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RESEARCH ARTICLE

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First recorded eruption of Mount Belinda volcano (Montagu Island), South Sandwich Islands

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Abstract The MODVOLC satellite monitoring system has revealed the first recorded eruption of Mount Belinda volcano, on Montagu Island in the remote South Sandwich Islands. Here we present some initial qualitative observations gleaned from a collection of satellite imagery covering the eruption, including MODIS, Landsat 7 ETM+, ASTER, and RADARSAT-1 data. MODVOLC thermal alerts indicate that the eruption started sometime between 12 September and 20 October 2001, with low-intensity subaerial explosive activity from the island's summit peak, Mount Belinda. By January 2002 a small lava flow had been emplaced near the summit, and activity subsequently increased to some of the highest observed levels in August 2002. Observations from passing ships in February and March 2003 provided the first visual confirmation of the eruption. ASTER images obtained in August 2003 show that the eruption at Mount Belinda entered a new phase around this time, with fresh lava effusion into the surrounding icefield. MODIS radiance trends also suggest that the overall activity level increased significantly after July 2003. Thermal anomalies continued to be observed in MODIS imagery in early 2004, indicating a prolonged low-intensity eruption and the likely establishment of a persistent summit lava lake, similar to that observed on neighboring Saunders Island in 2001. Our new observations also indicate that lava lake activity continues on Saunders Island.

Keywords Mount Belinda volcano · Montagu Island · Mount Michael · Saunders Island · South Sandwich Islands · Satellite monitoring · ASTER

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Introduction

New volcanic activity was initiated in September or October 2001 at Mount Belinda, on Montagu Island in the remote South Sandwich Islands, according to both automated and visual interpretation of thermal satellite imagery (Smithsonian Institution 2003, 2004). This eruption is especially significant in that it is the first recorded volcanic activity on Montagu Island, and its detection was facilitated by the global MODVOLC satellite monitoring system, based at the Hawaii Institute of Geophysics and Planetology (Wright et al. 2002, 2004).

Data were subsequently gathered from a variety of sources to document the eruption at Mount Belinda (Table 1). The detection of activity and initial analysis were performed using the automated MODVOLC thermal alert system. Covering an observation period from the start of the eruption (October 2001 to May 2004), MODIS (Moderate Resolution Imaging Spectroradiometer) thermal images (1 km pixel size) showed the relative changes in heat flux that could be related to variations in activity. The MODVOLC system allowed us to quickly and easily generate heat flux time series capable of revealing such variation (Wright and Flynn 2004). Several visible band MODIS images (250 m pixel size) showed the progression of eruptive activity at the summit. Supplementing these data, Landsat 7 Enhanced Thematic Mapper Plus (ETM+) images (15–60 m pixel size) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images (15–90 m pixel size) provided higher spatial-resolution snapshots of the impact of eruptive

Table 1 Summary of key observations for Montagu Island

Date	Source	Observation
Sept 1992	Hand-held photographs	No signs of activity; summit ice covered
1995–1998	AVHRR	Possible low-intensity intermittent activity
6 Mar 1998	RADARSAT-1	No signs of activity
Jan 1997	Visual observation from neighbor island	No signs of activity; summit ice covered
24 Jan 2001	Landsat 7 ETM+	No signs of activity; summit ice covered
12 Sept 2001	ASTER	No signs of activity; summit ice covered
20 Oct 2001	MODIS (thermal)	First thermal anomaly
23 Dec 2001	ASTER	Elongate tephra deposit E of summit
4 Jan 2002	Landsat 7 ETM+	Ash plume, small lava flow
19 May 2002	MODIS (visible)	Tephra deposit W of summit
Aug 2002	MODIS (visible and thermal)	Apparent escalation in activity, lava or tephra deposit N of summit
Early Feb 2003	Photographs from HMS Leeds Castle	Ash plume from summit
2 Mar 2003	Visual observations from RRS Ernest Shackleton	Prominent ash plume from summit
1+17 Aug 2003	ASTER	2 km long lava/debris flow
9 Aug 2003; 30 Oct 2003	RADARSAT-1	Observations on morphology of Mt. Belinda and recent lava flows
7 Dec 2003; 9 Feb 2004	ASTER	Small plume and tephra cover SE of Mount Belinda
May 2004	MODIS (thermal)	Thermal anomalies present at time of submission

products on the surface of the ice-capped island. RADARSAT-1 synthetic aperture radar (SAR) imagery (C-band, 9–30 m pixel size) completed the suite of satellite data available for eruption tracking purposes. Finally, visual observations and photographs of the island taken from two passing ships corroborated the eruptive activity.

