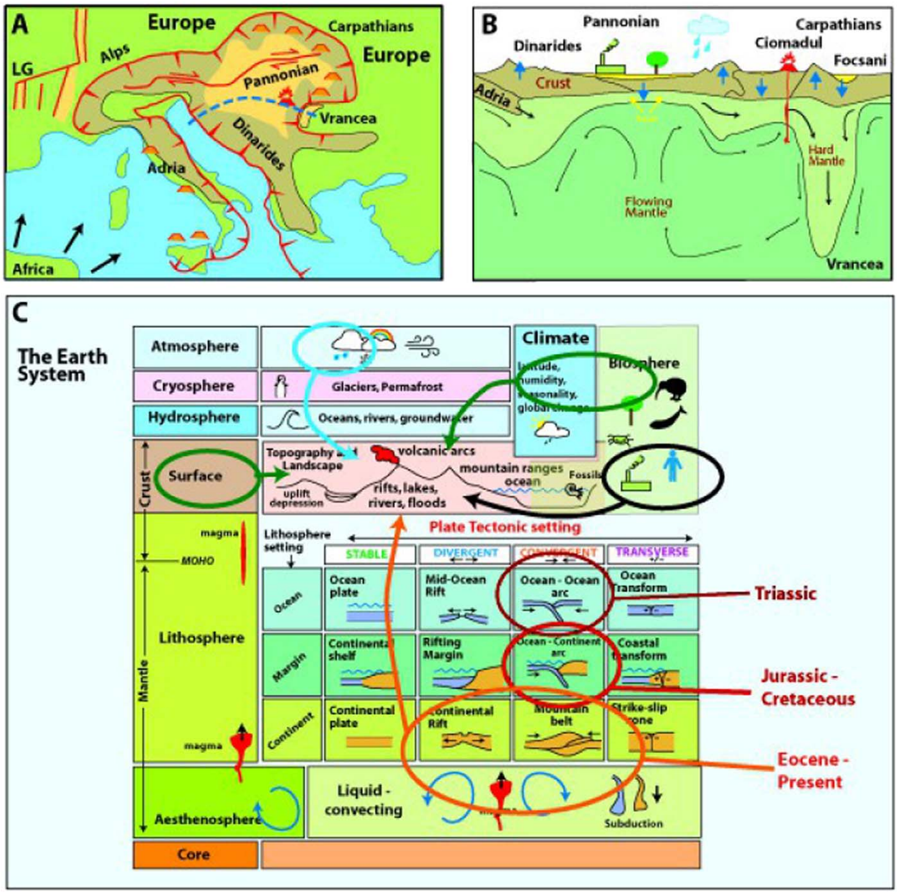


Fig. 12. The Pannonian basin and its geodynamic context in a simplified description. **A**. The main situation within the Africa – European Continent convergence. The main mountain belts are shown in brown, with their front faults in red, with spikes pointing downward the main sutres. The red strike-slip fault crossing the basin is caused by the push from the Ardiatic plate. **B**. The cross section indicated with the blue dotted line in A. This shows the flowing mantle (asthenosphere) that sinks with the Vrancea zone hard mantle (Lithosphere) and which rises under the basin delivering heat. The plunging Adria plate under the Diaride mountains is shown. Surface effects of this are the Focsani basin that sinks at the side of the Vrancea slab, the uplifting Carpathians, and the Ciomadul volcano, related to mantle flow and melting. The tectonics creates dynamic topography that interacts at the surface with the atmosphere and hydrosphere to develop the biosphere, including anthropogenic activity. Biosphere and anthroposphere also play a role in modifying the surface processes, and the surface environment. **C**. The Earth system, showing, with rough ellipses the spheres of activity in the Pannionian geological environment. First in red, is the tectonic history from ocean basin closure, with rifting and continental collision, that has gone to create the still developing topography. This interacts at the surface (ellipse) with atmosphere (blue ellipse), climate and biosphere (dark green ellipse) and the black ellipse of anthopogeny, to produce the very dynamic Pannonian environment. The conjunction of map, cross section and table allows the Pannonian system to be displayed, and the interactions described. This gives context to the system and allows any single area to be put in this context. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Dinarides Mountains through the gradual formation of a large number of Miocene detachments or low-angle normal faults creating individual sub-basins (e.g., Balázs et al., 2016; Matenco and Radivojević, 2012; Tari et al., 1999; Ustaszewski et al., 2010; van Gelder et al., 2015).

The eastward translations and rotations took place in such a way that the Carpathian shortening was entirely accommodated by the Pannonian extension until their Late Miocene collision (Fig. 11, e.g. Matenco et al., 2016).

The Miocene extensional sub-basins were ultimately buried beneath thick post-rift sediments, the overall deposition being driven by the evolution of thinned lithosphere seen in a large scale thermal anomaly presently observed beneath the Pannonian Basin (Fig. 11; e.g. Harangi and Lenkey, 2007; Szabó et al., 2004; Balázs et al., 2017).

Starting with the latest Miocene times (~7–8 Ma), indentation of the Adriatic continental unit inverted many of the former extensional structures and created a complex pattern of contractional to strike-slip strain transfer distributed across the entire Dinarides Mountains and Pannonian Basin (e.g. Bada et al., 2007; Dombrádi et al., 2010; Fodor et al., 2005; Jarosinski et al., 2011). The ongoing Adriatic indentation has been coeval with differential vertical movements that still take place in the SE Carpathians and their foreland. These movements have resulted in the deposition of 13 km of Miocene - Holocene sediments in the Focsani Basin foredeep (Fig. 11, Leever et al., 2006; Matenco et al., 2007; Tărăpoancă et al., 2003). This deformation was driven by the evolution of the high-velocity anomaly presently observed beneath the SE Carpathians and their foreland, interpreted as a remnant of the subducted slab still connected with the European continent, which is associated with the large cluster of intermediate-mantle-depth and crustal earthquakes recorded in the Vrancea seismogenic zone (e.g., Bokelmann and Rodler, 2014; Ismail-Zadeh et al., 2012; Koulakov et al., 2010; Martin and Wenzel, 2006; Oncescu and Bonjer, 1997; Ren et al., 2012).

Several geodynamic scenarios have been proposed to explain the evolution of the Vrancea slab and the associated seismicity, for instance slab detachment, delamination or lithospheric mantle thermal re-equilibration (see discussion in Ismail-Zadeh et al., 2012). Amongst these, (partial) delamination of continental mantle lithosphere (Gîrbacea and Frisch, 1998; Knapp et al., 2005) appears to explain best the post-collisional structural evolution, observed differential vertical movements, the present evolution of topography, deep geophysical observations and inferred mantle dynamics (Göğüş et al., 2016).

A system of Middle Miocene - Pliocene deltaic progradation fed by the surrounding mountain chains rapidly filled the accommodation space created by the extensional structures in the Pannonian Basin and by the subsidence recorded in the South and SE Carpathians foreland. This has led to the present-day situation of the Danube Delta interface with the Black Sea (Magyar et al., 2013; Matenco et al., 2016; Giosan et al., 2006). This pattern, with the massive influx of the large river system draining the surrounding mountain chains creates significant, rapid present day changes of the Danube and Tisza rivers in the Pannonnian Basin, driving natural hazards, such as frequent flooding and landslides (e.g., Timar et al., 2005).

The Miocene - Quaternary tectonic evolution of the Carpathians, Dinarides and Pannonian Basin was associated with significant magmatism. A complex system of Calc-alkaline to extensional magmatism was dominantly recorded in all areas until ~5 Ma, while showing a gradual migration with time along the East Carpathians margin of the system (e.g. Harangi et al., 2006; Szabó et al., 2004; Cvetković et al., 2000; Pecskay et al., 1995). This was followed by emplacement of calk-alkaline, potassium and sodic alkaline volcanics in the interior of the Carpathians, interpreted to be related to the evolution of the stratospheric thermal anomalies observed beneath the interior of the SE Carpathians and Pannonian Basin (e.g. Kovács et al., 2012).

Many of these volcanic edifices are important for geoheritage sties. For instance, the Ciomadul volcano located at the interior of the SE Carpathians (Fig. 11) formed by the release of magmas at 150 and 32 K is interpreted as resulting from deep mantle melting associated with the asthenospheric uprise beside the sinking Vrancea slab (Harangi et al., 2015a, 2015b; Göğüş et al., 2016).

As well as volcanic geoheritage, the inherited structural and geodynamic scenario controls the present-day rapid evolution of the entire river-delta system with major societal relevance in terms of natural hazards (earthquakes, flooding, landslides, active channel modifications) reflected in many heritage-related sites, such as the UNESCO Danube Delta World Heritage Biosphere Reserve (e.g. Giosan et al., 2006; Matenco et al., 2016; Radoane and Vespremeanu-Stroe, 2017).

