Bull Volcanol (2000) 62 : 188–198 

RESEARCH ARTICLE

P. J. Mouginis-Mark · H. Snell · R. Ellisor

# GOES satellite and field observations of the 1998 eruption of Volcan Cerro Azul, Galápagos Islands

Received: 27 April 1999 / Accepted: 21 February 2000

**Abstract** The 1998 eruption of Volcan Cerro Azul, Isla Isabela, Galápagos Islands, was observed in near real-time by the Geostationary Operational Environmental Satellite-8 (GOES-8) weather satellite. Due to the remote location of the eruption site, 3.9-μm radiance values derived from GOES band 2 provide the best timing of the start and termination of the eruption, which occurred on 15 Sept. and 21 Oct., respectively. Throughout the 36-day long eruption, a total of 1335 thermal infrared images were collected, of which 851 were cloud-free and permitted the thermal anomaly to be detected. A detailed chronology including 77 separate events was assembled from the GOES data and field observations. Numerous attributes of the eruption were observed from the GOES data, including the sizes and dispersal of seven eruption plumes and the occurrence and timing of intra-caldera effusive activity. The growth of a lava flow on the SE flank, the formation of smoke and volcanic haze from the flank vent, and burning of vegetation caused by lava flows entering vegetated areas were monitored both on the ground and with the satellite data. In most cases GOES images were processed as they were received every 30 min and were then distributed over the Internet within minutes of reception. These data provided timely high-temporal information to field parties as well as enabled the documentation of the eruption. The GOES observations of Cerro Azul serve as a further example of the way in which the remote sensing community and field volcanologists can collaborate during future eruptions, and permit the temporal and spatial resolution requirements for future satellites systems to be better defined.

**Key words** Remote sensing · GOES · Galápagos Islands · Volcan Cerro Azul

Editorial responsibility: C. Newhall

Peter J. Mouginis-Mark (✉)
Hawaii Institute of Geophysics and Planetology, and Hawaii Center for Volcanology, University of Hawaii,
2525 Correa Road, Honolulu, HI 96822, USA
e-mail: pmm@pgd.hawaii.edu
Fax: +1-808-9566322

Howard Snell
Charles Darwin Research Station, Puerto Ayora, Isla Santa Cruz, Galápagos, Ecuador

Rachel Ellisor
Department of Geology, University of Idaho, Moscow, Idaho 83844, USA

## Introduction

Prior to the 1998 event described herein, Volcan Cerro Azul on Isla Isabela in the Galápagos Islands (0.90°S, 91.42°W; Fig. 1) last erupted in February 1979, with activity on the southeastern flank that lasted several weeks (McClelland et al. 1989, p 532). Monitoring of this 1979 eruption was difficult because of the remote location of the volcano, which is ~30 km from the only inhabited part of the island and is distant from the usual routes taken by tour boats. Thus, when an eruption of Cerro Azul took place in 1998, a new opportunity arose to test the utility of near real-time data from geostationary weather satellites for volcano monitoring to complement ground activities. Here we use data from the Geostationary Operational Environmental Satellite (GOES) to document the 1998 eruption of Volcan Cerro Azul, use field observations made during the eruption to further define the chronology of events, and provide a perspective on the future use of satellite observations in documenting other similar eruptions.

## The satellite data set

Harris et al. (1997, in press) have shown that GOES data can be used for frequent observations of erupting volcanoes. In the case of the 1998 Cerro Azul erup-