Background

Montagu Island and the South Sandwich Islands

The South Sandwich Islands lie between approximately 56° and 60° S latitude, and 25° and 30° W longitude, at the eastern extremity of the Scotia Sea, approximately 2,000 km south-east of the Falkland Islands and about the same distance north of the Antarctic continent (Fig. 1). This young (<5 Ma) volcanic arc is a product of westward subduction of the South American plate beneath the South Sandwich plate, with lavas ranging from tholeiitic and calc-alkaline basalts to basaltic andesites, with minor occurrences of more silicic rocks (Pearce et al. 1995; Leat et al. 2003). Stratovolcanoes are the dominant morphology in the group, typically composed of sequences of lava flows and pyroclastic rocks (LeMasurier and Thomson 1990). Active fumaroles are, or have been, present on Leskov, Zavodovski, Candlemas, and Bellinghausen Islands, steam emission has been reported from the summit craters on Visokoi, Saunders, Bristol and Thule Islands, and historic eruptions have been observed or inferred for Zavodovski and Bristol Islands (Holdgate 1963; LeMasurier and Thomson, 1990). A large explosive submarine eruption occurred from Protector Shoal (about 56 km north of Zavodovski Island) in 1962, producing a raft of pumice that drifted as far as New Zealand (Gass et al. 1963; Coombs and Landis 1966).

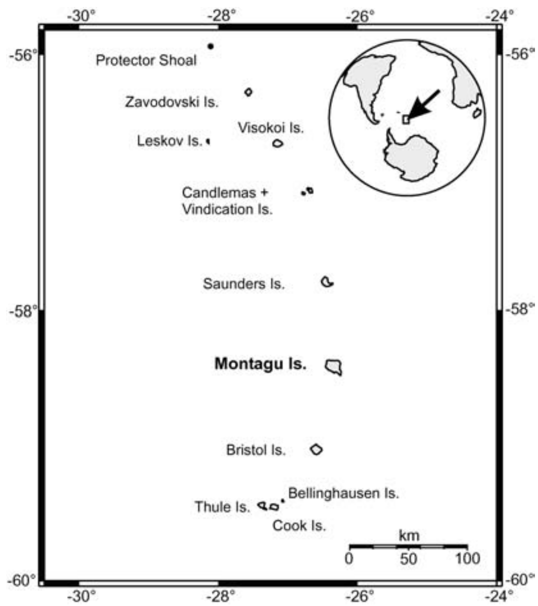

Fig. 1 The South Sandwich Island archipelago, located in the Scotia Sea. The South Sandwich Trench lies approximately 100 km east, paralleling the trend of the islands

Montagu Island is the largest of the South Sandwich Islands (Figs. 1, 2), measuring approximately 12 km by 10 km (note that these dimensions differ from those indicated on the only published topographical map of the island, by Holdgate and Baker (1979), which featured an incorrect scale bar). Mount Belinda, named after Belinda Kemp (Kemp and Nelson 1931), rises to 1,370 m asl and is a small summit peak situated within an extensive very gently sloping icefield that fills the largest caldera known in the island group. Mount Oceanite is a small satellite center, larger than Mount Belinda, which forms a conspicuous promontory on the south-east corner of the is-