The rapid landscape changes with massive sediment influx are relevant for understanding the current changes observed in many geoheritage sites situated along the Danube river and its tributaries. For instance, the Natural Park Iron Gates (Djakarta) located at the Danube crossing over the South Carpathians is a site of spectacular mountainous landscape with significant archaeological relevance (e.g. Bonsall et al., 2015), created by the invasion of the Danube waters from the Pannonian Basin to the Carpathians foreland (e.g. ter Borgh et al., 2014). Understanding this site requires an appreciation of the rapid changes caused by hydropower construction (Iron Gates Dam) and other societal interventions (Hein et al., 2016; Irvine et al., 2016). Such societal-relevant changes can be understood only in the context of the inherited geological evolution, and its present activity.

3.1.2. Popular description

The Pannonian basin and its surrounding mountains are part of the progressive convergence of Africa and Europe since the Triassic, with the closure of the Tethys Ocean (Fig. 12). The Pannonian Basin itself is a continental rift, produced initially by divergence over a subducting oceanic plate. It is ringed by continental collisions that have closed oceans, buckling up the old ocean sediments into the mountain ranges of the Dinarides and Carpathians. While the oceans closed by subduction, volcanic arcs, and volcanism also spread due to the hot mantle uprise in the thinned basin (Fig. 12).

Europe – Africa convergence continues today, with the Adriatic plate impacting the area and causing uplift of the Dinarides. The root of the Carpathians is also subducting in the Vrancea zone, creating both strong sinking and uplift.

The Pannonian basin fits into the framework table (Fig. 12) in several boxes. In Fig. 12C the plate tectonic setting is seen to change from oceanic in the Triassic, through the arrival of small continental plates in the Jurassic - Cretaceous and then to rifting and finally continental collision from the Eocene – Present. This evolution has contributed to the creation of the present day topography (as shown by the red arrow in Fig. 12C).

The Pannonian area contains all the possible continental margin and continental environments, as well as convergent oceanic and subduction settings, divergent rifting, *and* lithosphere downwelling and asthenospheric upwelling. Within this evolution, volcanism has created the Carpathian arc, and, tectonic inversion has resulted in relief inversion, by which the root zones of the volcanic edifices have been spectacularly exposed. Thus most continental and lithospheric setting environments are covered on the Earth system, reflecting this rich and diverse history.

We are now in the last stages of collision in most areas around the basin, and the surface is rapidly changing because none of the processes have stopped – the continents are still converging. This tectonic environment is creating a dynamic landscape, with interaction in the hydrosphere-atmosphere-biosphere (*See* Fig. 12C – *where circles of atmosphere, climate, biosphere, anthroposphere and tectonic converge to create the distinctive dynamic landscape*). Erosion of the mountains by rain and snow feeds rivers and lakes that create the environments for the biosphere, including human habitation. Both uplift and depression allow the surface processes to shift environments rapidly, and sudden changes occur during strong weather as the climate changes. Human activity modifies the river systems, critically changing the environmental balance from place to place. A prime example is the rapidly changing Danube river system, which responds to all the influences from tectonic to anthropogenic, with multiple feedbacks (e.g. Matenco et al., 2016).

3.2. *Chaîne des Puys - Limagne Rift*

The Limagne Rift is part of the Western European Rift (also called European Cenozoic Rift System), which curves around the Alps (Ziegler, 1992; Merle and Michon, 2001; Michon and Merle, 2005; Dèzes et al., 2004). This site is much smaller than the previous example, which covered a whole geological province with multiple mountain chains and basins.

The Chaîne des Puys - Limagne Fault is limited to a coherent site relating to one main geological process: continental rifting. Its location is shown in Fig. 12A, with respect to the Alps and the Pannonian area. In geodynamic terms, it can be loosely compared with the previously mentioned Focsani basin, as both areas are the product of extension related to descending continental lithosphere. The Focsani is at the early stage of rift deepening, while the Limagne is now at a later stage of rift inversion and uplift. An earlier and possibly compatible theory originated from Cloos (1932), that the rifting was related to doming, and lithospheric flexure. Such flexure has not yet been proposed for the Massif Central, but has been suggested for elsewhere (e.g. Cloetingh and Burov, 2011; Göğüş et al., 2016), and may contribute an added element to the uplift.

The Chaîne des Puys - Limagne fault comprises a representative portion of a rift margin fault (the Limagne Fault), the Limagne margin sedimentary environment, the rift shoulder of Hercynian rocks and the Chaîne des Puys monogenetic volcanoes (Figs. 13 and 14).

This landscape has developed from an orogenic collision with major igneous activity and volcanism (Hercynian), through large scale strike-slip faulting (at the end of collision), to denudation and a continental peneplain (Jurassic-Tertiary), to an orogenic foreland rift in the Eocene. The rift has been inverted in the Pliocene-Quaternary, with up to 1000 m of uplift and exhumation through rift sediment erosion (Scarth, 1966). The denudation has been controlled by lithologies, uncovering the resistant Limagne fault plane. Also resistant lavas that flowed over the fault, from 20 Ma to 9500 years ago are now sculpted into inverted relief (Jerram et al., 2017; Scarth, 1966). The history of this area, with extracted symbols from the framework table is shown in Fig. 14. This illustrates how the table can be used to show the time dimension, as also indicated for the evolution of the Pannonian basin (Fig. 12).

The site differs from the previous example, in that it is a small part of a larger geological environment. It is part of the Limagne Rift, which itself is part of the Western European Rift System, a 3000 km long tectonic feature. The Western European Rift itself is genetically and spatially associated with the Alpine Orogenic belt, which formed in the context of the collision between Africa and Europe and the closure of the Tethys Ocean.

This illustrates that one compact site can be cast into the context of a much greater geological environment, and that it can be representative of a larger system. This contextualisation allows, for example, researchers working on the area's inverted relief, or the Chaîne des Puys volcanoes, to extend the implications of their work to become relevant for the whole rift and to make connections with other sites in different geodynamic contexts.

So, for example, the relief inversion in the Eiffel, or the Czech republic, can be seen in the context of the Western European Rift, and of different vertical and denudation responses in the larger picture of the Alpine orogenic area. Another example where different environments can be connected is the role of alpine lithospheric sinking on the Limagne rift and its volcanism (e.g. Merle and Michon, 2001; Michon and Merle, 2005), or the role of Alpine – Pyrenean compression (Ziegler, 1992; Dèzes et al., 2004).

This sort of contextualisation had already been made by Scrope (1825), when he used the Limagne fault area as an example of slow landscape evolution to examine the concept of uniformitarianism. He used the site as an example that could be applied elsewhere. We do this as well, in the next section to compare the rifting in the Limagne with that of the Danakil in Ethiopia.

The Limagne area is shown with its global framework in Fig. 13. Here elements of the landscape, such as the inverted relief, can be linked to areas of the framework such as the hydrosphere, volcanism, and the broader tectonic passive and active rifting with uplift. The time dimension of this area is illustrated in Fig. 14, where the framework table is used to move through successive environments.

Other features, such as the core-generated magnetic reversals, can be linked to the lavas which record them. The volcanoes can also be linked through groundwater to anthropogenic activities such as Volvic water. While these two are slight digressions, they show that the framework can be used to show connections between geology and other elements of the Earth system.

The framework table can be used to set out a systems diagram. This is shown in Fig. 15A. Two previously established systems are also shown. A pentagonal diagram in Fig. 15B is used to show the comparison between tectonic and volcanic sites and the Chaîne des Puys in the UNESCO nomination dossier (Conseil Génerale du Puy de Dome, 2013), and 15C is a process-feature diagram to explain the interrelationships between Rifting, Volcanism and Inverted Relief (Conseil Departmental du Puy de Dome, 2015).

