Chapter

Volcanoes: Identifying and Evaluating Their Significant Geoheritage Features from the Large to Small Scale

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Abstract

Across the globe, volcanoes and volcanic terrains present one of the most complex geological systems on Earth that, depending on magma type, viscosity, and water and gas content, form a diverse range of products in terms of geomorphology, lithologic suites, structures, and stratigraphy. In broad terms, magmas, with their diagnostic composition, derive from specific tectonic settings, *e.g.*, basalt-dominated oceanic crusts, acidic magma from continental plates, and andesitic convergent-plate margins. In addition to magma composition and volcanic rock types, there is a wide range of volcanic products, manifest at all scales, dependent on how magma interacts with the Earth's surface, varying, for instance, from lava flows such as vesicular lava beds and flow-banded to flow-laminated lava beds, to breccias, tephra (ejecta) deposits, and bombs, amongst others, each commonly with their diagnostic small-scale lithological/structural features. This wealth of rock types, stratigraphy, and structures linked to geologic setting, potentially has geoheritage significance, and we provide here methods tailored for volcanoes and volcanic rocks of identifying, classifying and evaluating the complex and heterogeneous nature of volcanoes so that the full complement of their geology for a given region can be appreciated and incorporated into thematic geoparks, Nature Reserves and protected areas. For sites of geoheritage significance, we present (1) a globally-applicable Geoheritage Tool-kit to systematically identify volcanic geoheritage sites, (2) a technique to classify/categorise geoheritage sites, and (3) a semi-quantitative method to evaluate the geoheritage significance of volcanic sites.

Keywords: volcanoes, volcanic geology, geoheritage, geoconservation, geoparks

1. Introduction

Volcanoes and volcanic terrains are one of the most complex geological systems on Earth forming a range of products from the megascale and large scale to small scale that have varying geological significance. Of necessity, the ensuing text is a brief summary of a very complex and diverse subject matter, presented to a level sufficient to convey their comparative diversity and scale of expression for purposes of geoheritage and geoconservation. More detailed and comprehensive treatment of volcanoes can be found in various encyclopaedia and text books [1–13].

Magma composition is highly variable across volcanic terrains and at a single volcano, with attendant variation also in viscosity, gas content, water content, and behaviour of the erupted material. Magma can range in composition from basic (*e.g.*, basalt) to intermediate (*e.g.*, andesite) to acidic (*e.g.*, rhyolite, rhyodacite, dacite). Volcanoes extrude magmas in any of the Earth's surface environments though most are located at plate boundaries (terrestrial and submarine rift zones, subduction and collision zones, and transform zones); they can also extrude in intra-plate and cratonic settings. Commonly, magma composition is linked to global geological setting or to regional geological setting, with basaltic magmas (basic magmas) deriving from oceanic crusts, andesitic and associated magmas (intermediate magmas) deriving from collision between oceanic crust and continental crust, and a range of acidic magmas deriving from continental crusts. Continental crusts, with their lithological variability reflecting craton heterogeneity, metamorphic history, and sedimentary basin-filling, hold scope through melting, diffusion, and mixing to create a wider range of magma compositional types than ocean-crust-derived basic magmas. Thus, in continental situations, depending on geological setting, vertically-ascending magma plumbing or conduits that feed/supply volcanic eruptions can traverse variable crust types from cratons and Precambrian stratigraphic sequences to polylithic, stratified Phanerozoic sedimentary basins, to submarine seafloors. As such, in the process, this magma plumbing or conduits incorporate material from the host rocks they traverse via such processes as partial melting of host rocks, chemical diffusion from host rocks, and plucking and melting of solid fragments to form enclaves, xenoliths, and xenocrysts.

Volcanoes can erupt in a wide variety of environments, including relatively dry terrestrial environments, water-saturated terrestrial environments, continental edge, submarine environments, and from under ice (glaciers) and, thus, at the large scale, they can have a variety of lithologic/structural expression and a variety of geological structural and stratigraphic relationships to the host rocks that they intrude into or erupt from. Depending on a number of factors including gas content and contact with water, eruptions at one extreme can be extremely explosive (*e.g.*, phreatomagmatic eruptions where magma interfaces with groundwater; *cf*. Németh & Kósik [11]), sending tephra (various-sized pyroclastic material or ejecta such as lapilli and ash composed of rock fragments and glass), gas, and magma high up into the atmosphere (with some of the more explosive eruptions dispersing ash as plumes hundreds of kilometres from their eruptive source) or, at the other extreme, involve more quiescent effusive lava flows (for review see Németh & Kósik [11, 13]). The ejecta can be fine-grained ranging to fine-grained with or without included bombs, or can be dominated by coarse-grained to boulder-sized material and (depending on magma type, gas content, water, and geological setting) volcanic ash can be dominantly lithoclastic, or crystal-rich, or (volcanic glass) shard-rich, or mixtures of these [5].

Water and gas are important components of volcanism and play major roles in magma viscosity, development of vesicles, development of pumice, syn-eruption rain, post-eruption rain-storms, and moisture condensation effects. With an eruptive plume passing through a cloud, or volcano-associated rain-storms, or condensation of moisture within an expanding plume, there can be development of accretionary lapilli [14–16] and, with post-eruption rain and erosion, the potential for slurries of pyroclastic material, rocky debris and water (*e.g.*, lahars) which can be erosive into the layered tephra, or can become interlayered with the volcanic deposits all producing complex stratigraphy.

At the Earth's surface, at the large scale, volcanoes are expressed in a variety of geometric and stratigraphic arrays, *viz*., stratovolcanoes, shield volcanoes, and volcanic fissures leading to sheet flows, amongst others, with the geometry dependent on whether extrusive material, at one extreme, is tephra-dominated (mainly ash and lapilli) and built to relatively high relief (*e.g.*, cinder cones and stratovolcanoes) or, at the other extreme, lava-dominated and built to relatively low relief (*e.g.*, shield volcanoes and dome volcanoes), or intermediate with alternating tephra and lava layers and built to high relief (*e.g.*, stratovolcanoes).

