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World Heritage Volcanoes

A thematic study: A Global Review of Volcanic World Heritage Properties: Present Situation, Future Prospects and Management Requirements

IUCN Protected Areas Programme - World Heritage Studies

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WORLD COMMISSION
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World Heritage Convention

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Cover photo: June 1996 eruption of Mt Ruapehu, which is one of four andesitic volcanoes in New Zealand's Tongariro National Park, a World Heritage Cultural Landscape. © Harry Keys

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Table of Contents

Annexes

Summary

This Global Theme Study examines the position of volcanoes and volcanic features in relation to the World Heritage List. It was commissioned by the IUCN, following a request of the World Heritage Committee which observed that volcanic features are now well represented on the List and any future nominations of volcanic World Heritage properties[1] should be limited only to those that fill the most significant gaps in the present coverage. The study therefore has set out to define what constitutes a volcanic World Heritage property and establish a technical framework under which such properties might be evaluated in the future and possible priorities for further recognition. It has also considered the particular challenges that might be faced by a State Party in the management of a volcanic World Heritage property.

The study examined the records of the 878 properties on the current World Heritage List (including all properties listed up to and including the Committee meeting in 2008 (32nd Session of the World Heritage Committee, Québec City), as well as 1468 sites proposed for nomination in the Tentative Lists of State Parties. It was found that while there are 57 properties that have some volcanic geology, 27 of these contain active volcanoes[2]. Furthermore, because many of the properties with active volcanism contain more than one volcano, it is estimated that the World Heritage List may contain over 100 active volcanoes, which is over 6% of all the world's Holocene subaerial volcanoes. Examination of the Tentative Lists revealed a further 40 volcanic properties, 25 with one or more active volcanoes, these latter properties containing over 70 Holocene volcanoes.

The World Heritage List therefore represents a most important mechanism for protecting the global volcanic estate. The volcanic properties on the List display a wide variety of volcanic forms and features, including single active, dormant or extinct volcanic edifices; complex, large scale, active volcanic groups and landscapes representative of particular plate tectonic settings; individual volcanic landforms or features, or combinations of these; eroded remains of former volcanoes; and significant hydrothermal and fumarolic systems. The study found that the volcanic properties on the World Heritage List exhibit virtually all types of major and subsidiary constructional and erosional (destructional) volcanic landforms.

While the World Heritage List appears to possess good overall representation of volcanic features, deeper analysis in the context of plate tectonic setting, landform and geopolitical boundaries has revealed some gaps that might be filled by future nominations. For example, some important features of basaltic volcanism not so far included are fissure volcanoes, sub-glacial volcanic edifices and continental flood basalts, while features of more silicic volcanism that might be better represented are calderas and large ash or pumice flows (ignimbrites). Also worthy of consideration for nomination to the World Heritage List are some of the world's most iconic volcanoes.

In its consideration of the management of volcanic World Heritage properties, the study has discussed the concept of 'integrity' in relation to existing and proposed future volcanic World Heritage properties. This concept is important in defining and containing the volcanic 'system', and the protection of geological values,

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[1] The World Heritage Convention and its Operational Guidelines consistently refer to World Heritage Sites as 'Properties' (i.e., the area of land inscribed on the World Heritage List is a "property"). The term World Heritage property is therefore used throughout this report in preference to the term World Heritage site. However, the use of the word "property' in this context should not be confused with the use of the word "property" to mean a quality or characteristic (i.e., as in the properties or characteristics of a volcano, or its scientific properties).

[2] volcanoes listed in the database of the Smithsonian Institution's Global Volcanism Program as having been active during the Holocene period, or the last 10,000 years.

both in themselves and as a part of integrated ecosystem management. One other important aspect of management not usually so dominant in other natural World Heritage properties is the hazardous behaviour of many volcanoes, necessitating the scientific monitoring of volcanic activity, as well as the preparation up of Hazard Assessments, Hazard Zone Maps and Risk Contingency Plans.

Introduction

Volcanoes are perhaps the best known and most spectacular of the Earth's geological features, and the importance of some as outstanding earth-science features is recognised in their status as natural World Heritage properties. From the beautiful, soaring cone of Mt Kilimanjaro in Kenya, to the infamous Krakatau, a part of the Ujung Kulon National Park in Indonesia, or the giant slumbering caldera of Yellowstone in the United States of America, World Heritage volcanoes provide a diverse range of volcano types, geographical locations and eruptive activities.

Plate 1: 1977 eruption of Krafla, NE Iceland, a fissure volcano on Iceland's Tentative List (photo: S. A. Thorarinsson)

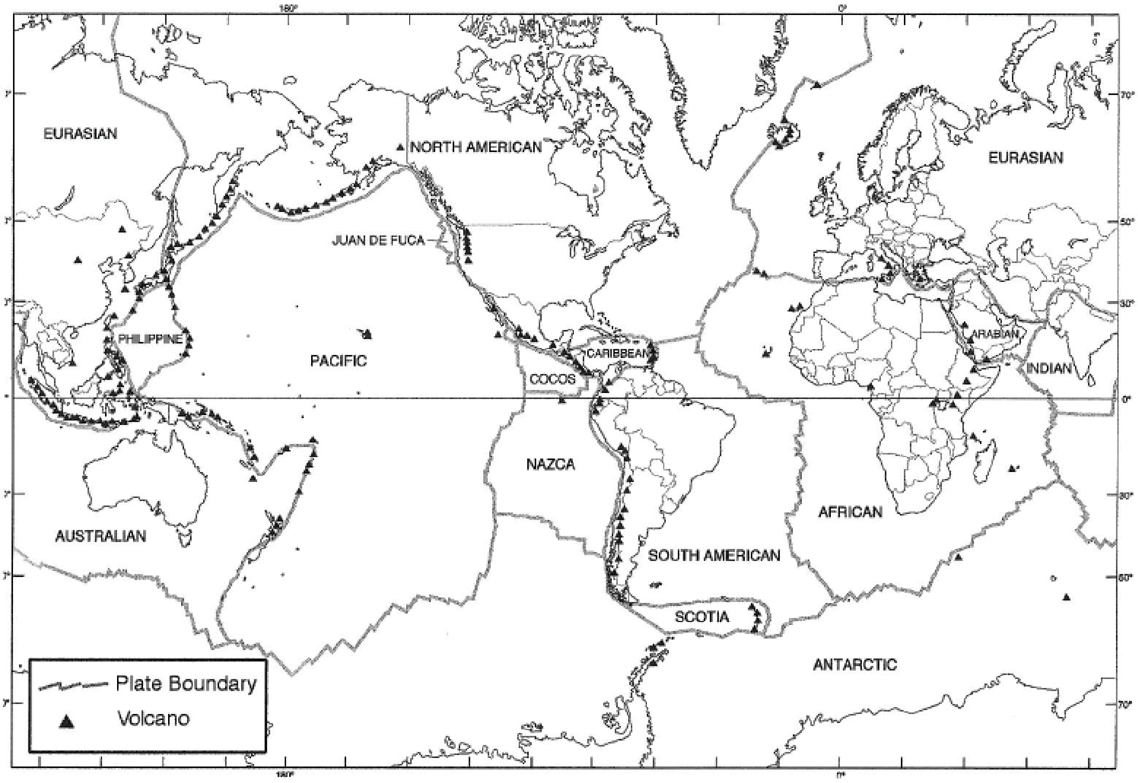
Volcanoes capture the public's imagination not only as beautiful and fascinating landforms, but also features whose enormous power may threaten society. Not so widely appreciated is that the formation of the planet and the existence of life on it have been dependent upon the activity of volcanoes throughout geological time. If the ocean floors are included, over 80% of the Earth's surface is of volcanic origin, while the gases emitted from volcanoes over hundreds of millions of years were instrumental in forming the Earth's earliest oceans and atmosphere. These gases provided the ingredients vital to evolve and sustain life. Volcanoes are therefore true wonders of the planet and it is appropriate that notable ones have been recognised to be worthy of special protection through their inclusion on the World Heritage List.

Volcanoes are not randomly distributed over the Earth, but are found over areas where hot liquid rock (magma) has been able to rise and escape onto the Earth's surface. As seen in Figure 1, volcanoes occur mainly along the boundaries of the Earth's lithospheric (tectonic) plates, or at places in the interior of plates where rising magma has punctured the crust (a place known as a 'hot spot'). However, it should be remembered that the present-day distribution of volcanoes is a reflection of the current arrangement of lithospheric plates, and that in the geological past the pattern of plates and therefore the distribution of volcanoes changed constantly throughout time. This means that in addition to present day volcanoes, we also find evidence of ancient volcanism in the historical, or stratigraphical, record, at locations typically remote from any current plate boundary or hot spot.

What are volcanoes? To the scientist, they provide vital clues on the internal workings of the Earth. They represent the places where hot, buoyant magma ascends from the upper mantle or lower crust and migrates toward the Earth's surface. The magma's ascent may be arrested in the crust, where it may crystallize to form an intrusive body of igneous rock, or it may travel to the surface and break out (erupt) to build a suite of diverse volcanic landforms. However, the landforms that the erupting material constructs are varied in scale and form, determined both by the chemical and physical properties of the magma, and the style and environment of the eruption.

Crucial to the behaviour of any volcano is the rheological, or flow, properties of the magma, the most important being its viscosity. Viscosity in turn is determined by the magma's chemical composition, gas content and degree of crystallisation. The more viscous the magma, the more explosive the eruption, producing a higher proportion of ejected fragmentary material. Thus, if the magma is relatively fluid (low viscosity), its effusion will

Figure 1: Map showing the Earth's tectonic plates and distribution of active volcanoes (courtesy of USGS).



normally take place without significant explosive activity (unless water enters the system), which is a style of eruption that will form lava plains, lava fields and low-angled shield volcanoes. If the viscosity of the magma is high, escaping gases are released explosively, blasting magma and fragments of the pre-existing volcano into the air, to fall back to Earth as bombs, lapilli, or ash, collectively known as pyroclastic material. Such activity, combining lava flows and pyroclastic deposits, builds steep conical mountains, known as stratovolcanoes, surmounted by one or more craters of different types. As a further variant, magma with particularly high viscosity can be slowly extruded from vents, like toothpaste from a tube, to form mounds of varying sizes, known as lava domes. However, this is a very simple interpretation, and in reality there is a great diversity of eruption styles and volcanic constructions.

Given their large scale, and their powerful and unpredictable behaviour, the protection of the heritage values of volcanoes and volcanic landscapes is a challenging task. To date, their conservation has been rather haphazard, partly because of the remoteness and apparent barrenness of volcanic terrains, and also because many conservation agencies have considered that such geological resources are little threatened. However, this approach is far from the truth and the integrity of many of the world's volcanic landscapes and features are under threat from such things as recreational overuse, mineral extraction and encroaching development. In addition, it should not be forgotten that volcanoes are hazardous environments, and while management intervention is often necessary to achieve conservation goals, it is also an essential means by which the risks to communities living on and around volcanoes may be reduced.

The purpose of the study

This report provides a review of the volcanic landforms and landscapes inscribed on the World Heritage List. It also reviews those included on the Tentative Lists of States Parties to the World Heritage Convention that may be proposed for nomination in future, and other significant volcanic features that might have the potential to be added to the List. The report arises following a decision adopted by the World Heritage Committee (Decision 31 COM 8B.17, paragraph 6):

> *"The World Heritage Committee requests IUCN to evaluate the volcanic systems inscribed on the World Heritage List and on the Tentative Lists of States Parties and to present a thematic study for consideration of the Committee."*

This decision was made in response to the advice of IUCN that volcanic features are relatively well represented on the List, and thus suggesting a decreasing potential for further nominations of volcanic properties related to the remaining gaps in the present world coverage. Reporting to the World Heritage Committee in July, 2007, IUCN drew the Committee's attention to this issue and recommended undertaking a thorough global analysis, as follows:

> *"IUCN notes that volcanic systems are relatively well represented on the World Heritage List, including several properties whose inscription was justified on the basis of arguments that are considered by a number of experts to be rather narrow. There are a large number of volcanoes worldwide and at a detailed level every one of these can assert that it is in some way unique. In 1996 IUCN noted that the World Heritage Committee had already asked "how many volcanoes should there be on the World Heritage List?"*
>
> *In the interests of maintaining the credibility of the World Heritage List, IUCN considers that there is increasingly limited scope to recommend further nominations for inclusion on the World Heritage List. In particular, IUCN recommends that the World Heritage Committee should consider indicating clearly to State Parties that further volcanic nominations should only be promoted where:*
>
> - *There is a very clear basis for identifying major and distinctive features of outstanding universal value that has been verified by a thorough global comparative analysis;*
> - *The basis for claiming outstanding universal value is a significant and distinctive feature of demonstrable and widespread significance, and not one of many narrow and specialized features that are exhibited within volcanic terrains. IUCN recommends that State Parties considering volcanic nominations carry out an initial global comparative analysis* ***prior*** *to proceeding with the development of a full nomination, in order to minimize the possibilities of promoting a nomination that will not meet the requirements of the World Heritage Convention, including those concerning the conditions of integrity."*

The brief for this study therefore calls for a review of sites included, or with the potential to be included, on the World Heritage List. Sites to be reviewed have been defined by IUCN as:

a) Landscapes that are formed by the primary action of volcanic and igneous processes and are of potential Outstanding Universal Value (OUV), but will not include landscapes formed in igneous terrains by secondary processes.

b) Volcanic and igneous features of outstanding and universal importance in relation to geoscience, including its accessibility and comprehension by civil society (i.e., does not include sites with values that are only of a specialised scientific importance), and an overview of the requirements necessary to meet the conditions of integrity and management at such sites.

The purpose of this study is therefore to advise State Parties on:

a) the scope of volcanic values already represented on the World Heritage List;
b) the potential and priorities for future recognition of volcanic landscapes and features on the World Heritage List;
c) the requirements for integrity and management that should apply to such sites.

Defining the scope of the study

What is a volcanic World Heritage property?

This report defines a volcanic World Heritage property as one that contains geological structures and landforms constructed from volcanic, or igneous, rocks (see Text Box 1 for definition). These are rocks derived from a liquid magma that was *intruded* into, and often *extruded* onto, the Earth's crust. Such activity has been prevalent throughout geological time, and while eruptions that have taken place in the recent past still exhibit, or are still building, constructional landforms on the Earth's surface, the results of older eruptions have been partly or wholly destroyed by surface erosive processes. Yet, even when deeply eroded, volcanic terrains may include important landforms, either as features formed by the dissection of the volcanic cone, or by the complete removal of the weaker material of the cone to leave the hard skeleton of the intrusive features upstanding in the landscape (sometimes known as inverted topography).

Volcanic features therefore may be divided into:

1. Primarily constructional features - those principally formed by explosive and/or effusive volcanic activity (i.e., formed by *endogenetic* processes, or those geological processes originating from within the body of Earth)
2. Primarily destructional features - those formed by the weathering and erosion of the Earth's land surface (i.e., formed by *exogenetic* processes, or those originating outside of the Earth's crust, at the interface of the lithosphere with the atmosphere, hydrosphere and biosphere).

There is inevitably overlap between these two types of features, because even during their construction new volcanoes suffer some exogenetic degradation, such as landslides, fluvial and even glacial erosion, and one should consider the forms of many volcanoes to have evolved from a mixture of both types of processes.

This study of volcanic World Heritage properties has been approached from the standpoint of geomorphology, or physical landscape. It embraces volcanic landforms and landscapes that have been formed by varying combinations of endogenetic or exogenetic processes. Furthermore, it recognises that volcanoes may vary greatly in shape and size, ranging from small cinder cones and tuff rings to enormous edifices, such as the towering stratocone of Sangay, Ecuador, or the gigantic volcanic shields of Mauna Loa and Mauna Kea, on Hawaii Island, USA, which are the largest individual mountain structures on the planet. It is also important to note that these larger structures will contain on their flanks a range of subsidiary features, including such phenomena as calderas and craters, rift zones and fissures, lava domes, collapse scars, scoria cones, tuff cones and tuff rings, maars, pit craters, lava flows with lava channels and lava tube caves, and debris lobes produced by collapse or lahars (see Figure 2). A further consideration is that scientists now recognise that several apparently individual volcanoes may be parts of the same volcanic system, each volcano tapping a common magma source, as explained in Text Box 1.

The conceptual approach taken here has been to consider volcanic World Heritage properties within the general term *volcanic landscape*, and that each landscape is composed of an assemblage of *volcanic landforms*. However, it should also be recognised that there are some 'volcanic' landscapes that do not have distinctive landforms, but contain abundant evidence in their rocks and underground structures of former volcanic activity. Adding further complexity to the definition is the fact that a volcanic landform may be a composite feature (e.g., a polygenetic stratovolcano), representing a single landform in its own right, but also containing a range of subsidiary features.

TEXT BOX 1: Nomenclature and diversity of igneous rocks

Igneous rocks are those that are formed by the cooling and crystallization of a liquid magma. As will be explained below, magmas have a wide range of chemical compositions, and each may crystallize to produce a variety of minerals. Igneous rocks are aggregates of these interlocking mineral crystals, the relative proportions of the various minerals being dependent upon the unique chemistry of the original magma.

Nearly all magmas are silicate melts, or ‘liquid’ glass (there are a few rare and unusual classes of igneous rocks, such as carbonatites, that are derived from magmas composed primarily of non-silicate minerals, such as carbonates). On crystallization of a silicate melt, different minerals form when the silicate molecule combines with other elements. The common families of minerals forming igneous rocks are quartz, feldspars (and feldspathoids), micas, amphiboles, pyroxenes, and olivines. Silica accounts for 40-75% of most igneous rocks by weight and modern classifications categorize igneous rocks according to their relative proportions of the silicate minerals.

Thus:
Rocks whose minerals have a high silica content, such as rhyolites or granites, are termed felsic or silicic (the word felsic is derived from feldspar and silica),
Rocks whose minerals have a low silica content, such as basalts or gabbros, are termed mafic or basic (the word mafic is derived from magnesium and ferric, or iron).

A further important point is that mafic minerals crystallize at higher temperatures than do the felsic minerals. In other words they appear earlier in a cooling magma.

Classification of igneous rocks

Igneous rocks may be classified on the basis of their silica content and texture. Texture relates to the size of the mineral crystals that make up the rock, larger crystals signifying slower cooling, providing a longer time for crystals to grow, while smaller crystal signify more rapid cooling. Sometimes magma may be cooled so fast that there is no time for discrete crystals to grow, and the resulting rock has the appearance of a glass.

A simple classifiction of igneous rocks is as follows:

Texture	**Mode of Occurence**	**75%-------------------Composition (silica content)---------------40%**			
		Acid (Felsic or silicic)	Intermediate	Basic (mafic)	Ultra-basic (Ultra-mafic)
Coarse	Large intrusion	Granite	Diorite	Gabbro	Peridotite
Intermediate	Small intrusion	Diorite		Dolerite	
Fine	Extrusive (lava)	Rhyolite	Andesite	Basalt	Komatite
Glassy		Obsidian			

Black or grey-coloured basalt is the archytypal basic, fine-grained rock (coarse-grained equivalent is known as gabbro). It has low silica content and is composed primarily of the minerals plagioclase feldspar, pyroxene and olivine. In contrast, the most felsic fine-grained rock is rhyolite (coarse-grained equivalent is granite). This rock is light in colour, has high silica content, and consists largely of quartz, feldspar and mica. Intermediate between these are rocks known as andesites.

For further understanding of the diversity of igneous rocks and their classification, the reader is directed to one of the standard physical geology texts, such as Press et al. (2004), or Murck and Skinner (1999).