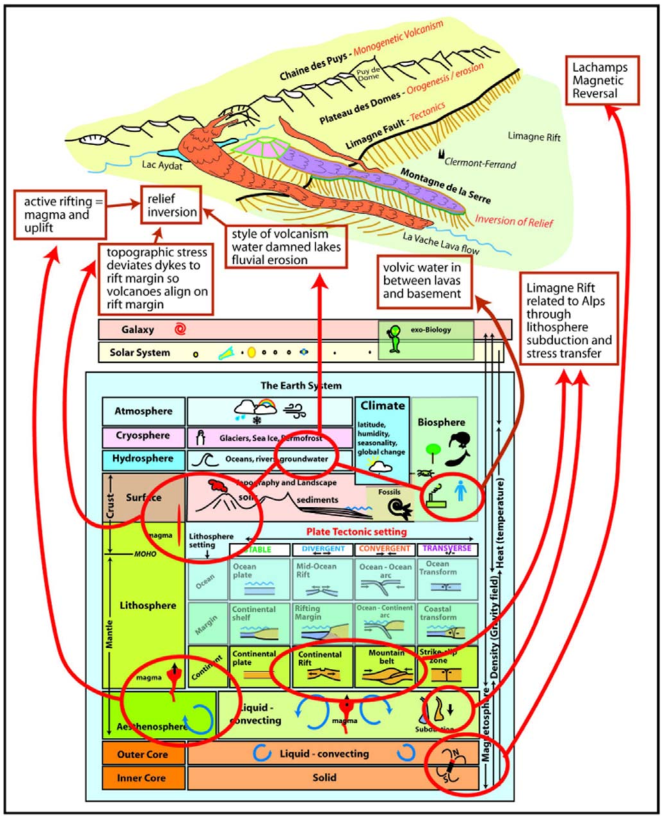


Fig. 13. Top Sketch diagram for the Chaîne des Puys – Limagne fault. This sketch was developed to explain to UNESCO ambassadors the linkage between the rift elements of fault, volcanoes and inverted relief. The lower part of the figure shows the global framework, with some of the elements circled that are relevant for the ensemble of tectonic and volcanic elements that make up the site. So the plate tectonic context of continental rift, related to a mountain belt, is one part of the context, with the development of asthenosphere up-rise related to alpine lithosphere subduction. This (and the rifting) provide magmas, that are deviated by topographic induced stresses to the rift margin, to create the Chaîne des Puys. The same uplift and erosion has created the inverted relief. Other elements are added, from systems that can be held slightly separate: the link between the core and magmas recording magnetic reversals, and the link between volcanoes, topography and water, that is exploited by the Volvic water industry.

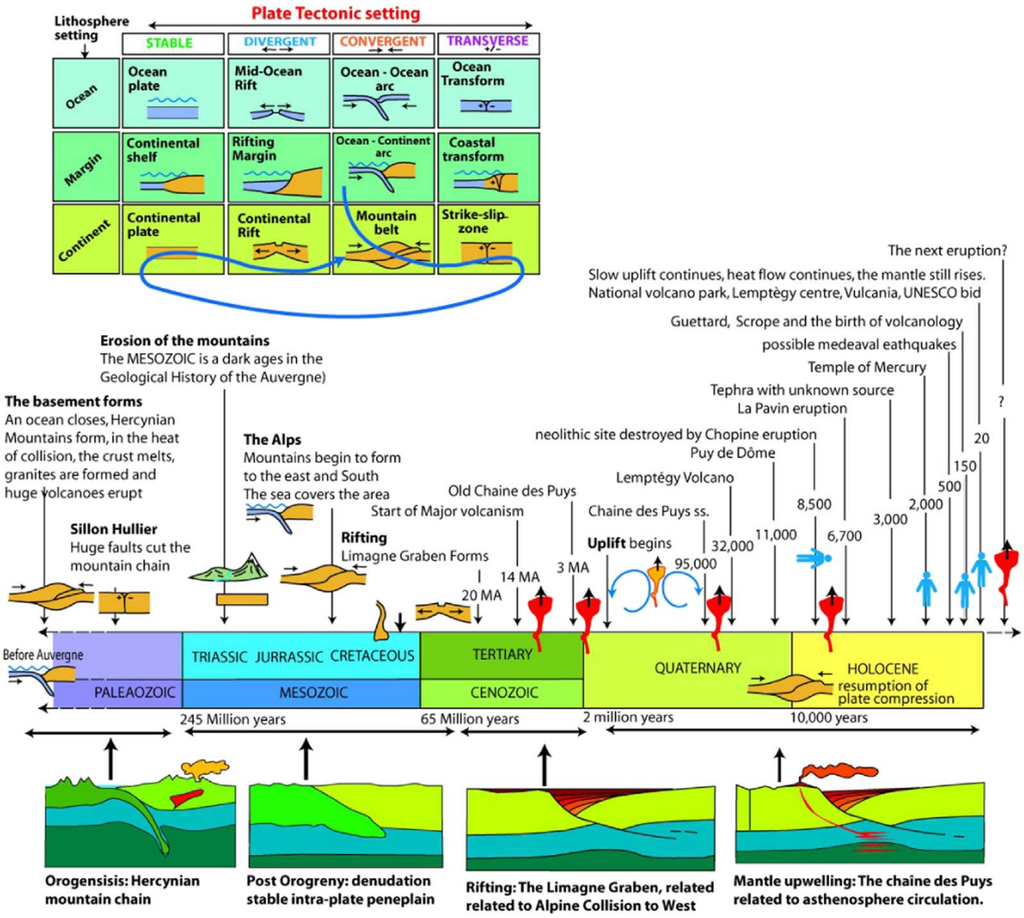


Fig. 14. Time and the framework: the history of the Chaîne des Puys – Limagne rift shown on a timeline, with the symbols from the framework added. This enables the reader to go back to the initial framework table and trace the evolution of the site, through time, by moving from environment to environment across the table. The trace of lithospheric evolution is shown on the extracted plate tectonic setting part of the table. Original diagram from Conseil Departmental du Puy de Dome (2015).

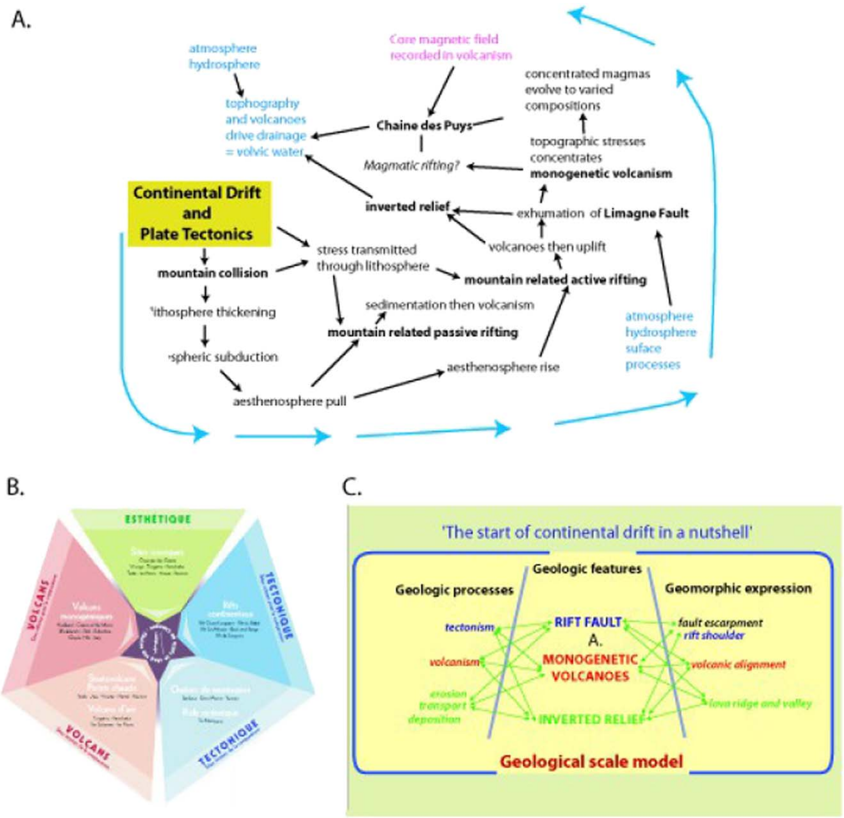


Fig. 15. Different representations of a geological system system. A. A systems diagram to describe the situation and evolution of the Chaîne des Puys - Limagne fault. **B**. The pentagon used in the first comparative analysis of 2013 for the Chaîne des Puys – Limagne Fault (Conseil Génerale du Puy de Dome, 2013). This shows the volcanic and tectonic features that are compared with other comparable sites around the world. **C**. A process diagram for, which shows the linkage between geologic processes, geologic features and their geomorphic expression (Conseil Departmental du Puy de Dome, 2015).

The global framework also allows the Limagne Fault to be compared with other rift fault sites, such as the Baikal rift faults, or rift faults in East Africa, and the Rio Grande. Each can be seen in relation to their specific environment.

For one example, Baikal is probably a similar orogenic margin rift to the Western European Rift, but there is less volcanism, possibly due to the lack of nearby orogenic lithospheric subduction. The Baikal passive rift has not been inverted into an active rift as the Limagne area has.

For another example, looking at the East African Rift, hot spot activity impinged on the continent to create uplift and volcanism before the rifting, so the sequence of events is different from the passive environment of the Limagne. This has created a different landscape where the Limagne has large amounts of relief inversion, while the East African Rift has very little. When dealing with an isolated system such as rifts or volcanism, a smaller system diagram can be sufficient, such as the Merle (2011) one in Fig. 6, for this case.

