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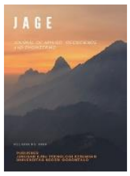

An Assessment of The Scientific Value of Krakatoa, Indonesia From a Geoheritage Perspective

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ABSTRACT

Krakatoa is the most active volcanic complex located in Lampung Province, Indonesia. Throughout human history, several devastating Krakatoa eruptions have shocked the world and turned it into a global attraction. Recognizing its scientific value, Krakatoa has been designated as a geoheritage site. This study refers to the Standard Scientific Value Assessment published by Center for Geological survey of Indonesia, which applies seven main parameters, including well-published scientific reviews, to assess the feasibility of geoheritage sites. In conclusion, the Krakatoa volcanic complex is a highly regarded geoheritage site, scoring 92.5/100. Its significance extends globally, offering insights into the evolution of volcanic islands and their unique geological features. Additionally, the historical records of global catastrophes and the potential for future eruptions warrant further investigation. As a geoheritage site, Krakatoa serves as a reminder of the possibility of subsequent devastating eruptions and its natural history, making it crucial for sustainably maintaining, preserving, and managing its potential for educational, conservation, and scientific purposes. Considering the natural history, the study recommend further consideration of several sustain steps, particularly for sites around the Krakatoa area. Regular and systematic scientific observations and records of natural conditions are significant for maintaining and enhancing Krakatoa as geoheritage.

1. INTRODUCTION

Krakatoa, a volcanic island complex located in the Lampung Province, plays a significant role in shaping human history (Winchester, 2004). Its existence has been recognized since at least 416 AD, as conveyed in Javanese folklore, and confirmed scientifically by geological and volcanological studies (Soloviev and Go, 1974; Yudhicara and Budiono, 2008; Ismail et al., 2020). The global recognition of Krakatoa emerged after its eruption in 1883, which caused widespread destruction and attracted the attention of researchers worldwide. Currently, Krakatoa remains active and poses a potential threat (Paris et al., 2020; Hunt et al., 2021). Given its historical significance, Krakatoa has been designated as a global geological heritage or geoheritage. Geoheritage represents the diversity of geology, unique features, and high scientific value of Earth's processes (Brocx and Semenjuk, 2007; Gordon, 2018). By this study, we highlight the importance of Krakatoa as a geoheritage site in connecting nature and world-wide community.

Geoheritage and conservation are closely intertwined, with the former encompassing sustainable development, geological sites, and conservation enhancement through research and education (Fauzi and Misni, 2016; Brilha, 2018). Geoheritage sites comprise various features such

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as landforms, minerals, rock types, and fossils, which hold immense value for research and educational purposes. In 2017, the Center for Geological survey of Indonesia published a guide for geoheritage assessment that covers scientific, educational, and risk of degradation aspects. This study focused on assessing the scientific aspects of Krakatoa and its surrounding areas in Lampung Province, following the guidance of published assessment parameters. The findings of this study can serve as a reference for managing and protecting Krakatoa against potentially destructive anthropogenic threats. Going forward, it is essential to establish a suitable approach to ensure the sustainable conservation of Krakatoa's geological heritage. To achieve this goal in the future, we suggest to adopt the geopark concept, which emphasizes the responsible and sustainable management of geoheritage sites.

2. METHOD

This study refers to the Technical Guide to the Assessment of Geological Heritage Resources, a guide to Geoheritage Assessment published by the Center for Geological survey of Indonesia in 2017. The study focuses on evaluating the scientific value of Krakatoa and its surrounding areas using a scoring system based on specific indicators for each of the seven criteria listed in the guide: (1) geological outline; (2) key sites; (3) scientific understanding; (4) site conditions; (5) geodiversity; (6) significance; and (7) site constraints. Each criterion was reviewed based on the existing scientific literature, and the final score was determined based on a predetermined weight (in %). **Table 1** provides detailed information on the scoring systems used in this study.

Table 1. Criteria and indicator in scientific value of geoheritage site assessment*

	Criteria	%	Indicators	Score
1	Geological Outline	30	The site is the best representation to illustrate elements or processes related to the geological outline.	4
			The site is well-represent to illustrate elements or processes related to the geological outline.	3
			The site is a common representation to illustrate elements or processes related to the geological outline.	2
			The site lacks to represent the geological outline.	1
2	Area of Interest (key location)	20	The site is known as GSSP or ASSP by IUGS or as IMA reference sites*	4
			The site is used as a reference for research related to the geological outline, globally scientific published (well-known in international scientific-indexed publication).	3
			The site is used as a reference for research related to the geological framework, locally scientific published (only published in Indonesian scientific-indexed publication)	2
			The site mentioned in unpublished reports (about its geological outline)	1
3	Scientific Understanding	5	There are international scientific publications (articles/papers) discussed about the site.	4
			Only local (Indonesia indexed) scientific publications (articles/papers) discussed about the site.	3
			There are just abstracts (briefs/summary) that are presented at international science activities, such as international conferences.	2
			There are just abstracts (briefs/summary) that are presented at local science activities, such as domestic (national) conferences.	1
4	Site Condition	15	All geological features (in geological outline) are very well preserved.	4
			At least, the main geological features (in geological outline) are well preserved.	3
			The site is unwell-preserved, but the main geological features are still intact.	2
			The site is unwell-preserved, and the geological features have undergone changes or modified (unnatural).	1
5	Geodiversity based on: Petrology, mineralogy,	5	The site has more than four (4) scientifically related geological features that are significantly unique and rare in regional countries.	4
			At least, the site has four (4) scientifically related geological features that significantly unique and rare in Indonesia (domestically).	3