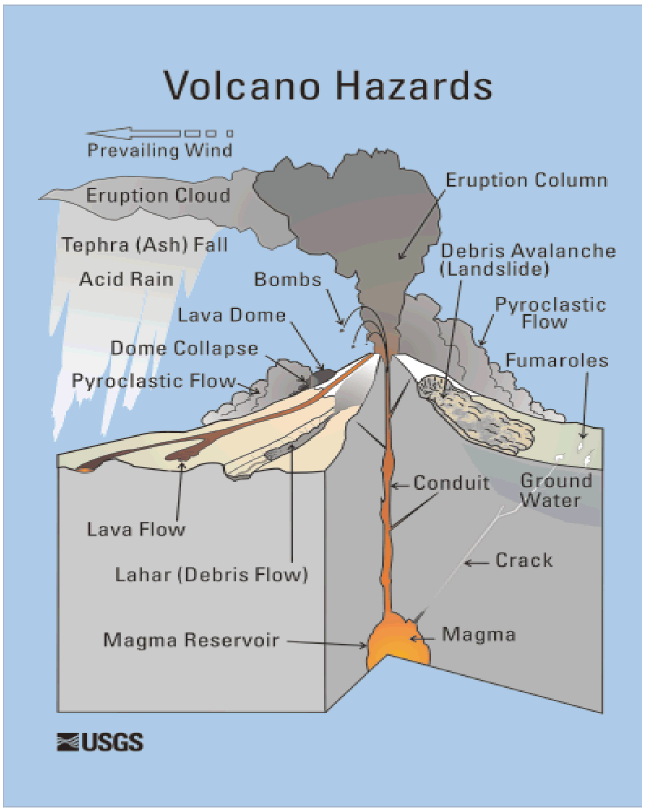
What is an active volcano?

Any volcano, if it is not currently erupting, may be in a period of repose between eruptions, when it is said to be dormant, or in fact is not likely to erupt again, when it is said to be extinct. The usual assumption is that an active volcano is one that is currently erupting or has erupted during recorded history. However, the Smithsonian Institution’s Global Volcanism Program (GVP), the most authoritative source on the activities of the world’s volcanoes, takes a longer term view:

> *“Because dormant intervals between major eruptions at a single volcano may last hundreds to thousands of years, dwarfing the relatively short historical record in many regions, it is misleading to restrict usage of the term “active volcano” to recorded human memories: we prefer to add another identifying word (e.g. “historically active” or “Holocene volcano”).”*

On the basis of its database of volcanic activity around the world, the GVP notes (see Text Box 2) that at any one time there may be 20 volcanoes in eruption, while the historical record has shown that roughly 60 volcanoes erupted each year in the 1990s, 154 in the decade 1990-1999, about 550 in the historic period, and as many as 1573 in the last 10,000 years - a period of geological time known as the Holocene. This review will adopt the definition of ‘active volcano’ provided by the GVP as one that has been in activity in the last 10,000 years and will use the term ‘holocene volcano’ as one synonymous with ‘active volcano’.

Figure 2: Diagram showing eruptive processes and products (courtesy of USGS).



TEXT BOX 2: How many active volcanoes are there in the world?

Abstracted from Smithsonian Institution’s Global Volcanism Program, Frequently Asked Questions, see: http://www.volcano.si.edu/faq/index.cfm?faq=03

Usage [of the term “volcano”] has varied widely, [and has been] applied to individual vents, measured in meters, through volcanic edifices measured in tens of kilometers, to volcanic fields measured in hundreds of kilometers. We have tended toward the broader definition in our compilations, allowing the record of a single large plumbing system to be viewed as a whole, but this approach often requires careful work in field and laboratory to establish the integrity of a group’s common magmatic link. The problem is particularly difficult in Iceland, where eruptions separated by many tens of kilometers along a single rift may share the same magmatic system. A “volcanic field”, such as Mexico’s Michoacán-Guanajuato field (comprising nearly 1,400 cinder cones, maars, and shield volcanoes derived from a single magmatic system, dotting a 200 x 250 km area) may be counted the same as a single volcanic edifice. Perhaps the most honest answer to the number question is that we do not really have an accurate count of the world’s volcanoes, but that there are at least a thousand identified magma systems - on land alone - likely to erupt in the future.

How many active volcanoes known?

Erupting now:	perhaps 20
Each year:	50-70
Each decade	about 160
Historical eruptions	about 550
Known Holocene eruptions (last 10,000 years):	about 1300
Known (and possible) Holocene eruptions:	about 1500

Note: This does not include the large number of eruptions (and undescribed volcanoes) on the deep sea floor. Estimates of global magma budgets suggest that roughly 3/4 of the lava reaching Earth’s surface does so unnoticed at submarine mid-ocean ridges.

Volcanoes are complex constructions

An important consideration is that volcanoes are formed from repeated episodes of volcanic activity, many forming over a time span of hundreds of thousands of years, and some remaining active for millions of years (e.g., the activity which built Jeju Island (Mount Halla), Korea, began about 0.8 million years ago, while the Las Cañadas edifice, Tenerife, Spain, may have an age of over 3.5 million years). This means that older edifices may be the complex constructions of a relatively long history of eruption, this activity usually being punctuated by large sector collapse (landslip), or violent caldera collapse, and suffering from continuous degradation by weathering and erosion.

Chemical changes in the magma chamber

A further consequence of the longevity of some volcanic systems is that the magma chamber beneath the volcano may cease to be refreshed from its deep magma source and, as the magma cools, it may undergo a process of fractional crystallization (see Text Box 3) to produce progressively more silicic and/or alkalic melts. This means that over time the eruption style and therefore the form (shape) of the volcano may also change, the volcanic edifice having started as a basalt plateau, shield or scattered mafic cones, but eventually being surmounted by a steeper stratocone built from the more explosive products as the magma evolves.

Degraded volcanic cones and domes

As noted above, volcanic cones are relatively unstable features and easily collapse or are prone to dissection, particularly by fluvial and glacial erosion. Because these processes are exogenetic in origin, they are often overlooked by volcanologists, but erosional features may be of significant form and scale, transforming the shape of the original edifice. They may include immense collapse scars and debris lobes, as on the flanks of the islands of Tenerife and La Palma in the Canary Islands (Spain), or extensive canyons and gorges cutting deep into the structure of volcanoes. Volcanic islands in the moist tropics are particularly prone (but not exclusively so) to such dissection, with ash cones patterned by radiating stream-cut gullies and ravines, and larger edifices spectacularly dissected by immense amphitheatre valleys, and ‘erosion calderas’. Such exogenetic volcanic landforms have not previously been the subject of a World Heritage property nomination, although the impressive valleys and amphitheatres dissecting the giant shield volcanoes of Reunion Island in the Indian Ocean is a proposed future nomination on the Tentative List of France (Pitons, cirques et remparts de l’Ile de la Réunion).

Exposed intrusive forms

In addition to contemporary volcanic processes and landforms, geologists are interested in the remains of ancient volcanoes that have been buried within the stratigraphical succession of rocks laid down over time. Evidence of former volcanic activity may be found in vertical geological sections exposed in cliff faces and valley sides, or in the patterns made by rock structures on the ground surface. Exposures, or sections, of volcanic rock sequences from the geological past have not, to date, been considered strong candidates as the subject of a World Heritage nomination. The exception is when beds of volcanic rock coincidentally form parts of a larger stratigraphical series that illustrate a particular tectonic event, or when they have become exposed because of collapse or the explosive disruption of the flanks of a volcano. Such rock sequences are difficult to identify from the documentation of World Heritage properties and while attempts will be made here to identify all sites with volcanic bedrock, its significance cannot be effectively evaluated unless the volcanic beds form recognisable landforms.

TEXT BOX 3: Reasons for magmas of different compositions

Magma originates in the Earth's mantle and lower crust as a result of melting of the mantle rock. Such melting is controlled by three things: composition of the material being melted, temperature and pressure, However, the generation of magma is complex, requiring understanding of a number of separate processes. The overall term for the various processes by which magmas are generated and undergo further chemical change during cooling and emplacement is known as ***magmatic differentiation***. As the term implies, the end products are magmas and igneous rocks which are chemically distinct one from another.

Partial melting

Magma is thought to be produced by partial melting of the mantle rock. Laboratory experiments have shown that an igneous rock does not melt completely at any given temperature. This is because the minerals composing the rock melt at different temperatures. As temperatures rise, at any particular temperature some minerals have melted, while others remain solid. The fraction of rock that has melted at a given temperature is called the ***partial melt,*** and clearly the magma that is generated by this process will have a very different chemical composition than the rock from which it originated, or a magma that was generated at a higher or lower temperature.

Processes leading to melting of the mantle rock

The two most important reasons for melting of mantle rock are:
1) lowering of the confining pressure as hot mantle material rises toward the crust in convection currents and plumes
2) the role of water in lowering the melting temperature.

1) Pressure and temperature in the Mantle increases with depth. Clearly, pressure deep in the Mantle is many thousands of times higher than pressure at the surface, and this pressure at depth keeps mantle rock solid, even at very high temperatures. It therefore follows that the lower the pressure, the lower the temperature required to melt a rock.

It is thought that radiactive decay of some minerals and the great heat generated at the core/mantle boundary raises the temperature of mantle rock sufficient to make it expand. This expansion lowers the density of the rock, causing it to rise bouyantly, and convect. As the rock rises through the mantle, the surrounding pressure decreases below a critical point, enabling the convecting rock to melt. Geologists call this process ***decompression melting***, and it is responsible for the production of the greatest volume of molten rock.

2) Experiments have also shown that volatiles (especially water) play an important role in lowering the melting temperature of mantle rocks. This is particularly important at convergent plate boundaries where water contained in ocean floor sediments and rocks may be carried deep into the subduction zone, then released into the mantle wedge above the subduction zone, inducing rocks there to partially melt. This mechanism is known as ***fluid-induced melting.***

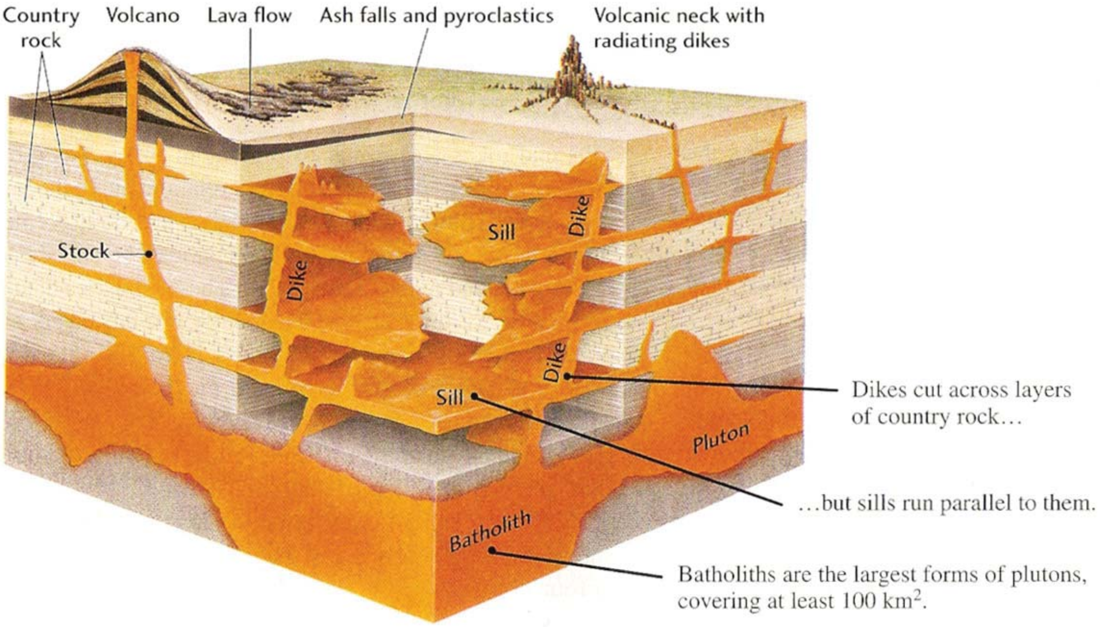
Magmas generated by decompression melting tend to be of basaltic composition because in the main they originate from the partial melting of mantle rock, , known as peridotite, which is rich in iron and magnesium. This basaltic magma erupts in great volumes at mid-ocean ridge and hot spot volcanoes.

In contrast, magmas generated by fluid-induced melting are more varied depending on how much and what kind of materials make-up the subducting ocean floor. These materials include water, mixtures of seafloor sediments, and a mixture of basaltic and felsic crust. As they subduct into deeper regions these rocks are exposed to higher pressures and temperatures, in the process losing water and other materials to the wedge of mantle that lies between it and the base of the Earth's crust. This generates magma that rises bouyantly to form magma chambers in the overlying crust. As this magma rises, its chemistry may be changed as a result of cooling and fractional crystallization (see below), contamination by the assimilation of wall rocks, the mixing of two or more magmas, or even mixing with later injected magma. The result is the production of a great diversity of igneous melts, whose rock equivalents are more felsic (i.e., silicic) than those rocks erupted at mid-ocean ridges and hot spots.

Fractional crystallization

Fractional crystallization is one of the most important mechanisms that contribute to magmatic differentiation. It is the term given to the segregation and removal from the melt of mineral precipitates. The process operates in a cooling magma chamber and takes place because different minerals crystallize at different temperatures (we have already seen that different minerals melt at different temperatures). Thus, as temperature falls in a magma chamber, early formed higher temperature crystals sediment out, leaving a liquid depleted of the chemical elements used to build those crystals. The process is very complex, particularly in nature, and some of the early formed mineral crystal may react with and continue to influence the chemistry of the melt, while other will be lost altogether from the melt. Nevertheless, because minerals of basic composition tend to be the earliest formed, the process generally means that melts become progressively enriched in silica and in some cases alkalis. Gradual evolution of the magma in a magma chamber is the reason for even long-lived basaltic ocean-ridge or hot spot volcanoes to erupt felsic lavas toward the end of their life.

Figure 3: Diagram showing igneous intrusive forms (abstracted from Press et al., 2004, copyright W. H. Freeman and Company)



One area of debate is whether or not landscapes and landforms representing ancient, degraded volcanic features should be included in this review. Figure 3 illustrates the range of intrusive forms that may be present in the Earth's crust, while Plate 2 Devil's Tower demonstrates the sometimes spectacular and scientifically significant nature of such landforms. Volcanic necks, dyke swarms, sills, ring dykes, cone sheets and diatremes, all represent parts of the underground "plumbing systems" of former active volcanoes, and may significantly contribute to the geomorphological distinctiveness of ancient volcanic terrains. The same may be claimed for the larger intrusions of rock, such as those technically termed batholiths, laccoliths and lopoliths. These represent enormous reservoirs of magma that once accumulated in the Earth's crust, and which, now cooled and crystallized, have become exposed at the land surface after millions of years of erosion removed the overlying rock strata. Batholiths and laccoliths are typically felsic (acidic or granitic) in composition and mostly associated with present and former lithospheric plate subduction zones and large scale mountain building. In contrast, most lopoliths are mafic (basic or gabbroic) and while some are claimed to be associated with large impact events, others form parts of basaltic Large Igneous Provinces (LIPs). Only some of these large scale intrusions now exposed at the Earth's surface may have fed surface volcanic activity (i.e., as magma chambers feeding either silicic volcanoes, such as the Yellowstone caldera, or basaltic volcanism such as that associated with the opening of the North Atlantic basin). Nevertheless, these structures are exposed over vast areas of Earth's surface, and granites in particular not

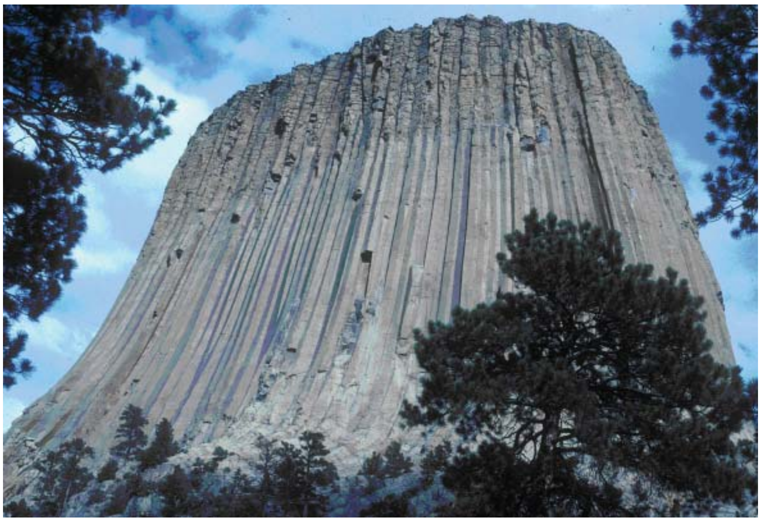


Plate 2: Devil's Tower, Wyoming, USA, showing spectacular columnar jointing - the origin of this intrusive volcanic feature is controversial and it may represent a part of a former laccolith or a volcanic neck. Photo: T. Kusky.

only form the cores of the world's greatest mountain ranges, but give rise to a distinctive geomorphology in their own right (e.g., as recognised in such World Heritage properties as Yosemite National Park, USA, and Huangshan and Sanqingshan National Parks, China). The decision on whether or not to include intrusive volcanic landforms in this review is therefore a difficult one. The view that is taken is to exclude the exposed large scale intrusions (batholiths, laccoliths and lopoliths), which provide no evidence of having supplied active volcanoes on the Earth's surface, but to include the smaller features, which are more obviously the remnants of former volcanoes and their subterranean feeder systems.

Hydrothermal phenomena and solfataric fields

Another group of features that require some discussion are hydrothermal phenomena and solfatara fields, such as hot springs, geysers, mud pools and fumaroles. Hot springs occur where geothermally-heated groundwater emerges from the Earth's crust. They are found all over the planet, including on the ocean floors. They are formed when water percolates deeply enough into the crust to come into contact with hot rocks, although it should be noted that because temperature rises with depth underground, the origin of hot springs is not always volcanic. Nevertheless, the most abundant and spectacular hot springs are associated with volcanic areas, and if water comes close to the magma reservoir at depth it may boil, become superheated, and build up steam pressure until it erupts as a geyser. At less dramatically explosive hot springs, the acidic water may dissolve the surrounding rock, thickening the water with muddy clay, which bubbles when steam and other gases escape through the layers of mud. In contrast, narrow vents that noisily expel gases such as steam, hydrogen sulfide and sulfur dioxide are known as fumaroles, and areas displaying fumarolic activity are known as solfataric fields (named after the Solfatara crater, near Naples, Italy). All of these phenomena in sub-aerial volcanic terrains build distinctive, and sometimes large, shallow, cone-shaped mounds and craters, made of deposited material and minerals such as sinter and travertine, and coloured by minerals dissolved from the bedrock, and/or by heat loving (thermophilic) bacteria. In the marine environment, water rich in dissolved minerals may escape from vents on the ocean floor, building tall chimney-like structures, with predominantly black mineralisation if the water is very hot and rich in iron and sulfide (known as 'black smokers'), or white if the water is cooler and contains compounds of barium, calcium and silicon (known as 'white smokers'). All sub-aerial and sub-marine hydrothermal phenomena build important, rare and fragile landforms, and may also harbour unusual and rare forms of life. They are therefore included in this review.

