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The Tertiary sequence of Varkala coastal cliffs, southwestern India: An ideal site for Global Geopark

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Research Paper

The Tertiary sequence of Varkala coastal cliffs, southwestern India: An ideal site for Global Geopark

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ABSTRACT

Varkala, along the southwestern coast of Peninsular India, has a unique place in Indian geology and geomorphology due to the presence of coastal lateritic cliffs, which exposes the entire Mio-Pliocene sequence of Warkalli Formation, and is declared as the type area. Stratigraphically, this formation exposes carbonaceous clay with lenses of lignite and sticks of marcasite, followed by variegated clays and sandstone. The presence of variegated lithounits endows beauty to these cliffs. Varkala cliffs, edging the Arabian Sea, run for a length of 7.5 km. These cliffs, together with confined beaches, made Varkala a popular tourist destination. Several geodiversity spots within the Varkala Cliff geoheritage site make Varkala geologically unique, just like the vestiges of the last separation of Indian subcontinent from the Mascarene Plateau; showcasing lateritization and distribution of beach placers, and jarosite, formed as a diagenetic replacement mineral from marcasite and considered as a Martian analog, are distinctiveness of the cliff. Additionally, Varkala is an internationally acclaimed beach tourist destination. Furthermore, there are several geoheritage sites as well as socio-cultural-historical sites in the hinterland of Varkala Cliff geoheritage site, which are within the proposed Varkala Global Geopark jurisdiction. Thus, this area fulfills all the criteria to be a Global Geopark. The socio-economic-environmental analysis showcases the changes that have occurred in these 3-end members. When the economic sphere was unaffected, the social scenario was slightly affected (25%) whereas the environmental aspect then drastically deteriorated by 75%. But, the SWOT analysis still elects Varkala as a potential Global Geopark. The concept of geopark contributes to at least one of the 17 goals in Agenda 2030 Sustainable Development Goals (SDG) of the United Nations (UN). Consequently, this work also aims at propagating, not only the need for converting the geologically prominent areas to a geopark, but also attaining SDG, whatever is possible through geoparks.

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1. Introduction

The United Nations Educational, Scientific and Cultural Organization (UNESCO) defined Global Geopark as a single, unified geographical area where sites and landscapes of international geological significance are managed with the holistic concept of protection, education and sustainable development (www.en.unesco.org). Such an area should display outstandingly rare geological landforms in an undisturbed state of preservation. Moreover, such areas should be unique, representative, aesthetic and rare, and on the one hand should be capable of hosting both immense educational and recreational potential and promote earth's heritage, as well as sustain local communities on the other.

In this backdrop, the Geological Survey of India (GSI) in its 49th Central Geological Planning Board (CGPB) meeting, held at New Delhi during August 2011, resolved to identify and develop a collage of geologically important sites in India to be earmarked as National Geoparks, with the intent of promoting them as elite member of the Global Geopark Network (GGN). However, even after a decade, there was no nomination of Indian sites, although there are quite a few potential sites of unique geological make-up and national significance. One such site is the coastal cliff of Varkala (Fig. 1a,b) (Anand, Saluja, & Singh, 2014; Sajinkumar, 2012; Sajinkumar, Ramachandran, & Singanenjam, 2014; Sajinkumar & Rani, 2015), which was declared as a National Geoheritage Site by the GSI in 2014. This study aims to focus attention and awareness regarding the importance of this coastal cliff (which is