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	Criteria	%	Indicators	Score
	paleontology, geodynamic, geomorphology		At least, the site has three (3) scientifically related geological features that differ locally (less unique).	2
			At least, the site has two (2) scientifically related geological features, and it's too common to find.	1
6	Significance	4	The site is the only example that is related to the geological outline.	4
			There are two (2) other sites similar to this site.	3
			There are three (3) other sites similar to this site.	2
			There are more than three other sites similar to this site.	1
7	Access Restrictions and obstacles (Constrain)	3	There is no restriction (permit, etc.) for sampling activities or field activities.	4
			After accomplishing the standard permission, the field activities and sampling could apply.	3
			After accomplishing the standard permission, the field activities could apply, but sampling is too complicated.	2
			The field activities and sampling are impossible.	1

* translated from Indonesian standard of geoheritage assessment, published by Center for Geological survey of Indonesia (2017)
* GSSP: Global Boundary Stratotype Section and Point; IUGS: International Union of Geological Science
ASSP: Auxilary Boundary Stratotype Section and Point IMA: International Mineralogical Association

3. RESULTS AND DISCUSSION

3.1 Criteria 1: Geological outline

The Krakatoa complex is located in the Sunda Strait between Java and Sumatra in Indonesia (**Figure 1**). Geologically, it is part of the Sunda Arc, a volcanic arc formed by subduction of the Indo-Australian Plate beneath the Eurasian Plate. The complex consists of four main islands, with Anak Krakatau being the youngest and the most active. It is situated at the intersection of two major tectonic features, Sunda Trench and Sunda Strait Fault, which are responsible for the area's high seismic activity (Nishimura et al., 1992). The Sunda Strait is known for its complex tectonic history, which has been shaped by collision of the Australian Plate with the Sunda Plate. This collision has led to the formation of numerous faults and fractures in the area, which have contributed to development of the Sunda Trench and Sunda Strait Fault (Ninkovich, 1976; Nishimura et al., 1986; Harjono et al., 1991). The region influenced by the presence of a mantle plume as well, which caused development of basaltic volcanic activity in the area.

Recent studies have shown that the Sunda Trench is not just a simple subduction zone. It has a significant strike-slip component, meaning that the plates slide past each other horizontally as well as vertically. This has important implications for the seismic hazard of the area, as strike-slip faults can generate large earthquakes and tsunamis. The complex tectonic regime of the Sunda Strait, combined with volcanic activity, makes it a fascinating and challenging area of study for geologists and other scientists. The magma of Krakatoa is believed to be strongly influenced by upper-to-lower crustal magmatism, as indicated by the presence of clinopyroxene and plagioclase minerals. According to Dehren et al. (2012) suggests that the magma originated from shallow crustal to sub-moho magma. It is believed that there is a magma plumbing system beneath the recent Krakatoa complex in addition to the magma generated by tectonic plate subduction. This geological setting has resulted in several series of basaltic to andesitic eruptions in Krakatoa (Camus et al., 1987; Mandeville et al., 1996).

Krakatoa eruptions (1883 AD) cause global disturbances to the Earth's atmosphere, such as drastic changes in global temperature. This condition is caused by ejection of fine volcanic material that spreads into the troposphere. It spreads along the equator and then to the northern and southern hemispheres. This fine material blocks solar radiation significantly and is known as a volcanic winter (Simkin and Fiske, 1983; Schaller et al., 2009). During the 1883 AD eruption, there was also a global optical effect seen in many parts of the world (i.e., Europe and America). At that time, the whole region around Krakatoa became very dark during the day, and on the other side of the earth, it looked like vivid red sunsets, purple, blue-greenish, and red for many months (Bradley, 1988; Schröder and Wiederkehr, 2000).

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Krakatoa is a well-known volcano located in the middle of the sea that has a history of causing tsunamis during eruptions, now referred to as Volcanic Eruption-Induced Tsunamis. The 1883 Krakatoa tsunami event was well documented scientifically, and a destructive tsunami of over 40 m in height caused the loss of at least 36,000 lives along the western coast of Indonesia. The combination of flank collapse of the volcano body, caldera collapse, pyroclastic flows, and submarine explosive eruptions can trigger such massive tsunamis. Choi et al. (2003) simulated the distribution of the tsunami impact from the 1883 Krakatoa volcanic eruption, showing that the resulting impact was broad with a trans-oceanic tsunami impact. A recent Krakatoa eruption-induced tsunami that occurred in December 2018 (Ye et al., 2018). Although the volcano destroys itself during eruptions, it re-emerges on the sea surface and grows higher in a short period.

Krakatoa has undergone several cycles of eruption and succession, and despite the collapse in December 2018, new habitats have emerged. The environmental conditions of Krakatoa allow for rapid colonization of pioneering species. Whittaker et al. (1989) and Partomihardjo (2003) have extensively studied the natural succession process on the island, which is best suited to the environmental conditions of Java and Sumatra.

