



Geosite Recognition Based on Qualitative-Quantitative Assessment in the Light of Core Geological Features of a Mio-Pliocene Volcanic Arc Setting of the Coromandel Peninsula, New Zealand

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Abstract

The far north part of Coromandel Peninsula can be considered a good place for geoeducation and geotourism, which is justified by the remnants of Miocene-Pleistocene volcanic integration with marine environment. These processes in collaboration with old Jurassic and quaternary sediments create a diverse geological and geomorphological constructions forming the abiotic environment of areas surrounding Port Jackson and Fletcher Bay. These two locations have been chosen as two main campsites of the north Coromandel Peninsula, which are maintained by the Department of Conservation (DOC) of Coromandel Peninsula. Hence, the campsites should be considered as main places for camping for the trips of different purposes. They provide an access coastal way and/or trails leading to the main geologically important locations presenting some knowable features like Pinnacles and Sugar Loaf spread through the region. To highlight these locations of interests, “geosites,” we developed qualitative-quantitative assessment of geodiversity for geosite recognition based on 8-m DEM and 1:1250,000 scale geological map and QGIS (3.28 “Firenze”) software. The methodology utilizing 8-point evaluation system applied for geological formations of the studied region and its multiplication with morphological slope degree. The result of assessment has been expanded and justified with geological, cultural, and geomorphological database acquired from literature review and direct field trips of the studied areas. The conclusion demonstrates the main geological knowledge of recognized geosites together with description of drawbacks and possible obstacles for tourism and education in the region of the northern Coromandel Peninsula.

Keywords Geodiversity · Geotourism · Geoeducation · Geosite · GIS modeling · Coromandel Peninsula · QQG assessment

Introduction

Geosite is a term used to define specific locations, often on the basis of geodiversity, which may demonstrate information about formation of abiotic nature in the area of research (Brilha 2016, 2018; Gordon et al. 2018; Gray 2018). Recognition of geosites is the first step in several types of research on topics like geoeducation, geotourism, and geoconservation. However, recognition of geosites requires field observations describing geological formations and structural elements interlinked with landforms and landscape features. This may lead to critical issues related to the size of research areas, commonly viewed as the scale problem (Zwoliński et al. 2018; Zakharovskiy and Németh 2021b; a; Zakharovskiy and Németh 2022b). Geodiversity is a description of all abiotic nature and may describe a number of different elements like geological, geomorphological, hydrological, biological and human footprints

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(Gray 2004, 2005, 2008; Zakharovskiy et al. 2022). This term has been refined for the last 40 years as an analogy to biodiversity. Currently, it is seen as important within the scientific community and relevant to conservation strategies. Additionally, geodiversity forms one of the scientific pillars to establishment of geoparks under the recognizable global brand of United Nations Educational, Scientific and Cultural Organization (UNESCO). According to UNESCO definition: geopark is location of protection of geological heritage with unique geological significance, visual attractiveness, and knowledge of geological history (Patzak and Eder 1998). The first criteria for proposition of UNESCO Global Geopark is unified geological area with significant sites and/or landscape suitable for main purposes of geopark: protection, education, and economic development (Henriques and Brilha 2017). Hence, recognition and description of specific geological locations is the first step for proposition of geopark. To solve this issue, several methodologies have been developed for geodiversity assessments and geosite recognition. The most recognized method for describing geodiversity is applying systematic literature reviews to geoheritage values (Gordon and Barron 2013; Gray 2013), geological and geomorphological mapping (Pereira et al. 2013; Najwer et al. 2023), and direct field observations of specific geological and geomorphological features. In our research we demonstrate the strength of combining these three ways, based on modeling utilizing Geographical Information Systems (GIS), literature review and direct field observation based on territory of the north part of Coromandel Peninsula.

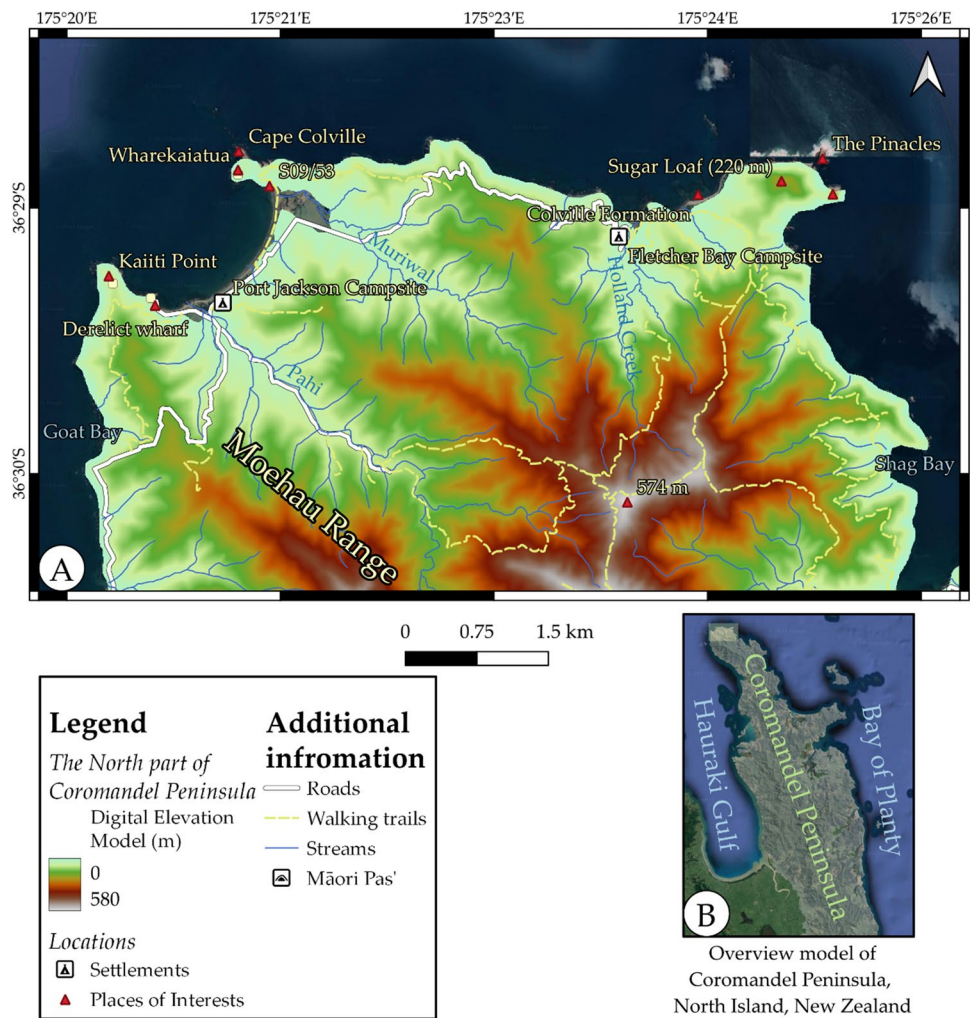
Qualitative-quantitative assessment of geodiversity (QQG) has been proposed in previous research as a specific tool for quick recognition of potential geosites (Zakharovskiy and Németh 2021b; a; Zakharovskiy et al. 2023), based on the range of abiotic elements and their evaluation system mainly concentrated on global parameters for geological and geomorphological elements (rock rareness and slope angle respectively). In our current research this methodology is utilized to minimize the area of geosite search, utilizing general database provided by open access 1:250,000 scale New Zealand Geological Map (Q-Map Series - <https://www.gns.cri.nz/data-and-resources/geological-map-of-new-zealand/> - accessed on 23 May 2023) and a digital elevation model (DEM) downloaded from Land Information New Zealand (LINZ) (<https://data.linz.govt.nz/layer/51768-nz-8m-digital-elevation-model-2012/> - accessed on 23 May 2023). QQG assessment is not able to recognize geosites by itself due to limitation of information, which can be included into methodology, but it is a good tool to minimize area of the search for next field observation, description, and confirmation of recognized sites. In our view, GIS calculation is a tool which helping researcher to concentrate on some specific locations

for their description, then scientific literature reviews and discussion with other researchers must be occurred to claim statues of geosite. Hence, several potential geosites have been studied in period of 2021-2022 with their description. Then, additional data have been extracted form scientific literature reviews of the north part of Coromandel Peninsula. All these information has been utilized for description of each geosite occurred in the studied area. The description of geosites have been made for students and tourists interested in understanding of geological processes which formed the north part of the Coromandel Peninsula.

The territory of research is the northern region of the Coromandel Peninsula in the North Island of New Zealand. This region has several geosites with important features for education and tourism spread throughout the Peninsula. Our research will concentrate on describing two specific locations: Port Jackson and Fletcher Bay (Fig. 1) as these areas demonstrate a variety of geomorphological data, including superb coastal exposures combined with an esthetically pleasing rolling hill country within the land-mass. In addition, geological features in the region are associated with attractive phenomena of volcanism known to act as a magnet for tourism. The region represents a graphic example of the interaction of Miocene intermediate volcanism with shallow marine and coastal terrestrial sedimentation. Fletcher Bay contains information about interactions between Miocene volcanism and marine sedimentations, while Port Jackson represented by the remnant of Miocene andesite volcanic rock formations clearly visible at the north-western Coromandel Peninsula. The result of our research is a description of geosites in Port Jackson and Fletcher Bay to evaluate the interest for this area for geotourism and geoeducation. Geotourism is natural area tourism oriented toward geology and landscape, which also promotes learning and conservation (Newsome and Dowling 2010), while geoeducation is primary tool to introduce knowledge about geological environment (Farsani et al. 2011). Both terms are highly connected as geotourism promotes geoeducation for public increasing their awareness about geology and provide recreational activities (Hose 2012).

The aim of our research is to describe potential geosites, which have been recognized through qualitative-quantitative assessment of geodiversity, direct field observations occurred in 2021-2022 in the Coromandel Peninsula, and literature reviews. Additional goal of this manuscript is to provide guidance for travelers interested in geological formations and scenic views. Establishing potential geotrail routes for walking or driving may provide geoeducational and geotouristic benefits to visitors and residents, thereby providing a holistic overview of the natural and geological environment of the north part of Coromandel Peninsula.