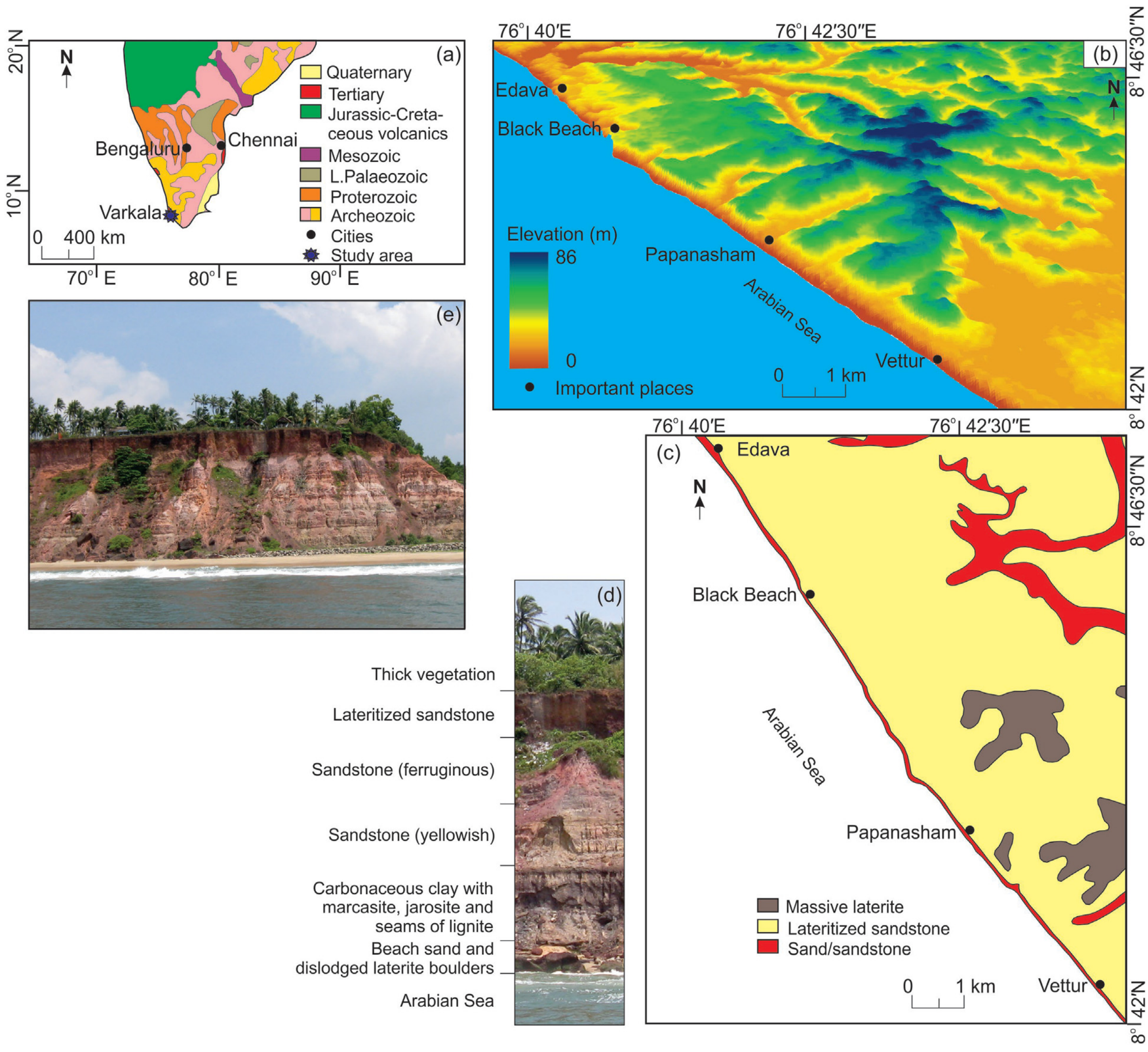

Fig. 1. (a) Geological map of southern India depicting different lithounits ranging from Archean to Recent. (b) ALOS PALSAR Digital Elevation Model (DEM), draped over hill shade, is shown to provide a bird's eye view of Varkala and adjacent area. (c) Geological map of Varkala cliff and adjacent area. (d) A field photo depicting the entire litho-stratigraphic units of Varkala Cliff. (e) A part of Varkala coastal sedimentary cliff, exposed near Vettur.

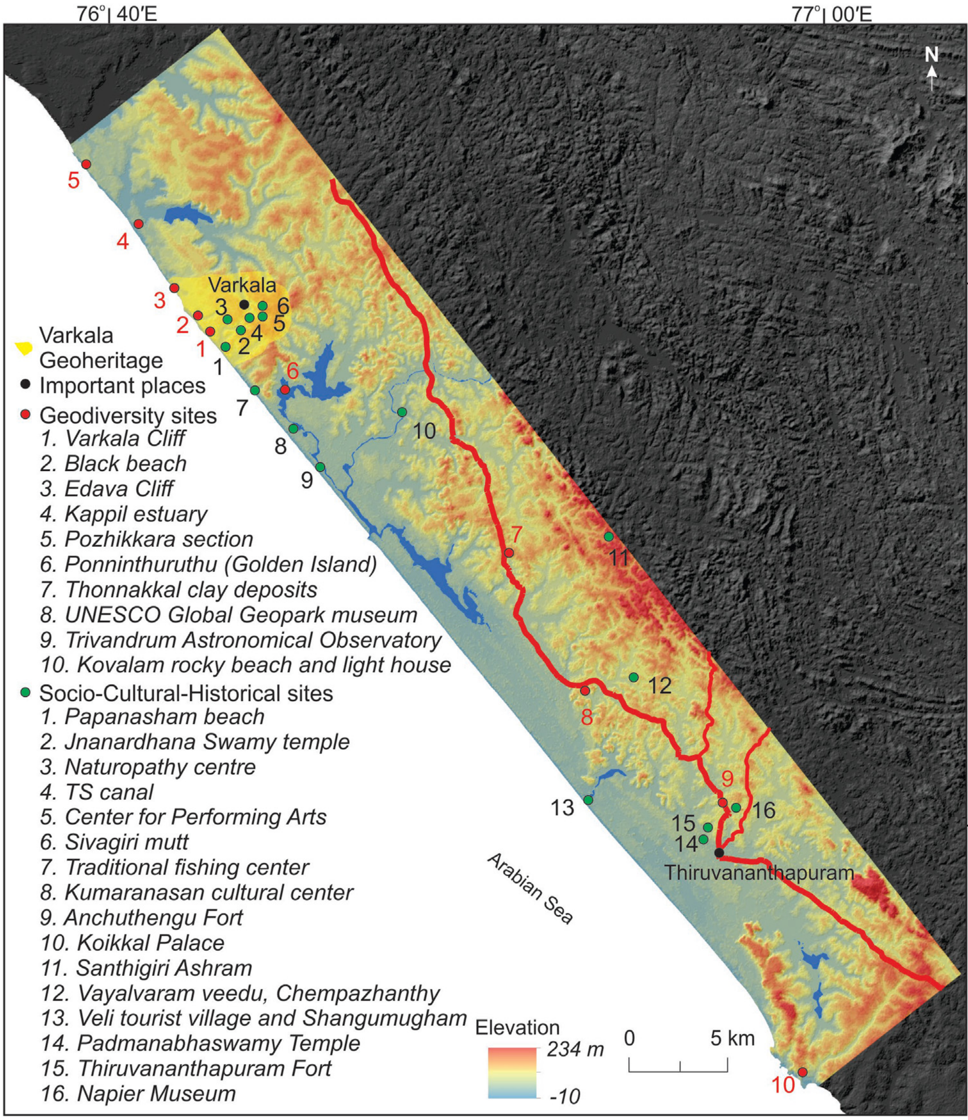

Fig. 2. Distinctive geoheritage and geodiversity sites of the proposed Varkala Global Geopark (ALOS PALSAR DEM, draped over hill shade).

the type area of the Warkalli Formation (*sic*) of sedimentary rocks, initially described by King, 1889), so that future unscientific and unplanned developments could be avoided/barred, minimized or if necessary, precluding anthropogenic modifications to protect the cliff, and finally, to popularize the need and necessity of converting this unique heritage site and its hinterland with distinctive socio-cultural-historical elements as a Global Geopark.