Volcanoes on the ocean floors

Most volcanoes that come to public attention lie in the terrestrial environment (i.e., on the continents, at continental edges and on ocean islands). Yet it has been estimated that the greatest number of volcanic structures and the most active occur in the ocean basins. Recent research has revealed that the ocean floor is dotted with volcanoes, which one study (Hillier & Watts, 2007) estimates could number over 3 million: 39,000 of which rise to more than 1000m above the ocean floor. The same study found over 200,000 submarine volcanic cones (seamounts) over 100m high. These facts are important reminders that there are very special and vulnerable volcanic features beneath the oceans, although the majority of these are not included in this review, because the World Heritage Convention and other international conservation conventions do not extend beyond the legal jurisdiction of national territories. Nevertheless, ocean floor volcanoes that do project above the ocean surface are included in this review. It is also noted that efforts are being made by the relevant States to consider a trans-national serial World Heritage nomination with the purpose of protecting important and accessible heritage, including volcanic features, of the Mid-Atlantic Ridge.

Summary of scope of the study

In conclusion this review is constrained by the following:

1. It defines volcanic World Heritage properties (current or proposed), not solely as properties with active volcanoes, but as all those containing volcanic, or igneous, rocks.

2. The term ‘active’ volcano is used to refer only to those volcanoes listed in the database of the Smithsonian Institution’s Global Volcanism Program as having produced some activity in the Holocene period, or last 10,000 years.

3. The distinction is made between younger constructional (endogenetic) landforms and older eroded (exogenetic) landforms, the latter being dissected and degraded cones and domes, or at a more mature stage of degradation, the harder rock skeletons (inverted topography) of former volcanoes or volcanic fields. It is also recognised that the distinction between constructional and destructional volcanic landscapes and landforms is not clear-cut, and even active volcanoes may suffer significant degradation by exogenetic processes.

4. While recognising that batholiths and other large scale igneous intrusions may give rise to surface volcanic activity, this study does not include such features, which more appropriately might be considered as a separate subject for review, although smaller scale intrusions that result in distinctive landforms are included.

5. Included here, but with the weakest argument for inclusion in the study, are sites which contain evidence in their rocks of ancient volcanism, but which possess no distinctive volcanic landforms. These are included for the completeness of the record and in recognition of the contribution they make to the record of the Earth’s history.

6. Due to the limitations of the World Heritage Convention in relation to protecting marine heritage beyond the 200 nautical mile limit of a nation’s Exclusive Economic Zone, only the sub-aerial parts of ocean floor volcanoes and sub-aerial hydrothermal vents will be included in the review.

Volcanoes and volcanic features on the World Heritage List

This study has examined the complete World Heritage List, the Tentative Lists of States Parties to the World Heritage Convention, and a list of nominations submitted for consideration since 1972 that were not inscribed or were withdrawn. The source of the data has been the lists maintained by UNESCO's World Heritage Centre and retrievable from their website (http://whc.unesco.org - World Heritage List and Tentative Lists), and from unpublished material provided by the IUCN Programme on Protected Areas. More detailed information on any particular site was also retrieved from the data sheet provided by the World Conservation Monitoring Centre (although WCMC data sheets were not available for all sites), from published literature and web search. It was necessary to consider all properties on all of the lists because many important volcanic properites are inscribed or are proposed to be nominated under criteria other than the geological criterion (Criterion (viii)). For example, some important volcanic sites inscribed on the World Heritage List under biological, landscape or cultural criteria include: Ujung Kulon National Park, Indonesia (which contains the famous volcano Krakatau), Kilimanjaro National Park, Kenya, and the Pico Island Vineyard Culture, Azores, Portugal (on the flanks of Pico volcano), while on the tentative lists are Mt Fuji, Japan, and the Grenadines Island Group, Grenada (which contains Mt St Catherine stratovolcano and the active seamount Kick em' Jenny).

In total, the details of 2349 sites inscribed or proposed to be nominated by State Parties in 2008 were examined, comprising 878 sites on the World Heritage List, and 1488 sites on the Tentative Lists. The third list, which was not a public document, contained approximately 750 sites. This last list was only cursorily examined to

Table 3: Analysis of Tables 1 and 2

Description	**List of World Heritage properties (Table 1)**	**List of sites included on Tentative Lists (Table 2)**	**Notes**
Number of actual or potential WH properties with significant volcanic geology	57	40	
Number of actual or potential WH properties containing an active (Holocene) volcano (i.e., embraces the whole volcano or includes at least one active vent - as listed in the database of the Smithsonian Institute's Global Volcanism Program)	27	25	
Number of actual and potential WH properties located on Holocene volcanic bedrock, but not embracing the whole volcano or including an active vent	7	3	
Number of actual and potential WH properties located on older volcanoes or volcanic bedrock	23	12	
Estimated number of active (Holocene) volcanoes located within actual and potential WH properties	101	73	There is large uncertainty in these numbers, which must be considered to be an under-estimate
Number of settlements permanently or periodically buried beneath volcanic deposits	5	0	
Number of actual or potential WH properties noted for their important intrusive landforms, excluding large scale gabbroic - granitic intrusions	4	0	
Number of actual or potential WH properties inscribed or proposed to be nominated under: - Category (vii) - all sites - sites with Holocene volcanoes - Category (viii) - all sites - sites with Holocene volcanoes	 27 14 (52%) 19 14 (74%)	 18 15 (83%) 17 14 (82%)	View data from Tentative Lists with caution - nomination criteria often not given, so data is incomplete

establish if any important Holocene volcanoes had been nominated but not inscribed in the past. Examination of this list showed that all of the relevant nominations were eventually re-submitted (sometimes with a new name) and inscribed on the World Heritage List.

Tables 1 and 2 (see Annex 5 and 6) show details of the important sites revealed by this study, while Table 3 provides an analysis of the first two tables. Table 2, which provides details of volcanic sites on the Tentative Lists, should be treated with caution because the site descriptions provided by some states or entered onto the UNESCO website are limited or incomplete (for example, many lack the criteria under which they are proposed to be nominated). Figure 4 shows the current world distribution of volcanic World Heritage properties.

There are several issues arising from this analysis, as follows:

Types of volcanic World Heritage properties

This research for this review began by separating from the World Heritage List and the Tentative Lists all the sites that were considered to contain significant volcanic, or igneous, bedrock. Such properties may have been nominated, or may be proposed to be nominated, as natural, cultural or mixed category sites. Further refinement then sought to establish which of the filtered sites had been nominated, or were proposed to be nominated, under Criterion (vii) (natural beauty), Criterion (viii) (geology), or other criteria, as defined in the World Heritage Committee's Operational Guidelines (2008). The World Heritage properties identified as volcanic were then grouped into a number of types, as follows:

Type 1. **Extensive volcanic landscapes with multiple eruptive edifices and associated features**, e.g., Air and Ténéré Natural Reserves, Niger; Tongariro National Park, New Zealand; Galapagos Islands, Ecuador.

Type 2. **Individual active, dormant or extinct volcanic edifices**, e.g., Hawaii Volcanoes National Park; Kilimanjaro National Park, Tanzania; Yellowstone National Park, USA

Type 3. **Particular features of larger volcanic edifices**, e.g. Teide National Park, Spain (as the summit vents and caldera of the Las Cañadas edifice, Tenerife); Jeju Volcanic Island (lava tube caves and tuff cone of Mt Halla volcano), Korea

Type 4. **Identifiable landforms or landscapes which represent the erosional remnants of former volcanoes**, e.g. Giant's Causeway, UK; Pitons Management Area, St Lucia; Old and New Towns of Edinburgh, UK.

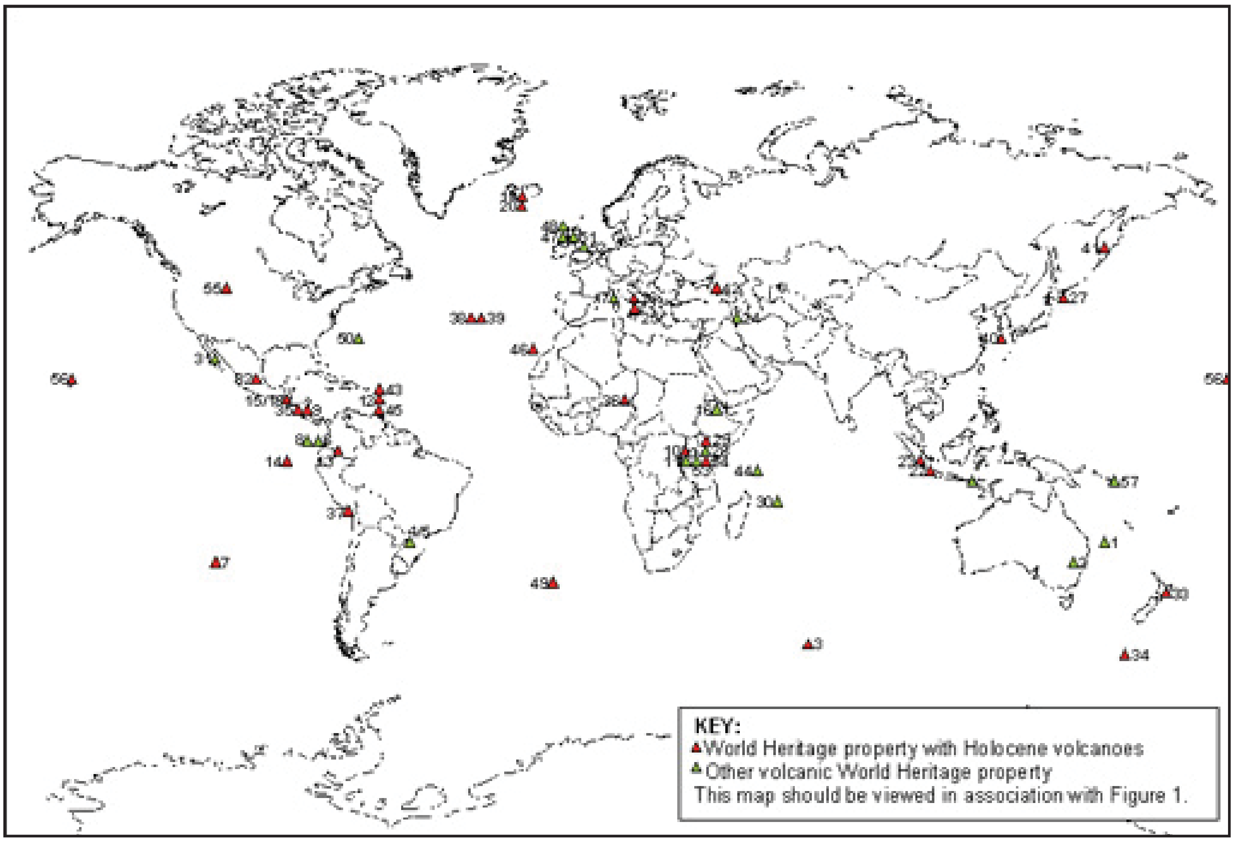
Type 5. **Properties with significant volcanic deposits, but without particularly distinctive volcanic landforms**, e.g., St Kilda, UK; Vallée de Mai Nature Reserve, Seychelles.

Type 6. **Significant hydrothermal systems and solfataric fields**, e.g., Yellowstone National Park, USA; Volcanoes of Kamchatka, Russian Federation.

Types 5 and 6 sites require some further explanation.

Type 5 sites are properties on the World Heritage List identified because they possess volcanic or igneous bedrock, although they may not contain notable landforms. There are 23 sites in this category. The identification of such sites is problematic - and potentially inconsistent or incomplete - because there is a lack of relevant information in the data sheets and the geographical area of search is so immense (i.e., because volcanic rocks cover extensive tracts of the Earth's surface). Finding such sites therefore has involved considerable

Figure 4: World map showing the distribution of volcanic World Heritage properties



detective work and inevitably some within this category may have been missed. Sites in this group contain notable volcanic deposits, and their importance lies in the stratigraphical evidence they provide of volcanism in the geological past.

Type 6 sites are significant hydrothermal and solfataric systems. Once again the numbers that are present in World Heritage properties is extremely difficult to estimate, because there is minimal information in the data sheets. The term ‘significant’ has been used here because, by definition, all Holocene volcanoes and many older ones have hydrothermal and solfataric systems and it is only the scientifically important or public noteworthy that may be identified from the literature. The World Heritage properties that contain the best developed hydrothermal systems are Yellowstone National Park, USA; The Volcanoes of Kamchatka (Valley of Geysers), Russian Federation; and Tongariro National Park (representing a part of the Taupo Volcanic Field), New Zealand.

Number of active (Holocene) volcanoes in World Heritage properties

The analysis has shown that 27 properties on the World Heritage List and 25 properties on the Tentative Lists contain volcanoes that have been active in the Holocene and are listed in the GVP database. In addition there are another seven properties on the World Heritage List and three on the Tentative Lists that are located on the flanks of, or deposits from, Holocene volcanoes (in total 34 inscribed sites and 28 tentative sites lie on Holocene volcanic deposits). However, because many World Heritage properties contain more than one volcano, the actual number of Holocene volcanoes is a minimum of 101 located in properties on the World Heritage List and 73 located in properties on the Tentative Lists (amounting to a minimum of 174 separate Holocene volcanoes). Identifying an exact number of Holocene volcanoes on the World Heritage List and Tentative Lists has not been possible because maps of the boundaries of World Heritage properties were not available during this review. For example, the UNEP/WCMC (World Conservation Monitoring Centre) datasheet claims that the Kamchatka

Peninsula has over 300 volcanoes, although only 114 Holocene volcanoes are listed in the GVP database. This discrepancy may have arisen because the UNEP/WCMC data may include pre-Holocene volcanoes, and/or counting all vents and cones as individual volcanoes (when in fact many will represent subsidiary vents of larger volcanic systems). Furthermore, many of the 300 'volcanoes' mentioned on the WCMC datasheet possibly lie outside of the boundary of the Kamchatka Volcanoes World Heritage property - as indeed do some of the Holocene volcanoes listed by the GVP.

Other examples of sites with multiple Holocene volcanoes are:

World Heritage List	
Virunga National Park, Democratic Republic of Congo	5
Galapagos Islands, Ecuador	12
Isole Eolie, Italy	4
Tongariro National Park, New Zealand	3
Sangay National Park, Ecuador	2
Tentative lists	
Las Parinas, Argentina	2-15
Ogasawara Islands, Japan	more than 12
Great Rift Valley Ecosystem, Kenya	over 20
The Sublime Karsts of Papua New Guinea	3

Archaeological sites and settlements periodically buried beneath volcanic products

There are a small number of cultural sites on Tables 1 and 2 (see Annex) that are either important archaeological sites or are exposed to repeated burial beneath fall deposits, pyroclastic flows, landslides or lahars. The most notable examples in the World Heritage List are The Archaeological Areas of Pompeii, Herculaneum and Torre Annunziata, Italy; the Joya de Ceren Archaeological Site, El Salvador; and Antigua Guatemala, Guatemala. These sites have been included in the 33 Holocene volcanic World Heritage properties, but not in the list of 27 sites containing Holocene volcanoes.

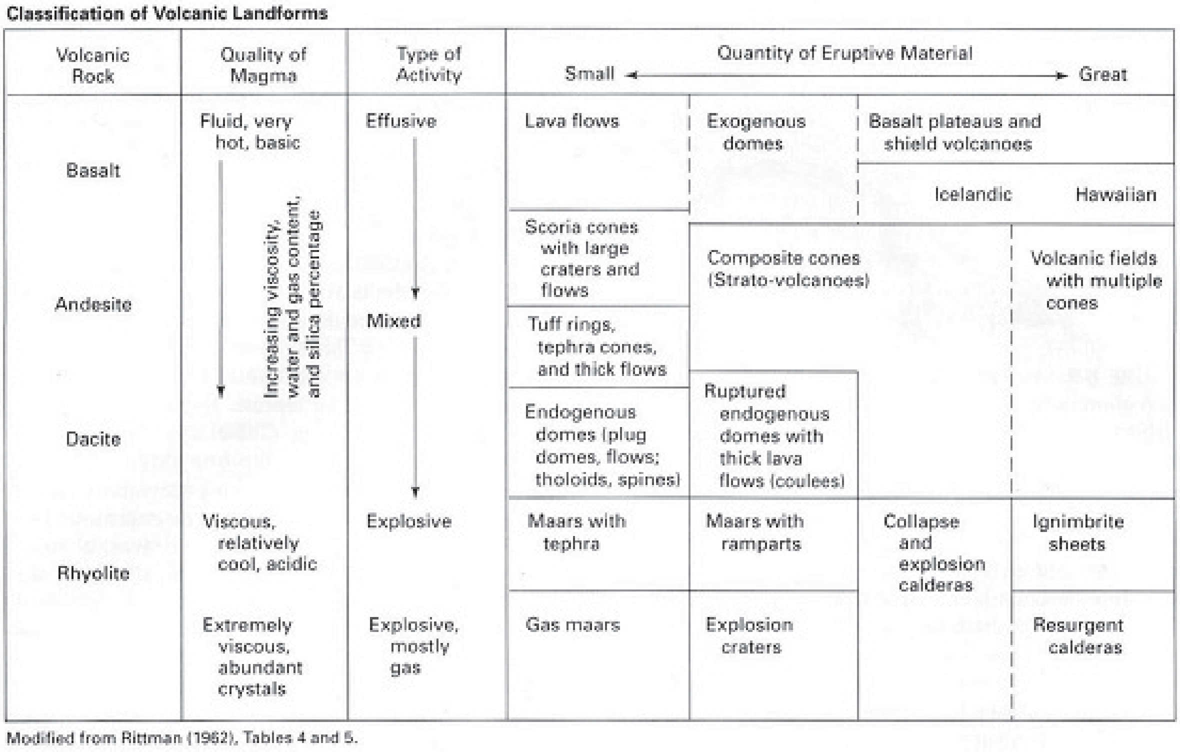
Atolls and reef-fringed volcanic islands

One type of landform that has not been included here, but is usually built on a volcanic basement (a seamount) and therefore should at least be acknowledged, is an atoll. This category might also include other ocean islands which have a volcanic basement, but are capped with carbonate deposits and with some fringing reefs. Thus, while atolls are not volcanic landforms, they are very often formed around volcanic peaks that may once have protruded above the surface of the ocean, but whose sub-aerial part has since been eroded back to sea-level. There are many atolls or reef fringed islands on the World Heritage List. Most of the world's atolls are in the Pacific Ocean and Indian Ocean, with just one group in the Atlantic Ocean and one in the Red Sea. They have not been included in this study because: 1) the sub-aerial exposure of volcanic rock is frequently limited, and 2) atolls were identified as a separate group of geological phenomena in the IUCN's theme study Geological World Heritage: A Global Framework (Dingwall et al., 2005).

Technical framework for gap analysis

Before undertaking evaluation of the volcanic sites on the World Heritage List and Tentative Lists, a reasoned framework must be established that will enable sites to be grouped and compared. There are a number of different ways that volcanoes and volcanic landforms have been classified, and it will be impossible here to identify or devise a single scheme that will provide adequate grouping of the World Heritage volcanoes, so an evaluation framework will be devised from one or more of the established classification systems. For example, volcanoes may be classified on the basis of their monogenetic or polygenetic origin, the scale of their explosive activity, the chemistry of their magma, their plate tectonic (or geotectonic) setting, or their landform. Below is a brief description of the principal classification systems.

Figure 5: Classification of volcanic landforms after Bloom (1998), modified from Rittman (1962).



Classification of Volcanic Landforms

Volcanic Rock	Quality of Magma	Type of Activity	Quantity of Eruptive Material Small ← → Great			
Basalt	Fluid, very hot, basic	Effusive	Lava flows	Exogenous domes	Basalt plateaus and shield volcanoes	
					Icelandic	Hawaiian
Andesite	Increasing viscosity, water and gas content, and silica percentage	Mixed	Scoria cones with large craters and flows Tuff rings, tephra cones, and thick flows	Composite cones (Strato-volcanoes)		Volcanic fields with multiple cones
Dacite			Endogenous domes (plug domes, flows; tholoids, spines)	Ruptured endogenous domes with thick lava flows (coulees)		
Rhyolite	Viscous, relatively cool, acidic	Explosive	Maars with tephra	Maars with ramparts	Collapse and explosion calderas	Ignimbrite sheets
	Extremely viscous, abundant crystals	Explosive, mostly gas	Gas maars	Explosion craters		Resurgent calderas

Modified from Rittman (1962), Tables 4 and 5.