To summarize the earlier review, we can highlight significant geological features of Krakatoa, including: (1) The Sunda Strait's geotectonic setting, which is related to geomorphological form of the Krakatoa complex; (2) The variations in magma origin sequences, which have resulted in several large-scale series of eruptions; (3) The potential for volcanic eruption-induced tsunamis during Krakatoa's eruption; and (4) The proper environment of Krakatoa, which facilitates the rapid recovery of habitats through the natural succession process.

3.2 Criteria 2: Area of Interest

Presently, there has been no reference stating that the Krakatau area is a Global Boundary Stratotype Section and Point (GSSP) or the Auxiliary boundary Stratotype Section and Point (ASSP) by the International Union of Geological Sciences (IUGS) or the International Mineralogical Association (IMA). After a significant eruption in 1883, Krakatoa became a worldwide research reference for comparative volcanology. Besides geologically, there are many scientific types of research abroad from various disciplines, such as biology, oceanography, meteorology, climatology, and even social scope studies. Through the advancement of Krakatoa’s study, many perceptions of volcanoes have been developed and enhanced worldwide.

Krakatoa has long been a concern of researchers around the world. This global concern emerged at least very well recorded after the catastrophic eruption of 1883. Reports of witnesses were quickly disseminated through the local telegraph station in Anjer Port (known as Anyer) after the eruption occurred. The Ceylon Observer (an English language daily newspaper in Sri Lanka at the time) reported on the eruption of Krakatoa on August 28, 1883, with the title Volcanic Action in and around the Strait of Sunda. This newspaper reported the alarming telegraph from Java, which warned that the seas between Java and Sumatra were dangerous for ship navigation due to Krakatoa eruptions. They provide information on broad-coast areas damaged by the earthquake. The correspondence compared it with Mt. Etna and Mt. Vesuvius volcanic catastrophe eruptions, which are even more destructive. Harper's Weekly (an American political magazine based in New York City) also reported a similar incident published on September 28, 1883, which reported the emergence of the volcanic island of Krakatoa after a major eruption on August 28, 1883.

A similar report was announced by the London China Telegraph (a weekly newspaper in London) on October 1, 1883, titled The Volcanic Eruption in the Sunda Strait. They reported that the locals of Singapore hear that the Krakatoa explosions were distinctly audible-like heavy ordnances fired some little distance off. This report shows that the explosion of Krakatoa's eruption was heard, at least in Singapore. On January 22, 1884, Walter White, the Royal Society's Assistant Secretary (a London independent scientific academy), made a letter of appointment to initiate the Krakatoa Committee chaired by George Symons FRS, a meteorologist. The Krakatoa Committee organized the withdrawal of correspondents and witnesses from around the world to send reports on the eruption of Krakatoa (Symons, 1888). This act makes the eruption of Krakatoa an early example of global crowdsourcing data for understanding a natural hazard event.

