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Geological monitoring in protected areas

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A B S T R A C T

Recognition of geoheritage values and conservation of their geodiversity elements are largely neglected in protected areas. As geoheritage and geodiveristy were recognized as a part of nature conservation by IUCN recently, understanding the characters of geoheritage sites and the development of proper monitoring measures have been important among managing communities and stakeholders. It is suggested that different monitoring methods and indicators should be developed depending upon physical setting of protected areas and tourism conditions. This paper deals with various monitoring methods and indicators to be carried out for geo-conservation and sustainable use. This will help managers build up a basic management plan for geological monitoring.

1. Introduction

Geological monitoring (geo-monitoring *herein*) is a tool to measure the conservation state of any significant geo(morpho)logical features and ongoing processes, or threats to them. To conserve geoheritage values and their associated geological elements in protected areas continuous monitoring plan and practices within integrated governance system are essential. Some geodiversity elements can be quite dynamic, representing ongoing Earth's surface processes to form long-term geological products. Also, unlike biodiversity and ecosystem, geodiversity constituents tend to be more durable, thus last much longer as outcrops but they are non-renewable. Once they are damaged by natural or manmade processes, it is not possible to restore them. Therefore, it is essential to conserve geoheritage sites before they are damaged unintentionally or disappear naturally. For natural changes it is common that geological features tend to be significantly damaged by catastrophic events rather than ongoing daily, seasonal and annual routine processes. Thus it is necessary to understand overall controlling factors to maintain their natural conservation state. Selecting and studying appropriate monitoring indicators considering attributes are the keys to its success. Appropriate sets of monitoring indicators should be carefully determined to maintain geodiversity and geoheritage values of protected areas based on scientific investigation of controlling factors. In addition, natural processes have become more unpredictable due to recent rapid climate changes due to global warming. Thus, it is necessary to keep baseline records of some geological phenomena and vulnerable sites with potential susceptible changes. However, it has not yet been explained elsewhere how to carry out geological monitoring in protected areas (World Heritage sites, geosites in National and Global Geoparks, etc.). The objectives of this paper are to raise the significance of geo-monitoring for geoheritage sites in protected areas, to discuss various monitoring methods, and to introduce how to develop monitoring indicators in a variety of geological settings for geoheritage conservation.

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2. Monitoring methods

Monitoring activities aim for the following goals: 1) evaluating the conditions and changes of natural systems, thereby producing basic scientific evidence; 2) understanding controlling factors of geological (and geomorphic) sites for their long-term changes and for conservation; and 3) assessing the progress of natural and manmade changes, and designing and implementing proper protection and management plans for nature conservation and visitor satisfaction based on continuous effective monitoring. Various methods of monitoring may be carried out by different institutions at different times depending on the characteristics of the monitoring indicators and their details. Thus there needs to be a platform open for regular communication and cooperation among relevant organizations. Through the platform, different agencies will be able to efficiently divide their work scope and exchange monitoring outcomes. Thus it is necessary for the organization responsible for management of protected areas to collect and compile all the monitoring results to establish implementation plan. For tourism area, monitoring of infrastructure safety and tourists can be equally important as geo-monitoring. There are various kinds and levels of geo-monitoring methods from in situ field monitoring at small geological site even to monitoring by suitable equipment from air (airplane to satellite). Most commonly used geo-monitoring methods are introduced here.

2.1. Physical monitoring methods on site

2.1.1. Photo monitoring

This is suitable for fragile outcrops commonly composed of sediments, unlithified sedimentary rocks or outcrops with potential rock-falls and mass flows. In showcaves, carbonate speleothems can be effectively monitored by regular photographing at some vulnerable sites. Periodicity of photo monitoring can be variable, however it is useful to take photos of outcrops after every severe physical impacts, i.e., hurricane, tsunami, earthquake, etc. The periodicity of photo monitoring in showcaves should be determined by management office because it depends upon the type of tourism and the number of visitors. Photo monitoring can be carried out for the damage of trails and infrastructures by tourists, or other features or purposes (Fig. 1). (See Table 1.)