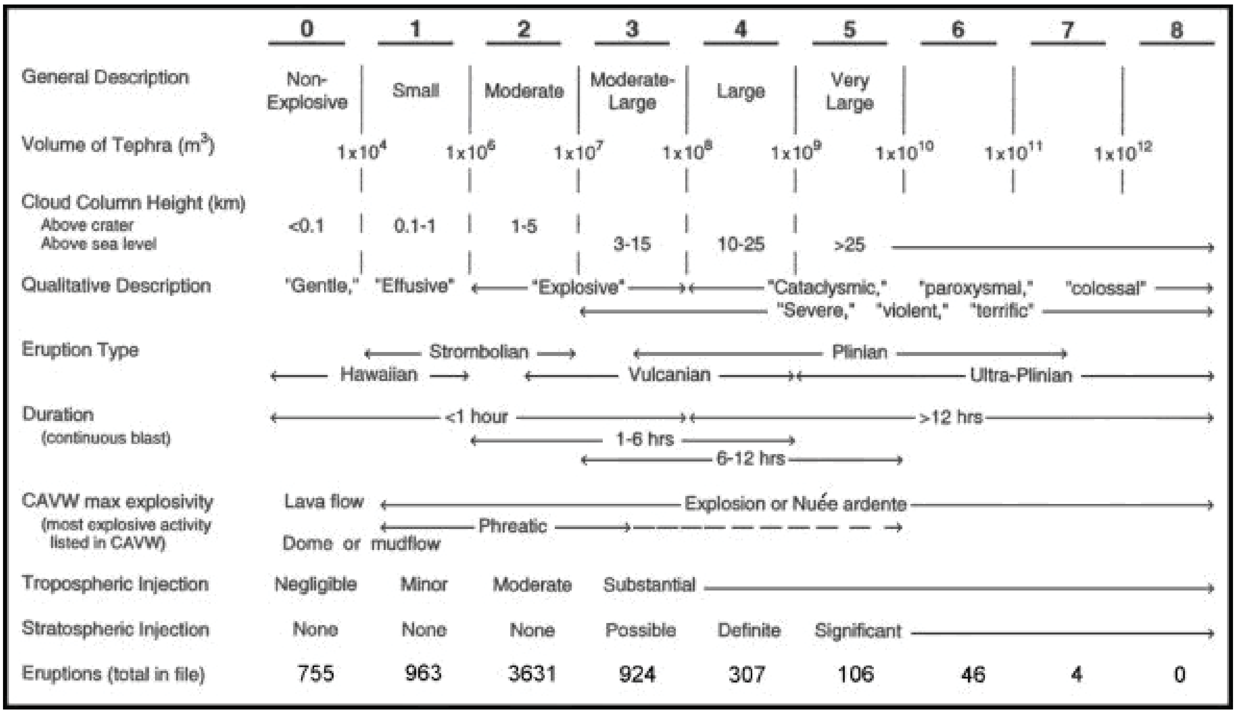
Genetic classification

The varying chemistry and volatile content of magma is the driving force in the diversity of volcanic activity and form. Francis (1993) identified the chain of cause and effect as follows:

> *‘1. the chemical composition dictates the melting temperature*
> *2. temperature, volatile content and degree of polymerization dictate viscosity*
> *3. viscosity and volatile content dictate ease of vesiculation and degassing*
> *4. ease of degassing dictates the explosive potential of an eruption*
> *5. explosiveness of an eruption dictates whether lavas or pyroclasts are produced’*

Thus, at one end of the range volcanoes that effuse basaltic, usually fluid, magma from which the volatiles escape relatively easily have low explosive activity and therefore produce abundant lavas and only limited amounts of pyroclastic material. These volcanic eruptions may emanate from fissures or central vents, and form extensive lava plains or low-angled ‘shield’ volcanoes. In contrast, at the other end of the range are

Figure 6: Volcanic Explosivity Index (Source: www.volcano.si.edu)



volcanoes that erupt more silicic and therefore viscous magma (such as andesites and rhyolites), meaning that their volatiles may only escape explosively. In so doing the magma and older rocks around the vent are fragmented into abundant pyroclastic material, and the effusion of lavas is more limited. Such activity builds cones with steeper slopes. There are of course gradations between these extremes, while it should be also noted that the larger central volcanoes tend to be polygenetic (involving a number of different phases and modes of construction), frequently having evolved over hundreds of thousands of years. It is also notable that the presence of water interacting with rising magma may cause an eruption to be violently explosive (phreato- or hydro-magmatic). A well known scheme showing these variations and resulting volcanic forms was constructed by Rittman (1962), and modified by Bloom (1998) (Figure 5).

Styles of eruption

As explained above, volcanic eruptions may be differentiated by the power or explosiveness of their activity. This was quantified by Newhall and Self (1982) and their Volcanic Explosivity Index (VEI) is shown with modifications in Figure 6, as it appears in the GVP website (www.volcano.si.edu).

Related to the VEI is an older scheme of grouping volcanoes according to their style of activity first introduced by Lacroix in 1908, but developed subsequently by other volcanologists. This is an observational scheme that identifies the different eruption styles of historic ‘type’ volcanoes. This scheme has been summarised in Figure 7, also abstracted from Bloom (1998).

A further type in addition to those noted in Figure 7 is the group of explosive phreatomagmatic, or hydromagmatic, eruptions (i.e., those that occur when external water is in contact with magma). At the less intense end of this range is the “wet” variety of Strombolian activity, known as Surtseyan (named after the eruption that formed a new island in 1963-67 off the south coast of Iceland), and more recently it has been recognised that Vulcanian and Plinian eruption styles may also have phreatomagmatic varieties (for example, phreatoplinian).

Figure 7: Types of volcanic eruptions after Bloom (1998), modified from Short (1986).

Types of Volcanic Eruptions (modified from Short, 1986, Table 3-1)

Type	*Characteristics*
1. Icelandic	Fissure eruptions, releasing low-viscosity basaltic magma; non-explosive, gas-poor; great volumes of lava issued, flowing as sheets over large areas to build basalt plateaus.
2. Hawaiian	Fissure, caldera, and pit crater eruptions; mobil basalt lavas, with some gas; quiet to moderately explosive eruptions (VEI: 0 or 1); occasional rapid emission of gas-charged lava produces fire fountains; only minor amounts of tephra; builds lava domes.
3. Strombolian	Summit crater with lava lake; moderate rhythmic to nearly continuous explosions resulting from spasmodic gas escape (VEI:1–3); clots of lava ejected, producing bombs and scoria; periodic more intense activity with outpourings of lava; light-colored clouds (mostly steam) reach upward only to moderate heights.
4. Vulcanian	Stratocones (central vents); viscous lavas; lavas crust over in vent between eruptions, allowing gas buildup below surface; eruptions increase in violence until lava crust is broken up, clearing vent, ejecting bombs, pumice, and lava flows from top of flank after main explosive eruption; dark ash-laden clouds, convoluted, cauliflower-shaped, rise to moderate heights depositing tephra along flanks of volcano. (Note: Ultraplinean eruption has similar characteristics but results when other types (e.g., Hawaiian) become phreatic and produce large steam clouds, carrying fragmental matter.)
5. Vesuvian	More paroxysmal than Strombolian or Vulcanian types; extremely violent expulsion of gas-charged intermediate-composition magma from stratocone vent; eruption occurs after long interval of quiescence or mild activity; vent tends to be emptied to considerable depth; lava ejects in explosive spray (glow above vent), with repeated clouds (cauliflower) that reach great heights and deposit tephra.
6. Plinian*	More violent form of Vesuvian eruption (VEI: 3 or more); last major phase is uprush of gas that carries cloud rapidly upward in vertical column for kilometers; narrow at base but expands outward at upper elevations; cloud generally low in tephra.
7. Peléean	Results from high-viscosity silicic lavas; delayed explosiveness; conduit of stratovolcano usually blocked by dome or plug; gas (some lava) escapes by lateral blasts or by destruction or uplift of plug; gas, tephra, and blocks move downslope in one or more blasts as nuées ardentes producing directed deposits.
8. Katmaian	Variant of a Peléean eruption characterized by massive outpourings of fluidized ashflows; accompanied by widespread explosive tephra; ignimbrites are common end products, also hot springs and fumaroles.

*named for the Roman scholar, Pliny the Younger, who wrote a detailed narrative of the Vesuvian eruption of A.D. 79.

While the VEI and type volcano classification schemes are not synonymous, they are often used together to describe the activity of any particular eruption. Furthermore, although the different degrees of explosiveness influence the type of deposit and landform produced, different eruptions of the same volcano may have different eruption styles and VEIs, and so these schemes do not assist in the classification or grouping of the World Heritage volcanoes.

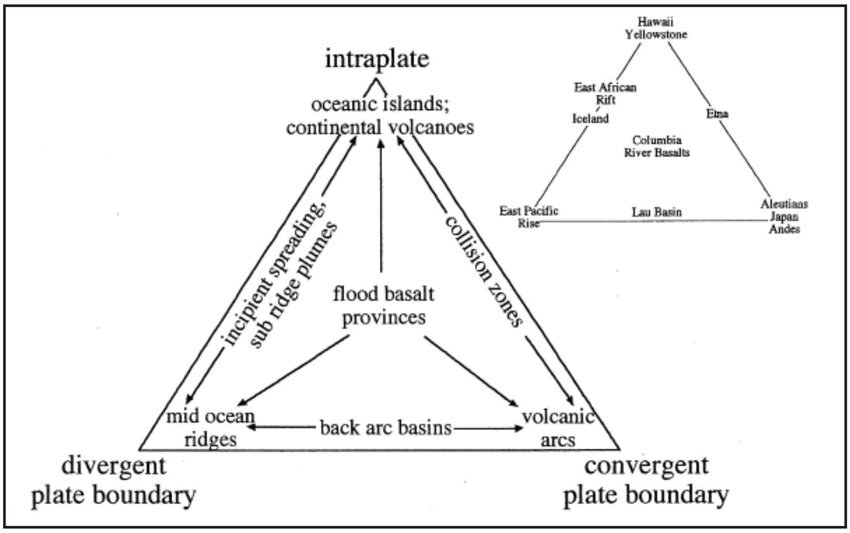
Plate tectonic setting

The geochemistry and petrology of volcanic rocks are closely related to the tectonic environment in which they originated, since ultimately the chemistry of magmas is related to plate tectonic processes. Volcanoes from different plate tectonic environments are therefore distinct in terms of the composition of their source magmas, their eruptive behaviour, the characteristics of their volcanic deposits and the morphology of their volcanic landforms.

Figure 1 shows the boundaries of the world's tectonic plates and the distribution of the world's major active volcanoes (not necessarily World Heritage volcanoes). It is clear from the map that the highest densities of volcanoes coincide with plate boundaries. Such boundaries are defined by geologists as either constructive, where two plates separate (such as along the Mid-Atlantic Ridge or Juan de Fuca Ridge), or destructive, where plates converge in regions known as subduction zones (such as those within the Pacific 'Ring of Fire', or the islands of the Caribbean). There are also volcanoes that occur within plates (i.e., beyond plate boundaries). These are associated with 'hotspots' over plumes of rising magma in the Earth's mantle, and are called intraplate volcanoes. Volcanoes also occur in areas of plate collision and in rare instances are associated with transform boundaries (where plates slip past one another in a horizontal movement along faults). As explained in Text Box 3, the relationship between plate tectonics and volcanism is fundamental: the mechanisms of plate tectonics influence the formation of magma in the mantle, either through decompression of hot, solid mantle material at constructive margins and mantle plumes, or the lowering of melting temperature of mantle material by the addition of volatiles (mainly water), as at destructive plate margins. These different processes give rise to variations in the composition of magmatic melts.

Thus, in simplified terms, magma erupted at mid-ocean ridges (constructive margins) are typically basic in composition, producing fissure volcanoes, extensive lava fields and lava shields. Most of these volcanoes are underwater, so they are not visible, but where the ocean ridges coincide with rising mantle plumes, large volcanic islands, such as Iceland, may be formed. It should also be noted that even in this setting, the magma beneath a longer-lived volcano may fractionate to become silica enriched, resulting in more explosive activity and the building of a composite cone. A similar form of volcanism exists where intraplate (as opposed to ridge) volcanoes are built on the ocean floor over hot, rising mantle plumes. Intraplate mantle hotspots may also penetrate the crust of a continent, but here the crustal rocks are partially melted and assimilated by the rising mantle plume. This produces a wider range of magmas, with higher silica and alkali content, in turn influencing the eruption styles and products. In the past, mantle plumes have caused eruptions on both continental and oceanic crust at a much greater scale than anything experienced in the historic period, resulting in enormous outpourings of basaltic magma. These gigantic eruptions are known as Flood Basalts and are to be found

Figure 8: Diagram showing the plate tectonic settings of volcanoes, after Perfit and Davidson (2000, modified from Pearce 1996



today in areas of the world known as Large Igneous Provinces (LIP). For example, in India the Deccan Traps are the remains of a late Cretaceous (60-65Ma) flood basalt event, and comprise piles of lavas nearly 2km thick, the remains of which still cover an area of 500,000 km^2 .

Volcanism is also associated with active rifting of continental crust, such as at the African Rift Valley. Such volcanism is produced because of extension (stretching) of the crust, and it may also be associated with mantle plume activity. One product may be outpourings of basalts, but on a lesser scale and with lava more chemically diverse than that of flood basalts. Assimilation of continental crust by the rising magma gives rift volcanoes some of the characteristics more generally associated with subduction volcanoes, such as having a wider range of rock types and explosive habits, including rare types of magmas such as carbonatites and highly alkaline melts.

Figure 9: Surface volcanic forms and features, after Short (1986)

Domes and cones of basaltic lava Basalt cones Central and fissure vents Flank outflows of lava Basaltic lava shield (small) Basaltic dome (shield) structure Icelandic spatter cones Scoria cones	**Craters and calderas** Craters Pit craters Caldera Glencoe Krakatau Multiple Erosion caldera
Lava plateaus and plains Ignimbrite plateaus Basalt plateaus Fissure eruptions Phonolite plains Basalt plains	**Viscid lavas, Coulées and Tholoids** Convex lava flows Cumulo domes Obsidian domes Plug domes Spines
Lava fields Lava tongues Ponded lavas Pahoehoe: tumulus, squeeze-ups, pressure ridges Block pahoehoe Block aa Block and ashflows Fire fountains Scoria mounds (cinder cones) Adventive cones	**Tephra showers and nuées ardente** Vulcanian ash phase Nuées ardente (First order) Plateau building (Ignimbrite sheet) Nuées ardente (Second order)
Exposed intrusive features Laccoliths Dikes, Sills	**Tephra-built stratified (with lava) cones** Ash cones Young cones Composite (stratified) cones Multiple cones Parasol ribbing Lahars (mudflows)
Maars and tuff rings Maars Ubehebes Basaltic tuff rings Diatremes	**Erosion features** Ravine cuts (Barrancos) Planeze stage of dissection Necks and plugs Erosion calderas Eroded dome Lava ridges (inverted topography) Lava palisades
Rifts Rift valley Rift lines	

The great majority of sub-aerial volcanoes are located at convergent plate boundaries, also known as subduction zones. Subduction may take place where two ocean plates, or an ocean plate and continental plate, are driven against one another and one bends and sinks beneath the other. The descending plate releases volatiles (principally water) as it gets heated, and these lower the melting temperature of the mantle wedge above the subducting slab. This process causes, magma to be generated, which on rising to the surface of the overriding plate creates a chain of volcanoes, known as a volcanic arc. Where two ocean plates converge, the line of volcanic islands produced is called an island arc system (e.g., the Lesser Antilles island group of the Caribbean, or the Aleutian Islands of the Bering Straits, USA); where an ocean plate subducts beneath a plate with continental crust, a continental volcanic arc will be formed (e.g., along the eastern side of South America). Partial melting of the mantle wedge above the subducting plate and fractional crystallisation of the ascending magma produce magmas generally richer in silica and alkaline minerals, so that andesites, rather than basalts, are more characteristic of island arc volcanoes. At continental margins, while andesites are produced, assimilation of continental crust may make the magma even more silicic, erupting as rhyolite or dacite in composition.

Figure 10: Classification of volcanic landforms with emphasis on volcanic mountains, after Thouret (2004).

Monogenetic hills and small mountains (1) pyroclatic landforms: cinder or scoria cones; hydromagmatic tuff cones and tuff rings, maars and diatrmes (2) lava-made landforms: endogenous and exogenous domes, crater row and fissure vent (3) Mixed landforms of intra- or subglacial volcanoes: tuya (table mountains) and mobergs (4) submarine landforms: seamounts and guyots
Medium to large, high composite volcanic mountains (1) stratovolcanoes: simple cone with summit crater; composite cone with sector collapse scar (summit amphitheatre), composite cone with a caldera or a somma (2) twin cones; compopund or multiple cones with elongate ridge; cluster of cones (3) shield volcanoes with shallow-sloped flanks and caldera in summit region: Hawaiian shields and domes; Galapagos, Icelandic, and scutulum-type shields
High plateaux with altitudinal range and dissected relief (1) continental flood basalt plateau (2) dissected plateau of ash flows and ignimbrite sheets (3) Intermediate-silicic multivent centres that lack a central cone; rhyolitic centres; silicic volcanic lava field with multiple domes and calderas
Calderas on stratovolcanoes or on uplifted basement (1) collapse and explosion somma (2) collapse on Hawaiian shield volcano (3) collapse in basement and resurgent caldera (4) very large and complex resurgent calderas
Landforms resulting from a combination of eruptive and/or ersoional processes on volcanic mountains (1) horseshoe-shaped avalanche caldera from a flank failure or magmatic (Bezymianny-type), gravitational (Fugendake) or mixed origin (Bandai-san, La Reunion cirques) (2) amphitheatre-shaped, erosional calderas (Haleakala, Maui)
Landforms resulting from denudation and inversion of relief (1) eroded cone; inverted small-scale landforms: necks, culots (2) much eroded cone, inverted lava flow and planeze (3) roots of palaeo-volcanic mountain: dissected cauldron and hypovolcanic complex

The large amount of melting that takes place in the lower crust produces great volumes of silicic magmas, which migrate upward to accumulate in great intrusive bodies known as batholiths. If these come close to the surface, such magma bodies may cause volcanic eruptions of enormous magnitude, ejecting thousands of cubic kilometers of pyroclastic material over vast areas (seen in the rock known as ignimbrite). In some parts of the world (e.g., in Argentina and in the Colorado San Juan volcanic field) there are expansive ignimbrite plateaus, representing a scale of eruption not seen in the historic period. Associated with this activity may be collapse of the roof of the magma chamber, forming a gigantic caldera (e.g., Cerro Galán in Argentina).

The relationships between volcano types and tectonic region are shown schematically in Figure 8, abstracted from Perfit and Davidson

Classification of volcanic landforms

The literature on the geomorphology of volcanic landforms or landscapes is very limited, and there are very few classifications of volcanic forms. A good review was provided by Short (1986) in a paper prepared for NASA (the context for this was therefore volcanic forms viewed from space, as analogies of landforms observed on other planetary bodies). He noted that while there have been many standard reference and text books on volcanology, the treatment of landform has been subsidiary to that of petrology and process. Nevertheless, two works that were written specifically to describe volcanic landforms are *Volcanoes as Landscape Forms* (Cotton, 1952 - important text, but problematic in its restricted geographical references) and *Volcanic Landforms and Surface Features: A Photographic Atlas* (Green and Short, 1971). More recently, Francis (1993 - subsequently revised by Francis and Oppenheimer, 2003) provided a chapter on landscape forms in his book *Volcanoes*.

