The surface geology of the Prince Edward Islands: refined spatial data and call for geoconservation

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Abstract

Volcanological maps of the sub-Antarctic Prince Edward Islands were first published in 1968, with a revised surface geology map of Marion Island produced in 2006. These maps have been widely used in terrestrial studies on the Prince Edward Islands but they have limitations in spatial accuracy and detail. Using high-resolution satellite imagery and digital elevation data, more spatially accurate data for both Prince Edward and Marion Island's surface geology are presented here. In particular, Marion Island's volcanology on the western coast, including the 1980s lava flow, and the newly exposed Central Highland following the disappearance of extensive ice and snow cover is mapped with greater detail and verified through field observations. The spatial data are downloadable as ESRI layer packages, which can assist in future investigations of island biotic-abiotic processes and interactions and enable improvements in spatial modelling. In addition, this paper highlights geological features and specimens from the Prince Edward Islands as unique examples of geodiversity in a South African context. An overview of these features are provided in terms of their geoheritage value to enable a more comprehensive geoconservation strategy be incorporated into the Prince Edward Islands Management Plan.

Introduction

The Prince Edward Islands are the only South African territories in the sub-Antarctic and an important platform for South Africanled terrestrial science in the greater Southern Ocean (Chown and Froneman, 2008; Ansorge et al., 2017). Surface geology is a significant spatial variable in most terrestrial research on the Prince Edward Islands (e.g. Boelhouwers et al., 2003; McGeoch et al., 2008; Hugo-Coetzee and Le Roux, 2018; Dilley et al., 2019). Furthermore, the geology is a key variable in the fine scale linkages between the abiotic landscape and biotic ecosystems and ecological responses to climate change (Chown and Froneman, 2008; Myburgh et al., 2007; Mortimer et al., 2012; Hodgson et al., 2014; Ansorge et al., 2017; Moon et al., 2017; Hugo-Coetzee and Le Roux, 2018; Nel et al., 2020). However, much of the spatial data reflecting the surface geology of the Prince Edward Islands (e.g. Hedding, 2006) have been reproduced from the original volcanology and geology maps charted by Verwoerd and Langenegger (1968) which are limited in spatial accuracy and detail.

The islands enjoy the highest level of protection afforded to any natural area under South African law (National Environment Management: Protected Areas Act 57 of 2003) and are managed under the Prince Edward Islands Management Plan (PEIMP) (DST-NRF

CIB, 2010). Conservation efforts on the Prince Edward Islands have focussed on the conservation of biological species, preservation of archeological artefacts, the management of pollution and waste and preventing the further introductions of alien species (see De Villiers and Cooper, 2008), but the conservation of 'geodiversity' has received limited attention. The current PEIMP specifies protocols for the removal of (sensitive) geological samples from the islands, and lists certain features for "geoconservation" (DST-NRF CIB, 2010). However, the management plan only lists two features for conservation, namely, lava tunnels and tubes (DST-NRF CIB, 2010) but does not specify the nature of 'sensitive' (removable) geological specimens, an issue not unique to the management of the Prince Edward Islands only (e.g. Carincross, 2011). This presents two shortcomings in the PEIMP, the first is that some (removable) geological specimens are rare and valuable specimens of geoheritage but are not mentioned or defined. The second is that the islands host a greater range of geodiversity than described in the PEIMP and, if unnoticed, may not receive suitable attention from conservation efforts or policy in the future (see Cairncross, 2011; Ruban, 2012). For this reason, anthropogenic impacts pose possible threats to the geodiversity of the Prince Edward Islands, but these can be mitigated by including a more detailed record of the Island's geodiversity and a suitable geoconservation strategy in the PEIMP. This paper presents revised geological maps for the Prince Edward Islands at a refined spatial accuracy as downloadable ESRI layer packages in supplementary data files archived in the South African Journal of Geology repository (https://doi.org/10.25131/ sajg.124.0014.sup-mat). In addition, to lay an improved foundation for more targeted geoconservation of the Prince Edward Islands under the current PEIMP (DST-NRF CIB, 2010), an overview of important geological elements of geodiversity is provided.

The Prince Edward Islands (~46°50´S, 37°50´E)

The Prince Edward Islands, located in the southern Indian Ocean (Figure 1), are the peaks of two closely related, coalescing shield volcanoes with oceanic basalts from the Atlantic suite (Kable et al., 1971; Verwoerd, 1971; Chevallier, 1986; Le Roex et al., 2012). The two islands - Marion and Prince Edward - lie 300 km south of the South West Indian Ocean Ridge and are believed to be the product of an oceanic intraplate hotspot, similar to the Hawaiian type of eruption (McDougall et al., 2001). The current subaerial extent of Marion Island is 293 km² and it has a summit peak at 1240 m a.s.l. (Hedding, 2008; Meiklejohn and Smith, 2008), whereas Prince Edward, a younger island (McDougall, 1971; Verwoerd, 1971), is a mere 46 km² in surface area with a summit at 672 m a.s.l. (Boelhouwers et al., 2008) (Figure 1). Estimated to be less than one million years old, the two islands exhibit a simple sequence of outflows (Verwoerd, 1971). On Marion Island, the oldest lava flows range between 50 to 450 ka and the younger flows, predominantly aa, with some pahoehoe, are <10 ka and cover most of the island (Verwoerd, 1971; McDougall et al., 2001). The oldest dated sample from Prince Edward Island is 215 ± 20 ka (McDougall, 1971). The approximately 130 scoria cones, scattered across Marion Island (Hedding, 2020), are believed to have originated throughout the Holocene, but their ages have not yet been constrained (Verwoerd, 1971). Modern-day eruptions have been recorded on Marion Island in 1980 (Verwoerd et al., 1981) and in 2004 (Meiklejohn and Hedding, 2005), confirming that at least one of the islands was recently active. Minor mineralogical differences distinguish the islands from one another and characterize the older from the younger outflows on both islands (see Kable et al., 1971; Le Roex et al., 2012). However, these differences are practically indistinguishable at macroscopic and microscopical levels (Verwoerd, 1971). For this reason, rock colour and texture are more commonly used to differentiate between the different outflows (Verwoerd, 1971).