2.1.2. Monitoring for cracks

Numerous geological sites are subject to cracking. The outcrops sensitive to mechanical weathering, volcanic sites with rapid cooling of lavas, karst areas with potential collapse, etc. are the sites necessary for crack monitoring. There is a high resolution gauge to measure the distance of cracks. However, a simple method is to put a glass plate glued on cracks where the cracks have a potential to become wider (Fig. 2).

2.1.3. Monitoring for rock-falls

Rock-falls take place at the foot of rock cliffs or mountains with steep sides. It is also common in limestone and lava tube caves. A simple monitoring method for rock-falls in caves is to cover a cloth or a mat over possible rock-fall sites. It is extremely convenient in lava tube caves where the cave passage is under a traffic road (Fig. 3). However, other methods may be needed at outside outcrops using a 3D scan method (see below).

2.2. 3D scan monitoring

It is extremely convenient to measure subtle changes of rock exposures which are susceptible to physical changes due to natural disasters such as hurricanes, tsunamis, etc. (Fig. 4). The surface of mountains with sliding and slumping is also a good site for

Fig. 1. Photo monitoring result of one vulnerable stalactite in Baegnyong Cave, Korea. Note the damaged stalactite by visitor.

Table 1
General monitoring indicators for geological sites in protected areas.

Locality		Monitoring indicators
General monitoring indicators applicable to all the sites below		Seismicity, volcanic activity, sea-level rise, temperature, humidity, wind velocity, water temperature and salinity
Cave	General indicators for caves	Physical surface condition, temperature, humidity, partial pressure of CO_2 and radon contents in caves, lampenflora, dust input, vegetation cover
	Limestone cave	Damage of speleothems, water discharge & quality, cave fauna
	Lava tube cave	Rock fall, stability of roof, shape of entrance, damage of lava speleothems, soil & sediment input, cave fauna, input-water quality, water level, traffic load & vibration
Geological sites	General indicators	Precipitation & snow cover, frequency of storms (hurricanes), vegetation cover, rock fall, slope failure, soil quality (pollution) & creep, fossil conservation, natural and manmade landform changes
	Rocky outcrop	Inland: Soil erosion, outcrop retreat & collapse
		Coast: Cliff retreat & collapse, erosion by waves and storms, oil spill, tectonic subsidence or uplift, frequency and intensity of storms, hurricanes, and tsunami
		Riverside: Valley erosion, cliff retreat & collapse, water level & discharge rate, water conditions & quality (temperature, pH, EC, toxic elements, turbidity, etc.), local sedimentation along river sides
	Coastal sediments	Sediment transportation and distribution, organic contents in sediments, toxic element contents in sediments, the amount of suspended matter, longshore drifts and sediment loss, influence of manmade structures, oil spill
	Coral reef	Nutrient and trace element (including toxic elements) concentrations, carbonate sedimentation rate and growth rate of coral reefs, and supply rate of terrestrial input as suspended loads (if applicable)
	Volcanic site	Frequency of mass movements and rockfall, temperature and chemical contents of ground and surface water
Tourist site		Potential physical threats toward tour sites (e.g., stability of surrounding slopes, landslide, volcanic activities, flooding, tsunami, etc.), cracks in rock outcrop in situ & slope failure, number of visitors (students, international visitors including nationality, group tour, etc.), infrastructure safety (bridge, steps, etc.), signboard condition, electrical safety, damage and capacity of trail route, trash collection and monitoring, pollution by visitors, toilet condition

3D scanning. Even though it is a little expensive, but it can contain numerous detailed digital data. It can be also very effective in dark caves to locate numerous carbonate speleothems and their damages in digitized data.