Fig. 1 **A** Overview of the northern region of the Coromandel Peninsula. The elevation model made from 8-m DEM based on topographic map of Coromandel Peninsula (<https://data.linz.govt.nz/layer/51768-nz-8m-digital-elevation-model-2012/> - accessed on 26 May 2023). All additional information also have been downloaded from Land Information New Zealand (LINZ) (<https://data.linz.govt.nz/layer/53382-nz-roads-addressing/> - roads; <https://data.linz.govt.nz/layer/52100-nz-walking-and-biking-tracks/> - walking trails; <https://data.linz.govt.nz/layer/50327-nz-river-centrelines-topo-150k/> - streams; <https://data.linz.govt.nz/layer/50308-nz-pa-points-topo-150k/> - Māori Pas'; - accessed on 26 May 2023). Settlements and Places of Interests have been extracted from Topographic map of New Zealand (<https://data.linz.govt.nz/layer/50767-nz-topo50-maps/> - accessed on 26 May 2023). **B** Overview model of Coromandel Peninsula made from Google satellite image (<https://earth.google.com/web/@-36.89331954,175.6870617,17.28715125a,158313.05788441d,35y,0.00000355h,0.09968113t,0r> - accessed on 26 May 2023)



State of Art of Knowledge of Abiotic Nature in the Northern Coromandel Peninsula

Geodiversity, Geosite, and Geoheritage Context

Our research will describe geological locations in the northern region of Coromandel Peninsula, which will be defined as geosites. By defining them as geosites we connect the term together with geodiversity and geoheritage. Geodiversity is a broad definition applied to abiotic nature and within the environment, in contrast to biodiversity which describes flora, fauna, and other biotic factors. The definition includes sequences of elements grouped under two broad categories: main and additional (Zakharovskiy et al. 2022). Main values include geological and geomorphological elements, which are describing parameters and forms of rock formations. Additional values include other abiotic elements which are influencing the main ones' (geology and geomorphology) such as: climate, hydrology, solar and cosmic energies, tectonics, biological and anthropological footprints, and soils. Assessing geodiversity allows researchers to select specific

locations which may be defined as geosites. These locations will demonstrate abiotic processes and may contain a record of specific geological processes and associated deposits and formations. Historical significance, and value for research and education is recognized through geoheritage values applied to the geosite. In our research we concentrate on recognizing and describing geosite locations, which we will describe in a geotouristic and geoeducational context.

Fletcher Bay

The research area for this assessment concentrated on two known Department of Conservation (DOC) camp sites (Port Jackson campsite – <https://www.doc.govt.nz/parks-and-recreation/places-to-go/coromandel/places/northern-coromandel/things-to-do/port-jackson-campsite/> - accessed on 23 May 2023) (Fletcher Bay campsite <https://www.doc.govt.nz/parks-and-recreation/places-to-go/coromandel/places/northern-coromandel/things-to-do/fletcher-bay-campsite/> - accessed on 23 May 2023) and their surrounding territory on the north Coromandel Peninsula: Port Jackson and

Fletcher Bay (Figs. 1-A and 2). Fletcher Bay is one of the furthest north points accessible by road, reached by a 36.6 km long (around an hour) unsealed road suitable only for 4WD vehicles from the nearest town Colville. It include a public camp-site, and house with basic facilities owned by DOC (<https://www.doc.govt.nz/news/media-releases/2021-media-releases/access-improvements-at-fletcher-bay-campsite/> - accessed on 3 Feb 2024), which can be rented by visitors (Fletcher Bay campsite <https://www.doc.govt.nz/parks-and-recreation/places-to-go/coromandel/places/northern-coromandel/things-to-do/fletcher-bay-campsite/> - accessed on 23 May 2023). A search through scientific data bases like Google Scholar (<https://scholar.google.com/> - accessed on

23 May 2023) and Web of Science (<https://access.clarivate.com> - accessed on 23 May 2023) provide only few articles considering the geological context of Fletcher Bay. Firstly, we consider the most important published research “Colville Formation-A new formation possibly correlative with the Waitemata Group” written by Skinner (1969) (Skinner 1969). This geological study describes Colville Formation (Fig. 1-A) (Tertiary sedimentary rocks) and its correlation with Waitemata of the Auckland Region. Moore and Wallace (2000) describe petrified wood in Miocene volcanic sequences of the Coromandel Peninsula and describe samples from the intermediate volcanoclastic successions exposed in the coastal cliffs of Fletcher Bay (Moore and Wallace 2000).

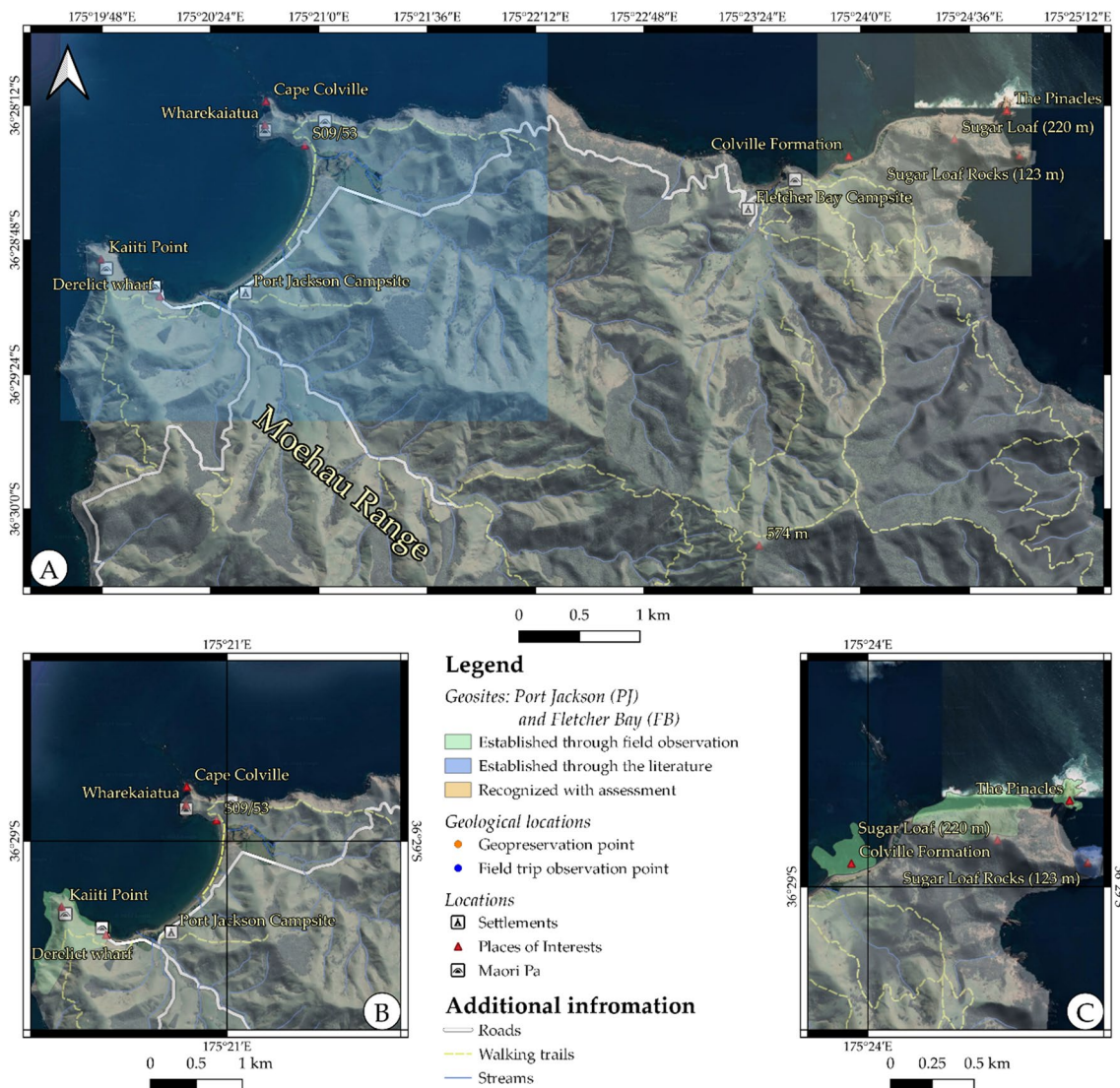


Fig. 2 A The overview model of the north part of the Coromandel Peninsula with geosites. B Geosites on territory of Port Jackson. C Geosites on territory of Fletcher Bay. Google satellite image (<https://earth.google.com/web/@-36.49800348,175.36638491,154.44934497a,13878.7123792d,35y,0.00000365h,0.09747609t,-0r> - accessed

26 May 2023) has been used as background. Geosites are based on results of assessment of QQG for territories of Port Jackson (Fig. 3) and Fletcher Bay (Fig. 5), and then assessed with Google Satellite imagery to highlight vegetation-free areas

Port Charles Andesite (Sugar Loaf Rock, and Sugar Loaf rocks) (Fig. 1-A) consists of intermediate coherent and clastic volcanic rocks that are inferred to be the remnant of Miocene stratovolcanoes. The petrified wood has been captured in volcanic breccia of hot pyroclastic flows and some laharc successions. In addition, these volcanics are known to be the oldest volcanic unit through the entire Coromandel Peninsula, hence it represents the onset of the arc volcanism of the Miocene volcanic arc of New Zealand (Ballance et al. 1982; Ballance et al. 1985; Hochstein and Ballance 1993; Hayward et al. 2001). “K-Ar ages of early Miocene arc-type volcanoes in northern New Zealand” published by Hayward et al. (2001) concentrate on the late Cenozoic eruption history of the Northland Volcanic Arc (Hayward et al. 2001), where Fletcher Bay is noted only for the presence of basaltic cobbles. Four other researchers have focused on andesite volcanological formations exposed on the north-east side from Fletcher Bay nearby the exposures of the Colville Formation (Fig. 1-A). Once more Fletcher Bay has been mentioned in the description of the Waitemata Group of Auckland by Benson (1976) (Ballance 1976), where the Colville Formation is described as a distal, fine-grained, and thin bedded flysch of the Waitemata Group. Finally, the territory of Fletcher Bay has also been referenced in research into the Moa bird and its habitat areas in Auckland and the Coromandel Peninsula regions (Gill et al. 2020). Hence, Fletcher Bay contains some scientific information, providing specific details to a range of disciplines studied in the region. However, it is notable for a lack of general geological or environmental descriptions in the context of geoheritage or geodiversity.