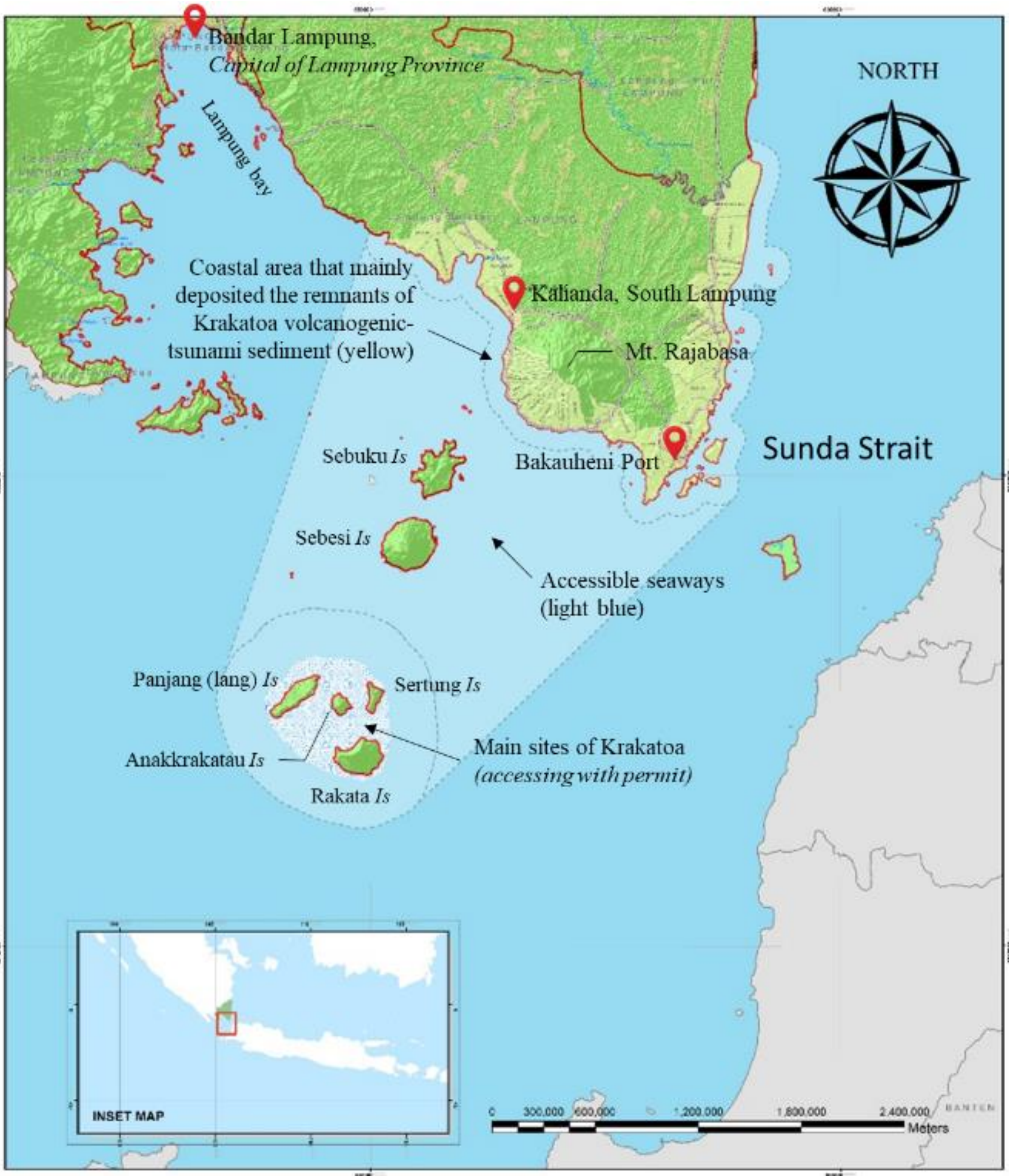

Figure 1. Maps of Krakatoa complex as geoheritage site (study area).

Firstly, J. Prautz (a passenger of a vessel from London to Singapore, in Batavia) provided a detailed report on the eruption of Krakatoa when he was in the Bay of Batavia (the current Bay of Jakarta), which recounted a loud banging sound throughout the day on August 26, 1883, and during the day on August 27, 1883, it became dark as night; the raining of strong-sulfur-smelling dust in the shipyard. Krakatoa's banging sounds can be heard loudly. The following information is well recapped by Royal Society London (2019). A similar occurrence was reported by Forbes (1883), Campbell (1883), Bealby (1883), and Vereker (1883).

With the existence of the Krakatoa Committee (led by the Royal Society), various studies from diverse fields began to emerge, providing a better scientific understanding of Krakatoa. One of the widely accepted researchers is RDM Verbeek, who published The Krakatoa Eruption in Nature (a

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well-prestigious scientific magazine) in 1884. RDM Verbeek was a Dutch researcher assigned to the Dutch East Indies (Indonesia) at the time. In addition, one year after the 1883 eruption, several researchers from abroad provided explanations, impacts, and sequence of events of the Krakatoa eruption at that time (see Flammarion, 1884; Metzger, 1884; Boutelle, 1884; Bishop, 1884). Krakatau continues to be a reference object for researchers worldwide to study potential volcanic impacts and other possible future events (see Dammerman, 1922; Wexler, 1951; Harkrider and Press, 1967; Self and Rampino, 1981; Latter, 1981; Simkin and Fiske, 1983; Nakamura, 1984; Whittaker et al., 1989).

In the modern era, research on Krakatoa has been growing and improving. This proceeded with the advancement of volcanology perspectives, methods, and technology in data collection and processing. Concerns about Krakatoa continue to persist because of the dynamics of Krakatoa's activity till presently, which is yet active and often poses a threat to destructive impacts, such as the Krakatoa volcanogenic-tsunami that occurred on December 22, 2018. Currently, several noticeable researchers applied Krakatoa as a reference (see Nomanbhoy and Satake, 1995; Deplus et al., 1995; Carey et al., 1996; Gleckler et al., 2006; Abdurrahman et al., 2018; Heidarzadeh et al., 2020; Novellino et al., 2020; Madden-Nadeau et al., 2021) and also several books about Krakatoa authored by Thornton (1997) and Winchester (2004).

3.3 Criteria 3: Scientific Understanding

Research on Krakatoa has been ongoing for over 100 years since its eruption in 1883. This volcano has been investigated and studied from various scientific points of view, such as geology, volcanology, geophysics, geography, biology, and others. Generally, the geological features have been well understood from the eruption mechanism, the history of the eruption, and the broad impact of eruptions such as volcanogenic tsunamis.

Sutawidjaja (2006) and Ismail et al. (2020) studied the dynamic growth and volcanology of Krakatoa. This study combines literature, shoreline analysis, field observations, and petrographic analysis. A geological section was also proposed to provide summaries of the Krakatoa complex subsurface. They also reconstructed the conditions of the volcano from 416 AD until 2020 AD. At least 30 rock units consisted of 22 extrusive igneous rocks (lava origin) and eight pyroclastic origins. Additionally, Novellino et al. (2020) mapped changes in Krakatau's shoreline after the lateral collapses that caused the tsunami in December 2018.