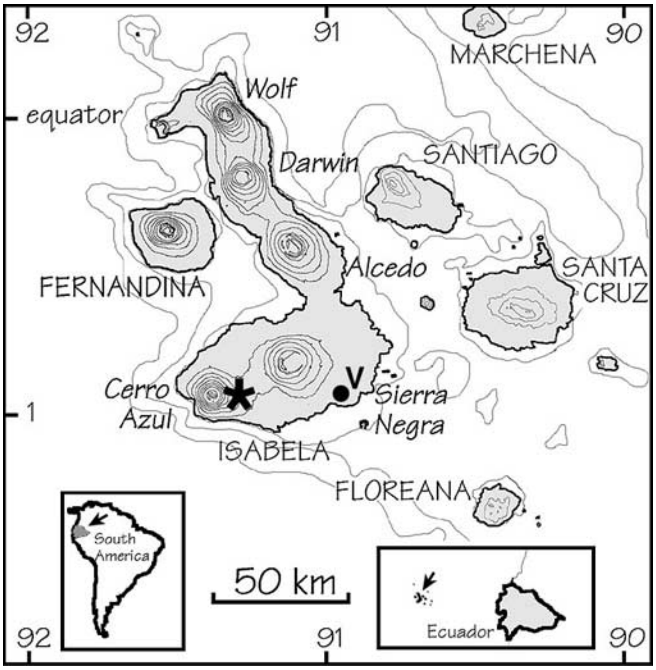


**Fig. 1** Location map of the Galápagos Islands (modified from Rowland 1996) shows the approximate location of the Sept. 1998 Cerro Azul vent (*asterisk*). Islands are in shaded tone, with subaerial contours at 200-m intervals. Bathymetric contours (generalized) are at a depth of 100 m and then multiples of 1000 m. The town of Villamil is indicated by *V*. *Insets* show at left the location of Ecuador in South America (*arrow*) and at right the Galápagos Islands (*arrow*) to the west of Ecuador

tion, the GOES-8 satellite imaged the activity every 30 min. Only during special events, such as the passage of Hurricane Georges through the Caribbean and SE United States in late Sept. 1998, was this routine coverage interrupted in order to provide higher temporal coverage over other portions of the GOES field of view. As a result, fewer than ten daytime images of the Galápagos Islands were obtained on 21, 23, and 29 Sept. Images of the Cerro Azul eruption were processed and displayed within a few minutes of their acquisition on the University of Hawaii's web site (http://volcano1.pgd.hawaii.edu).

Despite the high temporal coverage, there were many days when few cloud-free images of the eruption were obtained. Although there were many instances when a thermal anomaly could be detected through thin cloud (Fig. 2), approximately 36 % (484) of all the scenes (day and night) could not be used due to excessive cloud cover. Cloud cover also precluded the acquisition of high-resolution (10–30 m/pixel) views of the surface from the SPOT 4 and Landsat 5 spacecraft during the eruption. In addition, no Local Area Coverage (LAC) data were obtained by the Advanced Very High Resolution Radiometer (AVHRR) instruments on the polar-orbiting National Oceanic and Atmospheric Administration (NOAA) weather satellites, so that the GOES data presented here represent the highest spatial resolution satellite data available for this eruption.

Band 1 GOES data (0.52–0.72 μm) are particularly useful for the morphological analysis of plumes during daytime, since these data have a spatial resolution of 1 km per picture element ("pixel") and the plumes can be easily identified by virtue of their high reflectivity compared with that of the ocean. Although GOES data collected between 3.78 and 4.03 μm (band 2) and 10.2–11.2 μm (band 4) have a spatial resolution of 4 km/pixel, they are the most useful bands for detecting effusive eruptions due to the high radiance values (Harris et al. 1997; Harris and Thornber 1999). A wide range of area/temperature combinations exist for the surface that will saturate bands 2 and 4, but the pixel-integrated saturation temperature for each band is ~50 °C (Harris et al. 2000). In instances where the active lava flow occupies an area that is smaller than the entire pixel, the subtraction of brightness temperatures derived from band 4 from those derived from band 2 highlights sub-pixel hotspots and reduces the effects of solar heating (Harris et al. 1995, 2000).