2.3. Geophysical monitoring

This includes air photo (satellite) image monitoring, remote sensing, LIDAR monitoring, etc. These types of monitoring may be expensive, however it can cover a wide areas including remote places or some places hardly accessible. Air photo monitoring is relatively cheaper, but can detect drastic changes on the surface such as slides, slumps, or vegetation pattern (Fig. 5A&B). LIDAR is a surveying method that measures distance to a target by illuminating the target with pulsed laser light and measuring the reflected pulses with a sensor. Differences in laser return times and wavelengths can then be used to make digital 3-D representations of the target. LIDAR sometimes is called 3D laser scanning, a special combination of a 3D scanning and laser scanning. It has terrestrial, airborne, and mobile applications (https://en.wikipedia.org/wiki/Lidar). The basic effect of laser scanning is the point cloud. Thus, depending upon the density of point cloud, LIDAR can have very high resolution 3D images from the air or on land with vertical and horizontal errors with ±15 cm and ± 50 cm, respectively (Fig. 5C). Thus, it can even trace soil creeping with time from the air.

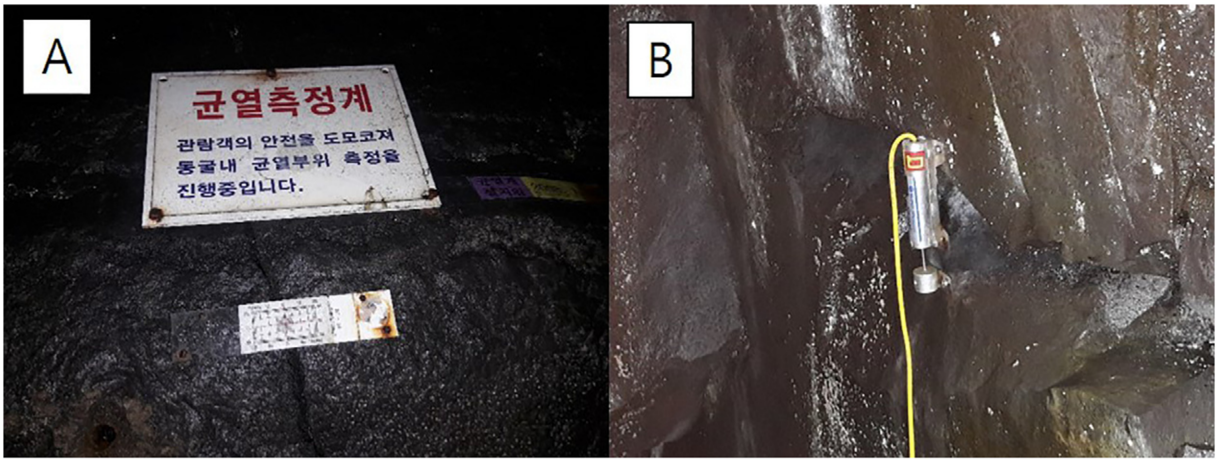

Fig. 2. Crack monitoring using glass plate (A) and monitoring gauge (B) in Manjanggul Cave (lava tube), Jejudo Island, Korea.

Fig. 3. Monitoring for rockfall using a plastic net in Manjanggul Cave (lava tube) which is located under the traffic road.

3. Monitoring indicators

Monitoring tasks can be costly, so it is important to select only the most important parameters would be selected. It is important to understand what indicators are needed to be monitored for an organization, thus an organization should select based on natural processes of a protected area and visitor and infrastructure pressure on it. Monitoring activities are performed for the attributes which constitute various geological features in protected areas and their controlling factors. Development of clearly identifiable and useful monitoring indicators for geological site condition, infrastructure condition, and visitor satisfaction is necessary. Monitoring indicators are suggested in a variety of geological and geomorphological settings. Development of monitoring indicators for any geological sites should be approached quite differently from ecological protected areas because some geological sites containing similar geoheritage features may have quite different physical settings. For example, Messel Pits, Joggins Cliffs and Dorset Coast are all significant fossil sites, but their physical environments are entirely different. This means that different monitoring indicators for each site should be considered respectively.