Marion Island's (46°54'S, 37°45'E) volcanic history is dominated by basaltic effusions that were interrupted by explosive events, in turn giving rise to distinct lava flows and scoria cones (Verwoerd, 1971; Verwoerd and Chevallier, 1987; Roberts et al., 2019). The descriptions from early visits to the island produced a simple but effective classification system for the geology (Verwoerd, 1971). The Island's basalts were called 'grey lava' and 'black lava' referring to the older "Pleistocene" aphanitic and the younger "Holocene" porphyritic outflow sequences, respectively (Verwoerd, 1971) (Figure 2A). A third rock type is described as 'scoria', referring to the material on the many explosive cones jotted around the island (Verwoerd, 1971) (Figure 2A). Verwoerd (1971) further subdivided the 'grey lava' into an eastern and western succession, and the 'black lava' into four groups based on local superposition (Verwoerd, 1971:49). Verwoerd (1971) warns that this classification, which is based on rock colour and texture alone, could sometimes be ambiguous and did not mean to imply a relation between equally grouped flows from different localities, nor does it infer an age. Young non-vesicular flows can appear grey; and older porphyritic flows can appear black (Verwoerd, 1971: 48). Still, this naming system, i.e. 'grey', 'black', 'scoria', implying stratigraphical differences has subsequently been adopted in various landscape studies (see McDougall et al., 2001; Hall et al., 2011; Hodgson et al., 2014; Nel et al., 2020).

Although Prince Edward Island (46°37'S, 38°E) is smaller, it has considerable vertical relief with a markedly asymmetric profile. Like Marion Island, Prince Edward Island comprises scoria cones, hummocky black lava flows and "Pleistocene" grey lavas (Verwoerd, 1971). The island comprises an elevated massif, which Verwoerd (1971) refers to as a "proto island". Notable features include a remarkable stratified grey tuff ring on the Western Coastal Plain which juts out to form the two spectacular bastions of the Golden Gate and Kent Crater (Verwoerd, 1971) (Figures 2G and 6) and Wolkberg, a steep scoria cone with a breached crater (Figures 2G and 6). Wolkberg ejected large numbers of lava bombs and crystal fragments, including transparent glassy plagioclase and black lustrous pyroxene (Verwoerd, 1971). No major geological or geomorphological research has been conducted on Prince Edward Island since the

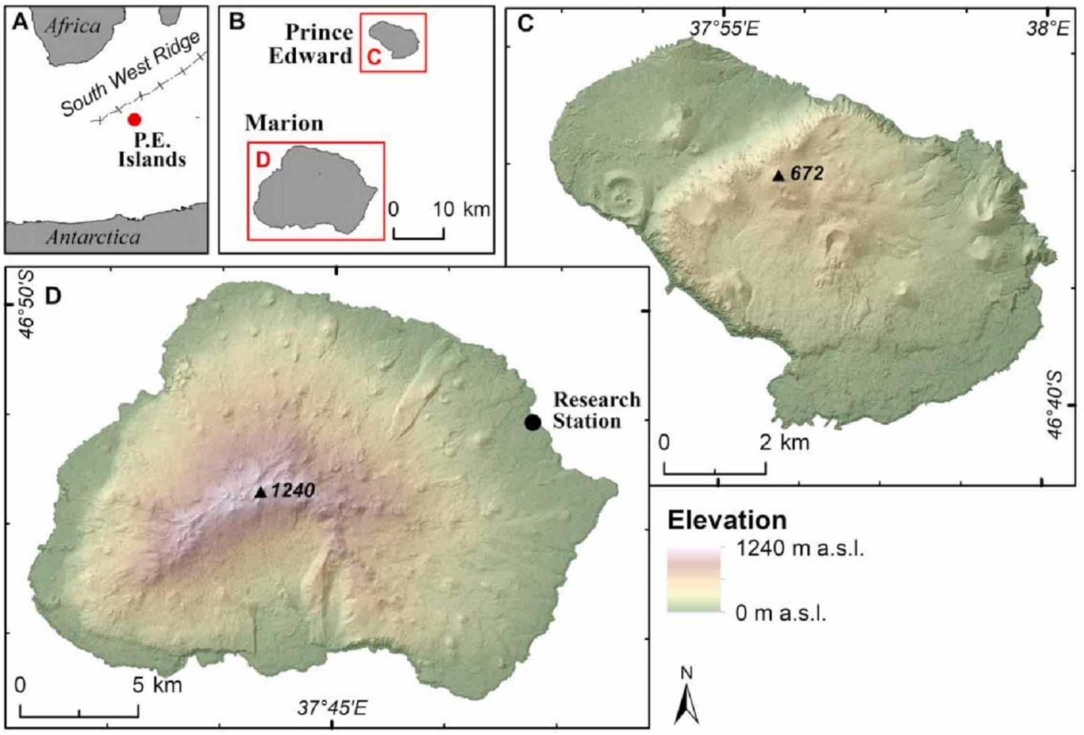

Figure 1. The location of (A) Prince Edward Islands in relation to the South West Indian Ocean Ridge (McDougall et al., 2001) and (B) Prince Edward and Marion Islands' positions relative to one another. (C) A digital surface model with 1 x 1 m resolution of Prince Edward and (D) Marion Island. The South African National Antarctic Programme's research station is located on Marion Island. Map projection: Transverse Mercator Lo37.

initial geological research of Verwoerd (1971), McDougall (1971) and Kable et al. (1971).

