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RESEARCH ARTICLE

Geological evolution and construction of a glacierized active intra-oceanic arc volcano: Visokoi Island (South Sandwich Islands)

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Abstract
Visokoi is a small volcanic island in the remote South Sandwich Islands and is unique in being dominated by the basaltic andesite products of highly explosive eruptions. Here, its geology is described in detail for the first time and can be used to characterize the construction of an active glacierized volcano in an intra-oceanic volcanic arc setting. More than 90% of the volcano is submarine and is composed of (1) a ~ 2.5 km-high mound formed of pillow lava and tuff breccia flanked by a low apron of mass flow deposits, together with (2) an overlying unit ~ 200 m thick composed of Surtseyan volcanic products representing a shoaling (and ultimately emergent) volcanic stage. The succeeding island commenced as a small volcanic shield composed of subaerial ʻa ʻā lavas whose construction terminated in a caldera collapse that repressurized the magma chamber, presaging a major transition to highly explosive pyroclastic eruptions. They were mainly of sub-Plinian and Plinian type and their recognition on the island provides the first viable explanation for the presence of compositionally similar marine tephras sampled by drilling > 500 km from source, previously considered enigmatic. Eruptions probably took place under ice-poor conditions but evidence for quenching of juvenile clasts suggests that the magmas interacted with water high in the conduit sourced from melting of a small ice cap. The major period of high-discharge sub-Plinian and Plinian eruptions appears to have ended and any future events shall probably comprise small-volume eruptions forming Strombolian scoria cones or glaciovolcanic tuff cones.

Keywords Pillow mound · Strombolian · Surtseyan · Violent-Strombolian · Sub-Plinian · Plinian · Lateral collapse · Marine tephras · Magma-water interaction

Introduction

Visokoi Island is one of the northernmost of the South Sandwich Islands, a chain of emergent active volcanoes situated between the very deep South Sandwich Trench and the East Scotia Sea back-arc spreading centre, at the junction between the Southern Ocean and the South Atlantic (Fig. 1; Larter et al. 2003; Leat et al. 2003, 2016). The southern islands were discovered by Cook in 1775 and the northern Islands (including Visokoi) by Bellingshausen in 1819 (Holdgate 1963). The island group is one of the world's best examples of an intra-oceanic volcanic arc (Pearce et al. 1995; Leat et al. 2003). Studies have focussed mainly on the petrology of lavas of the islands and their importance for models of the formation of intra-oceanic arc magmas and evolution of continental crust, because of their isolated location far from an influence of continental sediments on the subduction system. As a result, the petrology is established and relatively well understood.

By contrast, volcanological details of the islands are sparse (Holdgate and Baker 1979; Tomblin 1979; Smellie et al. 1998; Allen and Smellie 2008), and it is unknown how the islands compare with other intra-oceanic arc systems in their volcanic evolution under a glacierized climatic regime. Overviews of the submarine morphology of the South Sandwich arc and back-arc have been published, showing the major volcano-tectonic structures and morphological development (Leat et al. 2010, 2014, 2016). The islands have also been cited as the likely sources of numerous marine tephras recovered by drilling in the South Atlantic region

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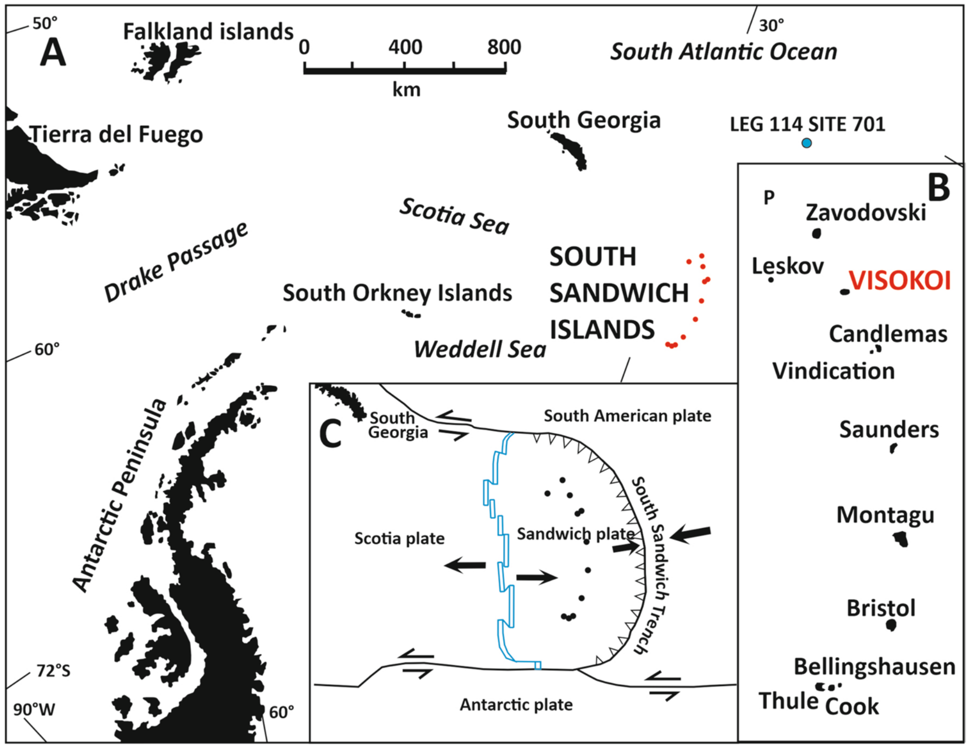


Fig. 1 Maps showing A. the location of the South Sandwich Islands (islands shown as red dots); B. the position of Visokoi Island within the island group (P = Protector Shoal); and C. the simplified tectonic setting (after Vanneste and Larter 2002). The location of ODP Leg 114, site 701 (the site where Quaternary marine tephras were recovered), is also shown

and East Antarctica, based on a broad petrological similarity (Ninkovich et al. 1964; Ciesielski et al. 1988; Hubberten et al. 1991; Basile et al. 2001). Yet the only published volcanological information on the islands (e.g. Baker 1990) suggests that they are overwhelmingly composed of lavas and Strombolian deposits lacking sufficient eruptive energy to disperse tephras the hundreds to thousands of kilometres to where they have been recovered (Holdgate and Baker 1979; Tomblin 1979; Baker 1990; unpubl. information of the authors). Tephras are extremely useful in ice core, marine and lacustrine stratigraphical correlations, using their elemental and isotopic compositions as ‘fingerprints’ (e.g. Basile et al. 2001; Hillenbrand et al. 2008). Thus, an enigma exists, and has been unexplained for more than 60 years, in identifying the source(s) of many of these distal ashes.

In this paper, the geology and eruption characteristics of Visokoi Island are described and used to illustrate the geological evolution and construction of a mafic volcanic edifice within a classic intra-oceanic island arc in a sub-Antarctic setting. Our study determined that Visokoi volcano is unique in the South Sandwich archipelago in being dominated by an unusually thick accumulation of red-brown-coloured, often ash-rich pyroclastic deposits erupted under sub-Plinian and Plinian conditions. For the first time it can therefore be considered a viable source for at least some of the tephras described by others. There is also evidence, which we discuss, that the volcano has undergone at least two caldera collapses, including one of the youngest calderas on Earth, which probably formed ~ 1829 CE.

Tectonic setting

The South Sandwich Islands are situated on the small Sandwich plate, which is converging with the South American plate at 70–85 mm yr^{-1} (Fig. 1; Pelayo and Wiens 1989). Much of the plate was formed by oceanic spreading along the active East Scotia Ridge back-arc spreading system. According to Larter et al. (2003), the spreading began at least 15 Ma ago, making it the world’s longest lived extant back-arc basin. The islands comprise one of the world’s best-defined intra-oceanic island arc systems. It is dominated by mafic magmatic compositions, with lesser dacites and andesites (Fig. 2; Baker 1978, 1990; Pearce et al. 1995; Leat et al. 2003, 2004; Kürzinger et al. 2023). They form the eastern boundary of the Scotia Sea and are composed of 11 volcanic islands, although numerous additional submarine volcanic centres are also present (Leat et al. 2014). The South Sandwich Trench, situated ~ 150 km east of the island arc, is one of the world’s deepest (> 8000 m). The comparatively well-understood simple tectonic setting and dominance of mafic magmas make the islands an excellent natural laboratory for studying the relative influence of the subducting slab and associated oceanic sediments on the mantle wedge in an absence of continental contamination (Pearce et al. 1995; Leat et al. 2003, 2004).

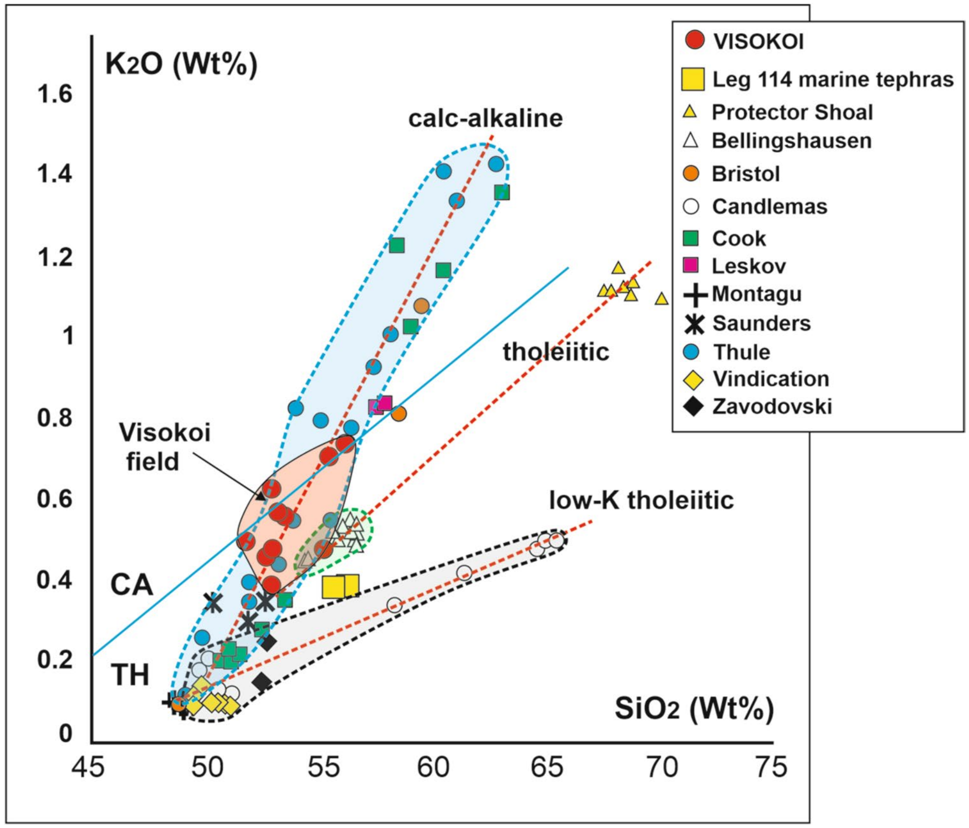


Fig. 2 Plot of K_2O versus SiO_2 illustrating the magmatic affinities and lineages of lavas in the South Sandwich Islands and Visokoi Island in particular. Data for sideromelane in Quaternary tephras recovered during ODP Leg 114 are also shown (from Hubberten et al. 1991; see Fig. 1 for location). Note that unquantified seafloor alteration (leaching) affecting K in the marine glasses will affect their position in this diagram and a greater similarity with Visokoi lavas is likely. Labelled lineages are modified after Pearce et al. (1995) and Leat et al. (2003). Visokoi Island lavas form part of the calc-alkaline lineage. CA – calc-alkaline; TH – tholeiitic

Geological background

The South Sandwich Islands formed as a result of subduction of the South American plate westwards beneath the Scotia Sea. Petrologically, they are dominated by tholeiites. At least three magmatic lineages can be distinguished (Fig. 2; Pearce et al. 1995; Leat et al. 2003, 2007). Lavas on Candlemas and Vindication islands form a prominent low-K tholeiite lineage that is also distinguished by high ratios of fluid-mobile trace elements relative to less fluid-soluble elements (e.g. Ba/Th; Leat et al. 2003). Lavas on Zavodovski and Montagu islands may follow a similar trend. Other islands, including Cook, Thule and Bristol (Freezland Rock) define a calc-alkaline trend. An intermediate tholeiitic trend is well-defined in lavas from Bellingshausen Island and some pumice-like blocks dredged from Protector Shoal seamount. Samples from Visokoi Island occupy a position in Fig. 2 favouring a calc-alkaline affinity.

The islands form the summits of large submarine edifices with basal diameters up to 25 km that rise from bathyal depths of ~ 2500 m. The larger edifices and many submarine centres are prominently elongated along northeast—southwest and east—west axes, probably reflecting a structural control on the Sandwich plate. The individual islands are small, typically just 4–8 km in diameter but varying from 900 m in diameter (Leskov Island) to ~ 20 km (Montagu Island). The summit elevations vary from just 250 m above sea level (m asl; Bellingshausen Island) to 1400 m (Montagu). Only four isotopic ages are published, ranging from 3.1 ± 0.1 to 0.3 ± 0.1 Ma, all by K–Ar (Baker et al. 1977) and the islands are believed on morphological grounds to be generally < 1 Myr old (Baker 1990).

Because of their remoteness, extensive ice cover and continuous cliff coastlines, the islands have been subject to only two substantive geological campaigns, in 1964 (3 weeks; Holdgate and Baker 1979) and January—February 1997 (6 weeks; this study). Brief geological visits to individual islands, usually only involving a few days, have also occurred (e.g. Derrien et al. 2019; Liu et al. 2021) but none have visited Visokoi because of its inaccessibility. All of the islands have recorded historical and recent volcanic activity apart from Leskov Island (disputed observation) and Cook Island (Baker 1990; Patrick et al. 2005; Patrick and Smellie 2013). Mount Michael, on Saunders Island, is also distinguished by the intermittent presence of a lava lake discovered during the present investigation (Lachlan-Cope et al. 2001), and validated by further satellite observations (Patrick and Smellie 2013; Gray et al. 2019; Global Volcanism Program 2021; see also Liu et al. 2021).