In addition to current controlling factors which influence on geological characteristics at present, it is necessary to consider potential impacts in the future such as climate change, sea-level changes, etc. Effective ongoing maintenance requires the development of protocols, schedules and checklists to ensure the geological sites maintain or improve their current condition for integrity. Each action plan should provide monitoring indicators which are clearly determined based on controlling factors encompassing all the geodiversity elements for better management of protected areas. Thus it is significant to characterize and understand controlling factors for geo-monitoring and their susceptibility to diverse factors and threats. Applicable monitoring indicators are listed as below.

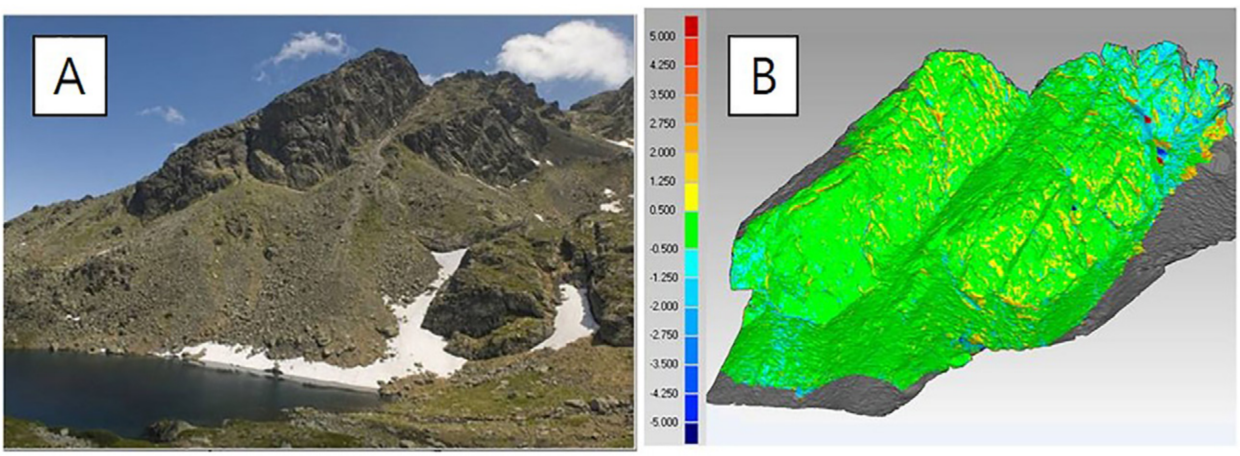

Fig. 4. 3D scan image (B) of the geological outcrop (A) for monitoring of sediment movements at the geological site susceptible to mass flows in Jeju Island, Korea.