Varkala (8°44′46”N and 76°41′48″E), a coastal hamlet in the Thiruvananthapuram District of State of Kerala in southern India, attracts a large number of both national and international tourists round the year. The charm of this place is the wave-cut-backshore cliffs (about 20–30 m high and attractively hued in shades of deep brown and light yellow occasionally turning to off white) and land-fast beach of golden sands. The cliff-forming rocks are a sequence of non-marine clastic rocks (GSI, 2005) consisting of beds of variegated sandstones and grits alternating with lenses/beds of light brown coloured clays grading laterally and/or vertically into arenaceous sediments and capped by a rather thick layer of (3.0–5.0 m) of ferruginous laterite grading downward to clays and sandstones. Similar wave-cut backshore cliffs with land-fast beaches occur edging the Arabian Sea at Edava (8°44′35.75″N, 76°41′54.21″E) to the north and Vettur (about 40.0 m amsl; 8°43′59.34″N, 76°42′19.91″E) to the south, adding up to a cumulative length of nearly 7.5 km. A foot-path for tourists runs on the top of the edge of the cliff throughout the length of this cliff. The picturesque cliff, standing like a protective edifice edging the shoreline, endows spectacular natural beauty, creating magnificent memories in the minds of the tourists. King (1882) in his report says that this deep-brown-coastal cliff of layered rocks visible to the mariners in the vessels passing through the coastal ocean is like a 'light house' position locator. Considerable research on coastal livelihoods, juxtaposing tourism and fishing in Varkala exist (McMinn, 2006). Varkala is the backdrop of some recent English fiction too (Salim, 2016).

Table 1
Criteria, indicators, and parameters used for the quantitative assessment of the potential educational value (after Brilha, 2016).

Criteria and indicators (the situation in Varkala in italics)	Parameters (points)	Weightage	Value
A. Vulnerability	2	10	20
There is the possibility of deterioration of main geological elements by anthropic activity: Anthropogenic and natural processes are degrading the main element, which is the picturesque cliff, along with its Mio-Pliocene sequence which preserves the Warkalli Formation.			
B. Vulnerability	4	10	40
Site located less than 100 m from a paved road and with bus parking: Being a tourist centre, the location is highly accessible, with even a helipad located on the cliff top.			
C. Use limitations	4	5	20
The site has no limitations to be used by students and tourists: There are no restrictions to access any site in the location, other than physical barriers created by fallen large laterite boulders onto the beach.			
D. Safety	4	10	40
Site with safety facilities (fences, stairs, handrails, etc.), mobile phone coverage and located less than 5 km from emergency services: Varkala is a religious destination, a touristic destination, as a well as an educational destination, and all facilities exist in the near vicinity.			
E. Logistics	4	5	20
Lodging and restaurants for groups of 50 persons less than 15 km away from the site: Being a tourist destination accommodation from budget to high-end are aplenty.			
F. Density of population	4	5	20
Site located in a municipality with more than 1000 inhabitants/km^2: high-density population, just like in all parts of Kerala.			
G. Association with other values	4	5	20
Occurrence of several ecological and cultural values less than 5 km away from the site: Janardhana swamy temple, religious renaissance leader Sree Narayana Guru's ashram, beach, cove, cliffs, backwaters.			
H. Scenery	4	5	20
Site currently used as a tourism destination in national campaigns: a highly valued and liked destination that has featured in the government's Kerala Tourism Development Corporation's and Vision Varkala Infrastructure Development Corporation's international ad campaign.			
I. Uniqueness	4	5	20
The site shows unique and uncommon features considering this and neighbouring countries: unique cliff sections, beach processes and landforms, mineralization, ocean-river interaction.			
J. Observation conditions	3	10	30
There are some obstacles that make difficult the observation of some geological elements: Natural processes have led to beach and cliff sections becoming inaccessible due to large laterite boulders blocking continuous movement along the beach.			
K. Didactic potential	4	20	80
The site presents geological elements that are taught at all teaching levels: vestiges of Gondwana split-up, ideal location to study Mio-Pliocene section, geomorphology of laterite cliffs fronting the ocean, varied fossils assemblages, natural springs, lateritization processes, placer processes, Martian analog minerals, tunnels and canals, sandstones with reducing environment and potential for U mineralization.			
L. Geological diversity	4	10	40
More than 3 types of geodiversity elements occur in the site (mineralogical, palaeontological, geomorphological, etc.): *as listed under K.*			
Total	45	100	370
Percentage of the maximum possible score			86

2. Geodiversity of Varkala geoheritage site

The proposed Varkala Global Geopark, though focusing on geoheritage site at Varkala Cliff, consists of distinctive geoheritage and geodiversity sites apart from scores of socio-cultural-historical sites in its hinterland (Fig. 2). A few prominent sites are elaborated and remaining is narrated in Supplementary Material 1. The educational value of the Varkala site is high when being assessed by using the Brilha (2016) matrix, scoring a high value of 86% (summarized in Table 1 and also touched upon in the sections to follow). Varkala geoheritage site is already a must-visit location in the itinerary of the geology field trips of several universities in India, and affords pleasurable relaxation and deeply involved geological investigations. Like the Hwaseong Geopark, the candidate for Korean National Geopark (Cho et al., 2021), Varkala also offers educational opportunities at all levels.

2.1. General geology

Peninsular India displays a variable geologic milieu, with rock formations ranging in age from Precambrian to Recent (Fig. 1a) and grouping under different geologic regimes, such as Deccan Volcanic Province (DVP), Peninsular Gneissic Complex (PGC), and several crustal blocks to the south including Coorg, Nilgiri, Madurai, Trivandrum and Nagercoil, in addition to the major khondalite belts in Mercara and Trivandrum (Santosh, 2020). Voluminous Tertiary and Quaternary sediments skirt the continental margins (Nair, Padmalal, & Kumaran, 2006). The Indian coastline of 7517 km exhibits diverse geomorphic features like rocky and sandy beaches, deltas, spits and bars, and tombolo. However, sedimentary coastal cliffs are a few and are mainly confined between

Table 2
Stratigraphy of Varkala Cliff.