Previous geological maps of the Prince Edward Islands

The first set of comprehensive maps for the Prince Edward Islands were published after a dedicated scientific survey in the late 1960s (Van Zinderen Bakker Sr. et al., 1971). A topographical map (1:50 000 with a 50 m contour interval) (Langenegger and Verwoerd, 1968) and volcanological map (Verwoerd and Langenegger, 1968a, 1968b) provided a generalised surface classification of the islands' topography and geology, but these were not without limitations. The surveys were mostly conducted on foot, rendering the analysis of inaccessible areas dependent on the available Royal Air Force aerial imagery taken in 1961, but, even then, parts of the islands were obscured by cloud cover (Langenegger and Verwoerd, 1971). Moreover, the then extensive snow and ice cover in the Central Highland of Marion Island prevented the mapping of the areas above 750 m a.s.l. (Langenegger and Verwoerd, 1971; Verwoerd, 1971). Nonetheless, the maps produced from the survey (Verwoerd and Langenegger 1968a, 1968b) and the geological classification (Verwoerd, 1971) were widely used in subsequent botanical, biological and geomorphological studies (e.g. Hall, 1980; Scott, 1985; McDougall et al., 2001; Smith and Steenkamp, 2001; Sumner et al., 2002). Ensuing studies did update the geological knowledge of Marion Island to improve our understanding of the Island's volcanic history (see Verwoerd et al., 1981; Chevallier et al., 1992), but it was not until the early 2000s that major advances in the acquisition of spatial data and subsequent mapping of the islands were made. With the advent of Global Positioning Systems, updated topographical data (Chief Directorate: Surveys and Mapping, 2002) and georeferenced aerial imagery (South Africa, 1988), the spatial accuracy and detail of the islands' surface geology was somewhat improved (e.g. Hedding, 2006; Boelhouwers et al., 2008). In particular, the disappearance of the extensive snow cover from Marion Island's interior (Sumner et al., 2004) enabled the Central Highland to be mapped for the first time (Hedding, 2008). The aid of Geographic Information Systems (GIS) also made it possible to produce a digital geological map for Marion Island (Hedding, 2006), based on the pioneering work of Verwoerd and Langenegger (1968a). The original volcanological map was scanned, georeferenced to the 2005 topographical map (Chief Directorate: Surveys and Mapping, 2005) and heads-up digitised with the aid of contour data (Chief Directorate: Surveys and Mapping, 2005) (Hedding, 2006). This digital geological map was readily adopted (Boelhouwers et al., 2008; Hall et al., 2011) but still the spatial accuracy of the map was limited to the 10 m contour data, and the topography of several locations (e.g. Marion Island's west coast) remained interpolated from RADARSAT™ data (Chief Directorate: Surveys and Mapping, 2005).

Geoconservation and the Prince Edward Island Management Plan

Geoconservation refers to the conservation of geodiversity and geoheritage (Erikstad, 2013; Gray 2019). Geodiversity is the variety of natural abiotic features that are of geological, geomorphological, hydrological or pedological origin (Gray, 2013) and that provide certain value to society (Gray, 2019). Geoheritage, on the other hand, focusses on scientifically important abiotic elements that can provide insights into the Earth's history (Erikstad, 2013). Since natural abiotic features are generally not as sensitive to climate change or anthropogenic impacts as living organisms, these abiotic elements have received little attention from conservation programmes in the past (Pemberton, 2001; Gray, 2019). On the rare occasion that conservation plans incorporate geodiversity, they tend to concentrate only on sites that are spectacular (e.g. karst, active volcanic and glacial sites), scientifically significant (e.g. type sections) or that show evolutionary links (e.g. fossil sites) (Pemberton, 2001). Still, "geodiversity underpins biodiversity" (Burek, 2001; p. 21), and these abiotic elements ought to receive suitable attention for their conservation in order to protect geoheritage and promote the management of, and an appreciation for, geodiversity (Erikstad, 2013; Gray, 2019). As such, increasingly, efforts are made to integrate the geosciences into environmental management (Gray et al., 2013) and promote the importance of geoconservation to public and policy (e.g. Erikstad, 2013; Ruban 2017; Bétard and Peulvast, 2019; Gray, 2019). Geoconservation essentially aims to protect geodiversity, or geoheritage, because it offers certain value to society, whether on a local, regional or global scale and/or the features face potential threats to their destruction (Bétard and Peulvast, 2019; Gray, 2019). As 'geodiversity' encompasses a multitude of features, which can exist at various spatial scales, it is a very complex concept to quantify or evaluate (e.g. Knight, 2011; Ruban 2011; Bétard and Peulvast, 2019). Gray (2013) identifies five broad spheres against which the value of geodiversity can be measured: its • intrinsic, natural value;

- economic value;
- aesthetic or cultural value;
- research or educational value; and
- functional value as part of Earth's physical or ecological systems.

An aspect not included in Gray's (2013) list, but expanded in detail by Cairncross (2011), is rarity. None of these qualities are mutually exclusive and it thus becomes difficult to measure the value of features or certain specimens of a region against another (Knight, 2011), especially with differences in local, regional and international definitions, priorities and policies (e.g. Cairncross, 2011; Ruban, 2012; Erikstad, 2013; Bétard and Peulvast, 2019).

The International Geoscience and Geoparks Programme, a joint venture between the UNESCO Global Geoparks and the International Union of Geological Sciences (IGGP, 2012), uses ten focus areas against which to assess the geoconservation potential of a region on an international scale (UNESCO, 2017). These focus areas, which are an expansion of Gray's (2013) criteria, include evaluating the region's: scientific significance (e.g. unique fossil record); the potential to study past climates or monitor current climate change (e.g. records of glaciations, peat deposits); suitability to promote awareness of geological hazards (e.g. volcanoes) or educational opportunities (e.g. school trips, tourism) (UNESCO, 2017). A feature or area will only be designated a UNESCO Global Geopark once evaluated by scientific professionals on the basis of peer-reviewed publications of geological research conducted in the said area (IGGP, 2012). Such a (geo)park is generally identified as a "single, unified geographic area", as opposed to being defined by an individual feature (IGGP, 2012).

In a South African context, legislation provides the opportunity for the inclusion of geodiversity in environmental management and conservation plans through, amongst others, the Geoscience Act 100 of 1993, the National Heritage Resource Act 25 of 1999, and the National Environmental Management Act 107 of 1998 (amended 2003). The Prince Edward Islands are designated as a "Special Nature Reserve" by the National Environment Management: Protected Areas Act 57 of 2003, which by default grants any (unspecified) elements of geodiversity or geoheritage at the Prince Edward Islands the highest form of protection. In addition, the scientific value of the Prince Edward Islands is recognised by its inclusion in the South African National Antarctic Programme (SANAP) (Ansorge et al., 2017; DEA, 2020) and protected by the implementation of the PEIMP (DST-NRF CIB, 2010). The geology of the Prince Edward Islands is unique in a South African context, but its individuality is often absent in review works on South Africa's geoheritage (e.g. Viljoen and Reimold, 1999; Grab and Knight, 2015) and, therefore, seldom appreciated. This may be due to the exclusive nature of the islands and the fact that they do not experience any direct threat through tourism. The islands do, however, present a suite of geodiversity that warrant dedicated conservation. Being oceanic volcanic islands, the Prince Edward Islands provide South Africans with a unique opportunity to access, study and appreciate geological and petrological samples of volcanic origin, found nowhere else in continental South Africa.