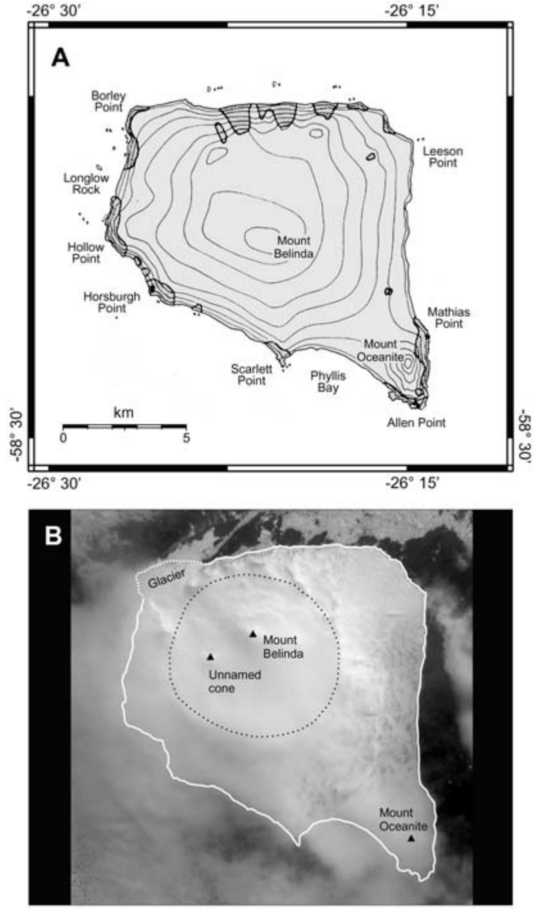

Fig. 2A, B A) Map of Montagu Island, adapted from Holdgate and Baker (1979). Stippled areas show rock outcrop, the remainder is snow or ice covered. Relief is shown by *form lines*, which should not be interpreted as fixed-interval contours. Note correction of scale from original figure. North is up. **B)** 12 Sept 2001, pre-eruption ASTER visible band composite image (Bands 3-2-1). Note the difference in location of Mount Belinda. The *black dotted line* shows the rough boundary of the apparent caldera

land (Fig. 2). Although no reliable topographic data exist for the island, examination of the high spatial-resolution imagery (ASTER and ETM+) indicates that Mount Belinda is a small summit cone on the larger shield volcano edifice represented by Montagu Island. The broad summit caldera is approximately 6 km in diameter and is entirely filled by permanent ice of uncertain depth. The outlet of the summit icefield is a tidewater glacier reaching the sea at the NW corner of the island, resulting in a temporally-variable shoreline in that area. Mount Belinda represents the youngest post-caldera eruptive center known on the island. Other likely centers, probably cinder cones in various states of degradation, are present as a small unnamed peak on the west side of the caldera, and two considerably degraded outcrops on the south-east outer flank facing Mount Oceanite (Fig. 2 and unpublished information). The steep-sided Mount Oceanite is capped by a 270 m diameter summit crater, which is about 100 m deep based on the interior shadow and sun elevation angle of the ETM+ image. The ASTER image (Fig. 2b) improves upon the positioning of the topographical features from the original coarse-resolution form-line map (Fig. 2a) of Holdgate and Baker (1979).

The island as a whole is about 90% ice covered, with most of the exposed rock limited to vertical sea cliffs. Because of this inaccessibility, landings have only been made on a handful of occasions, and just a few localities (Borley, Scarlett, Horsburgh, Allen and Mathias points) have ever been sampled (LeMasurier and Thomson, 1990, and unpublished information). The rocks range from basalt to basaltic andesite (49–53 wt.% SiO_2) with low amounts of Na_2O and K_2O. There was no prior record of Holocene activity on Montagu, though this is likely to reflect its remoteness, inaccessibility and extensive ice cover, which also prevent a thorough study of the island (LeMasurier and Thomson 1990).

Satellite imagery and the MODVOLC thermal alert system

Because of its remote location and the persistently bad weather there have been just three formal scientific expeditions to Montagu Island, those of the RRS *Discovery* in 1930 (Kemp and Nelson 1931), HMS *Protector* in 1964 (Holdgate and Baker 1979, see also Holdgate 1963), and by the British Antarctic Survey in 1997 (Leat et al. 2003). The fact that no future expeditions are being planned at the current time is not surprising: Captain James Cook, the well-traveled explorer who discovered the South Sandwich Islands in 1775, referred to them as being 'the most horrible Coast in the World', and the region in general as 'a Country doomed by Nature never once to feel the warmth of the Sun's rays, but to lie for ever buried under everlasting snow and ice.'' (Cook 1775). That regular field studies in this region are so unlikely underlines the potential stand-alone role of satellite data for monitoring volcanic activity in the South Sandwich Islands.

Previous eruptions have been recorded in the archipelago, but ongoing volcanic activity has only recently been detected and studied in the South Sandwich Islands. These islands are sufficiently distant from population centers and shipping lanes that eruptions, if and when they do occur, can easily go unnoticed. Visual observations of the islands probably are generally limited to no more than a few days each year (LeMasurier and Thomson 1990). Satellite data have recently provided observations of volcanic activity in the group, and offer the only practical means to monitor activity in the islands. Specifically, using Advanced Very High Resolution Radiometer (AVHRR) data, Lachlan-Cope et al. (2001) discovered and analyzed an active lava lake at the summit of Mount Michael volcano on Saunders Island, north of Montagu Island.