Visokoi Island measures 8 km by 5 km and rises to ~ 1200 m asl at Mount Hodson (Fig. 3). It has an oval shape in plan view, with tall cliffs on its north, west and

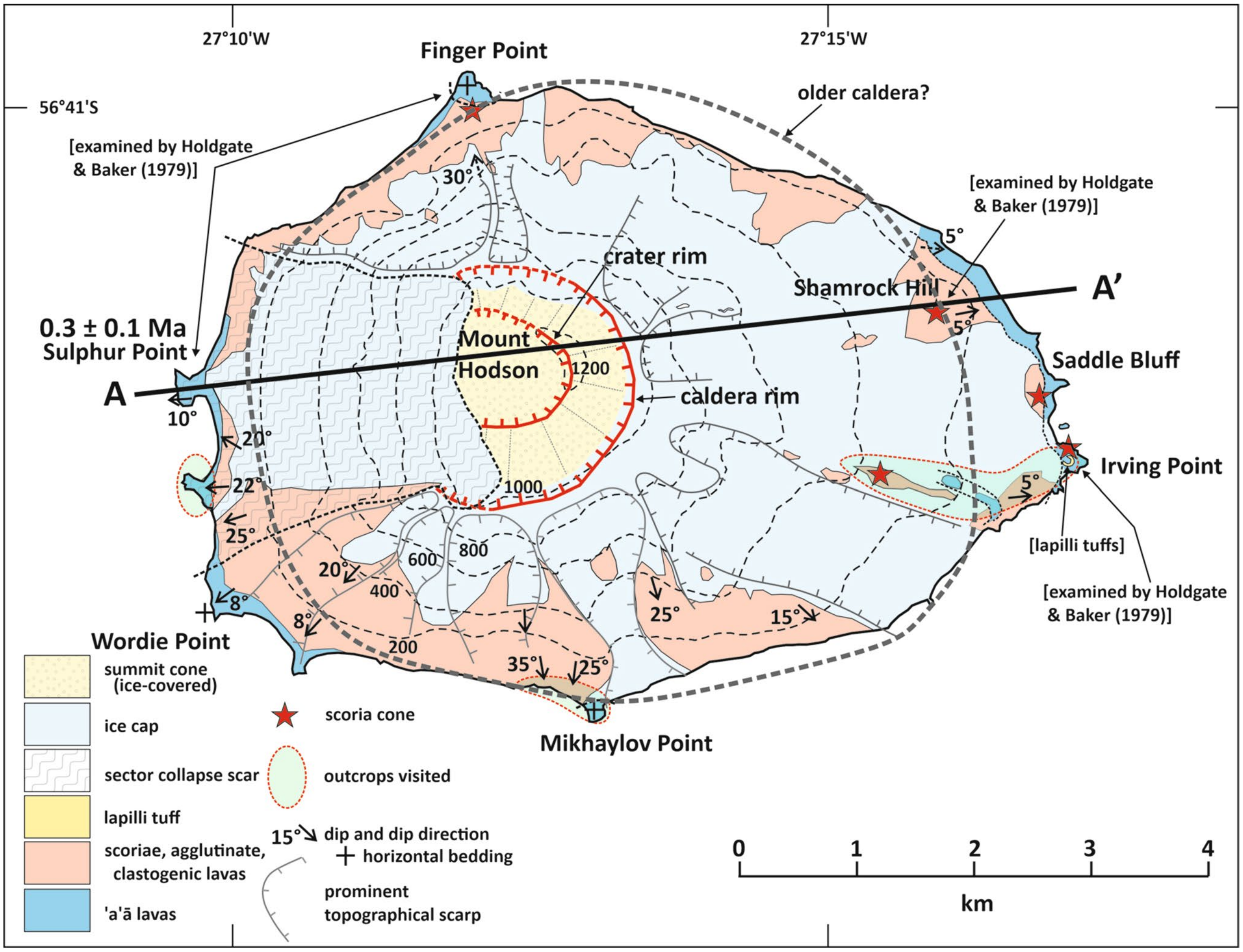


Fig. 3 Geological map of Visokoi Island. The topography and contours (in metres) are after Leat et al. (2014, modified). Volcano-tectonic features are also shown. A—A' = line of section used in Fig. 12

south sides due to enhanced marine erosion caused by the predominant winds coming from those directions (Kemp and Nelson 1931; Holdgate and Baker 1979), tapering off to low-elevation Irving Point in the east. Original estimates of the summit elevation, by Kemp and Nelson (1931; ~ 915 m asl) and Holdgate and Baker 1979; ~ 1005 m asl), respectively, are superseded by that of Leat et al. (2014; 1209 m asl; see Methodology section). The island is a single stratocone with a classic inverted-cone shape comprising asymptotic, concave-up flanks that steepen upward signifying eruptions almost exclusively from crater(s) at the apex. It represents the subaerial portion of a much larger edifice extending to a depth of ~ 2500 m below sea level (Leat et al. 2014). The island is largely covered by ice generally 30–70 m thick (authors' estimate) but increasing to ~ 80 m in fringing ice cliffs (Kemp and Nelson 1931). The glacial cover forms a prominent ice cap terminating in hanging and tidewater glaciers (Fig. 4). The ice extends down to sea level everywhere except at isolated and small rocky headlands, mainly in the west and east (e.g. Sulphur Point, Wordie Point, Irving Point, Saddle Bluff), making it one of the most heavily ice-covered in the South Sandwich Islands.

Visokoi is generally inaccessible due to the steep encircling ice and rock cliffs, and the rare narrow boulder beaches are subject to continual crashing waves and a strong undertow (Kemp and Nelson 1931, and authors' observations). Geological knowledge of the island is slim. Supplementary Information Table S1 lists the visits known to have occurred in which information useful to understanding the geology of the island was obtained. The historical observations indicate that the Visokoi volcano is active, with plumes observed from the summit on more than one occasion (see section on 'Mount Hodson caldera and post-caldera activity', below). Kemp and Nelson (1931, pp. 164) reported that the cliffs on Visokoi were formed of '*red and grey rock*, *sometimes stratified*

Fig. 4 View of Visokoi Island with the summit typically shrouded in cloud. The photograph demonstrates well how generally inaccessible the island is (see also Fig. 7). View looking north with selected named localities indicated. Photograph provided by FI RAF 1312 Flight

and frequently intersected by vertical dykes'. In their account of all the islands, they suggested that, in general, the islands were founded on a circular lava platform (as exemplified by Zavodovski Island), which, however, they said was absent on Visokoi. This account was enhanced by Holdgate and Baker (1979), who described interbedded lavas and pyroclastic rocks with consistent dips pointing out from the summit at angles of 5–20° and which were mainly erupted from the main volcanic centre at Mount Hodson. They described headlands at Sulphur Point and Wordie Point formed of lavas interbedded with red scoria and blocks whereas at Finger Point the low foreshore was formed of a '*well-preserved lava flow*' showing broadly crescentic ridges and furrows that was thought to be of relatively recent origin (Fig. 5). The lava was backed by a steep scree slope within which an eroded scoria cone cropped out and a second, petrologically different and older lava cropped out on the west flank of the young lava. Local Strombolian cones were thought to be responsible for piles of reddish scoria and numerous blocks and bombs at Shamrock Hill, Saddle Bluff and a locality ~ 1.2 km west of Irving Point. A possible small crater within a 'low symmetrical dome' was identified at the latter locality. Deposits of brown ash and lapilli were also recorded at Irving Point. Mikhaylov Point was thought to be formed of morainic material but was not visited. Visokoi Island is compositionally restricted, dominated by basaltic andesites with minor basalts that together form a tholeiitic to calc alkaline magmatic lineage (Fig. 2; Table 1). A basaltic andesite lava from Sulphur Point was dated as 0.3 ± 0.1 Ma (by K–Ar; Baker et al. 1977). Although it seems reliable, there is no independent corroboration and it should be accepted with caution.

The submarine edifice has been described from multibeam data by Leat et al. (2010). It is asymmetrical, with steep slopes and deeper water in the west and gentler slopes and shallower water in the east (Fig. 6). Gradients of 5–12° characterise slopes in the north, west and south, which also have a rugged topography comprising numerous conical shapes interpreted as constructs of lava domes or cones and effusion of lavas. On the western slopes, the volcanic features are crossed by landslide chutes that pass downslope into hummocky terrain with features up to ~ 100 m high interpreted as collapse debris. By contrast, the eastern submarine flank is < ~ 500 m deep and consists of a broad (~ 15–17 km) smooth, featureless plateau that passes eastwards into an area cut by deep canyons probably generated by mass wasting.

Methodology and terminology

Access to landing sites throughout the South Sandwich Islands is limited by compulsory modern protocols for the safety of Antarctic wildlife and to avoid disturbance, including the prevention of overflying wildlife by helicopters and drones, and is enforced by the Government of South Georgia and the South Sandwich Islands (see https://gov.gs/wildlife-protected-areas/; and https://documents.ats.aq/recatt/att224_e.pdf; Derrien et al. 2019). Thus, Finger Point, which was successfully studied by Holdgate and Baker (1979) and originally designated as a target for our study, was found to

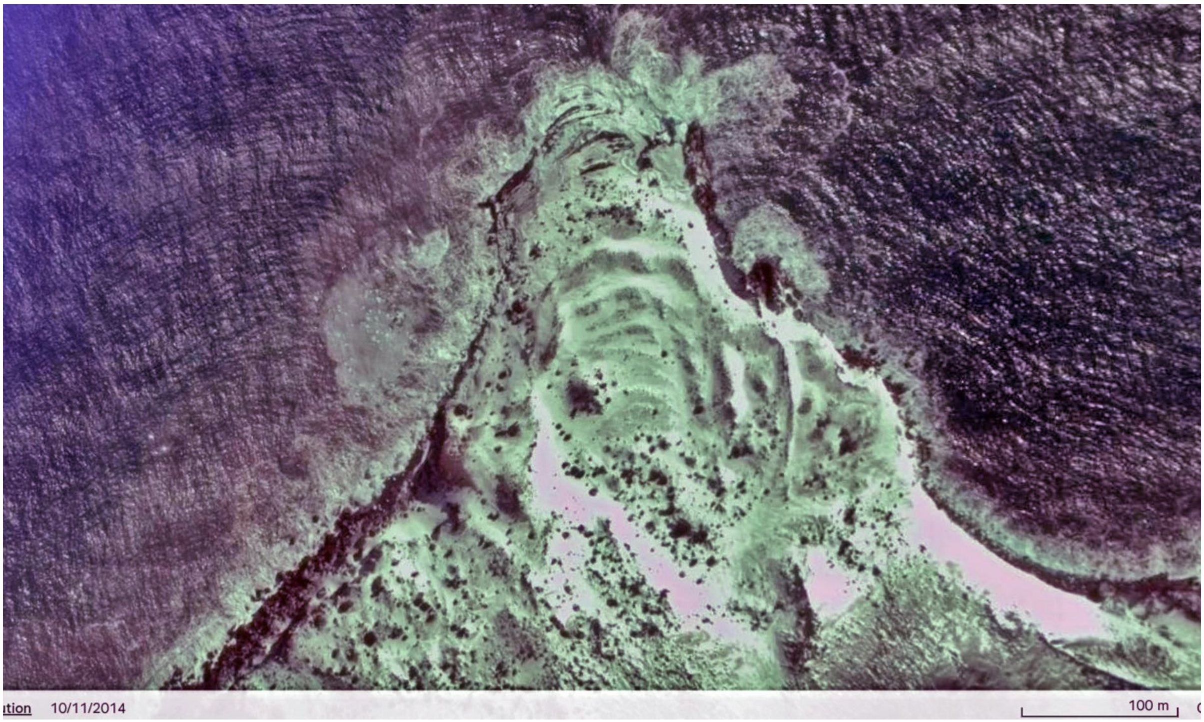


Fig. 5 Google Earth satellite image of Finger Point showing prominent arcuate flow folds on the surface of a lava flow. The lava is approximately horizontal and is interpreted as the subaerial caprock of a lava-fed delta. Data attribution: Maxar Technologies, Data SIO, NOAA, U.S. Navy, NGA, GEBCO; imagery date: 10/11/2014

be extensively occupied by penguins during the investigation and had to be omitted. However, landings by helicopter were made at Mikhaylov Point, Irving Point and a small unnamed point situated mid-way between Sulphur Point and Wordie Point (areas marked as 'outcrops visited' in Fig. 3). Thus, in addition to localities visited by Holdgate and Baker (1979), all of the accessible sites have been examined and sampled for petrography and geochemistry. Nonetheless, because of the difficult and limited access to outcrops, any studies should be regarded as essentially reconnaissance. However, the inaccessible cliffs were also observed during helicopter flights and basic interpretations were made. A short overflight of the summit was also carried out, during which the ice-covered caldera and an intra-caldera crater were discovered and photographed for the first time. Results of the petrological study of the island group were published by Leat et al. (2003), although Visokoi Island was not specifically discussed in that paper. Representative analyses of Visokoi are presented in Table 1. Bedding orientations were estimated in the field and from photographs (Fig. 3).

The new summit height for Visokoi Island published by Leat et al. (2014; 1209 m asl) was calculated using the Reference Elevation Model of Antarctica (REMA) v2 (Howat et al. 2022). The model was opened in GIS software and the highest point on the island was identified. This height was then converted from ellipsoidal to geoidal, to approximate height above mean sea level at the location (personal communication from Peter Fretwell and Laura Gerrish (British Antarctic Survey), May 2024).

The nomenclature for volcaniclastic rocks by White and Houghton (2006) is used, modified to include lapillistones (after Smellie and Edwards 2016).

Geology of Visokoi Island

Description

The geology of Visokoi Island is divided into two sequences composed of contrasting lithofacies, i.e. a basal lava sequence with an exposed thickness of ~ 150 m and an overlying scoria-rich tephra sequence at least 1000 m thick with a conspicuous dull red or red-brown coloration. Details of the volcanic lithofacies are provided in Table 2. The basal sequence was examined at the unnamed headland between Sulphur Point and Wordie Point and in the coastal crags at Irving Point. It is composed of interbedded finely crystalline 'a'ā lavas with oxidised scoriaceous autobreccias that dip gently (~ 5–10°) to seaward (Fig. 3). They are well exposed in the headlands and cliffs between Sulphur Point and Wordie Point (Fig. 7). Individual lava thicknesses vary between ~ 20 and 100 m; the thickest

Table 1 Representative whole-rock compositions of lavas from Visokoi Island*

	STAGE 2**			STAGE 3**					STAGE 5**	
Sample	SSW.9.1	SSW.10.5	SSW.10.4	SSW.2.1	SSW.4.1	SSW.5.2	SSW.12.1	SSW.12.3	SSW.6.1	SSW.6.3
Locality	Finger point	Finger point	Finger point	Irving point	Irving point	Irving point	Sulphur point	Sulphur point	Shamrock hill	Shamrock hill
SiO2	51.96	53.06	56.34	53.08	55.37	55.66	53.09	52.88	53.39	53.64
TiO2	1.19	1.01	1.26	0.97	1.00	1.21	1.22	1.21	1.36	1.35
Al2O3	15.84	19.44	14.89	18.24	15.47	15.31	15.27	15.22	14.63	14.54
Fe2O3T	12.39	9.91	12.08	10.29	12.10	11.57	13.18	12.99	13.90	13.96
MnO	0.20	0.17	0.25	0.19	0.23	0.19	0.22	0.22	0.22	0.21
MgO	5.40	3.16	3.21	4.39	3.91	4.16	4.76	4.73	4.21	4.19
CaO	10.22	10.00	7.42	9.93	8.53	8.48	9.45	9.40	8.76	8.86
Na2O	2.35	3.00	3.62	2.58	3.04	3.02	2.63	2.68	2.79	2.72
K2O	0.50	0.63	0.74	0.39	0.48	0.71	0.48	0.46	0.57	0.56
P2O5	0.14	0.12	0.16	0.11	0.10	0.14	0.12	0.12	0.13	0.13
Total	100.19	100.50	99.97	100.17	100.23	100.45	100.42	99.91	99.96	100.16
V	325	278	331	272	324	307	329	345	395	400
Cr	42	32	25	27	34	42	40	42	42	41
Ni	12	7	10	7	7	12	10	8	11	9
Co	32	23	28	30	26	38	38	37	40	35
Cu	158	67	188	51	114	163	200	124	217	207
Zn	93	75	113	78	98	89	95	99	114	117
Rb	13	13	18	9	10	19	13	13	14	13
Sr	134	199	145	155	141	150	130	133	132	134
Y	28	26	35	24	27	28	30	28	33	33
Zr	82	69	91	64	70	90	79	76	90	88