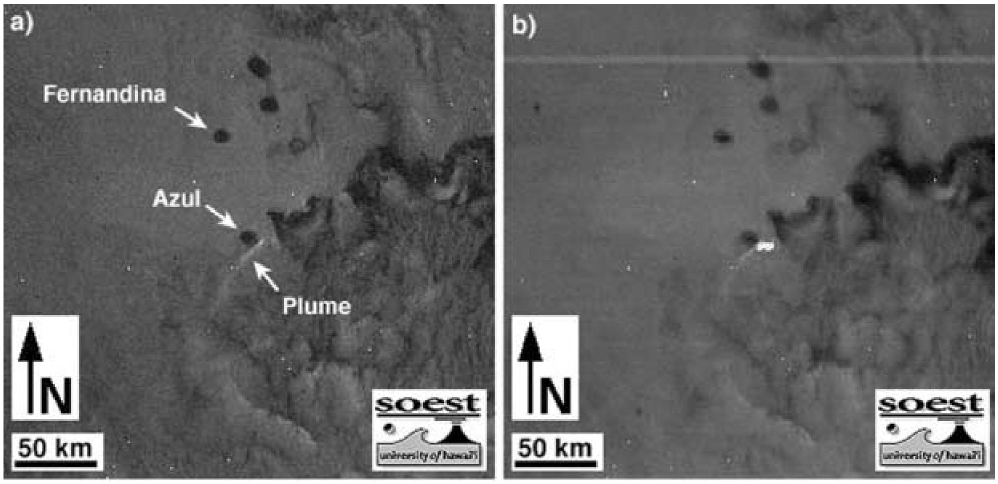


**Fig. 2a,b** Some observations of the eruption could be made even when clouds covered almost all of Isla Isabela. **a** In this early morning band-1 scene obtained on 10 Oct. 1998 (06:28 local time), a small plume has penetrated the cloud layer. **b** The coincident band-2 thermal infrared data show that the cloud was sufficiently thin to enable the thermal anomaly of the active flow to be observed. The field of view in both images is the same as in Fig. 4

The GOES-8 satellite collected 520 visible and thermal daytime images, and 815 nighttime thermal images, during the 36-day eruption of Cerro Azul. For correlation with field observations, the image acquisition times given in this paper are local times (i.e., 6 h behind Universal Time). These times have also been corrected for the 13-min time difference between the start of each new scene acquisition by the GOES Imager (the image is constructed from scan lines that start at the north pole) and the specific scan start time for the latitude of the Galápagos Islands.

## Observations of the eruption

Table 1 provides a 77-point summary of the major features of the eruption, including both satellite and field observations. The eruptions took place within the 5-km diameter caldera, and on the eastern flank of the volcano ~5.5 km from the eastern caldera rim. Several lava flows were formed, the largest of which was ~16 km long. This flow formed a broad flow field ~2 km wide at the vent but narrowed to ~700 m at its distal end.

Numerous features of the eruption were observed in the GOES data, including eruption plumes, thermal anomalies due to intra-caldera activity, and thermal anomalies due to active lava flows on the eastern flank. However, due to the low spatial resolution of bands 2 and 4, the summit activity could not always be identified as a separate event after the flank eruption commenced. At some times either the caldera or the flank were obscured by clouds, whereas at other times the low spatial resolution of the data may have caused the anomalies to merge. Retrospective analysis of field observations also indicates that other aspects of the eruption were seen in the GOES data, including smoke from burning vegetation at the edge of the active flows and haze plumes produced from degassing at the vents.

The onset of the Cerro Azul eruption was first noticed from the GOES data by C. Okubo (University of Hawaii) within an hour of the eruption beginning using the University of Hawaii's near real-time hot-spot website and automatic "eruption alert algorithm" (Harris et al. 2000). Four additional successive images after this initial detection were studied prior to contacting the authorities in the Galápagos Islands (see Appendix for the criteria that we used to confirm this eruption). This notification was given ~8.5 h before independent confirmation from the town of Villamil reached the Charles Darwin Research Station (CDRS) on the adjacent island of Santa Cruz.

Because no air or field observations were made until the next day, the GOES observations made on 15 Sept. have proven to be most important for reconstructing the earliest sequence of events. In particular, GOES band-2 radiances allowed the timing and location of the first activity to be accurately determined.

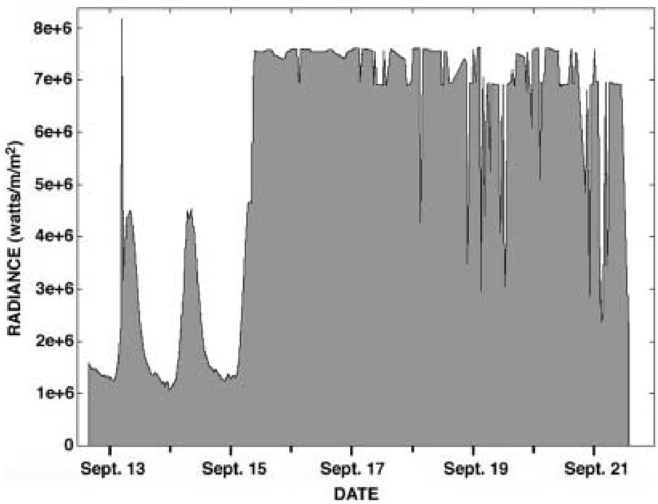


**Fig. 3** Plot of all band 2 (3.78–4.03 μm) radiance values for the onset of the Cerro Azul eruption. The eruption began on 15 Sept. 1998. Prior to this time, radiance values follow the normal diurnal heating cycle for the volcano. The spike early on 13 Sept. is an instrument artifact. Note that bands 2 and 4 of the GOES sensor were saturated for all observations except where cloud cover obscured part of the eruption site