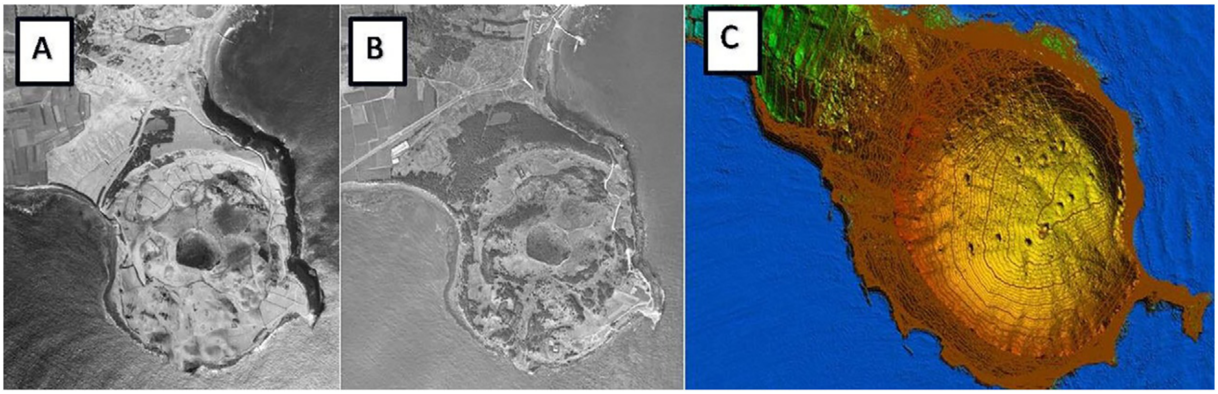

Fig. 5. (A & B) Air photos of Mt. Songaksan taken in 1979 (A) and in 2008 (B), Jejudo Island, Korea. Note the vegetation changes which can be easily detected. (C) LIDAR data of the Seongsang Ilchulbong Tuff Cone, Jejudo Island, Korea.

3.1. Monitoring indicators applied to most protected areas

If some protected areas have scenic and geoheritage values with vegetation and fauna, biodiversity elements should be monitored. Seismicity (the frequency and intensity of earthquakes), volcanism (the frequency and intensity of volcanic eruptions), sea-level change, sliding & slumping, flooding, mass flows, tsunami, etc. are commonly monitored indicators in most protected areas where applicable.

Atmosphere monitoring is necessary for geological sites with vegetation cover and soils because they may be intimately related to stability of slopes as well as scenic views. Atmospheric monitoring of temperature, humidity, and CO_2 and Rn contents are important in showcaves because original cave condition can be changed by visitors and Rn in atmosphere can be harmful to visitors (Cigna & Forti, 1988). It is basic requirement to understand atmospheric conditions in caves before development to maintain natural conditions afterwards. Continuous atmosphere monitoring can provide significant information on climate changes for a long period.

Water quality can influence on biodiversity in protected areas which may contribute scenic geoheritage values. Water temperature, oxygen contents, and pH should be regularly measured. Also, nutrients, trace element compositions including toxic elements should be checked. In some places the water level changes in streams and rivers are critical because they may influence the safety of visitors. The amount of precipitation in catchment area should be monitored together with corresponding water level. The water level in limestone tourist caves must be also monitored with scientific interpretation because it is extremely critical to visitor safety and it is sometimes very difficult to predict without scientific investigation.

3.2. Monitoring of rocky outcrops

When sediments and rocks are exposed, it is important to keep the outcrop condition intact. It is very common that rock surface is covered with vegetation, lichen, moss, etc. Chemical weathering of rock surface is much faster when the surface is covered (Blatt, 1992), thus to conserve significant geological outcrop it is sometimes necessary to treat them properly if they are not significant species. Photo monitoring of vegetation-covered outcrops may help find a way to improve outcrop conditions.

Exposure condition of inland outcrops depends upon climate condition (temperature, humidity, the amount of precipitation, etc.), which control chemical weathering rate on outcrop surface. Warmer and more humid conditions induce faster chemical weathering which may be able to damage rock exposure conditions very rapidly (Blatt, 1992). Here, vegetation distribution can be a problem if rock exposure site is a keystone feature in some protected areas. In alpine and high latitude areas mechanical weathering becomes dominant (Blatt, 1992). Breakdown of rocks should be investigated and monitored. In mountainous regions, soil creep and mass movements (sliding, slumping and mud flows) need to be monitored (Hyndman & Hyndman, 2010). Potential breakdown of rocks at the steep-sided slopes or cliffs can be hazardous to visitors. In fluvial and lake systems, climate also plays a role. Water monitoring should be carried out while considering hydraulic system to protect ecosystem especially in catchment areas. In desert (or arid climate) region, chemical weathering is very slow, however salt weathering may be active (Evans, 1970). Sand migration rate should be monitored in this region.

Rocky outcrops along the coast are continuously attacked by physical attacks by waves and tides. Continuous erosion may reveal fossils hidden in rocks. The Joggins Cliffs (World Heritage Site) is a good example that fossils have been continuously revealed by macrotidal currents (https://www.jogginsfossilcliffs.net/). Denudation rate of rock cliffs should be monitored.