One of the specific objectives of the PEIMP is to "protect geological and geomorphological features, natural landscapes and wilderness attributes" (DST-NRF CIB, 2010). These objectives are accomplished by assigning a level of protection to sensitive areas through management zones 1 to 5, designating the type and frequency of activity that is allowed (DST-NRF CIB, 2010). Permits are required for any type of activity in these management zones, but as the zone level increases, the measure of protection increases and the type of activities allowed becomes restricted: from general maintenance or service works in Zone 1, to exclusive and rare scientific studies in Zone 5 (De Villiers and Cooper, 2008). Marion Island is divided into protective zones 1 to 4, while the entire Prince Edward Island is demarcated Zone 5. On Marion Island, Zone 4 represents a zone of limited access where all sites potentially sensitive to human interference are demarcated as areas for restricted activity (DSTNRF CIB, 2010). These sites include some breeding and study colonies of pelagic bird and penguin species, and sites of historical significance or sensitive geological features (DST-NRF CIB, 2010). The PEIMP further stipulates protocols for the collection of geological samples from the islands and lists certain geological features for conservation within Zone 4 (Marion Island limited access zone) and Zone 5 (Prince Edward Island protected area). However, the scope of what is meant by removable "geological samples" is not specified and only "lava

Figure 2. The main geological surfaces found at the Prince Edward Islands (A) grey and black lava outflows and scoria cones. On Marion Island features of importance for geoconservation include (B) lava tubes, (C) lava tunnels, (D) stalactite-type features found in lava tunnels, (E) modern lava flows and (F) lava bombs. (G) Features of geoheritage value on Prince Edward Island. See Figures 5 and 6 and text for details.

tunnels" and "tubes" are listed for geoconservation (DST-NRF CIB, 2010). Omission of such detail has in the past created conflict between policies and geoheritage management in (continental) South Africa (e.g. Cairncross, 2011).

Common threats to the preservation of geodiversity are anthropogenic impacts and climate change (Bétard and Peulvast, 2019). Human activities can include anything from mining and urbanization, to that of amateur souveniring or tourism (Bétard and Peulvast, 2019; Gray, 2019) and, to a lesser extent, unethical research practices. Notwithstanding the difficulty in quantifying or evaluating geodiversity, geoconservation becomes challenging when it tries to maintain the benefits it provides to society (Gray, 2019) whilst preserving or promoting sustainable use of the geological feature/resource (Erikstad, 2013). Fortunately, on the Prince Edward Islands human activities such as 'tourism' or 'infrastructural development' are already restricted by legislation and the PEIMP. Still, the islands are not free from human impacts. The main anthropogenic threats to the islands' geodiversity are by trampling, the unauthorised collection of specimens (i.e. souveniring) (Cooper, 2008) and graffiti. The impacts of (human) trampling on Marion Island's vegetation have already been highlighted by Gremmen et al. (2003) but investigations on the significance of such impacts on geological (and geomorphological) landforms, is lacking. Climate change does not pose an immediate threat to geological diversity, but the effects on geomorphological features as another element of geodiversity have been noted (see Boelhouwers et al., 2003; Sumner et al., 2004; Hedding, 2008; Nel, 2012). Although there is currently little to be done about curbing the impacts of climate change, it is possible to control anthropogenic impacts by limiting activities such as trampling and graffiti, through designating restricted zones and by explicitly identifying certain geological specimens for elevated protection status.

Materials and methods

In order to produce the improved surface geological maps of the Prince Edward Islands, the geology layer shapefile of Hedding (2006) and high-resolution satellite imagery and a digital surface model (DSM) were used for mapping in ArcGIS®. The mapping process was coupled with field observations for ground truthing purposes, and a record of geologically sensitive features for the attention of geoconservation initiatives was compiled. All the mapping and image processing was completed in a Transverse Mercator projection (WGS '84 datum) with longitude 37°E (Lo37) as the central meridian. The DSM was developed in 2019 by the National Geo-spatial Information Directorate of the South African Department of Rural Development and Land Reform through photogrammetry using stereo Pléiades imagery. This DSM, with a 1 x 1 m cell size resolution and vertical accuracy of 0.7 m, was imported into ArcGIS® and used to generate a hillshade raster and drainage lines (see Figure 3C). The hillshade was generated using the 'Hillshade' tool, accepting default parameters. The drainage lines were generated using the 'Hydrology' tool sets by first generating 'Fill', then 'Flow Direction' and then 'Flow Accumulation', the last with a conditional >50 000 parameter (Figure 3C). Satellite imagery from Quick Bird (QB), WorldView 1 (WV1) and WorldView 2 (WV2) were imported into the GIS, using prominent confluence intersections from the calculated drainage lines as reference points for georeferencing. The QB imagery was captured on 27 August 2009 and has a 2 m cell-size resolution; the WV1 was captured on 15 May 2011 with a 0.5 m resolution. Imagery from WV2 was captured on 11 January and 6 May 2012 and has a resolution of 0.5 m and 1.8 m for panchromatic and multispectral imagery, respectively. It covers all of the Prince Edward Island but only parts of Marion Island (Figure 3A). The WV2 panchromatic and a true colour image, comprising Blue (450 to 510 nm), Green (510 to 580 nm) and Red bands (630 to 690 nm), was primarily used during the mapping process (Figure 3B). The QB and WV1 imagery were consulted for the regions on Marion Island not covered by the WV2 imagery. The original shapefile of Hedding (2006) was modified in the GIS, adjusting polygon boundaries, creating new features where needed and recategorizing existing features. The hillshade model was used to identify slope breaks (e.g. the edge of a scoria cone), whereas the satellite images were used to identify changes in surface colour or texture (e.g. between grey and black lava) which aided the delineation and interpretation of surface geology (Figure 3B to D). These interpretations were supplemented with aerial photographs from 1988 (South Africa, 1988), maps from earlier geological surveys (Verwoerd and Langenegger, 1968a; Hedding, 2006) and nearly two decades of ground observations (e.g. Nel, 2001; Hedding, 2006; Rudolph, 2020; Nel et al., 2020). The classification system used by Verwoerd (1971:49), wherein the older Pleistocene lavas are referred to as 'grey' and the younger Holocene lavas as 'black', was maintained due to its established use amongst earth scientists (e.g. McDougall et al., 2001; Hall et al., 2011; Nel et al., 2020).