No thermal anomaly was detected at 12:28 on 15 Sept., but 31 min later an anomaly was present (Fig. 3). By 13:28 a bright (high reflectivity) anomaly in the band-1 image had formed at the caldera (Fig. 4a) and a two-pixel band-2 thermal anomaly was present. The band-1 image collected at 13:58 showed that a broad plume (plume 1) was spreading in a 90° arc (from almost due north to due west) and that there was a prominent circular cloud (plume 2) over the volcano (Fig. 4b). Shadow-length measurements indicate that plume 2 rose to an altitude of ~8 km (C. Okubo, pers. commun.). No altitude could be derived for plume 1 due to the lack of a prominent shadow, so it is inferred that plume 1 was at a lower altitude than plume 2. We believe that the thermal anomaly was located within the caldera since it was co-located with the point of origin of the eruption plumes, as determined by manually retracing the trajectories of plumes 1 and 2 on hard-copy versions of the band-1 images.

The GOES data also define the time of onset of activity at the SE flank vent. The critical satellite observation was made prior to the arrival of field observers, although distant sightings of an indeterminate form of activity were reported from the town of Villamil on 15 Sept. around 17:00. During late evening on 15 Sept., a prominent thermal anomaly comprising two GOES band-2 pixels was located at the site of the daytime thermal anomaly (Fig. 5). This thermal anomaly had been in the same position since the beginning of the eruption, although it had been decreasing in size since 20:28 on 15 Sept. From the GOES data, we interpret this anomaly to be located within the caldera. However, between 03:58 and

