Volcanic Geoheritage in the Light of Volcano Geology

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Abstract

Volcanic geoheritage relates to the geological features of a region that are associated with the formation of a volcanic terrain in diverse geoenvironmental conditions. These features include the volcanic processes, volcanic landforms and/or the eruptive products of volcanism that form the geological architecture of that region. Volcanic geoheritage is expressed through the landscape and how it forms and evolves through volcanic processes on various spatio-temporal scales. In this sense it is directly linked to the processes of how magma released, transported to the surface and fragmented, the styles of eruption and accumulation of the eruptive products. Volcanic geoheritage is directly linked to the natural processes that generated them. Geocultural aspects are treated separately through volcanic geosite identification and their valorization stages. Identification of volcanic geosites, based on various valorization techniques, have been applied successfully in the past decades to many geological heritage elements. Volcanism directly impacts societal, cultural, and traditional development of communities, hence the "*living with volcanoes*" concept and indigenous aspects and knowledge about volcanism can and should play important roles in these valorization methods through co-development, transdisciplinary approaches by including interconnected scientists in discussions with local communities. Elements of volcanism and volcanic geoheritage benefit of the geoculture of society so volcanic geoheritage sites are ideal locations for community geoeducation where resilience toward volcanic hazard could be explored and applied more effectively than it is done today. Geoparks within volcanic terrains or volcanism-influenced regions should be the flagship conservation, education and tourism sites for this message. Volcanism can be an integral part of processes operating in sedimentary basins. Here volcanic eruptive products and volcanic processes contribute to the sediment fill and geological features that characterize the geoheritage of that region.

Keywords

Geoheritage • Geodiversity • Geoconservation • Geoeducation • Volcanic facies • Eruption style • Explosive • Effusive • Pyroclastic • Volcano geology • Monogenetic • Polygenetic • Stratovolcano • Caldera • Submarine volcanism

1 Introduction

Volcanic eruptions are frequently the subject of global and local media attention because volcanism fascinates people, even in areas not hosting active volcanoes. In fact, volcanic events generate more interest from people than any other geological processes (Erfurt-Cooper 2011; Erfurt-Cooper 2014) (Fig. 1). This behavior has been identified as one of the main driving forces behind volcano tourism, a special type of geotourism associated with adventure tourism (Erfurt 2018). Volcanic geology has been incorporated into methods for evaluating the geoheritage values of volcanic terrains especially from the perspective of UNESCO World Heritage site nominations. The main international body that stands behind the UNESCO World Heritage site selections mostly by providing advice and recommendation of the scientific value of the proposed sites, The International Union for Conservation of Nature (IUCN), has published two thematic

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Fig. 1 Volcanic eruption during the 2021 Geldingadalir, Iceland eruptive events the full array of a typical mildly explosive, dominantly effusive basaltic volcanic eruption can be observed (**a**) that fascinate the visitors (**b**). Photo by *Gisli Gislason*

studies on volcanoes (Wood 2009; Casadevall et al. 2019). The first issue, published in 2009 (Wood 2009), outlines the significance of volcano science and volcanic landforms in the selection criteria for granting UNESCO World heritage site status to a volcanic terrain. This report, however, lacks a practical, systematic comparative study that nominating bodies could readily deploy. Hence where sites proposed for UNESCO World Heritage status had strong association with volcanism it became apparent that further study was warranted. A new report, released in 2019 as the World Heritage Volcanoes document (Casadevall et al. 2019), recommends classification methods, knowledge gap analysis and some recommendations about how future sites should be accepted for listing. While this report, and the stronger involvement of IUCN in this process, with the aid of geoscientists with expertise on volcano geology is certainly a major step forward, it is still very general and lacks definitive guidelines.

Volcanic geoheritage is currently used in a very broad sense, essentially to any volcanic terrain, feature, processes, deposit or eruption that are in some way unique to or associated with some geocultural perspective (Nemeth et al. 2017). The historic eruption record, oral traditions from indigenous cultures or strong geocultural links are used to define the volcanic geoheritage. Volcanic geoheritage is commonly viewed as an attribute serving geotourism or geoeducation purposes. While there is no doubt that volcanism is a key element of many geotourism projects, development of geopark models and heavily linked to its geoeducation potential, volcanic geoheritage is somehow a more broader concept and it should be viewed through our current knowledge on how volcanoes work or evolve (Fig. 2a), their role in creating or modifying landscapes (Fig. 2b, c), and how they vanish over time (Fig. 2d). In this chapter we provide a working approach to view volcanic geoheritage as a universal and absolute value of geoheritage that also provides a scientifically established background of qualitative and quantitative geodiversity estimates of volcanic terrains or volcanism-influenced sedimentary basins. The proposed approach provides a firm foundation of how volcanic geoheritage can be utilized in geoconservation strategies or for geotourism purposes. Here a proposed approach is outlined that provides a non-biased, geologically validated approach to express the attributes of volcanic geoheritage. Later, we discuss the geocultural aspects including indigenous cosmovisions on volcanism that can act as a driving mechanism to valorize geoheritage values to identify, locate and map volcanic geoheritage sites.

2 Geoheritage—Geodiversity—Geoconservation from Volcano Science Perspective

There is general confusion and convoluted usage of terms and methods used to define volcanic geoheritage. The same issue exists in how we treat and define geoheritage in general. Current systematic research, based on study of the published scientific data shows that a largely inhomogeneous approach exists to define geoheritage and consensus has not been reached yet (Nemeth et al. 2021a, 2021). In many cases geoheritage, geoheritage site and geodiversity are mixed terms that are inconsistently applied with few if any synonym terms. "*Geoheritage*" is a generic but descriptive term applied to sites or areas of geologic features

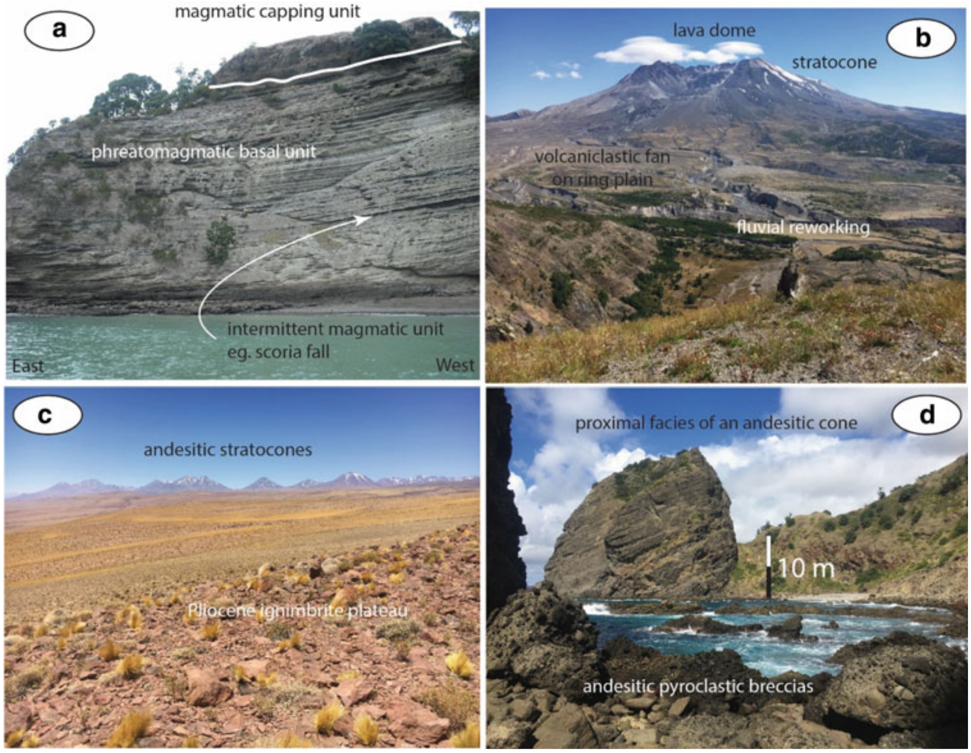

Fig. 2 **a** Eruptions styles control the overall architecture and even the volcanic landform characteristics as well as they reflected in the deposit characteristics in meso and micro scales. In the Motukorea/Browns Island in the quaternary Auckland volcanic field a typical basal phreatomagmatic tuff ring section is capped by magmatic explosive eruptions that generated scoriaceous capping units. **b** Most of the volcanic eruptions have short to medium term (e.g., thousands of years to maybe few millions of years) landscape-modifying effects. This can be observed from Mount St. Helens that after the 1980 eruption deposited extensive volcaniclastic fans in the ring plain. Since the eruption, the newly accumulated volcaniclastic fan gradually incised by local stream network and remobilized and redeposited significant part of it providing and advancing volcaniclastic fan in the distal regions of the volcano. **c** In exceptional cases volcanic eruption are significant landscape producing events that shape the landscape dramatically as the case in most of the large ignimbrite flare up events in the Earth History such as the Pliocene ignimbrite plateaus at the Andean Central Volcanic Zone in Chile. The Pliocene ignimbrite sheets cover the region over several hundreds of metres thick ignimbrite successions providing light pink tone to the landscape and acting as a base on the Pleistocene and Holocene intermediate (andesite, dacite) polygenetic compound, composite and stratovolcanoes grown in the last hundreds of thousands of years. **d** Erosion can alter volcanic landscape and produce visually and aesthetically unique landscape elements such as the dissected and exhumed core of Miocene stratovolcanoes proximal sections at the Fletcher Bay of the Coromandel peninsula, New Zealand

with significant scientific, educational, cultural, and/or aesthetic value (Brilha 2018b; Macadam 2018). According to this widely adapted definition geoheritage is widely accepted as a site-specific definition that can be defined by various valorization techniques including its scientific, educational, cultural and aesthetic values (Brilha 2016, 2018a). The value is heavily influenced by the societal and cultural activities associated with the site. However, if we wish to express, for comparative reasons, the geoheritage values of a specific site's essential to do so in its geological and geomorphological context independent of human society and culture. Geoheritage is something that reflects the heritage elements of Earth History and the processes that generate the geological and geomorphological features (Fig. 3). Geoheritage in this perspective treats Earth's processes and history as the controlling factors regardless of Recent interactions with human society. Geoheritage sites are those which has been identified and studied to generate inventories and comparative studies expressing the relative values of those locations (Brilha 2016) (Fig. 4). In this context scope and scale of the features are important. Within the framework of valorization, the various methods applied are generally linked and heavily dependent on the recognized scope of the site. The most common approach is for geotourism where the valorization shows strong linkages to the cultural activities associated with the identified geosite. Hence strong arguments can be made to include geocultural or even indigenous elements in the geoheritage element description. The perspective proposed here aims to avoid this confusion by putting geoheritage as the absolute value on which to base our current and best scientific view of a geological or geomorphological entity (Fig. 3). To create a workable framework to identify the geoheritage elements a systematic overview looking at the geological and geomorphological features from a topological aspect (e.g., descriptive sense) and the processes operating at the time of their creation (Fig. 5). The processes then can be interpretative as they are commonly inferred from some measurable and/or observable parameters in the geological or geomorphological record. Intuitively, this method should be independent of the way we gain information to solve the problems, e.g., how the arguments and assessment probe the observed geoheritage element. To put it simply, the geoheritage value of a geological feature should be entirely dependent on the current scientific understanding of the processes that created the feature regardless of the pathway followed to reach that knowledge.