Lastly, to develop the scope of geoconservation in the PEIMP, a record of documented geological features was evaluated from existing publications (Verwoerd, 1971; Hedding, 2008) and field observations. Geomorphological or pedological features were not included in this evaluation. A list of features considered to be at risk to anthropogenic impacts or valuable in terms of their rarity (see Cairncross, 2011), or heritage value (see IGGP, 2012; Erikstad, 2013; Gray, 2019) was compiled. In addition, where possible, the approximate locations of these geological features, except for removable specimens, are given based either on coordinates obtained in field or identification from the satellite imagery.

Results and discussion

Improved spatial accuracy and detail of geological maps

The spatial accuracy and detail of geological maps for the Prince Edward Islands were improved by remapping the surface geology onto a DSM with a 1 x 1 m spatial resolution, and using high-resolution satellite imagery and digital elevation data coupled with ground truthing. The spatial data of these maps are available in digital form as ESRI layer packages under the supplementary data associated with this paper.

Presented here are improvements made to the spatial representation of the surface geology, and simplifications of the classification system used in the original maps by Verwoerd and Langenegger (1968a, 1968b) and subsequent improvements by Hedding (2006) (see Figures 4, 5 and 6). The total surface area cover of each geological class (presented for the first time) on Marion and Prince Edward Island is shown in Table 1.

The accuracy with which features are mapped in Marion Island's Central Highland (above 750 m a.s.l.), along the west coast and especially for the modern lava flows, was increased (see Figure 4). On Prince Edward, the spatial accuracy of the geological units was also improved. The geological classification of Verwoerd (1971) and Verwoerd and Langenegger (1968a, 1968b) was maintained as far as the three different rock 'types' are concerned (grey and black lava, and scoria cones) (Figures 2A and 4). The main motivation for keeping this classification system, other than its established use (e.g. McDougall et al., 2001; Hall et al., 2011), is that the distinction between the two lava types is generally easy to observe in the field. At specific sites where the lava types could not be visibly identified (see Verwoerd, 1971:48) the original classification by Verwoerd and Langenegger (1968a, 1968b) was used. Where Verwoerd (1971) categorised the black lava flows into four groups based on superposition, here the features were all grouped into a single geological unit while still digitising the outline of individual black lava flows (Figure 4).

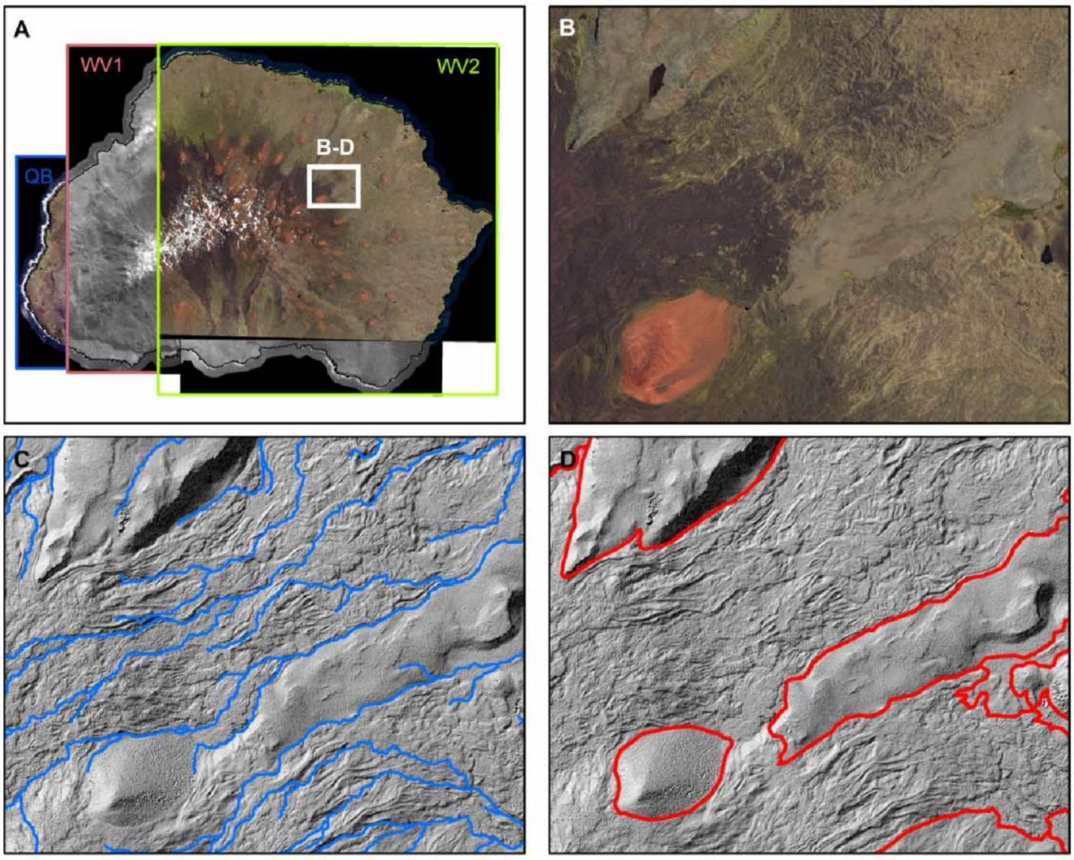

Figure 3. A comparison of the available data sources: the spatial coverage of satellite imagery for Marion Island: (A) the Quick Bird (QB), WorldView 1 (WV1) and WorldView 2 (WV2) imagery. (B) The imagery, e.g. WV2, used along with (C) the DSM derived hillshade and drainage lines to (D) delineate the surface geology.

The purpose of this paper is to present a map that refines the delineation of the surface geology and Verwoerd's (1971) subcategories make no inference on absolute age or petrological properties of the black lava flows. Our approach also avoids the assumption that similarly grouped flows are supposedly of similar ages. Further, the labels 'Pleistocene' and 'Holocene' previously used to distinguish grey and black outflows (see Le Roex et al., 2012) are not used, as recent findings from 36Cl exposure age dating (see Rudolph et al., 2020) suggest that a review of the 'Holocene outflows' age bracket is needed (Nel et al., 2020).