**Table 1** Chronology of significant events

| Date | Local time | Day/night | Event |
|---|---|---|---|
| 15 Sept. | 12:58 | Day | First saturated band-2 pixel ($\sim 6.9 \times 10^6$ watts/m per square meter) detected within caldera |
| 15 Sept. | 13:28 | Day | Bright flash over caldera, plume 1 forming |
| 15 Sept. | 13:58 | Day | Plume 2 starting to form |
| 15 Sept. | 14:58 | Day | Plume 1 reaches Isla Fernandina, 30 km to north |
| 15 Sept. | 15:58 | Day | Plume 2 appears to be stopping |
| *15 Sept.* | *17:00* | *Day* | *First visual eruption observations from town of Villamil* |
| 15 Sept. | 17:28 | Day | Plume 2 no longer visible |
| 15 Sept. | 21:00 | Night | GOES eruption notification sent to CDRS[a] |
| 16 Sept. | 04:28 | Night | A new band-2 thermal anomaly detected to SE of original anomaly |
| *16 Sept.* | *05:30* | Dawn | *Reports of visual sightings reach CDRS* |
| 16 Sept. | 05:38 | Dawn | CDRS distributes announcement of eruption |
| 16 Sept. | 06:28 | Dawn | Bright "plume tower" observed over vent |
| 16 Sept. | 06:58 | Day | Plume 3 extends to west for 50 km. Possibly two sources? |
| *16 Sept.* | *11:00* | Day | GNPS[b] *crew flies over sites; radial fissure confirmed on SE flank* |
| 16 Sept. | 15:58 | Day | Plume 3 extends 75 km to west. Two distinct thermal anomalies; implies intra-caldera activity and flank eruption |
| 16 Sept. | 18:58 | Night | Large band-2 anomaly on SE flank; fountaining? |
| 17 Sept. | 06:28 | Dawn | Plume 4 visible over vent |
| 17 Sept. | 09:28 | Day | New eruption forms plume 5 |
| *17 Sept.* | 12:00 | Day | Radial 1-km-long fissure on flank located from air. Fresh intra-caldera flows/extensive steam plumes identified from air |
| 17 Sept. | 12:30 | Day | Flow from flank vent reaches point 8 km east of radial fissure |
| 17 Sept. | 15:28 | Day | Possible plume 6 |
| 17 Sept. | 18:28 | Night | Saturated band-2 thermal anomaly on SE flank |
| 18 Sept. | 01:28 | Night | Two distinct band-2 thermal anomalies; implies intra-caldera activity |
| 18 Sept. | 16:28 | Day | Plume 6 extends to NW >60 km |
| 19 Sept. | 00:59 | Night | Large band-2 anomaly on SE flank; fountaining? |
| 20 Sept. | 00:59 | Night | Two distinct band-2 thermal anomalies observed for next 5 h; implies intra-caldera activity for this period |
| 20 Sept. | 05:58 | Night | GOES indicates probable activity both within and outside caldera |
| 20 Sept. | 06:58 | Day | No plume visible despite cloud-free conditions |
| 20 Sept. | 20:58 | Night | Two distinct band-2 thermal anomalies; implies intra-caldera activity |
| 21 Sept. | 00:58 | Night | Two distinct band-2 anomalies observed for next 3 h; implies intra-caldera activity during this period |
| 21 Sept. | 06:28 | Dawn | Plume 7 extends $\sim$30 km to south |
| 21 Sept. | 20:58 | Night | Two distinct band-2 thermal anomalies; implies intra-caldera activity |
| *22 Sept.* | 02:00 | Night | Visual observations of flank eruption from offshore SE coast |
| 22 Sept. | 20:58 | Night | Last confident observation of ongoing intra-caldera activity |
| *23 Sept.* | *All night* | Night | Field observations of fountaining and active lava channels |
| 24 Sept. | 08:28 | day | Vog plume extends to Fernandina. Smoke from flow edge? |
| 24 Sept. | 09:28 | day | Large band-2 anomaly on SE flank; fountaining? |
| 25 Sept. | 08:58 | Day | Large vog plume extends beyond Fernandina |
| *25 Sept.* | 13:30 | Day | Last field confirmation of ongoing intra-caldera activity |
| 26 Sept. | 06:28 | Dawn | 10-km plume extends SW from summit |
| 26 Sept. | 08:58 | Day | Thin plume extends 50 km to WSW |
| *26 Sept.* | 09:00 | Day | Flow to SSE appears to threaten nesting habitat of endangered tortoises |
| 26 Sept. | 15:58 | Day | Extensive vog plume visible at low-Sun angle |
| 27 Sept. | 06:58 | Day | $20 \times 10$-km vog cloud over vent area |
| *27 Sept.* | *09:00* | Day | GNPS and CDRS decide to remove 15 tortoises from area to create a captive breeding population |
| 28 Sept. | 18:58 | Night | First observation without prominent intra-caldera band-2 anomaly |
| 30 Sept. | 17:28 | Dusk | 10-km plume heading NNW above cloud cover |
| *1 Oct.* | *15:00* | Day | Over-flight of caldera confirms summit no longer active |
| 1 Oct. | 16:58 | Day | 5-km plume heading NNW above cloud cover |
| 2 Oct. | 06:58 | Dawn | 10-km plume heading NNW above cloud cover |
| *2 Oct.* | *15:00* | Day | Field observations of flows east of vent confirms lower level of activity. Active flows south of vent continue until at least 19:00 on 7 Oct. |
| 4 Oct. | 05:58 | Dawn | Plume over vent area |
| *5 Oct.* | *12:00* | Day | Field parties complete removal of 15 tortoises |
| 5 Oct. | 15:58 | Day | Probable smoke plume from flow. Vog from vent |
| 6 Oct. | 06:28 | Dawn | 5-km plumes from vent and flow |
| 8 Oct. | 06:58 | Dawn | 5-km plumes from vent and flow |
| 8 Oct. | 13:58 | Day | Possible vog over northern part of volcano |
| 8 Oct. | 15:28 | Day | Prominent vog plume to 50 km north of volcano |
| *9 Oct.* | All afternoon | Day | Field observations of prominent fountains at vent |
| 9 Oct. | 16:28 | Day | Vog plume extends 40 km west of volcano summit |
| 9 Oct. | 17:28 | Dusk | 10-km plume extends SW from vent above cloud deck |