3.3. Dallol in the Danakil Depression, Ethiopia

Dallol is a salt-dominated mountain in the Danakil Depression of Ethiopia (Holwerda and Hutchinson, 1968; Beyene and Abdelsalam, 2005; Franzson et al., 2015). The area lies within the Afar rift, where crustal thinning has advanced to the point of ocean formation. The Danakil is below sea level and has been invaded by the sea at times during the last few million years. At present, the basin is divided from the Red Sea by volcanic massifs and a slightly raised rift shoulder.

Like the last example, of the Limagne, the Dallol area is representative of rifting processes. Both contain comparable elements of volcanism, tectonic faulting, sedimentation and evidence of uplift and depression. However, the combination of these and the geodynamic context are very different.

First, the geodynamic context for the Limagne is convergence and a mountain-related rift, linked to lithospheric subduction, and subsequent asthenosphere rise. Dallol's context is divergence and the Afar Plume, with a far field influence of the pull of the subducting Arabian plate below Eurasia.

These differences can be located on the global framework, and the representative blocks in it extracted to compare the two sites (Fig. 16).

Second, the combination of processes as seen through the landforms are different. The Dallol area is sinking, and deposition dominates over erosion in the rift. For the Limagne, erosion is not dominant due to regional uplift. The Dallol rift shoulder has been heavily eroded in the past (when uplift there was strong), while the Limagne has only recently been eroded. Volcanism at Dallol is rift enclosed (in fact confined at present under the salt), while in the Limagne it is located high on the rift shoulder (e.g. Maccaferri et al., 2014). Other differences, such as the climate (Afar is hyper-arid and hot, Limagne is temperate and humid), also can be displayed on the framework.

Fig. 16 provides an additional example of Vatnajökull Iceland, to show how extracted blocks from the table can form the framework to clearly differentiate sites.

3.4. Aeolian Islands and Kamchatka

These two sites are put together, as they are both volcanic areas, and listed on UNESCO's World Heritage List specifically for their volcanoes. They are both arcs related to subduction zones (Fig. 17A). The Aeolian Islands are an oceanic arc – continental margin, set in the context of the Mediterranean Sea. Kamchatka is a continental arc, related to the subduction of the Pacific Ocean. If we take just the World Heritage inscribed areas, we see that the main islands of the Aeolian arc are included, minus the urbanised areas. The undersea parts are not included. The Kamchatka site contains a series of areas, encompassing many volcanoes. The UNESCO World Heritage website (http://whc.unesco.org/) provides a description and justification of each inscription. This is very short for both regions, and in neither case is the tectonic environment mentioned. For Stromboli, the volcanoes are described as a type example of volcanic islands, and for Kamchatka they are described only in relation to their interaction with glaciers.

We note that just describing the Aeolian Islands as volcanic islands does not distinguish them from oceanic islands such as Hawai'i or the Galapagos, which are also inscribed on the World Heritage List. A much more specific framework is required to make a clear distinction between the sites and to put them in context. This can be done on the framework (Fig. 17).

We provide the context here: the Aeolian islands are a small volcanic arc that is the manifestation of a small subduction zone of Mediterranean crust under a slither of African continental crust, that of Calabria and Sicily (Fig. 17A). This small subduction zone is set in the greater context of the European-African plate boundary, which is made up of the Alpine Orogenic belt and a complex area of small oceanic basins and continental blocks. Part of the Aeolian Arc (Lipari and Volcano) are on a strike-slip fault, normal to the main arc; which may result from the subduction zone's curvature.

For Kamchatka, the volcanoes are part of a continent – ocean margin, where convergence is manifested by the subduction of Pacific oceanic crust (some of the oldest oceanic crust on Earth) below the Asian continent. The convergence is oblique, so strike-slip faults appear along the volcanic margin, and the margin is in extension due to roll-back of the subduction, creating a subduction related rift.

With Kamchatka, it is worth exploring the other aspects in for which it is inscribed, to see how they fit into the framework. This, glaciers and glacial landforms are mentioned, and these can be cast into the Cryosphere box of the framework (Fig. 17A). So there is a connection between convergent margin, magmatism, the production of volcanoes and glaciation. The glaciation itself is reduced in Kamchatka at present, due the present warm period, which is partly associated with solar radiation, but also possibly due to anthropogenic effects that could be slowing, or reversing the possible arrival of a new glacial. We might also point out that the northerly position of Kamchatka is due to the present arrangements of the continents, which is ultimately related to

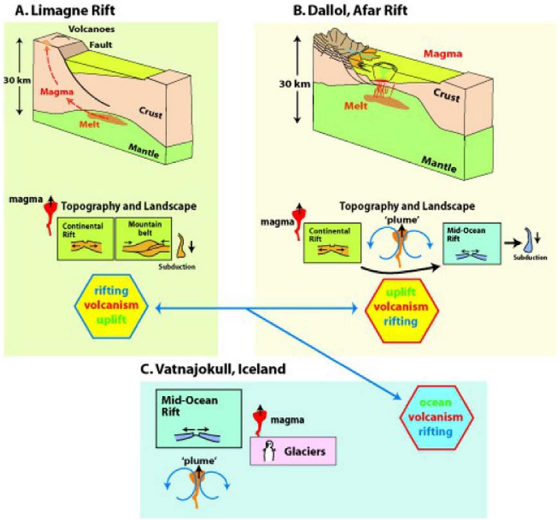
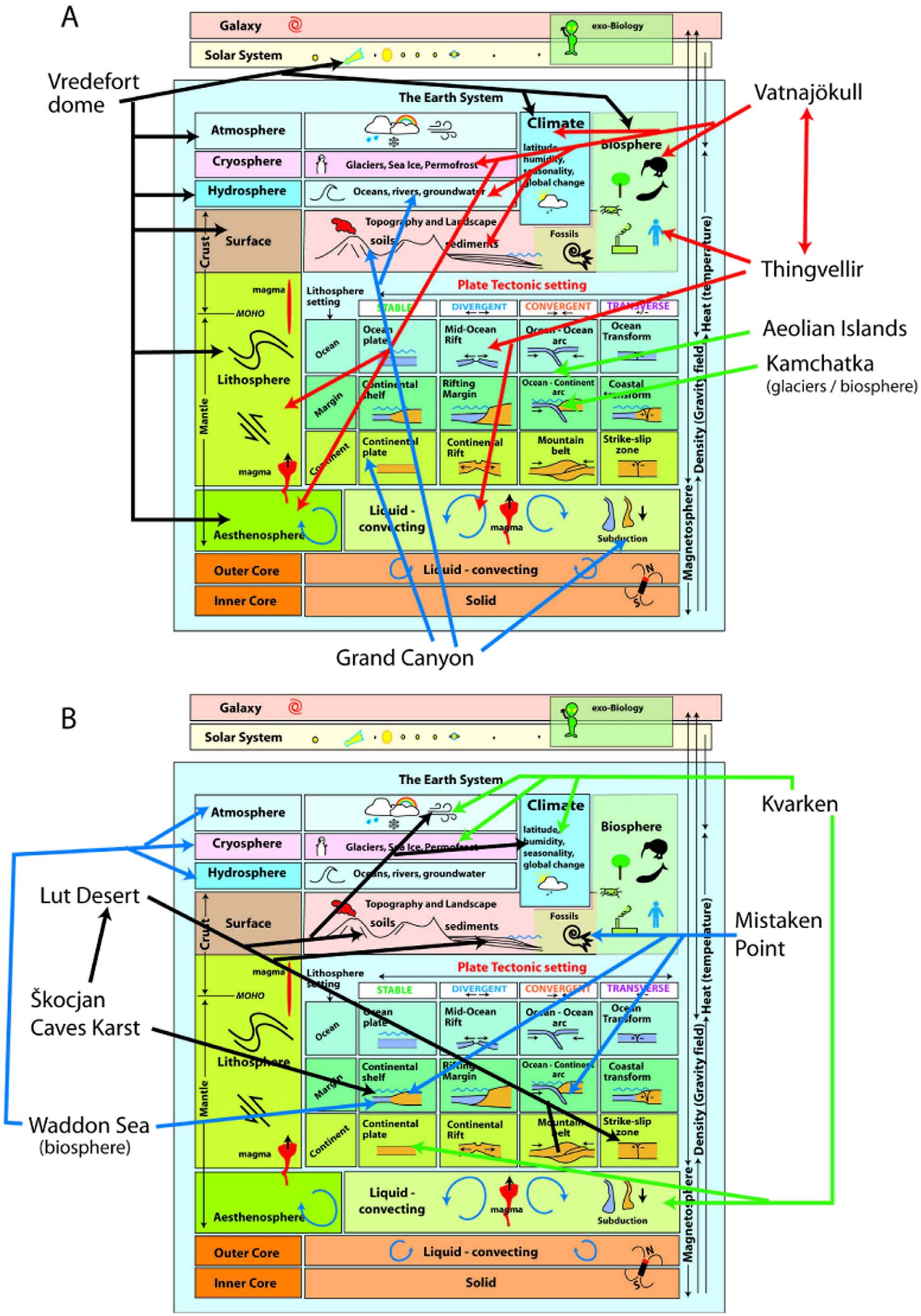


Fig. 16. A comparison between the Limagne Rift and the Dallol area of the Danakil Depression in Ethiopia and Vatnajökull in Iceland. **A.** The left side shows a block diagram of the Limagne, with bellow the extracted elements from the geological framework. **B.** The right side shows the Dallol area of the Danakil Depression, where continental rifting with plume influence is transitioning to a mid ocean ridge. The physigraphic and geological differences are linked to each sites' context and can be expressed as the contrasting sequences of rifting – volcanism – uplift (Limagne), or vice versa for the Danakil (shown in the hexagons). The geodynamic driving force for the Limagne is convergence and continental subduction, while for Dallol is hot spot and far field pull from oceanic subduction (shown with the black arrow to the subduction symbol). **C.** Vatnajökull, is on the mid-Atlantic ridge, an oceanic rift, with plume interaction. A notable difference with the other sites is the interaction between glaciers and volcanism (this is developed below).