At the medium scale, there is an abundance of features expressed in volcanic extrusions, *e.g.*, layered lithologically-similar ash beds, layered lithologically-heterogeneous ash beds, structureless lava beds, vesicular lava beds, flow-banded to flow-laminated lava beds, lava beds with spherulitic structures, pillows and their associated structures and mineralogy, deuteric minerals formed within lava pillows, layered ejecta deposits (ash beds), volcanic bombs, volcanic blocks, post-solidification polygonal jointing, mega-breccias and meso-breccias, micro-breccias, lava tunnels, mixing of magma types, formation of obsidian by the rapid cooling of magma to form glass, formation of pumice by super-heated, highly pressurized magma being violently erupted, diatremes and maars, secondary dykes, amongst many others [6, 9, 10].

At the small scale, there is deformation of ash-bed layering/lamination by bombs, flow-breccia structures, xenoliths and xenocrysts, surge structures, stalactitic and stalagmitic structures, lamination in obsidian, deformation (stretching) of vesicles of lava and pumice by flow, lapilli and accretionary

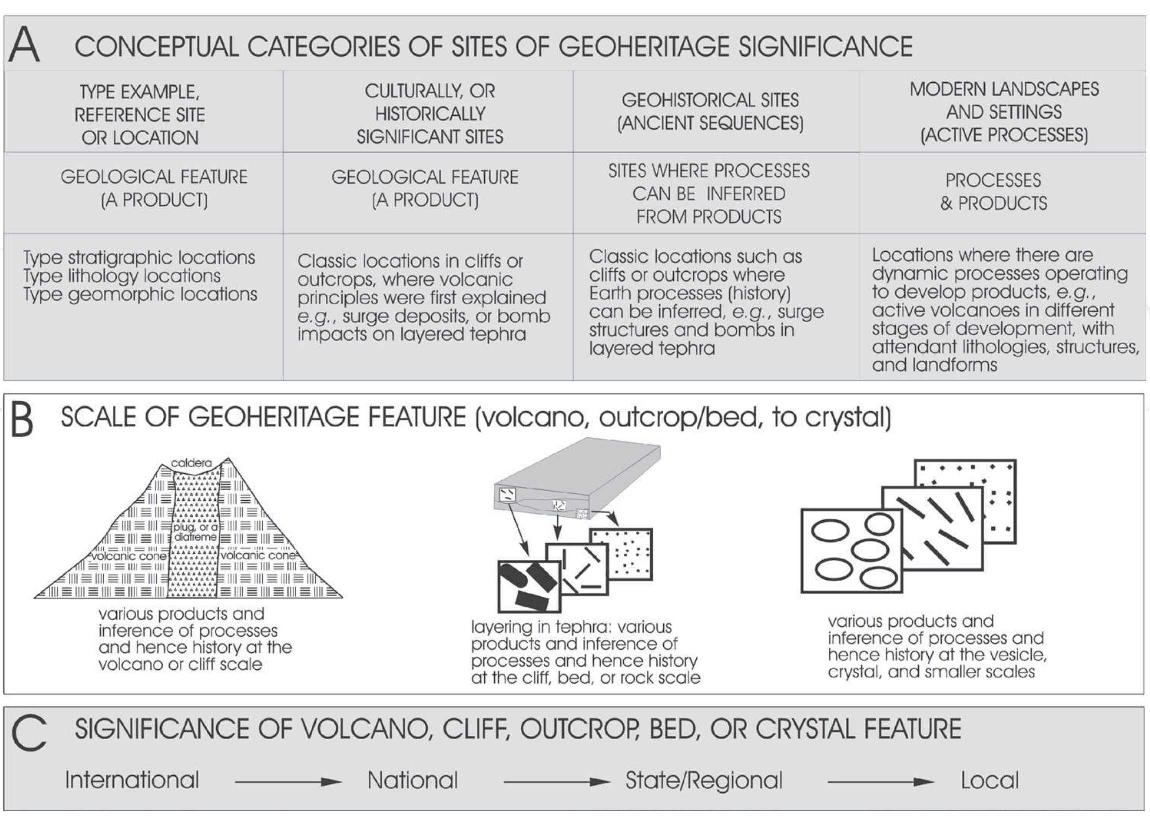

Figure 1.
The categories of sites of geoheritage significance (modified from Brocx & Semeniuk [1] and tailored for volcanoes).

lapilli, a wide range of vesicle-lining or vesicle-filling minerals, crystal types and forms (*e.g.*, zeolites, calcite, quartz, chalcedony, epidote), mineral-filled fractures, small-scale fumarolic fissures or vents (empty, or filled with crystals, filled with massive lava, or filled with vesicular lava), alteration of the