*fromPearce et al. 1995

**Stage numbers refer to constructional phases described in this paper (1—oldest; 5—youngest)

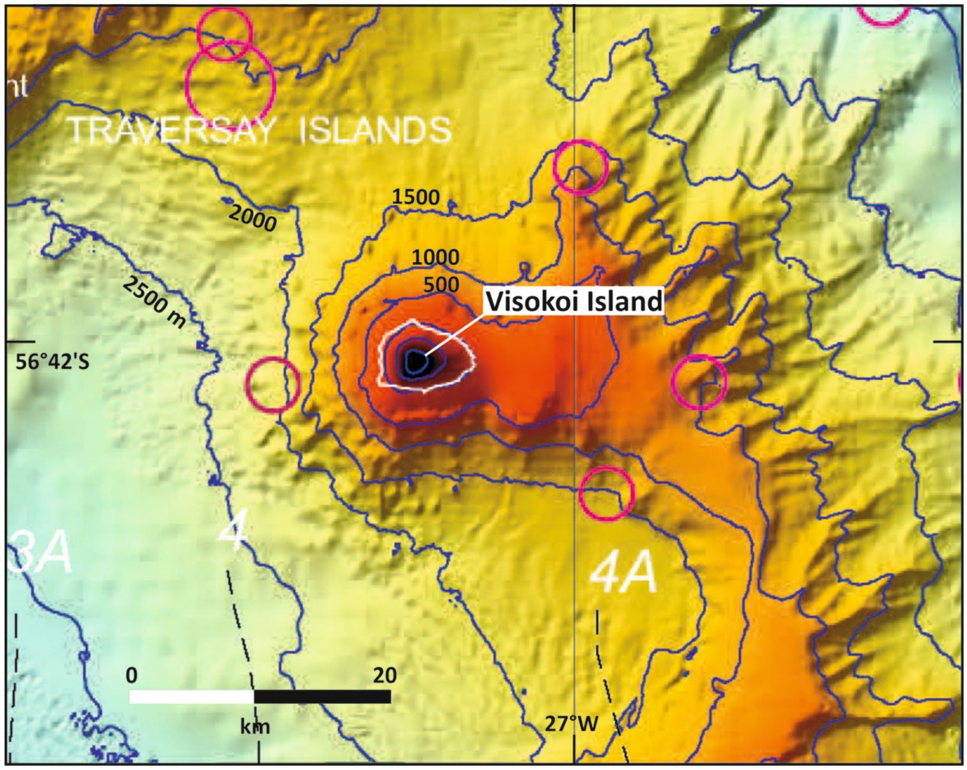


Fig. 6 Swathe bathymetry of the sea floor surrounding Visokoi Island showing the morphology of the submarine volcanic edifice. See text and Leat et al. (2010) for description. Image from Leat et al. (2014), modified

lava observed forms the prominent eastern coastal bluffs extending between Irving Point, Saddle Bluff and the bluff ~ 2 km to the north-west below Shamrock Hill. The basal lava at Wordie Point shows coarse columnar joints (Holdgate and Baker 1979; Fig. 7). The full thickness of the basal lavas is unknown. They are exposed up to at least 100–150 m asl. Mikhaylov Point is a low rocky platform formed of a sub-horizontal lava showing prominent curved ridges and furrows ('flow folds' or ogives), like those on the lava described by Holdgate and Baker (1979) at Finger Point (Fig. 5) but less continuous and with smaller amplitudes and wavelengths. Both lava outcrops have been strongly eroded by the sea and are overlain by recent beach and moraine deposits. Irving Point also contains a deposit of thinly stratified fine lapilli tuff several metres thick (probably the 6 m-thick 'brown ash with blocks' mentioned by Holdgate and Baker 1979), which may be interstratified with the local sequence there, but the field relationships are unclear.

The surface separating the two sequences is not well seen but it must be very uneven as the base of the overlying sequence of pyroclastic rocks is at ~ 100–150 m asl in the west and east but is at and below sea level in the north and south. Its geometry is unknown but the occurrence of younger rocks at significantly lower elevations in the centre of the island may indicate the presence of a caldera with a minimum diameter of ~ 5 km (north—south width of the island; Fig. 3). The outcrops and bed orientations suggest that the younger sequence may overstep the caldera margins in the west and east.

The basal lava sequence is overlain by pyroclastic lithofacies that form a second (younger) sequence which generally has substantially steeper dips than the basal lavas; dips generally increase upslope (~ 8–35°; Fig. 3). It is constructed from at least seven pyroclastic lithofacies (Table 2). Stratigraphical division is made based on lithofacies associations: it comprises a younger lithofacies association 1 composed of maroon to red scoria lapillistones, agglutinate and grey clastogenic lavas, and an older and much more extensive lithofacies association 2 consisting of dull red- and red-brown-coloured lapilli tuffs, scoria lapillistones and tuff breccias. Lithofacies association 1 crops out in several small cone relicts exposed at Irving Point, Shamrock Hill, above Finger Point and probably at Saddle Bluff, together with a large collapsed block of similar lithology measuring > 20 m across that occurs on the beach west of Mikhaylov Point (Fig. 8a). The small relict cone on the north side of Irving Point comprises a sequence ~ 70 m thick that dips to the south-west but becomes ~ horizontal eastwards. At Saddle Bluff, crude stratification dips west at ~ 10° and overlies an irregular lava surface. It may be the 'cinder cone' mentioned by Holdgate and Baker (1979) but it was not re-examined. The outcrop west of Irving Point forms a low east—west-aligned ridge formed of reddened welded scoria and prominent thick clastogenic lavas dipping gently to the east. It lacks the dome-like morphology mentioned by Holdgate and Baker (1979).

Table 2 Descriptions of lithofacies on Visokoi Island

Lithofacies*	Location	Characteristics	Interpretation	Illustration
Sheet lava [sL]	Basal lava sequence	Interbedded massive grey sheet lavas, individually c. 20–100 m thick; thicker lavas may be coarsely columnar jointed; pass up and down gradationally into breccia [lithofacies cB]	Subaerial ʻaʻā lava	Figures 7, 8b
Breccia, clast-supported [cB]	Basal lava sequence	Monomict lava breccia; fines-poor/free, finely crystalline vesicular clasts, generally red coloured (oxidised)	Lava autobreccia formed by mechanical disruption of chilled crust during flow; subaerial environment	
Lava with ghost-like clastic textures [Lcl]	Upper tephra sequence, late scoria cones	Finely crystalline pale grey lava in platy lenses and sheets variably 10 cm to 7 m thick, poorly to moderately vesicular	Clastogenic lava associated with scoria cones	Figure 8a
Basalt intrusions, irregular and sheet-like [dL]	[not applicable (intrudes all sequences)]	Pale grey finely crystalline planar sheets (dykes) 25 cm to 2 m wide, sinuous and often anastomosing, with chilled (not glassy) margins and coarse crude polygonal joints	Hypabyssal intrusive sheets (mainly dykes)	Figures 8b, 10
Interbedded scoria lapillistone and agglutinate [Lag]	Upper tephra sequence, late scoria cones	Well sorted maroon-grey scoria lapillistone essentially like lithofacies L, interstratified with agglutinate, deep maroon coloured, weakly indurated, formed of moderately to highly vesicular close-packed scoria with frothy rims, some showing expansion fractures, sometimes flattened; bombs up to 2 m long; some are poorly vesicular and have curved surfaces, spindle shapes and ropy surfaces; fines-poor/free; typically associated with clastogenic lava [Lcl]	Magmatic scoria cone deposits, formed by ballistic fall under dry subaerial conditions	Figure 8a
Lapillistone [L]	Upper tephra sequence, stratocone	Well sorted (fines-poor), monomict; lapilli blocky to cuspate; strong red coloration; massive beds, thicknesses uncertain, 0.3 m up to several m?; variably coarse tuff to fine lapilli-size (c. 2–3 mm ranging to c. 3 cm); variable proportion (to c. 10–20%) of angular lava lithic blocks rarely up to 1.3 m	Magmatic fallout deposits from sustained eruption columns; presence of dispersed angular lava blocks suggests more explosive detonations at times incorporated accessory lava fragments torn from the vent walls	Figure 11

Table 2 (continued)

Lithofacies*	Location	Characteristics	Interpretation	Illustration
Lapilli tuff [LT]	Upper tephra sequence, stratocone	Dominant lithofacies? Possibly two types, relative proportions unknown; both types strongly red coloured, in massive beds usually a few to several metres thick: LT1 dominated by coarse/very coarse tuff matrix (c. 80–85%), lapilli cuspate to often fluidal; and LT2 dominated by fine/very fine tuff matrix (85–90%), sideromelane vesicularity very variable (poor to high), with blocky to cuspate shapes; matrix sideromelane in both variants often poorly to non-vesicular, blocky, frequently tachylitic	Both lithofacies are dense (i.e. granular fluid based, sensu Branney and Kokelaar 2002) pyroclastic density current deposits; type (1) may be linked to magmatic explosivity; type (2) involves magma:water interaction	Figures 8b, 11
Tuff [T]	Upper tephra sequence, stratocone	Rare lithofacies, only seen interbedded with lithofacies LTsp; forms bed 35 cm thick, rusty red coarse/very coarse tuff, massive, with few dispersed fine scoria lapilli; poor planar stratification locally present formed of trails of scoria, few mm to 1 cm in diameter; sideromelane moderate to (mainly) highly vesicular, often fluidal	Uncertain, either fallout deposit or (preferred) product of relatively dilute magmatic pyroclastic density currents	
Diffusely stratified lapilli tuff [dsLT]	Basal lava sequence? Isolated outcrop at Irving Point (relations uncertain)	Indurated, thinly stratified (beds cm-dm thick), khaki grey fine lapilli tuff; lapilli typically 1–4 mm, up to a few cm, many abraded (subrounded), blocky to cuspate, non to highly microvesicular; c. 10% tachylite; fine to coarse tuff matrix; accessory lithic clasts absent?	Tuff cone deposits formed by deposition mainly from pyroclastic density currents; probably subaerial	
Spatter-rich lapilli tuff [LTsp]	Upper tephra sequence, stratocone	minor lithofacies; poorly sorted, monomict red-coloured deposits distinguished by abundant dark grey moderate to highly vesicular fluidal spatter clasts 2–20 cm in diameter dispersed in 50–60% matrix formed of coarse tuff to fine lapilli; some flattened spatter clasts are imbricated (c. bed-parallel); scattered bombs 50–90 cm in length	Spatter-rich ignimbrite (sensu Mellors and Sparks 1991); possibly special circumstances required for generation (see text)	Figure 8c

Table 2 (continued)

Lithofacies*	Location	Characteristics	Interpretation	Illustration
Lithic tuff breccia [TBlith]	Upper tephra sequence, stratocone	Massive, coarse breccia formed of angular blocks of crystalline mafic lava set in lapilli-rich matrix; occurs as dispersed blocks and lens-like concentrations often < 2 m in extent but ranging up a few tens of metres and 1.5–6 m thick; comprises c. 10–30% angular clasts of nonvesicular grey lava mainly ≤ 10 cm in diameter (up to 3 m by 1.5 m), some with prismatic joints or maroon scoriaceous crusts; blocks are locally clast supported but are usually contained in ruddy-orange to yellow matrix composed of monomict fine scoria lapilli and tuff with up to 30% grey poorly and highly vesicular lapilli ≤ 3 mm in diameter	Pyroclastic density current deposits formed during episodes of greater explosivity associated with vent/conduit widening	Figure 8b
Pebbly sandstone [PS]	West of Mikhaylov Point	Weakly cemented, greenish-grey, very coarse sandstone with dispersed subrounded cobbles and boulders, monomict-looking and at least 1.5 m thick	Beach deposit	Figure 11
Sandy conglomerate [SC]	West of Mikhaylov Point	C. 0.5 m of poorly consolidated, polymict sandy conglomerate with rounded to rarely sub-angular cobbles and boulders up to 50 cm in diameter (mostly < 10 cm) that are locally close-packed (almost an orthoconglomerate)	Beach deposit	Figure 11

*lithofacies notation after Smellie and Edwards (2016), modified

Fig. 7 View of Wordie Point showing a sequence of lavas. The lowest exposed lava in the foreground is ~ 20 m thick (estimated) and shows prominent coarse columnar jointing. The ice-covered slope behind Wordie Point and extending to the ridge leading down to Sulphur Point is the topographical scar left after a major sector collapse described in the text. Photograph provided by FI RAF 1312 Flight

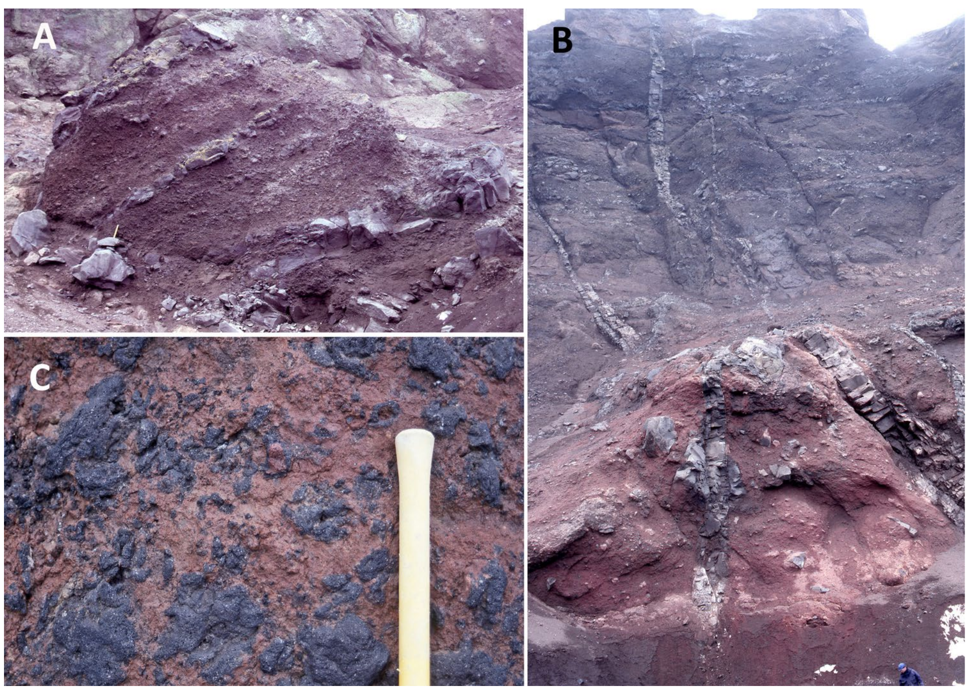


Fig. 8 Compendium of photographs of lithofacies on Visokoi Island. **A**. View of part of a large fallen block of crudely stratified maroon-coloured scoria and agglutinate with clastogenic lava lenses (lithofacies Lag and Lcl; Table 2; lithofacies association 1), west of Mikhaylov Point. The block is ~ 10 m across in the view. **B**. View of cliffs above Mikhaylov Point formed of lithofacies association 2 (mainly lithofacies LT) and showing the prominent red- to red-brown coloration, thick massive beds forming a crude ill-defined planar stratification, numerous sinuous dykes and (towards the top) a few thin interbedded lavas. Note also the dispersed large angular accessory lava blocks in the lapilli tuffs in the foreground and as breccia concentrations (lithofacies TBlith) high in the cliffs behind. Figure at bottom right gives scale. **C**. Close view of spatter-rich lapilli tuff (lithofacies LTsp); west of Mikhaylov Point. The hammer shaft is ~ 28 cm long

Shamrock Hill is a prominent mound. Based on Google Earth imagery, it is ~ 300 m in diameter and ~ 80 m high. It is composed of red scoria, blocks and bombs, with a steeper eastern (seaward) flank and a gentle western (upslope) gradient (Fig. 9). The sequence dips at ~ 15–20° to the east-northeast. It lacks a crater and Holdgate and Baker (1979) suggested that it may also be a scoria cone. Holdgate and Baker (1979) also identified a smaller scoria cone remnant

Fig. 9 Aerial view of Shamrock Hill, a small scoria cone on eastern Visokoi Island, ~300 m in diameter. Despite the dark coloration in this view, the in situ rock is maroon-red-coloured throughout. Saddle Bluff is seen at top right. The photograph illustrates well the heavily eroded state of the outcrop and lack of any primary landform that typifies all the scoria cone outcrops on Visokoi Island, probably due to erosion by a formerly much-expanded ice cover. Photo provided by HMS *Endurance*, taken in 2000

above Finger Point, similarly lacking a crater but without providing further details.