The satellite data used here span a wide range of spatial and temporal resolutions (Table 2). MODIS imagery is acquired on average twice daily over a given spot, and is composed of 20 thermal infrared bands at

Table 2 Sensor characteristics

Sensor	Selected channels	Pixel size (m)
MODIS	1:0.62–0.67 μm	250
	2:0.841–0.876 μm	250
	21:3.929–3.989 μm (high gain)	1,000
	22:3.929–3.989 μm (low gain)	1,000
	32:11.77–12.27 μm	1,000
ASTER	1:0.52–0.60 μm	15
	2:0.63–0.69 μm	15
	3:0.76–0.86 μm	15
	13:10.25–10.95 μm	90
Landsat 7 ETM+	1:0.45–0.52 μm	30
	2:0.52–0.60 μm	30
	3:0.63–0.69 μm	30
	4:0.76–0.90 μm	30
	5:1.55–1.75 μm	30
	6a: 10.4–12.5 μm (high gain)	60
	6b: 10.4–12.5 μm (low gain)	60
	7:2.08–2.35 μm	30
	8:0.50–0.90 μm	15
RADARSAT-1	C-band (5.6 cm): Fine mode	9
	C-band (5.6 cm): Standard mode	30

1 km pixel size, 14 visible and infrared bands at 500 m, and two visible bands at 250 m. Of the many hundreds of MODIS images acquired during the study period (Oct. 2001–May 2004) only 107 triggered the MODVOLC thermal alert system, limited either by fluctuations in activity level or, more importantly, visibility of the island due to cloud cover. Of these 107 images, all but 10 were nighttime, and thus the 250 m visible band data were useless as a complement for the majority of the thermal anomaly observations. Landsat 7 ETM+ has a much longer repeat period (16 days), with channels ranging from 15 m pixel size (panchromatic) to 60 m (thermal infrared). Again, while almost a dozen ETM+ images were acquired over Montagu Island during the eruption period, only one was sufficiently cloud-free to be of use. ASTER has infrared bands with a nominal spatial-resolution of 30 and 90 m, and visible bands at 15 m. However, its repeat period is variable since coverage must be requested and scheduled in advance. A pre-eruption, as well as five syn-eruption, ASTER images were used here. Several RADARSAT-1 SAR amplitude images (C-band; 5.6 cm), acquired in both fine (9 m pixel size) and standard (30 m pixel size) modes, improved our visualization of the island's morphology. These data have the benefit of being unaffected by cloud cover.

Thermal anomalies in MODIS data were detected and analyzed using the automated MODVOLC satellite monitoring system (Wright et al. 2002). The alert system offers global detection of high-temperature phenomena (volcanic activity, industrial hotspots and forest fires), with data displayed within 24–72 h of image reception at http://modis.higp.hawaii.edu. The detection algorithm exploits the characteristic differences in radiance of hot (in this case volcanically active) ground surfaces compared to that of background surfaces among MODIS bands 21, 22 and 32 (see Table 2). Anomalous pixels are flagged and their locations posted on the website for analysis, but the algorithm does not yet take the role of alerting the user to new or unusual activity. Indeed, anomalies at Mt. Belinda were only discovered by analysts some months after their initial appearance, during the course of examining anomalies at nearby Mt. Michael volcano on Saunders Island.

Because the MODVOLC data are openly available on the web and the original MODIS data are free of charge from the United States Geological Survey, the costs of the imagery used here were limited to the two Landsat ETM+ (currently US $600/image), six ASTER scenes (US $55/image), and two RADARSAT-1 images (US $16/image). This kept the data cost of the entire 2.5-year satellite monitoring effort to less than US $1,600.

Chronology of activity

Here we divide the eruption into four phases based upon MODIS thermal anomaly intensity and inferred activity style from the high spatial-resolution imagery.

Pre-eruption activity (1992–2001)

There is no previous record of definitive volcanic activity on Montagu Island. Based on AVHRR images obtained in the period March 1995 to February 1998, apparent plumes and unreported single anomalous pixels were observed intermittently on images of Montagu Island and may indicate rare and sporadic (and unverified) volcanic activity prior to that now observed (unpublished observations of T Lachlan-Cope and JLS). However, during field investigations by one of us (JLS) in January 1997, Montagu Island was viewed from both Saunders and Bristol islands and was apparently inactive, with the summit region entirely clothed in snow and ice. Hand-held photographs of the island obtained in September 1992 also show the summit to be wholly inactive. Those observations suggest that the activity reported here is likely a recent phenomenon, and has probably increased relative to previous unconfirmed 1995–1998 levels.