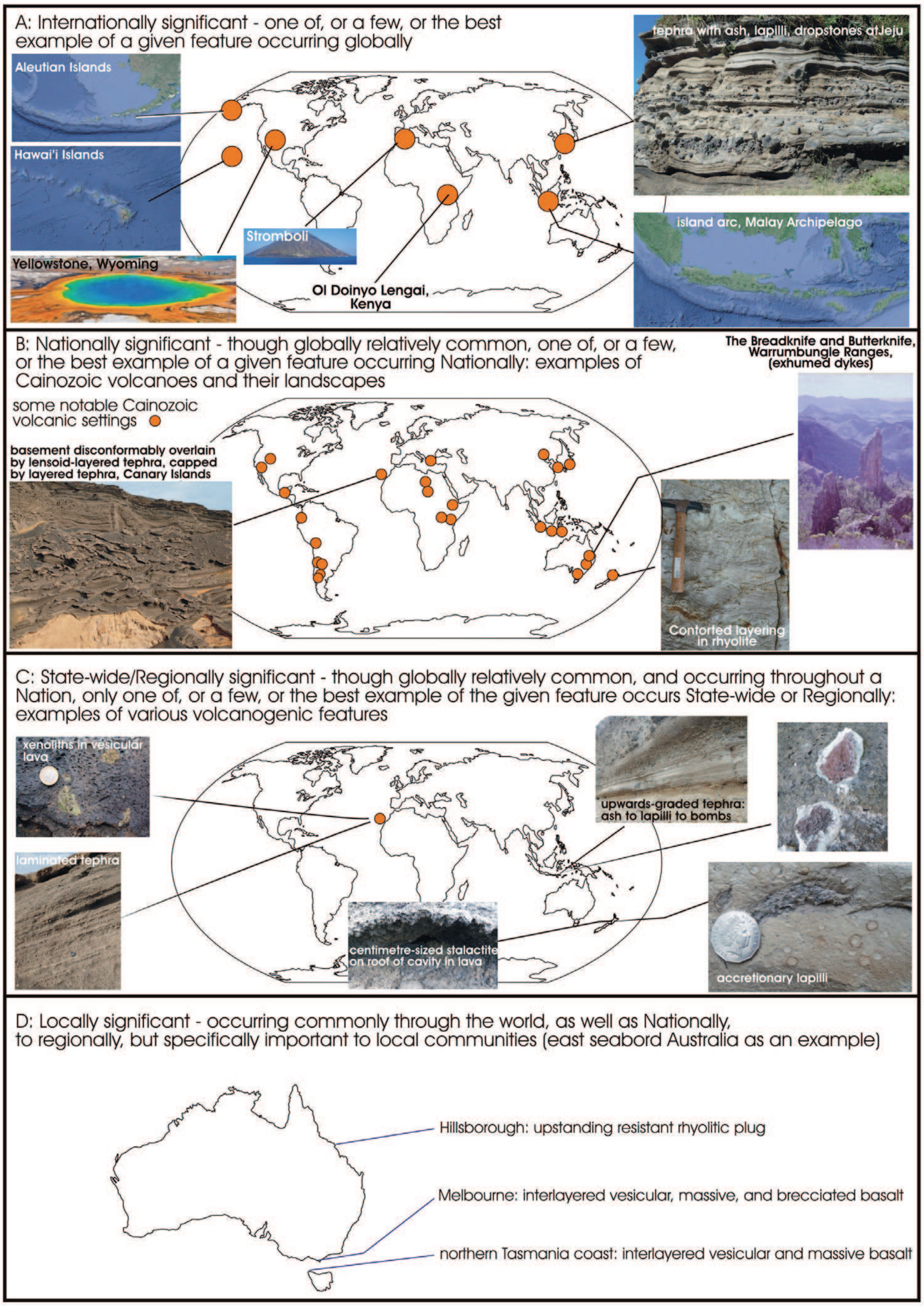

Figure 2.
Following Brocx & Semeniuk [17], the four levels of significance recognised in this Chapter (modified from Brocx & Semeniuk [17, 18] and tailored for volcanoes): International, National, State-wide to Regional, and Local. Examples of many volcanoes and their deposits are included in this diagram.

primary texture and mineralogy by interactions with either fluids within the magma (deuterism [or autometasomatism]) or by fluids in the near-surface environment.

A selection of diagrams to illustrate the principles of Geoheritage and how to categorise volcanic sites and evaluate their significance are presented in **Figures 1**-**3**, and a series of photographic plates illustrating the variety of geometric, stratigraphic arrays, and lithology and mineralogy of volcanoes and volcanic geology are presented in **Figures 4**-**8**.

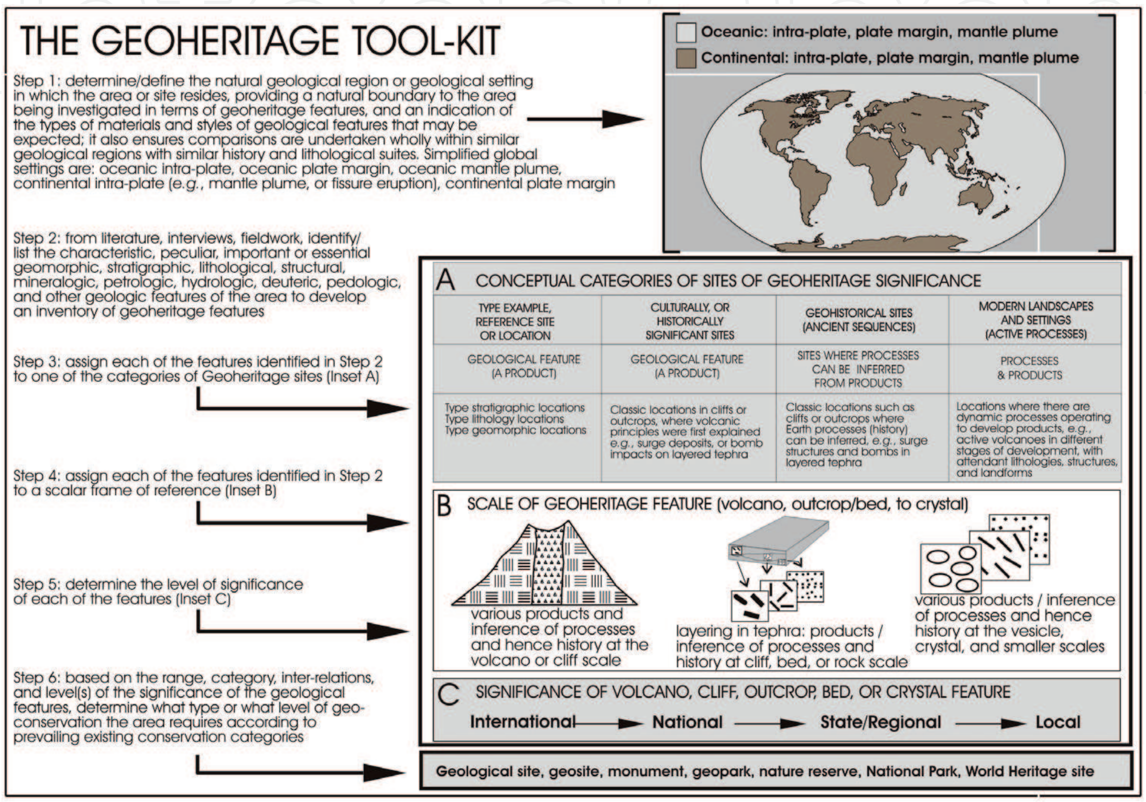

Figure 3.
The Geoheritage Tool-kit used to systematically identify and assess sites of geoheritage significance (modified from Brocx & Semeniuk [17] and tailored for volcanoes).