Age	Formation	Lithology
Recent	Kadappuram	Beach sand
Recent to sub-recent		Laterite
Tertiary	Warkalli	Current-bedded friable variegated sandstone interbedded with plastic clay and variegated clays
		Carbonaceous and alum clays with lignite seams
		Gravel and pebble beds. Base marked by gibbsitic clay
Unconformity		
Archean	Kerala Khondalite Belt	Crystalline rocks

Edava and Poovar for a length of 23.25 km (Kumar, Seralathan, & Jayappa, 2009). These cliffs mainly expose the Tertiary Warkalli Formation and at a few places, the older Tertiary Quilon Formation. Thus, the coastal cliffs find a unique place in the geology as well as the geomorphology of Peninsular India.

2.2. Vestiges of Gondwana split-up

The nearly straight west coast of India (a consequence of the West Coast Fault- WCF) as noticed in Varkala, is a manifestation of several episodes of tectonic activity. The Indian Peninsula, once part of the Gondwana Supercontinent, on breakup, detached from the Mascarene plateau during early Tertiary, which is believed to be the last episode of Gondwana split-up (Plummer & Belle, 1995). The WCF, between Panvel to Kanyakumari, also reflecting the straight aspect of the west coast, was supposedly the zone of detachment. The split-up had occurred in two stages: (i) it occurred as a narrow fracture along the northern part of the margin during the late Jurassic-early Cretaceous (Biswas, 1982; Owen, 1976) and (ii) it extended further south during the Tertiary (Owen, 1976). Chandrasekharam (1985) constructed three models to describe the structural evolution of the eastern continental margin of India. Model 3 of Chandrasekharam (1985) shows a structure along 9°15′N and suggests that it was developed mainly by the counterclockwise rotation of the Indian plate during the early Tertiary due to the parting of the Mascarene plateau from the southern part of the western margin of India (Owen, 1976). Vertical movements of the block adjacent to the WCF during the late Tertiary initiated deposition of marine and continental sediments, which Raha, Roy, and Rajendran (1983) reported as the Tertiary sequence, the youngest of which is the Warkalli Formation. Thus, Varkala and adjacent areas form a remnant of the Gondwana Supercontinent.

2.3. Geology of Varkala Cliff

Areas east of Varkala form a part of Kerala Khondalite Belt (KKB) of the Southern Granulite Terrain (SGT) of Indian Peninsula, and the Tertiary Warkalli Formation unconformably overlies the Precambrian crystalline basement with no representation of rocks of Paleozoic and Mesozoic age. Varkala Cliff is the type area for the Warkalli Formation of Mio-Pliocene age (King, 1882), where the cliff exposes all the lithounits of this formation such as ferruginous and non-ferruginous sandstones and grit, variegated clays, white plastic clays and carbonaceous sandy clays enclosing intermittent thin seams and lenses of lignite (GSI, 2005). These beds are almost horizontal in nature. Carbonaceous clays, carrying lenses and laminae of lignite, often contain sticks and nodules of marcasite indicating a reducing environment (Soman, 2002). Warkalli Formation is also a source of organic remains, which are useful in the study of fossil DNA (Shukla, Kumar, Prakash, Srivastava, & Kumar, 2000; Srivastava, Shukla, Kumar, Kumar, & Prakash, 2006). Based on the lithology and spatial distribution, Rao (1968) suggested the Warkalli Formation as a shallow water shoreline littoral deposit. The Cenozoic sedimentary succession in the onshore part of the Kerala Basin is dominated by siliciclastic sediment (Reuter et al., 2011). The geological map of this area is shown in Fig. 1c-e. The modified generalized stratigraphy of Paulose and Narayanaswami (1968) pertaining to this area is shown in Table 2.

2.4. Unique geomorphologic features of Varkala Cliff

The Varkala Cliff, a part of the cliffed shoreline of Kerala with a land-fast beach, stands as an edifice on otherwise flat coastal plains (Fig. 3a). Almost a couple of meters above the toe of the cliff, but at the contact between the carbonaceous clay and superjacent ferruginous sandstone, there is a cluster of springs, the discharge forming rivulets flowing across the beach to join the Arabian Sea (Fig. 3b). These rivulets swing their flow direction based on the tidal influence. The citadel-like morphology of the cliffs in other parts of the world has provided advantageous for construction for forts and palace (Mascarenhas, 2006), like the Bekal Fort in the north of Kerala. This cliff is at the intersection of the fluvial and marine processes driven by tectonic forces, which has led to the landward retreat of the cliff between 10 and 40 m, over a 100-year interval (1915–2015) (Sajinkumar, Kannan, Indu, Muraleedharan, & Rani, 2017). The retreat was highest during the last three decades, the time-span when prolific tourism activities were at the zenith along the cliff.

Kappil lagoon, a scenic backwater at the confluence of Ayiroor River with the Arabian Sea, located a short distance north of Varkala, has potential for facilitating recreational water sport. The several islands in the lagoon (e.g., the verdant Golden Island)

Fig. 3. (a) A view of the Varkala cliff, depicting the morphology. (b) A rivulet, originating from the springs, find its way to the Arabian Sea, within a few meters of its origin. (c) Kappil backwater, formed by Ayiroor River, and its estuary (estuary shown by arrow) can be seen along the long beaches of Kappil. (d) Amber in carbonaceous clay. (e) The older Quilon and the younger Warkalli Formation as seen in the cliffs at Pozhikkara. (f) Fossiliferous limestone of Quilon Formation. (g) Springs spouting from the cliff at the contact between overlying sandstone and underlying carbonaceous clay. (h) Big boulder of laterite, dislodged from the top layer, resting in the beach. (i) Beach placers in Black Beach. (j) Jarosite, depicting efflorescence texture, formed as diagenetic replacement process in lignite/peat rich layer.

are home to a vibrant ecosystem composed of a variety of flora and fauna. A spit, separating Kappil lagoon or backwater from the Arabian Sea, often gets breached during the southwest monsoon season (Fig. 3c).