The tectonic setting of Krakatoa is strongly tied and affected by the Sunda Strait and Semangko faults. The opening (extensional) of the Sunda Strait was initiated in the early Late Miocene, following the initiation of the Sumatra fault system in the Middle Miocene (Harjono et al., 1991). Since then, three major graben systems have been developed: the West and East Semangko Grabens, and the Krakatau Graben. These graben systems can be regarded as pull-apart basins, and they developed within the releasing fault overstep area between the main straightness of the Sumatra fault and the southern faults in Ujung Kulon. This reveals that the most known crustal earthquakes in the Sunda Strait area occur in three main areas: (1) Beneath the Krakatau complex, where earthquakes are frequently generated by double couples and are of tectonic origin; (2) below the graben in the western part of the Sunda Strait; and (3) in the below-scattered zone to the southern Sumatera. The mono (and combined) of its focal mechanisms (identified inside the Sunda Strait) shows an extensional regime. A stress tensor, which was deduced from the individual focal mechanisms of earthquakes of Krakatau, shows that the tensional axis is oriented NW-SE. This study confirms that the Sunda Strait is in an extensional tectonic regime due to the northwestward movement of the Sumatra Sliver Plate along the Semangko Fault Zone (Susilohadi et al., 2009).

The 1883 Krakatoa eruption ejected approximately 12.5 km^3 of magma containing 90% rhyodacite, 4% mafic dacite, 1% andesite, and 5% other lithic materials. This indicates that the 1883 Krakatoa magma chamber was compositionally dominated by homogenous rhyodacite-magma (at 880-890°C), overlying more mafic-dacite-magma (at 890-913°C) and a small portion of andesite-magma (at 980-1000°C). Mafic dacite represents a hybrid magma formed by mixing small amounts of andesite with more significant amounts of differentiated rhyodacitic magma (Jaxybulatov et al., 2011). Mandeville et al. (1996) and Abdurachman et al. (2018) found indications of a multilayered structure of a magma chamber system beneath the Krakatau complex based on petrological and geochemical studies. This suggests that there are partial melting

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mechanisms in the mantle wedge. It caused mantle upwelling in the upper mantle by thinning the subducted tectonic plate beneath the Krakatoa Volcano and Sunda strait fault extensional regime.

In volcanology, the relative sizes of volcanic eruptions are grouped by the value of the volcanic explosive index (VEI). This value is used to compare volcanic eruptions with other eruptions. The main aspects of VEI are calculated based on the volume of pyroclastic material produced during an eruption. In addition, the eruption characteristics, frequency and duration of the eruption, and height of the eruption column were investigated. They are used to determine the eruption index value of a volcano. The VEI is divided into eight (8) index values, with a scale of 0 for non-explosive to a scale of 8 for mega-colossal, an ultra-Plinian eruption. The eruptions of Toba (74,000 BC), Taupo (26,500 BC), and Yellowstone (630,000 BC) are examples of eruptions with VEI values on a scale of 8. The 1883 Krakatoa eruption, categorized as VEI with an index of 6, a value greater than the eruption Vesuvius (79 AD) and Mount Agung (1963 AD)–VEI 5 (Špičák, 2008). The 1883 Krakatoa eruption was comparable to that of Pinatubo (1991 AD) and Santa Maria (1902 AD).

VEI-6 is described as a plinian to an ultra-plinian by the colossal eruption scale. Another researcher also described that the 1883 Krakatoa eruption had an explosive power 21,574 times that of the atomic bomb in World War II (Sutawidjaja, 2006; Kurniawan, 2014). This eruption produced ± 10 km^3 dense-rock equivalent (DRE), also caused tsunami waves that killed more than 30,000 people and globally caused long-term changes in atmospheric conditions (Paris et al., 2014; Rampino and Self, 1982).

Thus far, the remains of the 1883 Krakatoa exist, including both the body of the volcano and its volcanogenic tsunami deposits. The remains of the Krakatoa volcano are currently under the Balai Konservasi Sumber Daya Alam Lampung-Bengkulu (a national agency for the conservation of natural resources in this region). This area is categorized as the Cagar Alam (CA) and Cagar Alam Laut (CAL) Krakatau (an area for nature and marine sanctuary). There are 4 islands in this area, namely Sertung (Verlaten), Panjang (Lang), Rakata, and Anakkrakatau. There are definite laws that limit human activity in this area. Education and research may only be conducted in these areas through formal permits. In addition, Pusat Vulkanologi dan Mitigasi Bencana Geologi (a national geological agency for volcanology and its hazard) plays a role in monitoring Krakatoa activity and strengthening national volcanology studies in this area. They coordinated management activities with local governments. Conservation in this sanctuary is essential to maintain the naturalness of Krakatoa, which has the ability to succession and colonize species that accelerate ecosystem recovery in the area after the destructive eruption. Specific vegetation, invertebrates, and reefs are known to act as pioneers in the natural succession of Krakatoa (New, 2015; Thornton, 1997; Partomihardjo, 2003; Yukawa et al., 2000).

Meanwhile, other areas outside the sanctuary are under the authority of each local government. Especially in Lampung province, there has been no particular attention to sites on the coast of mainland Lampung and the small islands around it regarding managing the key site of the 1883 Krakatoa eruption evidence for further research and education. Nakamura (1984) and Carey et al. (2001) pointed out that Sebesi Island, Sebuku Island, and southern Sumatera's coast might reserve the critical evidence of 1883 Krakatoa volcanogenic-tsunami.