Port Jackson

Port Jackson has been subject to more research on a variety of scientific subjects. This research has not necessarily concentrated on Port Jackson as an area, but rather focused on specific subjects, which happen to be related to this location. The most popular topics of research we have observed relate to archeology, flora, fauna, and geology. The earliest recorded archeological excavation is S09/53 (Fig. 1-A), which has been described as a location of preserved fossils of shellfish, fish, birds, and marine mammals (Smith and James-Lee 2010). Evidence of past flora and fauna (James-Lee 2015) such as New Zealand moa (e.g., *Dinornis robustus* and *Dinornis novaeseelandiae*) (e.g., *Dinornis robustus* and *Dinornis novaeseelandiae*) (Gill et al. 2020; Gill 2022), remnant of leeches' populations (*Richardsonianus*) (Burreson 2020), New Zealand kākā (*Nestor meridionalis*) (Davidson 2018), lands nails (Brook 2000) have provided dating constraints and proof of earlier habitats. Additionally archeological sites have provided evidence of human use of bone resources for producing implements such as fish-hooks (Furey 1990). Then, some publications also mention this place as a point

of transportation of Kauri (*Agathis australis*) timber before early 1900, until kauri-logging became unsustainable due to poor management and over-exploitation of resources (Boswijk 2010). Port Jackson is noted as an observation location for research into native lizard habitats in the northern region of the Coromandel Peninsula (Towns 1971, 1972; Benson 1976; Woolley et al. 2022). The research we have noted demonstrates the high scientific value of Port Jackson; however existing research is heavily weighted to biotic nature of this area. Research outputs on abiotic elements of the region such as geology and geomorphology are relatively rare. Of particular significance, published research by Skinner (1975) described the Moehau Range (Fig. 1-A) (Skinner 1975), which includes andesite and dacite plugs and dikes. This led to formatting the rock assemblages formally grouped into the Kaiti Porphyrites lithostratigraphy unit and the granodiorite and quartz-diorite of the Paritu Plutonics informally described as the “Coromandel Granite.” In addition to focusing on the intrusive rocks, he has also described the Kaiti Point (Fig. 1-A) – Miocene Andesite Formation (Fig. 3) occupying the region just east of Port Jackson. Distribution of eruptive products of the 1314 AD (± 12 years) has been researched by Hogg et al. (2003) and Sahetapy-Engel et al. (2014) (Hogg et al. 2003; Sahetapy-Engel et al. 2014) This research has described accumulated tephra horizons from the Kaharoa volcanic eruption found in the Bay of Islands, the Coromandel Peninsula, eastern Bay of Plenty and northern Hawke's Bay. Tephra identified in Port Jackson's dunes is most likely from the last eruption of the Kaharoa series (Furey et al. 2008). Finally, in a geoheritage context, we note research describing distributions of Lead-Zinc-Copper-Silver-Gold mineral deposits in the Hauraki region extending from Port Jackson to Te Aroha (has not been demonstrated on Fig. 1 as located out of the studied region) (Brathwaite and Rabone 1985). In summary, the Port Jackson region has been subject to extensive scientific research describing geological and archeological aspects of the area, which has importance for promoting geoeducation and geotourism perspectives.

Geomorphology and Geology of the North Part of Coromandel Peninsula

The study area for our research on the Coromandel Peninsula is all the territory to the north of Goat Bay on the west coast to Shag Bay (Fig. 1-A) on the east coast, featuring mainly gradual hills mostly of a north-western orientation known as Moehau Range (Fig. 1-A). All of them have been shaped by erosion and current orography presented by Jurassic Graywacke as basement and the oldest rock found on through the Coromandel Peninsula. Geomorphologically, the elevation of the region increases from the north-west to south-west, with the highest point 574 m (Fig. 1-A) above

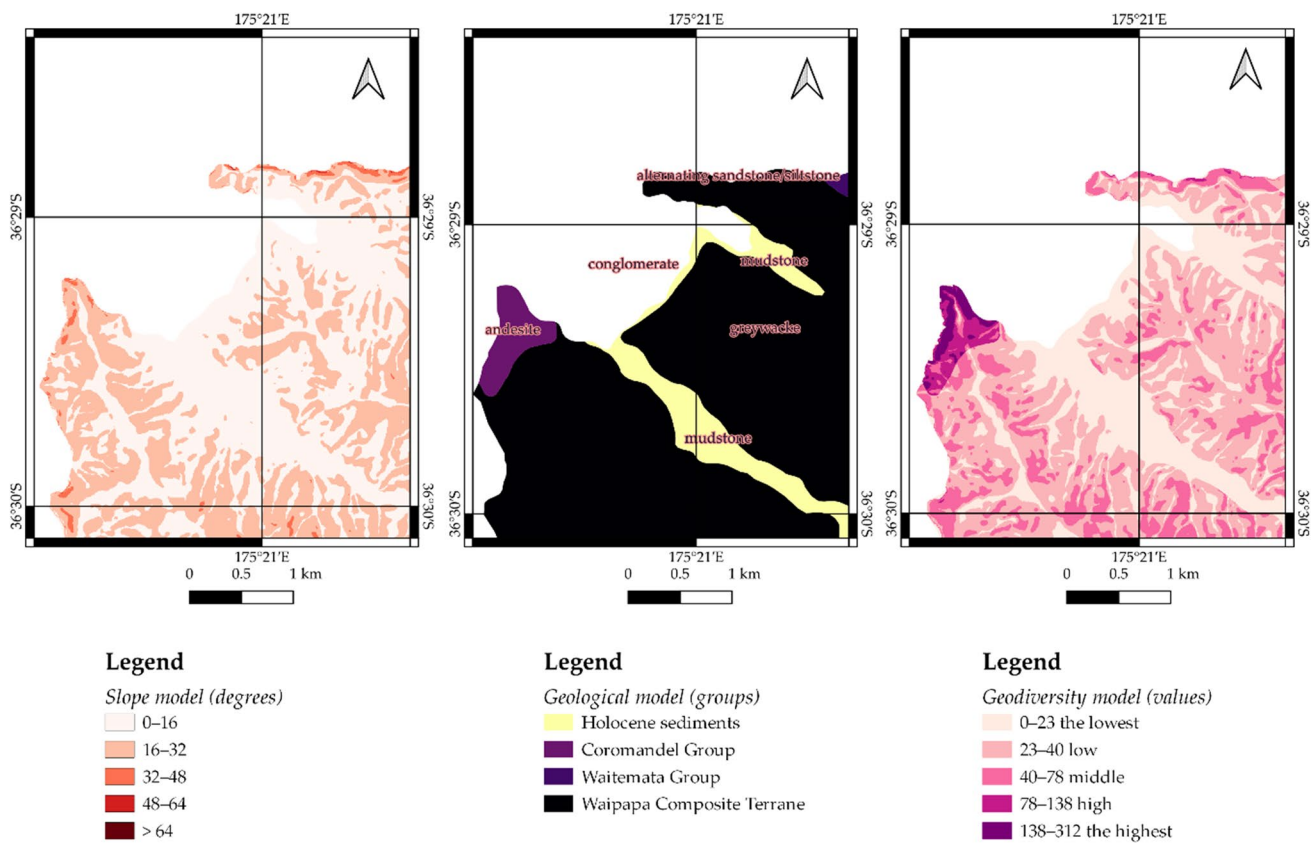


Fig. 3 Geomorphological data base on Slope model created from 8-m DEM based on topographic map of Coromandel Peninsula (<https://data.linz.govt.nz/layer/51768-nz-8m-digital-elevation-model-2012/> - accessed on 26 May 2023); Geological model based on 1 to 250,000 scale geological model of New Zealand (Q-Map Series - <https://www.gns.cri.nz/data-and-resources/geological-map-of-new-zealand/> - accessed on 23 May 2023); Geodiversity model is calculated utilizing QQG assessment for geosite recognition, where high and the highest values can be considered potential locations of interest

sea level. Greywacke hills are dissected by several streams derived from high hills all convolving into two large streams: Muriwal and Pahi (Fig. 1-A). Both streams flow toward the north-west, falling to the ocean from the north and south part of Port Jackson. A few streams originate closer to the east, and merge into Holland Creek (Fig. 1-A), flowing to Fletcher Bay, where it discharges into the ocean. Geological elements of the northern part of the Coromandel Peninsula consist of four different rock formations. The Jurassic Graywacke, which forms nearly 70 % of the surface rocks of the entire territory. Miocene andesites form two notable features: Kaiiti Point (Fig. 1-A) in the west and Sugar Loaf (Fig. 1-A) on the north-east. Both rock assemblages are important for studying of Cenozoic volcanism. Miocene marine sediments outcrop at the south-east borders of Sugar Loaf and on the northern part of the research area. Finally, some young, Quaternary sediments are observed concentrated around the streams and creeks mentioned above. Hence, geomorphological and geological settings on the north part of the Coromandel Peninsula shows sufficient variety to describe locations demonstrating enough geological values to define them as geosites.

[gns.cri.nz/data-and-resources/geological-map-of-new-zealand/](https://www.gns.cri.nz/data-and-resources/geological-map-of-new-zealand/) - accessed on 23 May 2023); Geodiversity model is calculated utilizing QQG assessment for geosite recognition, where high and the highest values can be considered potential locations of interest

Methodology

Qualitative-quantitative assessment of geodiversity (QQG) for geosite recognition is a tool to target areas for field observations to minimize the area necessary for field observations. QQG assessment is based on standard multiplication of geodiversity elements and basic geological and geomorphological data (Zakharovskiy and Németh 2021b, 2022a; Zakharovskiy and Nemeth 2023). The qualitative part of the methodology is seen in the evaluation system, which also is the main drawback of QQG. The correctness of result is always dependent on the evaluation system and its ranking, which always can be argued by other researchers. QQG methodology is an open tool, which can include as much additional information as possible, but it must be attached to appropriate location and evaluated. Another issue is inability for a tool to recognize by itself good scenic views, which we tried to solve through visibility model calculated with “viewshed” module of QGIS (Saga GIS plugin) (Fig. 12 see the “Discussion” section). Our evaluation system has been developed specifically for geological

components, based on the rareness of rocks found on the surface, based on the work of Blatt and Jones (1975) “Proportions of exposed igneous, metamorphic, and sedimentary rocks” (Blatt and Jones 1975). This framework utilizes an 8-point evaluation system, where 1-point is the most abundant type of rock and 7-points are rare in addition, the value of 8 points has been added specifically for the rarest rock types, which are distinctive from the rest with less than 1% found on the surface (Zakharovskiy and Németh 2022a; Zakharovskiy and Németh 2023). Geomorphological values can be also used for evaluation, but recent research on comparison of geomorphological models for geosite recognition demonstrates that this type of evaluation system can be avoided (Zakharovskiy and Németh 2022a). This is especially the case with low resolution Digital Elevation Models (DEM) such as Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global (<https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-shuttle-radar-topography-mission-srtm-1> - accessed on 23 May 2023). Using a 30-m spatial resolution this model is unable to accommodate steep slopes at a scale of less than 30 m. We consider slope model as one of the best data sources for qualitative-quantitative assessment of geodiversity, as it acts as a proxy for geomorphological element classification (Zakharovskiy and Németh 2022a). The quantitative framework of the assessment describes the number of geodiversity elements, which provides a more accurate description of the abiotic environment. However, the limitation of the tool requires additional field observation for recognition of specific geological and geomorphological features, which can be occurred in outcrop or scenic view. Currently, our methodology concentrates more on geology and geomorphology assessments, with an aim to find out the locations of interest, rather than provide a full description of the abiotic environment. Subsequently, our qualitative-quantitative assessment of geodiversity for geosite recognition is based on multiplication of geomorphological and geological data. Geological aspects have been previously evaluated with the 8-point system according to rock types of rareness. However, for geomorphological values and descriptions we use parameters of slope angle as a proxy.