In view of the shortcomings in the literature relating to the classification of volcanic landforms, Short (1986) attempted his own classification (Figure 9). The present study finds this classification unsatisfactory in that: (1) it is more of a list than a classification; (2) it confuses landforms with processes and tectonic structures. These shortcomings are acknowledged by Short, who comments that his classification is nevertheless valuable as a listing of the common larger surface features attributable to volcanism. It is on this basis that Short’s table is included here.

Geomorphology textbooks also provide poor or limited consideration of volcanic landforms. There is usually a chapter or sub-chapter on volcanoes, but typically it is rather cursory. Bloom (1998) provides one of the best treatments of volcanic landforms, basing descriptions on a classification adapted from Rittman (1962) (Figure 5), while Summerfield (1991) usefully places landforms associated with igneous activity in their global, plate tectonic setting (his text also includes the landform classification provided by Bloom).

Most recently Thouret (1999) published a review of the geomorphology of the volcanoes on Earth, and as a part of the review recommended that classifications of volcanic landforms should be improved to take care of the complexity of their formation, because varied magmatic systems, styles of eruption, and the nature of the erupted material all influence morphology. Thouret noted that the traditional classifications of volcanic landforms are based on types of activity, magmas and erupted products. He states that improved classifications might also be based upon geomorphic scale, constructional versus erosional origin, mono or polygenetic form, types of activity, and type and volume of magma and erupted material. In his 1999 paper he proposed six main types of constructional and erosional landforms, and in a subsequent paper (Thouret, 2004) he further developed his classification with a view to better definition of the different types of volcanic mountains. Thouet’s 2004 classification is reproduced in Figure 10.

Conclusion: A framework for gap analysis

The brief for this report calls for a general framework within which to place the World Heritage volcanoes and as a basis for undertaking gap analysis. It also demands that any such framework must not be an over-complicated taxonomy of volcano types and forms. This study finds both Short's and Thouret's classifications too detailed for the purpose of this review and instead groups World Heritage volcanoes on the basis of their plate tectonic, or geotectonic, setting, while providing a simplified combination of Short's and Thouret's classification as a checklist for assessing the variety of landforms in the World Heritage volcanic estate.

Identifying the gaps

Gaps in the range of volcanic World Heritage properties

With 57 inscribed volcanic properties, containing a minimum of 101 Holocene volcanoes, it can be claimed that there already is adequate representation of the world's volcanoes on the World Heritage List. However, Tables 4 (Plate tectonic setting of World Heritage Volcanoes), and 5 (Volcanic World Heritage properties by Geographical Region), do reveal some gaps in the plate tectonic and geopolitical settings of these volcanoes. Furthermore, while it has not been possible because of shortfalls in the basic data to establish the complete range of landforms in each of the 57 properties; it is known that some important landforms types are not represented. This section will examine if it is necessary to fill all the gaps and if so how this might be done from sites proposed in the Tentative Lists, or ultimately by suggesting suitable new sites that might be added to the tentative lists of relevant State Parties.

Figure 7 provides the basis for classifying volcanic sites on grounds of their plate tectonic setting and Table 4 indicates the number of sites in each setting. The table shows that the 57 volcanic properties on the World Heritage List are relatively well distributed through the various plate tectonic settings, with 14 sites representative of divergent plate boundaries, 17 of convergent boundaries, 6 of collision zones, and 14 of intraplate volcanism (6 sites are pre-Tertiary - too old to sit in this scheme). Volcanoes of continental and island arc systems, plate collision zones and mid-ocean ridges are well represented, while least represented are flood basalts and back-arc basin volcanoes. Nomination of examples from these latter groups might be encouraged from sites already listed on Tentative Lists, whilst new entries to the Tentative Lists might include examples of continental intraplate and flood basalt volcanoes (e.g., Columbia River Basalts, USA; Deccan Traps, India).

Scaling-up the view to regional plate tectonic environments and volcano groups, the Volcanoes of Kamchatka World Heritage property is a good representative of an ocean subduction environment, although the addition of the Ogasawara Islands from Japan's Tentative List as a trans-national serial extension would enhance the range of volcanic forms represented within this tectonic group. In contrast, Holocene continental arc volcanism is not well represented on the World Heritage List by any single large group (although some smaller sites do lie in this environment), and Las Parinas on Argentina's Tentative List is one possibility that could enhance this category. Larger representation of continental and oceanic rifting (divergent margins) may eventually be realised through the current proposals for serial trans-national nominations covering the Mid-Atlantic Ridge and the Great Rift Valley of Africa.

When the geopolitical distribution of volcanic World Heritage properties (Table 5) is examined, it is clear that because of the haphazard process of site selection and nomination of World Heritage properties by State Parties, the distribution of volcanic properties on the World Heritage List does not necessarily conform to priority global conservation sites that might be determined purely on scientific grounds. The Table also illustrates the fact that volcanoes are not distributed evenly across the Earth's surface. Thus, Table 5 shows poor representation of sites in Africa beyond East and Central Africa, South-Central and Northern Asia, Australia, and Eastern Europe, principally because these are relatively stable areas of the Earth's crust. While there are some Holocene volcanoes on the mainland of Europe (Germany, France, Spain) the high number of volcanic World Heritage properties in this region relate only to those in the Mediterranean and overseas (mainly ocean) territories. Most surprising is the lack of any sites in Melanesia and Polynesia (although these will have some sites which are overseas territories of European countries), and the relatively few sites in North America, which has many excellent, well studied and accessible examples. On regional grounds, there does appear to be some need to consider representation from Oceania and North America.

Table 4: Plate tectonic setting of World Heritage volcanoes

Plate tectonic setting after Perfitt and Davidson (2003)	Number of sites WH List	Tent. Lists	Examples of volcanoes from the WH List
Divergent plate boundary			
- mid-ocean ridge	7	8	Surtsey, Galapagos
- continental rifting	7	2	Nyamuragira
Intraplate			
- oceanic islands	6	9	Teide, Mauna Loa
- continental volcanoes	5	0	Kilimanjaro, Yellowstone
- flood basalt provinces	3	0	Iguazu (Parana FB), Giants Causeway (Antrim FB)
Convergent plate boundary			
- continental arc	8	5	Sangay, El Misti
- island arc	9	12	Shiretoko, Qualibou
- back arc basin	0	0	
Collision zones	6	0	Vulcano/Stromboli
Pre-Quaternary volcanic sites	6	4	
Total sites	57	40	

Table 5: Volcanic World Heritage properties by geopolitical region

World Regions (UN Macro regions)	Number of WH sites	
Africa		
- Northern Africa	0	
- Eastern Africa	7	
- Western Africa	1	
- Middle Africa	2	
- Southern Africa	1	Total: 10
Asia		
- Eastern Asia	2	
- South-central Asia	1	
- South-eastern Asia	3	
- Western Asia	1	Total: 7
Europe		
- Eastern Europe	2	
- Northern Europe	7	
- Southern Europe	3	
- Western Europe	3	Total: 15
Latin America		
- Caribbean	3	
- Central America	6	
- South America	8	Total: 17
North America	2	Total: 2
Oceania		
- Australia and New Zealand	5	
- Melanesia	1	
- Polynesia	0	Total: 6

The most difficult gaps to identify are in the range of landforms contained within the 57 volcanic World Heritage properties. On the one hand, with a minimum of 101 Holocene volcanoes covered by these sites across the range of plate tectonic settings, it is likely that most of the features identified in Bloom's and Thouret's classifications will be covered. On the other hand, while it is possible to classify the larger volcanic structures at any volcanic site, identification of the full suite of subsidiary landforms on these structures is not possible because of negligible or at best limited local information.

Table 6 lists the main types of volcanic landforms and examples of inscribed properties in which these features may be found. The table is a much simplified adaptation of Short's and Thouret's classifications and the examples are based on the author's and reviewers' knowledge of particular World Heritage properties (which is far from comprehensive). It is clear from the table that the two main forms of large volcanoes - shield volcanoes and stratovolcanoes - are well represented on the World Heritage List, although Icelandic type shield volcanoes are missing. With so many island arc and continental arc stratovolcanoes (Kamchatka, Philippines, Indonesia, South and Central America), it can confidently be claimed that simple and composite structures, with craters and calderas of different types are adequately represented. Interestingly there are no fissure volcanoes, although the proposed Mývatn-Laxa site on Iceland's Tentative List contains the active volcano Krafla (Plate 1). Furthermore, while the newly-inscribed World Heritage property of Surtsey represents a style of shallow water phreatomagmatic eruption that constructed a tuya-like edifice (table mountain), fissure and central volcanoes erupted beneath water or ice forming hyaloclastite ridges and tuyas respectively are poorly represented. These could be covered in a proposed extension to Iceland's Þingvellir World Heritage Site, which incidentally might also include the classical Iceland shield Skjaldbreiður, and the Herðubreiðarlindir and Askja site from Iceland's Tentative List, as a potential serial property with Surtsey.

There are many examples of smaller scale monogenetic vents (scoria and tuff cones, tuff rings, maars - e.g., Aïr and Ténéré Natural Reserves, Niger; Jeju Volcanic Island, Korea), and all of the different types of lava flows (pahoehoe, aa and block, couleés, etc) are present. The current volcanic World Heritage properties also contain the full range of subsidiary lava landforms, including lava tube cave systems (Hawaii Volcanoes NP, USA, and Jeju Volcanic Island, Korea). There are fine examples of lava domes, including emergent domes on active stratovolcanoes (e.g., Sheveluch Volcano, Kamchatka) and eroded remnants of historic features (e.g., the Pitons Management Area, St Lucia). While two flood basalt provinces are represented (Paraná at Iguaçu, Brazil/Argentina and North Atlantic at Þingvellir, Iceland) there may be scope to consider a more classical example of this phenomenon, such as the Columbia River Flood Basalts, USA, or the Deccan Traps, India (neither of these are on the USA or Indian respective Tentative Lists). Not so well represented are large scale ash flows and ignimbrite sheets, although the site, Las Parinas, on Argentina's Tentative Site might eventually provide some good examples.

There are a range of different types of calderas on the World Heritage List. This could be enhanced by the inclusion of the Taal Volcano Protected Landscape from the Philippines Tentative List, which is a complex, historically active, Holocene resurgent caldera, designated a Decade Volcano by the International Association of Volcanology and Chemistry of the Earth (IAVCEI) because of its large, destructive eruptions.

Poorly represented are intrusive landforms, and in fact none appear to have been ever specifically put forward for nomination (for example, the Aïr and Ténéré Natural Reserves, Niger, which contain the largest ring dike structure in the world, were not inscribed under the geological category (viii)). There is scope also to consider proposals that reflect some of the world's outstanding intrusive landscapes (options to consider might include the Shiprock volcanic neck (a diatreme) and dike complex, New Mexico, USA; the Great Dyke of Zimbabwe, or the classical Scottish Tertiary Igneous Province, U.K., etc).

Table 6: Landform types in volcanic World Heritage properties

Type of volcanic landform	Represented (Yes or No)	Example from the World Heritage List
Monogenetic landforms and fields		
- cinder or scoria cones		Galapagos Islands, Hawaii Volcanoes NP
- tuff cones and tuff rings	Y	Jeju volcanic Island
- maars and diatremes	Y	Jeju volcanic Island
- monogenetic volcanic field	N	
- tuya	Y	Surtsey Volcanic Island (but not classical sub-glacial
- moberg ridge	N	table mountain)
- lava domes	N	
- lava flows and lava fields	Y	Pitons of St Lucia, Kamchatka
		Þingvellir NP, Hawaii Volcanoes NP, Giant's Causeway and the Causeway Coast
- lava tube cave systems	Y	
- continental flood basalts	Y	Rapa Nui, Jeju Volcanic Island, Hawaii Volc. NP
- ash flows and ignimbrite sheets, plains and plateaus	Y	Giant's Causeway, Iguazu/Iguacu NPs Some in Yellowstone NP
Polygenetic volcanoes and calderas		
stratovolcanoes:		Sangay NP, Kamchatka
- simple with summit crater	Y	Teide National Park, Kamchatka
- composite with sector collape scar and/or caldera	Y	Volcanoes of Kamchatka
- compound or multiple volcanoes	Y	
- rhyolitic centres	N	
- silicic volcanic lava field with multiple domes and calderas	N	
caldera:		Volcanoes of Kamchatka
- explosion (somma)	Y	Krakatau
- collapse-explosion (Krakatao)	Y	Hawaii Volcanoes NP, Galapagos Islands
- collapse-shield	Y	Yellowstone NP
- resurgent caldera (Valles)	Y	
- large and complex (Toba)	N	
Shield volcanoes		
shields and domes- types		
- Hawaiian	Y	Hawaii Volcanoes NP
- Galapagos	Y	Galapagos Islands
- Icelandic	N	
Volcanic landforms resulting from eruptive and/or erosional processes		Teide NP
- avalanche caldera from a flank failure of magmatic, gravitational, or mixed origin	Y	
- erosion caldera and amphitheatre valley	N	
Volcanic landforms resulting from denudation and inversion of relief		
- eroded cone, eroded pyroclastic-flow deposit and sheet	N	
- inverted small scale forms: necks, culots, dykes and sills	Y	Old & New Towns Edinburgh, Frontier Roman Empire
- eroded lava flow, inverted relief and planeze	N	
- roots of palaeo-volcano, cauldron, and hypovolcanic complex	Y	Aïr and Ténéré Natural Reserves

Missing iconic volcanoes

Interestingly, the World Heritage List does not contain many of the volcanoes that might be commonly recognised by the general public. The best known inscribed sites are probably Kilauea and Mauna Loa, on Hawaii Island, USA; Krakatau, Indonesia; and Mounts Kenya and Kilamanjaro, Kenya. Although not inscribed specifically, Vesuvius is represented by the Pompeii, Herculaneum and Torre Annunziata archaeological World Heritage property, which lies on the slope of the volcano. Not on the List are such iconic or world-renowned volcanoes as, for example: Mt Etna, Italy; Thera (Santorini), Greece; Mt Fuji, Japan; Paracutin, Mexico; Mt Mayon, Philippines; Mt St Helens and Crater Lake, USA; Laki, Iceland; Mt Pelée, Martinique, and Tambora, Indonesia. Mount Fuji is particularly significant because the volcano and its surroundings receive more public visits in a year than any other on the planet.

Just because these volcanoes are well-known and used as examples in classroom teaching it does not mean that they are necessarily scientifically important. However, those that have come to the notice of the general public, and have been instructive to science because of their recent historic eruptions, have been Mt Pelée, Martinique; Mt St Helens, USA; and Paracutin, Mexico. Mt Fuji is the only volcano mentioned above that is on a Tentative List (of Japan).

Filling the gaps

This analysis has shown that there is already good representation of the world's volcanoes and volcanic landforms on the World Heritage List, but that there are some gaps that might be filled in the future to make the list of World Heritage Volcanoes more complete, balanced and comprehensive. These volcanic sites are shown in Table 7, with the reasons for their choice, and whether or not they are already listed in the Tentative Lists. In compiling this list of sites consideration was given to plate tectonic setting, world geopolitical regions and landforms.

Table 7: Possible future candidate volcanic features or areas for inclusion on the World Heritage List

Name of volcanic feature	Comment and suggested action
Volcanic features	
Fissure volcanoes	Not represented - **potential properties:** 1) extension of Þingvellir NP WHS, Iceland, 2) future inscription of Mývatn-Laxa area, Iceland, tentative site (this will include the volcano Krafla - cover picture).
Hyaloclastic mountains (tuyas) and ridges	Not well represented, just Surtsey Volcanic Island - **potential properties:** 1) consider a future nomination tuya from type-area in Canada; 2) extension of Þingvellir NP WHS, Iceland
Icelandic type shield volcano	Not represented - **potential properties:** 1) extension of Þingvellir NP WHS, Iceland, to include Skjaldbreiður, 2) future inscription of extended Herðubreiðarlindir-Askja site on Iceland's tentative list (boundary to include appropriate shield(s)).
Continental Flood Basalts	Not well represented - **potential properties:** consider new nomination of Columbia Flood Basalt Province, USA and/or Deccan Traps, India
Resurgent calderas	Yellowstone NP, USA, is one example - **other potential site:** 1) Taal is a good example on the Philippines tentative list; 2) other posiblilities not on existing tentative lists are the Valles Caldera, New Mexico, USA; Toba Caldera, Indonesia; and Cerro Galán Caldera, Argentina.
Large ash flows and ignimbrite sheets/plateaus	Related to the above. Not well represented, but requires more detailed investigation of existing sites - **potential properties:** Las Parinas tentative site, Argentina; consider alternative new nominations from, say, USA or S America.
Intrusive landforms	Not well represented - **potential properties:** will require new nominations, e.g., Shiprock, New Mexico, USA; Scottish Tertiary Igneous Province, UK.
Whole landscapes	
Basaltic plains	Not well represented - **potential properties:** new nomination, for example, Snake River Plain, Idaho, USA, or extension of Herðubreiðarlindir-Askja tentative site, Iceland, to include the expansive lava plain known as the Odaðahraun.
Silicic volcanic field	As for resurgent calderas and ignimbrite plateaus, above
Mid-ocean ridges (may also incorporate some aspects of ocean floor)	Existing proposal for a Mid-Atlantic Ridge transnational serial nomination
Continental rifts	There is an existing proposal for an African Great Rift trans-national serial nomination
Iconic sites	Not well represented - to be considered on indivudual merits on basis of notoriety, scientific importance, and cultural and educational value - **some possible properties:** 1) Mt Fuji is on tentative list of Japan; 2) others such as Mt St Helens and Crater Lake, USA; Mt Pelee, Martinique; Laki, Iceland; Mt Mayon, Philippines; Thera, Greece; Mt Etna, Italy.

Requirements for integrity and management that should apply to sites with volcanic geology

This discussion will focus on the concept of integrity as it applies to the geological values of a volcanic World Heritage property, even if the property was not inscribed under the geological criterion (Criterion (viii)).

In the context of this study, integrity is an important idea that provides an intellectual framework for considering the scientific values and management of properties containing whole or major parts of volcanic systems, or specific volcanic landscapes or landforms. However, the concept is much less relevant in those sites that contain only limited volcanic deposits, are isolated from source vents, or have volcanic deposits from the deep geological past. These latter sites will be predominantly managed to protect the biological and cultural values for which they were inscribed, and therefore lie outside of the subject of this discussion.

Meeting the condition of Integrity

In order for it to be inscribed, the World Heritage Committee must be satisfied that a nominated property is of Outstanding Universal Value (OUV), meets the Condition of Integrity as set out in the Committee's *Operational Guidelines for the Implementation of the World Heritage Convention* (UNESCO, 2008), and is effectively protected and managed.

Integrity is a most important concept developed in the Operational Guidelines (2008, Section IIe, paras 87 - 95), where it is defined as:

> *'Integrity is a measure of the wholeness and intactness of the natural and/or cultural heritage and its attributes.*
>
> *Examining the conditions of integrity, therefore requires assessing the extent to which the property:*
>
> *a) includes all elements necessary to express its outstanding universal value;*
> *b) is of adequate size to ensure the complete representation of the features and processes which convey the property's significance;*
> *c) suffers from adverse effects of development and/or neglect.'*

Further definition of integrity has been provided in the Operational Guidelines for each of the four criteria relating to natural sites. For example, properties nominated under Criterion (vii) (natural beauty) are required to *'include areas that are essential for maintaining the natural beauty of the property'*, which include all of the factors which may influence change to the visual or aesthetic quality of a site. Similarly properties proposed under Criterion (viii) (geology) should *'contain all or most of the key interrelated and interdependent elements in their natural relationships.'* Ensuring that a site has integrity is therefore of fundamental importance, and relates to the completeness of the scientific case for inscription, as well as for its management. The need to ensure integrity also explains why the area of a World Heritage property should be of a scale adequate to contain and protect the essential parts of the system for which it was inscribed, and why accurate determination of the boundary of the site is so important.