Lithofacies association 2 is much more voluminous and covers most of the island above the basal lava sequence, extending down to sea level in the north and south coasts and up to the summit (i.e. > 1000 m thick). It is largely inaccessible but was studied west of Mikhaylov Point. Although dominantly red to red-brown in colour (Fig. 8b), the rock surfaces are locally patchily stained khaki yellow. The sequence often looks massive but it consists of interbedded poorly sorted lapilli tuffs (LT; Table 2) and well sorted scoria lapillistones (L). Lenses of coarse tuff breccia (TBlith) are also frequently present but volumetrically minor. A possible intraformational unconformity was seen in the cliffs east of Mikhaylov Point and may indicate the presence of at least two eruptive vents (Fig. 10). However, the cross-cutting relationship to underlying beds suggest that the surface is more likely a slump scar produced by a local flank collapse; it is overlain conformably by further tephra deposits. Overall, the sequence seems to be continuous vertically. The proportions of the two main lithofacies are uncertain owing to the poor access and cloudy conditions but lapilli tuffs appear to predominate. They are rich in tuff matrix (~80–90%) and two types are distinguished: LT1 is characterized by highly vesicular sideromelane lapilli with cuspate and fluidal shapes and coarse tuff matrix whilst sideromelane lapilli in LT2 are variably moderate to highly vesicular with blocky to cuspate shapes and fine tuff matrix. Accessory clasts (crystalline lavas) are rare. Matrix sideromelane in both variants is

Fig. 10 View of cliffs east of Mikhaylov Point, showing a cross-cutting unconformity that may represent a scar caused by a flank collapse during the formation of the upper tephra sequence (lithofacies association 2). It is conformably draped by further tephras of lithofacies association 2. Note the crude ill-defined bedding and massive beds, some of which may be deformed by minor syn-eruptive slumping events. Numerous thin sinuous dykes are also present. The cliffs are ~400 m high (estimated)

often blocky, poorly vesicular or tachylitic. Lithofacies L, LT1 and LT2 form ill-defined, thick, planar, massive beds typically a few to several metres thick that dip radially away from the summit (Fig. 3). Additionally, a minor associated lapilli tuff lithofacies is distinguished by abundant fluidal spatter clasts (LTsp; Fig. 8c). Tuff beds (T) are thin and rare. Numerous dykes (dL) are present cutting both the basal lava sequence and upper pyroclastic sequence and are particularly prominent in the latter (Figs. 8b, 10).

Sedimentary lithofacies were only observed ~ 1 km west of Mikhaylov Point, where they crop out close to sea level (Fig. 11). They are banked against a large mass of columnar-jointed crystalline lava 5–7 m across that is probably an in situ eroded inlier of the basal lava sequence. The steep contact is interpreted speculatively as the margin of the older caldera postulated above. The sediments form two beds. The lower bed is a pebbly sandstone (PS) ~ 1.5 m thick (base obscured). It passes up gradationally into polymict sandy conglomerate (SC) ~ 0.5 m thick that is, in turn, overlain by volcaniclastic lithofacies of the upper sequence, of which the basal ~ 30 cm consists of clast-supported, massive, monomict fine scoria lapillistone (L), ruddy coloured and well sorted (fines-free), with clasts 1–2 cm in diameter. The overlying deposit comprises ruddy-coloured fines-rich lapilli tuff (LT1) with dispersed angular lava blocks.

Interpretation

The basal sequence consists of ‘a‘ā lavas whose characteristics (crystalline groundmasses, oxidised autobreccias, coarse columnar cooling joints) indicate that they were emplaced under essentially dry subaerial conditions throughout eruption of the sequence. The lavas form a platform or shield that is exposed intermittently around much of the island (Fig. 3). The lava with prominent flow folds at Finger Point was interpreted as a very young feature by Holdgate and Baker (1979), and a similar lava is now known to crop out at Mikhaylov Point. However, there are no obvious source vents in the slopes above and the field relationships with overlying volcanic deposits are unclear. The lavas are also eroded and overlain by modern beach and moraine deposits. Our preferred interpretation is that the lavas at both localities are part of the basal lava sequence, but future dating, preferably by the $^{40}Ar/^{39}Ar$ method, should provide clarification. The sub-horizontal attitudes of the lava surfaces are most easily explained if they represent the subaerial lava caprocks of lava-fed deltas, which are common features on oceanic volcanic islands (Mitchell et al. 2008; Ramalho et al. 2013).

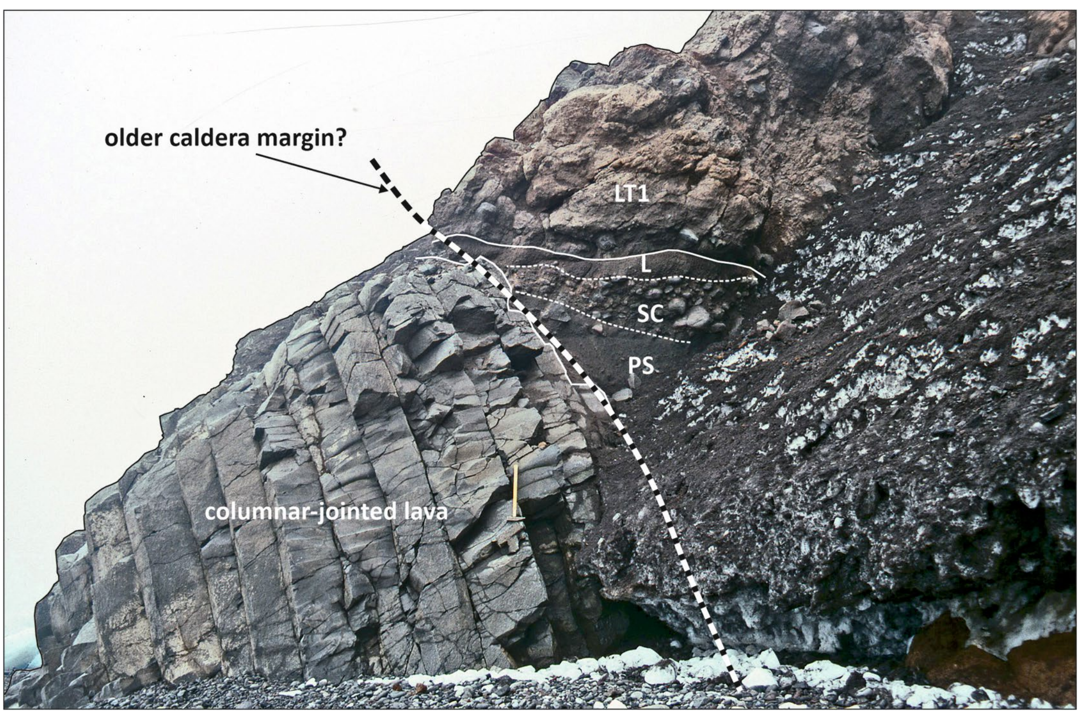


Fig. 11 View ~ 1 km west of Mikhaylov Point showing poorly consolidated pebbly sandstone and sandy conglomerate beds (PS and SC, respectively; Table 2) banked against a large mass of columnar jointed lava (lithofacies sL) of the basal lava sequence. The sediments are overlain by lapillistone and lapilli tuff (L and LT1) of the upper tephra sequence (lithofacies association 2), which also form the overlying cliffs (out of view). The steep contact with the columnar lava may be the margin of the older caldera postulated in this study. The hammer is ~ 60 cm in length

They may thus represent far-travelled lavas sourced from the contemporary summit crater (much lower at the time), which reached the sea and advanced into it. The apparent absence of pyroclastic deposits suggests that the activity during the construction of the basal sequence was dominantly effusive and that water generally did not gain access to the vent during the period. A possible exception includes the small lapilli tuff outcrop observed at Irving Point which, if interbedded with the basal sequence, may signify local violent magma-water interaction and generation of a tuff cone or tuff ring in a flank vent on the coast, as observed on many other volcanic islands (Sohn 1996; Zanon et al. 2009). A littoral cone origin is less likely. Littoral cones are often associated with lava-fed deltas, including those fed by ‘a‘ā lava. They may display features indicative of hydrovolcanic activity, including a high ash content, blocky clasts and quench textures. Deltas fed by ‘a‘ā lavas are thought to generate higher-intensity explosive hydrovolcanic activity compared with pāhoehoe, hence can contain a higher proportion of ash (Mattox and Mangan 1997), but most littoral cones are dominated by spatter (often welded), oxidised clasts, thin dispersed deposits of Pele’s hair and limu-o-Pele and other features unlike products of explosive hydrovolcanic eruptions (Jurado-Chichay et al. 1996; Mattox and Mangan 1997; Holt et al. 2021) and are dissimilar to the lapilli tuffs at Irving Point.

In the overlying tephra sequence, lithofacies association 1 is dominated by lapillistones whose general characteristics (maroon to red coloration, abundant and commonly large bombs, agglutinate, clastogenic lavas, crude lenticular stratification on a decimetre scale, paucity of fines; Fig. 8a) are characteristic of Strombolian and Hawaiian deposits in scoria cones (Valentine and Gregg 2008; Taddeucci et al. 2015). The colour is interpreted as an oxidation effect due to high heat retention (> 600 °C) during deposition, and indicative of rapid accumulation of pyroclasts under high redox conditions (i.e. in a dry subaerial setting) and reduced cooling rates (D’Oriano et al. 2013; Houghton and Carey 2015; Moore et al. 2022). Oxidation is a thermal effect that is common in vent-proximal locations undergoing rapid pyroclast accumulation and reflects a growth or alteration of iron-oxide mineral species, with their characteristic red colour. The cones form principally by ballistic fall during weak-intensity, intermittent magmatic explosions involving bursting gas bubbles, and lava fountaining. Such deposits are the products of weak magmatic explosivity and characteristically form small scoria cones with steep flanks, small craters and limited lateral extent. They constructed several flank vents on Visokoi (Holdgate and Baker 1979; Fig. 3). Despite a relatively young age (they appear to be amongst the latest eruptive products), the outcrops are highly eroded, and no primary landforms are preserved, which implies eruption in an ice-poor environment followed by substantial erosion by wet-based ice much thicker and more extensive than that present today.

Lithofacies association 2 is rich in scoria lapilli and characterized by a pervasive dull red or red brown coloration broadly similar to Strombolian deposits. However, the pervasive coloration in lithofacies association 2 occurs in a sequence at least 1000 m thick and 5–6 km in diameter, which is substantially thicker and much more laterally extensive than is typical for Strombolian successions. The sequence also appears to be continuous (lacks significant time breaks) and lacks black (non-oxidised) scoria interbeds. If the pervasive dull red coloration is an oxidation effect, it implies rapid accumulation of hot pyroclasts. However, thin section analysis indicates that the coloration is a superficial stain that affects the margins of sideromelane clasts and is not due to oxidation; the narrow margins of many dykes are also similarly stained and the staining is often more intense along steep fractures in the sequence, implying a secondary, low-temperature alteration effect probably linked to the high iron contents of the lavas forming the constituent clasts (Table 1). There is also abundant ash in the lapilli tuffs which, together with an absence of associated agglutinate and clastogenic lavas, indicates a generally more highly explosive nature for lithofacies association 2. This is consistent with the wide distribution of the tephras on the island (> 3 km from the summit). An origin by Strombolian eruptions thus seems highly unlikely: Strombolian eruptions form small scoria cones with a dispersal of lapilli-size clasts typically < 1 km from the source vent (Wood 1980; Hasenaka and Carmichael 1985). Moreover, no scoria cones have been observed exposed in cross section in the steep coastal cliffs, hence they are unlikely to be the cumulative deposits of multiple overlapping small scoria cones. Instead, the radial bedding orientations in lithofacies association 2 indicate a central source for eruptions focussed on the summit. The thick massive beds characteristic of lithofacies association 2 are also more characteristic of deposits from sustained eruption columns (Houghton and Carey 2015). Taken together with the dominance of ash-rich lapilli tuffs, a link to more highly explosive eruptions and sustained eruption columns is implied, i.e. violent-Strombolian, sub-Plinian or even Plinian eruptions (Houghton et al. 2004; Valentine et al. 2005; Pioli et al. 2008; Valentine and Gregg 2008; Cioni et al. 2015).

An origin for the lapillistones in lithofacies association 2 (lithofacies L; Table 2) by fallout is consistent with such eruptions. However, the lapilli tuffs have a high proportion of fine tuff matrix and they lack impact structures (although possibly because the deposits mainly occur in thick massive beds). They also have a wide distribution all over the island, apparently without concomitant clast size reduction (i.e. clasts are still coarse (lapilli grade) in coastal outcrops > 3 km from the presumed summit vent(s)). They are thus not magmatic fallout deposits. The features of the lapilli tuffs most clearly resemble deposits of pyroclastic density currents (PDCs) linked to collapsing eruption columns. Kemp and Nelson (1931) highlighted that the deposits on Visokoi were '*sometimes* stratified', probably in reference to the thick massive nature of the crude bedding. The lack of thin stratification may be significant. Thin diffuse stratification is characteristic of fully dilute PDCs ('pyroclastic surges'; cf. Branney and Kokelaar 2002) and its absence may signify transport predominantly within dense (granular fluid-based) PDCs ('pyroclastic flows').

Of the two lapilli tuff lithofacies recognized, one (LT1) was probably linked to magmatic explosivity (Table 2). By contrast, although lithofacies LT2 contains highly vesicular cuspate juvenile lapilli, it is dominated by poorly to non-vesicular lapilli- and ash-sized sideromelane with blocky shapes suggesting rapid cooling. It is explained here as a likely result of quenching and fracturing by contact with water. Overall, the juvenile clast characteristics resemble those formed during violently explosive magma-water interactions in hydrovolcanic eruptions (Heiken 1972, 1974; van Otterloo et al. 2015).

The rare spatter-rich lapilli tuffs (LTsp; Fig. 8c), which are also rich (up to ~ 85%) in tuff matrix, are also interpreted as deposits of PDCs. With their poorly to non-vesicular matrix sideromelane with blocky shapes, rapid chilling during water-magma interaction is also indicated. They most closely resemble spatter-fed ignimbrites described on Santorini (Greece; Mellors and Sparks 1991). Those deposits are characterized by abundant spatter with low to moderate vesicularity, a fine pumiceous matrix, presence of very coarse clasts even several kilometres from the vent, spatter-clast imbrication and prominent inversely graded bed bases. They were envisaged forming when external water temporarily gained access to the vent, thus triggering violent explosions. However, they require somewhat special additional conditions involving largely degassed lava that had accumulated in a deep crater prior to being disrupted by the hydrovolcanic explosivity. If similar conditions were required at Visokoi, it would explain the scarcity of the LTsp lithofacies.

The presence of associated lithic block lenses (lithofacies TBlith), formed of cogenetic crystalline lava fragments, suggests that vigorous excavation of the vent walls occurred at times, possibly during episodes of vent widening (Houghton and Carey 2015).