2.5. A storehouse of fossils

The Varkala cliff section yielded several microfossils and ichnofossils (caused by bioturbation), apart from plentiful amber (Fig. 3d). The carbonaceous clay beds, and lenses and laminae of peat have yielded a well-preserved bounty of palynoflora (Kumaran, Soman, Kamble, & Joseph, 1995), including pteridophytic spores, fungal remains and angiospermous pollens (Ramanujam, 1987). The fossil assemblage represents a blend of ecological niches such as lowland, fresh water and sandy beach. The recognition of salt glands signifies that the palynoflora has affinity with mangrove swamp/coastal vegetation. The relative abundance of fungal remains is indicative of an environment of high organic input, a warm, humid climate with heavy rainfall at the time of deposition. Based on several palyno-samples and Coexistence Approach, Kern, Harzhauser, Reuter, Kroh, and Piller (2013) reconstructed the paleo-climate, which indicated a temperature regime much similar to the present day condition but with a contrasting precipitation pattern. Unlike what exists today, Kern et al. (2013) proposed the preponderance of tropical climate both along the western and eastern coast of Peninsular India. Occurrence of *Skolithos linearis* and *Planolite beverleyensis*, two ichnofossils, indicates that the sediments were deposited in shallow water near-shore marine environment with moderate to high energy conditions (Mude, Sarkar, Ukey, & Jagtap, 2012; Verma & Singh, 2018). The carbonaceous sediments of this formation hold the potential to generate gaseous hydrocarbons (Mathews, Singh, & Singh, 2018).

Another potential site for fossil hunting is the Pozhikkara sea cliff section (8°48′21.68″N, 76°39′12.22″E) (Fig. 3e), a geologically well-known site where a cliff face exposes both the older Quilon and younger Warkalli Formation. It is in close proximity to Varkala Cliffs (13 km north). Quilon Formation is characterized by thin beds of fossiliferous limestone rich in foraminifers, gastropods, bivalves, corals, echinoids, crabs, ostracods, bryozoans, sperulids and shark teeth, which were widely used for paleobiogeographic reconstructions and stratigraphic correlations (Briguglio, Ćorić, & Rögl, 2018; Harzhauser et al., 2007, 2009) (Fig. 3f). Chattopadhyay, Kella, and Chattopadhyay (2020) reported microbivalve, which were considered the adult stages of the small-sized organism. Reuter et al. (2011) reported seagrass from Quilon limestone, which is a prolific angiosperm in the present day Indo-Pacific Ocean (Hoeksema, 2007). Seagrass evolved during late Cretaceous in the erstwhile Tethys (Ivany, Portell, & Jones, 1990), which is an ideal place for carbonate production (Reuter et al., 2011). Hence, seagrass from Quilon formation can be an analog to reconstruct the Tethys ecosystem.

2.6. Varkala Cliff as host for free-falling springs

Groundwater occurs under confined conditions in Warkalli Formation where sandstone and grit, capped by thick laterite, overlying the carbonaceous clay acts as aquifers while the latter is an impermeable zone. As the sedimentary basin extends towards sea, submarine discharge is common along the coastal stretches, but contrary effects are seen in Varkala (Unnikrishnan, Srinicas, Ramaswamy, & Suresh Babu, 2021). Groundwater spouting as clusters of free-falling springs are noticed at more than one location in the cliff face section (Maya, Das, Sreelash, & Narendra Babu, 2018) (Fig. 3g). The horizontal attitude of the lithounits resulted in the formation of a set of perennial springs along the lower foot of the cliff face. These springs are the ones that have the highest yield as compared to the other springs seen in the khondalite belt with a cumulative discharge of 2023.2 million liters per day with noticeable changes during pre-, post- and monsoon seasons (Maya et al., 2018). The spring waters of the Varkala cliffs are revered and highly reputed for their medicinal properties. The acidic nature (4.77 to 4.88 pH) (Maya et al., 2018) of the water, due to the addition of dissolved ions supplied by oxidation could be the reason why it is considered as of medicinal value. Dissolved load in the waters makes this spring water potable.

2.7. A field laboratory of lateritization

The soft and friable arenaceous rocks and plastic clay lenses of Warkalli Formation are capped by hard ferruginous laterite (Fig. 3h), which is formed during the second lateritization phase in Kerala (post-Warkalli). Laterites capping the Warkalli sediments are formed under subaerial conditions. Varkala and their equivalents in other parts of the west coast are perhaps the only examples in India where laterites have been derived from a suite of arenaceous and argillaceous rocks. Lateritisation is a process following the Law of Equifinality, in that irrespective of the nature of parent clastic sediment or hard crystalline rock, the end product of chemical weathering under a tropical climate with alternating spells of wet and dry seasons is laterite (Gunnell & Fleitout, 1998).

2.8. Embodiment of heavy minerals (beach placers)

The beach sand of Varkala qualifies as black sand placer deposit, as it is enriched in ilmenite, rutile, zircon, monazite, sillimanite and garnet. Rejith, Sundararajan, Gnanappazham, and Loveson (2020) reported a total heavy minerals content of 52.33%. The black beach (Fig. 3i), which marks the northern end of the North Cliff, derived its name from the abundance of these placers. Though not mined, the area remains an enclave for geoscientists to study one or the other aspects of the deposit. The provenance of this assemblage is the charnockite and khondalite suites of rocks, as well as the laterites, from which the detritus was brought to the sea as river sediment load and later concentrated by marine action. Monazite is the radioactive mineral in these sediments, of 0.1–0.3% uranium and 5–7% thorium (Divya, Kaliprasad, Narayana, & Prakash, 2019), although Kulkarni, Pillai, and Ganguly (1974) reported higher concentration of these radioactive elements in the beach placers of Kerala. Divya et al. (2019) reported that the significantly higher activity of ^{232}Th present in monazite, which could have adverse effects on the inhabitants of the region. Jayaprakash, Sajeev, and Kumar (2016) identified high concentration of rare earth elements (REE) in the sediments off the coast of this region and attributed it to the beach placers.