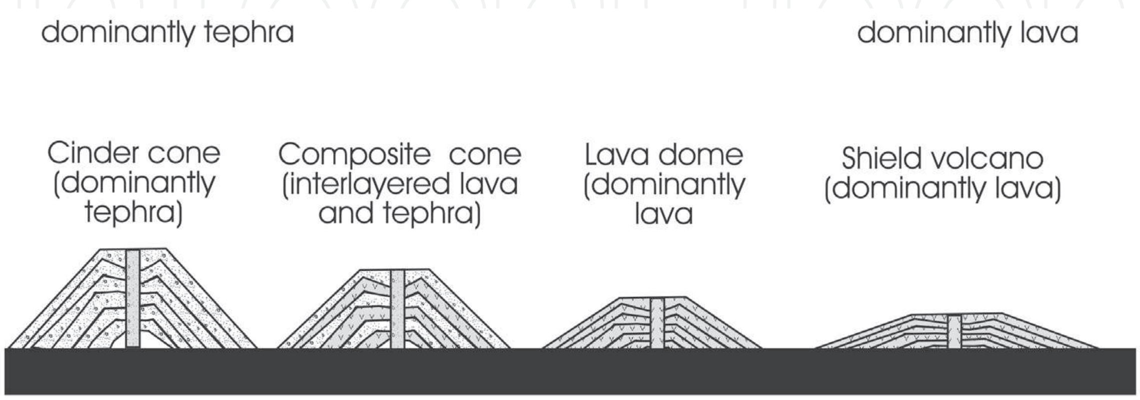

Figure 4.
The variety of geometric and stratigraphic arrays of volcanoes, viz., *cinder cones, composite (stratovolcanoes), lava cones, and shield volcanoes. This diagram emphasises the gradation from tephra-dominated to lava-dominated eruptions and the corresponding changes in stratigraphy and form of the volcanoes. Fissure vents, and sheet flows are not included.*

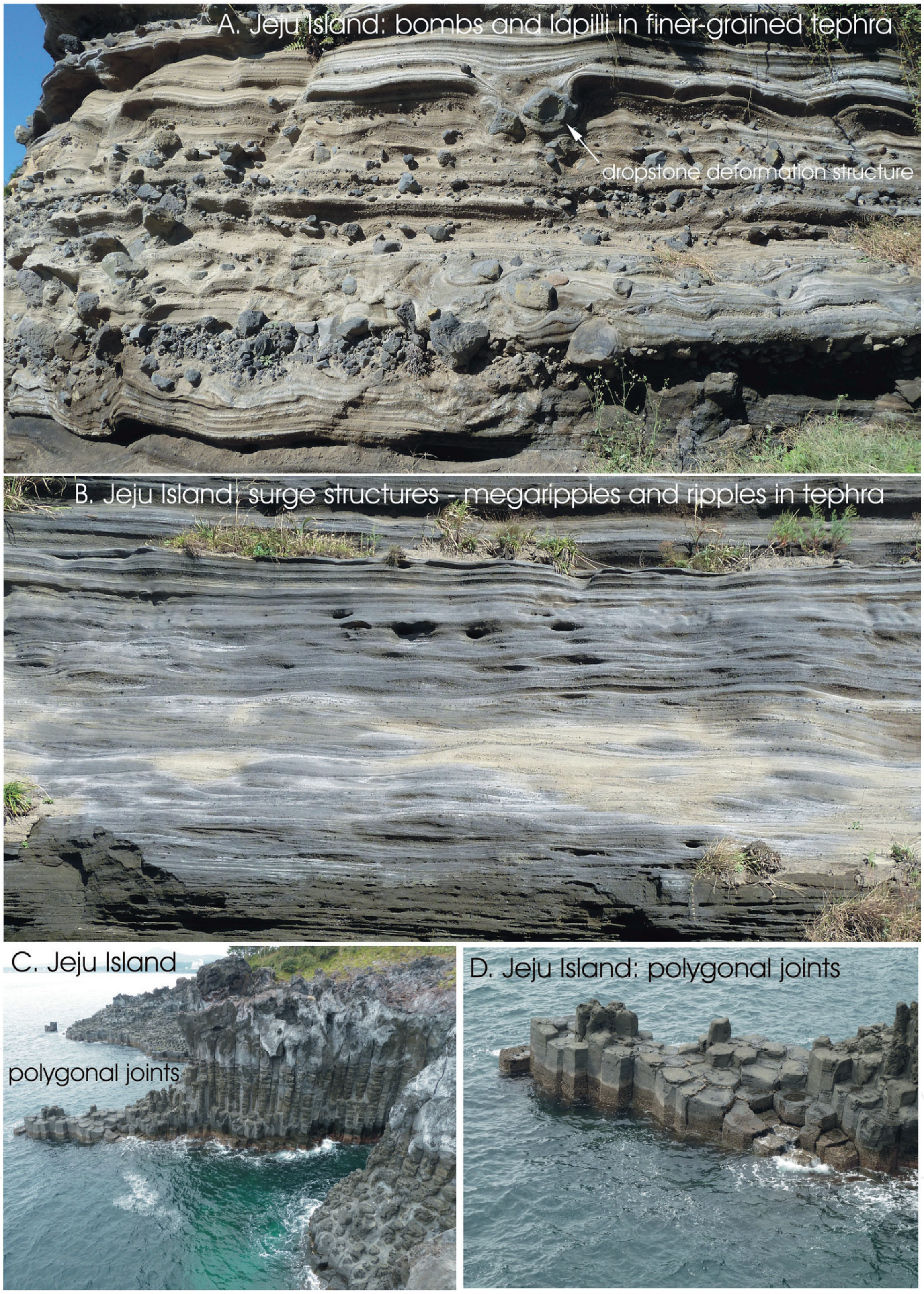

Figure 5.
Illustration of a selection of volcanic features at Jeju Island that are of geoheritage significance (photographs also are annotated). A. Bombs and dropstone structures in finer-grained tephra. B. Surge structures of megaripples and ripples in tephra. C & D. Polygonal (hexagonal) columnar jointing in basalt.