The volume of lithofacies association 2 deposits is very large. The bedding is truncated by the present-day cliffs on the north, west and south sides of the island, indicating that it formerly extended out much further than the present coastline on those sides. To calculate the original volume of pyroclastic products represented by lithofacies association 2 deposits, we assume that the island was symmetrical (approximately circular, with a radius taken as the horizontal distance between Mount Hodson and Irving Point, i.e. ~ 4.5 km), a conical pre-caldera shape (extending down to sea level and neglecting summit craters) and an original summit elevation of ~ 1500 m asl (see next section). Two estimates are then possible. (1) if we assume that lithofacies association 2 overlies a domical shield-like surface unaffected by collapse of the older caldera we have postulated and composed of the basal lava sequence with the same radius but rising to ~ 600 m asl (Fig. 12), empirical calculations suggest that lithofacies association 2 deposits represent a volume of erupted deposits estimated as ~ 19 km^3. (2) Alternatively, if we assume that lithofacies association 2 deposits overlie an older caldera that removed the upper 600 m of the basal lava sequence prior to its eruption

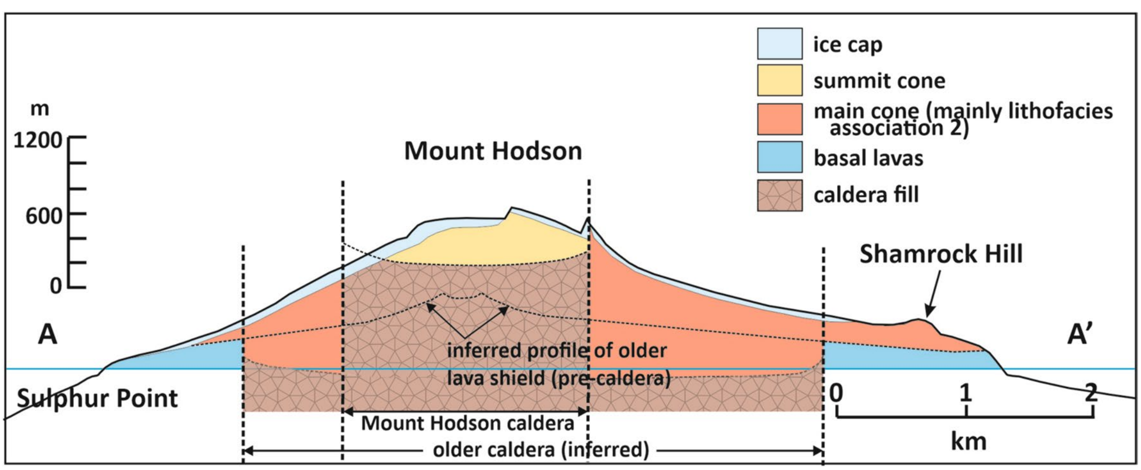


Fig. 12 Schematic true-scale cross section of Visokoi Island showing the geology and configuration of caldera fills (assuming two calderas) used to calculate the approximate volume of lithofacies association 2 products. The low, shield-like profile of the basal lava sequence prior to the inferred collapse of the older caldera, is also shown. See text for further details

(Fig. 12), the calculated volume of pyroclastic products (above sea level, i.e. neglecting an uncertain volume of caldera fill below sea level) increases to ~ 28 km^3. The crude stratification observed in the cliffs (Figs. 8b, 10) most resembles the complex multi-storey architectures characteristic of Plinian and sub-Plinian eruptions, comprising a mixture of fallout and PDC beds linked to fluctuating eruptive pulses (Cioni et al. 2015). We return to this theme in the Discussion, below.

The two epiclastic beds seen west of Mikhaylov Point (Fig. 11) are coarse sandy conglomerates and pebbly sandstones with conspicuously abraded (subrounded) clasts. They are likely beach deposits formed when the island was at a lower elevation and subsequently uplifted (by ~ 5 m). The deposits are overlain depositionally by reddish-coloured lapillistone and lapilli tuff that form the local base of the lithofacies association 2 sequence. The relationships thus indicate that the sediments were formed during a relatively early period in the growth of the volcano and are not recent deposits.

Mount Hodson caldera and post-caldera activity

Because of the cloudy weather that prevails in the South Sandwich Islands, the summit of Visokoi Island is seldom seen (Fig. 4), either by passing ships or even from aircraft. The island was, however, sketched on 23 December 1819 by Paul Mikhaylov, artist on the Bellingshausen Antarctic Expedition, when the summit was clearly seen (Fig. 13a). The island was described as being '*quite clear of fog, with a high mountain in the middle of it and sides covered with snow; its steeper slopes, where the snow and ice could not lie, were dark in colour*' (Debenham 1945). No volcanic activity was recorded. Bellingshausen observed volcanic activity on Zavodovski and Saunders islands, so its absence on Visokoi is presumably accurate. The sketch by Mikhaylov also shows no plume in the summit region.

Mikhaylov's sketch is remarkably accurate in its depiction of island shape, despite some vertical exaggeration,

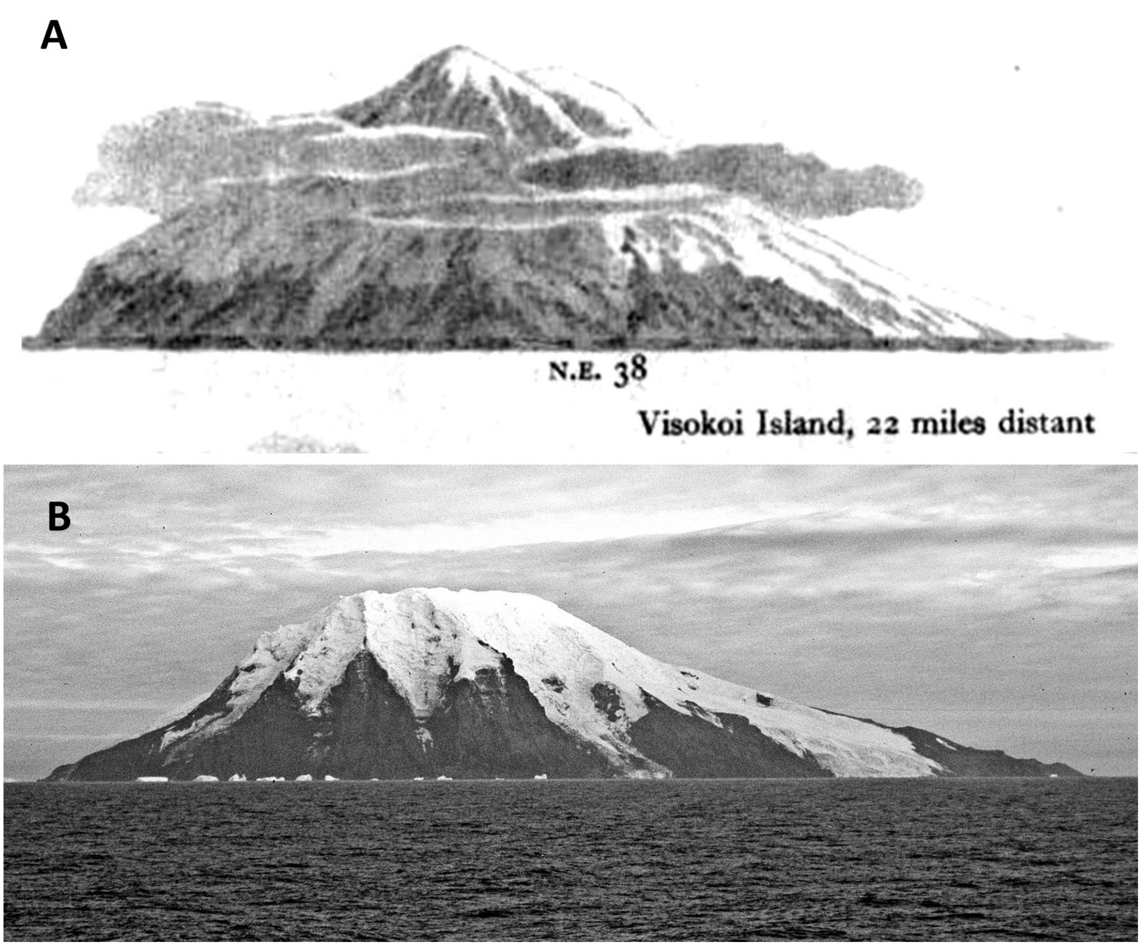


Fig. 13 Comparative views of Visokoi Island, both looking approximately to the north-east. **A**. Sketch by Mikhaylov in 1819 (vertically exaggerated; see Fig. 16). **B**. Photograph taken in 1997. Note the prominent twin summit peaks shown in A. They are absent in B, in which the island now has a conspicuously flat top

and the distribution of ice and snow-free ground. It also shows two prominent conical summit peaks, both of which are absent today. Multiple conical peaks are a characteristic feature of several of the South Sandwich Islands (Allen and Smellie 2008), and are particularly well seen on both Bristol and Cook islands, so their former presence on Visokoi Island is not unreasonable. However, the summit area now is clearly a truncated surface signifying that the morphology changed significantly after 1819 (Fig. 13b). Observations of the summit were also made in 1930 by Kemp and Nelson (1931), who viewed the island briefly free of cloud '*at some miles distance*'. They suggested that a crater (said by the authors to be '*unconfirmed*') might be present. An overflight by helicopter during our study showed for the first time that the flat summit comprised a small ice-covered caldera together with an intra-caldera crater, also ice-covered (Figs. 3, 14). Our observations of a caldera and crater were also confirmed by new satellite

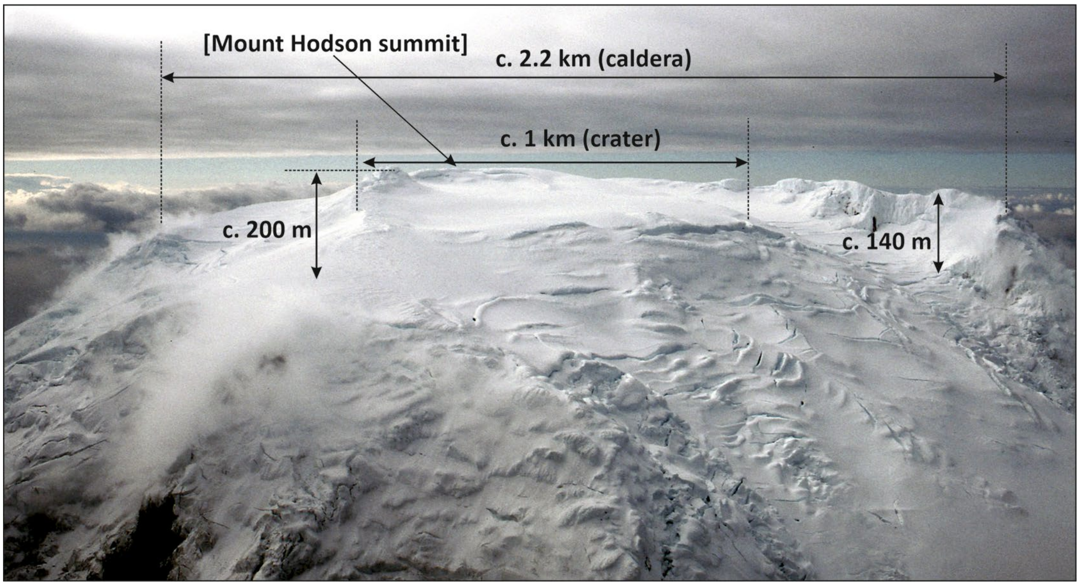
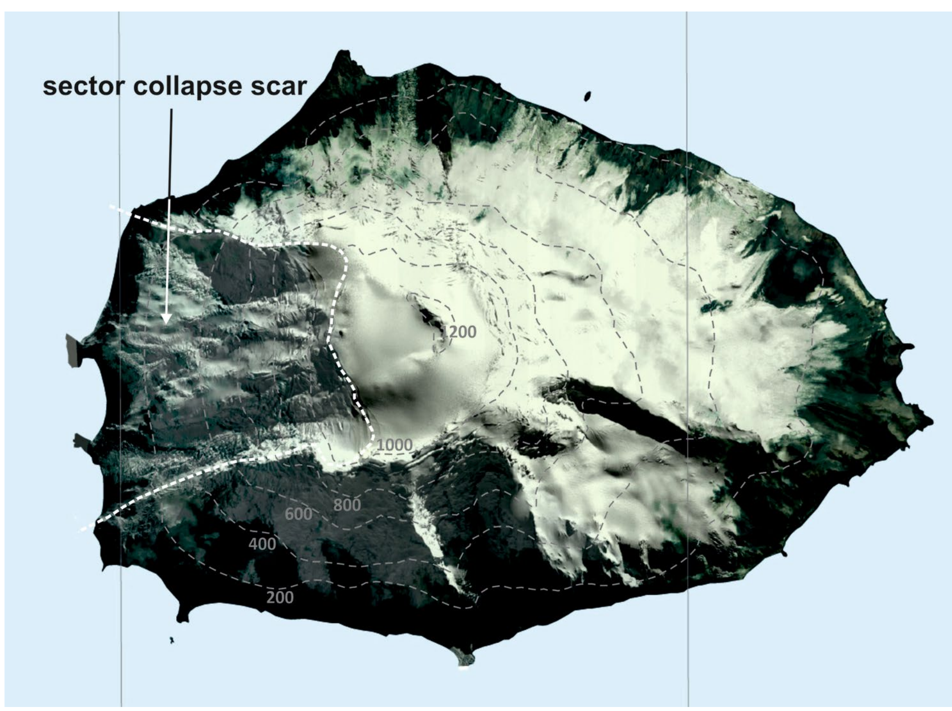


Fig. 14 Photograph of the summit of Visokoi Island (Mount Hodson), looking east

Fig. 15 Satellite image of Visokoi Island showing the morphology of the summit, with its ice-covered caldera and intra-caldera crater, and the western sector collapse scar. From Leat et al. (2014, modified). Underlying imagery from MAXAR Technologies, Image ID: 101001000CECB5



imagery (Patrick and Smellie 2013; Leat et al. 2014; Fig. 15).

Dating the caldera-forming event is quite well constrained by historical observations, described in Supplementary Information Table S1 and is discussed here. The caldera was clearly absent in December 1819 but in December 1830, Visokoi Island was described as '*a burning mountain with smoke issuing from several places*', a description that suggests the caldera had collapsed and the volcano hydrothermal system had been significantly disturbed to give widespread venting of gases from numerous locations. The collapse therefore occurred after December 1819 but probably before December 1830 and the conspicuous nature of the gas venting in 1830 suggests that the collapse occurred within a few years prior to 1830. The young age makes it one of the youngest calderas on Earth (Geyer and Martí 2008; Supplementary Information Table S2). There are no obvious pyroclastic deposits on Visokoi that might be linked to the caldera collapse episode (i.e. deposits highly charged with lithic debris).

Kemp and Nelson (1931) also noted that their 'summit crater' had '*one edge … broken away*' [presumably on the west side]. The description clearly indicates that a significant lateral collapse had taken place by 1930, which affected the west flank of the island and reached up as far as the summit region. Our visit also proved that both the caldera and intra-caldera crater are truncated by a lateral collapse feature that widens downward, reaching the coast at Wordie Point and north of Sulphur Point (Figs. 3, 15).