(caption on next page)

Fig. 17. Positioning of the different sites described on the framework. The diagram is shown twice to give space of the most connections to be seen. **A.** Kamchatka and Aeolian Islands, Þingvellir, Vatnajökull, Grand Canyon, Vredefort dome. **B.** Mistaken point, Lut Desert, Škocjan Caves Karst, Waddon Sea, Kvarken and Swedish High Coast.

mantle circulation.

The large amounts of volcanism are also related to the rapid movement of the Northern Pacific plate, which itself is due to ridge push, slab pull and mantle flow. (These processes are not included in the basic framework, but could be in a more dedicated system.)

3.5. Þingvellir

Þingvellir is inscribed on the World Heritage List as a cultural property relating to the location of the Icelandic parliament that started in 930, and for evidence of 1000 years of land husbandry. The World Heritage descriptions loosely mention the rift setting. This is a geological site, as it lies on one of the branches of the Mid-Atlantic plate boundary, and contains rift faults and lava flows belonging to the mid-Atlantic rift system. These appear, for example in a Google images search, far more significant in a landscape sense than the cultural site. The geological elements are the essential backdrop for the cultural setting (Fig. 17A).

We can put the anthropogenic site into context, moving from the human into the broader geological context. The site became free for use for the parliament due to the owner being convicted of a killing and having to secede his lands. At the same time the site is located in an area with woods, water and plain, near the more settled areas of the country. Thus, the site had all the elements required for a large meeting. Importantly, these elements are created by the particular geology and biological environment, and the cultural site of Þingvellir can be set in this broader framework.

Thus the site is on the eastern divergent boundary of the N-America plate, set in a mid-oceanic ridge plate tectonic context, in an oceanic environment, with added plume input, which has increased magmatism and led to thickened crust, maintaining the area above sea level (Fig. 17). On the geological framework, this connection from mid-ocean ridge and hotspot to anthropogenic activity is shown (Fig. 17). The exact link between the rifting, which creates a depression that holds the water and shelters the trees is not developed here (due to space) and requires a more in-depth link that could be expanded within the framework and by using sketches and system diagrams.

One question that can be asked is if Þingvellir is representative of the Icelandic tectonic setting, and thus if it could be inscribed under UNESCO for the rift features as well as culture. Here, Þingvellir may fall short in that while it does contain the rift and lavas, it is otherwise not geologically diverse.

Iceland, with the hot spot and its particular maritime and cold climate setting has much more geological diversity. A larger area would be better to fully represent this geological environment. At present there is a movement to propose the Vatnajökull National park as a UNESCO World Heritage site (Baldursson, 2015; Höskuldsson, 2015). This larger area comprises many more of the features associated with the Iceland environment than Þingvellir. These are shown in Fig. 17A, and developed again in the final Figs. 18 and 19, and in the discussion below.

If Þingvellir was not included in the proposed, larger Vatnajökull site, it could at least have an underpinning of geological information, that could give it greater context, and allow visitors to more fully understand the background to the cultural features.

3.6. Grand Canyon

The Grand Canyon (Fig. 2B) is known globally and has been on the World Heritage list since 1979. It is mainly famous for the scenery of the deep canyon. The UNESCO World Heritage description of criterion (viii) descries it thus.

> *"Criterion (viii): Within park boundaries, the geologic record spans all four eras of the earth's evolutionary history, from the Precambrian to the Cenozoic. The Precambrian and Paleozoic portions of this record are particularly well exposed in canyon walls and include a rich fossil assemblage. Numerous caves shelter fossils and animal remains that extend the palaeontological record into the Pleistocene."*
>
> (UNESCO WH http://whc.unesco.org/en/list/75)

The geological context of the Grand Canyon is much more diverse than this description and can be described in the following way: the Colorado Plateau was an originally stable continental interior from the Precambrian to the Cenozoic. However, this interior became influenced by a convergent continental margin due to low-angle oceanic subduction of an oceanic rift and associated mountain building. Due to these events, the lithosphere below Colorado sank by continental lithosphere delamination leading to the plateau uplift. (e.g. Schmandt et al., 2011; Levander et al., 2011). The uplift has been accompanied by the gradual incision of the Canyon by the meandering Colorado River.

The elements and the geological succession of events can be fitted into the framework and, through this generic overview, which fits into the framework, the physical elements of the Grand Canyon, such as time, erosion styles and rates, and volcanism can be understood in their global context. For example in Fig. 17A the Grand Canyon's place in the framework is clearly very different from the rift sites such as Þingvellir, Limagne or Dallol, or from subduction sites like Kamchatka.

Using the diagram a person can simply put their finger on the differences. For example, volcanism from Vulcan's Throne, an accessory part of the Grand Canyon area, could then be understood, through the arrival of asthenosphere after delamination, heating up the lithosphere, causing magma to form and rise. This erupted and contributed to the evolution of the surface by blocking and modifying the Canyon.

In addition, the Anthropocene can be integrated by discussing the effects of dams that have changed the hydrography of the river, and affected the delta in the gulf of California. The lava dams might have had an equivalent, if smaller, effect.

3.7. Mistaken point

This is a fossil site in Canada, that contains Ediacra fauna preserved in turbiditic shales and sandstones with intercalated tephra layers. It was inscribed on the World Heritage List in 2016. The site is part of the Avalonia Terrane, included in the Appalachian Orogen, and originally may have been formed by sedimentation in part of the Pan-African Orogenic belt, or originally residing near the West African craton in the Rhodinia supercontinent (O'Brian et al., 1983; McNamara et al., 2001).

The fossil assemblage is one of the the earliest known for the Ediacran (580–560 million years), so far, and is well preserved. The assemblage and its sedimentary environment provides the setting for a geological and biosphere system in a deep sea environment, at the edge of a continent, close to a subduction zone volcanic arc. The palaeomagnetic data puts the area near the Equator at the time of deposition (McNamara et al., 2001).

This geological setting is very different from the present day one, of a stable continental shelf, with a steep erosive coast, in northern latitudes, recently covered by the Laurentian Ice Sheet, and now in an interglacial. The area is outside the zone of glacial isostatic uplift (Daly et al., 2007), and is responding to relative sea level rise with the formation of coastal cliffs, and thus a good exposure of the rocks containing the fossil assemblage.

The larger geological context for Mistaken Point, cast in the global geological framework helps increase the potential for appreciating the site, adding value by providing a narrative that can be compared with other sites (Fig. 17B).

Mistaken Point's existence can be seen through a combination of geological events and processes that deal not just with the expansion of life forms in the Cambrian, but also with the development and splitting of super-continents, continental drift, environments up to the present day and sea level rise. The present environment is both stable enough to preserve the sequences but dynamic enough to illustrate ongoing environmental changes, such as were instrumental in the development of the Cambrian life expansion.

3.8. Lut desert

The Lut desert was inscribed on the World Heritage List in 2016, most notably for its Yardangs, large ridges formed by aeolian erosion. The desert was placed in a collisional setting by Goudie and Seely (2011); more specifically the Lut basin is located along the Nyaband fault, a major strike-slip fault that relays transcurrent motion within the Zagros fold belt (Foroutan et al., 2014).

The Lut Desert is thus the product of millions of years of of transpressional tectonics and basin formation in a continental collision, were the tectonic setting has combined with the climate to produce spectacular scenery.

The desert landforms can thus be set in this generic overview (Fig. 17B), which fits into the global framework. It is part of a convergent margin, that of the greater Alpine – Himalayan convergence and more particularly of the Zagros belt collisional zone between Arabia and Asia, which is on the hinterland of the last stages of an oceanic subduction (under the Persian Gulf). All features, such as the fault and volcano, can be understood in this framework, and the geoheritage site is by this means given a broader context.