For the assessment of the northern region of the Coromandel Peninsula, we utilized information from our earlier research on geomorphological influence for geodiversity assessment (Zakharovskiy and Németh 2022a), whereby the 1 to 250,000 scale geological model of New Zealand (Q-Map Series - <https://www.gns.cri.nz/data-and-resources/geological-map-of-new-zealand/> - accessed on 23 May 2023) has been calculated with a slope model based on SRTM (Zakharovskiy and Németh 2021b, 2022a). The result has been presented in a grid formation with cells 6.25 km² used to define general locations for further assessment. Here, applied our model at a higher resolution to two areas in the northern

region of the Coromandel Peninsula, namely Port Jackson and Fletcher Bay as described here in sections 2.1.1 & 2.1.2. Additionally, to improve the result, the SRTM model has been replaced with the 8-m DEM model based on the topographic map of the Coromandel Peninsula (<https://data.linz.govt.nz/layer/51768-nz-8m-digital-elevation-model-2012/> - accessed on 23 May 2023). This new geomorphological model provides a more accurate slope model with a higher resolution. Thereby specific and potentially important areas of interest and associated values are more clearly. The calculation was performed by utilizing QGIS (3.28 “Firenze”), where the slope model was created with “Slope, aspect, curvature” (Saga GIS module) (Zevenbergen and Thorne 1987). Then the geological model was evaluated according to the 8-point system and multiplied with default values of the slope model. The final step is ranging the results based on Natural breaks (Jenks) mode (Jenks 1967) to clarify the local geodiversity, which highlights 5 categories of region from the lowest to the highest (Fig. 3-C).

The results of the assessment have been magnified and applied specifically to the Port Jackson and Fletcher Bay areas located in the northern region of the Coromandel Peninsula. Then the sites with high and highest values of local geodiversity have been corrected utilizing Google Satellite imagery (<https://earth.google.com/web/@-36.47572254,175.36035435,27.5040222a,13522.16005758d,35y,0.00000609h,0.09747065t,0r> - accessed on 23 May 2023) to highlight vegetation which may conceal geosites in otherwise high value areas. To date this process has not been automated, and here we apply it to a select few geosites. Development of an automated process would be of benefit for larger projects and study areas. In the “Results” section, we describe geosites with more precise details based on information found in existing literature and field observations made on the Coromandel Peninsula over 2021 and 2022. Moreover, description of geosites will also include information about settlements, places of Interest, locations of historic Māori settlement, roads, walking trails, and streams (Fig. 13 see the “Discussion” section) (downloaded from Land Information New Zealand (LINZ) (<https://data.linz.govt.nz/layer/51768-nz-8m-digital-elevation-model-2012/> - accessed on 23 May 2023). Such holistic descriptions applied to the area and its geosites will be of benefit for touristic and educational ventures.

Results

In this section, we provide a detailed description of geosites recognized through a combination of modeling, literature review, and field observations on the Coromandel Peninsula (2021-2022). Areas of study are Port

Jackson and Fletcher Bay. More in-depth information will be provided for each territory separately.

Geosites of Port Jackson

Location: West side of the north part of Coromandel Peninsula (Fig. 2-A).

Geomorphology and geology: The research area we define as Geosites001 contains two hills, which are visible from both sides of the sand beach located east section. The standalone volcanic south hill is comprised of various rocks of the Miocene andesite assemblages while the other hill is formed by rocks of the Jurassic Greywacke also forming a number of gradual hills growing to the east part.

Result of assessment: Our QQG assessment demonstrates that Port Jackson contains around 6 potential locations of interests with high and the highest values. However, only the site PJ 1 is considered a geosite, as this location contains geological information and is readily accessible tourists, while potential geosites located in the north of this study area (Geosites001) may have obstacles to safe access.

Geosite Port Jackson 1 (PJ 1)

Description: The geosite Port Jackson (Fig. 4) represented by remnants of Miocene Andesite, which is a part of the Coromandel Volcanic Group of the Coromandel Peninsula. Named Kaiiti Point it is present within a mixture of andesitic volcaniclastic rocks and greywacke.

Purposes: Valuable for the study of Miocene Volcanism, especially to demonstrate the explosive nature producing block-and-ash flows that accumulated in a coastal region where they entered the shallow marine environment. Therefore, this location provides a graphic example of this geoenvironment where intermediate volcanism has interacted with marine sediments.

Difficulty of recognition: This site is readily recognized through modeling, well described in literature, and highlighted on the topographic map of Coromandel Peninsula.

Obstacles to visitation: The site is situated on the far north of the Coromandel Peninsula. With its remote location visitors must come prepared for poor connections and lack of food supplies. However, it is located nearby to the Port Jackson campsite (<https://www.doc.govt.nz/parks-and-recre>)

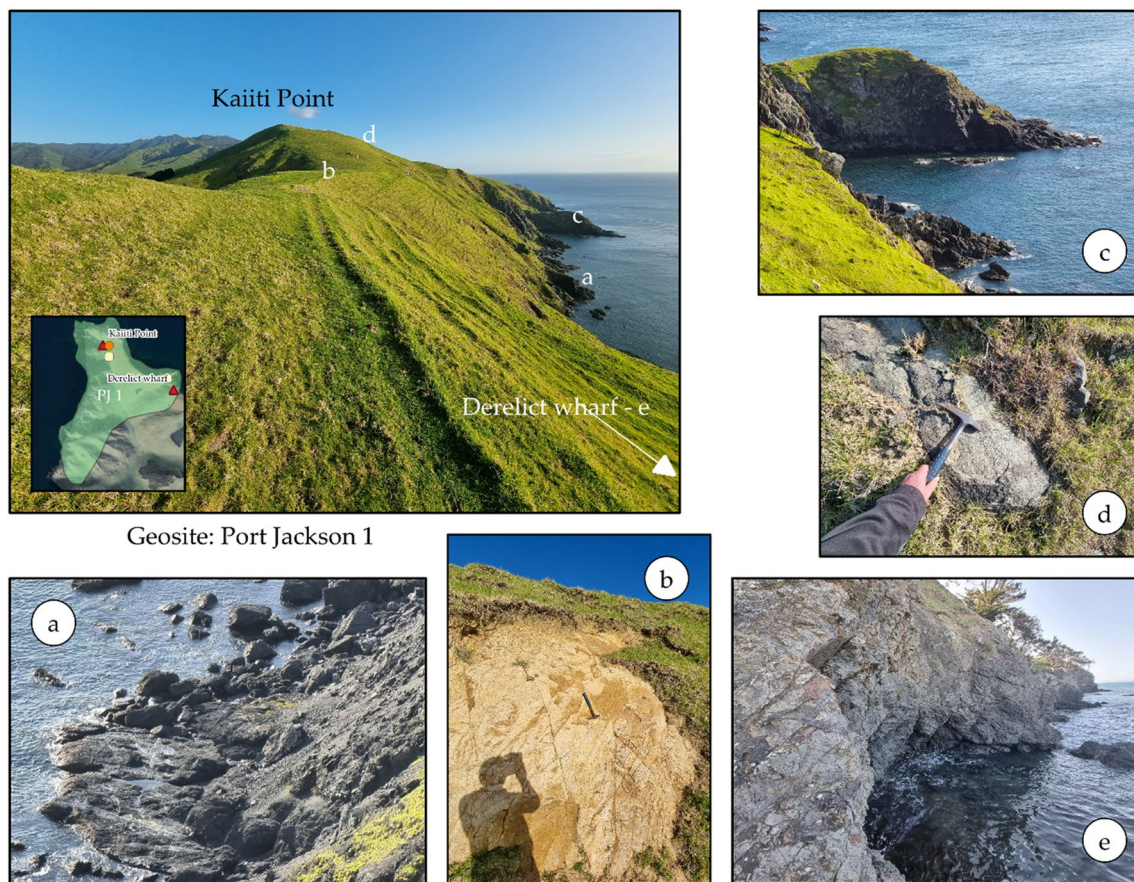


Fig. 4 Port Jackson geosite 1 (PJ 1). The “main” picture presents overview of geosite and contains letters “a–e,” which are magnified with smaller pictures of respected symbol

[ation/places-to-go/coromandel/places/northern-coromandel/things-to-do/port-jackson-campsite/](https://www.gns.cri.nz/data-and-resources/geological-map-of-new-zealand/) - accessed on 23 May 2023).

Result: Geosites 001 could be considered important for geoeucational, heritage, and touristic ventures. However, with its remote location in the far north of the Coromandel Peninsula with the nearest substantial settlement the township of Coromandel, up to 2 hours each way by vehicle is required to reach the site. Additionally, it is inconvenient for general tourism, as each point of interest is separated by long walking distances. However, with suitable commitment and support, the site could have benefits for geoeucation and niche geotourism.

Geosites of Fletcher Bay

Location: East side of the north part of Coromandel Peninsula.

Geomorphology and geology: Geologically speaking, the east part of Fletcher Bay contains large remnants of Miocene Andesite volcanological activities (Coromandel Group).

This area features a large hill surrounded with ocean on the north and east, while Jurassic greywacke forms gradual hills extending from the south and west parts.

Result of assessment: The result of our QQG assessment (Fig. 5) has highlighted a relatively large area, which could be considered a location with geological interest. To refine our results, we utilized Google satellite imagery to highlight the locations devoid of vegetation cover. Additionally, we include the Colville formation, which was not recognizable by our QQG methodology as geological and geomorphological data were not included for this area. Fletcher Bay (FB 1-5) contains 5 locations with geological significance, which could be considered geosites. However, Fletcher Bay 5 has not been include in our assessment as it has been recognized by our QQG modeling, but no supporting information from literature reviews or field observations.