3.4 Criteria 4: Site Condition

Currently, remnants of past (older) Krakatoa can still be found on the islands of Rakata, Sertung, and Panjang. These three islands did not change significantly after the 1883 eruption. Meanwhile, the prime cinder cone of Krakatoa often changes with eruptive activity. Ismail et al. (2020) described the morphological development of Krakatoa for further investigation. Sustainability can be maintained with the role and responsibility of national agencies in managing this area.

However, locals have also reported that floated urban trashes (mainly plastics) are often piled up in several parts of this area. They are carried naturally from the mainland of Java and south by sea currents. In some cases, plastic trash is also often brought to this area by illegal visitors. Meanwhile, many human activities occurred in Sebesi and Sebuku (even before the 1883 eruption). Residential activities, fisheries, plantations, and cattle are expanding on this island (Johan 2016; Kurniasih and Tejapermana 2018). Similar conditions are the same as those in mainland southern Sumatra (particularly in the South Lampung region).

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3.5 Criteria 5: Geodiversity

In the geodiversity review, the diversity of geological features is examined from five main aspects: petrology, minerals, paleontology, geodynamics, and geomorphology. This geological diversity represents the geological outline of Krakatoa and the current existence of these five aspects. In this case, five aspects are briefly discussed to determine the geodiversity around Krakatoa as geoheritage.

Petrological aspect. Based on investigation by Dahre et al. (2012) affirmed that there is evidence for multiple magma storages. Based on his research on Krakatoa rocks, from pre-1883, in the 1883 eruption, and to 2002, the characteristics of basalt, andesite, and rhyodacite were intensively obtained in its eruptions, even at relatively close periods. A comparison between thermobarometry and seismic tomography illustrates several distinct magmatic storages (Jaxybulatov et al., 2011). These conditions as sign and indication of rock and mineral variations in this area as well. Ismail et al. (2002) have identified numerous rock units to describing volcano-stratigraphy in this area. In 2018, there were 27 rock units in the Krakatoa volcanotratigraphy. Most of these are volcanic products. These rock units do not include other rock units that can be found outside of the Krakatoa complex, such as Sebesi Island, Sebuku, and the southern coast of Sumatra. Mangga et al. (1993) showed that Sebesi Island is a young volcanic rock unit (Holocene), and Sebuku Island consists of an andesitic lava rock unit with columnar features (Pliocene). This is similar to the southern coastal area of Sumatera (around Bakauheni). However, apart from the young volcano (Mt. Rajabasa), plain andesite lava rock units, and several Plio-Pleistocene tuff rock units. This tuff rock unit consists of various variations, such as pumiceous tuff, rhyolitic tuff, welded tuff, tuffaceous claystone, and tuffaceous sandstone (Sihombing et al., 2021; Harbowo et al., 2021). Considering the frequency of the Krakatoa volcanogenic tsunami event, it is possible that the alluvial units in this area store the Krakatoa tsunami deposits.

Mineralogical aspect. Camus et al. (1987) have examined the petrologic evolution of Krakatoa, which indicates that fractional crystallization of Krakatoa magma plays the most critical role in the variation of its minerals. Based on the results of a review of mineralogical data, at least until the 1981 eruption, the plagioclase minerals commonly found (in the form of phenocryst, to microphenocrist), some of which are bytownite, andesine-labradorite, labradorite. In addition, orthopyroxene minerals, such as hypersthene and bronzite, can also be found. Clinopyroxene and olivine minerals were also present in the Fe-rich rims. The most common oxide minerals were titanomagnetite, ilmenite, and hematite.

Paleontological aspect. The paleontological features that can be found in the Krakatoa area are typically remnants of living organisms that were deposited together with materials from the eruption and tsunami. These features may be relatively young but significant in representing the geological outline of Krakatoa and the magnitude of the impact of the eruptions. Paleontological proxies, such as foraminifera, marine mollusk fragments, and corals, are often used to reconstruct paleotsunami deposits and events and provide information on the magnitude of tsunamis. Putra and Yulianto (2016, 2017) traced the tsunami deposits of the 1883 eruption in several areas, including Tarahan and Teluk Semangko in the Lampung Province, using foraminifera as a proxy. This suggests that there are likely many other locations in southern Sumatera with similar features that could be studied further.

Geodynamical aspect. As previously examined, the fault system in the Sunda Strait and Sumatran fault system has a significant influence on shaping the characteristics of Krakatoa. Although this feature does not frequently occur as an outcrop, it manifests clearly as lineaments of geomorphological patterns. Generally, these geodynamic features can be observed in both the subsurface seismic section and seismic activity related to local tectonic dynamics. Harjono et al. (1991) and Susilohadi et al. (2009) have conducted studies related to this. The tectonic activity in this area is derived from Sunda arc subduction and Sumatran strike-slip. It was also concluded that the dominant tectonic regime that has recently acted in the Krakatoa area is more likely to be an extensional regime.