Scoria cones were digitised based on Verwoerd's (1971: 46) classification, which depends on shape or an associated process. Single "conical" cones were generally easy to demarcate whereas cones with indistinct topographical breaks, or loose scoria around the outer edges, were treated as "modified" cones (e.g. Hendrik Fister's Kop on Marion Island, see Figure 4B1 and 2). The process-origins of the cones were not investigated and the surface cover was classified as 'wind-blown ash' only if Verwoerd (1971) assigned this classification. Otherwise, it was merely designated as 'scoria'. For classification purposes, "breached" cones were connected to their associated lava flow, from either the centre crater or a side vent (e.g. Marion Island's Junior's Kop, see Figure 4B1 and 2) while "composite" cones (e.g. Marion Island's Hunchback, see Figure 4A1 and 2) were

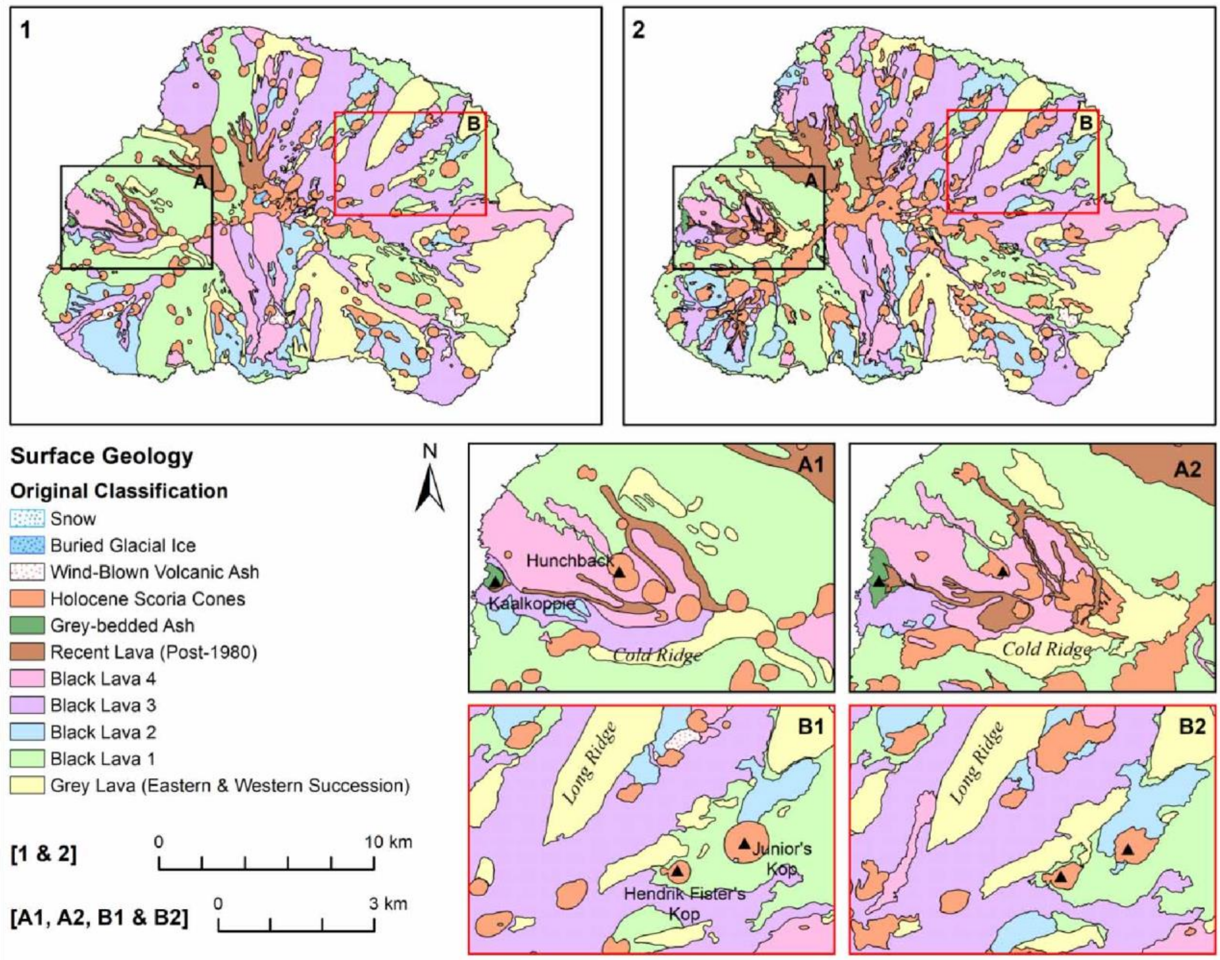

Figure 4. (1) The original digitised geological map of Marion Island with the original classification and colour scheme used by Verwoerd and Langenegger (1968a) and Verwoerd (1971) with modifications by Hedding (2006). (2) The new geological surface map using the original colour classification scheme for comparison. Improvements include (A1) and (A2) the spatial accuracy and detail of the mapping of lava flows on the western escarpment and (B1) and (B2) the representation of black lava flows and scoria cones. Map projection: Transverse Mercator Lo37.

digitised as a single entity of continuous scoria cover. The greybedded ash cones mapped by Verwoerd and Langenegger (1968a, 1968b) were subsequently described as bedded ash, or grey tuff cones, by Verwoerd (1971:52, 58, 59). We used the initial classification (grey-bedded ash) for Marion Island's Kaalkoppie (see Figure 4A1) and Prince Edward's Vaalkop and Kent Crater (Figure 6). Several new features (previously unmapped) were delineated from the imagery, including scoria cones on the south west coast (Figure 4A2 and B2) and grey lava surfaces in the Central Highland.

The maps of the surface geology and their associated spatial data layer packages presented here will aid in the increased precision of field investigations, spatial analyses and modelling in both biotic (e.g. Dilley et al., 2019) and abiotic (e.g. Hedding et al., 2015) studies. Researchers can employ these spatial data layers to extract suitable sampling points and, coupled with topographical data, detect smaller scale variations that need to be avoided (or included), before fieldwork commences. It is prudent to highlight that the present classification of surface geology is based on rock colour and/or texture and not petrological or age-dating determinations. Improved spatial coverage of petrological studies and formation age-dating of lava flows and scoria cones are needed to better differentiate between geological units where colour or texture may be misleading (e.g. Verwoerd, 1971: 48); particularly since improvements in dating techniques, e.g. Ar-Ar or U-series, have been made since the studies of Verwoerd (1971), Kable et al. (1971) and McDougall et al. (2001). Only once such studies have been completed will it be possible to develop a more refined classification system and establish better temporal constraints on the island's volcanic origin and evolution.