Geosite Fletcher Bay 1 (FB 1)

Description: This geosite features layers of Miocene Sediments (Waitemata Group), which have been tilted and

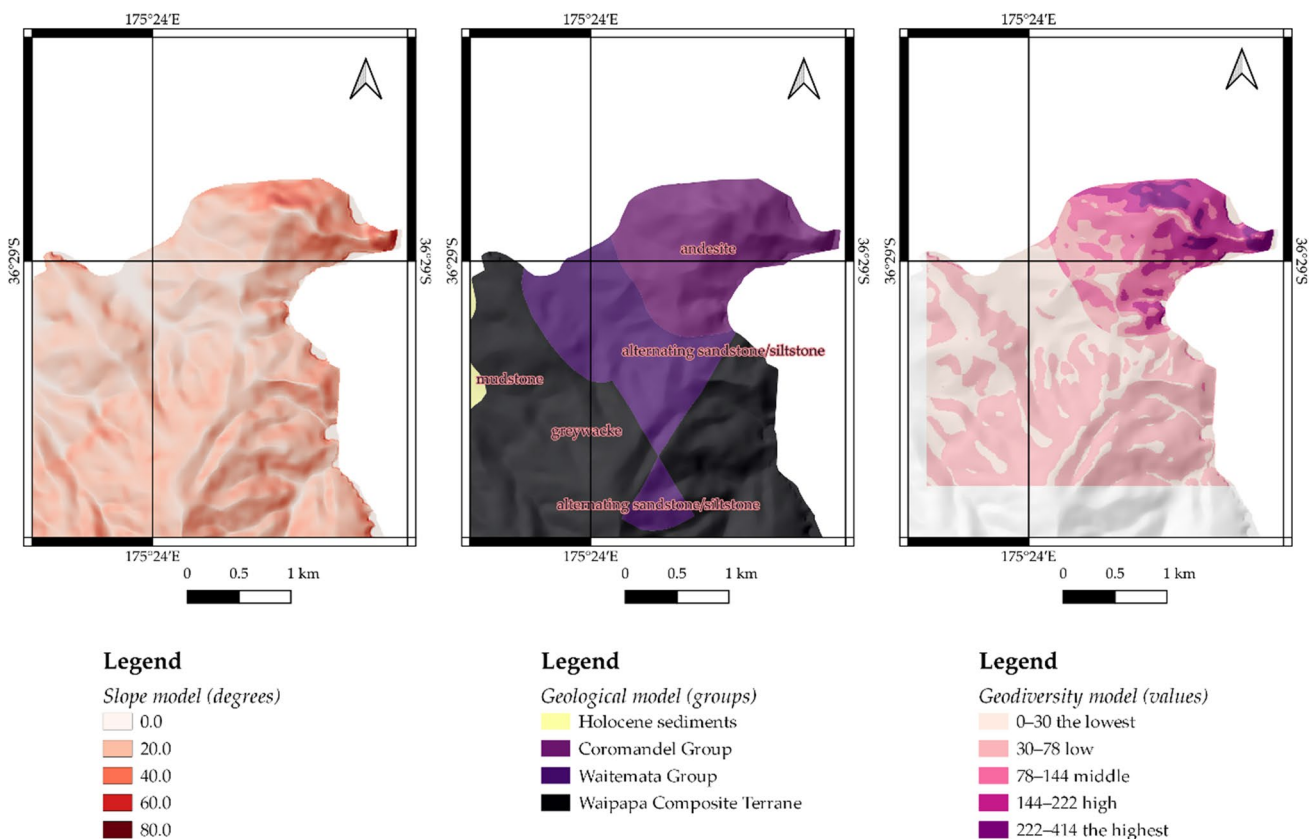


Fig. 5 Geomorphological data base on Slope model created from 8-m DEM based on topographic map of the Coromandel Peninsula (<https://data.linz.govt.nz/layer/51768-nz-8m-digital-elevation-model-2012/> - accessed on 26 May 2023); Geological model based on 1 to 250,000 scale geological model of New Zealand (Q-Map Series

- <https://www.gns.cri.nz/data-and-resources/geological-map-of-new-zealand/> - accessed on 23 May 2023); Geodiversity model is calculated utilizing QQG assessment for geosite recognition, where high and the highest values can be considered potential locations of interest

exposed on the tidal platform (Fig. 6-a), however a large proportion is under water. At low tide an extensive shoreline platform can be accessed on foot. Additionally, some volcanic conglomerate can be observed, adding value to the volcanic heritage of the region as it demonstrates the earliest manifestation of Miocene volcanism in the Coromandel Peninsula and graphically showing the interaction between volcanism and marine sedimentation (Fig. 6-c). The shore platform is particularly valuable for demonstrating biological weathering (Fig. 6-d).

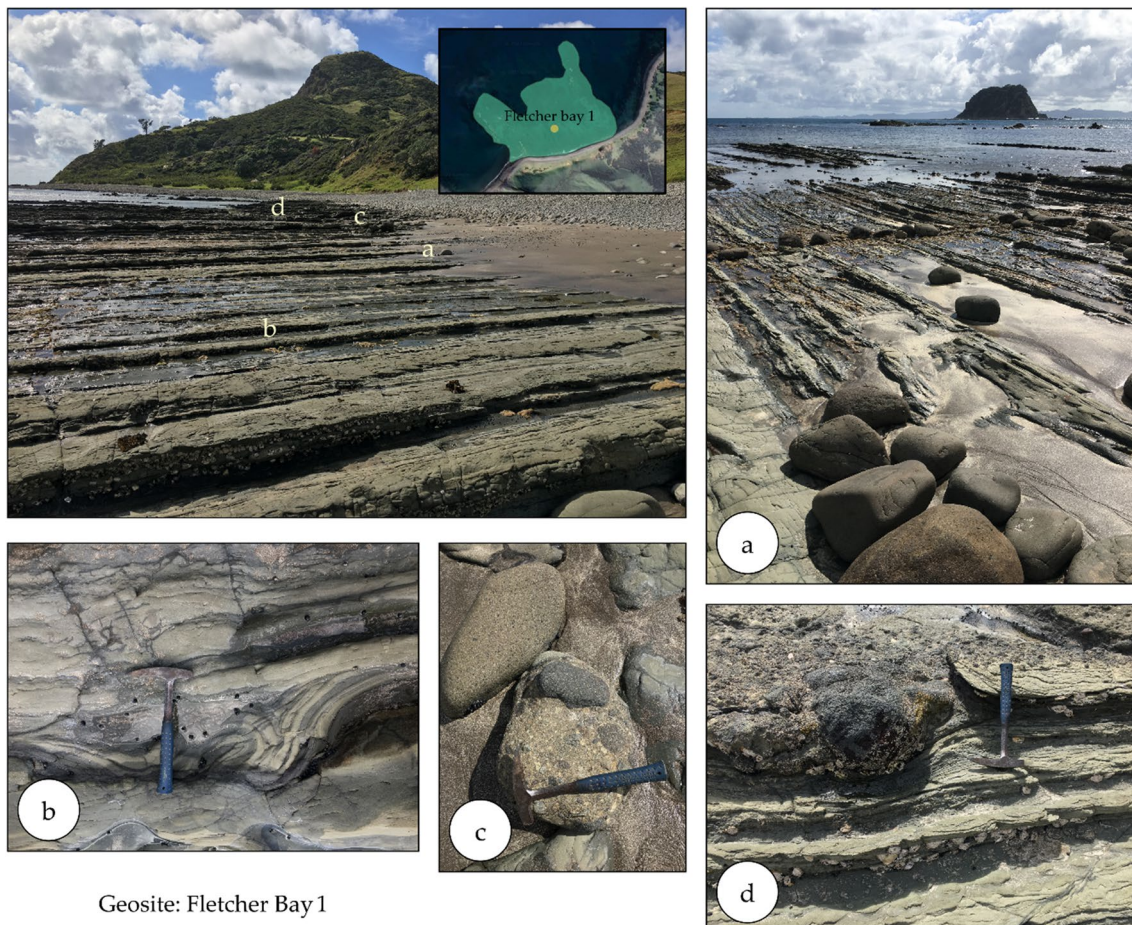
Purposes: Valuable for the study of Miocene sedimentology and marine weathering processes.

Difficulty of recognition: This site place is not recognized with our modeling as it was not included in our assessment due to lack of geological information on maps completed to date, and the flat homogenous terrain. The site can be observed from nearby high value sites in the Fletcher Bay area, and has been studied by Skinner (1969) and Benson (1976) (Skinner 1969; Ballance 1976) and described in Literature review section.

Obstacles to visitation: The site is in the far north of the Coromandel Peninsula, with no mobile reception, lifelines, amenities, and food supplies. The Fletcher Bay camp site has some facilities for backpackers provided by the Department of Conservation (DOC) (<https://www.doc.govt.nz/parks-and-recreation/places-to-go/coromandel/places/northern-coromandel/things-to-do/fletcher-bay-campsite/> - accessed on 23 May 2023), however visitors must be well prepared and supplied. Colville formation (Fletcher Bay 1) can be accessed only by walking tracks and during low tide period, which must be considered as well.

Geosite Fletcher Bay 2

Description: Geosite FB 2 (a) (Fig. 7) features remnants of Miocene Andesite, which is a part of the Coromandel Volcanic Group occurring on the Coromandel Peninsula. Sites 1 and 2 (Fig. 7-1 and 2) are part of the Sugar loaf (SL) formation with a 220 m peak forming the highest point on the nearby coastal stretch area. SL formation is



Geosite: Fletcher Bay 1

Fig. 6 Fletcher Bay 1. The “main” picture presents overview of geosite and contains letters “a–d,” which are magnified pictures of respected symbol

surrounded with Miocene sediments on the western flank, as described in Fletcher Bay 1, while Jurassic Greywacke (Basement of the Coromandel Peninsula) forms rolling hills toward the south-west. Within the boundaries of this geosite many breccia deposits can be observed.

Purposes: Valuable for demonstrating the growth of a composite volcano as part of the Miocene arc volcanism of the region against a background of historic and active marine sedimentation. Geological value of the geosite is enhanced by examples of dynamic marine shoreline weathering processes.

Difficulty of recognition: This site is readily recognized with remnant andesite formations visible on the geological map, with marine weathering processes creating a cliff structure, which can be seen on the slope model.

Obstacles to visitation: The same situation as Fletcher Bay 1 but located about 800 m further.

Description: Geosite FB 2 (b) (Fig. 8) is formed by remnants of Miocene Andesite, which is a part of the Coromandel Volcanic Group occurring on the Coromandel Peninsula. Sites 3 (Fig. 8-3) is included as part of the Sugar Loaf rock, which is separated from the main cliff side. This site place contains several charcoal and mineral inclusions clearly visible within the main rock formation.

Purposes: Valuable for the study of Miocene Volcanism and marine weathering, as the site is an exposed marine cliff. This location is also a key site where charred wood can be seen preserved in a volcanoclastic succession formed by a hot pyroclastic flow (block-and-ash flow) successions that accumulated in a proximal section from to the source vent. This outcrop is also a place for relative chronology.

Difficulty of recognition: This site is not recognized in our geomorphological or geological model as a definitive geosite location, as it is very small, and beyond the low resolution of tens of meters of the DEMs used in our modeling. Forming a section of the beach and often submerged, it is unlikely to be incorporated into standard cartographic assessments. However, this place can be recognized during direct field observations and from satellite images such as Google Satellite ones (<https://earth.google.com/web/@-36.47073431,175.4065509,-0.1884895a,657.61380831d,35y,0.00000609h,0.09727425t,0r> - accessed on 23 May 2023).

Obstacles to visitation: The same situation as Fletcher Bay 2 (a). It is relatively easy to walk on shore.