2. What is Geoheritage and how does it relate to volcanoes?

Geoheritage, and its sister endeavour, geoconservation, are concerned with the identification, categorisation, and preservation of significant Earth geological features, and are recognised globally as important, as reflected in

Figure 6.
Illustration of a selection of volcanic features at Jeju Island that are of geoheritage significance (photographs also are annotated). A & B. Various interlayered vesicular and massive basalt (coins for scale). C. Vesicular lava filling a small-scale fissure. D. Carbonate stalactites and stalagmites formed by dripping groundwater in a lava tube. E. A complex arrangement of vesicle types (large, medium and small) in basalt. F. Layered tephra with various brown and black lithoclasts in laminated tephra (walking stick is 1 m long). G. Tree trunk (30 cm diameter) that was buried by vesicular lava (north island New Zealand).

various international and intra-national bodies set up for conservation, with agreements, conventions, and inter-governmental initiatives [17, 19–24]. Both endeavours are integral components of the preservation of geological features, geo-education, geotourism, planning and environmental management globally

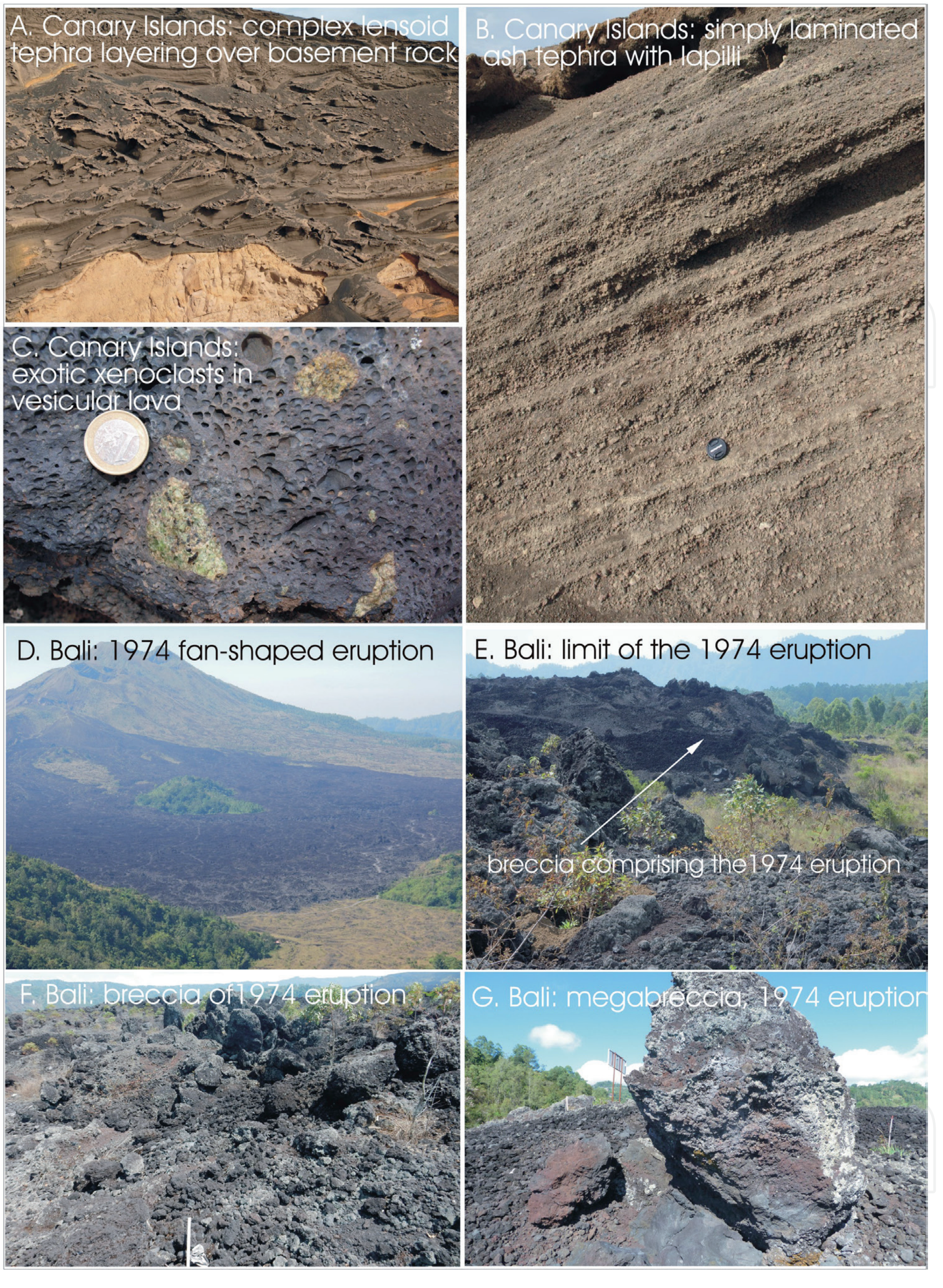

Figure 7.
Illustration of a selection of volcanic features in the Canary Islands (A, B, C) and at Bali (D, E, F, G) that are of geoheritage significance (photographs also are annotated). A. Complex tephra layering overlying basement rocks. B. Exotic xenoliths in vesicular lava (coin for scale). C. Simple laminated ash with lapilli laminae (lens cap for scale). D. The fan-shaped volcanic deposit emanating from Mt Batur is the 1974 eruption. E. The edge of the 1974 eruption, and the breccia nature of the eruption. E & F. Breccia and mega breccia comprising the rocks of the 1974 eruption (stick in foreground of E is 0.5 m long).