**Table 1** (Continued)

| Date | Local time | Day/night | Event |
|---|---|---|---|
| 10 Oct. | 06:28 | Dawn | 20-km plume extends SW from vent above cloud deck |
| 11 Oct. | 21:58 | Night | Large band-2 anomaly on SE flank; fountaining? |
| *11 Oct.* | *21:00* | Night | Last field observation of active flows |
| 12 Oct. | 06:28 | Dawn | 30-km plume extends SW from vent above cloud deck |
| 13 Oct. | 06:28 | Dawn | Small plume just to east of summit seen above cloud deck |
| 13 Oct. | 21:58 | Night | Large band-2 anomaly on SE flank; fountaining? |
| 16 Oct. | 02:58 | Night | Large band-2 anomaly on SE flank; fountaining? |
| 17 Oct. | 06:28 | Dawn | Small plume over vent |
| 17 Oct. | 07:28 | Day | Large band-2 anomaly on SE flank; fountaining? |
| 17 Oct. | 08:58 | Day | Narrow plume extends to SW for 50 km |
| 21 Oct. | 05:28 | Night | Last saturated band-2 pixel ($\sim 7\times10^6$ watts/m per square meter). End of eruption? |
| 21 Oct. | 14:28 | Day | Band-2 radiance $\sim 5.6\times10^6$ watts/m per square meter |
| 22 Oct. | 03:58 | Night | Band-2 radiance $\sim 3.9\times10^6$ watts/m per square meter |
| 23 Oct. | 07:28 | Day | Band-2 radiance $\sim 1.3\times10^6$ watts/m per square meter |
| 24 Oct. | 10:58 | Day | Band-2 radiance $\sim 1\times10^6$ watts/m per square meter. No obvious daytime anomaly |
| 26 Oct. | 00:58 | Night | Band-2 radiance $\sim 5.5\times10^5$ watts/m per square meter |

Events listed in italics are from observations made by field crews in the Galápagos
[a]Charles Darwin Research Station
[b]Galápagos National Park Service

04:28 on 16 Sept., a new extension of the anomaly developed to the SE (Fig. 5). This extension was seen as a strong band-2 minus band-4 thermal anomaly that grew to be four pixels in size by 05:58 and remained prominent for many days (Table 1). Two early morning band-1 GOES images on 16 Sept. also show that two plumes had formed, one from the summit and one from the SE flank. We interpret this change in the size and shape of the GOES thermal anomaly as marking the start of the flank eruption, although we caution that the large size of the GOES band-2 pixels (4 km) makes it difficult to be certain of this interpretation. Support for this idea nevertheless comes from the observed extension of similar GOES thermal anomalies during eruptions at Kilauea volcano, which have been shown to be due to the features related to the growth of lava flows (Harris et al., in press). Strong thermal anomalies (at least one saturated GOES band-2 pixel) were associated with the eastern flank for all subsequent cloud-free scenes through 21 Oct., strongly suggesting that the flows were active for the entire period. This persistent lava flow activity was also seen in the field until the end of observations on 11 Oct.

Key field studies of the Cerro Azul eruption augment the satellite data and provide a more complete characterization of the activity. Airborne observations were made on 16, 17, and 18 Sept., and on 1 Oct., and field data were collected by us and by personnel of the Galápagos National Park between 21 Sept. and 11 Oct. (Table 1). In particular, our flight on 17 Sept. identified a radial fissure vent at the 600- to 640-m elevation level on the volcano at 0° 57.277′S, 91° 19.773′W, and that an active flow had already traveled 8 km east to 0° 57.224′S, 91° 15.479′W. Given that the start time of the flank eruption was 04:15 ± 15 min on 16 Sept., this implies that the fissure-fed flow traveled 8 km in 38 h ± 15 min, at an average speed of ~210 m/h. Further estimates of the location of the distal end of the flow were made from the air on 18 Sept. and showed that the flow had progressed an additional ~2.3 km in the following 23 h, implying a now-slowing lava flow with an average speed of ~100 m/h. We note that due to the spatial resolution of the GOES data, no comparable speed estimates could be made from the satellite data.

Although the GOES data have insufficient spatial resolution to study the geometry of the flow or its rate of advance, the general characteristics of the activity can be identified and correspond well with the field observations. Figure 6a is our earliest aircraft observation of the flank vent, taken ~36 h after the start of the flank eruption. Particularly vigorous activity, defined as occurring when the thermal anomaly comprised more than ten saturated band-2 pixels, was detected by GOES on 17 Sept. (18:28) almost concurrent with the observed fire fountains along an active fissure (Fig. 6a). Additional large thermal anomalies (all more than ten band-2 pixels) were also detected by GOES on seven other days (Table 1) and most likely corresponded to fountaining events at the vent (Fig. 6b) and active lava channels (Fig. 6c). Similar variations in radiant intensity in GOES observations are modeled in detail for Kilauea volcano by Harris and Thornber (1999) who showed that such variations can indeed be related to these types of surface activity. Thus, we infer that valid general interpretations of the Cerro Azul eruption can be made when GOES data are the only information available.