Description: The geosite FB 2 (c) (Fig. 9) is represented by remnants of Miocene Andesite, which is a part of the Coromandel Volcanic Group occurring on the Coromandel Peninsula. This site forms part of a cliff side of the Sugar

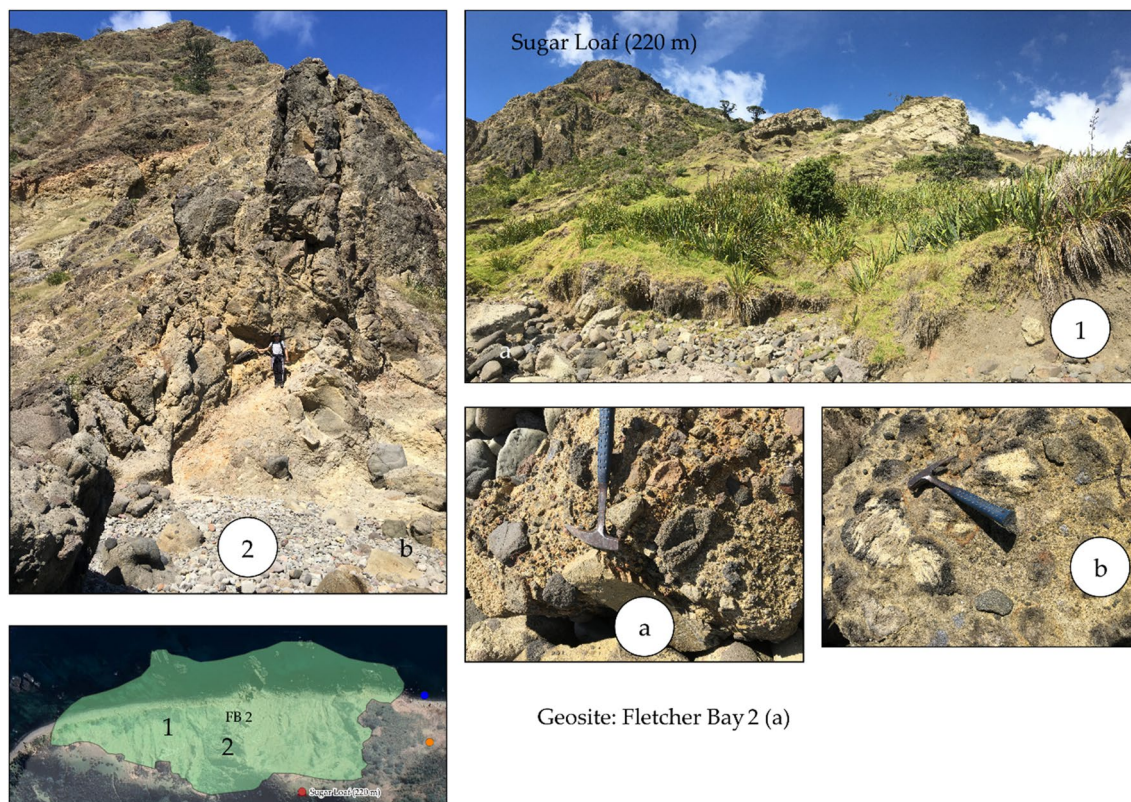
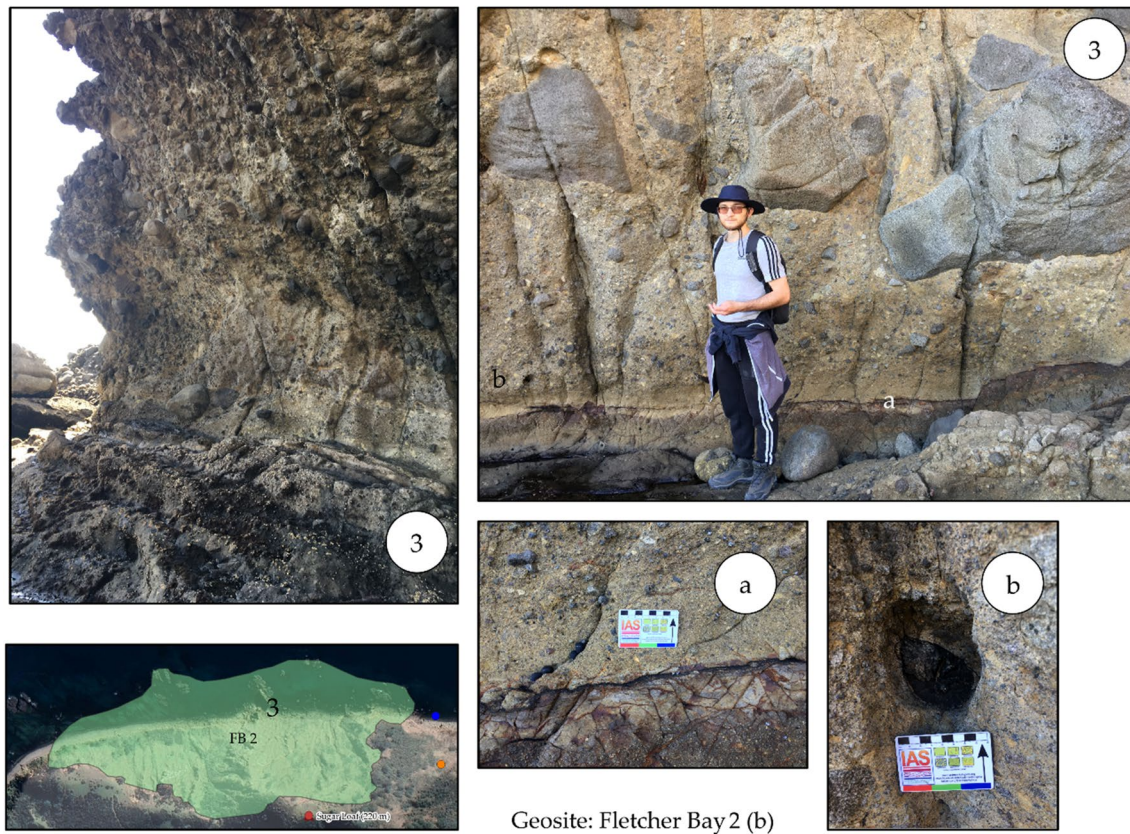


Fig. 7 Fletcher Bay 2 (a). The pictures “1” and “2” presents geosite and contains letters “a” and “b” respectively, which are magnified pictures of respected symbol. “Overview” model has been separated and has no arranged symbol



Geosite: Fletcher Bay 2 (b)

Fig. 8 Fletcher bay 2 (b). The picture “3” presents geosite and contains letters “a” and “b,” which are magnified pictures of respected symbol. “Overview” model has been separated and has no arranged symbol

Loaf rock (Fig. 7-1) and contains pyroclastic deposits (Fig. 9-4, a and c).

Purposes: Valuable for study of the proximal volcanic succession of a growing stratovolcano as it interacted with its shallow marine background geoenvironment in the Miocene. It is also a superb site where t coastal erosion processes and shallow marine weathering are clearly visible. The site is also a place for mass movement processes such as rocks and debris’ falls.

Difficulty of recognition: The place is easy recognizable with modeling like FB 2 (a).

Obstacles to visitation: The same situation as Fletcher Bay 1 but located 1000 m further.

Geosite Fletcher Bay 3

Description: The geosite FB 3 (Fig. 10) is formed by remnants of Miocene Andesite, which is a part of the Coromandel Volcanic Group occurring on the Coromandel Peninsula. Sites 1 and 3 are formed by distinctive pinnacles (Fig. 10-1 and 2) and are separated from the main andesite formation of Sugar Loaf rock. The pinnacles reach 75 and 35 m above sea level (Fig. 10 “overview” on the left) according to 8-m

DEM based on topographic map of the Coromandel Peninsula (<https://data.linz.govt.nz/layer/51768-nz-8m-digital-elevation-model-2012/> - accessed on 26 May 2023), and feature a succession of pyroclastic rocks.

Purposes: Valuable for study of the core, proximal elements of an intermediate andesitic volcano that has been dissected by coastal and shallow marine abrasion and erosion. This location is nearly 100% exposed and shows evidence of explosive eruptions that formed the polygenetic volcano considered one of the first during the onset of the Miocene arc volcanism in the region. The location is also a perfect site to see coastal erosion processes and a dynamic interface between the land and marine environment.

Difficulty of recognition: Hard. Pinnacles are readily recognized at the location during observation, and are labeled on the topographic map as well as mentioned in literature (Ballance et al. 1982; Ballance et al. 1985; Hochstein and Ballance 1993; Hayward et al. 2001). However, the geological map has no information about this area.

Obstacles to visitation: The same situation as Fletcher Bay 1 but it is located in the end of the coastal accessible shore. Note that it is reachable only in low tide.



Fig. 9 Fletcher bay 2 (c). The picture “4” presents geosite and contains letters “a–c,” which are magnified pictures of respected symbol. “Overview” model has been separated and has no arranged symbol

Geosite Fletcher Bay 4

Description: The geosite FB 4 (Fig. 11) is represented by remnants of Miocene Andesite, which is a part of the Coromandel Volcanic Group occurring on the Coromandel Peninsula. Site 1 is Sugar Loaf rocks (Fig. 11-1) which are separated from the main andesite formation generally referred to as “Sugar Loaf.”

Purposes: Valuable location to observe volcanoclastic successions on the completely exposed shore platform. Fine details of the depositional processes are visible within the accumulations of these volcanoclastic successions. Coastal erosion and abrasion provide dramatic and esthetic qualities to this site, which may give it greater appeal beyond niche geotourism.

Difficulty of recognition: Easy. This site is well defined in our modeling and well covered by published literature (Ballance et al. 1982, Ballance et al. 1985, Hochstein and Ballance 1993, Hayward et al. 2001) and mentioned on topographic map of Coromandel Peninsula.

Obstacles to visit: The same situation as Fletcher Bay 1 but this is the most remote geosite (1600 m) and return time must be calculated for safe walk back.