under the World Heritage Convention (and especially in the United Kingdom and in Pan-Europe, *i.e.*, Continental Europe), and across the Globe under various national instrumentalities [19]. Of the large range of geological phenomena that can be assigned to sites of geoheritage significance listed in Table 1 of Brocx

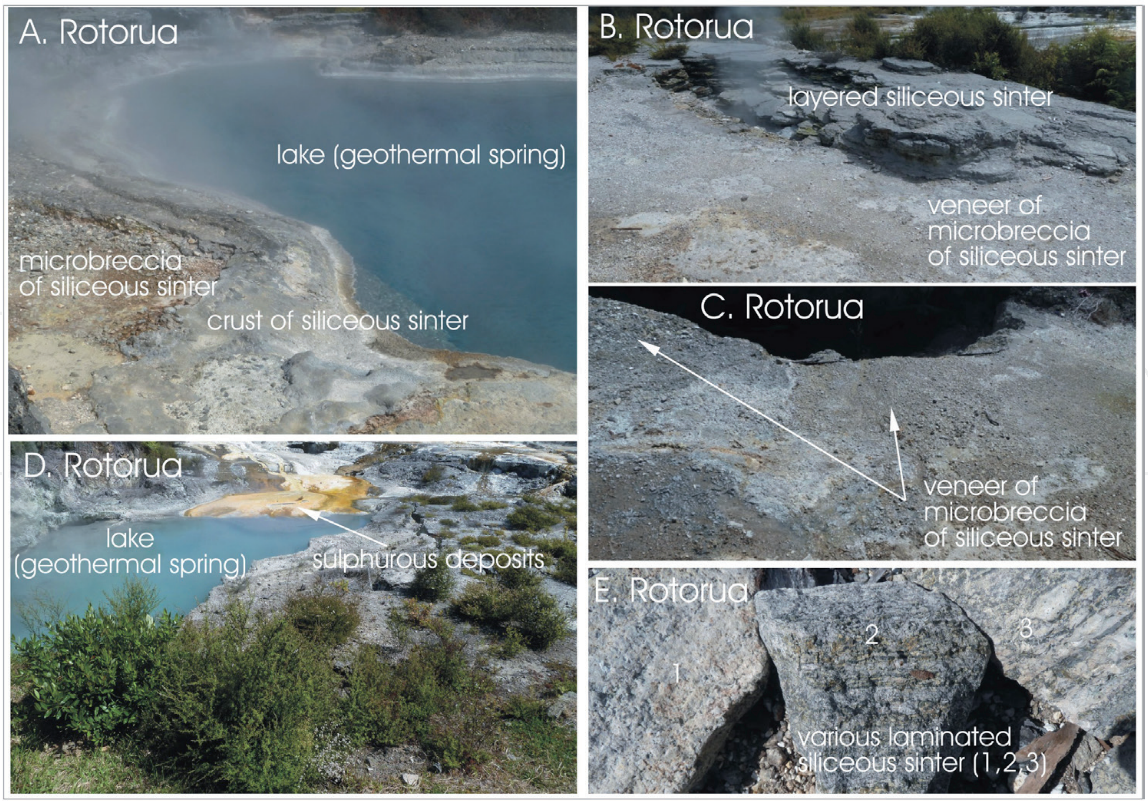

Figure 8.
Illustration of a selection of volcanic features at Rotorua, New Zealand. The Rotorua volcanic area presents a complex of rhyolitic lavas and ignimbrites (including dacitic and andesitic lavas), with development of a large caldera and a series of smaller geothermal springs; these images focus on the active geothermal springs and their associated laminated siliceous sinters and sulphurous deposits. Annotated images show geothermal lakes, layered siliceous sinter lining edges of lakes, microbreccia of fragmenting sinter, sulphurous deposit precipitating from a geothermal spring, and closeup of three laminated siliceous sinters.

& Semeniuk [17], three of the most complex are coastal zones, volcanoes, and caves in that they encompass a plethora of large-scale to small-scale features. Volcanoes are particularly important in that various types of magma erupting at the Earth's surface interact with water, atmosphere, and (pre-existing) rocks, and result in a large variety of volcanic products - this Chapter is focused on the geoheritage significance of volcanoes and their associated diverse geological products.

In an overview, Geoheritage encompasses the legacy of global, national, state-wide, and local features of geology, at all scales from mountain ranges and island arcs to crystals, that are important intrinsically, scientifically, historically, or culturally, offering information or insights into the evolution of the Earth, or into the history of Science, or that can be used for research, education/teaching of geological science, or used for reference [17]. As geoheritage focuses on features that are geological, the scope and scale of what constitutes Geology will determine what is included under the umbrella term 'geoheritage'. The discipline of Geology includes igneous, metamorphic, and sedimentary rocks, stratigraphy, structural geology, geochemistry, fossils and other aspects of palaeontology, geomorphology, soils and pedology, and hydrogeology/hydrology (as listed in Table 1 of Brocx & Semeniuk [17]). From there, all that is encompassed by the discipline of Geology can be included under the umbrella of geoheritage.

The many-and-diverse large- to small-scale features of volcanoes hold potential to be of geoheritage significance particularly as they present diverse magmas, occur in a vast range of Earth-surface settings and, depending on what materials they interact with, present a large variety of lithologies, structures, and geological relationships between volcanic materials and country rock. Further, volcanoes and volcanic sequences, depending on setting, often present an ensemble of inter-related geological features. For instance, while there may be a degree of structural and volcanic-stratigraphic overlap, the volcanic rock associations, lithologies, and structures of basaltic volcanoes in a submarine and emergent-volcanic-island settings are different to those of andesitic settings to those of rhyolitic settings.