An ASTER image acquired on 12 September 2001 constrains the start of the recent eruption as being after this date, as the summit region contains no visible deposits or thermal anomalies (Fig. 2b). Furthermore, an earlier Landsat 7 ETM+ scene, dated 24 January 2001 (not shown), also lacks any signs of activity, and indicates that the September ASTER scene likely does not contain any recent deposits that may have simply been covered by the preceding months of Antarctic winter snows. A pre-eruption RADARSAT image (5 March 1998, not shown) shows arcuate fractures in the ice cover approximately 2 km east of Mount Belinda which resemble those resulting from subglacial volcanism (Gudmundsson et al. 1997), however their position on steep terrain and lack of recent confirmed activity suggests that these are topographic crevasses.

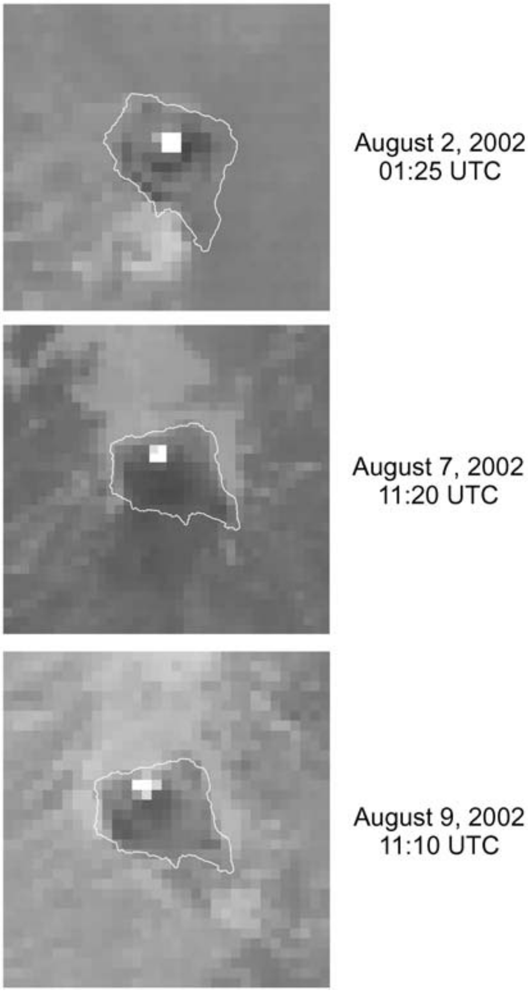

Fig. 3 Selected MODIS images showing thermal anomalies at Montagu Island. Band 21 is shown here. The thermal anomalies at Montagu appear to be located near the summit of Mount Belinda (see Fig. 2). Images are not georeferenced in order to maintain radiance integrity, therefore coastlines are approximate

Phase 1 (Oct 2001–Feb 2002): minor thermal anomalies, limited lava flow

The first MODVOLC thermal alert on Montagu Island occurred on 20 October 2001, with a single anomalous pixel on the north side of the island, indicating that the activity started at some point in the preceding five weeks since the September ASTER acquisition. Subsequent anomalies between October 2001 and February 2002 were generally one to two pixels in size, and of low intensity relative to the subsequent phases of the eruption. Visual inspection of the Band 21 imagery revealed that these and all subsequent anomalies were located near the summit of Mount Belinda, changing slightly in position either due to satellite viewing geometry or actual migration of hot material (Fig. 3). The temporal trend of all the MODVOLC thermal alerts for the duration of our study period is featured in Fig. 4, which shows the total radiant heat output throughout the course of the study period calculated from MODIS Band 21 nighttime imagery using a simple empirical relation (Kaufman et al. 1998; Wright and Flynn 2004).