The riverside is composed of rocky outcrops and sediments along the river, and is constantly influenced by water flows. It is important to monitor not only the outcrop conditions but also the physical and chemical changes of river water. Monitoring for valley erosion, cliff retreat & collapse, river water level & discharge rate, water conditions & quality (temperature, pH, EC, toxic elements, turbidity, etc.), and local deposition and distribution of sediments along river side need to be carried out.

3.3. Monitoring of caves and karst area

Karst area includes a variety of karst landforms such as sinkholes and caves. Running surface water can disappear into underground or sometimes resurge as karst springs (Ford & Williams, 2007). Scientific investigation and cave mapping should be conducted together to predict surface collapse. Water monitoring should be carried out where there is an area with potential groundwater contamination. Surface stability from collapse is another important monitoring indicator. Caves are special underground environment. Due to no light in caves, only animals can dwell in and cave fauna need to be investigated and monitored. Depending upon the location relative to water table or the mode of limestone cave formation, streams may flow in caves (Woo, 2002). Air and water monitoring should be carried out for conservation of cave fauna habitats and for preventing groundwater contamination downstream. It is also significant to carry out water monitoring in catchment area to protect cave fauna. In lava tube caves, rock-fall needs to be monitored below traffic road for safety. Monitoring indicators of limestone showcaves are lampenflora, black staining (by touching or dust), cave lighting (electrical safety), 3D scanning or photo monitoring of speleothems, rock-falls, vegetation on the surface, etc. Monitoring indicators of lava tube showcaves are lampenflora, cave lighting (electrical safety), 3D scanning or photo monitoring of speleothems, rock-falls, seismicity, vegetation distribution and intensity near skylight, etc.

3.4. Monitoring of coastal sediments

Delta and estuary are located near river mouths. The balance between the rate of riverine sediment supply and physical energy (waves or tides) will determine coastal landforms as delta being the most dominated by sediment supply (Reineck & Singh, 1973). Monitoring indicators are terrestrial sediment supply of both bedloads and suspended loads, annual discharge rate, and sedimentary rate. Migration of submarine or subaerial bars (sometimes as barrier islands or tidal bars) may be investigated and monitored. The influence on sedimentation pattern or rate by manmade infrastructure such as dams should be considered and monitored.

Tidal flats are deposited by tidal currents and they are dominated by mud deposits in intertidal and supratidal flats which are occasionally intercalated with sands by storms or hurricane activities (Reineck, 1972). When coasts are affected more by wave system, submarine bars, beaches, and dune develop. Along wave-dominated coasts sands tend to be transported by longshore currents (Seibold & Berger, 2017). These longshore drifts can be unidirectional or seasonally changing bidirectional. Monitoring indicators in these areas are movement of sedimentary bodies (dunes, bars, etc.), sediment gain or loss of beach deposits, nutrients level of tidal sediments, vegetation distribution on dunes, etc. The movement may be intimately related to gradual habitat changes and a long-term ecosystem. It may be critical if the movement of sediments is affected by artificial structures.

3.5. Monitoring of coral reefs and adjacent areas

Coral reefs and surrounding areas are susceptible to physical and chemical conditions of seawater (James & Wood, 2014). Recently climate changes may influence on carbonate production of coral reefs and carbonate-secreting organisms in shallow marine environments. Global warming has resulted in sea-level rise and coral bleaching. Long-term management plan is required to mitigate these threats. Monitoring indicators are temperature, salinity, nutrient and trace element (including toxic elements) concentrations, carbonate sedimentation rate and growth rate of coral reefs, and supply rate of terrestrial riverine input as suspended loads (if applicable). Above all it is significant to monitor short-term pollution changes of nutrients and toxic elements transported by manmade activities such as the Great Barrier Reef as an example.

3.6. Monitoring of volcanic area

In the protected areas with potential volcanic eruptions, management structure should consist of geologists. Monitoring should be conducted by geologists as well as managing staffs. Air and water monitoring should be continuously carried out. Monitoring indicators are seismicity, mass movements (sliding, slumping and mudflow) in addition to geologic mapping of the region to investigate the periodicity of volcanic eruption history.