Volcanoes and volcanic geology have existed from Precambrian times to the present, but the emphasis in this Chapter, for purposes of addressing geoheritage values, is on modern and sub-recent examples (*i.e.*, the latter Cainozoic to the latter Quaternary - older volcanic deposits carry with them the complication of imprints and overprints of geomorphic modification, sedimentary reworking, epigenesis, pedogenesis, metamorphism, and structural modifications [18, 25], and thus are outside the scope of this Chapter. However, the principles developed in this Chapter can be applied to these older deposits.

While many sites and features of geoheritage significance can be an isolated geological phenomenon or a stand-alone isolated feature (*e.g.*, Mato Tipila [The Devils Tower] in Wyoming [26–28], a volcanic feature appearing to be related to monogenetic volcanism [28]; or Pamukkale [the Cotton Castle in Turkey] [29]), the same perspective also applies to some aspects of volcanic geology. However, more typically, the majority of volcanic features occur as ensembles of geological phenomena. Thus, a volcano can carry with it several or many of the following that can be (in isolation or collectively) of geoheritage significance: 1. geomorphic form; 2. lithology-specific volcanic form; 3. internal layering of a volcanic cone; 4. complex stratigraphic layering and relationships internal to the volcano; 5. layering of distally-dispersed tephra (*e.g.*, fine-grained ejecta); 6. tephra that is lithologically and granulometrically diverse; 7. tephra with diverse structures (*e.g.*, surge structures, drop-stones structures); 8. tephra interlayered with lahar (water-saturated mudflow or debris flow composed of pyroclastic material and rocky debris); 9. rocks of diverse lithology, such as lavas, plugs, dykes, sills, and diatremes associated with volcanoes; 10. breccia and mega-breccia; 11. lapilli and accretionary lapilli; 12. lava-filled, or empty fumarolic vents (mostly small-scale fissures that are venting gases); 13. dykes (concordant to discordant to volcano layering); 14. lava tubes; 15. lenses/wedges of slumps/avalanches deriving from and inter-layered with fine-grained tephra; and 16. rain-induced mobilisation of tephra forming lenses/wedges of reworked material.

For sites of geoheritage significance, Brocx & Semeniuk designed a globally-applicable Geoheritage Tool-kit to identify geoheritage sites [17, 30, 31] (that is currently recommended by the IUCN [20] and, using Brocx & Semeniuk, the Geological Society of Australia [31]), presented this Tool-kit to categorise geoheritage sites [17]), and a semi-quantitative method to evaluate them [17]. Modified versions of these procedures, tailored for volcanoes and volcanic rocks, are illustrated here in **Figures 1** and **2**. The techniques for classifying/categorising sites of geoheritage significance are applied (following Brocx & Semeniuk [17]) in **Table 1** to four relatively geologically simple localities: 1. bomb-rich tephra, Jeju Island, 2. grainsize-graded tephra, Bali, 3. basement disconformity influencing tephra layering, Canary Islands, and 4. rhyolitic geothermal springs and sinters, Rotorua, New Zealand. Further examples of systematically evaluating levels of significance of geoheritage sites are provided in Tables 1-3 in Brocx & Semeniuk [30].

Geological feature	Type of site, and its scale (category of site from Figure 1)	Significance (based on criteria of Figure 2)	Rationale for assigning the level of significance
Jeju Island (Figures 5 and **6)**: a regional framework of mainly Pleistocene to Holocene basaltic to trachyandesite to andesite (lavas, tephra, ignimbrites), with lapilli-rich layers alternating with lapilli-depauperate layers, alternating with bomb-rich layers; bomb-rich sequence with local deformation structures of dropped bombs; surge structures (megaripple and ripple lamination) [32]	Geohistorical site; medium scale to small scale; also can be reference site for (1) the variety of tephra deposits, (2) the dropstone effects of bombs, and (3) the stratigraphic/structural record of surges	International	Well-exposed cliff site of multi-lithologic sequence of tephra types and, in particular, the deformation effects of bombs as drop stones and the evidence of surge deposits as ripple lamination and megaripple lamination; useful for research, education and geotours
Bali (Figure 7**)**: a regional framework of basaltic to dacitic volcanism (lavas, tephra, ignimbrites), a layered deposit of relatively fine-grained tephra (ash), overlain by coarse grained ejecta (lapilli), in turn overlain by bomb-sized and block-size ejecta [33, 34]	Though the volcanoes of Bali represent active geological sites, the cliff illustrated in **Figure 7B** is a geohistorical site; medium scale to small scale; also can be reference site for the graded upward coarsening of tephra deposits	State-wide to Regional	Well-exposed cliff site of grain-size-graded ejects grading from relatively fine-grained to block-sized showing a history of increasing intensity of volcanic activity; useful for research, education and geotours
Canary Islands (Figure 7**)**: within a framework of diverse volcanic rocks ranging from basalt and basanite to trachyte to trachyandesite in which are recognised five developmental stages, there are local occurrences of basement topographic highs which influenced layering in deposition of tephra [35–38]	Ancient geohistorical site; medium scale to small scale; can be reference site for the effect of basement rock topography on tephra layering	National	Well-exposed site of Cainozoic tephra with complex lensoid layering above a basement topographic high followed by horizontal tephra layering; useful for research, education and geotourism
Rotorua (Figure 8): a framework of rhyolitic lavas and ignimbrites (including dacitic and andesitic lavas) forming a large caldera and a series of smaller geothermal springs; active geothermal springs are forming laminated siliceous sinters and sulphurous deposits [39, 40]	Active volcanic site; medium scale to small scale; plethora of surface features and derivative products from siliceous sinter (*e.g.*, microbreccia of fragmenting sinter)	International	Well-exposed site of rhyolitic rocks and ignimbrites, geothermally-derived siliceous sinters, active geothermal springs; useful for research, education and geotourism

Table 1.
Features of geoheritage significance Jeju Island, Bali, Canary Iislands, and Rotorua, and the rationale for the assessment.