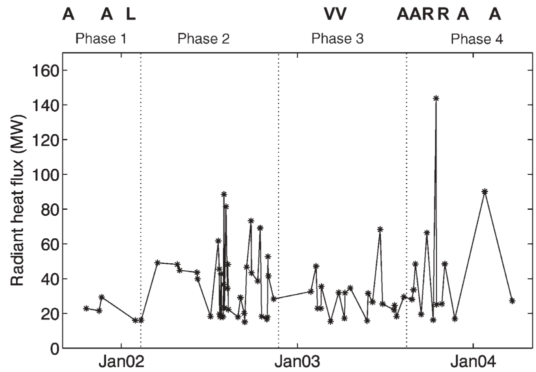

Fig. 4 Total radiant heat output in MegaWatts at Montagu Island from the start of the eruption (Oct 2001) to the time of writing (May 2004), calculated from the MODVOLC analysis of MODIS nighttime Band 21 data (Wright and Flynn, 2004). *Letters* denote acquisition dates of high-resolution imagery, ASTER (A), Landsat ETM+ (L), and RADARSAT (R), as well as the date of visual observations from ships (V)

A night-time ASTER image dated 23 December 2001 (not shown here), shows the island lacking any overt signs of volcanic activity, with the exception of a subtle elongate feature extending north-east from the summit that exhibits a slightly higher radiance than the surrounding snow and ice. The lack of lateral confinement on this feature, which would be expected for a lava flow emplaced on the ice cover, suggests that this is a solar-heated tephra deposit.

Significant volcanic activity on Mount Belinda was confirmed by a Landsat 7 ETM+ image acquired on 4 January 2002 (Fig. 5a). A distinct steam/ash plume can be seen drifting south from the summit, while the entire north and east flanks are tephra covered. A large summit thermal anomaly is present in the thermal infrared Band 6 indicating a significantly heated surface, and smaller anomalies are present in Bands 5 and 7, indicating temperatures greater than about 210° C (Flynn et al. 2001). With a source at the summit anomaly and trending NE, there is an elongate high temperature feature that appears to be a short lava flow, extending ~600 m with a width of ~210 m.

Phase 2 (Feb 2002–Nov 2002): High radiance anomalies

The trend of the MODVOLC thermal alerts shows an apparent rise in activity level in February 2002 (Fig. 4), possibly indicating increased explosive activity at the summit. Total radiant heat output reached a local maximum on August 2, 2002, and during that week some of the largest thermal anomalies in our study period were observed (up to four pixels). The visible band MODIS images indicate that tephra was being deposited on the north flank of Belinda at this point. We can now discount the emplacement of any significant amount of lava in this

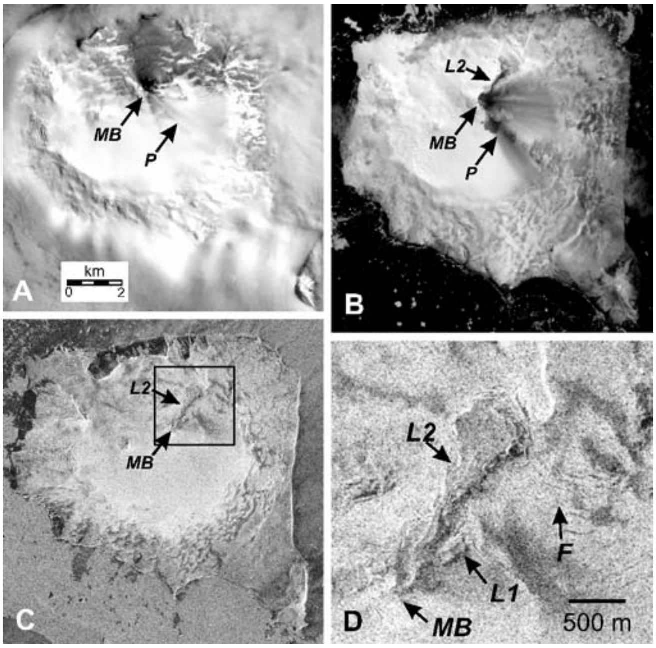

Fig. 5A–D Selected high spatial-resolution images of Montagu Island. North is up. **A)** Landsat 7 ETM+ Band 8 image from 4 Jan 2002 showing diffuse plume (*P*) emanating from Mount Belinda's summit (*MB*) and tephra deposits on north flank. Scale bar applies to **A, B** and **C. B)** ASTER visible band composite image (Bands 3–2-1) on 7 Dec 2003, showing tephra deposits and 2003 lava flow (*L2*). **C)** RADARSAT-1 image from 30 Oct 2003 showing recent morphology, with inset **(D)**. Arrows point to approximate summit of Mount Belinda and vent location (*MB*), ash plumes (*P*), 600 m long lava flow first observed in Jan 2002 (*L1*), entrenched 2 km long lava flow first observed in Aug 2003 (*L2*), and arcuate fractures unrelated to this eruption (*F*). RADARSAT image was provided by the Alaska Satellite Facility, and is copyright 2003 CSA

period (Smithsonian Institution 2004), as analyses of high spatial-resolution data acquired later in the eruption bear no evidence of alteration to the icefield. It is possible that the August maximum represents an unusually clear viewing period (as supported by the increased number of clear images), and may not reflect relative activity level.