3.7. Monitoring indicators for tourist sites

This is especially important to showcaves because the number of visitors can affect cave atmosphere and more than the maximum capacity in showcaves may cause other problems such as damage of speleothems and infrastructure. However, visitor numbers is other protected areas may also influence on natural conditions in a protected area. The items to be checked are visitor number (daily, monthly and annual visitors), type of tourism (self-guided tour, guided tour, and group tour), visitor nationalities, levels of students (elementary school, middle and high schools, and college), geoscientists and geoscience-major students, and different levels of school teachers. Visitor pressure on infrastructure and trails have to be regularly checked. The information above can be a basis to calculate maximum capacity of visitors (Cigna & Forti, 1988). It is encouraging to monitor visitor satisfaction of tour sites and interpretation facilities. The state of infrastructure and electrical circuits are critical for the safety of tourists. Trash and oil spill also need to be monitored.

4. Monitoring of geoheritage management practices

Management of geoheritage in protected areas may involve a number of operations and practices and there will be concerns that these have been implemented effectively. Management effectiveness evaluation is one form of monitoring that may be undertaken as part of managing for geoheritage in protected areas. Management effectiveness evaluation, as can be seen, is more than assessing the outcomes of geoheritage projects. It is a suite of assessments that ensure all aspects of a project are undertaken as effectively as possible. IUCN has adopted a management effectiveness framework which guides such assessments and this framework includes six key elements (Hockings, Leverington, & Cook, 2015).

4.1. Context

This element assesses the status and threats to geoheritage in a protected area. What is the condition of the geoheritage phenomenon and what is its trend in condition and is it threatened? How well this assessment is completed will influence whether any intervention action is taken by management.

4.2. Planning

Identifies where we want to be with the geoheritage and how we get there. How well this planning is completed can mean the success or failure of an intervention. The objective for an intervention needs to be clear, as do the project or task milestones. How well this planning is completed can mean the protection of geoheritage or the loss of the phenomenon.

4.3. Inputs

Geoheritage management actions need resource inputs that typically include people, funds and materials. Getting the right materials for the task and delivered in a timely manner is important. There may be specialist materials needed such as the metals used in permanent monitoring stations on volcanoes that monitor sulfur dioxide levels. The success of a geoheritage protection project will be dependent on the effective management of such inputs including attention to detail.

4.4. Processes

How we go about geoheritage management can be effective, or it can be disorganized. Assessing systems of management and procedures is an important part of geoheritage management that includes safety management. This may apply to emergency management procedures or dealing with incidents associated with geoheritage phenomena such as unexpected volcanicity, lahars and earthquakes.

4.5. Outputs

Given the planning, organization of inputs and processes, we can assess the effectiveness of geoheritage conservation and protection outputs that have been achieved. What was done and what products and services were achieved for the effort and inputs involved can be evaluated. Such assessments would normally account for the degree of difficulty that may be involved with processes that need to be used for geoheritage protection in protected areas.

4.6. Outcomes

Every geoheritage project needs to assess what was achieved. This would normally be assessed against the original planning objectives but it would also take into account “big picture” appraisals of how geoheritage conservation has been progressed by the management actions undertaken.

5. Conclusions

Numerous protected areas include geoheritage sites which should to be conserved in a sustainable way because geological elements cannot be restored once they are damaged. Continuous monitoring is the best way to conserve geoheritage characteristics and to maintain natural conditions of geoheritage sites in protected areas. Geo-monitoring methods are introduced, and various physical settings for geo-monitoring are interpreted. For effective monitoring, monitoring indicators and their proper monitoring methods should be developed considering the physical controlling factors of the target sites. This paper will help managers and stakeholders of protected areas to understand proper guidelines for effective geo-monitoring in the future.

Credit author statement

Kyung Sik Woo made a draft of this manuscript, and Graeme Worboys contributed the Section 4 (Monitoring of geoheritage management practices).

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