Discussion

Our qualitative-quantitative assessment of geodiversity resulted in defining 10 arguably superb locations in the northern part of Coromandel Peninsula, which have been allocated high, or the highest possible value, for geosite recognition within our study area subject to QQG assessment. Four locations have been selected in the east extending from the Fletcher Bay (FB) area and include sites featuring outcrops of the Colville Formation, Sugar Loaf, Pinnacles, and the Sugar Loaf rocks. The first FB site features tilted Miocene Sediments which are exposed and clearly visible during low tide named “Colville Formations.” The Colville Formation is not recognized well by our geodiversity modeling as this site is not featured

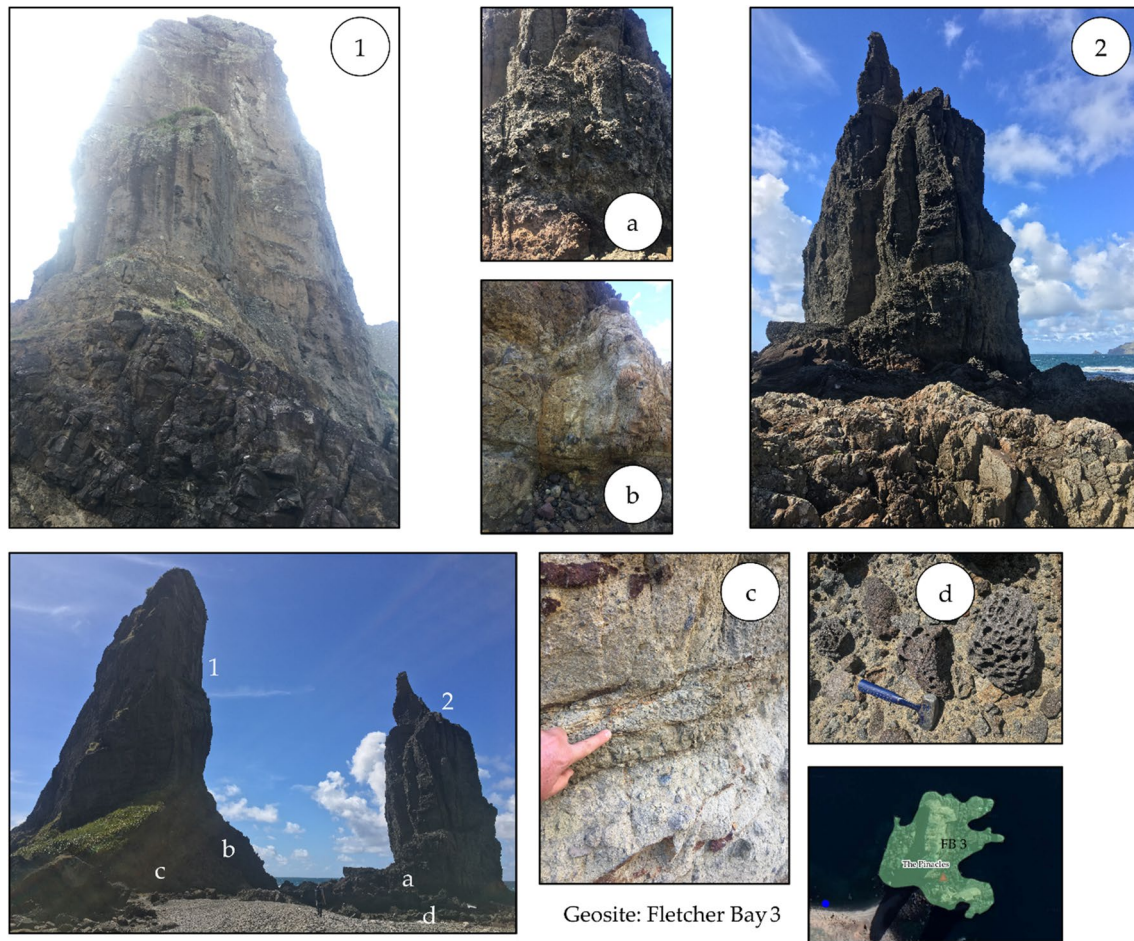


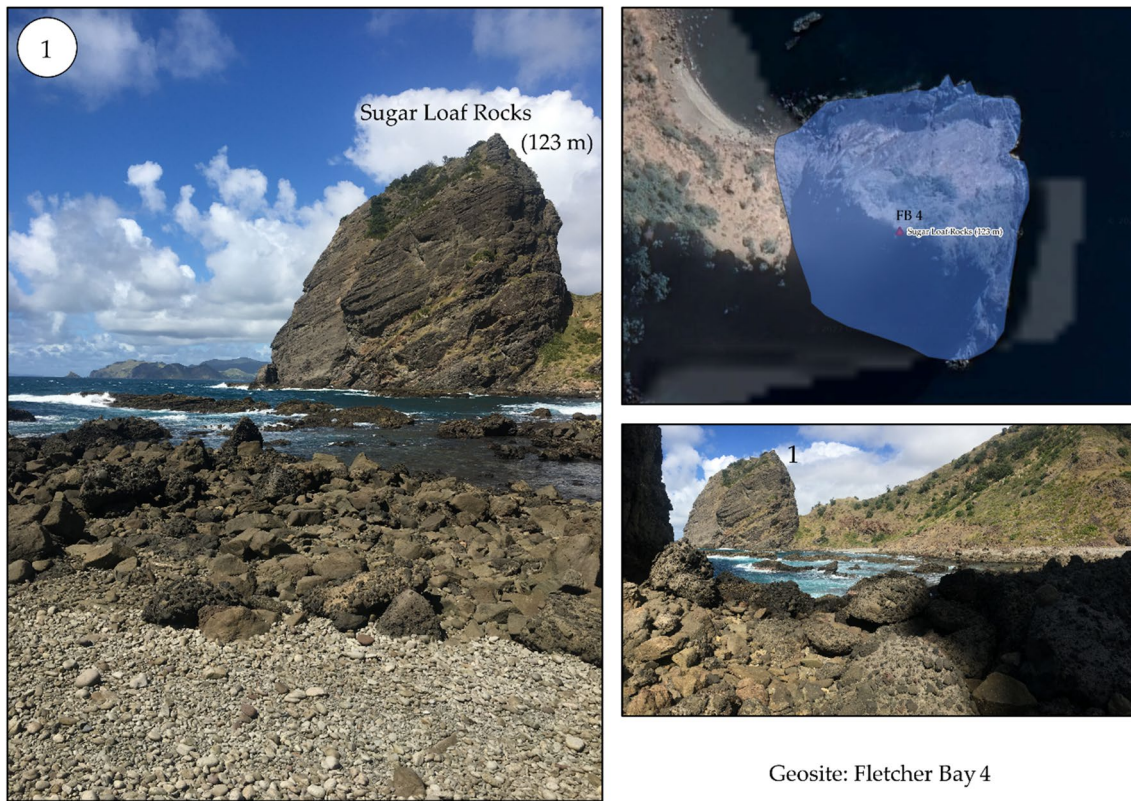
Fig. 10 Fletcher Bay 3. The picture “1 and 2” presents two-part geosite. Two “Overview” model has been separated and has no arranged symbol, which contains letters “a–d,” which are magnified pictures of respected symbol

in geological and geomorphological models, but it is scientifically recognized and visible during field observations. The Sugar Loaf, the Pinnacles, and the Sugar Loaf rocks were formed by Miocene Andesite, creating several geological formations such as lava remnants, breccia, dike, and coal measures associated with abundant organic material burned and subsequently incorporated into block-and-ash flow deposits. These locations have all been highlighted through our geodiversity modeling and we have labeled them as FB 2-4.

Meanwhile, our QQG assessment recognizes 6 locations on the territory around the Port Jackson campsite. The first and largest area contains high, and the highest value sites, in the south-western part. Miocene Andesite forms a site known as Kaiiti Point, allowing scenic views to other areas of the Peninsula and surrounding waters, is covered with grassland, and features exposed rock cliffs on the coastal areas. Meanwhile, 5 other locations of interests on the northern shore east of Cape Colville have not been included due to difficulty accessing them and associated safety issues. The

main geological values of these sites are all associated with Jurassic Greywacke. Therefore, our modeling has described 10 locations with high or the highest values, but only 5 of them are in readily accessible areas making them suitable for touristic and/or educational purposes.

Additionally, a visibility map has been created for our area of research to demonstrate the most visible parts of the landscape in the northern part of the Coromandel Peninsula (Fig. 12). The visibility model is based on a viewshed tool which recognizes a binary value for visibility of areas, based on the point of observation. Using this tool highlights areas which can be observed on distance 5 km (default parameter). For our modeling, walking tracks and roads have been analyzed, showing a range of areas with a color range from dark to light, where lighter areas mean a higher number of overlapping visible areas from different points. The darkest areas on the map show those areas which are areas, not observable from tracks and roads. Hence, the central part of the north Coromandel is highly visible, especially north-east, and south slopes leading to Kaiiti Point and south-east slopes to Fletcher Bay.



Geosite: Fletcher Bay 4

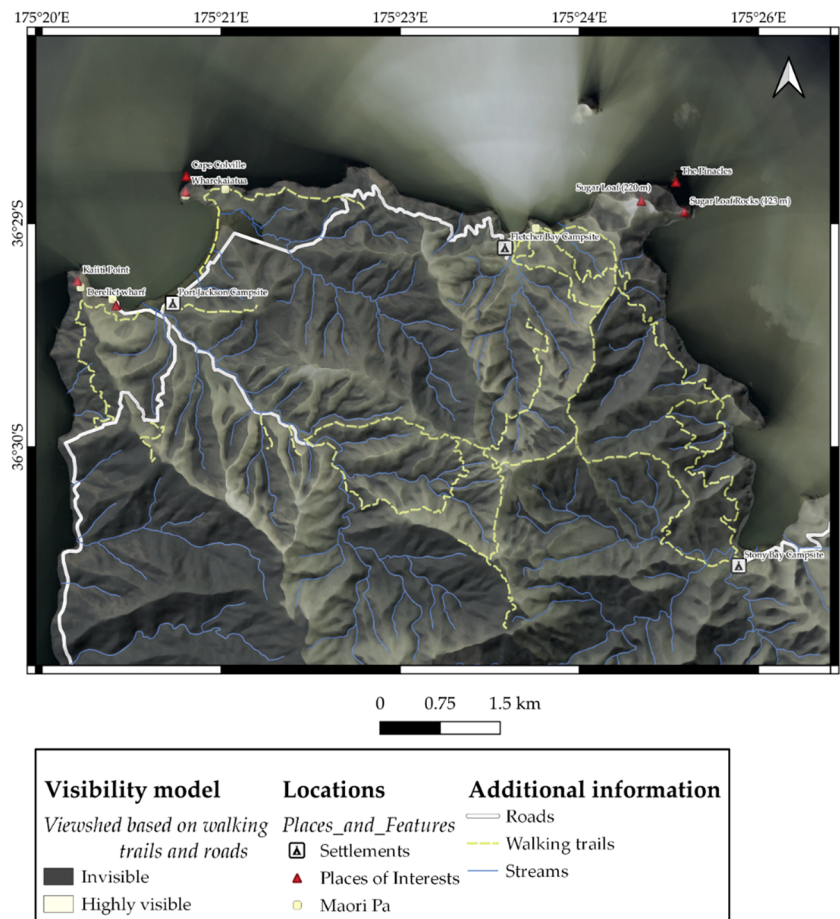
Fig. 11 Fletcher bay 4. The picture “1” presents geosite. Two “Overview” model has been separated and has no arranged symbol

Overall, according to the maps, Port Jackson and Fletcher Bay campsites (Figs. 1, 13) can be easily visited by car, and moreover convenient for short stay (around a week). However, some decent drawbacks are present as well, like no access to phone connection and no main food or tool stores in nearby distance. Hence, currently the journey to any of the mentioned geosites must be planned, especially for food, petrol, and first aid perspectives. Then any kind of a trip will require at least one full day for observations due to the long distances, which must be covered by foot. Port Jackson is the most convenient option as it is still located not far away (one hour by car) from Colville, which contains general shop, fire station, and coffee place. But, in emergency you must be ready to drive up to Coromandel Township (1 hour 30 minutes). Therefore, Port Jackson can be studied in two days as the main geosite “PJ 1” is located 5 min walk from the campsite. Meanwhile, Fletcher Bay contains even more problems such as distances to closest towns prolongs by 20 minutes driving. But staying in this region must be considered for 2 days at least as the closest geosite FB 1 “Colville Formation” is located 1 kilometer walking distance by stony beach area starting from Fletcher Bay campsite using “Coastal trails” (Fig. 13), then to reach the FB 5 “Sugar loaf rocks” is 2700 m long walk. Hence, for visiting all geosites the trip will take at least whole day just to get to the final point with time

suspended for geosite descriptions and resting. Additionally, it requires around an hour plus to reach the highest point in “Sugar Loaf,” which opens a view toward Moehau Range and “Pinnacles” (Fig. 14). Meanwhile, Port Jackson and Fletcher Bay relates to numbers of walking trails with length around 11800 m, which can become a good opportunity for sport tourism and studying of geomorphology of the central-north part of the region which clearly opens visibility toward the north-east from the walking ways according to visibility model (Fig. 12). Hence, the north part of Coromandel Peninsula contains a range of opportunities for geotourism and geoeducational perspectives, however due to lack of facilities in these areas the field trips must be planned.