3. Application of geoheritage and geoconservation principles.

Unlike significant single geological features, such as the Siccar Point unconformity in Scotland [41] or the K/T contact at Gubbio in Italy [42], volcanoes commonly present a multitude of interrelated geological features from the large scale to the small scale each of which frequently carry geoheritage significance. Given this wide range of volcanic features on Earth in terms of their diversity, magma type, the interactions with pre-existing rocks, magma, and water, and scale of features, volcanoes and their multitude of products, in practice, present complex systems to classify and assess as sites of geoheritage significance. Leaving aside the older volcanic deposits, the modern and sub-recent examples on their own are diverse and significant enough and provide important stories about the Earth and important insights into the functioning and geochemistry of the Earth crust. For instance, at a global level, geochemically, volcanoes illustrate the chemical variability of the Earth's crust latitudinally, longitudinally, as well as in terms of geological settings (*viz.*, in broad terms, oceanic *versus* continental). At smaller scales, volcanoes and their products, in interacting with rocks, water, and atmosphere, provide a wealth of geological features that are great stories of the Earth and hence of great heritage (geoheritage) significance. In this context, the geoheritage significance of volcano types, volcanic deposits, volcanic landscapes, and secondary volcanic landscapes (such as landslides and rockfalls) was recently addressed in the Journal *Geoheritage* [43–47] and in [48].

The best way to comparatively assess and deal with the geoheritage significance of volcanoes and volcanic products is to address their diversity (often *incomparable* from site to site) and commence with an approach of geological setting, magma types, and scale. This is because volcanoes, volcanic activity, and volcanic products, though branded together under the 'umbrella' term of volcanoes, can be markedly different in the various geological settings, expressed as a diversity of magma types, and will express various and different geological phenomena at various scales - from these perspectives, volcanoes in these different environments are not comparable. There are proposed four spatial scales with which to systematically deal with volcanoes and their products (**Table 2**).

Examples of global to sub-global scale volcanic features
Geological setting: oceanic crust; sites of mantle plumes; island arcs; continental margin volcanoes; intra-continental plate volcanoes
Magma type(s): basaltic suite; andesitic suite; acidic volcanic suite
Examples of regional scale volcanic features
Types of volcanoes geomorphologically; types of volcanoes behaviourally; chains of volcanoes; fissures; lava tubes
Examples of local scale volcanic features
Massive lava; layered/laminated lava; brecciated lava; bombs; pillow lava; disconformities; complex stratigraphy; types of tephra; layering in tephra; structures in surge deposits; lava tube; diatremes and their complex stratigraphy; dykes; geothermal springs; sinters
Examples of small scale volcanic features
Vesicles; stretched vesicles; lapilli; accretionary lapilli; crystal fill of vesicles; crystal fill of fractures; deuteric precipitates; stalactitic and stalagmitic deposits in lava tube; bombs and their deformation (dropstone) structures in tephra; fissures and crystal or lava filled fissures; lithoclasts/xenoliths; xenocryst; shards

Table 2.
Examples of large to small scale volcanic features occurring at the four spatial scales.

Given the scope of volcanic geology, the list above, axiomatically, is not exhaustive, but provides an insight on how to assess and evaluate the geoheritage significance of volcanoes. Outside of the spatial scale (or size) that volcanic features can occur, there is also a significance or evaluation that can be attributed to them, as follows (**Figure 3**):

1. Internationally significant.

2. Nationally significant.

3. State-wide to regionally significant.

4. Locally significant.

For geoconservation, once a site, area, or region is assessed as being of geoheritage significance, then measures should be undertaken to protect the more significant sites, and/or utilise them for conservation in perpetuity, or for research, education, and geotours in a managed manner. Sites, areas, or regions can be allocated/inscribed for geoconservation as World Heritage Sites, National Parks, geological conservation reserves, type localities for rocks and minerals, reference sites or reference localities for volcanic features, a geological monument, a geopark, or a geotrail (as described and discussed by Brocx & Semeniuk [49, 50]). Where there is an ensemble of volcanic features illustrating the story of volcanoes on the Earth, the suite of features would be ideally integrated into a thematic geopark, such as at Jeju Volcanic Island, Yellowstone National Park, and Hawaii (Hawai'i) National Park.

The large-scale sub-global array of volcanoes forming island arcs in the Malay Archipelago and that in the Aleutian Islands, being unusual and/or unique in the World, would be viewed as globally significant World Heritage Sites [51, 52]. The smaller-scale presentation of tephra deposits, their complex stratigraphy, and bombs such as that cropping out at Jeju Island would be (and is) a smaller-scale World Heritage Site [32]. So too, the island chain system located on a hot mantle plume at Hawaii (Hawai'i) would be a World Heritage Site [53]. Other volcanic centres that exhibit unusual or extraordinary features such as the carbonatite eruption at Ol Doinyo Lengai in Kenya [54, 55], and the rhyolites, tuffs, and some basalts in the Yellowstone Caldera [56, 57] also would be World Heritage Sites. Many of these volcanic sites are already allocated to globally-significant conservation reserves but the point of this text is to highlight that they have features ranging from sub-global scale to smaller scales that qualify them as being of geoheritage significance in contrast to many other volcanic sites that have a different (but also significant) set of attributes that have yet to be rigorously allocated to geoheritage significance.

In, as a result of the complex interplay between magma in the Earth's interior, its ascent through the crust, and its eruption at the surface, there is a rich geological variability in volcanoes in terms of conclusion geometry, structure, stratigraphy, lithologies, volcano-to-country-rock relationships, contact metamorphism, and near-surface alteration often specific and relevant to a particular geological region or province. Across the globe, this results in a geological natural-history resource and geological museum of geoheritage significance that is useful for research, education and geotours, and provides a window into near-surface Earth processes, deep-Earth processes, the history of the Earth and, given crustal heterogeneity, development of specific suites of volcanic features restricted to particular tectonic settings.

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