Other features of the eruption were also seen in the GOES data. Five additional plumes were identified between 16 and 22 Sept. (Table 1). These plumes

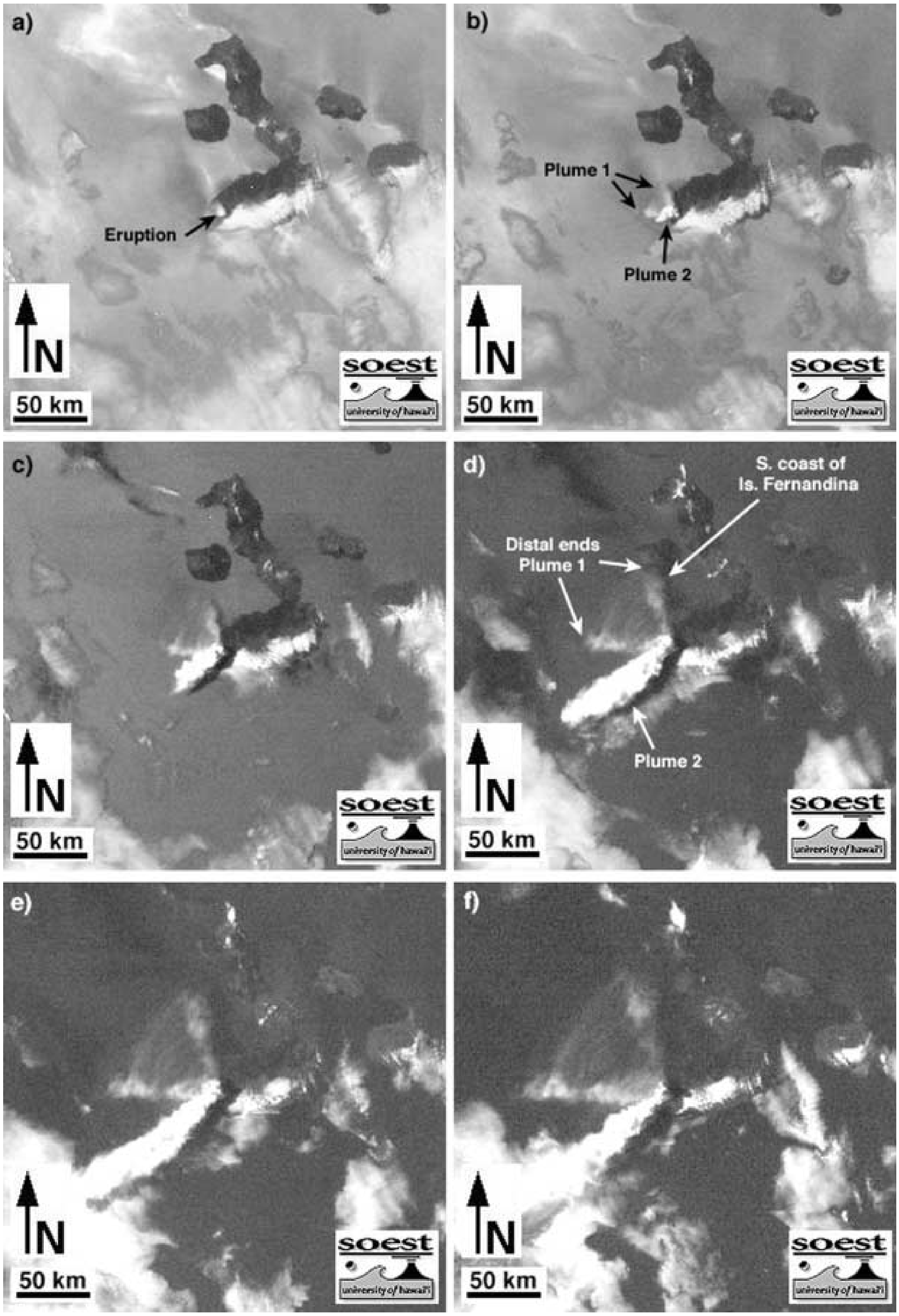


**Fig. 4a–f** Band 1 (0.52–0.72 μm) GOES observations of the first two eruption plumes detected on 15 Sept. 1998. Images were obtained at the following local times: **a** 13:28; **b** 13:59; **c** 14:28; **d** 14:58; **e** 15:28; and **f** 15:58. No plume was present in the 12:59 image (not shown). Note that in the final image (**f**), the edge of plume 2 is becoming distorted. The next image in this series (not shown) indicates that the event producing this plume had shut off and that the plume was dissipating. The field of view is the same as in Fig. 2