Lateral collapses on a range of scales are a common feature of tall volcanoes, especially active volcanic ocean islands (including intra-oceanic island arcs; Maccaferri et al. 2016; Hildenbrand et al. 2018, and references therein) and are well represented on the submarine flanks of the South Sandwich Islands (Leat et al. 2010, 2014, 2016). The scar on Visokoi Island is ~ 1.8 km across at the summit and increases to ~ 2.8 km wide at the coast. It is also noticeable that the west flank of the island was considerably higher in 1819, by ~ 250–300 m (estimated), compared with today, which may be confirmation that a substantial flank (sector) collapse occurred subsequent to that year. Using these numbers and the reconstructed pre-collapse topography shown in Fig. 16 we suggest that the combined volume of rock (*above sea level*) lost by the combined sector collapse and caldera collapse of the summit is ~ 1.4–1.7 km^3. This is comparable with lateral collapses that occurred at Kobandai volcano and Mount St. Helens (1.5 and 2.8 km^3, respectively; Siebert 2002). Moreover, Holdgate and Baker (1979) described how the '*ice-free ground above Wordie Point appears in photographs taken in 1962 to be partly covered in avalanche debris*'. The avalanche debris might be remnants of the sector collapse event. The relatively small collapsed volume suggests that post-collapse eruptive vents are unlikely to relocate to within the collapse scar, as occurs following giant (> 100 km^3) collapse events on volcanoes due to deflection of dyke trajectories under the redistributed crustal loading stresses (Maccaferri et al. 2016).

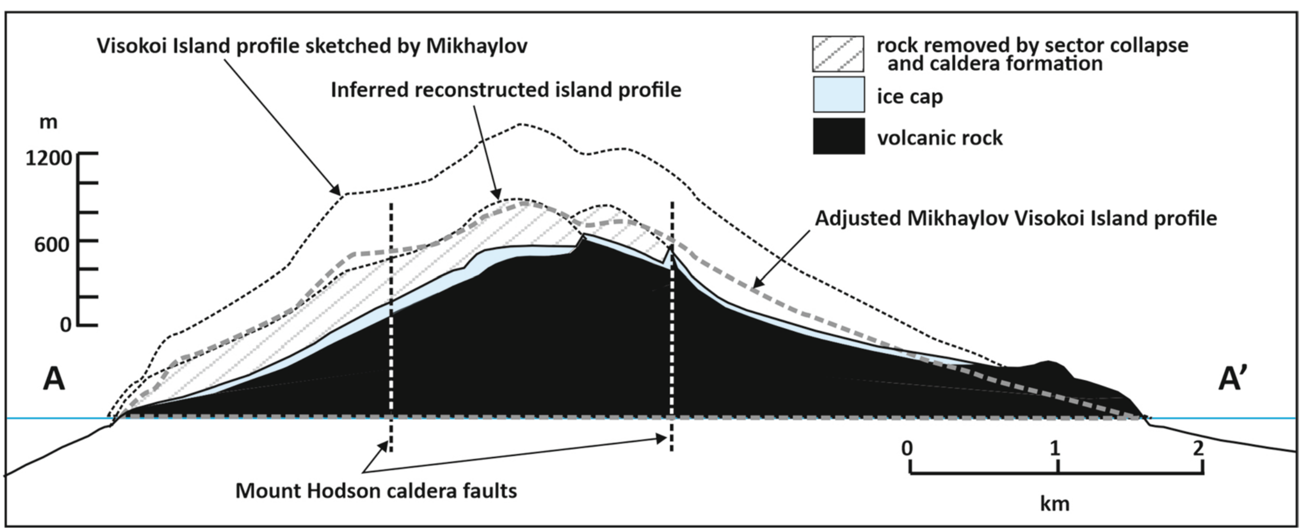


Fig. 16 True-scale cross section of Visokoi Island (in solid black, draped by ice). The profile of the island sketched by Mikhaylov in 1819 is also shown and is clearly exaggerated vertically. It has been reduced until it intersected the true island profile at its highest point, while retaining the lateral extent of the island ('Adjusted profile' in the figure). An inferred pre-sector collapse island profile is also shown, reconstructed to reproduce the revised Mikhaylov profile as closely as possible and retaining the two prominent summits sketched by Mikhaylov. The reconstructed profile is then used to infer the volume of rock that was removed from the west side of the island during the sector collapse event (see text for calculation). The location of the faults bounding the Mount Hodson caldera (pre-sector collapse) are also shown

Both the caldera and intra-caldera crater are completely draped by ice (Fig. 14). The caldera is 2.2 km wide and its rim is lower on the north side, by ~ 140 m, compared to the south side. The steep-dipping (~ 70°) caldera wall on the south side is ~ 140 m high. The intra-caldera crater is ~ 1 km in diameter, with a crater rim that rises ~ 200 m above the caldera floor on the north side. The outer flanks of the crater have gradients of 30° and 20° on the north and south sides, respectively. The crater products fill the caldera floor and are banked up against the caldera wall, so the elevation of the caldera floor is unknown. It is clear from the photo of the summit and satellite imagery now available, that the west flanks of both the caldera and intra-caldera crater were substantially reduced during the lateral collapse of the west side of the island (Figs. 3, 14, 15).

The age of eruption of the intra-caldera crater is less well defined (see Supplementary Information Table S1). However, observations in the summer of 1927–28 indicated that white steam was being emitted from a small summit crater. Although it is unlikely that the crater itself would have been visible from sea level, the white colour is consistent with steam emission rather than a magmatic or hydrovolcanic eruption. Hence, we can state with certainty that the crater existed by summer 1927–28 but it probably erupted some months or perhaps 1–2 years previously and was in a post-eruptive cooling-down state when observed. Steam rising from the summit region was again observed in 1930, confirming that the crater was also definitely present then, with a state of activity similar to that observed in 1927–28; a fumarole was also actively steaming above Finger Point indicating a disturbed hydrothermal system. There were no observations of dark ash covering the summit ice cap in 1927/28 and 1930, consistent with a lack of volcanic explosivity and no ash generation. Further observations of volcanic activity are absent and Visokoi volcano has been dormant since 1930, at least. However, intriguingly, a prominent plume was seen emanating from Mount Hodson on a NASA MODIS image-of-the-day dated 2 September 2012 (https://spaceref.com/status-report/nasa-modis-image-of-the-day-september-2-2012-plume-from-mount-hodson-visokoi-island-south-sandwich-islands/). The plume curves in an arc to the north and north-east (convex to the west) and other islands of comparable size in the group apparently lack similar plumes although the degree of cloud cover is relatively high. It may indicate recent activity but an eruption remains unconfirmed. Similar plumes are frequently observed emanating from other South Sandwich Islands (Massimetti et al. 2020).

The style of eruption from the intra-caldera crater is unknown. There are no known deposits and the eruption itself was not observed. The crater is large (~ 1 km in diameter; Fig. 14) and at the upper limit for 'dry' eruptions of Strombolian type. However, craters characteristic of explosive hydrovolcanic eruptions yielding tuff cones and tuff rings 500–1000 m wide (up to 2.5 km) are common and have flank gradients varying from a few degrees near rim crests in tuff rings, to 10–45° (mainly 20–30°) in tuff cones (Sohn 1996; Brož and Nemeth 2015). The steep gradients of the upper flanks of the intra-caldera crater on Visokoi are more characteristic of tuff cones. Water may gain access to a vent either as groundwater or surface water. If the intra-caldera crater is hydrovolcanic, the most obvious potential source of water is meltwater derived from an associated ice cap present during or immediately prior to the eruption, when melting would have been greatly enhanced by a high geothermal gradient. Evaporating meltwater caused by geothermal activity is the likely cause of the white steam plumes observed in the summit region in 1927/28 and 1930. Moreover, the crater is truncated by the sector collapse event, hence it presumably formed prior to that event, when any meltwater would probably have ponded within the caldera. In such a circumstance, eruption as a tuff cone in an englacial lake is favoured and is our preferred interpretation. Because of the wide geographical extent of the Visokoi ice cap and its steep gradients, any ash that fell on the island outside of the caldera would have been advected away quite rapidly and lost to the terrestrial record.

Discussion

Eruption of lithofacies association 2 tephras

Most of Visokoi Island consists of a large volcanic cone formed of scoria and ash of lithofacies association 2 that, from the strong red coloration (Fig. 8), might be confused with products of Strombolian eruptions. However, as described above, classical Strombolian eruptions are small-volume (typically < 0.05 km^3) and short-lived (weeks to years; Wood 1980; Pioli et al. 2008). By contrast, the volume (~ 19–28 km^3), thickness (~ 600–1000 m; the lower estimate assumes no older caldera and is probably unrealistic), lateral extent and abundance of tuff-rich PDC deposits, are not Strombolian characteristics. The apparent absence of internal erosional surfaces also suggests that the sequence is continuous and may have accumulated without substantial breaks in activity. The deposits were evidently formed during a prolonged eruptive episode, and probably linked to sustained eruption columns. A possible scenario by which lithofacies association 2 might have formed is discussed in the next section.

Products of violent-Strombolian, sub-Plinian or Plinian eruptions?

Many large central volcanoes and smaller monogenetic cones with mafic compositions undergo explosive events characterized by tall eruption columns (> 20 km) and wide tephra dispersal well beyond the source vent (e.g. Walker et al. 1984; Arrighi et al. 2001; Houghton et al. 2004). Such events are termed violent-Strombolian, sub-Plinian or, more rarely, Plinian, and are characterized by sustained eruption columns. Eruption columns are tall and increase in height from violent-Strombolian through sub-Plinian to Plinian eruptions. Each is capable of a wide dispersal of tephra (tens to hundreds of kilometres from source), predominantly by fallout in medial and distal locations.

There is no agreement about why violent-Strombolian eruptions occur but they may include some form of magma-water interaction (Martin and Németh 2006). However, a consensus is growing that favours the pressurization and rapid uprise of volatile-rich (typically arc-related) magma within the vent or shallow crust (Houghton et al. 2004; Pioli et al. 2008; Cioni et al. 2015; Métrich et al. 2021). The volatile content of magmas on Visokoi Island is unknown but arc magmas are generally rich in volatiles (Leat et al. 2007; Wallace et al. 2015). Although the Visokoi magmas are essentially mafic, with low SiO_2 contents (typically ~ 53 Wt %; Table 1), they are also relatively evolved (basaltic andesites), with low MgO, Cr and Ni contents, which will enhance the concentrations of incompatible volatiles. Violent-Strombolian, sub-Plinian and Plinian eruptions are characteristically pulsatory on a scale of minutes to hours, which may be a consequence of variations in the rate of magma discharge (MDR) at the surface relative to the rate of supply from the magma chamber (MSR). If MDR exceeds MSR, the fragmentation surface migrates down the conduit until the eruption stops due to cessation of fragmentation (Cioni et al. 2015). Decreasing MSR is favoured by a high magma viscosity (more evolved magma tapped), groundmass crystallization and a decrease in the conduit diameter. As indicated above, Visokoi magmas are relatively evolved and coeval crystallization is evident in the form of crystallites in the juvenile sideromelane. Constriction in the conduit can be caused by the progressive development of an annular lining of cooled (crystallizing) magma that restricts flow in the faster-rising central core (Houghton et al. 2004). Because of the pulsatory nature of the columns, column buoyancy also fluctuates, resulting in repeated column collapses to form ground-hugging PDCs rich in ash, thus providing a ready explanation for the prominent lapilli tuff lithofacies on Visokoi. The quench textures of sideromelane in LT2 and LTsp lithofacies indicate a likely additional role for external water.

The absence of agglutinate and clastogenic lavas in lithofacies association 2 is also significant for interpreting the formation of the deposits. Both lithofacies are common in lithofacies association 1. They are characteristic products of low-energy Strombolian eruptions. By contrast, they are absent in lithofacies association 2 consistent with a different origin. If formed from sustained high eruption columns, the flight times of ejecta will be too great during fallout for the individual clasts to retain the high temperatures necessary to weld on deposition, let alone transform into clastogenic lavas (rootless flows; Valentine et al. 2005), although rapidly accumulated PDC deposits can weld (but were not observed). Moreover, violent-Strombolian, sub-Plinian and Plinian deposits are characteristically thick and massive to crudely stratified, similar to Visokoi (Cioni et al. 2015). Thus overall, an interpretation of lithofacies association 2 as deposits of violent-Strombolian, sub-Plinian or Plinian products is strengthened, as is the interpretation of lithofacies association 1 deposits as products of small-volume Strombolian cones. By comparison, the other South Sandwich Islands have few pyroclastic units other than small-volume Strombolian cones and rare, comparatively small tuff cones (Holdgate and Baker 1979; see below, section on 'Comparison with volcanic activity elsewhere in the South Sandwich Islands').

We are unable to distinguish between the three eruptive styles based on information from Visokoi alone. Moreover, because it is an oceanic island surrounded by deep water, Visokoi tephras cannot be traced laterally, hence isopach and isopleth data are unavailable and the outcrop extent and eruptive volumes are unknown (cf. Walker 1973; Pyle 1989; Longchamp et al. 2011). However, Hubberten et al. (1991) recovered Quaternary mafic tephras in ODP Leg 114 (Site 701) marine cores ~ 550 km north-east of Visokoi Island (Fig. 1). They have compositions which the authors matched generally to the South Sandwich Islands, the closest volcanic source to the drill site (Fig. 2). With the more highly explosive eruptive activity that we have inferred for Visokoi volcano, it becomes a plausible source for those tephras. Moreover, they are compositionally basaltic andesites, as are lavas on Visokoi (Fig. 2). However, the precise magmatic affinity of the tephras to any volcano source in the South Sandwich Islands is uncertain, owing to the tephra analyses being made on glass fragments and thus displaced to more evolved compositions, and because the effects of alteration on alkali elements in the tephras in the marine environment are unquantified. Allowing for these effects greatly improves the likelihood of a compositional match (Fig. 2).

The multiple marine ash layers described by Hubberten et al. (1991) at Leg 114 Site 701 occur in three broad groups. The ages of the groups are not well defined but empirically, by extrapolation using the age scale of Ciesielski et al. (1988; see also Fenner 1991), they might have approximate ages of ~ 300, 267 and 217 ka. Individual layer thicknesses are up to 7 cm, although ash is dispersed throughout the cored section. An origin as airfall was favoured by Ciesielski et al. (1988). They are unlikely to be deposits of far-travelled gravity flows linked directly back to Visokoi Island because of the presence of the extremely deep (8000 m) South Sandwich Trench between Visokoi Island and Leg 114 Site 701

(Fig. 1). The same argument also applies to cored South Atlantic marine tephras described (but not analysed) by Ninkovich et al. (1964), which were also interpreted as deposits of sediment gravity flows. However, if the water column was overloaded with tephra derived by airfall, vertical sediment gravity flows can develop, sink to the sea floor and travel laterally following the local sea floor gradients (Manville and Wilson 2004). Thus, we favour a compound origin for the Quaternary marine tephras described by Hubberten et al. (1991), initially as primary airfall volcanic input followed, in some cases at least, by vertical then lateral transport as sediment gravity flows. The presence of basaltic andesite tephras deposited so far from the islands (requiring frequent eruptions of great magnitude), and in relatively thick layers, has till now been regarded as enigmatic (Ciesielski et al. 1988). We suggest that Visokoi is the only plausible source volcano in the South Sandwich Islands.