Phase 3 (Nov 2002–Jul 2003): Low radiance anomalies

MODIS thermal anomalies between November 2002 and July 2003 were generally low to moderate in intensity (Fig. 4), and no high-resolution images were recorded during this period. At the behest of the British Antarctic Survey, observations were taken from the HMS *Leeds Castle* in early February 2003 providing the first photographic proof of the eruption, in which a low-level plume was shown rising above a tephra-covered icefield (Fig. 6). This remains the only ground-based photograph of the eruption in almost 3 years of monitoring by satellites, illustrating the significant difficulties in acquiring information in this remote region. One month later, a British Antarctic Survey research vessel was diverted to gather observations of the island, and although heavy fog prevented a clear view of the flanks, a prominent ash plume was observed rising from the summit on 2 March 2003.

Fig. 6 Photograph of Mt. Belinda volcano in eruption in early February 2003, courtesy of the HMS Leeds Castle. View is looking to the south at the north coast of the island. Note the thin mantle of tephra covering the glaciers

Phase 4 (Jul 2003-May 2004): High radiance anomalies, long lava flow

Anomalies were detected in MODIS imagery up until the time of writing (last on 22 March 2004), indicating that activity has persisted. Radiant heat flux reached its highest observed levels in this phase (Fig. 4), with a distinct spike on 16 October 2003.

ASTER images acquired on 1 and 17 August 2003, show a dark sinuous lava flow extending north-east from the summit. The 1 August image (not shown here) also shows a substantial dense billowing plume, which is absent on 17 August. The latter image is the clearer of the two and shows a dark tephra deposit also directed north-eastward but slightly offset to the south of the flow, and a minor plume extending less than a km from Mount Belinda summit (Fig. 7). The lava is about 2 km in total length. It broadens from about 100 m wide close to source, to 200 m at 1.5 km, at which point it swells to a paler-colored fan-shaped flow front about 600 m in diameter with a crescent-like termination and at least one arcuate ridge-like feature. The narrow proximal section of the flow appears radiant in the thermal infrared (Band 6) on 17 August, at which point it is at least two weeks old, and surrounding shadows suggest syn-emplacement downcutting into the ice and resulting lateral confinement similar to lava flows at Westdahl volcano, Alaska, in 1991 (Dean et al. 2002). A 7 December 2003 ASTER image (Fig. 5b) and 30 October 2003 RADARSAT image (Fig. 5c, d) show this downcutting well. It is unclear whether this lava channel terminates as a lava-fed delta, entering a small meltwater lake as occurred in the 1983 eruption of Veniaminof (Yount et al. 1985).

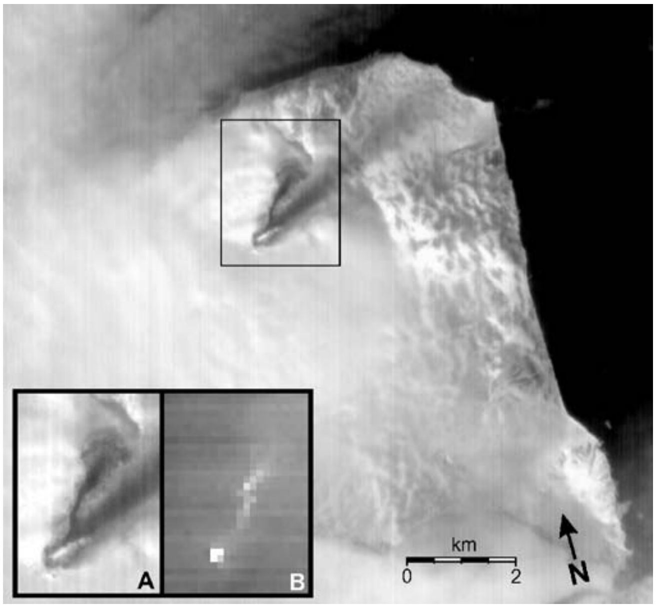

Fig. 7 ASTER visible band composite image (Bands 3-2-1) on 17 Aug 2003, showing lava flow. The insets show (A) a visible band close-up of the lava flow and debris fan extending from the summit of Mount Belinda and (B) the equivalent view in the thermal infrared (ASTER Band 13)

The most recent ASTER image (9 February 2004, not shown) has Mount Belinda emitting only a faint plume, with thermally anomalous pixels at the vent and on the proximal sections of the still-cooling 2 km long lava flow. The distal fan-shaped portion of this flow appears to be snow covered. The lack of new lava in this image indicates that the high heat flux values observed on 16 October 2003 (Fig. 4) were not related to lava effusion.