Geodiversity, in contrast, is something that expresses the diverse nature of the geoheritage elements from the perspective of the processes that formed the feature (Gray 2018a, b; Zwoliński et al. 2018). Geodiversity is commonly defined as the variety/natural range/range/diversity of the non-living (abiotic) environment. This assessment of a feature is intended to be all-embracing encompassing 'geological nature/geological features/the geological environment'. This definition holds two logical directions, (1) all geological and geomorphological elements be included and (2) determine how this variety of features can be expressed. There are those who propose geodiversity should be treated in a similar way to biodiversity, as an expression of number/density of features (Fig. 6). This is a promising and interesting idea, but very difficult to develop and test. While the idea is commendable and would expand the current application of biodiversity to include the abiotic aspects there are some significant issues that need to be explored further. Namely, biodiversity calculations are almost exclusively based on a selection of species and look at their population density within various regions. The selection of a species is a kind of "*singularity-defined*" approach as the definition of species—especially in comparison to the scale of the observations (and measurements) are well defined, and easy to adapt. In a simple way, we know exactly how to identify the specific species and we can develop methods about how to measure their appearance in a specific spatial dimension. The definition of a species, or even higher

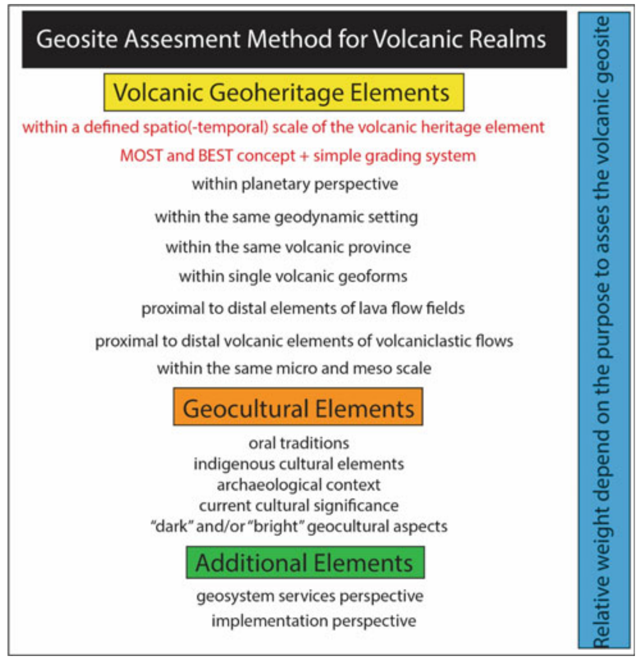

Fig. 4 Geosite valorization aspects in volcanic context as a model that needs to be specifically designed for volcanic terrains. The methods essentially based on the main versus additional values that are pre-set for the scope of the valorization such as in most of the cases serving geotourism. The methods in volcanic terrains should reflect the identified volcanic geoheritage elements as a key framework along the search for the "most and best" site should be identified

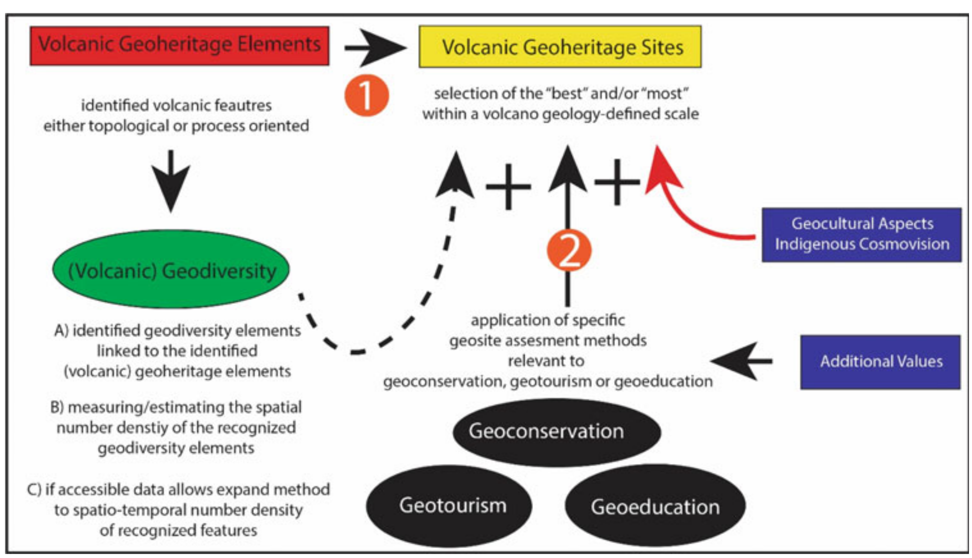

Fig. 3 Conceptional framework to outline the interlinkages of geoheritage elements—geoheritage sites and geodiversity and their connection to geotourism and geoeducation specifically expressed in a volcanic geological context

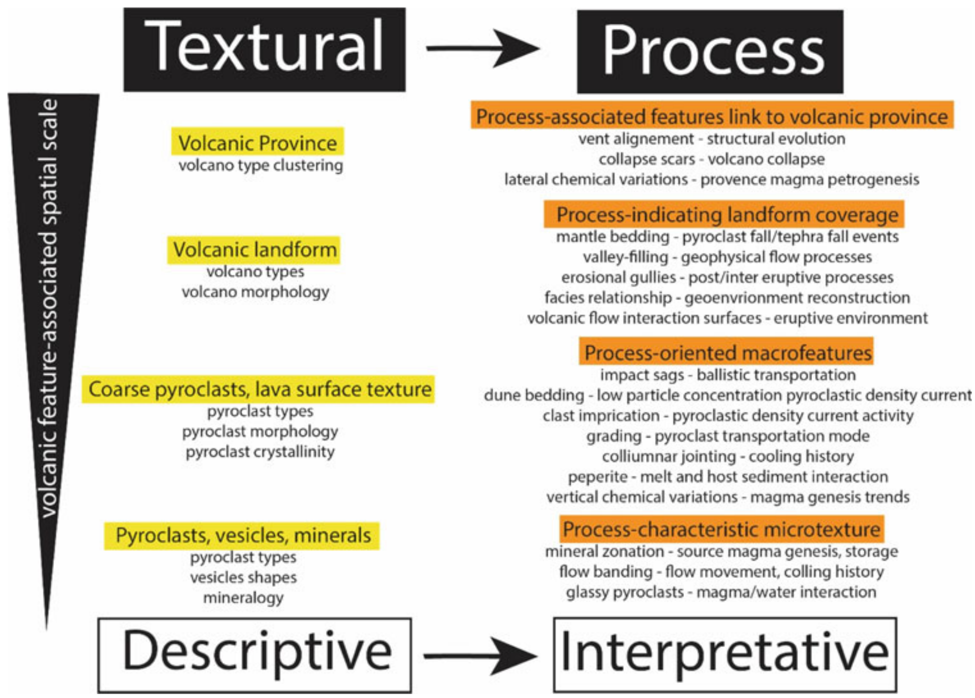

Fig. 5 Textural versus process associated volcanic geoheritage elements. Textural elements can be linked to descriptive features, for instance elements that can be expressed in some geometrical scales (e.g., landforms, fields, edifice etc.), while process elements are those that show strong link to a specific key volcanic geology process

biological orders are clear and tested over many decades, hence no, or little, ambiguity exists within the counting methods. The measurable biotic elements (e.g., a species of animal) that move across the spatial region in question, are generally small compared to the size of territory and the biodiversity being defined. However, we have no guidance or even recommendation on the best way to define the geological or geomorphological "unit(s)" we wish to measure in similar context. The current recommendations that geodiversity elements be as inclusive as possible can create confusion as various elements could be treated with equal weight in the estimation methods (Coratza et al. 2018; Zwoliński et al. 2018). Often geological and geomorphological elements are sizable with dimensions similar to the study area where the geodiversity is being assessed. To assess the spectrum of landscapes, landforms and geological/geomorphological processes if a region we need to define the measurable geological features to be included in the geodiversity calculation. Geodiversity estimation produced a great number of outputs recently commonly utilizing advanced technologies as spatial statistic or GIS applications (Benito-Calvo et al. 2009; Bradbury 2014; Argyriou et al. 2016; Araujo and Pereira 2018; Betard and Peulvast 2019; Albani et al. 2020). Probably the best approach is to utilize the available geological maps at various mapping scales; these provide the raw data pertaining to the geological elements of the region. The geological maps provide lithology-based information which are relatively easy to define, identify, or reproduce even by end-users not deeply involved in geological research.

On the basis of the geological maps, the measurable elements can be expanded to include processes associated with the lithological entities. In addition, geological maps contain data about the structural elements of the region. These are another measurable variable.