Fig. 4. (a) TS canal in a dilapidated condition due to siltation, dumping of waste and growth of weeds. (b) Sivagiri Mutt, abode of the social reformer and sage Sree Narayana Guru. (c) Janardhana Swamy Temple in Varkala, which is considered as Benares of the south. (d) Anchuthengu Fort, the East India Company's first factory and fort. (e) Center for Performing Arts, a space for performing art forms. (f) Naturopathic treatment that uses natural remedies to help the body heal itself. (g) Traditional way of fishing by the inhabitants along the coast of Varkala. (h) Lighthouse resting on the charnockite country rock of Kovalam.

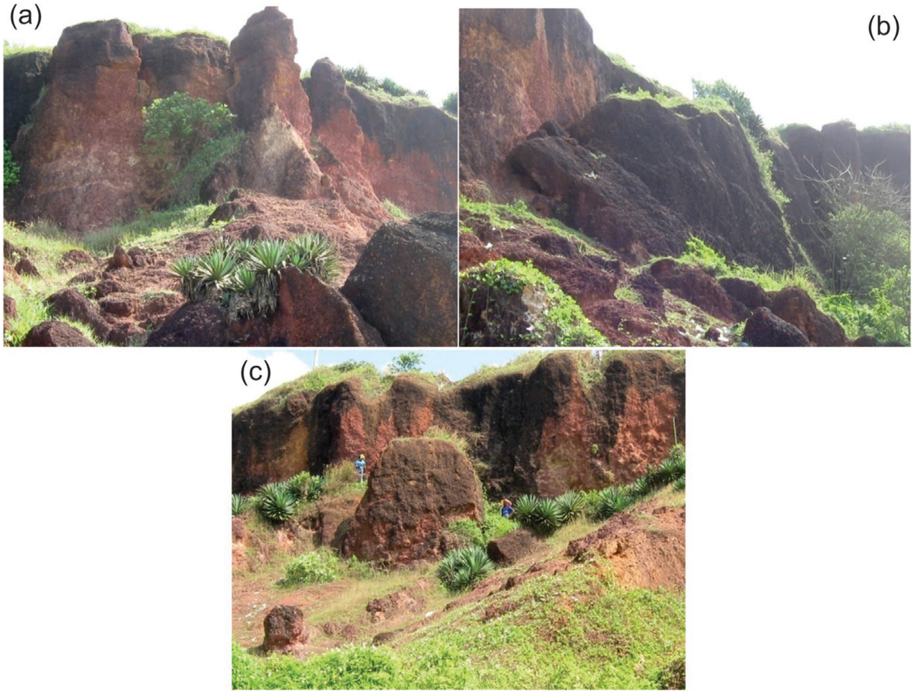

Fig. 5. Landward retreat of coastal cliffs in the form of toppling (a), debris slide (b), and slump (c).

2.9. Martian analog site

Jarosite, a basic hydrous sulfate of potassium and ferric iron (Fe-III), and a key mineral indicating aqueous, acidic and oxidizing condition, occurs as encrustations in the carbonaceous clay in the cliff. Singh, Rajesh, Sajinkumar, Sajeev, and Kumar (2016) proposed that it was formed by diagenetic processes and occurred as efflorescence (Fig. 3j) on the carbonaceous cay carrying the ubiquitous sulphide mineral marcasite. After fifty years, Tassel (1965) first reported natrojarosite from this cliff section, jarosite came to occupy center stage after the report by Singh et al. (2016), in light of the current interest in Martian analogs. Jarosite has been reported from the Martian terrains like Eagle crater (Klingelhöfer et al., 2004), Meridiani planum (Squyres & Knoll, 2005), Terra Sirenum (Wray, Murchie, Squyres, Seelos, & Tornabene, 2009), Mawrth Vallis (Farrand, Glotch, Rice, Hurowitz, & Swayze, 2009) and from Terra Meridiani (Poulet et al., 2008) in association with other hydrous minerals and provides a robust piece of evidence for the presence of water on Mars in the past.

3. Noteworthy socio-cultural-historical sites within the proposed Varkala Global Geopark

Apart from the distinctive geological components of Varkala Cliff, there are several culturally and historically famed locations. The Travancore-Shoranur inland waterway or the TS canal (Fig. 4a), once an important inland water transport artery, passes through the eastern part of this area and in the past had been a strategic as well as cheap freight traffic route, connecting north-central and southern Kerala, offering logistic support to several coir, cashew and fishing industries as well as rice paddy produce. However, this inland waterway is practically unserviceable due to organic and inorganic sediment accumulation, encroachments, dumping of wastes as well as prolific growth of weeds.

The Sivagiri Mutt (Fig. 4b) is a pilgrim centre built in 1904, where the social reformer and sage Sree Narayana Guru's Samadhi (the final resting place) is located; the Janardhana Swamy Temple (Fig. 4c) is a 2000 year old temple of Lord Vishnu and is considered as the 'Banaras of the south; the Papanasham area is associated with this temple, which is a place for performing ablutions honouring ancestors and therefore a pilgrim centre is the important religious cynosures of Varkala. The erstwhile East India Company established the first factory and fort for trade in the south of Anchuthengu Fort (Fig. 4d), and this is a place of great archeological and historical importance.

Kerala has rich traditional art forms such as Kathakali, Theyyam, and Nangiarkoothu, apart from the UNESCO tagged Koodiyattom, known as masterpieces of the oral and intangible heritage of humanity. The Center for Performing Arts at Varkala (Fig. 4e) is a space for researching, learning and practicing these art forms and indeed is a sublime attraction for tourists. Naturopathy treatment is also a flourishing service industry in Varkala (Fig. 4f). Coir and fishing (Fig. 4g) industries are traditional and also forms a part of Varkala Geopark concept. The Kovalam lighthouse, resting on the rocky beach constituted by charnockites, is one of the prime tourist location, situated in the hinterland of Varkala (Fig. 4h).