Geodiversity of the Prince Edward Islands

Lava tunnels are open-ended tubes or passages within a lava flow, formed as the surface cools sufficiently to form a crust, creating a roof below which the more mobile lava can continue to drain (Whittow, 2000) (Figure 2B). In certain instances, the tunnel ceilings also comprise small stalactite-type lava features (Figure 2D). The value of these features rests on the three aspects of rarity, heritage or scientific value and their sensitivity to human impacts. Lava tunnels and tubes on the islands are protected under the PEIMP (Zone 4) (DST-NRF CIB, 2010) and they are extremely rare. They have only been documented on Marion Island at two localities. Furthermore, they have intrinsic scientific value as the entrances of the tunnels provide unique environments for lichen and moss to colonise (see Medeiros and Howarth, 2017; Acosta, 2019) and they further act as sediment traps, which may harbour interesting dust or pollen records from palaeo-climates. The tunnels and tubes are also fragile and can easily be damaged through trampling and some stalactites have already been subjected to plundering at some localities.

Other geological features that should be regarded as important elements of geodiversity include large landforms as well as removable specimens. Marion Island's Pyroxene Kop (Figure 5) and Prince Edward Island's Wolkberg (Figure 6) are scoria cones with exceptional petrological value in terms of the volcanic evolution of the island (see Verwoerd, 1971; Roberts et al., 2019). These cones are not necessarily vulnerable to trampling, but to the removal of specimens which are found on, or in close proximity to, these cones. Such geological specimens include, but may not be limited to, pyroxene megacrysts and lava bombs (Figure 2F), which have been subjected to souveniring and (un)authorised sample collection. Pyroxene crystals and lava bombs could be considered rare in their abundance and as features of a particular shape or form (see Cairncross, 2011). Other features of interest, again found only on Marion Island, are the modern-day lava flows and ash cones (Figures 2C, 4A1 and 5). Since their age is known and documented (Verwoerd et al., 1981), these landforms provide pristine laboratories for studying real-time ecological colonisation by island species. However, their scientific value only remains for as long as they are undisturbed by trampling. Unfortunately, hiking routes are already established across some of these ash cones (e.g. Kaalkoppie, see Figure 5), but there is an opportunity to conserve less frequented higher-lying lavaflows, like the 1980 flows originating inland of Hunchback (Figure 5).

Geoconservation at Marion Island is rightly recognised by the PEIMP (DST-NRF CIB, 2010), but can be strengthened by designating a few additional areas under the protection of Zone 4 restrictions (see Figure 5, inset). For example, we suggest that a radius of 20 m around known lava tunnels and tubes should be demarcated as Zone 4 to sufficiently avoid trampling. In addition, one of the modern lava flows behind Hunchback, should also be designated Zone 4 to enable long-term ecological succession studies (see Figure 5, inset). To protect rare geological specimens, it would be prudent to implement more severe restrictions on the collection and removal of lava bombs or samples from Pyroxene Kop, and not just protect these specimens under the wider "geological sample" category (DST-NRF CIB, 2010). Prince Edward Island (and all of its geological features and specimens) already

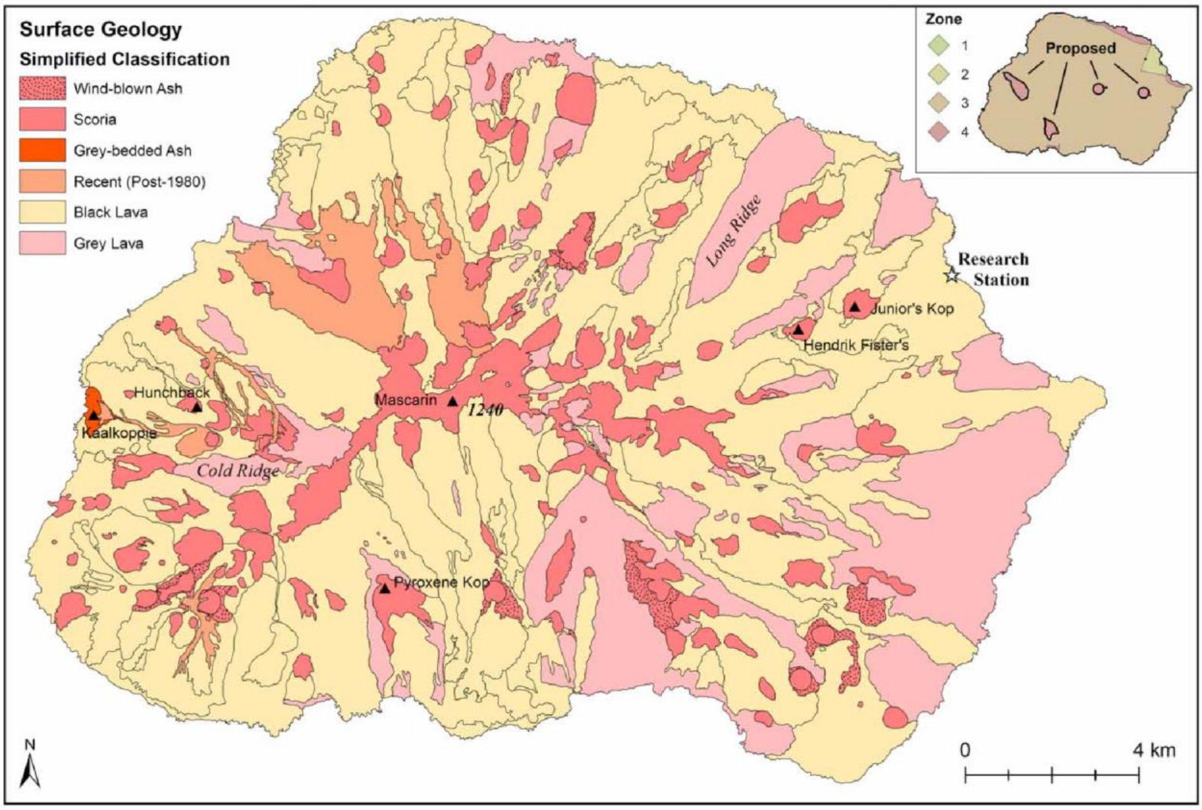

Figure 5. The improved volcanological map of Marion Island using a simplified classification scheme, adapted from the FGDC (2006) recommended colour scheme for volcanic features. The inset shows the current PEIMP conservation management zones (DST-NRF CIB, 2010) and four new locations proposed for Zone 4. Map projection: Transverse Mercator Lo37.