For a volcanic World Heritage property to have scientific integrity means that the scientific justification and protection of all of the essential features that distinguish that particular volcanic system are complete. Thus, with respect to a Holocene volcano, it will be essential to protect the vent(s), as well as its range of lavas, pyroclastic deposits and subsidiary landforms. Care should also be taken to include features that demonstrate the geochemical and petrological characteristics of the volcano, which may have changed during the lifetime of the volcano (for example, through progressive fractional crystallization in, or zonation of, the magma chamber).

One problem in volcanic sites is the nested scales of the systems to which scientific integrity should relate. For example, in referring to the integrity of volcanic sites, the Operational Guidelines specifically recommends (Section IIe, para. 93) that *'...in the case of volcanoes, the magmatic series should be complete and all or most of the varieties of effusive rocks and types of eruptions represented.'* This statement is rather confusing and does not mean that all sites should contain all volcanic products and forms known to science: that would be impossible, because as we have seen, eruption style and therefore products and forms are dependent on the particular tectonic setting of a volcano. Nevertheless, scientific integrity does mean that all components of the volcanic system to be managed, whether a single volcano or a volcano group, are adequately represented, and the area of the property is sufficient to ensure the effective protection of that resource.

There are also practical challenges in delineating and protecting the entire scientific system of a volcano or volcano group. For one thing, as explained in Text Box 1, volcanologists now regard a 'volcanic system' as encompassing all of those eruptive phenomena fed by a common magma source. Then, even if the system is represented by just a single volcano, the size of any area required to protect it may be very large. A further difficulty in defining boundaries is that volcanoes and volcanic fields are frequently lived in and farmed, and economic activity may compromise the choice of area that could be protected. Nevertheless, creative solutions to these problems have been found on many existing World Heritage volcanoes, as explained with the following examples.

Example 1 - Jeju Volcanic Island, Republic of Korea

Jeju Island represents the sub-aerial part of the Mt Halla volcanic edifice, a basaltic shield volcano that developed on the floor of the Yellow Sea. The island is oval in shape, 74km long and 32km wide, with a central volcanic cone rising to a height of 1950m above sea level. As an autonomous province of the Republic of Korea, Jeju has a well-developed economy that is largely dependent on tourism, and a population of nearly one million people, approximately half living in Jeju City.

Plate 3: The Jeju Volcanic Island World Heritage Site contains many large lava tube caves (photo: K. S. Woo)

The volcano was built in c.100m deep water on the stable continental shelf, over a hot spot probably caused by decompression melting of the shallow asthenosphere. In its initial stages, the volcanic activity involved extensive hydromagmatic activity, followed by sub-aerial effusion of large volumes of basalt, and ultimately the building of a central cone by lavas and pyroclasts from a more evolved (basaltic-trachytic) magma source. There has been no activity of the volcano since the eleventh century. Especially noteworthy are the many well-developed features illustrative of the volcanic history of the island. These include a variety of rocks demonstrating chemical evolution in the magma chamber beneath the island, and a large number of well-developed subsidiary landforms and other features. These latter include 360 cinder cones, tuff cones and tuff rings, excellent coastal cliff exposures of pyroclastic deposits and columnar jointing, trachytic domes, basaltic lava flows and many long lava tube caves. Unable to nominate the whole island because of difficult land ownership and management problems, Korean scientists came up with two solutions to demonstrate the outstanding universal value, complexity and variety of the Halla volcanic system: either protection by means of several discrete sites scattered over the island (a serial approach), or the protection of one or more radiating wedge-shaped (more correctly keyhole-shaped) slices, each originating at and encircling the summit area of Mt Halla and widening toward the coast to contain important scoria cones, lava flows and cave systems. Eventually it was decided to develop a serial approach with three key elements of the volcano included: a tuff cone demonstrating the hydromagmatic mechanism of formation of the early island; a subsidiary vent, with its associated scoria cone, lava flows and lava tube caves, to indicate the scale and method of emplacement of the main body of the lava shield; and the summit area of Mt Halla showing the volcanic products and forms developed from a more evolved magma towards the end of volcanic activity.

Example 2 - Teide National Park, Tenerife, Spain

Teide National Park is located at the summit of the Las Cañadas volcano, which forms the main part of the island of Tenerife, Canary Islands, Spain. Like the Jeju example, Tenerife is a holiday island, with large settlements, but because the Las Cañadas volcano rises to 3718m, settlement and economic development does not seriously encroach onto the higher slopes of the edifice. The boundary of the park encloses an 18km long, oval-shaped caldera at about 2100m, and from the floor of this rise the imposing subsidiary stratocones of Teide and Pico Viejo. The Las Cañadas edifice is broken by three radiating rift zones in the shape of a Mercedes star centred on Teide, and while evolved magma of phonolitic composition has erupted in the caldera to build the stratocones, basaltic lava has erupted along the rift zones outside of the caldera to form significant groups of scoria cones. This phenomenon is thought to demonstrate some stratification of different magmas within the magma chamber. The last recorded eruption was from Teide in 1909.

Plate 4: Pico Teide viewed from the Roques de Garcia in the Las Cañadas caldera, Tenerife, Spain (photo: B. Bomhard)

The minor landforms within the caldera include an interesting range of silicic and basic lava flows, while pyroclastic deposits and structural features are exposed in the inward-facing cliffs of the caldera wall. Scarring the north slope of the Las Cañadas edifice is a large sector collapse (landslip), a feature that was possibly associated with the formation of the summit caldera.

It was found in this case that the integrity of the volcanic system could be demonstrated and protected within the boundary of the national park. Here there was evidence in the volcanic deposits and landforms of the varying chemistry of the magma, representatives of all the important landforms to be found on the larger edifice, the upper part of the sector collapse, and of course the caldera with its important pyroclastic and structural features that provide evidence of the caldera-forming processes.

Site management

Although this discussion is concerned primarily with the protection of volcanic geology and landscape, it is important to remember that volcanic sites have other natural values that are frequently dependent upon the special factors of volcanic terrain. Thus, the ecology of a volcano will be influenced by, or in some cases be dependent upon, the rock type, soil, geomorphology, and such features as micro-terrain, aspect, altitude, aridity and sometimes even volcanic disturbance. Indeed, as exemplified by the Surtsey World Heritage inscription, active volcanoes are about the only places on Earth where new land is created - a clean slate, or *tabula rasa* - and their protection and monitoring over time enables insights into the processes of biological colonisation.

In general, because of their large size, long eruptive lifetimes (usually spanning many hundreds of thousands of years), and inherent dangers, the most active volcanic systems are relatively undisturbed and little influenced by human behaviour. Indeed, on many occasions the interaction between humans and volcanoes is the reverse of that influencing other natural systems, because volcanoes can and do pose substantial hazards to life and property, and indeed to the conservation of important geological, biological and cultural features. Nevertheless, human activity does pose threats to many volcanic World Heritage properties, and include illegal dumping, pollution of ground water, inappropriate highway development, erosion of wilderness quality, commercial tourism (including ski development), recreational overuse, off-road driving, mineral extraction (removal of scoria and ash cones for construction aggregate and road ballast, and quarrying of lava flows for building stone) and the choking, pollution, and trampling of hydrothermal systems and their tapping for geothermal energy. Older volcanic structures and rock exposures also suffer damage from many of the above.

Geological conservation is an area of nature conservation that has received little attention until very recently, and the discipline remains relatively lightly developed at the world scale. There persists a view among many field managers that conservation of geological systems does not require management intervention. This is demonstrably not so when one considers the type of threats now seen to the World's volcanic estate, including those listed above. It is therefore of great importance that volcanoes and volcanic areas that have been inscribed, or are seeking inscription, as World Heritage properties, have management plans that consider the protection of their geological values, and those other values dependent upon the geology as key priorities. It is also important that site management plans are linked to regional plans, such as Minerals Plans and Development Plans, to ensure they fit within an effective regional and national planning and conservation framework.

A discussion was provided above on how sites might fulfil the Condition of Integrity in defining and embracing the complete scientific system. The maintenance of integrity should also be a goal of site management, and its pursuit will ensure that all important conservation values are protected. Prior research and a spatially-based resource database are important in determining what should and should not be included in a World Heritage property and particularly will help determine where the boundary should lie. The use of a buffer zone is less important in protecting a property inscribed solely for its volcanic geology, than for say a karstic or ecologically-important site. This is because, unlike the last examples, the energy and matter feeding the volcanic system are input from central or peripheral vents within the property, as opposed to inward and outward flows across the site boundary. However, a buffer zone will be appropriate if it is important to protect the associated biological, hydrological and hydrothermal values of a site, to provide some degree of control of encroaching urban development, or economic activity (such as farming, mineral extraction or tourism), and in hazard management.

Education and interpretation

Management objectives can also be achieved through education and interpretation programmes. Volcanoes are some of the world's most visited tourist destinations. For example, the Fuji-Hakone-Izu National Park, Japan, (i.e., the area around Mt Fuji) may annually receive as many as 100 million visits, while an estimated 300,000 people climb to the volcano's summit each year (source: Japan Ministry of Environment, National Park Service). The most visited volcanic World Heritage property is Teide National Park, Tenerife, Spain, with 3.2 million visits a year. All volcanic World Heritage properties provide some access for tourists, and on Kilauea, Hawaii Island, USA, and Stromboli, Aeolian Islands, Italy, casual visitors are able to safely view active volcanism as it is taking place. The educational value of the experience of viewing either a dormant or active volcano is immense, because like no-where else on Earth they demonstrate the power and importance of geology and the magmatic processes by which the planet was made.

Plate 5: Visitors experience views of active lava flows on Kilauea volcano, Hawaii (photo: USGS)

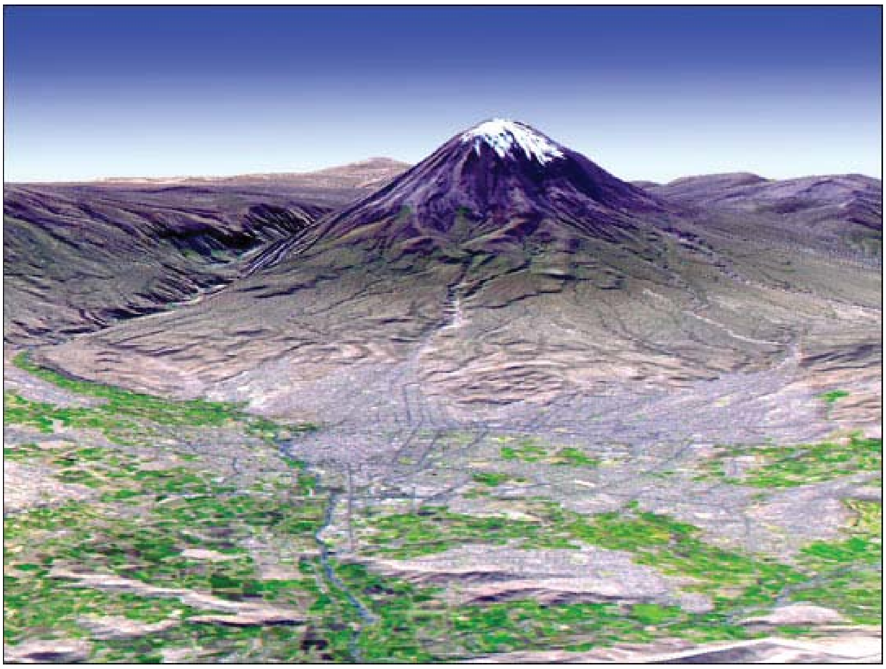
Excellent interpretive facilities are now being developed in many volcanic World Heritage properties (and in many other of the World's volcanic protected areas), notable examples being at Thingvellir National Park and the Vestmann Islands (for Surtsey Island), Iceland; Hawaii Volcanoes National Park and Yellowstone National Park, USA; Teide National Park, Tenerife, Spain; and Tongariro National Park, New Zealand. At the very innovative Stone Park on Jeju Island, Korea, superb graphical, 3D and interactive exhibits explaining the volcanic geology of the island are also linked with artistic interpretation of the basaltic rock and the island's folklore. Such exhibits, and associated interpretive publications and guiding services, fulfil an essential role in raising awareness, understanding and appreciation of the beauty and interest of volcanoes, and the importance of protecting this geological resource.

Monitoring

It is important that any protected site is monitored to assess whether or not the values for which it was established are threatened and undergoing change. Monitoring is a fundamental part of conservation management, but in volcanic World Heritage properties it is also important in assessing change in the behaviour of a volcano, as an indicator of a potentially hazardous event.

The methods available to monitor the behaviour of a volcano may be quite sophisticated and involve both remote sensing, and measurements on and around the volcano to detect movement of magma at depth. Instrumentation will measure underground seismic activity, geophysical and thermal profiles, ground deformation, the geochemistry of emitted gases, hydrological data, and the chemistry, heat and viscosity of lava. While volcano monitoring will not be undertaken at every Holocene World Heritage Volcano, most volcanic regions of the world have several volcano observatories that can at least provide some warning of impending eruptive

TEXT BOX 4: Preparation of updated volcanic hazards map for El Misti volcano, Peru
Abstract of paper by Mariño J, Rivera M, Thouret J-C, Salas G, Cacya L, Siebe C, Tilling R. (http://www.cosis.net/abstracts/)



Digital elevation model showing El Misti volcano towering 5822 meters high above the city of Arequipa, Peru. Arequipa is a World Heritage property. (Image by Mike Abrams, NASA/GSFC/MITI/ERSDAC/JAROS, and U.S./ Japan ASTER Science Team).

The city centre of Arequipa – second largest city in Peru (about one million people) – is located 17 km away from Misti Volcano (5822 a.s.l.) and about 3.5 km vertically below it. During the last 50,000 years, vulcanian and sub-plinian eruptions at Misti have produced about ten sizeable pyroclastic flows and twenty tephra falls (Thouret et al., 2001). However, numerous ash falls, pyroclastic flows, and lahars from prehistoric sub-plinian eruptions, as recent as 2,000 years ago, have affected the region of Arequipa around the volcano. Misti's only well-recorded historical activity consisted of small eruptions during the mid-15th century (Chávez, 1992). The Chili River and the main ravines (Pastores, San Lázaro, Huarangal, Huarangueros, Agua Salada) drain the W, S, and SE flanks of the volcanic edifice and cut through Arequipa city. Channelled through them, numerous pyroclastic flows and lahars have reached 12 to 25 km distance from source. Should El Misti Volcano awake in the future the volcanic and hydrological hazards associated with renewed eruptive activity and rainstorms would pose a serious threat to the people, infrastructures, and economy of Arequipa and its environs. Even though a number of volcano hazards maps and assessments have been made in recent years, these have not been entirely satisfactory due to the required detail or appropriate scale for use by decision makers in the preparation of contingency plans and risk reduction measures. In recognition of El Misti's enormous potential volcanic threat, the national geological agency of Peru – Instituto Geológico Minero y Metalúrgico del Perú (INGEMMET) – recently initiated a project to make a detailed geological map and updated volcanic hazard map of El Misti Volcano.

This new map was published in 2007 (Mariño et al., 2007).

activity (a full list of volcano observatories is published by the World Organisation of Volcano Observatories (WOVO, 2005)). In addition, many Holocene volcanoes now have undergone a Volcano Hazard Assessment (see Text Box 2), which is a descriptive summary of potential hazards, complete with a map showing areas that might be affected by future volcanic activity. The latter is useful to site managers, scientists, civil authorities and people living on or near the volcano to judge for themselves the relation between potentially dangerous areas and their daily lives. The Assessments are also critical for planning long-term land-use and effective emergency-response measures.

The city centre of Arequipa – second largest city in Peru (about one million people) – is located 17 km away from Misti Volcano (5822 a.s.l.) and about 3.5 km vertically below it. During the last 50,000 years, vulcanian and sub-plinian eruptions at Misti have produced about ten sizeable pyroclastic flows and twenty tephra falls (Thouret et al., 2001). However, numerous ash falls, pyroclastic flows, and lahars from prehistoric sub-plinian eruptions, as recent as 2,000 years ago, have affected the region of Arequipa around the volcano. Misti's only well-recorded historical activity consisted of small eruptions during the mid-15th century (Chávez, 1992). The Chili River and the main ravines

Assessment of environmental change in any volcanic World Heritage property is also important, and calls for monitoring of such environmental factors as air and water quality, hydrology, ecology, soils, and visitor impact. As a management tool, monitoring should comprise intermittent structured measurements set against indicators or targets in the management plan. Results should therefore feed back into the management strategy so that policies and programmes may be developed to halt, reduce, divert or repair detrimental change.

Risk management and contingency planning

Perhaps the feature that most attracts public interest in volcanoes is their great power, as exemplified in the well-publicised 1980 eruption of Mount St Helens, Washington State, USA, and the 1991 eruption of Pinatubo in the Philippines. Such events remind us also that volcanoes are hazardous, and in the past have taken many lives and extensively destroyed property. There are some particularly dangerous and threatening volcanoes on the World Heritage List (e.g., the eruptions of Krakatau 1883, Taal 1911, Pinatubo 1991, Stromboli 2002, Nyiragongo 1977 and 2002 - see Text Box 3), and as a part of the management planning process in World Heritage properties it should be obligatory to map hazards and potential impact zones, and to prepare hazard reduction schemes, including community preparedness programmes.

A good example of a successful hazard reduction scheme in a volcanic World Heritage property has been in New Zealand's Tongariro National Park. Threat of lahars (mud flows) caused by water spillage from Mt Ruapehu's summit lake has been of particular concern for the safety of skiers and ski infrastructure on its slopes, and for surrounding roads, farmland and settlements. A sophisticated crater-lake monitoring system and lahar warning system have been installed, and these proved to be of vital importance in reducing loss of life and property damage during a recent lahar event.

Volcano hazard maps are the most common methods by which scientists communicate risk to local authorities and citizens. In recent years new techniques and tools have been developed in order to improve the quality of such maps and especially to improve the way they are received and understood by land-use planners and decision-makers. Both static and dynamic maps are usually produced to aid prevention and crisis management respectively. Maps are based on field mapping and mathematical modelling, and different graphical techniques may be used depending upon the target audience of the local volcano hazard communication. Recent international initiatives have attempted to standardize some of the key issues that should be addressed by hazard maps.

In addition to working with scientists to document the possible threats from a volcano, managers must also work with the civil and emergency authorities and the local communities to prepare a contingency plan in the event of a serious incident happening (see Text Box 4). Risk contingency planning is now recognised to be very important in safeguarding the public in a wide range of risk situations, although in addition to public risk, managers of volcanic protected areas will also wish to understand and mediate against the risks to natural assets of high conservation value. Currently risk contingency planning in volcanic World Heritage properties is limited and further work in this area remains a major challenge for site managers in the future.

TEXT BOX 5: Volcanic hazards from Nyiragongo volcano, Virunga National Park, Democratic Republic of Congo
Abstracted and adapted from flyer: World Conference on Disaster Reduction, Kobe, Japan, 2005.