Individual features, such as the basaltic plateau, Gandom Beryan, which is an inverted relief feature originating from a small volcano on the Nayband fault, can thus also be placed into this context. This is an monogenetic volcano set in this intra-plate collisional zone, probably rooted in small scale melting in the mantle related to disturbances along the lithosphere-scale Nyband fault.

3.9. Škocjan Caves Karst

This site in Slovenia is one of the original sites for karst on the World Heritage List, inscribed in 1986. It is claimed to be where the term ‘karst’ originated, as well as other terms such as ‘doline’ (Ford and Williams, 2007). The location of the Skocjan Karst is in the Dinaride mountains that have been, since the Miocene, a site of strike-slip movement between the Adiria microplate and the Pannonian basin (Vrabec and Fodor, 2007).

Thus, the Škocjan Caves Karst is set in the same broad context as the greater Pannonian basin described above (Figs. 11 and 12), in the context of an initial stable platform in the Tethys sea, where Cretaceous limestone formed. Then the area became part of the Africa – European collision, and the Dinarides collision. Lateral escape structures have developed since the Miocene with the (ongoing) indentation of the Adrian plate.

This tectonic setting is active, and the karst can be placed in the context of a local conservative plate boundary in the broader context of continental convergence (Fig. 17B). This is set in the local climatic system for Slovenia, and the hydrogeological environment in which the karst has developed. The basic elements on the Framework in Fig. 17B are similar to those of the Lut desert (strike-slip faulting and collision) with the interactions of climate and hydrosphere, atmosphere. However, the tectonic elements in each box are connected to different surface environments. Thus Lut is arid, whereas the Škocjan Caves are more humid, and the rock types in the karst are limestone, compared with clastics and volcanics in the Lut.

3.10. The Waddon Sea

The Waddon Sea is an important biosphere environment that exists due to the geological environment in which it is set. The Waddon Sea is a coastal area that straddles the Netherlands, Germany and Denmark. The area has no major rivers, and is composed of barrier islands, mud flats, marshes and low lying inland plains. The area is at the limit of the glacial rebound from the Fennoscandian Ice sheet, and was not glaciated in the last Weichselian Maximum. The area is now responding to slow isostatic uplift, while also being affected by global rises in sea level. It is on the margins of the North Sea Basin, to the north of the Roer rift, and at present the North Sea Basin is slowly subsiding due to thermal relaxation, and inversion (Kooi et al., 1991; Vink et al., 2007; Kiden, 1995).

The Waddon Sea is therefore in a continental margin setting on the borders of a rift, which is not actively stretching at present (Fig. 17B). The context is of previous continental divergence (while the North Atlantic opened) and the development of a passive margin basin off the axis of the actual oceanic opening.

This setting provides the context for the presence of the sea (basin subsidence related to thermal relaxation and crustal warping), and in this lithospheric setting there is hydrospheric input from sea level changes, and cryospheric - lithospheric input from isostatic readjustment. This site can be contrasted with the next example, which is rapidly rising.

3.11. Kvarken and the Swedish High Coast

The Kvarken Archipelago and Swedish High coast are an area of the Baltic where high isostatic uplift is underway, related to isostatic rebound after the removal of the Fennoscandinavian Ice sheet. The site is inscribed as World Heritage for the uplift seen through the coastal features and for the glacial moraines, especially the De Geer moraines (Larsen et al., 1991; Benn and Evans, 1998).

The area's geology is well described in a special report (Breilin et al., 2004), and provides the basis for a setting that goes back 2000 million years. The first events were sedimentation in a marine environment on unknown bedrock that produced sediments that later were involved in the Svecofennian orogenic belt, an early subduction type orogen. The rocks became part of a collisional mountain range, were metamorphosed and magmas were intruded by granites and more shallow porphyritic intrusive rocks. The mountain range was denuded by 1200 Ma, and sandstones (Jotunian sandstones) where deposited. A final magmatic episode of basic dykes (a possible rift episode?) at about 1270 Ma signals the end of activity, the onset of erosion and peneplain formation and the establishment of stable continental interior conditions. Sedimentation continued, punctuated by a meteorite impact at 520 Ma (Soderfjarden impact).

Since the impact the Fennoscandian Shield has not been involved in major tectonic events; the Caledonian and the Hercynian orogenies were far from the area and the opening of the North Atlantic also did not affect the area.

With the advent of the Quaternary, the glacial episodes built ice sheets over the area, with a maximum thickness during the Weichselian. In the final, waning stages, ice flowed over the area from an ice sheet centred to the north and west.

The Kvarken area can be seen as a site based on a stable tectonic environment since 1200 Ma, and is the product of stable denudation of a Proterozoic continental collision (Fig. 17B). These elements set the framework for interaction between the stable continent and peripheral settings as the Scandinavian ice sheet grew up in response to the cold conditions in the Quaternary, but also to the presence of the Atlantic Ocean, and global circulation patterns. These allowed both precipitation to build up the ice mass (the opening of the Atlantic Ocean), and the growth of topography along the Atlantic margins, which enhanced the precipitation and guided ice flow. Thus, the Kvarken and Swedish

High Coast setting is framed not only in the context of a stable continental interior, but also related to far field rifting and ocean opening, the establishment of global oceanic circulation patters, changes in solar radiation and the development of ice flow related to topography.

While there geological elements can be clearly displayed on the geological Framework (Fig. 16B), the environmental elements would need an expansion of the diagram in the surface part of the table. In a similar way to the way we expanded the plate tectonic part of the framework, spheres (such as the hydrosphere and atmosphere) could be expanded to enable different climatic zones, for example, to be displayed.

3.12. The Vredefort Dome

This impact in South Africa occurred about 2200 Ma ago and formed a 300 km wide crater in the sedimentary Witwaterstrand basin, composed of banded ironstones, sandstones and lavas. The Dome is the central rise of the structure. This site was inscribed on the World Heritage List in 2005. The central parts of the dome are formed of greenstone-granite basement and ultramafic rocks, which are possibly part of the Proterozoic mantle raised near to the surface as a response to the impact (Tredoux et al., 1999; Lana et al., 2003). The Vredefort basement is part of the Kapvaal Craton formed in the Archean-Proterozoic, by early stage plated tectonics – subduction and rifting.

The context of the Vredefort Dome is thus a cratonic environment, stabilised after an early orogenic collision from the Archaean to the early Proterozoic. In this sense it is close to the Kvarken in geodynamic context. The impact itself is an extra-terrestrial event that caused the disruption of the lithosphere, down to mantle depths. Since the impact, the area has continued to be a stable craton, and thus shows how an area of lithosphere can remain little changed over billions of years. There has, however, been many km of erosion during this time to exhume the structure. Part of the uplift to expose the present structure is related to the opening of the Indian Ocean, so the craton has responded to far field events (Fig. 16B).

4. Discussion

The global framework provided here allows for any geological site, area or feature, of any size, to be placed into its global context. This has the advantage of giving the site a broader meaning and a significance that goes far beyond its geographical confines. The global framework is based on a systematic ordering of the main lithospheric contexts and main plate tectonic environments and on the processes operating within these, and with inner asthenosphere and core activity, as well as the outer spheres. This inclusivity and connectivity allows features to be seen outside their simple landscape nature, and to be connected to the whole Earth system processes that form them.

The framework can be used to contextualise research in geosciences, as well as to place in context natural sites for heritage, conservation, and exploitation. It can be used also as an educational and outreach tool. We envisage that the framework table could be used as a template for all sorts of discussion across disciplines and with non-scientists. It has the advantage of being a simplification of the Earth system that is all-encompassing, and thus the elements within it could be taught to, and understood by, all users. We note that the framework is simplified, but still not simple, so still requires some concentration and work to understand it. To aid this, the role of other pictorial diagrams and analogies is important.

Some similar frameworks have been developed (e.g. National Research Council, 1995), but the one proposed here is possibly the most complete, and is formulated with the aim to provide a clear picture of the Earth system, which can be used for communication within and outside the community. The framework presented here provides the opportunity to set up an internationally validated framework that can be used as a basis for discussion across the board.

The framework has limitations due to the immense complexity of the whole Earth system. It has to be simple to be general, and thus can hold only a certain amount of detail. However, this is an aspect inherent in any such large-scale framework. For specific usages, such as a local scale, or for a specific geological environment (e.g. a karst cave, or a volcanic vent, or a fossil site), a small scale framework, diagram or system can be drawn up that can then fit into the larger scale. Likewise, the spheres that are treated in general in the present table, such as atmosphere or climate, could be expanded when the focus of the local system requires it. Like with the expansion shown for lithospheric plate tectonics, all the other spheres could be likewise expanded.