The maximum downwind range of particles (> 500 km from Visokoi) is a function of column height, wind speed and direction, and particle size (Carey and Sparks 1986; Bonadonna and Costa 2013; Cioni et al. 2015). The Leg 114 Quaternary marine tephras have maximum and mean shard sizes of 0.3 and 0.1 mm, respectively (Ciesielski et al. 1988), which are coarse for deep sea deposits (Shaw et al. 1974). Under conditions of no wind, the maximum lateral distance travelled by a clast (in the umbrella region) is influenced most strongly by column height and deposits are arranged concentrically around the vent. However, no-wind conditions are rare and clast dispersal within the umbrella region of an eruption column would be unable to transport clasts as large as those recorded in the Leg 114 Quaternary ashes more than a few tens of kilometres (Carey and Sparks 1986). The great distance of the marine tephras from Visokoi (if they are related) thus suggests that the particle transport was probably strongly influenced by wind. With effectively just a single drill core locality to work with, it is impossible to determine the height of the eruption column with accuracy but, using the relationships published by Shaw et al. (1974), the relatively coarse grain sizes of tephras at 550 km from the likely eruptive source (Visokoi) implies that they are products of powerful eruptions, with a column affected by strong winds. A grain size of 0.1 mm would require an unrealistically high eruption column (> ~ 95 km) at low wind speeds (~ 10 m.s^{-1}) to disperse clasts > 500 km from source, and clasts 0.3 mm in diameter would require an even taller column. At higher wind speeds (e.g. 20 m.s^{-1}), a column height of ~ 40 km is indicated (for 0.1 mm clasts). Columns lower than ~ 20 km would require wind speeds in excess of 30 m.s^{-1} (60 knots), which are also possible. Taken together, a relatively tall eruption column and moderate wind speeds is the most likely scenario for deposition of the marine tephras, if they were sourced at Visokoi. A column height of ~ 20–40 km is sub-Plinian to Plinian and not violent-Strombolian. Violent-Strombolian events may also have occurred during the eruptive period but would not have been responsible for > 500 km of particle dispersal. 40 km is probably a maximum height for the dispersal of 0.1 mm clasts (i.e. Plinian); sub-Plinian columns are generally considered lower than that (~ 10–29 km (including 20% errors; Cioni et al. 2008; Bonadonna and Costa 2013). In any circumstances, there is a limiting maximum column height of ~ 50–55 km (Wilson et al. 1978). A powerful Plinian column may also be more likely to transport the maximum particle size present (0.3 mm). However, mean grain size is probably a better value to estimate 'average' eruptive conditions (Bonadonna and Costa 2013). With such a large eruption, the effect of wind will be to cause the plume to bend over in the downwind direction, creating an elliptical asymmetrical deposit with the vent located close to (but not at) the upwind apex. However, modelling suggests that, in eruptions of this magnitude, the plume will retain a high degree of circularity within several tens of kilometres of the source, before tailing off progressively in a downwind direction (Carey and Sparks 1986). Hence, the tephras should be recoverable over a wide area and they may potentially yield useful time markers for a large part of the Scotia Sea/South Atlantic region, depending on the wind directions that prevailed during eruptive phases.

In summary, we suggest that the Quaternary basaltic andesite tephras recovered during ODP Leg 144 were sourced in compositionally similar Visokoi Island and were dispersed downwind of the islands mainly by sustained highly explosive sub-Plinian to Plinian eruptions with tall eruption columns, probably 20–40 km high. Sub-Plinian eruptions have been divided into two types (Cione et al. 2008). The division was based on the greater abundance and thickness of mainly dense PDC deposits in the higher intensity and higher magnitude sub-Plinian I eruptions (VEI 4; column height ~ 15–20 km), which corresponds well with our interpretations of lithofacies exposed on Visokoi. There is much less correspondence with their category of sub-Plinian II eruptions (VEI 3; column height ~ 10–15 km), characterized by minor and thinner, mainly dilute PDC deposits and strongly developed (thin) stratification. Hence, for eruptions of Visokoi that were sub-Plinian in nature, those with higher column heights ('sub-Plinian I') are indicated. Sub-Plinian I eruptions are also characterized by intermittent, discrete Vulcanian-like explosions (Cione et al. 2008) that may be a source for the breccia beds and lenses observed on Visokoi.

Sub-Plinian and Plinian eruptions are generally linked to mildly to strongly evolved magma compositions. They are rich in fine ash and the ash fallout affects distal areas up to distances of hundreds of kilometres (Cioni et al. 2008, 2015), which is a logical explanation for the presence of ash layers deposited > 500 km from Visokoi. The presence of the layers is otherwise enigmatic, with no other feasible sources known. It is also noteworthy that violent-Strombolian eruptions lack phases of generation of PDCs fed by collapsing columns (Cioni et al. 2008), thus strengthening our favoured interpretation of most of lithofacies association 2 as products of sub-Plinian or Plinian eruptions. However, the intermittent occurrence of violent-Strombolian tephras is not precluded and may indeed be suggested by the presence of thin lava interbeds seen high in some cliffs, since lava effusion often accompanies violent-Strombolian eruptions (and some sub-Plinian).

Caldera formation on Visokoi Island

Two calderas have been identified on Visokoi Island, a larger basal one and a much smaller one on the island summit (Mount Hodson caldera). The absence of any obvious ellipticity of either caldera suggests a lack of a regional structural control (Acocella 2007), despite many of the South Sandwich island and seamount centres being aligned along structurally-controlled ridges (Leat et al. 2010, 2014). For Visokoi Island, there is insufficient knowledge of the surface and subsurface structural features, and particularly the subsidence extent, to estimate the evolutionary stage (maturity) of either caldera (cf. Acocella 2007). The supposed bounding fault of the basal caldera exposed west of Mikhaylov Point (Fig. 11) has the geometry of an inward-dipping normal fault but it is a small exposure and lends little to our knowledge of the deeper structure of the caldera. Under-pressured caldera systems, which may be the most common (Martí et al. 1994; Acocella 2007), are characterized by outward-dipping reverse to vertical faults. However, the geometry is complicated by peripheral inward-dipping normal faults at the surface formed at a late stage (Martí et al. 1994; Roche et al. 2000; Acocella 2007). Alternatively, it might be argued that the elevation increase (admittedly very minor) indicated by the raised beach sediments exposed on the north side of the outcrop (i.e. within the caldera margin) could suggest that the caldera was initiated by domal uplift, perhaps linked to shallow magma emplacement. However, caldera-related erupted products associated with the basal caldera appear to be absent. Thus, draining of magma causing under-pressurization of the reservoir and triggering caldera collapse is a possible alternative option. Lateral magma drainage in dykes linked to concomitant caldera collapse is well documented at numerous mafic—intermediate volcanoes (e.g. Bardarbunga (Gudmundsson et al. 2016), Kilauea (Neal et al. 2019), Miyakejima (Geshi et al. 2002) and Fernandina (Simkin and Howard 1970).

The summit (Mount Hodson) caldera is concentric with the basal caldera. Therefore, it is possible that the development of the younger caldera is simply an evolution of the older one, albeit with an intervening period of tephra eruption that constructed the prominent stratocone which dominates Visokoi Island today. There is no obvious compositional difference between the magmas erupted during each of the stages sampled (Table 1), so a magmatic trigger (e.g. influx of fresh magma or progression to more evolved, volatile-rich magmas) for the younger collapse seems unlikely. The smaller diameter of the younger caldera may simply be a consequence of the propagation of ring faults and progressive roof collapses up through the > 1 km-high stratocone associated with a small-diameter subsiding piston. However, if the summit collapse of the younger caldera is linked to doming, the collapse might be due to loading of the dome apex by the erupted products of the stratocone, causing downward flexing of the magma chamber roof and caldera collapse (Martí et al. 2008). Like the basal caldera, there are no obvious eruptive products associated with the caldera collapse event itself, i.e. deposits rich in lithic debris.

A climate control on the source of water during Visokoi eruptions?

Despite the current interglacial conditions, Visokoi Island is largely draped by an extensive ice sheet (Figs. 3, 4), and a similar or even greater ice cover presumably also existed many times during the past 300 ka with variations in ice volumes caused by glacial—interglacial climate fluctuations. Had an ice cap been present during effusion of the basal lava sequence, distinctive ʻaʻā lava-fed deltas would have resulted (Smellie et al. 2013). Even if the lavas had outrun the limits of a small ice cap, evidence for melting of the ice, such as interbedded fluvial or mass-flow sediments, would be present but were not seen (Smellie 2022). By contrast, tephra erupted in the presence of an ice cover will land on the ice and be advected to the sea and lost from the record on the island. Therefore, the presence of a thick tephra pile accumulated on Visokoi implies that any ice present during the eruptive period(s) was minor or even absent. Looking at a curve of relative Antarctic temperature, it is evident that temperatures above those of today, when any ice cover would be much diminished, are rare and short-lived during the past several hundred thousand years, apart from the period between ~ 120 and 130 ka (Fig. 17; Jouzel et al. 2007). Although none of the warmer episodes correspond to the supposed ages of the marine tephras given above (i.e. estimated as ~ 300, 267 and 217 ka; see section on 'Products of violent-Strombolian, sub-Plinian or Plinian eruptions?'), it is suggested that the tephras that dominate the island were erupted within a warm climatic interval, when ice on the island was much reduced, or possibly absent at times.

The source of the water that was involved in the generation of lapilli tuffs on Visokoi is unclear. However, given the pulsatory nature of the eruptions, we suggest that, during periods when explosivity temporarily shut down and the

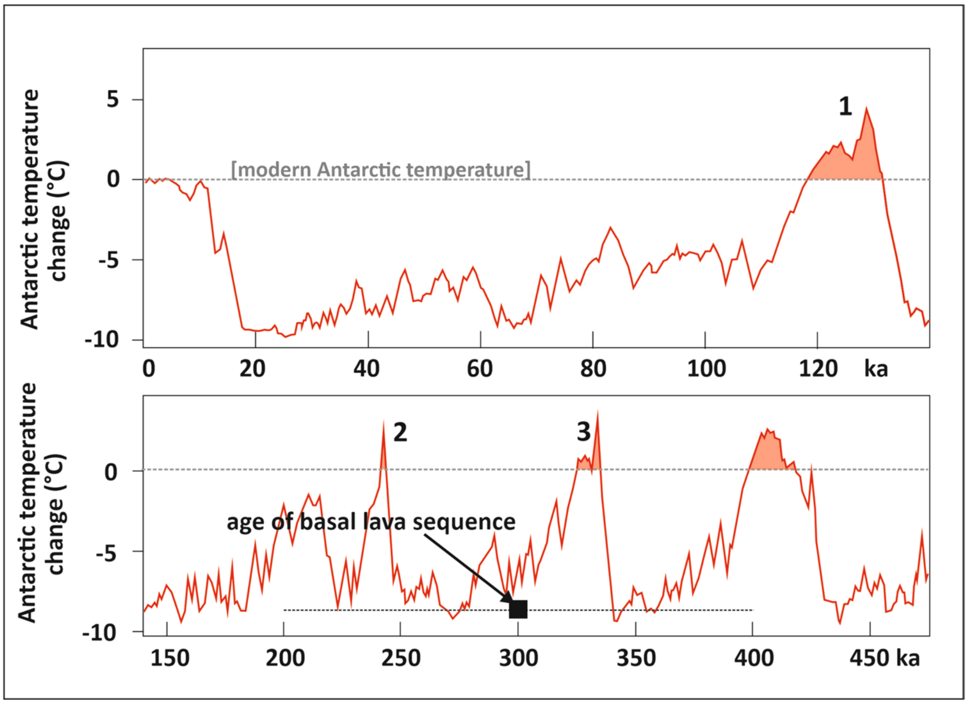


Fig. 17 Diagrams illustrating Antarctic temperatures (relative to today) as a function of time over the past 470 ka (after Jouzel et al. 2007). The age and 2-sigma uncertainties of the basal lava sequence on Visokoi are also shown. The temperature curve shows only a few peak periods (labelled 1–3) during which temperatures were higher than modern, when an ice cover on Visokoi Island would have been much reduced compared with today. It is inferred that the eruptions, which resulted in the construction of the Visokoi stratocone mainly by tephras of lithofacies association 2, probably took place within those periods, of which period 2 or possibly 3 may be the likeliest (see text for explanation). The highly eroded scoria cones of lithofacies association 1 may have been erupted during period 1. Note the different age scales used in both diagrams

column collapsed, the subsiding top of the magma in the vent conduit could have permitted the ingress of meltwater derived from a thin ice cap, much smaller than today and possibly formed largely of snow. In a warmer and moist climate (surrounded by the Southern Ocean), such a source would be a ready and easily replenishable supply, as snow falling on the summit of the island. Another possibility is that the low vesicularities of many pyroclasts in lithofacies LT2 might be an indication of an eruption tapping a complex reservoir ('crystal mush') containing multiple melt lenses (Cashman and Giordano 2014). Such eruptions are also thought to result in pulsatory eruptive activity alternating between protracted explosivity and lava effusion (Cashman and Giordano 2014), which are characteristics of many sub-Plinian and violent-Strombolian events. We are unable to distinguish unambiguously between these two options for Visokoi volcano and both are viable, but the blocky morphologies of many sideromelane clasts, which are often very vesicle-poor, appear to favour a hydrovolcanic origin.

The interaction presumably took place at a shallow level in the summit vent. Islands in the South Sandwich archipelago develop an ice cap once they reach an elevation at which snow is stable throughout the year, i.e. when it is above the local equilibrium line altitude, which is a function of mean summer air temperature, ground elevation and the surface area available for snow accumulation at that elevation (Barr et al. 2022). By comparison with other islands in the South Sandwich group, which erupted under the same climatic conditions as Visokoi, it is notable that ice is absent, or nearly so, on Leskov, Bellingshausen and Vindication islands (summits 190, 250 and 440 m asl, respectively), all of which are smaller and lower than Visokoi. A small asymmetrical ice cap was formerly present on Zavodovski Island (summit 551 m asl, island diameter 5.5 km) but is now a much-reduced snowfield (personal communication from Nicole Richter, 2024). Meltwater from both the ice cap and snowfield is probably responsible for at least some of the steam activity seen in permanent fumaroles within the Zavodovski crater. More extensive ice caps are present on the larger islands, i.e. those with a greater percentage of the island higher than ~ 400–500 m asl (e.g. Saunders, Thule, Cook, Bristol). Candlemas Island, which is smaller and lower (550 m) than Visokoi, represents an intermediate state. Fluctuations in the supply of magma would cause the top of the magma column to rise and subside, thus permitting meltwater to enter the conduit where it could interact with the magma as the conduit refills. With the temporary exhaustion of snow-sourced meltwater, the eruption could transition to magmatic and hence provide an explanation for lapillistones and lapilli tuffs lacking evidence for water interaction (lithofacies L and LT1; Table 2). However, given the South Sandwich climate, further snowfall on the summit of Visokoi would provide an inexhaustible, repeatedly replenished supply of meltwater available to interact with the next magma recharge event.