The volcano Nyiragongo is an important stratovolcano towering at 3,470m. It is well known for the permanent activity of a lava lake in the main crater. This lava lake emptied during a lateral eruption in 1977 and then later refilled in 1982 and 1994. The latest eruption occurred in January 2002, once again emptying the crater. Activity re-appeared some months later, and at the current time the lava lake is refilling.

The January 2002 eruption of volcano Nyiragongo deeply impacted the city of Goma: 18 % of its surface was destroyed, forcing the evacuation of some 300,000 persons and leaving 120,000 people homeless. About 110 people died as an immediate consequence of the eruption and approx. 80 % of the local economy was destroyed. Renewal of activity in the Nyiragongo crater occurred In November 2002, with the re-appearance of the active lava lake. Since then the level of activity has been growing, putting at risk an estimated population of some 460,000 people.

The permanency of the volcanic activity has also had a very deep impact on the environment. A huge volcanic gas plume is constantly emitted by the crater with sulfur dioxide quantities ranging from 12,000 to 50,000 metric tons per day. This represents approx. 50% of the total volcanic $SO2$ emitted by all volcanoes around the world. As a consequence, acid rains are burning forests and crops and very high concentrations of fluoride are polluting drinking water.
This constant volcanic activity could last for years or decades, exposing the population to direct volcanic risks. There is the constant possibility of a new eruption that would impact on the same population, with additional indirect risks, such as damage to crops, and pollution of air and water.

Conclusions and Recommendations

This study has reviewed all 2349 sites on the World Heritage List and the Tentative Lists to establish the extent to which volcanic values are represented, including all records available to December 2008. It has identified that 57 sites on the World Heritage List and 40 on the Tentative Lists are notable for their volcanic geology, while 27 sites on the World Heritage List and 25 on the Tentative Lists currently contain active (Holocene) volcanoes. Comparison with the Smithsonian Institution's Global Volcanism Program database revealed that World Heritage properties may contain over 101 Holocene volcanoes (6.4% of all the active volcanoes in the world); while a further 73 Holocene volcanoes may be present in sites on the Tentative Lists. However, an accurate estimate of the number of Holocene volcanoes in inscribed or tentative sites has been difficult to make because maps of sites showing the location of named Holocene volcanoes were not available to this study.

The study identified six types of volcanic World Heritage properties as follows:

1. volcanic landscapes with multiple vents
2. individual active, dormant or extinct volcanoes
3. particular features of larger volcanic edifices
4. identifiable landforms or landscapes which represent the erosional remnants of former volcanoes
5. sites with volcanic bedrock but without any particularly distinctive volcanic landforms or landscapes
6. significant hydrothermal and solfataric systems

The volcanic World Heritage properties were also analysed on the basis of their plate tectonic setting, landforms represented, and geopolitical location, in order to find gaps in their representation. This analysis showed that most volcanic phenomena are represented on the World Heritage List, although some gaps were identified, as follows:

Poorly represented are:

- intrusive landforms
- certain popularly-known or iconic volcanoes
- flood basalts
- basaltic plains
- back-arc volcanoes

Missing are:

- fissure volcanoes
- Icelandic type shield volcanoes
- hyaloctastic mountains (tuyas) and ridges
- Silicic volcanic fields
- large ash flows and ignimbrite sheets and plateaus,
- resurgent caldera

Strategies for enhancing the List are identified and it is considered that there is potential for a number of these gaps to be met by possible inscription of some properties currently included on Tentative Lists, or from extending established sites. A limited number of new sites (i.e., not on the existing Tentative Lists) might also be considered.

In regard to the management of volcanic World Heritage properties, attention is drawn to the importance of protection of the complete volcanic system, including evidence of its eruption styles, products and landforms. While there is recognition that volcanic geology is generally quite robust, there are human-made threats to geological values that may require management intervention. In most cases, these threat also impact on the site's ecology and possible cultural values, and where these values are strong such sites should be managed as integrated systems. An important aspect of management of sites containing active (Holocene) volcanoes is risk reduction from hazardous eruptions. The World Heritage List includes some notably dangerous volcanoes, and the monitoring of volcanic activity and risk contingency planning should be essential parts of the management process in all potentially active volcanic World Heritage properties.

Specific recommendations arising from this study are:

1. Reinforce to State Parties the message originally communicated to the World Heritage Committee in July 2007 that there is increasingly limited scope to recommend further nominations of volcanic sites for inclusion on the World Heritage List, and that any future nominations should seek to fill the gaps in the List as identified in this Theme Study;

2. In association with site managers, undertake further research to establish:

    a) A definitive list of named active (Holocene) volcanoes currently included on the World Heritage List;
    b) A list of the most hazardous volcanoes and an assessment of the risks they pose to their respective communities.

Annex 1: List of Figures

Annex 2 : List of Tables

Annex 3 : Data sources

Data sources drawn on for this study were:

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Annex 5: Glossary

Aa lava:	a lava flow with a rubbly or clinkery surface
Batholith:	a composite, intrusive, igneous rock body up to several hundred km lin extent, formed by the intrusion of numerous large packages (plutons) of magma in the same region
Block lava:	a lava flow with a surface broken into angular, smooth-faced blocks
Caldera:	a large circular depression with steep walls and a fairly flat floor, formed after a violent eruption when the centre of the volcano collapsed into the partially drained magma chamber.
Cinder cone:	a cone made of fragments of glassy rock, known as tephra, that were ejected from the volcano
Composite volcano:	a stratovolcano with a complex history, built-up of layers of lava alternating with beds of ash and other pyroclastics, with collpse scars, some whooly or partially covered by newer erupted material and material eroded from the higher slopes of the cone
Collapse scar:	a hollow left in the side of a volcano after a sector of it had collapsed
Collision zone:	a type of convergent plate margin in which two continents or island arcs have collided
Cone sheet:	an igneous intrusion, represented by a dyke shaped in cross-section like a cone dipping inwards to a central pluton.
Continental volcanic arc:	a long chain of sub-aerial volcanoes on the margin of a continent adjacent to a convergent plate boundary
Coulee flow:	a very thick, and relatively short, blocky lava flow, usually highly silicic in composition which has been extruded from a volcanic cone or fissure
Country rock:	any older rock into which magma is intruded
Crust:	the rock that makes up the outermost layer of the Earth
Diatreme:	a narrow, conical-shaped volcanic vent typically cut through non-volcanic basement rocks, that has formed by explosive action, often filled with angular fragments injected by gas fluidization
Dyke:	a sheet like intrusion that cuts across the stratification of the country rock, formed when molten magma is injected into a fault
Dyke swarm:	a collection of many radial dykes around a central intrusion, or many parallel to sub-parallel dykes occurring over a large region
Erosion caldera:	an erosion induced or transformed large depression on a volcano
Fissure:	a linear fracture in the Earth surface
Flood basalt:	expansive effusion of basaltic rock erupted from fissures, extending many tens of kilometres and covering a vast area of land in flat, layered lava flows, forming a lava plateau

Fumarole:	a vent that releases volcanic gases
Fumarolic field:	an area rich in fumaroles, sometimes also known as a solfataric field
Geotectonic setting:	setting in relation to plate tectonics and structure of the Earth
Geysir:	a vent that periodically erupts a fountain of steam and hot water
Hydromagmatic:	a violent eruption style caused by water entering the volcanic vent and reacting with the hot magma
Hydrothermal field:	an area underlain by rocks through which circulates hot water
Hot spot:	name given to the place where an ascending plume of hot mantle material penetrates the Earth's crust
Igneous melt:	magma, a liquid igneous rock
Igneous rock:	a rock formed by the solidification of a magma, before or after it reaches the Earth's surface
Intrusion:	a body of igneous rock that has been emplaced within, or intruded into, pre-existing rocks of the Earth crust
Ignimbrite:	a rock formed when when deposits of pyroclastic flows settle and solidify
Ignimbrite plateau:	extensive plateau made up of a succession of ignimbrite sheets
Intraplate volcano:	a volcano that has formed in the interior of a lithospheric plate, remote from any plate boundary, thought to be a product of an underlying mantle plume.
Island arc:	an arcuate chain of islands rising from the deep ocean floor and located where two ocean plates converge
Laccolith:	a type of magmatic intrusion in which a sill-like magma body domes up its roof to form a circular or oval lentitular body.
Lahar:	a torrential mudflow of wet volcanic debris produced when pyroclastic deposits mix with rain or the water of a lake, river or melting glacier
Lapilli:	fine-grade pyroclastic material
Large Igneous Province (LIP):	a voluminous emplacement of predominantly mafic extrusive and intrusive igneous rocks
Lava:	magma that has been extruded onto the Earth's surface
Lava Channel:	an open channel usually contained between two parallel levees (retaining walls) that conveys an active lava river down the axis of a lava flow
Lava dome:	rounded or bulbous secondary volcanic dome that develops within a caldera or blown-out crater from slow extrusion of very viscous lava
Lava flow:	elongated, active or solidified outpouring of lava, with distinctive form depending on how viscous the fluid material is
Lava tube:	a conduit formed within an active flow lobe that transports fluid lava
Lava tube system:	an integrated system of connected lava tubes that conveys fluid lava between the vent and the advancing flow front

Lava tube cave:	a lava tube or lava tube system from which the active flow has partially or wholly drained after the close of vent activity
Lava shield:	a low-angled cone composed predominantly of thick accumulations of mafic lava flows
Lithospheric plates:	alternative name for tectonic plates - the lithosphere is the rigid crust surrounding the Earth
Lopolith:	a large-scale, commonly mafic, bowl-shaped shallow intrusion
Maar:	a broad, low-relief explosion crater - may be surrounded by a **tuff ring** and underlain by a **diatreme**
Magma chamber:	a magma-filled cavity below ground thought to form as bouyant packages of melted rock rise to accumulate in higher regions of the Earth's crust
Mantle:	the thick layer of rock below the Earth's crust and above the core
Mantle plume:	a column of very hot rock rising up through the mantle that may originate near the core/mantle boundary
Mid-Ocean Ridge (MOR):	a sub-marine mountain range that may be more than 2km high that forms along a divergent plate boundary
Mineral:	a naturally occurring, solid, crystalline substance, generally inorganic, with a specific chemical composition - all igneous rocks are composed of an assemblage of different, interlocking minerals
Hyaloclastic ridge:	a volcanic ridge formed from a fissure eruption that took place beneath an ice sheet or on the ocean floor - composed of pillow lavas and hyaloclastite - an aggregate of fine, glassy debris formed when hot magma is rapidly chilled with water, ice or water saturated sediment
Monogenetic:	built from a single eruptive event
Pahoehoe lava:	a type of low viscosity lava flow characterised by a surface texture of smooth, glassy rope-like ridges - composed of accummulations of thin sheets, tongues and lobes that are fed by internally-formed distributary lava tubes.
Phreatomagmatic:	as for hydromagmatic, a type of violent eruption caused when water interacts with magma in the volcanic vent
Petrology:	the study of rocks, their nature and origin
Pit crater:	a depression formed by the collapse of the ground surface of the flanks of a volcano lying above a void or empty chamber
Plate tectonic setting:	the setting of a volcano or volcanic system relative to the Earth's tectonic plates and their structural features
Polygenetic:	built of many discrete eruptive events
Pyroclastic deposit:	any deposit of fragmental material violently ejected from a volcano
Pyroclastic flow:	a fast-moving avalanche that occurs when hot volcanic ash and debris mix with air and flow down the side of a volcano

Resurgent caldera:	a caldera on a much bigger scale than one associated with collapse of the summit of a central volcano, but similarly overlies a shallow magma chamber into which the crust has collapsed - characterised by a broad topographical depression with a central elevated area formed from post-collapse upheaval (resurgence)
Rift zone:	a series of fissures cutting a volcano and caused by inflation - a volcano may have several rift zones that may radiate from the summit, any one of which may at some time allow lava to be erupted from the volcano's flank rather than from its summit
Rift valley:	a long narrow trough bounded by parallel normal faults and inward-facing fault scarps
Ring dyke:	subvertical cylindrical sheet intrusion where magma has been intruded along a ring fault - the surface expression of the dyke is circular
Seamount:	a submerged volcano, usually extinct, built on the deep abyssal plain of the ocean
Scoria:	highly vesicular mafic glass - solidified lumps of frothy magma thrown out of fountains of lava in the vent
Scoria cone:	cone built of scoria and lapilli over the vent during a Strombolian or Hawaiian style eruption
Sector collapse:	collapse or landslide of a segment of a volcano
Shield volcano:	a sub-aerial volcano with a broad, gentle dome, formed either from accumulations of low-viscosity basaltic lava flows or from large pyroclastic sheets
Silicic:	magma which is rich in silica
Sill:	a sheet intrusion formed when magma penetrates between the strata of the country rock
Solfataric field:	an area rich in fumaroles
Stratovolcano:	a large cone-shaped sub-aerial volcano consisting of accumulations of lava and pyroclastic material
Subduction:	the descent into the mantle of a lithospheric plate at a convergent plate margin
Transform boundary:	a boundary at which one lithospheric plate slips laterally past another
Tuff:	compacted volcanic ash or tephra
Tuff cone:	a cone made up of very fine volcanic ash or tephra, formed after a hydromagmatic eruption
Tuff ring:	a ring of volcanic ash or tephra
Tuya:	a term given to flat topped mountains produced by sub-glacial eruption of a central vent volcano
Vesiculation:	cavities by formed by gas bubbles trapped and 'frozen' in a lava
Viscous:	a term for the 'stiffness' or resistance to flow of a material.

Volcanic landform:	a physical feature with an identifiable form (shape) formed by a volcanic process
Volcanic landscape:	an expansive area made up of different landforms of volcanic origin
Volcanic neck:	the rock that solidified in the throat of an ancient volcano, now exposed as an upstanding column because the softer flanks of the volcano have been removed by erosion
Volcaniclastic:	synonymous with pyroclastic
Volcanic system:	all the volcanic phenomena originating from a single magma source

Annex 6: Table 1: Properties with volcanic geology on the World Heritage List

Site Ref.	Name	Country	Smithsonian Holocene (active) volcano	Date of inscription	Inscribed under Category (vii) scenic beauty	Inscribed under Category (viii) geology	Inscribed under other categories			Observations
							Natural	Cultural	Mixed	
1	Lord Howe Island Group	Australia	N	1982	Y	N	x			Archipelago of volcanic islands
2	Gondwana Rainforests of Australia	Australia	N	1986	N	Y	ix, x			Mainly Tertiary volcanics. Serial nomination along Great Escarpment - includes Mt Barney intrusive complex, Foal Peak shield volcano, Mt Warning volcanic neck and erosion caldera, Barrington Volcano dissected plateau basalts.
3	Heard and McDonald Islands	Australia	Y	1997	N	Y	ix			Mt Mawson is Australia's only active volcano
4	Iguazu National Park	Argentina	N	1984	Y	N	x			Part of Paraná Mesozoic flood basalt plateau, covering a broad portion of the Botucata Triassic desert. Interleaved layers of sandstone and basalt remain.
5	Iguacu National Park	Brazil	N	1986	Y	N	x			Continuous with above. Rocks are mainly basalt lavas interbedded with sandstones
6	Malpelo Fauna & Flora Sanctuary	Columbia	N	2006	Y	N	ix			Archipelago of volcanic islandsin Pacific Ocean
7	Rapu Nui National Park	Chile	Y	1995	N	N		i, iii, iv		Composed of 3 principal volcanoes and more than 70 subsidiary vents. Rano Kau contains a flat bottomed 1km crater. Terevaku is a broad shield volcano capped by pyroclastic cones, less than 2000 years old.
8	Cocos Island National Park	Costa Rica	N	1997	N	N	ix, x			Pacific oceanic island of volcanic origin.
9	The Area de Conservación Guanacaste	Costa Rica	Y	1999	N	N	ix, x			Site contains a series of volcanoes including Rincón de la Vieja, which comprises at least 9 eruptive centres. Also contains Orosi, a cluster of four eroded and vegetated cones.
10	Virunga National Park	Democratic Republic of Congo	Y	1979	Y	Y	x			Site contains 5 large volcanoes, 4 of wjhich have been active in the Holocene. Nyamuragira, a large basaltic shield volcano, is Africa's most active volcano, while Nyragongo is an active stratovolcano.
11	Kahuzi-Biega National Park	Democratic Republic of Congo	N	1980	N	N	x			Two spectacular extinct volcanoes Kahuzi and Biega

Site Ref.	Name	Country	Smithsonian Holocene (active) volcano	Date of inscription	Inscribed under Category (vii) scenic beauty	Inscribed under Category (viii) geology	Inscribed under other categories			Observations
							Natural	Cultural	Mixed	
12	Morne Trois Pitons National Park	Dominica	Y	1997	N	Y	x			A basaltic spike remains of a former volcano. Contains two large lava dome complexes of Morne Trois Pitons and Micotrin. Landscape characterised by volcanic piles and deeply incised valleys. The Valley of desolation is a large fumerole of which contains the worlds second largest boiling lake.
13	Sanghay National Park	Ecuador	Y	1983	Y	Y	ix, x			Site contains 3 stratovolcanoes, Tunguarua, Alter and Sangay, the latter having one of the world's longest records of continuous activity. Sangay is an isolated stratovolcano, with a summit glacier and topped with two horseshoe calderas.
14	Galapagos Islands	Ecuador	Y	1978	Y	Y	ix,x			A volcanic archipelago consisting of 13 islands, the largest of which are the summits of shield volcanoes. There have been at least 50 eruptions in the last 200 years, and 14 volcanoes have been active in the Holocene.
15	Joya de ceren Archaeological Site	El Salvador	N	1993	N	N		iii,iv		Situated on the Rana pyroclastic flows. The town was buried under an eruption from the Laguna Caldera volcano.
16	Simien National Park	Ethiopia	N	1978	Y	N	x			Dissected basalt plateau
17	Gulf of Porto: Calanche of Piana, Gulf of Girolata, Scandola Reserve	France	N	1983	Y	Y	x			Some volcanic rocks of Permian age - porphyrys, rhyolites and basalts.
18	Antigua Guatemala	Guatemala	Y	1979	N	N		ii,iii,iv		The city is situated in a valley between three large, active stratovolcanoes - Fuego, Agua and Acatenago. The city has been twice destroyed by Mt. Agua lahars.
19	Thingvellir National Park	Iceland	Y	2004	N	N		ii, vi		The Þingvellir site demonstrate rifting due to the divergence of crustal plates along the Mid-Atlantic Ridge. It is situated on the Reykjaneshryggur-Langjökull rift system and its geology is exclusively post-glacial basaltic lavas.
20	Surtsey	Iceland	Y	2008	N	N	ix			Volcanic island born from phreatomagmatic eruptions 1963-67. Classically formed Tuya and give name to Surtseyan style of eruption.
21	Komodo National Park	Indonesia	N	1991	Y	N	x			Located in the centre of the Indonesian archipelago. No active volcanism.
22	Ujung Kulon National Park	Indonesia	Y	1991	Y	N	x			Designation includes the natural reserve of Krakatau. Collapse of the original structure in approximately 416AD formed a 7km wide caldera. Continuous rebuild and collapse resulted in the formation of Krakatau Island. The infamous 1883 eruption was Indonesia's second largest eruption in historical time.