4.1. A method for applying the global framework

We have showed various versions of the framework to non-scientists working in geoheritage, ecology, environment and applied geosciences. One main aspect of their feedback to be given an explanation of a method for using it. This was not our main objective, as we were foremost concerned with setting it up, and had already used previous versions in practical applications that have been presented above (e.g. in Figs. 7, 12, 13). However, it is also useful to return to the practical application at this point. The following steps give a basic method that has been applied to the sites described here. It is also applied to the final example (Fig. 18) that follows.

1. Keep a sequential record of all the below steps in placing an site in its environment, so that they can be checked and verified. They also should form a line from the most specific to the most general, and then return to focus in on the results of the global framework comparison.
2. Look for simplicity in the site in question and list the main elements.
3. Describe the site, in a little more detail around these main elements and look for connections within them and to the broader Earth system (especially look for unexpected links, such as with extra-terrestrial or deep earth forcing factors),
4. Place the main elements in the Global Framework – creating a network of arrows that connect to the broader links,
5. Extract the most significant elements, and their icons, and link them together as part of a system,
6. Adapt the global cross-section to fit to the elements (or just point them out), possibly use a more localised diagram, e.g. one slice of the Earth's spheres.
7. Make a system diagram showing the causal relationships.
8. Compare with other sites that have the same context.
9. Display the Global Framework, cross-section and system diagram plus any other graphical description on one figure (size may require a poster-sized one, or digital version), and make both a complete version with all the complexities and links, and a simple version(s) for communication.

4.2. The position of non-physical sites and data sets in the framework

The examples provided here are mainly drawn from geological Word Heritage sites or potential sites, where the physical landscape is a major element, although the example of the Pannonian basin is a much larger scale one.

There is, however a wealth of geoscience research that is not necessarily connected to a single site, or may use data other than the purely physical. For example, geophysical data also illustrates the nature of the lithosphere, as does geochemical data. These data are akin to intangible cultural World Heritage.

Such data are elements that also deserve a place in the framework, and examples could be the world stress map (Heidbach et al., 2010), World Gravity and Magnetic maps (Bonvalot et al., 2012) there elements could also be considered to be integrated at a future stage. The recently produced 'Atlas of the underworld' (van der Meer et al., 2017),

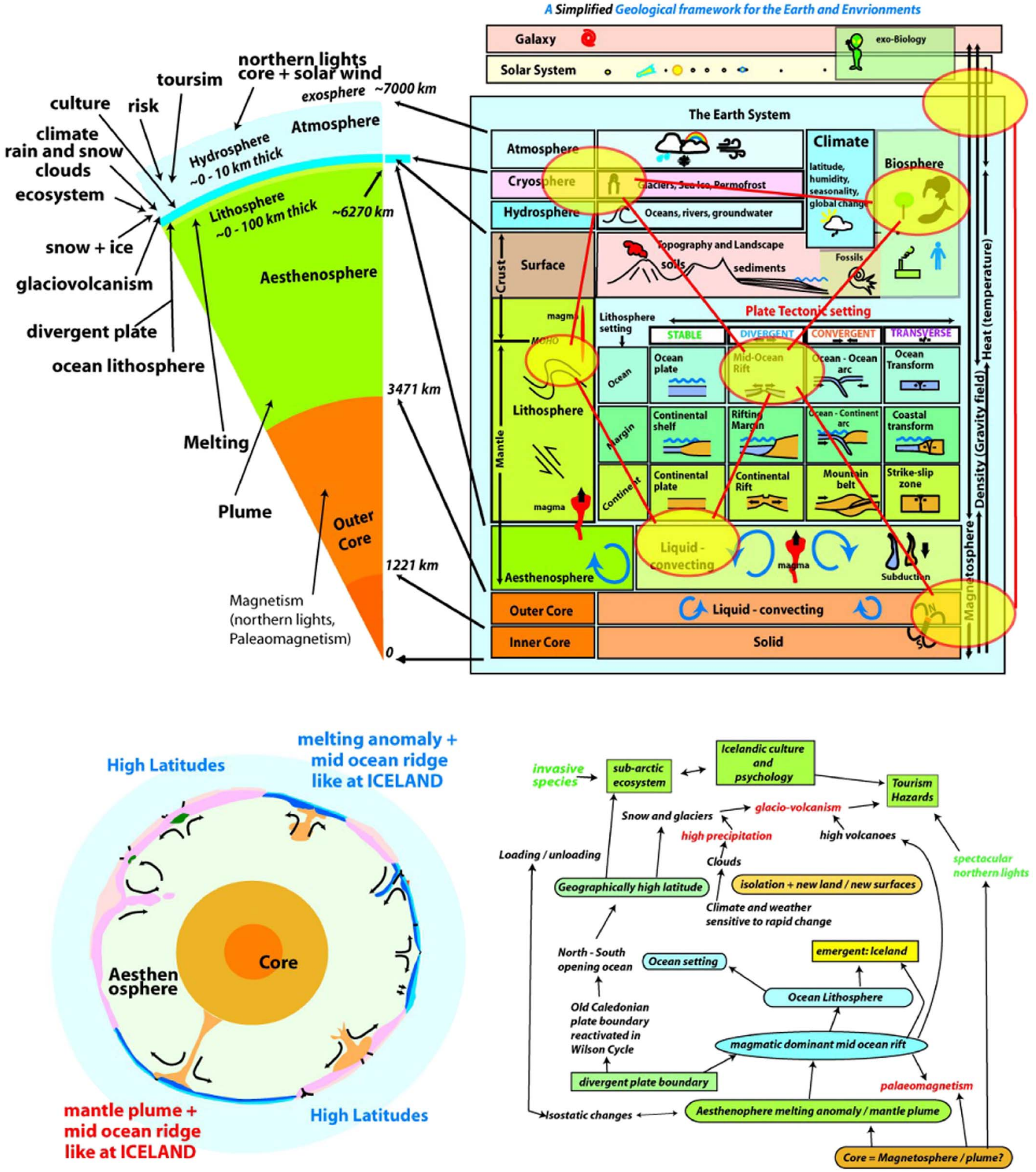


Fig. 18. Conclusion diagram and example of the use of a combination of the geological table, the Earth sketch and a system diagram to provide the context for a geological site. In this case we use Vatnajökull National park, and Iceland, although any case could be used, including, for example a cultural site like Þingvellir (by changing the system diagram), a biological reserve, karst property… etc. The top right part has the geological framework table, accompanied by a slice of the Earth giving a simple pictorial demonstration of where processes act. Below left is the full-cross section of the Earth, as given in Fig. 9. This has been slightly modified to show the two reigning hypotheses for Iceland (core driven plume and mantle melting anomaly, e.g. Foulger, 2010). The right side shows a systems diagram that with the main driving processes and environments for Vatnajökull. This goes from the core at the bottom to biosphere and human activity at the top. Due to the complexity of the whole system, this is much simplified, but separate sub-systems could be made for each element, such as glaciovolcanism, or invasive species, or even the Þingvellir parliament. There are many ways of producing such a diagram, and this particular one could be modified for different users with different skills and knowledge. It could, for example be enlarged with addition of a topographic and geological map, and illustrations to make a poster-sized explanation, that would have the ability to be visually very attractive and informative. In Fig. 19, the time – based evolution of Iceland is depicted using symbols extracted from the framework table.