Overall, the geoheritage, geoheritage site and geodiversity are three unique features interconnected by a conceptual framework that can be applied to define a region (Coratza et al. 2018). The scope and scale are important aspects when defining these three parameters. The scope will include either descriptive or process-related aspects of the above elements but also can be linked to the purpose of the research (e.g., geotoursim, geoeducation, urban planning etc. purposes). Scale is important and is commonly associated with research purpose-defined approaches and is looked at from regional, national or global aspects. This is a valid and functional approach, especially for geotourism, but probably not the best when studying geoheritage elements. Geoheritage elements should be investigated from an internal scale perspective and relate to the dimensions of the geological elements under investigation (Fig. 7). For instance, a specific sedimentary basin that produced a specific sediment deposit that lithified into sedimentary rock has natural (and measurable) spatial and temporal dimensions. Hence when

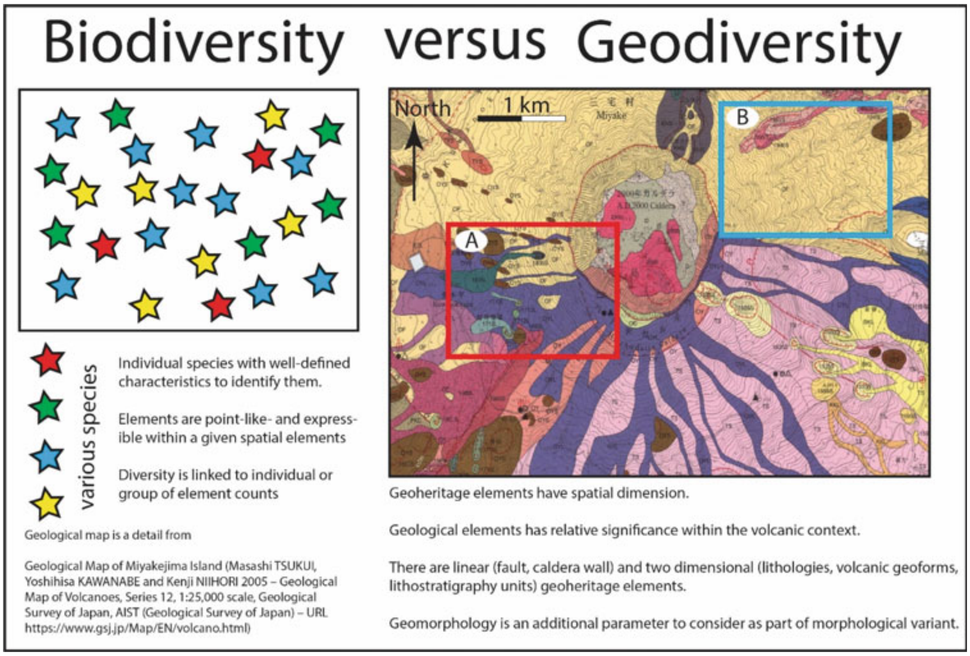

Fig. 6 Comparison of bio- and geodiversity highlighting the challenged geodiversity estimates faces with. Geological map is a detail from the Geological Map of Miyakejima Island (Masashi TSUKUI, Yoshihisa KAWANABE and Kenji NIIHORI 2005—Geological Map of Volcanoes, Series 12, 1: 25,000 scale, Geological Survey of Japan, AIST - available on https://www.gsj.jp/Map/EN/volcano.html). Note the potential variation of geodiversity based on the mapped volcanic geological elements marked on the geological map with 1–25,000 scale. "A" region has more geological elements than "B". While intuitively we estimate significantly higher geodiversity for the area "A", this needs to be evaluated as the large "orange" zone OF (Pleistocene Ofunato stage products) are complex volcanic succession. In modern volcanic settings, geological maps can be heavily biased by mapped erupted products toward younger features that is not obviously reflecting the created volcano geology diversity of the system. Such problem needs to be treated carefully as so far, no general strategy exists to deal with the timescale and volcanic architecture resolution. In general, we can assume that this problem eases toward Cenozoic volcanic terrains and geological maps can be more reliable source for geodiversity calculation in relationship with other geological entities mapped

looking at geological heritage elements that formed over time the time during which that element formed needs to be considered as well.

Overall, this theoretical approach to geoheritage should also embrace the concept of geological facies. For example, the typical geoenvironment in those features formed and the physical and chemical processes responsible for generating those geological features.

The following sections will explore how volcanic geoheritage fits to this theoretical approach and what makes volcanic geoheritage unique in respect to other geological and geomorphological phenomena.

3 Geoheritage Recognition and Value Estimates from Volcano Geology Perspective

Volcanoes are special geological features that manifest in great variety across the Earth and have throughout history have displayed diverse eruption styles, many of which are not occurring today. Volcanic eruptions can be classified according to the power (e.g., VEI—volcanic explosivity index) of the eruption and their potential to modify an existing or create a new landscape (Newhall and Self 1982; de Silva and Lindsay 2015) (Fig. 8a). The most frequent eruptions in Earth history are of moderate intensity (VEI = 1–4) producing eruptions that modify the landscape and with eruptive products that are "*locked*" into the geological record, commonly as part of sedimentary basin successions. The lifespan of such volcanic eruptions can be very short (days to weeks) up to over 100,000 years. This type of volcanism is known across the Earth surface and in world's oceans and typically produce monogenetic or polygenetic volcanoes (Fig. 8b). Monogenetic volcanoes in this context refers to the eruption that feed from a single volcanic conduit and last for only short period of time (hours to maybe years) and are clearly associated with a single batch of magma that finds its way to the surface via the same conduit. In contrast, polygenetic volcanoes are those that form and establish plumbing systems (de Silva and Lindsay 2015; Nemeth and Kereszturi 2015; Smith and Németh 2017). These are commonly fed from crustal magma storage places and can evolve over numerous eruptive episodes to build an

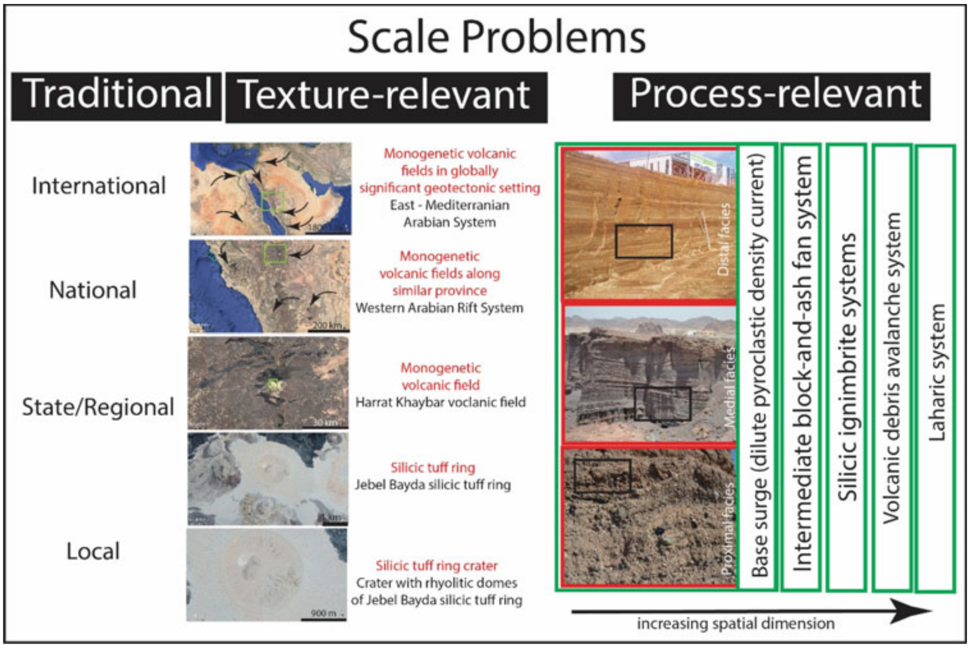

Fig. 7 Scale "problem" in a graphical expression. Conventional scale setting used in geoheritage valorizations are contrasted with volcanic process and features viewed in the scale the identified elements prescribe. The graphical representation is challenging to show process-relevant elements. The images show eruptive products highly relevant to processes in various scales following the volcanic facies concepts. The image frames refer to a typical monogenetic volcano-associated volcanic features (e.g., pyroclastic density current deposition). Green rectangles show other key geological processes associated with volcanism. Within those features various scales can be identified following the volcanic facies model

amalgamated and complex volcanic edifice such as a strato- or compound volcano. Polygenetic eruptions are only capable of some modification to the surrounding environment and their preservation potential is largely controlled by the climatic and geoenvironmental conditions. Over time, only the conduit or proximal volcanic successions are preserved, commonly forming distinct landscapes with volcanic plugs, exhumed upper conduits or completely inverted landscapes. Large, normally silicic (e.g., rhyolitic) eruptions commonly form extensive pyroclastic blankets such as ignimbrite sheets and distinct collapse features such as calderas all characteristically changing the appearance of the pre-eruptive landscape, hence these eruptions commonly referred to as landscape forming eruptions (Graettinger 2018) (Fig. 8c).

Volcanism produces spectacular geological features, however, in the last 600 million years volcanic geological elements are volumetrically well below that of sedimentary or metamorphic rock types, hence they are in general rare events despite their huge local impact, making volcanic geoenvironments a distinct geoheritage type. In addition, volcanism generally takes place in a far shorter time frame than any other geological processes thereby making their eruptive products valuable chronostratigraphic markers for understanding Earth history (Fig. 8d).

Volcanoes themselves and the associated eruptive products are diverse in their appearance. Defining the variety of volcanic features that may be associated with a volcano is a complex task, in part partially because they form much faster than other geological elements. Furthermore, their physical appearance is governed by their unique chemical and physical processes. The general magma chemistry, volatile content and the magma petrogenetic conditions all add to the complexity of the type of volcanic eruption that may result. The connection between the magma petrogenetic features and the geotectonic environment they are most likely to form in make volcanism and volcanic geoheritage the perfect avenue to link and identify key volcanic features used to define volcanic geoheritage elements. As a proxy the mapped rock types, such as basaltic to rhyolitic, could be used as distinct attributes associated with the volcanic geoheritage. Each of the mapped rock types somehow can be or should be linked to larger geotectonic processes such as convergent plate margin, intraplate, ocean island etc. setting.