Geomorphological aspect. The study conducted by Ismail et al. (2020) identified nine geomorphological units in Krakatoa. These units include the old Krakatoa caldera wall (pre-416 AD), the remnants of the Rakata Volcano ridge (pre-1883 AD), Krakatoa pyroclastic flow ridge (pre-1883 AD) in Rakata Island, Anakkrakatoa volcanic crater, Anakkrakatoa volcanic cone, the

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volcanic lava flow ridge of Anakkrakatoa, The remnants of Anakrakatoa volcanic ridge, the pyroclastic plains, the volcanoes center of Anakkrakatoa, and the alluvial plains of Krakatoa. It should be noted that these units exclude those found on the Sebesi and Sebuku islands, which are remnants of paleovolcanoes, as well as other units on the mainland coast of Sumatra. Coastal geomorphological units outside the Krakatoa area have not yet been fully delineated. However, satellite observations have shown the presence of various features such as an active volcano (Mt. Rajabasa), remnants of paleovolcanic islands, isolated islands, volcanic-association reefs, mangrove plains, isolated hills, sandy to rocky shores, volcanic springs, and others. These geomorphological units may change in response to the natural activities of Krakatoa in the future.

3.6 Criteria 6: Global Significances

To describe the significance of Krakatoa, we compared Krakatoa with other volcanoes worldwide. We conclude that Krakatoa is the second world's largest death toll after Tambora (1814 AD). Krakatoa was causing the deaths of more than 36,000 people. Most of these deaths were caused by tsunami waves generated from the eruption. At least 40 m high tsunami waves hit the surrounding coast. Choi et al. (2003) compiled the tidal waves recorded after the 1883 Krakatoa eruption. Anomaly waves have been recorded in several locations globally with different far distances from Krakatoa, including Port Blair, Andaman Island (2440 km); Colombo, Sri Lanka (3113 km); Bandora, India (4500 km); Rodriguez Island in the Indian Ocean (4653 km); Port Elizabeth, South Africa (7546 km); North-West Cape, Australia (2100 km); and Auckland Harbor, New Zealand (7767km). Using the recorded tidal wave data, he successfully modeled the transoceanic propagation due to the 1883 Krakatoa eruption.

Krakatoa's 1883 eruption produced the loudest boom ever heard in human history, which is believed by many to be a unique event. This deafening sound was heard from approximately 5000 km away and by people across 50 different locations worldwide. According to Winchester (2004) and Simkin and Fiske (1983), the magnitude of the boom is 172 dB at a radius of 100 miles, which is significantly larger than the sound of a typical jet engine (150 dB). Witnesses around the world heard the echo of the boom up to four times. Judd et al. (1888) have reconstructed a map showing the distribution of witnesses who heard the explosion directly. In addition, the presence of telegraph posts around Krakatoa during the eruption allowed for the rapid spread of news about events worldwide. Dorries (2003) noted that Krakatoa was the first natural disaster to be recognized worldwide almost immediately. This is an early example of how people can use "global crowdsourcing data" to identify and respond to natural hazards and catastrophic events.

Additionally, the eruption of Krakatoa in 1883 caused a global optical effect owing to the distribution of volcanic ash. This led to the refraction of sunlight by sporadic volcanic ash, which resulted in unusual phenomena such as blue to green moon, lavender sun, and vivid red sunsets in various locations, including New York, Poughkeepsie, and New Haven in America. This phenomenon lasted until October 21, 1883, and has been depicted in various artworks, such as The Scream by Norwegian artist, Edvard Munch. Therefore, based on the information presented, it can be concluded that Krakatoa is significant. Compared to other volcanoes, Krakatoa stands out because of its unique geological outline and global impact.

3.7. Criteria 7: Accessibility and Constrains

The main area of Krakatoa, which includes the islands of Sertung, Panjang, Rakata, and Anakkrakatau, is currently limited to entry for protection, conservation, and mitigation. This area is regulated by the Lampung-Bengkulu Natural Resources Conservation Center and the Center for Volcanology and Geological Hazard Mitigation. Access to this area requires permission from the relevant institutions for clear purposes.

However, research and educational activities are still permitted in these locations. Some areas that can be visited include the Sebesi and Sebuku islands and their seaways, as well as the southern coastal area of Lampung, where the remnants of Krakatoa's tsunami can be found. These areas are easily accessible and have adequate infrastructure. It takes only 345 minutes from Bandar Lampung. Land and sea travel facilities are available to the public.

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3.8 Geoheritage Criteria Scoring

Krakatoa Geoheritage was assessed using the Standard Scientific Value Assessment published by the Geological Survey Institute of Indonesia. We conducted a literature review to compare these indicators with scientific facts and existing data. Each indicator has a score, which is then added based on the weight of each criterion, with a maximum value of four for each criterion. Based on our scoring, the Geoheritage of Krakatoa received a score of 37/40, equivalent to 92.5/100. Detailed assessment assumptions can be found in **Table 2** and in the explanation below.

In terms of geological outline, Krakatoa is the best example in Indonesia and the world to explain the evolution of the development of a submarine volcano into a volcanic island. It is the only active volcano located on the strike-slip fault and subduction zones between offshore Java and Sumatra. Krakatoa is also the best example to explain the existence of a volcano with historical records of various types of eruptions, including ultra-plinian, which is the most destructive volcano eruption type. Furthermore, it is the only active volcano in this area with various sources and magmas, from sub-alkaline basalt to dacite and from crustal to upper mantle origin. Krakatoa is the best example at the equator, especially in Southeast Asia, with a reliable record of scientific data on its most destructive eruption and volcanogenic-tsunami event. Tsunami deposits can be found along the coast of the Sunda Strait, particularly in Lampung Province. Therefore, based on the geological outline criteria, we assigned a score of 4/4.