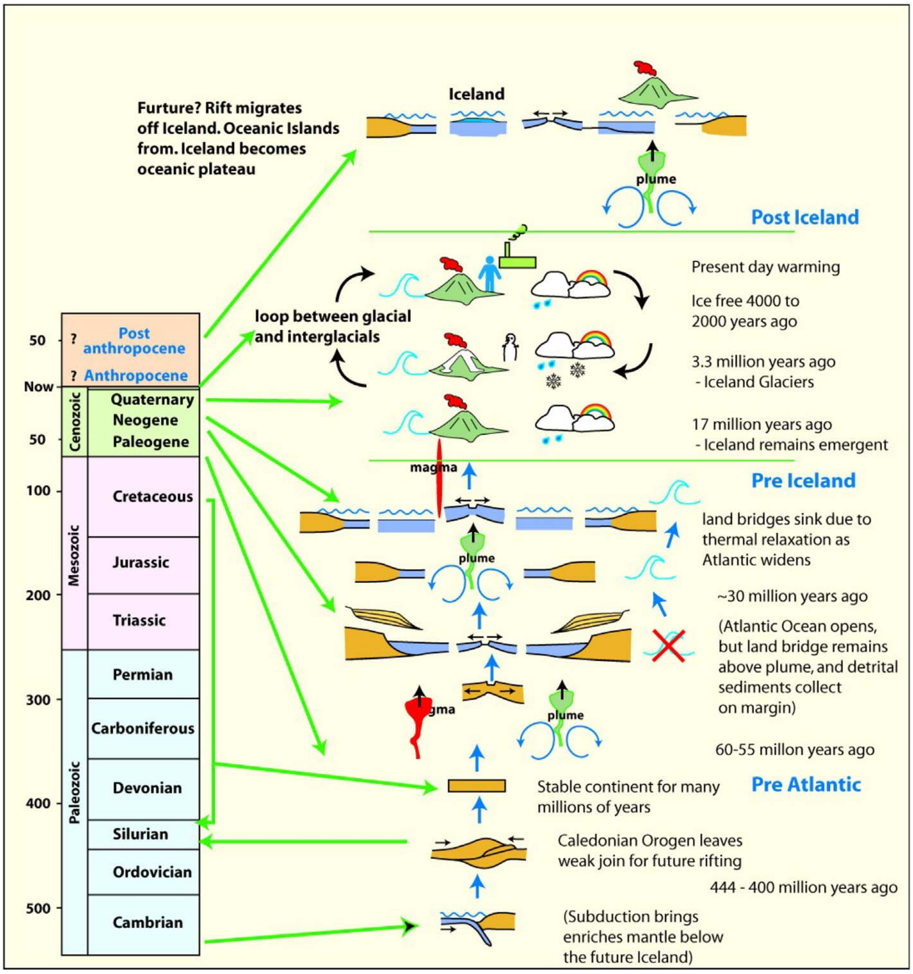


Fig. 19. Iceland over time. This starts with the closure of the Iapetus Ocean in the Paleozoic, then the long period of quiescence as the area was part of a continental interior. Continental rifting followed at the end of the Tertiary, and the Iceland progressively formed from a combination of plume and rifting tectonics. The land bridges with the two continents sank, and glaciation began to interact with tectonics and volcanism to shape the landscape. Man appeared recently (Anthropocene), and we take the timeline 50 million years into the future, when humans may have gone, and Iceland will probably be a submerged oceanic plateau, the plume and ridge having migrated relative to it.

is an example of a remarkable repository of ancient subducted slabs, through geophysical imaging, that deserves inclusion. The geomorphological system of Griffiths and Stokes (2008) could fit well into the global framework in the surface box (Tables 4A and 4B).

In a similar manner there are visualisation methods now available that have a strong role in outreach and research, the most obvious is the above- mentioned Google Earth, but 3-d visualisation techniques, such as presented by Rapprich et al. (2016) for the Czech Republic, or the plate tectonic reconstruction animation also have a role.

4.3. An example and a test of the applicability of the framework

The global framework presented here has the novelty of giving a table-based classification, coupled with a more commonly used global cross-section, a time line and a more esoteric system diagram approach. It has the potential to provide the geoscience community with one unified method of putting in context 'pure' geoscience research that links this to geoheritage, risk and resources.

To give an example, the Figs. 18 and 19, provide the geological framework setting for the Vatnajökull area, as discussed above. This is

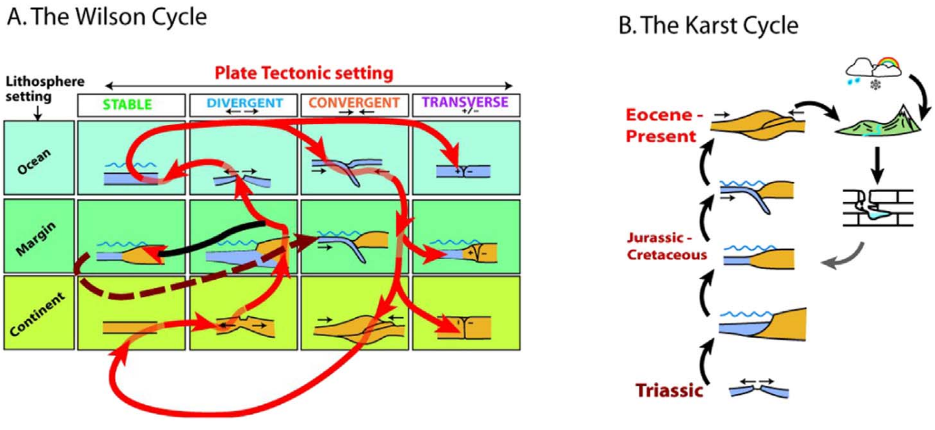


Fig. 20. Time and the Geological Framework. **A.** The Wilson Cycle traced onto the extracted lithospheric part of the framework table. Putting a finger on any part of the red track, it you can move around the cycle. For example, go from stable continental plate interior, through continental rifting, passing rifting margins, then stable margins (the dark red arrow), to ocean rifting, then take subduction, to continental collision and back to plate interior. There are excursions into transform margins an essential accommodating feature for plate tectonics. **B.** A karst evolutionary cycle (like for the Škocjan caves), which follows generally the Wilson Cycle as it is plate tectonics that ultimately controls the setting for karst. So, ocean opening creates the stable continental shelves for carbonate accumulation, then subduction and continental collision bring the limestone up into mountain belts, where the surface and atmospheric environment can create the karst system. Finally dissolved and eroded limestone is returned to the seas and may eventually be turned back into limestone. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

done with: 1) the table, 2) an Earth slice to scale the elements, and then 3) the Earth cross-section to show different hypotheses for the Iceland geodynamical situation (plume or plate dominated?), 4) a system diagram that shows the interrelationships of some of the the constituent parts and 5) a time line using the table icons. Iceland is an oceanic environment, that has evolved over more than 16 million years, and this evolution can also be followed on the table, and on an accompanying time line, that can show, for example the progressive opening of the Atlantic, the continued emergence of Iceland, and the arrival of glaciation in the Quaternary. More recently, the loss of ice at about 10,000 years and its re-emergence at about 200 years (Björnason, 2017) can be added, along with the arrival of humans, and the present warming trend. In the time line, we even take the liberty of going 50 million years into the future.

Finally, the use of the framework for showing evolutionary and time dependant geological phenomena is illustrated in Fig. 20. Here the Wilson Cycle is shown on the extracted lithosphere and plate tectonic part of the framework table. The cycle can be followed around like a board game. The evolution of a karst system is also shown, which also follows loosely the Wilson Cycle, as the karst environment is ultimately controlled by the plate tectonic history, interacting with the outer surface environment.

4.4. Testing and adopting the global framework

The Framework diagram has been through several editions in discussion for the paper, but the real test will be to see how successful it is in disseminating the context of this chosen site. So a study assessing what other scientists and non-scientists see in this, what they understand, is a necessary next step.

We suggest that, concurrent to such a study, it is also discussed, adapted and adopted by the main geoscience unions such as the IUGS and IUGG, by the international Union of Geoscientific Unions (ICSU), at UNESCO and as a general research and education tool.

5. Conclusions

To communicate geoscience to audiences of all types, from politicians to the general public, it is necessary to provide an clear idea of how the Earth works, and to provide a holistic picture of the Earth system.

The Earth system can be depicted in various ways. The table framework provided here gives a snapshot view with boxes that contain distinct geological environmental features. Even the evolution of these features can be followed as a site moves from one set of boxes to another with time.

Both research and outreach are enriched by the links provided in this framework. It thus provides a transversal means of valuing geosciences across different areas where global geoscience needs to be understood and employed in policy decisions.

Any site can, thus, be presented using its tectonic context, and will also have a surface process context and inputs from other parts of the system, so that no one place will fall into one single space. This allows the variability of a site to be described, and the links between different environments depicted. Sites can be compared, but also the change in a site's environment with time can be followed, as shown for example with the Pannonian example, where the Triassic to recent evolution is charted.

Different geological environments can also be shown in diagrams, such as a global cross section (Figs. 9 and 18). This allows a pictorial expression of a geological environment and the visual association of different elements. A systems diagram can also be drawn, which is less visual, but can show the link between the different processes in a geological environment. Such diagrams can become very complex, so limiting the boundaries of the specific system can be done.

The three approaches (table, sketch and system diagram) can be used together to depict a site, and this allows for it to be set in the global framework. This allows different areas to be compared and helps in communicating the significance of a site.

For the spheres of geoscience research and geoheritage this framework can assist in making connections between disparate pieces of research, to give them a greater global significance. For geoheritage it provides a general framework into which all sites can be set.

It allows all types of heritage sites to be connected to the processes that produce them and connects them to the fundamental research that gives them their scientific meaning.

It can also be used to depict such processes as climate change, and natural hazards, by bringing out the role of various spheres and the processes acting in them. Resources can also be depicted in the diagram, and the links used to show sustainability, or environments in which valuable resources are likely to be found, exploited and sustained. In this context, the framework can be used to show the links between geosystem and ecosystem services, and help strengthen the understanding that the geological foundation of ecosystems should always be taken into account.

We suggest that eventually this framework should be discussed, adapted and adopted first by the International Lithosphere Program and then to be proposed in a broadly agreed format to the IUGS and IUGG as an official framework for global geology.

The framework can play a role in geoscience outreach, but can also be employed by other users to communicate with geoscientists.

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