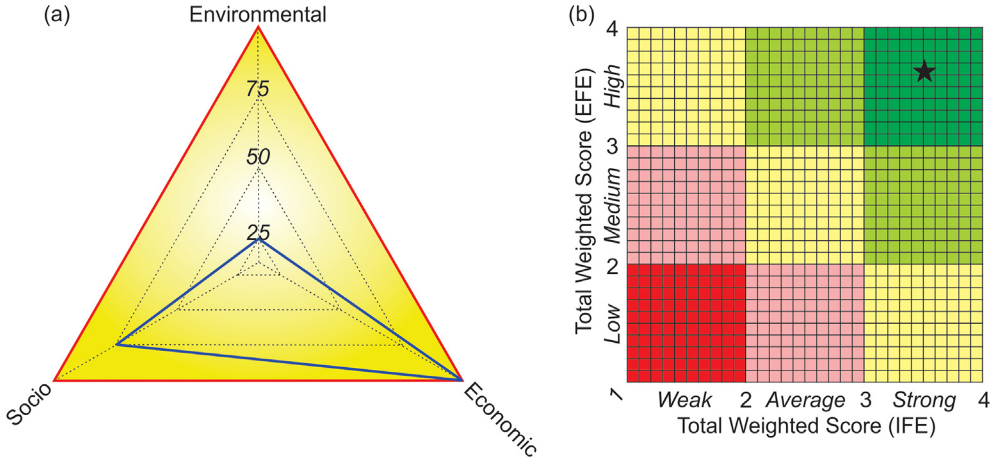

Fig. 6. (a) Changes in the socio-economic-environmental parameters of Varkala area. Red triangle indicates the initial condition and blue triangle is the current status. (b) Total weighted score of internal and external evaluation matrix indicating the potential of Varkala area as a Global Geopark.

4. Geopark, geoheritage and geodiversity prospective: A discussion

The concepts of geopark, geoheritage and geodiversity have been impregnated in the minds of geoscientists owing to the necessity of conserving geologically important sites for the posterity. The quintessential concept of all these are to impart educational, aesthetic and cultural value (Brilha, 2016). Another uniqueness of these concepts is incorporation of socio-cultural-historical components with the participation of local community. These concepts have also found acceptance in developing countries like India of late as most of the geologically important locations are under peril due to mining and other anthropogenic activities. Thus, the inventorying of the available georecords of such important locations through the concepts of geopark, geoheritage and geodiversity will serve as a blue print for the future geoscientist (Brilha, 2016). Thus, through this work we aim at creating an inventory of one of the perishing but interesting geological sites at Varkala in the southwestern Indian coast. Along with the plethora of geological and cultural highlights of Varkala area, mention should be made of several distressing factors. One such is the landsliding all along the cliffs, occurring round the year, irrespective of climatic conditions. Fall/toppling, debris slide and slump (Fig. 5a-c) are the common forms of landslides seen in this area. Fall and toppling are initiated by tension cracks (Sajinkumar et al., 2017). The cliff-edge-parallel lengthy tension cracks are noticed extensively on the surface of the laterite cap, facilitating percolation of water during the monsoon season, which over a period of time destabilizes the near vertically standing massive geometric columns of laterite forcing it to rotate at the basal contact, often leading to toppling. Therefore, the laterite caps are the most prone to fall and topple. The detached lateritic boulders are seen strewn all along the slope of the cliff face and at places these often deflect erosional energy like a sea wall (Sajinkumar et al., 2017). The spatio-temporal changes of coastline over a period of 100 years (Sajinkumar et al., 2017) shows a landward retreat of the cliff line by 10–40 m, with prominent changes after 1990. This lateral retreat exemplifies the fast retreat of this coastal cliff. Arulbalaji, Banerji, Maya, and Padmalal (2021) attributes the high rate of recession to the low shearing of clay beds, usually seen at the base of the cliff.

Based on the Coastal Regulation Zone (CRZ) (1991) notification issued by the Government of India and also on the basis of the Supreme Court of India judgment in 1994, the Government of Kerala prepared the *Coastal Zone Management Plan* (Ramachandran, Enserink, & Balchand, 2005). As per this plan, the area from high tide level (HTL) to 500 m inland is classified as CRZ. The CRZ rules say that 'the area up to 200 m from the HTL is to be earmarked as '*No Development Zone*'. No construction shall be permitted within this zone except for repairs of existing authorized structures not exceeding Floor Space Index (FSI), existing plinth area and existing density and for permissible activities under the notification including facilities essential for such activities.

Strict implementation of the CRZ rules will reduce the human pressure on the cliff. Being an important tourist destination, with the cliff and the pocket beaches being the center of attraction, the tourist influx is increasing yearly (Rajan, 2011). Construction activities in the form of resorts, restaurants and other shops have encroached up to the brim of the cliff. Vehicular movement along the edge of the cliff and parking of vehicle in the helipad on the cliff top has added to the vulnerability of this cliff. Littering of the area, especially with plastic, is a real threat to the aesthetic appeal of the cliff.

Furthermore, Rajan, Varghese, and Pradeepkumar (2013) have emphasized the need for strict monitoring of tourism development and associated policy implementation based on the carrying capacity of Varkala, as a management practice to conserve the heritage of this area. Sundar and Murali (2007) have suggested 2 m high gabion structures to protect the cliff from high-energy waves. Hard engineering practices like constructing gabions did not get acceptance as such structures usually hinder beach tourism activities. Though newer, underwater structures for creating wider beaches like those adopted for the Pondicherry beach, could be tried in Varkala (Misra & Ramakrishnan, 2020). Saluja and Anand (2017) have stressed the land use/land cover changes for 15 years and could identify drastic changes, and this could have deteriorated the stability of Varkala cliffs.

Table 3
Strengths and weaknesses of internal factor evaluation matrix (IFEM).