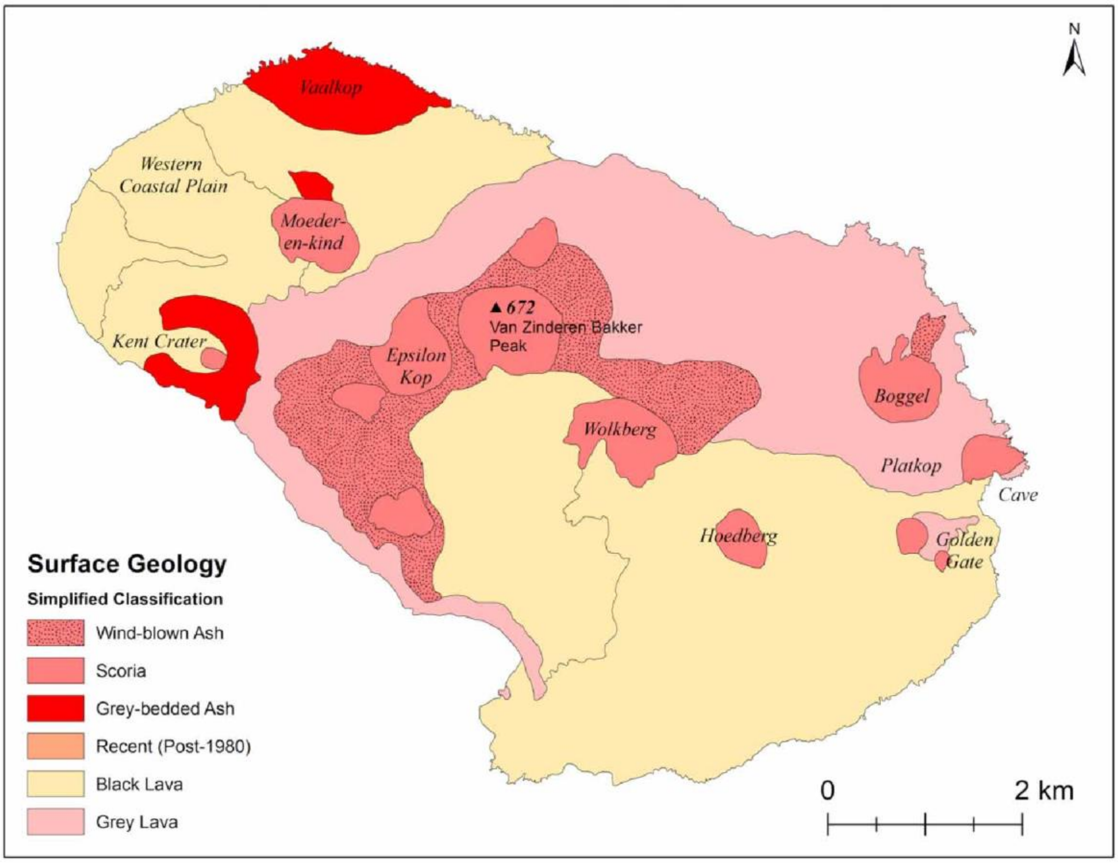

Figure 6. The improved volcanological map of Prince Edward Island using a simplified classification scheme, adapted from the FDGC (2006) recommended colour scheme for volcanic features. Map projection: Transverse Mercator Lo37.

receives the highest level of protection (Zone 5) under PEIMP (DST-NRF CIB, 2010). In addition, human visitations to Prince Edward are already severely restricted. The island is, therefore, not under the direct threat of souveniring or trampling. However, should this status change, we recommend that specific features such as lava bombs or pyroxene crystals and any region which comprises a high(er) density of these or similar features, should receive the same level of protection (or higher) as the features on Marion Island. Specific regions that may be considered for these reasons are Kent Crater, Wolkberg and the Golden Gate (Figure 2G and Figure 6). The Prince Edward Islands may not necessarily present international value in terms of UNESCO geoheritage standards (IGGP, 2012; UNESCO 2017), but they certainly contain geological features and specimens that are scientifically valuable and rare elements of geodiversity in a South African context and should be included in future assessments of South Africa's geoheritage.

Conclusion

This paper presents maps of the surface geology of the Prince Edward Islands with improved spatial accuracy and detail that will facilitate enhanced spatial analyses and modelling across scientific disciplines. The classification scheme used here is a simplification of previous systems (Verwoerd and Langenegger 1968a, 1968b; Verwoerd, 1971), employing rock colour and texture instead of inferring differences based on formation age or petrology - for which data are lacking. On Marion Island, the mapping of surfaces above 750 m a.s.l. and the spatial rectification of the geology at lower elevations and on the west coast represent the main improvements to previous geological maps. The refinements of the mapped surface geology will enable finer-scale field investigations. In its

Table 1. The total surface area cover of the different geological units on Marion and Prince Edward Island. Area was calculated in TM Lo37 projection.

Marion Island		Prince Edward Island	
Geological Unit	Surface Area (km²)	Geological Unit	Surface Area (km²)

Black Lava	183.29	Black Lava	23.16
Grey Lava	58.24	Grey Lava	11.46
Scoria	37.15	Scoria	4.21
Wind-blown Ash	3.41	Wind-blown Ash	4.24
Grey-bedded Ash	0.35	Grey-bedded Ash	2.02
Black Lava: Post 1980s	11.58		

digital form, the spatial data will aid in studies that aim to model various biotic and abiotic interactions. There remains a need for further research to improve the spatial coverage of petrological studies and age-dating of the basalts to enhance future geological maps of the Prince Edward Islands. This paper further includes a description of rare and / or unique geological features and specimens on the Prince Edward Islands that are of significant geoheritage value for South Africa. For large features such as lava tunnels, tubes and at least one of the 1980s lava flows, we recommend a Zone 4 designation to protect their structure. Whereas removable specimens such as lava bombs or rock samples associated with, for example, Marion Island's Pyroxene Kop or Prince Edward's Kent Crater, can be protected with more prescriptive collection restrictions. It is hoped that this new information will lay the foundation for a more comprehensive geoconservation strategy that will protect the geodiversity of the Prince Edward Islands.

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