Using volcano architecture through volcanic facies models (Cas and Wright 1987; Gamberi 2001) (Fig. 8f) enables the volcanic geoheritage to be defined by the petrochemical elements, and their link to the geotectonic features (De Vries et al. 2018) (Fig. 8e). Every volcano type has a point source, a vent that is linked to a conduit/magmatic plumbing system and through a crater connect to the proximal volcanic edifice. By increasing distances from the vent, the most common or typical

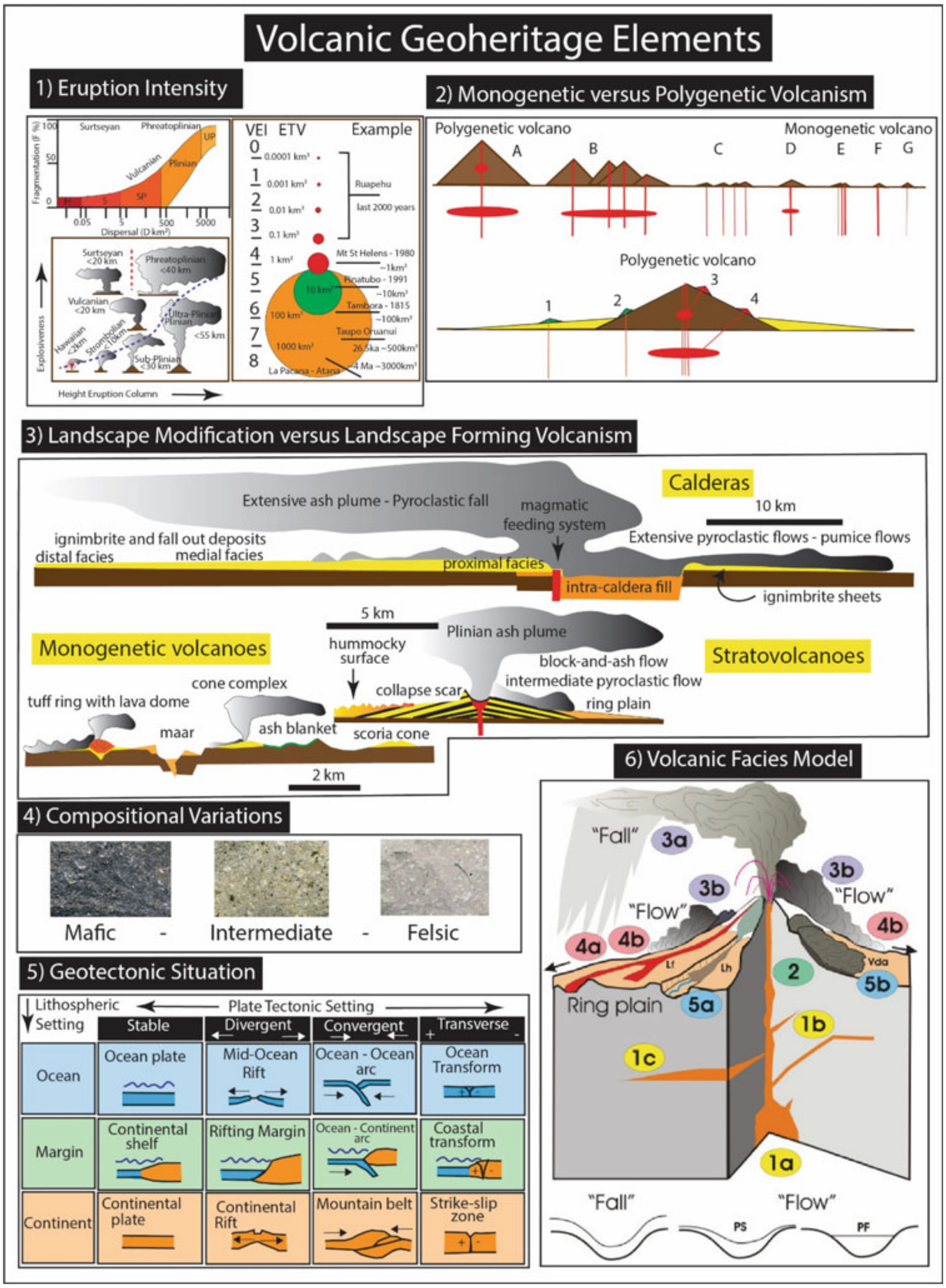

Fig. 8 Complex diagrammatic representation of key volcanic geoheritage elements. Please note, that these are just the most representative geological features that play key to define any volcanic systems. 1. Volcanic eruption intensity (size of an eruption) represented in three commonly referred cartoon where increased explosivity also means higher, more vigorous eruption plumes and higher VEI values. Diagrams are after from Walker (1973), Cas and Wright (1988), Newhall and Self (1982). 2. Monogenetic versus polygenetic volcanic systems in a conceptual model after Nemeth and Kereszturi (2015). Letters refer to **a** polygenetic volcano, **b** compound volcano, **c** monogenetic volcano cluster/field, **d** large volume monogenetic volcano with shallow crustal magma storage system, **e** polymagmatic compound monogenetic volcano, **f** polymagmatic simple monogenetic volcano, **g** sensu stricto monogenetic volcano. On the polymagmatic volcano cartoon numbers refer to as (1) deep-fed monogenetic volcano in the ring plain, (2) deep-fed flank volcanoes on the edifice, (3) shallow magma storage-fed small-volume volcano, (4) small volume volcano fed from edifice storage systems. 3. Landscape modifying and landscape forming volcanic systems such as calderas, stratovolcanoes and monogenetic volcanic fields. 4. Magma composition variations as reflection of the petrogenetic processes formed the volcano. 5. Geotectonic systems classified by the recently proposed Earth System approach of De Vries et al. (2018). 6. Volcanic facies architecture determent elements outlined by Nemeth and Palmer (2019). Pyroclastic "Fall" processes tend to generate mantling geometry of their product while pyroclastic "Flow" processes show more valley confined elements. (1a)—deep source chemistry and magma extraction, (1b)—magma source to surface transport, (1c)—magma temporal shallow storage processes, (2)—crystallisation and vesiculation, (3a)—pyroclast transportation through "fall" processes, (3b)—pyroclast transportation through "flow" processes [pyroclastic density currents including pyroclastic flows, ignimbrites, pyroclastic surges], (4a)—deposition processes from "fall", (4b)—deposition from "flow", (5a)—redeposition by laharic (Lh) currents of any type, (5b)—redeposition by volcanic debris avalanches (Vda) of any type. Lava flows are important lithostratigraphic components (Lf)

volcanic facies and facies associations are clearly distinguishable even in ancient settings (Németh and Palmer 2019) and hence can be used to establish the volcanic geoheritage elements.

Volcano types as monogenetic versus polygenetic are already suggestive that some sort of scale of observation has been utilized. Monogenetic volcanoes are about two magnitudes smaller by edifice type, impacted geoenvironment and eruption duration than those considered to be polygenetic (de Silva and Lindsay 2015). While it has not been adequately researched it seems that the boundary between monogenetic and polygenetic volcano types are far more continuous than has previously been considered (Nemeth and Kereszturi 2015). There are very complex volcanoes that still retain monogenetic characteristics from petrogenetic and volcano architecture perspective, but there are also polygenetic volcanoes that are not a lot different from the monogenetic volcanoes. Normally mafic magmas from intraplate (mostly intracontinental) settings produce single, on–off eruptions and generate monogenetic volcanoes, while more evolved magma types tend to form longer lived polygenetic volcanoes like strato- and compound volcanoes. Mafic volcanic rocks are volumetrically more dominant at the surface, hence volcano types fed by mafic magmas are common hence they are in most of the known geoenvironment and geotectonic settings.

Looking at the volcanic architecture and volcanic facies perspective is a scientifically valid approach to identifying volcanic geoheritage elements. Moreover, the volcanic facies approach to define the geoheritage elements of a volcanic terrain can be applied to ancient settings where the original volcanic landforms are heavily modified or already not recognizable.

The volcanic facies approach also can be applied to any volcano type regardless of whether they are dominantly effusive or explosive eruption processes, specific eruption styles (magmatic vs. hydromagmatic/phreatomagmatic), small-volume monogenetic or large volume polymagmatic. This approach could be used as a "*checklist*" of what to look out for when we try to identify the geoheritage elements associated with a volcano. To embrace volcanic facies approach in the volcanic geoheritage element recognition is also advisable as it fits perfectly to any volcano model, independent of its size, composition or geotectonic situation.

Recognition of geoheritage elements of monogenetic versus polygenetic volcanism is a challenge. While individual monogenetic volcanoes are small and the facies restricted to very small spatial scales, larger monogenetic volcanoes commonly form in groups of volcanoes that evolve over millions of years, effected by associated climatic and/or hydrological changes and the overall territory can be a magnitude larger than an average polygenetic volcano. This problem will be a very challenging one when setting out to establish the geoheritage elements defining the geodiversity or when providing fundamental background data to assist location of geoheritage sites through comparative analysis.

Recognizing the geoheritage elements of the largest landscape forming eruptions can also be difficult. It is common such volcanism produces large volume ($\gg$ 10 km^3), macroscopically laterally, very homogeneous ignimbrites associated with mega calderas (10 km + across) (Lindsay et al. 2001; Antonio Naranjo et al. 2018), however, distinct geoheritage elements may be associated with features at microscopic scales (e.g. minerals, xenoliths etc.), or phenomena largely associated with the interaction between the large volume ignimbrites and their geoenvironment (e.g. various peperites, fluid escape pipes, lag breccias etc.). The volcanic geoheritage aspects of such high intensity and landscape forming eruptions also can be linked to extensive tephra fall that can reach well beyond the vicinity of the eruption sources and form a significant geoheritage element in a "*foreign*" geological setting (Breitkreuz et al. 2014).

Volcanic geoheritage elements are very commonly viewed only from modern and active volcanic systems. Volcanic geoheritage of ancient settings are significantly underrated or abandoned (Migon and Pijet-Migon 2016, 2020). In ancient settings erosion commonly removes the majority of the medial and distal sections of a volcanic edifice, over time exhuming the crater and upper conduit facies. In extreme situations, volcanoes reaching a complete eroded phase form unique exposures where the deep interior, or even their magmatic plumbing system, is exposed ready to study or be utilized in geoeducation programs. Volcanic geoheritage of exhumed conduit systems should be considered seriously as they are also part of a volcano/magmatic system and act as a link between the source and the surface manifestation of magmatism.

The interaction of volcanism with the surrounding geoenvironment, or sedimentary basin, create valuable volcanic geoheritage elements (Fig. 9). Volcanic basins, especially along convergent plate margins where arc volcanism takes place, should be taken in account from their volcanic geoheritage perspective. While volcanic edifices erode and gradually diminish after a few millions of years, they may leave behind an exhumed pyroclastic breccia-filled conduit network and associated dyke, sill and other intrusive elements (Lefebvre et al. 2013; Latutrie and Ross 2019). Distal sedimentary basins can accumulate and preserve the volcanic activities well beyond the lifespan of their source volcano forming distinct volcanic-impacted sedimentary basins displaying a typical volcaniclastic sedimentary succession, e.g., the "*Pietra Verde*" in Northern Italy (Budai et al. 2005; Cassinis et al. 2008; Furrer et al. 2008; Németh and Budai 2009; Dunkl et al. 2019). Recognition of such volcanic geoheritage elements of a sedimentary basin is