Site Ref.	Name	Country	Smithsonian Holocene (active) volcano	Date of inscription	Inscribed under Category (vii) scenic beauty	Inscribed under Category (viii) geology	Inscribed under other categories			Observations
							Natural	Cultural	Mixed	
23	Tropical Rainforest Heritage of Sumatra	Indonesia	Y	2004	Y	N	ix,x			Site contains Mount Kerinci situated in the Kerinci National Park. It is Indonesia’s highest volcano and one of the most active in Sumatra. It contains a large summit crater partly filled by a small crater lake.
24	Takht-e Soleyman	Iran	N	2003	N	N		i, ii, iii, iv, vi		Located on the crater rim of the dormant Zendan-e Suleiman volcano.
25	Isole Eolie (Aeolian islands)	Italy	Y	2000	N	Y				The Aeolian Islands contain the Holocene volcanoes Stromboli, Panarea, Lipari and Vulcano. The site provides an outstanding record of volcanic island building and destruction and ongoing volcanism. There is a history of both Vulcanian and Strombolian activity.
26	Archaeological Areas of Pompeii, Herculaneum and Torre Annunziata	Italy	Y	1997	N	N		iii, iv, v		Areas buried by the AD79 eruption of Mount Vesuvius. Both sites have been excavated and made accessible to the public.
27	Shiretoko	Japan	Y	2005	N	N	ix,x			Formed of a range of volcanic peaks including Mt. Rausu and Mt. Lou.
28	Mount Kenya National Park	Kenya	N	1997	Y	N	ix			Mount Kenya is an extinct stratovolcano and the second highest peak in Africa.
29	Lake Turkana National Park	Kenya	Y	1997	N	Y	x			Positioned at the northern end of the Kenyan Great Rift Valley. The lake has three volcanic islands, Central, North and South Island. Northern Turkana has flood basalts, while in the south are 7 Pliocene volcanoes.
30	Le Morne Cultural Landscape	Mauritius	N	2008	N	N	iii,vi			Isolated basalt mountain on Le Morne peninsula
31	Islands and Protected Areas of the Gulf of Mexico	Mexico	N	2005	Y	N	ix,x			Volcanic ridges, including the Tortuga Volcanic Ridge, are situated between Isla Toruga and La Reforma Caldera-Santa Rosalia region.
32	Earliest 16th Century Monasteries on the slopes of Popocatepetl	Mexico	Y	1994	N	N		ii,iv		All fourteen monasteries comprising the site lie on the slopes of Popocatepetl.
33	Tongariro National Park	New Zealand	Y	1990	Y	Y		vi		ituated on the central North Island volcanic plateau, the volcanoes are mainly andesitic in composition. Three main volcanoes are Tongariro, Ngauruhoe and Ruapehu.
34	New Zealand Sub-Antarctic Islands	New Zealand	Y	1998	N	N	ix,x			Three of the five NZ Sub-Antarctic Islands are volcanic - Antipodes Island, Auckland Island and Campbell Island. The highest point and most active volcano is Mt. Galloway, on Antipodes Island.
35	Ruins of Leon Viejo	Nicaragua	Y	2000	N	N		iii,iv		The original city was destroyed by the 1610 eruption of Mt. Momotombo causing inhabitants to resettle. The city was excavated in 1960.

Site Ref.	Name	Country	Smithsonian Holocene (active) volcano	Date of inscription	Inscribed under Category (vii) scenic beauty	Inscribed under Category (viii) geology	Inscribed under other categories			Observations
							Natural	Cultural	Mixed	
23	Tropical Rainforest Heritage of Sumatra	Indonesia	Y	2004	Y	N	ix,x			Site contains Mount Kerinci situated in the Kerinci National Park. It is Indonesia's highest volcano and one of the most active in Sumatra. It contains a large summit crater partly filled by a small crater lake.
24	Takht-e Soleyman	Iran	N	2003	N	N		i, ii, iii, iv, vi		Located on the crater rim of the dormant Zendan-e Suleiman volcano.
25	Isole Eolie (Aeolian islands)	Italy	Y	2000	N	Y				The Aeolian Islands contain the Holocene volcanoes Stromboli, Panarea, Lipari and Vulcano. The site provides an outstanding record of volcanic island building and destruction and ongoing volcanism. There is a history of both Vulcanian and Strombolian activity.
36	Air and Tenere Natural Reserves	Niger	Y	1991	Y	N	ix,x			The Air Mountains consist of 9 circular massifs. The site consists of Tertiary and Quaternary volcanic features, but is most famous for having one of the largest ring dyke structures in the world. Phreatomagmatic tuff rings and over 100 basaltic strombolian cones are also present
37	Historical City of the City of Arequipa	Peru	Y	2000	N	N		i,iv		Built at the foot of El Misti, an andesitic stratovolcano. Approximately twenty or more tephra fall deposits and numerous pyroclastic fall deposits have been documented. Its most recent activity has been pyroclastic. The historic centre is built into volcanic sillar rock.
38	Landscape of Pico Island Vineyard Culture, Azores	Portugal	Y	2004	N	N		iii,iv		On slopes of active Pico volcano, Pico Island, Azores. The site is located on basaltic lava flows.
39	Central zone of the town of Angra do Heroismo in the Azores	Portugal	Y	1983	N	N		iv,vi		Located on Terceira Island, which consists of four overlapping stratovolcanoes built above a fissure zone : Santa Barbara, Pico Alto, Guilherme Moniz and Cinquio Picos.
40	Jeju volcanic island and lava tubes	Republic of Korea	Y	2007	Y	Y				Mt Halla is one of the worlds largest shield volcanoes. The Geomunoreum lava tube system is regarded as one of the finest examples in the world. The Seongsan Ilchulbong tuff cone exhibits exceptional evidence for the study of Surtseyan type eruptions.
41	Volcanoes of Kamchatka	Russian Federation	Y	1996	Y	Y	ix,x			he southern half of the Kamchatka Peninsula consists of two parallel mountain ranges. The western Sredinniy range is composed of dormant shield and stratovolcanoes whilst the eastern Vostochiniy range has nearly 30 young volcanoes making it the highest concentrated area of active volcanism in Eurasia. The site also exhibits scoriae and lava cones, calderas, lava streams, cinder fields, solfataras and many other volcanic features. In addition the Klyuchevskaya range of volcanoes is also the area of the largest centre of glaciation in Kamchatka, providing material for the study of interaction between active volcanism and glaciers.

Site Ref.	Name	Country	Smithsonian Holocene (active) volcano	Date of inscription	Inscribed under Category (vii) scenic beauty	Inscribed under Category (viii) geology	Inscribed under other categories			Observations
							Natural	Cultural	Mixed	
42	Western Caucasus	Russian Federation	Y	1999	N	N	ix,x			Mount Elbrus, a dormant stratovolcano is the highest mountain in the range.
43	Brimstone Hill Fortress National Park	Saint Kitts and Nevis	Y	1999	N	N		iii,iv		Situated upon the slopes of Mount Liamuiga, a stratovolcano which contains a 1 km wide crater. The most recent eruption 2000 years ago produced pyroclastic flows and mudflows. Active fumaroles are present in the crater.
44	Vallée de Mai Nature Reserve	Seychelles	N	1983	Y	Y	ix,x			Valley eroded into basaltic deposits - important for forest biology
45	Pitons Management Area	Saint Lucia	Y	2004	Y	Y				The Pitons are two dormant steep sided dacitic lava dome volcanoes. In the central depression lies the sulphur springs, which are surrounded by explosion craters, lava flows and pumice and ash deposits of the collapsed Qualibou volcano.
46	Teide National Park	Tenerife	Y	2007	Y	Y				This stratovolcano is the world's third highest volcanic structure. The park offers a rich and diverse collection of volcanic features that show different phases of construction and remodelling. Mount Teide offers an exceptional example of a relatively old slow moving, geologically complex and mature volcanic system.
47	Giants Causeway and the causeway Coast	United Kingdom of Great Britain and N Ireland	N	1986	Y	Y				Massive black basaltic columns which represent volcanic activity during the early Tertiary period. The Antrim Tertiary lavas represent the largest remaining lava plateau in Europe. The coastline is also cut through by tholeiite dykes.
48	St. Kilda	United Kingdom of Great Britain and N Ireland	N	1986	Y	N	ix,x	ii,v		The archipelago represents the remnants of a long extinct stratovolcano volcano rising from a seabed plateau.
49	Gough and Inaccessible Islands	United Kingdom of Great Britain and N Ireland	N	1995	Y	N	x			The Gough Islands forms part of the chain of South Atlantic volcanic sea-mounts on the east slope of the mid-Atlantic ridge. Inaccessible Island is the remnant of a larger, more eroded shield volcano.
50	Historic Town of St. George and Related Fortifications, Bermuda		N	2000	N	N		iv		Bermuda is a volcanic sea mount capped with carbonate (limestone) deposits.
51	Old and New Towns of Edinburgh, Scotland	United Kingdom of Great Britain and N Ireland	N	1995	N	N		ii,iv		Built on the remnants of a Carboniferous volcano
52	Frontiers of the Roman Empire	United Kingdom of Great Britain and N Ireland	N	2005	N	N		ii,iii,iv		Hadrian's Wall is built on the 30m thick Gt Whin sill

Site Ref.	Name	Country	Smithsonian Holocene (active) volcano	Date of inscription	Inscribed under Category (vii) scenic beauty	Inscribed under Category (viii) geology	Inscribed under other categories			Observations
							Natural	Cultural	Mixed	
53	Ngorongoro Conservation Area	United Republic of Tanzania	N	1979	Y	Y	ix,x			The Ngorongoro crater is the largest unbroken crater in the world which is neither active nor flooded. It formed when a giant volcano exploded approximately 2-3 million years ago.
54	Kilimanjaro National Park	United Republic of Tanzania	Y	1987	Y	N				Kilimanjaro is Africa’s highest mountain, consisting of three stratovolcanoes.
55	Yellowstone National Park	United States of America	Y	1978	Y	Y	ix,x			The Yellowstone Plateau volcanic field developed through three volcanic cycles over two million years. It provides evidence of some of the world’s largest known eruptions. The park is particularly notable for its large, shallow caldera and exceptional geothermal activity.
56	Hawaii National Park	United States of America	Y	1987	N	Y				Contains two of the world’s most active volcanoes, Mauna Loa and Kilauea. The landscape of the park is constantly being changed by eruptive activity which has formed unique lava flow formations. The latest eruption of Kilauea has last for 24 years.
57	Chief Roi Mata’s Domain	Vanuatu	N	2008	N	N	iii, v, vi			An archipelago of volcanic islands

Annex 7: Table 2: Properties with volcanic geology on the Tentative Lists

Site Ref.	Name	Country	Smithsonian Holocene (active) volcano	Date of submission	Listed under Category (vii) scenic beauty	Listed under Category (viii) geology	Listed under other criteria		General Category (mixed, natural or cultural)	Observations
							Natural	Cultural		
1	Las Parinas	Argentina	Y	2001	N	Y	ix,x		Mixed	Mixed Volcanic morphology is dominated with cones and lava deposits. Ojos del Salado. Is a massive active stratovolcano , the highest in the world.
2	La Saline de Pedra Lume	Cape Verde	N	2004	?	?	?	?	Mixed	Salt works within a former carter lake
3	Juan Fernandez Archipelago National Park	Chile	N	1994	N	N	x		Natural	Volcanic archipelago in South Pacific Ocean
4	Wudalianchi Scenic Spot	China	Y	2001	N	Y	ix		Natural	Volcanic field of 14 cones and associated lava flows in N China
5	Ecosystemes Marins de l'Archipel des Comores	Comoros	Y	2007	N	N	ix,x		Natural	Volcanic archipelago in Indian Ocean
6	Ecosystems terrestres et paysage culturel de l'Archipel des Comores	Comoros	Y	2007	N	Y	ix,x	v	Mixed	Volcanic archipelago in Indian Ocean
7	Mt. Chilbo	Democratic Peoples Republic of Korea	N	2000	Y	Y	ix		Natural	Natural Mountain is known for its variously shaped rocks formed by the long time erosion of the eruptive rocks of the Paekdu Volcanic Zone.
8	Sovi Basin	Fiji	N	1999	N	N		iii,iv,v	Cultural	Basin is encircled by volcanic peaks.
9	Levuka, Ovalau	Fiji	N	1999	N	N		iii, iv, v, vi	Cultural	Oval shaped volcanic island.
10	Pitons, cirques et remparts de l'Ile de la Reunion	France	Y	2002	Y	Y	ix		Natural	Reunion island is composed of two large basaltic shield volcanoes, one of which - Piton de la Fournaise is in frequent activity. These volcanoes are also notable for their deep dissection by fluvial processes, forming immense amphitheatre-headed valleys and erosion calderas.

Site Ref.	Name	Country	Smithsonian Holocene (active) volcano	Date of submission	Listed under Category (vii) scenic beauty	Listed under Category (viii) geology	Listed under other criteria		General Category (mixed, natural or cultural)	Observations
							Natural	Cultural		
11	Les Iles Marquises	France	N	1996	N	N		i, iii, v	Cultural	Volcanic archipelago in the South Pacific Ocean
12	Grenadines Island Group	Grenada	Y	2004	Y	N	x		Natural	The site includes several active undersea mounts including Kick em' Jenny which attest to the ongoing movement of the Caribbean and South American plates. The island of Grenada is composed of five volcanic centres including Mount Saint Catherine a stratovolcano with a horseshoe shaped crater with several lava domes.
13	Protected area of Lake Atitlan	Guatemala	Y	2002	Y	Y	ix		Natural	A crater lake formed as a result of four separate cycles of build and collapse. The lake is surrounded by the stratovolcanoes Atitlan, Tolima and Suchitan.
14	Breiðafjörður	Iceland	N	2001	?	?	?	?	Mixed	Area consists of Tertiary basaltic lava that has been eroded during glaciations. Some more recent volcanics and several geothermal sites are present.
15	Herðubreiðarlindir and Askja	Iceland	Y	2001	Y	Y	ix,x		Natural	Askja is a large basaltic central volcano that forms the Dyngiufjoll massif. It is truncated by three overlapping calderas. Its formation may be due to subglacial eruption. Hurðubreiðar is a well-formed table mountain or tuya.
16	Mývatn - Laxa	Iceland	Y	2001	Y	Y	ix,x		Natural	The area is a zone of active volcanism, with many diverse volcanic forms, located in northern part of the Neovolcanic Rift.
17	Núpsstaður	Iceland	N	2001	?	?	?	?	Mixed	Various types of lava, geothermal areas, tectonic fissures and a central volcano.
18	Reykholt	Iceland	N	2001	N	N		i, iii, vi	Cultural	Hydrothermal area with hot springs
19	Skaftafell	Iceland	Y	2001	?	?	?	?	Mixed	This glacier national park includes Oræfajókull, the largest active central volcano in Iceland. Also covers part of the ice-covered Grimsvötn volcanic system, eruptions of which can cause large scale flooding.
20	Bunaken National Park	Indonesia	N	2005	Y	Y	ix,x		Natural	Geological history of explosive volcanism evidenced by extensive deposits of volcanic tuff. The Park contains Manado Tua, a dormant volcano.

Site Ref.	Name	Country	Smithsonian Holocene (active) volcano	Date of submission	Listed under Category (vii) scenic beauty	Listed under Category (viii) geology	Listed under other criteria		General Category (mixed, natural or cultural)	Observations
							Natural	**Cultural**		
21	Banda Islands	Indonesia	Y	2005	Y	N	x		Natural	ituated in the Indo-Malayan archipelago the site contains Gunung Api,the summit of a massive active stratovolcano. Also present is the island of Manuk, a high truncated andesitic cone.
22	Ogasawara Islands	Japan	Y	2007	N	Y	ix,x		Natural	A series of volcanic oceanic islands which consist of the Ogasawara Archipelago, as well as several isolated islands. It is the only place in the world where bonite and transitional volcanic products can be seen showing the entire growth cycle of an ocean island arc.
23	Fujisan	Japan	Y	2007	N	N		iii, iv, v, vi	Cultural	The famous stratovolcano is Japan's highest peak. Fujisan is constructed above a group of overlapping volcanoes.
24	Great Rift Valley Ecosystem	Kenya	Y	2001	?	?	?	?	Mixed	his spreading continental rift contains a series of volcanoes including Longonot, Mount Kenya and Mount Elgon.
25	Volcan Masaya National Park	Nicaragua	Y	1995	?	?	?	?	Natural	Masaya is a large active basaltic caldera, lying within the massive Las Sierras pyroclastic shield volcano and adjacent to volcano Nindirí.
26	Auckland Volcanic Fields	New Zealand	Y	2007	N	Y		ii, iii, iv, v	Mixed	Site composed of 50 basaltic eruption centres. Includes the shield volcano Rangitoto and the extinct Pukaki. Site exhibits a series of maars, tuff rings, small lava shields and scoria cones.
27	Kermadec Islands and Marine Reserves	New Zealand	Y	2007	Y	Y	ix, x		Natural	An archipelago of which the four main islands are the peaks of volcanoes that rise high above sea level. There are several other volcanoes in the chain the do not reach sea level. The site includes the stratovolcano Raoul and the submarine volcano Curtis Island.
28	City of Granada and its Natural Environment	Nicaragua	Y	2003	?	?	?	?	Mixed	Contains the Apoyoeque volcanic complex, which occupies the Chiltepe Peninsula, which is part of the Chiltepe pyroclastic shield volcano. Also contains Mombacho a stratovolcano which has undergone edifice collapse.
29	The Sublime Karsts of Papua New Guinea	Papua New Guinea	Y	2006	Y	Y	ix,x	v	Mixed	Site includes the Nakani Mountains on the island of New Britain. Active volcanoes in the range include the stratovolcano Ulawun, the complex volcano Langila and the pyroclastic shield volcano Rabaul.
30	Mt. Malindang Range Natural Park	Philippines	Y	2006	Y	N	ix,x		Natural	Mt. Malindang is a stratovolcano which contains a small summit caldera.
31	Mt. Matutum Protected Landscape	Philippines	Y	2006	N	N	ix,x		Natural	A symmetrical stratovolcano.

Site Ref.	Name	Country	Smithsonian Holocene (active) volcano	Date of submission	Listed under Category (vii) scenic beauty	Listed under Category (viii) geology	Listed under other criteria		General Category (mixed, natural or cultural)	Observations
							Natural	Cultural		
32	Mt. Apo Natural Park	Philippines	Y	2006	Y	N	ix,x		Natural	Mount Apo is a large stratovolcano. It has a flat topped summit with 3 peaks containing a 500m wide crater,
33	Taal Volcano Protected Landscape, Batangas	Philippines	Y	2006	Y	Y	x		Natural	A caldera volcano, Taal is one of the most active volcanoes in the Philippines. It has produced some of the most powerful historic eruptions in the world.
34	Ilhas Selvagens	Portugal	N	2002	N	N	x		Natural	A series of oceanic islands. The islets represent the remains of volcanic peaks.
35	Algar do Carvao	Portugal	Y	1996	?	?	?	?	Natural	A 100m long volcanic cave, remnant of an eruption of Terra Brava, the centre of Terceira, a stombolian volcano with two cones.
36	The Commander Islands (Comandorsky State National Park)	Russian Federation	Y	2005	Y	Y	ix,x		Natural	Volcanic archipelago, being the westernmost extension of the Aleutian Islands arc. Mainly stratovolcanoes.
37	Fagaloa Bay - Uafato Tiavea Conservation Zone	Samoa	Y	2006	Y	N	x	v	Mixed	Upolu Island, on slopes Upolu shield volcano
38	The Prince Edward Islands	South Africa	Y	2004	Y	Y	ix,x		Natural	Marion island is South Africa's only historically active volcano. It was formed by two young shield volcanoes that rise above a flat topped submarine platform. The island features cinder cones, scoria cones and coastal tuff cones.
39	Mgahinga Gorilla National Park	Uganda	Y	2007	Y	Y	ix,x		Natural	Mount Muhavura is a stratovolcano with a small 40m wide lake in its summit crater. A small parasitic crater has been recently active.
40	Lake Letas	Vanuatu	N	2004	Y	N	ix,x		Natural	Volcanic crater lake on summit Holocene vol. Mt Gharat. Recent eruption.

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