Results of QQG assessment can be utilized for further direct field observation, but it is not guaranty us that every point obtained by calculation can be a geosite. The last statement contains some potential drawbacks connected with location of research, such as inability to come close to the cliffside, where we rejected around 5 possible geosites (PJ 2-6) in the north side of Port Jackson area (Fig. 2). Other, issue is vegetation, which can be avoided utilizing data about walking trails and satellite images with plant covering for example Natural Differences Vegetation Index (NDVI). Furthermore, improvement can be done to the 8-point evaluation system with additional values of geodiversity such as

Fig. 12 Visibility model of the north part of Coromandel Peninsula made utilizing “viewshed” module of QGIS (Saga GIS plugin) based on 8-m DEM based on topographic map of Coromandel Peninsula (<https://data.linz.govt.nz/layer/51768-nz-8m-digital-elevation-model-2012/> - accessed on 26 May 2023). All additional information also have been downloaded from Land Information New Zealand (LINZ) (<https://data.linz.govt.nz/layer/53382-nz-roads-addressing/> - roads; <https://data.linz.govt.nz/layer/52100-nz-walking-and-biking-tracks/> - walking trails; <https://data.linz.govt.nz/layer/50327-nz-river-centrelines-topo-150k/> - streams; <https://data.linz.govt.nz/layer/50308-nz-pa-points-topo-150k/> - Māori Pas’; - accessed on 26 May 2023). Settlements and Places of Interests have been extracted from Topographic map of New Zealand (<https://data.linz.govt.nz/layer/50767-nz-topo50-maps/> - accessed on 26 May 2023)



hydrology, which have not been utilized in this research to concentrate more on demonstration of geological location and introduction of it for tourism and education to encourage visitation in this area. Finally, the assessment can be improved by increasing the scale of research and create a model of Coromandel Peninsula with all geosites. However, this kind of project require a long time for calculations, direct observation, and descriptions, which can take a year, but result of this project would be a full model with touristic and educational spots for geological information of the peninsula. Hence, everything still can be improved and corrected to acquire the best result, which allow us to increase geological awareness of New Zealand.

Conclusions

The result of QGQ assessment for geosite recognition, provides 6 locations for Port Jackson, and 5 locations for Fletcher Bay areas. However, only PJ 1 and FB 1-4 have been included for description, because other sites are inaccessible, so they have not been recognized through field observations and literature reviews. Selected geosites have

been described according to information presented in literature reviews from previous year of geological research in this area. Hence, it resulted in one large geosite around Kaitiaki Point nearby Port Jackson, and 4 geosites nearby Fletcher Bay started with “Colville formation” and surrounding areas around “Sugar Loaf,” “Pinnacles,” and “Sugar Rocks.”

Port Jackson and Fletcher Bay campsites can be utilized as starting point for geotourism and geoeducation in the north Coromandel Peninsula. These areas contain an interesting geological formation constructed through the interaction of Miocene-Pleistocene volcanism and marine processes. Moreover, the campsites contain some general utilities giving an opportunity to stay in the north for few days to explore geomorphological and geological features of the region. However, the group should be ready for some challenges and preparations before to come to the region. All geosites selected in this manuscript can be reached by walking trails and coastal areas from the nearest campsites. However, sometimes tide level must be considered some places can become inaccessible with high tide. In average all walks are around 7 km long, where stopes for observations must be included into planning of a trip. Hence, this

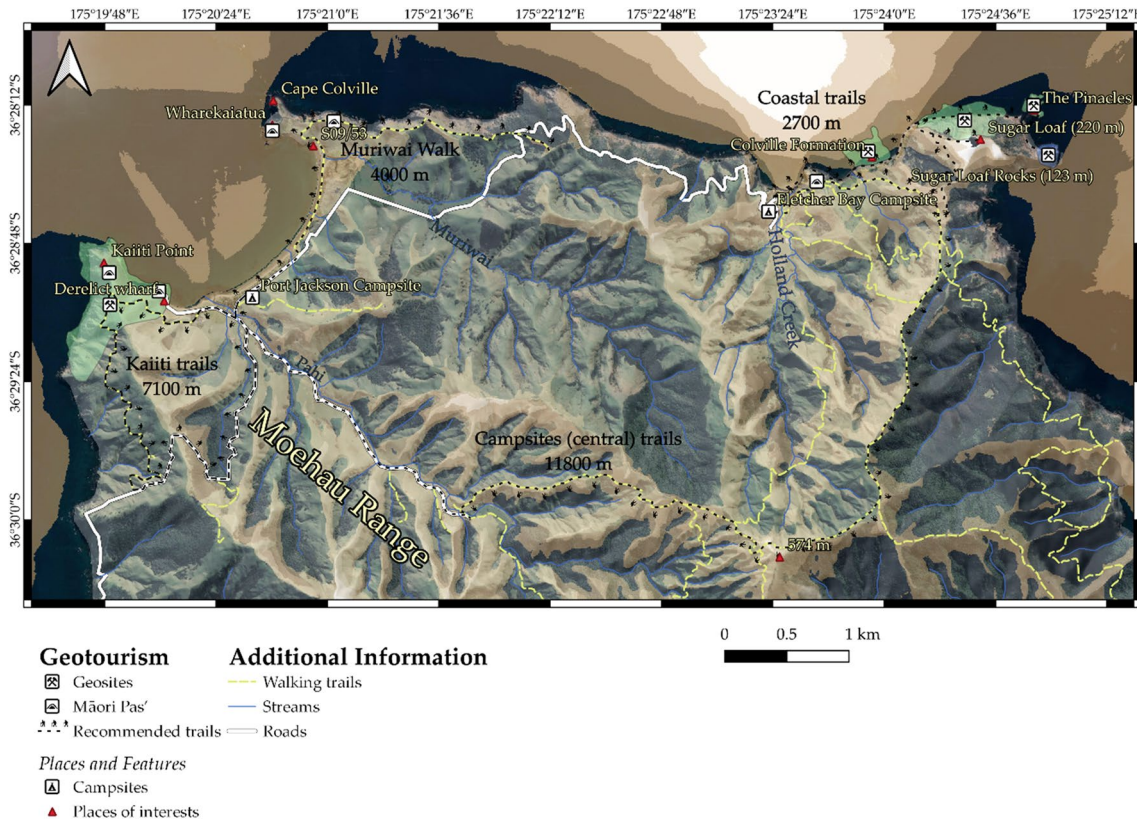


Fig. 13 Geotouristic model of the north part of Coromandel Peninsula. All additional information also have been downloaded from Land Information New Zealand (LINZ) (<https://data.linz.govt.nz/layer/53382-nz-roads-addressing/> - roads; <https://data.linz.govt.nz/layer/52100-nz-walking-and-biking-tracks/> - walking trails; <https://data.linz.govt.nz/layer/50327-nz-river-centrelines-topo-150k/> -

streams; <https://data.linz.govt.nz/layer/50308-nz-pa-points-topo-150k/> - Māori Pas'; - accessed on 26 May 2023). Settlements and Places of Interests have been extracted from Topographic map of New Zealand (<https://data.linz.govt.nz/layer/50767-nz-topo50-maps/> - accessed on 26 May 2023)

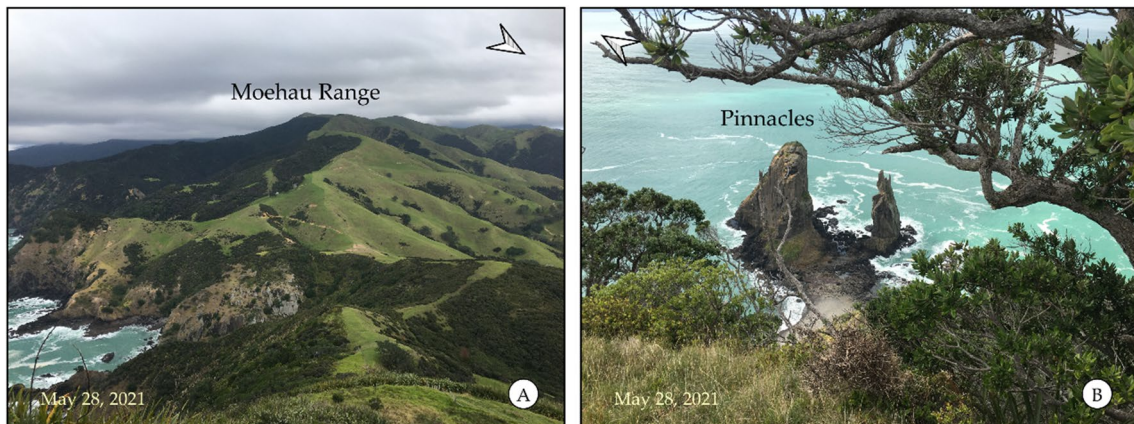


Fig. 14 Photos taken from Sugar Loaf on 28th of May 2021, during the field trip to the north part of Coromandel Peninsula. **A** View toward the south-west demonstrating Moehau Range. **B** View toward north-east picturing “Pinnacles”

manuscript can become a guide for people, who considered to visit this region.

Additionally, visibility map has been demonstrated in the research to show that roads and walking trails open the view on the landscape of the region, where north part and Kaiiti Point are areas with the highest visibility from the most parts of roads and trails. This manuscript is demonstrations of possibilities, which can be done utilizing QQG assessment with collaboration of direct field observations and literature reviews of the region. In further observations we are planning to improve evaluation system and utilize more additional information for more accurate calculation. Then, the scale of research should be increased to acquire a full geotouristic model of the Coromandel Peninsula with demonstration and description of all geolocations and facilities to increase geological awareness for travelers and students.

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Declarations

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