Concurrent activity at Saunders Island lava lake

An active lava lake in the Mount Michael summit crater on Saunders Island (Fig. 1) was first reported by Lachlan-Cope et al. (2001) using AVHRR imagery from 1995–1998. The MODVOLC system has detected repeated thermal anomalies throughout 2001–2003 in the summit area (Fig. 8), indicating that the lava lake has persisted. Anomalous pixels were detected intermittently and were nearly all one to two pixels in size, consistent with the relatively small confines of the crater. At the time of submission no anomaly had been detected for ~12 months (i.e. since May 2003), however the 2001–2003 period was marked by intervals up to 7 months, indicating that detection is strongly limited by viewing conditions or activity level.

Periods between observations are much longer at Michael (as much as seven months) compared with Mount Belinda, possibly due in part to their differing geometry. On Mount Belinda, material is erupted onto the volcano flanks, permitting any satellite zenith angle to view it. The maximum zenith angle for the MODVOLC

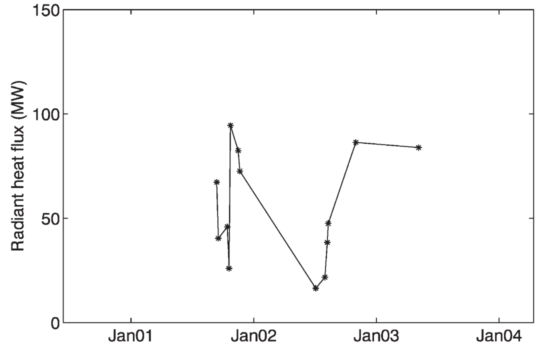

Fig. 8 Total radiant heat output in MegaWatts from Mt. Michael volcano, Saunders Island, as calculated from MODVOLC thermal alerts

thermal alert imagery analyzed at Belinda is 56.9°, which is approaching the maximum possible zenith angle, and the mean zenith angle is 20.5°. On the other hand, all of the hot material at Michael is within the ~700-m wide crater at an unknown depth, which may be variable (Lachlan-Cope et al. 2001). If sufficiently deep, only small zenith angles (i.e. closer to vertical) would permit an unobstructed view into the crater and onto the lava surface (Harris et al. 1997), similar to the situation at Shishaldin, Alaska, in 1999 (Dehn et al. 2002). The maximum zenith angle for the imagery at Michael is 28.4° and the mean is 15.2°, although the sample size is much smaller here than at Mount Belinda. The depth of the lava surface might be calculated with these values (Dehn et al. 2002), however, the 700 m diameter measurement is only a rough estimate and the actual conduit likely narrows considerably at some depth within this outer crater. Nevertheless, along with cloud cover the zenith angle is another critical factor in anomaly detection.

Anomaly detection may also be limited by the increasing pixel size at high zenith angles. For similar sensors, at extreme scan the spatial-resolution of the sensor is several times coarser than it is at nadir (Mouginis-Mark et al. 1994; Harris et al. 1997). For a small hot target, integrating its emitted radiance into these much larger areas may lead to a pixel-integrated radiance that is insufficient to trigger the MODVOLC detection scheme.

Conclusions

The South Sandwich Islands are a young active intra-oceanic volcanic arc whose remote location precludes the possibility of any comprehensive ground-based monitoring or research. As a partial remedy, satellite data offer the only realistic means of establishing the timing and evolution of the activity, as well as providing clues regarding the type, style and scale of the eruptive products. In this study, we have described the rough chronology of the first recorded eruption at Mount Belinda volcano, on Montagu Island, based almost solely upon an analysis of satellite imagery. This eruption is apparently still continuing. Its detection was made possible with the MOD-

VOLC satellite monitoring system, a tool which will now facilitate regular tracking of volcanic activity in the South Sandwich Islands and other remote regions.

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