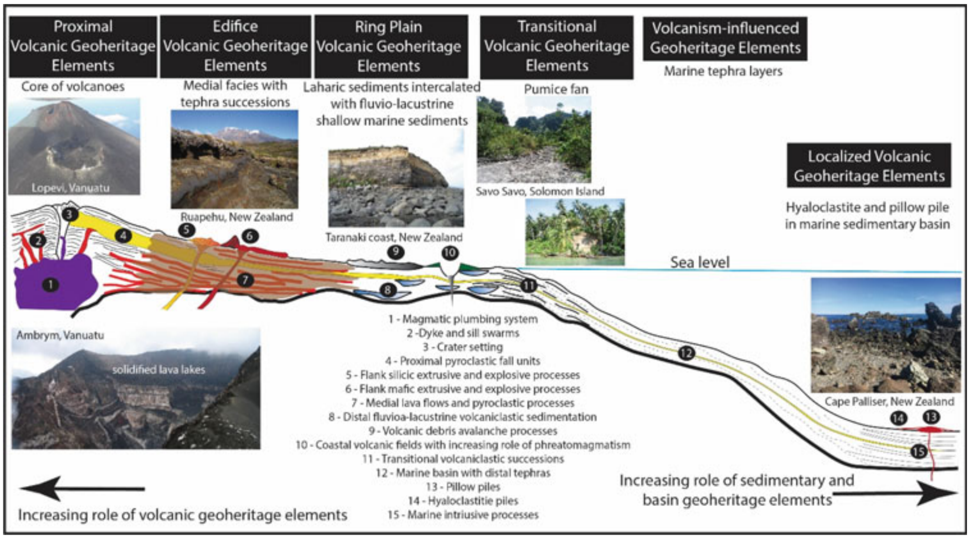

Fig. 9 Interface between volcanoes and the background sedimentary systems/basins in a highly schematic diagram that is not to scale. From the volcanic edifice a decreasing volcanic geoheritage dominance is shown toward the marine basin where "only" volcanism-impacted geoheritage elements can be recognized. Numbers represent key volcanic geology elements associated with the respected zone. Note that the same concept can be applied for eroded volcanic terrains where the core of the volcanic elements is exhumed and exposed. Applying such conceptual framework to identify the key volcanic geoheritage elements can help to link eroded volcanic terrains to modern setting and develop a geologically well designed geoeducation and geotourism program across volcanic geoheritage sites

imperative to recognize and incorporate into a volcanic geoheritage model to ensure it is complete, we call this the holistic vision of volcanism. While we may intuitively think that such scenarios are only or strictly associated with extensive marine basins along various segments of a volcanic arc, the volcanic input of pyroclastic detritus into terrestrial systems is also measurable and plays important part of the terrestrial sedimentary processes (Rees et al. 2018, 2019, 2020). This is particularly valid for intermediate polygenetic volcanoes where the central edifice is commonly surrounded by a complex and very extensive so-called ring plain that forms where sedimentation style is heavily dependent on the intensity of the volcanism, the frequency of the volcanic episodes and the changing climatological parameters affecting the surface water distribution configuration (Zernack et al. 2009, 2011; Németh and Palmer 2019; Zemeny et al. 2021; Zernack 2021; Zernack and Procter 2021).

Volcanism can also form local depressions that function as terrestrial depocenters for sedimentation. Interestingly small depressions, such as maar craters (Lorenz 2007; Christenson et al. 2015), are significant volcanic geoheritage elements (Moufti et al. 2013a, 2015; Yoon 2019; Becerra-Ramirez et al. 2020; Bidias et al. 2020; Megerle 2020b). These small and deep craters can form in terrestrial settings (Graettinger 2018) where they are infilled with terrestrial sediments over tens of thousands of years providing a high-resolution record of past terrestrial environments including climate change and paleoenvironments (Gruber 2007; Nemeth et al. 2008; Zolitschka et al. 2013; Lenz and Wilde 2018; Kovács et al. 2020). In large craters, such as caldera systems, significant volcanic geoheritage elements form as thick (hundreds of metres thick) lacustrine sequences (Branney and Acocella 2015; Christenson et al. 2015; Cattell et al. 2016). These have the potential to feed outbreak floods that can significantly alter the terrestrial environment of a large area such as happened numerous times in the North Island of New Zealand after caldera eruptions expelled large volume of pumiceous material that blocked fluvial networks (Manville 2002; Hodgson and Nairn 2005; Manville et al. 2007; Barker et al. 2021).

Volcanic geoheritage can also be recognized in distal areas far away from volcanoes. These rock successions include broad laharic fans and volcaniclastic fluvio-lacustrine networks associated with outflow drainage networks initiated from central volcanoes (Vallance 2000; Gudmundsson 2015; Procter et al. 2021). For example, in central Colombia major narrow, deep fluvial channels frequently captured lahars from Nevado del Ruiz, Tolima or Cerro Machin volcanoes in the Quaternary (Lowe et al. 1986; Voight 1990; Thouret et al. 2007; Murcia et al. 2008) (Fig. 10). The volcanic geoheritage element of these sudden, large volume sediment inputs into a sedimentary basin is commonly overlooked as volcanic geoheritage.

Intermediate sized eruptions, such as those in many volcanic islands such as in Ambrym, Vanuatu or Savo in Solomon Islands, from volcanic islands can produce alluvial fans that prograde into adjoining the marine basins forming a

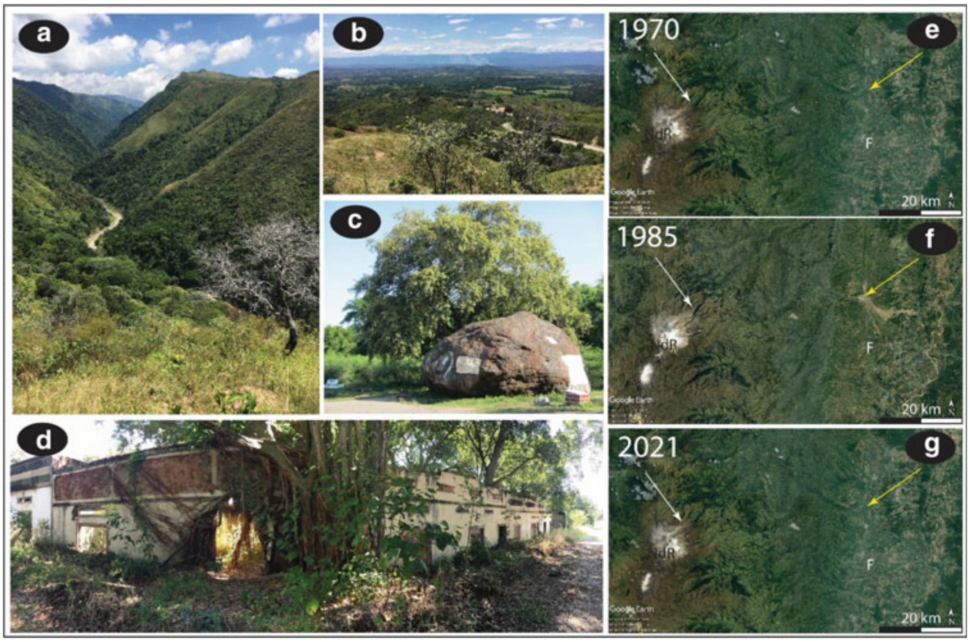

Fig. 10 Laharic geosystems are very important locations commonly associated with "dark" geocultural elements hence their geocultural link can be strong to actual volcanic disasters. Typical laharic facies variation from source to distant area from Nevado del Ruiz volcano and the surrounding catchment areas provide an excellent model how such geosystem can provide the basis of understanding the volcanic geoheritage context of the region. Narrow fluvial arteries (**a**) feed volcaniclastic sediments into the local terrestrial basin of the Magdalena River (**b**). In 1985 November a dramatic lahar event carried volcanic debris over 60 km length to the alluvial basin, capable to successfully move mega-blocks over 10 m in diameter to such distance (**c**) and inundate Almero township killing over 22,000 people. The laharic fan development is clearly visible on the pre-lahar January 1970 (**e**), the immediately after-lahar December 1985 (**f**) and the current July 2021 GoogleEarth Pro satellite images. Yellow arrows point to the location of Armero township. White arrows point to the initiating point of the valley channelized the lahars in 1985 from Nevado del Ruiz (NdR). Note the other Quaternary volcaniclastic fans in the region (**f**) providing evidences of the globally significant scale of lahar processes and their depositional impact on the terrestrial environment. In conjunction with the "dark" geocultural elements as a significant volcanic disaster, the region is the perfect location to look at it as a "best" and "most" in lahar-associated volcanic geology

unique geoenvironment (Petterson et al. 2003; Németh et al. 2009). The volcaniclastic volume contributes to landmass growth and probably plays an important role in the landscape evolution especially where volcanism is frequent. Active volcanic arc regions, such as the Taupo Volcanic Zone in the North Island of New Zealand, is an example of where volcanism has impacted landscape evolution (Manville 2002). Here active volcanism has contributed primary volcanic and volcaniclastic sediment into the surrounding landscape for c.1.8My (Alloway et al. 2005; Pillans et al. 2005). In that time long sedimentary transport arteries have evolved facilitating the transport of pumiceous deposits to broad coastal plains and beyond. This frequent volcanic activity and the associated large volume pyroclast-producing volcanic events have played a significant role in the development of the resultant geoenvironments. Hence, they should be considered an important volcanic geoheritage element.

Volcanism commonly produces large volume of lava on the surface. Lava flows and their accompanying surface textures are distinctive and recognizable. They are directly related to the processes that generated them and the physico-chemical conditions that existed at the source of the magma (Kilburn 2000). Recognizing the volcanic geoheritage of lava flow fields should lead to a search for specific facies of the flow field that relate to the source. In extreme cases, extensive lava flow fields form large igneous provinces, such as those in the Karoo, Columbia River Basalt or Deccan (Bryan et al. 2010; de Silva and Lindsay 2015; Sheth 2018). These all, cover thousands of km^2 and act as landscape-forming volcanic geoheritage elements. The best approach to understanding the volcanic geoheritage of these mega-features is to develop a "portfolio" based upon the observed volcanic facies.

Overall, we conclude the volcanic geoheritage of Earth is an absolute element and should be independent of the purpose, goal, scope or geocultural perspective from which it looked at. Volcanic geoheritage elements need to focus on the best possible volcano model and to recognize the features associated with it in a specific region. Identified sites can then be used to evaluate their relative significance through a preselected purpose-dependent scale and scope.