Comparison with volcanic activity elsewhere in the South Sandwich Islands

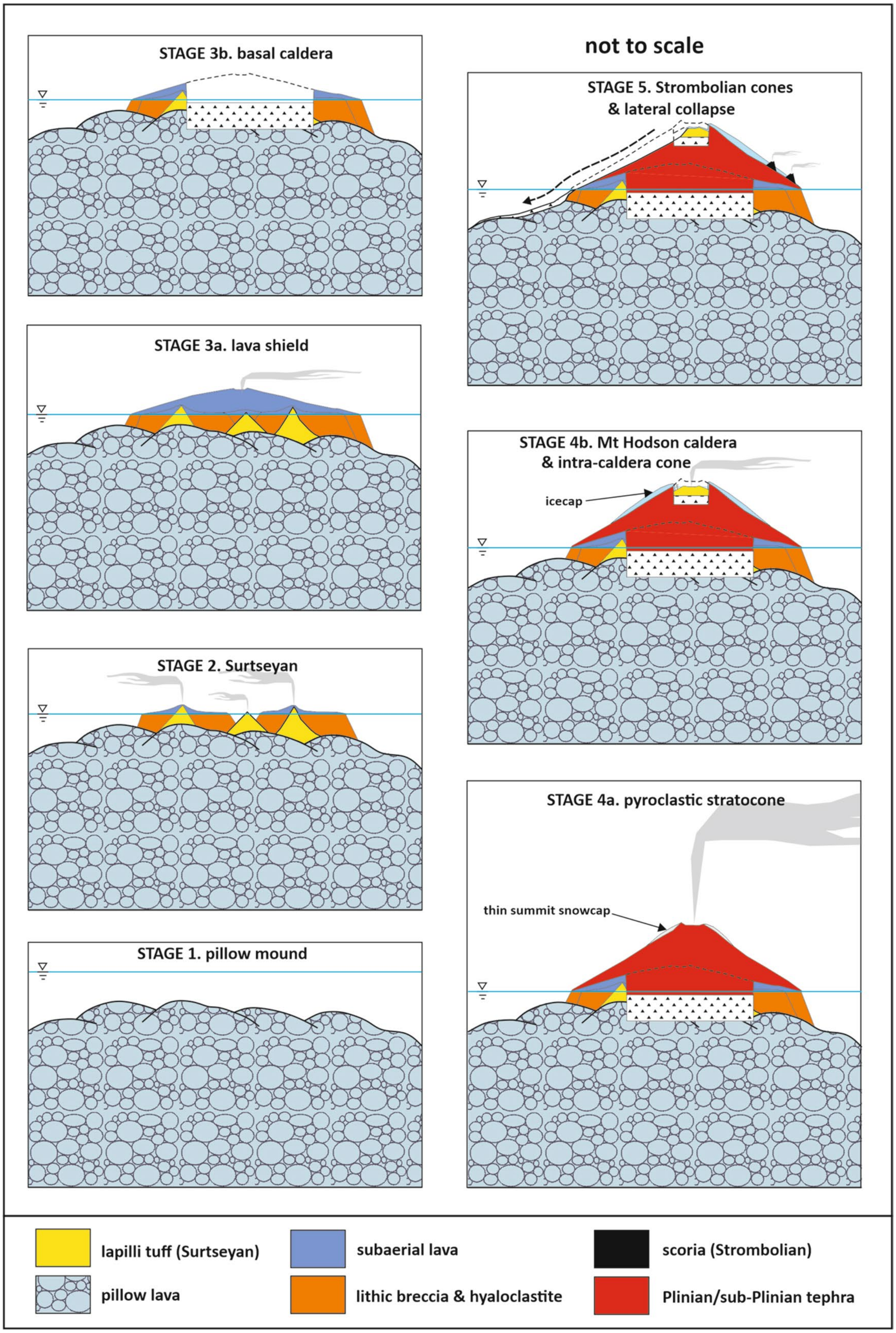
Visokoi Island is the only volcano in the South Sandwich group for which a dominant highly explosive pyroclastic behaviour has been proposed. Elsewhere, Thule Island is a conical volcano at the south end of the island group, about half the width of Visokoi. It is ~ 800 m high and has an ice-filled summit caldera 1.7 km wide within which a small glaciovolcanic eruption took place within a few years of 1961 (Holdgate 1963). Cliffs on the east and north-east sides of Thule show thick deposits (~ 200–300 m; estimated) of crudely and coarsely stratified tephras that extend down to sea level (observations of JS). They are also products of pyroclastic eruptions but they are more pervasively yellow-coloured reflecting a dacitic composition, and they are very rich in accessory lithic clasts. Their origin is still under investigation. Moreover, unlike Visokoi, they are capped by a thick sequence of grey lavas with oxidised autobreccias, so the later evolution of Thule island is the converse of Visokoi. Cook Island is another centre with locally prominent pyroclastic deposits. However, the tephras are Strombolian, with features like lithofacies association 1 on Visokoi, and were erupted from several small conical peaks on the island. Speculatively, a similar interpretation may also apply to Bristol Island. Although exposures there are much more limited, the several small peaks on Bristol Island are comparable in their size and conical shapes to those on Cook Island (and also covered by snow and ice). A cluster of tuff cones is prominent on Saunders Island (at Ashen Hills; Holdgate and Baker 1979) but they represent short-lived eruptive events and are unlikely to have dispersed voluminous ash beyond a few kilometres. Prominent cones with large craters are present on Zavodovski and Bellingshausen islands but they are small, low islands in an early stage of subaerial construction formed of interbedded lavas, Strombolian scoria and minor hydrovolcanic lapilli tuffs. Other volcanoes in the South Sandwich Islands are dominated by ʻaʻā lavas, some of which flowed into the sea and created conspicuous lava-fed deltas (e.g. Saunders and Candlemas islands). Thus, the dominance of highly explosive pyroclastic activity on Visokoi Island, associated with tall eruption columns and a wide geographical dispersal of tephra, appears to be unique in the South Sandwich Islands.

Future volcanic activity on Visokoi Island

It is noticeable that bedding within the upper scoria sequence is truncated by the modern cliffs, suggesting that the island outline was considerably wider when the tephras were deposited. An eruption of tephra today would not be able to accumulate on such steep slopes and would land in the sea and be lost to the terrestrial record. The relationships thus suggest that the upper scoria sequence probably accumulated progressively during a period of sustained pyroclastic activity. Following those eruptions, the island experienced substantial marine erosion on its west, north and south sides to yield today's cliffs, reducing the island coastline by at least 2 km on those sides. There is no evidence on the island for subsequent sub-Plinian or Plinian (or indeed violent-Strombolian) activity. Thus, it is possible that the major period of violent high-discharge volcanic eruptions of Visokoi volcano is ended and any future explosive events are likely to be sporadic and on a smaller scale, probably from small Strombolian scoria cones scattered on the flanks of the volcano, or as hydrovolcanic (glaciovolcanic) activity in the ice-covered summit crater.

Model for construction of an active glacierized intra-oceanic arc volcano

The construction of Visokoi volcano can be used to describe the construction of an oceanic island arc volcano. It is divided into five major constructive eruptive phases (Fig. 18), of which two are subaqueous (submarine) and three are subaerial. Only the last three phases were examined during our study but the distinguishing characteristics of earlier submarine phases can be inferred from a priori inference and knowledge of other shoaling submarine volcanoes. The **first stage** was the most voluminous and longest-lived, and characterized by submarine activity that produced pillow lavas. The pillow lava was probably associated with tuff breccia formed by gravity collapses in locations where the local gradients were steep, especially close to erupting vents where lava pillows pile up in metastable mounds. Leat et al. (2010) recorded many small topographical highs on the submarine slopes of Visokoi, individually up to 2 km in diameter and with local elevations of 350 m above the surrounding topography, together with conical shapes and deep down-slope scarps. They were interpreted as domes, cones or lavas. An origin mainly as pillow lava mounds and slump scars is consistent with that interpretation. Multiple erupting centres are likely throughout the construction of the basal pillow lava edifice but over time they would have coalesced into a major mound, which is ~ 2.5 km high today


not to scale
STAGE 3b. basal caldera
STAGE 5. Strombolian cones
& lateral collapse
STAGE 3a. lava shield
STAGE 4b. Mt Hodson caldera
& intra-caldera cone
icecap
STAGE 2. Surtseyan
STAGE 4a. pyroclastic stratocone
thin summit snowcap
STAGE 1. pillow mound
lapilli tuff (Surtseyan)
subaerial lava
scoria (Strombolian)
pillow lava
lithic breccia & hyaloclastite
Plinian/sub-Plinian tephra

◂**Fig. 18** Interpretive cross sections of Visokoi volcano illustrating the different stages in its construction. Not to scale. The existence of a thin (~200 m thick) Surtseyan stage is based on a priori reasoning (i.e. shoaling and emergence of the volcanic pile) but is also suggested by the presence of at least two, sub-horizontal, potential lava-fed delta capping rocks at the base of the basal lava sequence (at Finger Point and Mikhaylov Point; see Fig. 5). See text for further details

and ~ 20–25 km wide (Figs. 6, 18). Because of high water pressures, explosive magma-water interaction was probably virtually absent below ~ 100–200 m of the surface (White et al. 2003; Zimanowski and Büttner 2003) but localized submarine lava fountaining may have occurred at any depth, from vents experiencing high discharge rates, and may be responsible for some of the cone shapes described by Leat et al. (2010; Simpson and McPhie 2001; Davis and Clague 2003; Head and Wilson 2003). **Stage 2** commenced when the edifice shoaled to depths less than ~ 200–100 m and the volcano ultimately emerged. The lower water pressures would have triggered violently explosive hydrovolcanic activity (molten fuel–coolant interaction), forming Surtseyan tuff cones (Kokelaar 1983; Sohn 1996); the physical transition from pillow lava to explosive hydrovolcanic activity occurs over a short vertical interval (< 30 m), as described by Graettinger et al. (2013). Once the cones emerged and the vents became isolated from the surrounding water, further activity became effusive, resulting in laterally prograding lava-fed deltas. The two lavas with prominent crescentic flow folds seen at Mikhaylov and Finger points are probably the subaerial upper surfaces of lava-fed deltas sourced in stage 2 Surtseyan cones, or else far-travelled early stage 3 lavas.

Stage 3 comprised effusive activity and generation of ‘a‘ā sheet lavas (basal lava sequence) erupted under dry and ice-free subaerial conditions, probably from a major central vent at which the activity became focussed. We speculate that the stage ended with the formation of a caldera with a putative minimum diameter of ~ 5 km (Fig. 3). Its identification is based solely on interpretation of the geometry of the upper surface of the lava sequence and field relationships exposed west of Mikhaylov Point, which provide possible support for the hypothesis (Fig. 11). If the basal caldera is verified, it may be regarded as an important tectonomagmatic event that presaged a fundamental change in the prevailing magmatic—petrological conditions that led to the next distinctive eruptive phase. There is no information on what caused a caldera collapse at the end of stage 3. The apparent absence of caldera-related pyroclastic rocks suggests magma withdrawal rather than a major eruption. The shattering of the edifice during collapse would ease upward magma movement, favour the potential contact between magma and external liquids and promote phreatomagmatic activity (Scandone et al. 2007; Cioni et al. 2008). Although there is no evidence on Visokoi Island for such activity, its impact might be important only in the vent area, which is now entirely buried by tephras erupted during stage 4. However, caldera collapses cause a recompression of the residual magma in the reservoir due to the increased gravitational load (Martí et al. 2008; Cioni et al. 2015). Additionally, failure of the internal structure of the volcano creates a fracture network linking the magma storage region with the surface and permits buoyant magma to enter the system. We note that not all of the South Sandwich volcanoes followed the same evolutionary trend outlined here for Visokoi. For example, Kemp caldera, at the south end of the island group, is a submarine edifice, which developed a caldera while at the submarine stage, together with the evolution of dacites, also at the submarine stage (Kürzinger et al. 2023).

The next phase of activity, corresponding to **stage 4**, was characterized by major magmatic explosivity and formation of tephras of lithofacies association 2. With such a link in timing, it implies that stage 4 activity would have commenced relatively soon after caldera collapse. It was very different to the explosive activity associated with stage 2 (Surtseyan) and was characterized by sub-Plinian or Plinian eruptions (and possibly intermittent violent-Strombolian activity), which formed the lapillistones and lapilli tuffs that dominate the island. Sub-Plinian and Plinian eruptions have mass discharge rates of between 10^5 and 10^7 kg.s^{-1} and Volcanic Explosivity Indices (VEI) of 2–4 (Cioni et al. 2008, 2015; Bonadonna and Costa 2013). The eruption column heights of between ~ 20 and 40 km that we have inferred indicate that the stratosphere would have been penetrated: the tropopause over the South Sandwich Islands is at ~ 11 km (Evtushevsky et al. 2008). Fast-moving, sub-tropopause, westerly meandering jet streams, at elevations of 6–10 km, can also cause the strong lateral advection of weaker sub-Plinian plumes and thus might be implicated, at times, since tropospheric eruptions are most strongly affected by wind speed (Bonadonna and Costa 2013; Cioni et al. 2015). Although intrinsic factors (e.g. recompression of the magma caused by caldera collapse) were probably responsible for stage 4 pyroclastic activity, external factors such as infiltration and interaction with water also played a part and were probably involved in the generation of many lapilli tuffs (Houghton et al. 2004; Graettinger et al. 2019). Thus, meltwater derived from a small summit cover of ice or (mainly) snow) may be implicated. However, the extent of any snow or ice must have been small to explain the accumulation of such a thick pile of tephras since any tephra deposited on an extensive ice cover shall be advected to the sea and lost. For stage 4 tephras to be so thickly preserved on the island, it is suggested that eruptions took place during a relatively warm climatic period when the ice cover was substantially reduced (but not absent), perhaps corresponding to warm interval 2 or (less likely) 3 shown in Fig. 17. The tephra pile is capped by a small caldera formed ~ 1829 CE. It contains an intra-caldera cone, probably glaciovolcanic, formed much later (~ 1926–1927 CE). Final activity (**Stage 5**) is represented by Strombolian deposits (lapillistones, agglutinate and clastogenic lava) localized to several small pyroclastic cones (lithofacies association 1). The most recent event consist of a major lateral collapse of the west flank of the island, which transected the Mount Hodson caldera and intra-caldera cone, which occurred between 1927 and 1930 CE.

Conclusions

Visokoi is a small volcanic Island within the South Sandwich Islands. It can be used to characterize the evolution of an active glacierized intra-oceanic arc volcano. From the submarine morphology of the volcano, it is inferred that > 90% by volume is composed of pillow lava and probably lesser tuff breccia, the latter formed by local slope collapses around over-steepened pillow mounds, which have been identified on the submarine slopes of the volcano, together with a broad runout apron covered by mass flow deposits sourced in multiple flank collapses. During shoaling and emergence, the eruptive activity probably consisted of explosive hydrovolcanism capped by laterally extensive lava-fed deltas, the upper surfaces of two of which crop out on the north and south coasts of the island. They form a discrete Surtseyan stage with deposits at least 200 m thick that formed a platform with a broadly horizontal surface on which an extensive lava shield composed of subaerial ‘a‘ā lavas was constructed. The lava shield was topped by a steep stratovolcano dominantly composed of fines-rich pyroclastic density current deposits, scoria lapillistones and occasional lavas and the whole pile is extensively intruded by sub-vertical dykes.

Following eruption of the basal lava shield, a broad caldera collapse probably took place, which triggered a major change in the magmatic—petrological conditions in the magma chamber and presaged a transition to violently explosive pyroclastic eruptions, probably of sub-Plinian or Plinian type (or both). The large magnitude of the eruptions resulted in tephras being dispersed over a wide geographical area and likely correlatives have been recovered by sea floor drilling > 500 km from the volcano. However, most of the tephras deposited on the island were lapilli tuffs deposited from pyroclastic density currents. They were probably erupted during climatic period(s) in which the coeval ice cover was much reduced. There is evidence for magma-water interaction in many of the lapilli tuffs. The most plausible source for that water currently envisaged is by melting of a small summit ice cap perhaps formed mainly of snow and rapidly and repeatedly replenished due to the moist, cool climate prevailing in the South Sandwich region. It is the sole indication of a glacial influence on the erupted products, despite the ice cover today, which is extensive (and presumably was even greater during past glacial periods). Eruptions primarily occurring during ice-poor or ice-free conditions might suggest a climate control on the history of the volcano. The summit of Visokoi Island is now occupied by a small ice-capped caldera whose collapse can be dated by historical observations to ~ 1829 CE, making it one of Earth's youngest calderas. There is also a small intra-caldera cone that erupted in ~ 1926–27 CE. It is also entirely covered by snow and ice and is inaccessible, but it may be a glaciovolcanic tuff cone. The final volcano-tectonic event to affect Visokoi was a major sector collapse, which occurred on the west flank of the island between 1927 and 1930 CE. It is likely that the major period of high-volume pyroclastic activity is ended, and future volcanic activity shall probably consist of small eruptions of Strombolian or glaciovolcanic type from the summit crater or flank vents.

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