Table 2. The resume scoring scientific value of Krakatoa as geoheritage (result).

Parameter	Score	%	Final
Geological Outline	4	30	12
Key Location	3	20	6
Scientific Understanding	4	5	2
Site Condition	4	15	6
Geodiversity	4	5	2
Significance	4	15	6
Constrain	3	10	3
Total score (max. 40)			37
Equals (in 100 scale)			97.5

Based on the Area of Interest (key location) criteria, although it is not a GSSP and ASSP, Krakatoa has become a reference for worldwide researchers who have been published scientifically at an international level. Researchers from various disciplines have participated in understanding scientific facts and their information, such as geology, volcanology, paleontology, biology, and meteorology. The massive eruption of 1883 instantly made Krakatoa known to the world. Owing to the limitations of communication technology (in 1883), the Krakatoa eruption successfully triggered the emergence of an early example of global crowdsourcing data of humankind to understand a natural hazard event. Since then, the attraction of Krakatoa has been felt. Thus, on this criterion, we assigned a score of 3/4.

Reviewing criteria of scientific understanding, with many researchers and academics in the world interested in the eruption of Krakatoa, there have been many scientific publications that focus on Krakatoa. It has been more than 100 years (since 1883) since researchers worldwide have conducted and participated in Krakatoa studies. Scientific publications on the dynamic and natural succession of Krakatoa, tectonic settings, volcanic products, its environment, and catastrophic effect scale, so that their influence on human culture can be easily found and understood by the worldwide community. Some representative scientific references and reviews of Krakatoa are discussed in this publication. Thus, based on this criterion, we assigned a score of 4/4.

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Considering the site condition aspect, we consider that this location is the main area of Krakatau and is well-maintained. All geological features related to the geological outline were well-conserved. The national agency manages the protection and supervision of this area for the conservation of natural resources, and the national geological agency manages volcanology and its hazards. Not much damage was found, except for the eruption of Krakatoa. Thus, on this criterion, we give a score of 4/4.

In terms of geodiversity, we assessed that there are no similar geological features that can be equated with the Krakatoa context, at least in Southeast Asia. Krakatoa has a unique geological outline that makes the geodiversity variety features in this area unique. A detailed discussion of this geodiversity can be found in the previous discussion. Therefore, from the perspective of geodiversity, we assigned a score of 4/4.

From the significance criteria, we assess that Krakatoa is one of the most well-known globally affected volcanoes since 1600 AD. Krakatoa was causing the second most enormous death toll. Most of these deaths were caused by transoceanic tsunami waves. Krakatoa is the only known in human history that produces the loudest boom that echoes four times around the world. Its volcanic ash affects atmospheric conditions, which is known as the global optical effect. This has strengthened the global significance of Krakatoa. Therefore, for this criterion, we assigned a score of 4/4.

Based on the constraint criteria, there were no obstacles in terms of accessibility or infrastructure. However, standard permission (permit) is required to conduct field activities and sampling, especially those intended for educational and research activities. Permit was carried out at the relevant institution. Under this condition, we assigned a score of 3/4 to these criteria.

3.9 Further Insight

Through this study, it is evident that Krakatoa has immense scientific value in every aspect that has been assessed. It is undeniably a deserving of recognition as a geoheritage site, emphasizing the importance of conserving this area. This recognition should serve as a cornerstone for conservation efforts, which should be continuously supported by educational activities directed towards the wider public, accompanied by constructive research that supports sustainable local to global development. This study serves as a pioneer insight to the significance of Krakatoa as a geoheritage site. It also provides a foundation for future research for founding a new outstanding geopark. Recognizing the crucial role of the community, academics, and government in preserving the geoheritage of Krakatoa for future generations, it is essential to emphasize the importance of maintaining and conserving Krakatoa as a valuable site.

Krakatoa is worthy of being declared a geoheritage due to its significant scientific value in various field such as geology, volcanology, paleontology, biology, and meteorology. The catastrophic eruption of 1883 provided crucial data on volcanic behavior and its impact on the environment and humans. Moreover, Krakatoa has a complex and fascinating geological history, including the formation and evolution of the Sunda-arc and its role in the dynamics of tectonic plates. These characteristics make Krakatoa an attractive research subject for scientists and researchers worldwide. Recognizing Krakatoa as a geoheritage site, it is expected to be preserved for future generations and to serve as a collaborative educational object to raise public awareness of the importance of geodiversity, biodiversity, and environmental conservation.

4. CONCLUSION

Based on the Indonesian Standard Scientific Value Assessment for geoheritage, the Krakatoa complex area is classified as a high-score geoheritage. The score obtained based on these criteria was 37/40 or equivalent to 92.5/100. The significant geological aspect is that Krakatoa has global significance owing to its history and uniqueness. Management, conservation, and mitigation efforts also need to be respected to maintain the current scientific value in this area. Its excellence in education and research has provided new insights for humans to coexist with nature and even hazardous volcanoes. This effort must be continuously supported by the next generation by maintaining Krakatoa as a geoheritage site.

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