4 Identification and Comparison of Volcanic Geoheritage Sites and Developing a Volcanic Geodiversity Estimate

A general workflow outlined in several studies recommends the steps to follow to develop a volcanic geodiversity estimate for a region (Brocx and Semeniuk 2007, 2019; Brocx et al. 2021). The model proposed here consists of at least three major stages. In stage one it is necessary to define the purpose of the assessment that can be linked to the recognition of the various landscape elements of the volcanic geoheritage identified, its special variations and their significance to a pre-defined scope and scale. After setting up the method the selection of geosites and/or geomorphosites should follow. This work should be conducted after the recognition of volcanic geoheritage elements in region have been studied and following the conceptual framework outlined in the previous sections. After completion of this stage, it is possible to locate key volcanic geosites. These key sites are the geoheritage sites, that can also be named as geosites or geomorphosites depending on whether the main emphasis of the valorization is geology or geomorphology. Then the identification of various volcanic geoheritage elements suitable to locate volcanic geosites can be undertaken. This will involve identifying those places that contribute the most to our understanding of the volcanism in the study area, to see the best examples of the identified eruption styles, volcano types, volcano-geoenvironment interaction places or impacts to the surrounding biotic and abiotic nature including the human society. In the final stage of this progression attention should be paid to the management and conservation policies that need to be developed to preserve the key geoheritage features that form the basis for any geotourism and geoeducation initiatives that follow. It is imperative the most significant geoheritage elements should be identified clearly and linked to the original purpose of such research (Fig. 11).

Geosite valorization, in general, is a process where the "*most and best*" of the identified geoheritage elements are selected. The main aim is to develop a workflow model that produces objective and reproduceable results. In many cases subjectivity can be difficult to abandon so it is considered an achievement if the subjectivity can be reduced to a level where the resulting selection and associated valorization results in more or less the same results for each new study on the same location. Recently a series of works has been published proposing some sort of geoheritage toolkit that helps the user to work out the strategy and the actual valorization of geosites (Brocx and Semeniuk 2007; Brocx et al. 2021). The toolkit was tailored specifically to volcanoes to systematically identify and assess sites of geoheritage significance (Brocx et al. 2021). This toolkit is based on the identification of the (1) conceptual categories of sites of volcanic geoheritage significance, (2) the scale of volcanic geoheritage features recognized and (3) the recognition of the volcano (or volcanic geoheritage features) significance. This method provides a very good simple workflow to follow but also generate some ambiguity or imprecise categorization. For this reason, it is suggested the toolkit needs significant revision that introduces a more precise fit to the most recent scientifically backed volcano models (de Silva and Lindsay 2015; Martí et al. 2018; Németh and Palmer 2019). The first two steps of the toolkit involve the identification of the volcanic geoheritage elements. In this aspect, it is suggested the geotectonic concept is incorporated in more detailed way, similar to that suggested for the Earth System geoheritage recognition (De Vries et al. 2018). In the main part of the geoheritage element recognition of the magma to source perspective, petrogenetic aspects, volcano model application (e.g., monogenetic vs. polygenetic volcano types), the volcanic facies model (e.g., for both volcano types but also for the lava flow fields) and the interface recognition where the volcanism interacted with the geoenvironment (e.g., volcaniclastic sedimentation etc.). As outlined previously, this is a very important stage as it will form the basis of any valorization and site selection. In the third step each of the recognized volcanic geoheritage elements should be measured against the conceptual category suggested also by Brocx and Semeniuk (2007). Their categories focus either the product of volcanism such as the geoform of modern volcanoes, the preserved products of ancient settings and active volcanic sites. In the fourth step the scale of the geoheritage features should be determined and valorized (e.g., using its representativeness) while in the fifth step the significance of the volcanic geoheritage features should be evaluated. The final outcome of the entire valorization process should be a decision on the level of conservation or management that is applied to the location.

While this toolkit sounds like a reasonable first order proxy, the details contain some issues in particular the definition of the significance of the geoheritage feature. The techniques most commonly used are almost exclusively linked to an artificially defined spatial value which may be local, regional or global (Brocx and Semeniuk 2007). Here it is suggested that the significance of specific feature should initially be referenced to the scale of the identified volcanic geoheritage feature. For instance, the significance of a volcanic geoheritage feature identified in relationship with a monogenetic volcano should be measured against the individual feature itself, i.e. within a single scoria cone or tuff ring (e.g., this could translate to local), across the volcanic field (e.g., this could be regional scale) or volcanic field to volcanic field within a geotectonic situation (e.g., this could translate to international scale) or across the entire globe's all

Fig. 11 Modified volcanic geoheritage toolkit that is based on the concept of Brocx et al (2021). One of the main differences in this modified version that it takes the scale measured to the specific volcanic geology problems, process and measurable features. It is also better fit to the volcanic facies models and the interaction between volcanism and the background sedimentary processes. The following "Steps" suggested to follow: 1. Identification of volcanic geoheritage elements—some key elements listed. 2. Identification of the significance of volcanic geoheritage elements including textural and process associated features volcanism—some key approaches listed. 3. Identification of the geocultural elements (including indigenous aspects) associated with the identified volcanic geoheritage elements. Recognition of key additional values from the perspective of the purpose of the valorization—some key element listed. 4. Measure the significance of the volcanic geoheritage elements within the volcanic phenomena common scales. 5. Grade the identified volcanic geosites and create a systematics for the general purpose of the analysis. Define the level of conservation and protection. Please note that his is a theoretical approach and the basic concepts can be fine-tuned to the volcanic terrain under investigation

volcanic fields (e.g., this could be the global scale equivalent category). In a similar way we could apply the same volcano geology-based logic to polygenetic volcanoes such as (1) within the same volcano, (2) within the same volcanic province and/or volcanotectonic regime and (3) across the globe.

The scale of the geoheritage feature (step 4) is something that is difficult to comprehend, but intuitively a category that is likely related to the processes forming the various identified geoheritage elements and their scale where the appropriate evidence could be identified. This step could be further enhanced using a volcano model that is linked more directly to the conceptual framework of all volcanism manifest at various scales with various products such as magma generation (mineralogy, chemistry), magma transportation (various microtextural features, magma vesiculation and fragmentation (bubble textures, microlite distribution patters, pyroclast shapes and vesicularity etc., pyroclasts morphology), transportation and deposition (bedding features, transport indicators, outcrop-scale facies association, field-wide associations) and volcanic edifice/complex/geoform evolution (facies associations, 3D architecture, landscape scale features). It is evident that the suggested line of observable and measurable features link to specific observation scales that are more or less aligned to the suggested macro, mezzo and micro scale approach by Brocx and Semeniuk (2007). The advantage of the approach suggested here is that this method directly links to the volcanic processes generated by the identified volcanic geoheritage elements.

A recent study of the Garrotxa Volcanic Field, Catalunya, provided a very workable method to test how such an approach may work (Planaguma and Marti 2020). The presented method is not structured exactly as suggested in this work, but in the geosite identification and valorization stage naturally follow similar techniques outlined in this chapter. The volcanic geoheritage recognition has been based on the recognition of volcanic deposit types, produced by effusive and explosive processes associated with Strombolian-style explosive, violent Strombolian explosive and phreatomagmatic explosive eruptions (Planaguma and Marti 2020). From the list of volcanic geoheritage features it is evident that the studied volcanic field hosts most of the expected geoforms that form by the eruptive processes identified by volcanological research targeting volcanic fields over the past 100 years (Planaguma and Marti 2020). In the identification of the key volcanic geosites the conservation aspects played an important role following the notion that without a good initial conservation plan all the geosite inventory builder or volcanic geoheritage element documentation would just remain a theoretical work without significant effect on the planning and development of the region. From this, mostly economy-driven reason the volcanic geosite identification locates the most interesting outcrops and illustrate the great variety of the eruptive products in the field. The selected volcanic geosites need to, therefore, represent the main and most significant elements of the volcanic field. Additional geosites were selected mostly from their "additional value" perspective for activities, conditions, accessibility, land-use status, immediate surroundings, space and fragility (Planaguma and Marti 2020). The many aspects were exclusively centered around conservation measuring the current conservations state, the site abundance or uniqueness, its type, its link to other natural phenomena and diversity elements. Each track followed a three-point valorization model, and the final result represented the level of conservation interest (Planaguma and Marti 2020). This method is very similar to the most common geosite assessment methods (GAMs) used elsewhere in other regions, predominantly from a geotouristism point of view (Vujicic et al. 2011; Moufti et al. 2013b; Bratic et al. 2020; Cuevas-Gonzalez et al. 2020; Szepesi et al. 2020; Ibanez et al. 2021; Pal and Albert 2021). In summary it can be concluded that these methods are very specifically designed for a specific purpose, namely geotouristism and less commonly geoconservation purposes. Either way the valorization is biased toward the utility values of the sites and tend to be detached from the geoheritage site volcanic geoheritage values.

Here it is suggested a modified toolkit be used to valorize the volcanic geoheritage sites (Fig. 11). This toolkit would put a greater emphasis on the correct identification of the geotectonic situation, Earth System position, volcano type recognition as well as the application of the volcano model and volcanic facies to define key elements of the processes resulting in specific volcanic geoforms. In short, the higher and more precise usage of volcanic science applied to establish the volcanic geoheritage elements is recommended to generate a more science-aligned volcanic geoheritage model to identify key volcanic geosites. The updated toolkit then should operate within a more realistic conceptual categories, a better internal scale and volcanic process-defined significance categories.

Applying the above principals, we also can get closer to developing a better geodiversity (Gray 2018a, b; Zwoliński et al. 2018; Fox et al. 2020; Dias et al. 2021; Wolniewicz 2021) recognition method applicable to volcanic features (Dóniz-Páez et al. 2020; Quesada-Román and Pérez-Umaña 2020; Guilbaud et al. 2021; Vörös et al. 2021). Defining geodiversity itself is a subject that is under debate and recently evolving fast (Brocx and Semeniuk 2019, 2020; Gray and Gordon 2020), hence its application to volcanic regions still in infantry. For geodiversity estimates for volcanic regions the best possible available volcanology map is needed. A volcanology map should fulfil the expectations of geological map production with an additional feature that it is also specific to what a volcanic system can produce. Volcanic processes occur, in general, much faster than normal sedimentary processes, hence a volcanic terrain will contain a larger number of geological features that may change over much shorter distances at greater rates than other geological features such as those in a siliciclastic marine sedimentary system (Németh and Palmer 2019). Hence, the volcanic geodiversity is expected to be large in a given area in comparison to other normal sedimentary successions. This may not be visible on a standard geological map at a scale 1–50,000 or smaller. The problem we face here is similar to the problem of geological mapping and to find the best scale to visualize, in map format, volcanic eruptive episodes. This paradox can be resolved by using volcanic facies to identify volcanic geoheritage elements. The scale of the study sites in a typical polygenetic volcano such a strato, compound or caldera volcano allows the typical volcanic facies and volcano geology concept to adapt for geodiversity estimates. Within volcanic fields the size of individual volcanoes could be too small to capture appropriately the various geodiversity elements associated with monogenetic volcanism. On other hand, however, geodiversity estimates can be examined in a larger scale that fits the spatial scale of a typical monogenetic volcano (Smith and Németh 2017). In this respect the scope of generating geodiversity estimates for monogenetic volcanism should be identified and measured to the usual spatial scales of such volcanoes. This scale problem, however, will likely affect the comparison or fitting into a single geodiversity estimate map a volcanic terrain that consists of both monogenetic and polygenetic volcano types. To test this problem and develop a simple and workable method to handle this spatial discrepancy has not been done yet and signifies a knowledge gap that future research should target. In other hand, small monogenetic volcanoes can be treated as a single geodiversity “source” based on detailed studies of identification of the number and weight of geoheritage elements associated with the specific volcano types identified.