Item	Weight	Score	Weighted score
Presence of culturally significant sites near the geosite locations (Aesthetic and historical value)	0.2	4	0.8
Adventure sports activity, such as paragliding	0.1	4	0.4
Presence of already existing infrastructure like well-established transport network, banks, ATMs, Hospitals, means of communication, boarding and lodging (Infrastructural values)	0.2	3	0.6
Opportunity to understand the local culture due to the sites being very culturally unique.	0.1	3	0.3
Lack of government-imposed laws in favor of conservation and protection of geosites	0.05	4	0.4
Lack of awareness among locals about the geological significance	0.1	2	0.4
Lack of participation of local governing bodies in the protection of geologically significant sites	0.1	3	0.3
Lack of information in tourist information centers about geological and cultural significance	0.05	3	0.15
Lack of awareness on the economic opportunities created by geotourism	0.1	2	0.2
Total	1		3.55

Hence a socio-economic-environmental and a qualitative analysis were performed to understand the current status of Varkala area. The socio-economic-environmental parameter, which can also be considered as a 3-end member pattern for global geoparks was performed using three processes: field-survey (a biased survey of people over 50 to understand the long-term changes), literature review, expert review and authors' experience. This analysis showed that there is boom in economic activity, but the social and environmental parameters of Varkala have plummeted (Fig. 6a). The enhancement of economic activities is due to the increased tourism, but at the cost of traditional coir and fishing activities. The major social change is the migration of the younger generation to middle-east countries in search of higher-wage jobs. The biggest alteration was in the environmental scenario of the cliff. Fishermen have reported the presence of huge boulders of laterite about 100 m off the present day coastline, which used to be hotspots of fishing for mussels, crab, and other crustaceans. These huge boulders can be either a marine transported one or evidence for the former position of the cliff. The authors favor the second option as this has been suggested by the studies of Sajinkumar et al. (2017), where a cliff retreat of 10–40 m was mentioned for a century timeline.

For the qualitative analysis of the proposed sites, the methodology adopted by Reynard, Perret, Bussard, Grangier, and Martin (2016) was used. The strength, weakness, opportunity, and threat (SWOT) analysis is performed to assess the geo-touristic and cultural importance of the sites. The tourism sector routinely uses SWOT analysis as a base for development plans in a region (Narayan, 2000; Reihanian, Mahmood, Kahrom, & Hin, 2012; Zhang, 2012). It is also being used to develop geosites as potential tourist destinations across the world (Antić & Tomić, 2017; Chavan et al., 2022; Kalantari, Bazdar, & Ghezelbash, 2011). The strengths and the weaknesses are listed along with the opportunities to take advantage of the strengths of a particular site and to mitigate threats using the weaknesses. The strengths and the weaknesses (Table 3) belong to the internal factor evaluation matrix (IFEM), and the opportunities and threats fall under the external factor evaluation matrix (EFEM) (Table 4). Both the matrices must have a total weighted score (TWS) greater than 2.5. This is indicative of the strengths and opportunities that outweigh the weaknesses and threats. To calculate the TWS, the stakeholder's weight is used, which ranges from 0 (least significant) to 1 (very significant). The scores allotted range from 1 to 4 (1-poor, 2-average, 3-good, 4-excellent). The stakeholder's weight is multiplied by the score resulting in the weighted score. The weighted score, when summed up for each matrix, results in the TWS. The TWS for both the matrices is graphically represented in Fig. 6b to review the viability of the sites as a potential tourist destination.

The authors also strongly believe that the concept of geopark, geoheritage and geodiversity forms at least one realm of the Sustainable Development Goals (SDG) of the Agenda 2030 of the United Nations (UN). The goal 11, sustainable cities and communities, and goal 17, partnerships for the goals, best fits to the realm of SDGs. With the involvement of local people and through the partnership of stakeholders, the concept of geopark encompasses these two SDGs.

Table 4
Opportunities and threats of external factor evaluation matrix (EFEM).

Items	Weight	Score	Weighted score
Showcase of culture through tourism such as traditional fishing practices	0.1	4	0.8
Economic opportunities for the locals by selling traditional food products, showcasing traditional coir making and fishing	0.2	4	0.8
Expanding existing and establishing new ayurvedic and naturopathic hospitals and resorts	0.1	3	0.3
Establishment of exhibition centers based on geological and cultural aspects to provide educational value to the visiting tourists	0.1	3	0.3
Training and implementation of locals as tour guides	0.1	2	0.2
Seasonal erosion and degradation of cliff due to lack of conserving infrastructure	0.2	3	0.6
Destruction of cliff by encroachment by resort owners and unscientific building activity.	0.1	3	0.3
Pollution by local tourists	0.1	3	0.3
Total	1		3.6

5. Summary

The initiative by the Geological Survey of India (GSI), during the 48th CGPB, in identifying and developing geologically important places as 'National Geoparks' has led to designating the entire coastal cliffs of Varkala as a 'National Geoheritage Site' on May 28, 2014. With a plethora of geological features, and also by showcasing the vestiges of several geological processes, Varkala has the potential and right to be made an acclaimed global location, and a member of GGN. Through this project, the authors also aim at providing awareness to the public regarding the importance of this cliff, popularizing the subject of geology, the necessity for scientific deliberations, promoting geotourism activities, avoiding anthropogenic interference and finally, to protect the cliff itself for posterity. The inclusion of this area in the UNESCO GGN list will increase the footfall of tourists who would like to combine appreciation of the workings of nature and earth, with a relaxed vacation in the laid back ambience of a quiet beach tourism destination. This could promote quality tourism, where nature is valued and there would be an increased awareness among the stakeholders on preserving the cliffs in as pristine a form as possible. The traditional artisanal fishing and coir industries could also benefit from such responsible tourism and become part of the geopark as the concept of geopark encompasses the sustenance and thriving of local livelihood endeavors too. And hence this also forms a part of the SDG of Agenda 2030 of UN.

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Ethical approval

The data employed in this work is accessible to the public upon request and therefore ethical approval is not required. This paper is not being submitted to any other journal at the same time.

Declaration of Competing Interest

The authors declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service, and/or company that could be construed as influencing the position presented in, or the review.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijgeop.2022.05.003.

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