5 Link Between Volcanic Geoheritage and Other Geoheritage Elements

Following the conceptual framework of volcanic geoheritage outlined in previous sections, it can be expected that there will be a connection of the identified volcanic geoheritage elements and the non-volcanic geoheritage elements associated with it. Volcanoes are part of complex sedimentary systems, geoenvironments and geotectonic settings (Németh and Palmer 2019), hence they are a vital part of the overall geoheritage of any region. Separating volcanic geoheritage from other heritage elements is sensible only if (1) the studied terrain is dominated by volcanic geoforms and volcanic eruptive products or (2) the study is specifically targeted to understand the volcanic geoheritage elements and utilize them for other purposes such as conservation, geotourism or geoeducation. The separation of volcanic geoheritage and their treatment as a separate entity could lead to similar data and map sets common in the so-called thematic map series dealing with specific geospatial problems. The volcanic geoheritage, in this perspective, should be treated as a vital part of the total geoheritage scene and provide clear interlinkages to the other geoheritage elements it is embedded in. It is very important to follow the volcano geology framework outlined in previous sections as volcanoes commonly produce large volumes of eruptive products that eventually accumulate in sedimentary basins and provide unique scenarios such as various siliciclastic sedimentary rocks formed in sedimentary basins influenced and impacted by various types of volcanism. The role of volcanism on such sedimentary basin evolution is likely associated with those systems where prolonged periods of volcanism produces a relatively steady volume of volcanic detritus into a sedimentary basin (Németh and Palmer 2019). In such scenarios the geoheritage elements will be associated by normal sedimentary processes but the appearance of the resulting rocks could be distinctly different due to the volcanic origin of their constituent elements. Strictly speaking in such context, the identified geoheritage elements is not a volcanic one. Many greywacke basins would fall into such a category, where the sedimentary basin sedimentation is influenced by volcanism and a specific type of greywacke composed of volcanic lithics in a sand or finer grain sizes is found (Challis 1960; Roser and Grapes 1990; Laumonier 1998; Benedek et al. 2001; Floyd 2001; Bennouna et al. 2004; Bandopadhyay 2005) (Fig. 9). The geoheritage elements of such a scenario are more likely associated with the deep marine sedimentary processes than the distal volcanism itself. There will be a transition from deposits dominated by sporadic seafloor volcanism to medial eruptive products intercalated within siliciclastic sedimentary successions. In this perspective such locations can and should be viewed as a volcanic geoheritage element (Fig. 9). Moreover, a normal greywacke basin produces a thick pile of very monotonous rocks often used for geological terrain recognition (Michaux et al. 2018) that can change their appearance and macro and microtextures when such volcanic interbeds are present, hence such sites can form significant landscape features that may stand out and can be utilized for geotouristism or geoeducation purposes and even be part of a focused conservation effort. To define the boundary between when we call a setting a volcanic geoheritage element or a normal geoheritage element should follow the processes associated with volcaniclastic sedimentation such as the recognition and the number of incidents of primary eruption-fed pyroclastic successions within the non-volcanic background sediment. The volcanic facies model recognizes geoheritage elements of mixed volcanic and normal sedimentary settings are important and should be treated with great care as they can be utilized for geoeducation and geotouristism.

6 Geocultural Aspects on Volcanic Geoheritage

It is a common and recurrent argument is that the geoheritage elements should contain the geocultural aspects of the recognized features (Reynard and Giusti 2018; Kubalikova

2020). In the conceptual framework presented here it is suggested that the geoheritage elements be distinctly separated from any geocultural aspects including indigenous or alternative cosmovisions. The geocultural and the indigenous aspects of geoheritage sites, however, should be acknowledged in the geosite recognition and/or the valorization of such sites (Gravis et al. 2017, 2020). In addition, indigenous values are recently has been considered as measurable aspects of geoheritage, however the way how those should be included in any valorization method is currently not known. Perhaps indigenous values could play vital roles in geoconservation where living indigenous cultures act on the land or where archaeological sites are abundant (Turner 2013; Lim 2014; Clifford and Semeniuk 2019; Lewis 2020). This process, however, is more connected with the establishment of a complex valorization structure for geotouristism or geoeducation and should also incorporate geoconservation strategies. Currently geosite assessment methods underutilize the indigenous aspects of geosites such as exiting culturally significant sites or oral traditions associated with a region (Fepuleai et al. 2017, 2021; Reynard and Giusti 2018). Geodiversity estimates where distinct geoheritage elements are evaluated and counted within their spatial extent they commonly yield average or below values across a region especially when geological features are evenly distributed across the known geological assets. In such regions geosites that are significant from a geotouristism or geoeducation perspective should be incorporated into the available geocultural dataset, including the region's indigenous human settlement history. Within the framework of volcanic geoheritage, rich geocultural aspects of specific sites can be recognized either by the positive affect volcanism had on the human societal evolution or the negative, often destructive power, volcanism posed on the human beings through volcanic disasters (Cronin and Neall 2000; Scarlett and Riede 2019). The dark geocultural impact is a measurable fact that can be collated from participatory methods applied to understanding the oral traditions linked to volcanism as well as being part of cultural activities of everyday life and ritual-driven activities (Nunn et al. 2006, 2019; Cashman and Cronin 2008; Cashman and Giordano 2008; De Benedetti et al. 2008; Swanson 2008; Németh and Cronin 2009; Donovan 2010; Scarlett and Riede 2019; Wilkie et al. 2020). Impact of volcanism on the society manifest very diverse cultural responses hence volcanism commonly need to look from the "*living with volcanoes*" aspect that all together can form an intact and internally coherent knowledge system, cultural traditions or living practices all together can form a distinct geocultural aspect of volcanism (Kelman and Mather 2008). To explore and harvest the accumulated knowledge for a purpose of developing strategies to preserve this geocultural entity interconnected geoscientists are needed whom able to find the link among various knowledge systems and able to be part of participatory methods and co-development of development toward geoeducation, geoconservation or geotourism goals (Cronin et al. 2004a, b; Nahuelhual et al. 2016; Petterson 2019; Marin et al. 2020; Fepuleai et al. 2021). It is recommended a more structured approach and standalone treatment of the geocultural aspects of volcanism be developed to enable better comparison across regions and human societies. It is also a matter for debate how we treat indigenous knowledge and record natural phenomena associated with volcanism. One can argue that indigenous knowledge extraction differs from a so-called western data collection and could contain knowledge elements that differ from common western scientific knowledge. Such an issue is a real problem in regions where the western scientific knowledge of a volcanic terrain is limited, for instance by the pure lack of scientific research on the features. In such places it is particularly important to incorporate the traditional knowledge about volcanism and to utilize it within the earlier outlined volcanic geoheritage framework. Ideally such an approach should be followed in every volcanic terrain with multicultural and indigenous links.

In summary, geocultural aspects are additional values that can be decisive in geotouristism, geoconservation, rural and urban planning and geoeducation (Dóniz-Páez et al. 2011; Paulo et al. 2014; Riguccio et al. 2015; Zangmo et al. 2017; Megerssa et al. 2019; Beltran-Yanes et al. 2020; Hlusek 2020; Schwartz-Marin et al. 2020; Vizuete et al. 2020; Yepez Noboa 2020). Geocultural values play an important role in finding a sustainable approach for human society to live with volcanoes. As volcanoes equally provide a lifeline to human beings (e.g., good soils, agriculture, spiritual aspects) as well as destruction (e.g., volcanic catastrophes) the interaction between human society and volcanism function as a key element in understanding our environment hence it has huge heritage value. Especially as frequently active volcanoes such as polygenetic stratovolcanoes on convergent plate margin settings function create landforms the human population had to learn to live with. In this symbiotic relationship volcanism can be deeply embedded not only in the cultural practices and legends but also in everyday life activities. To a certain extent, human migrations are triggered, or evolution of civilizations heavily altered by volcanic eruptions hence volcanism plays a significant role in the development of a cultural landscape over a volcanic terrain (Plunket and Urunuela 2005; Pardo et al. 2015, 2021). It is probably a logical conclusion that geocultural aspect of volcanism in this regard are governed by the natural processes of volcanism that determine how societal evolution takes place. Determining the effect of the direct and unseparatable elements of volcanism on a region is a difficult problem. Landforms and geological processes have often shaped the cultural evolution of entire regions hence one can argue that this symbiotic interrelationship between volcanism and society should be included in the volcanic geoheritage element identification (Balmuth et al. 2005; Cecioni and Pineda 2006; Streeter et al. 2012; Black et al. 2015; Zeidler 2016; Oppenheimer et al. 2018). Here it is suggested that we separate this element as volcanism could have taken its course governed by the natural processes regardless of the existence of any society nearby and in sensu stricto volcanic geoheritage is the heritage of the natural processes generated them rather than a reflection of the human perception, cultural activity, socio-economic development. For this reason, the usage to treat this interface between natural (abiotic) and human (societal) heritage elements separately and define it as geocultural element is a very practical notion. In this way we can separate the individual elements associated with volcanism from its societal perspective and impact to make a clearer and easier to develop valorization suitable for geoheritage site identification. The validity of this is shown very well with the intraplate monogenetic Auckland volcanic field. This volcanic field consists of at least 53 individual monogenetic volcanoes with the majority initiated by a brief explosive magma-water interaction phase that changed to more magmatic explosive and effusive stages later in their eruption (Kereszturi et al. 2014, 2017; Hopkins et al. 2021). This trend is clearly evident in those regions where the available external water diminished quickly during the eruption producing a higher magma volume and rate resulting in volcanic landforms consisting of large complex scoria cones with sizeable craters. These scoria cone complexes are commonly located in slightly elevated regions and form visible landforms about 100 m above the coastal plains and the nearby harbors (Kereszturi and Nemeth 2016). Such scenes would have captured the attention of early Maori settlers who utilized them as defendable natural fortresses (Davidson 1993). The surrounding ash plains provided excellent volcanic soils for early horticulture and agriculture supporting Maori communities and their early urbanization for about 300 years after their arrival in Aotearoa (Davidson 2011). While estimates on total population associated with fortified cones provide large numbers of over several thousands, some archeology-based estimates suggests nearly a magnitude less, around several hundreds of population within association to a single cone (Fox 1983). Today, these scoria cone landforms are iconic landmarks, and they are strong geocultural sites linking Maori cultural and societal practices to their land. These scoria cones, while they are visually attractive, rarely contain exposed outcrops to see their geological buildup, but even if we have such outcrops, the scoria cones itself are just like any other scoria cones anywhere and in any geotectonic settings. The volcanic geoheritage elements of such scoria cones are restricted to basic geological features and not particularly unique or outstanding (Nemeth et al. 2021b). However, the indigenous and geocultural aspects of the scoria cones provide significant values and give extra protection status from a conservation perspective and in recent time from geotourism aspects. These cones are now under special conservation and land use policies, an excellent outcome of the heritage notion [https://www.maunga.nz/]. However, in the southern part of greater Auckland city, the geological conditions allowed for the formation of monogenetic volcanoes that are far more interesting and unique from a volcanological perspective (Agustin-Flores et al. 2014), in fact these are examples of the type of explosive eruptions that could occur to in now highly populated area of Auckland in the near future (Nemeth et al. 2021b). The volcanic architecture, their volcanic rocks and the information we could gain from these volcanoes are fundamental to our better understanding of monogenetic volcanism in Auckland and beyond. The volcanic geoheritage elements are enhanced by their geocultural aspects making these locations geologically more valuable because their geodiversity is greater than other volcanoes currently argued as high geoheritage value sites. Currently it is very difficult to argue they come under better protection policies. This is further exacerbated by strong urban growth pressure which will see valuable geocultural sites vanishing with rapid speed and without a policy change it is unlikely that they can be rescued for the future (Nemeth et al. 2021b). While significant effort over recent years has demonstrated the volcanic geoheritage elements of these sites and how those could be built into volcanic geosite identification methods, in practical sense this work has fallen on deaf ears and had little impact on policymaking.

The Auckland case also highlights the problem that volcanic geoheritage elements are underrated despite a better volcanic hazard model being successfully created and communicated at the UNESCO IGCP 679 project titled "Geoheritage for Geohazard Resilience". The gradually and rapidly vanishing sites in Auckland are especially important locations for such programs to adopt.

7 Geoconservation in the Light of Global Perspective of Volcanic Geoheritage

Above we outlined the importance of the geocultural elements of volcanism and demonstrated that clear separation of volcanic geoheritage elements and their geocultural aspects is needed to better identify their fundamental principles. This notion is probably a valid conceptual framework for geoconservation as well. From a volcanic geoheritage element perspective, geoconservation should clearly target the identified geoheritage elements. Geoconservation itself should serve as an internally coherent method to identify the volcanic geoheritage sites that are from the pure volcanic geoheritage perspective considered to be unique. To do this, the scope and scale concept is seemingly a valid approach. The scope in this respect should be something that embraces the identified volcanic geoheritage elements, for instance base surge beds in a tuff ring. The scale in this aspect is defined by (1) the hosting volcanic feature (like a tuff ring in the example before) hosting the volcanic geoheritage element, (2) the volcanic field itself where the tuff ring is located, (3) the volcanic fields that are part of the same volcanic province or geotectonic setting and (4) the global scene of Earth. As space exploration is bringing more and more new data about planetary geology, this logic could later on be expanded to an interplanetary scale.

The logical architecture of conservation will create a workable and transparent, scientifically based systematics of volcanic geoheritage that can provide good raw data for valorization, applying all those methods so far developed in many places (e.g., Geosite Assessment Methods- GAMs methods). The valorization then could also apply advanced technologies such as drone, LiDAR or other remote sensing data for data acquisition or GIS technologies for geospatial analysis of identified values to create thematic maps such as geoheritage intensity, geoconservation susceptibility or geoeducation value.

8 Volcanic Geoheritage as Basis of Geopark Concept

Volcanic geoheritage is a significant and unique element of potential conservation strategies as outlined in previous sections (Nemeth et al. 2017). Volcanic geoheritage can experienced by the fascinating processes of volcanic eruptions, the dark geocultural aspects through past and current volcanic disasters, as well as the huge impact volcanoes have had on human society. Together these make volcanoes an important element to be included in any formal conservation strategies and broader geoeducation programs. In addition, volcanoes and their volcanic geoheritage provides a foundation on which to utilize those geoheritage elements in formal and informal geoeducation programs targeting the aim of making society more resilient for volcanic disasters and better understanding of the role of volcanism in landscape evolution (Migon and Pijet-Migon 2016; Rapprich et al. 2017; Szepesi et al. 2017; Fepuleai and Nemeth 2019; Dóniz-Páez et al. 2020). Geoparks are a relatively new concept that became a globally significant avenue to promote Earth Sciences to a broader community, to act as engine of geotourism and something that can contribute to the local development of a region, hence bear values in respect of economical sustainability (Henriques et al. 2011; Lim 2014; Ruban 2017; Escorihuela 2018; Macadam 2018). The UNESCO World Heritage network recently outlined and identified the knowledge gaps within the framework of the World Heritage site listing while also making significant effort to promote geosciences through a global network of geoparks [https://en.unesco.org/global-geoparks]. While the World Heritage concept is based on the "*most and best*" or outstanding universal values concept, geoparks are more like a "*bottom to top*" approach to promote geosciences and protect their geoheritage elements (Henriques et al. 2011; Turner 2013; Henriques and Brilha 2017; Catana and Brilha 2020). Geoparks are normally expected to grow out from local community works and form part of a sustainable development design where the abiotic nature forms a core of such works (Brilha 2018b; Catana and Brilha 2020). In this concept ecosystem services can play an important role to define, pronounce and promote the "*services*" abiotic nature provides for the human society (Gray 2012; Gordon and Barron 2013; Gray 2018a, c; Fox et al. 2020). This also can be expressed in the form of direct economic figures and feed concepts to rural and urban development planning. Geoparks in this framework can form a scientifically well-designed and supported avenue where geoheritage elements form the base of conservation and education, largely serving the goal of transfer knowledge to everyone about our abiotic nature.

The level of recognition, which is somehow associated with the scope, scale and significance of the identified geoheritage elements can be expressed in the formal hierarchy of geoparks from locally protected conservation lands to be part of the UNESCO Global Geopark Network [https://en.unesco.org/global-geoparks]. Among UNESCO Global Geoparks many of the properties are strongly linked to some single or set of volcanic geoheritage elements or some additional component which would fall in the geocultural aspects of the region. Recently UNESCO Global Geoparks with pure volcanic geoheritage as a center of their core protection and education program are also common.

Geoparks with strong link to volcano geology are the perfect avenues to disseminate geological concepts associated with volcanic geohazards. The variety of geoparks in the global scale also provide an opportunity to interlink geoparks with similar volcanic geological geoheritage elements. Such method has been proposed in a far more direct way such as the European Volcano Road (Abratis et al. 2015) or the Pannonian Volcano Road (Harangi 2014) as potential examples. Volcanic geoheritage of extinct volcanoes is a common basis of geotourism development and subject of geoconservationa cross continental Europe (Migon and Pijet-Migon 2016; Pijet-Migon 2016; Pijet-Migon and Migon 2019, 2020; Megerle 2020a). The benefit is to focus on educationally well-designed interlinkages so that communities living in currently inactive volcanic regions can get direct knowledge from those similar volcanic geoheritage regions active today. This can help the people to embrace and understand the volcanic processes as well as the landscape evolution perspective of volcanoes. This is particularly important when we are looking at volcanic geoheritage properties of old and young settings. For instance, in regions like Auckland the young age of the volcanoes provide little opportunity for the people to “look inside” their volcanoes, hence transferring knowledge such as magma fragmentation or conduit processes are problematic. While interlinking a place like Auckland with locations where eruptive products of similar but much older volcanics, such as those in Central Europe exists, can help to understand what to envision, and more importantly, what to expect from a future eruption where magma fragmentation might occur. There is a huge age range, compositional, geodynamic and geoenvironmental settings within monogenetic volcanic fields formed across the Earth in the last 600 million years (Nemeth 2016a, b, 2017). These provide opportunity to study similar volcanic systems, with different exposure levels, focusing on different aspects of the same style of volcanism. Similar interlinkages are available for polygenetic volcanoes such as stratovolcanoes, or caldera volcanoes. To date, there has been very little direct attempts to do this.

The recognition of a region as geopark needs strong community support, strong scientific background and knowledge, and very clear valorization methods to see where the real values and what are the key geosites. In this work, the valorization from tourism or conservation perspective can play important role in manifesting the geoheritage elements in a workable framework. Geocultural aspects play key roles, especially in indigenous territories, where oral traditions, legends, cultural activities also exist and their preservation as well as passage through generations could function as a driving force to generate a geopark. Geoparks in this aspect should reflect true transdisciplinary nature and explore the identified geoheritage elements link, association or influence on the archaeological aspects, traditions, and contemporary cultural activities, including lifestyles or living practices (e.g., village culture, agriculture, culinary traditions etc.).

Overall, geoparks could be the engines of sustainable development and a contributor to inclusive conservation and education methods that point well beyond of the geological heritage itself. Volcanic geoheritage through, the experiences of volcanism in the past, is also a significant part of the conceptual architecture of geoparks.

9 Conclusion

In summary, volcanic geoheritage elements are those directly linked to the physical and chemical processes responsible to any volcanism. The special type of volcanic geoheritage elements reflects the conceptual volcano model framework such as the magma segregation, magma transportation from source to surface, the magma vesiculation, crystallization and fragmentation processes, the eruptive products transportation and deposition modes (either explosive or effusive the process) and the entire set of processes responsible by the remobilization, redeposition and reworking of volcanic material on the surface. Volcanic geoheritage elements can be categorized using general volcano models such as geodynamic settings, monogenetic versus polygenetic nature and chemical compositional distinction as well as the typical volcano architecture and associated volcanic facies. Only by applying complete volcano models to identify volcanic geoheritage elements will lead the correct view of a volcanic terrain be understood and scientifically established. Volcanic geoheritage elements are often viewed as independent from the volcanic region’s geocultural and it is suggested they be treated separately to help identify specific volcanic geosites mostly from geotouristic, geoconservation or geoeducation purposes. Geoconservation strategies are also recommended to embrace this concept as this way will guarantee the strong scientifically established backbone of specific conservation strategies. And finally, geoparks can be major and most significant conservation sites where volcanic geoheritage elements and their identified sites should form a logically designed and carefully interlinked array of concepts where we can transmit information to the general audience through various media including modern technologies (e.g., augmented reality, virtual reality, remote sensing, GIS etc.).

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