may have been associated with continuing activity, rather than separate new thermal events, but are identified here as separate features since the plumes could not be observed at night in the GOES data. Band-1 images indicate that the plumes all originated from the caldera, were much narrower (<5 km wide) than plumes 1 and 2, and had no detectable shadows (and hence were low-altitude plumes). This suggests that they were associated with low-energy events rather than explosive high-energy eruptions. Based on our observations from the air, we interpret these plumes to have been the result of the lava flows entering the caldera lake. We speculate that the different sizes of the "steam plumes" thus formed could have been driven by the emplacement of different volumes of lava, or that a decrease in plume size with time reflected the decrease in lake size as the water had been progressively boiled off by previous activity.

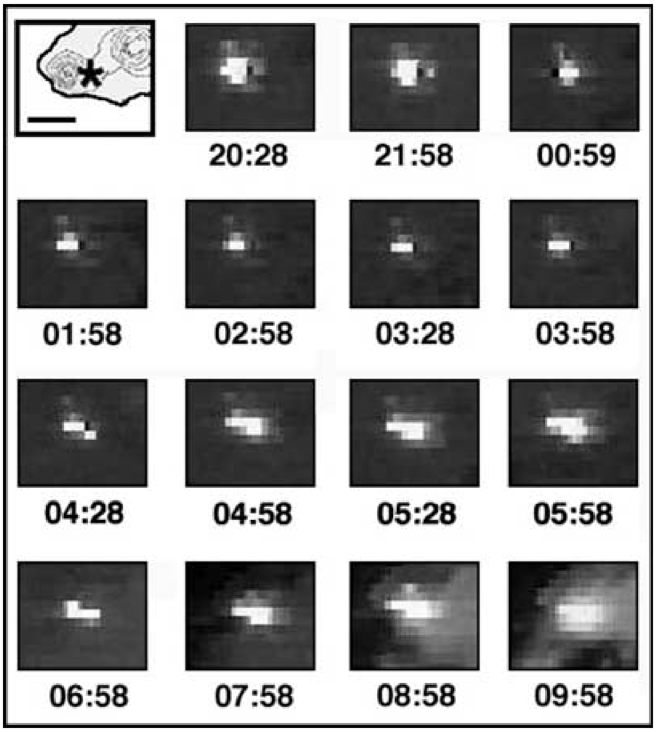


**Fig. 5** Time series of GOES band-2 minus band-4 observations of the onset of flank activity on Cerro Azul during the early hours of 16 Sept. Positive anomalies are shown in lighter shades. The first two images are from late on 15 Sept., and the first seven scenes (20:28–03:58) are shown to characterize the early activity that is interpreted to be intra-caldera activity. All images show the same area as the location map in the first panel, with the asterisk indicating the approximate location of the vent on the SE flank. Scale bar is 50 km

All of the instances where two discrete band-2 anomalies were present in the GOES images were limited to the first 7 days of the eruption (Table 1), suggesting that the intra-caldera activity was a transient early phase. During our flight on 17 Sept. we noted fresh flows within the caldera and extensive plumes of steam coming from the caldera lake. Our airborne observations on 1 Oct. (ca. 15:00) confirmed that the intra-caldera vents were no longer active.

Haze was also observed in daytime GOES band-1 images acquired during late September and early October (Table 1). For instance, on 25 and 26 Sept., volcanic haze ("vog") was seen to extend >50 km to the north of Cerro Azul. Although vog was not seen from the ground at these times because of low cloud cover (which often obscured the summit), colorful sunsets were observed on the ground throughout these periods of high haze, suggesting reflection from dense vog. In band-1 GOES images obtained on 6 and 8 Oct. at sunrise, two separate plumes were seen: one from the summit area and one from an area to the east of the summit. These two plumes are interpreted to have formed by degassing from the flank vent, and to be smoke from fires at the front and/or sides of the active lava flow, respectively.

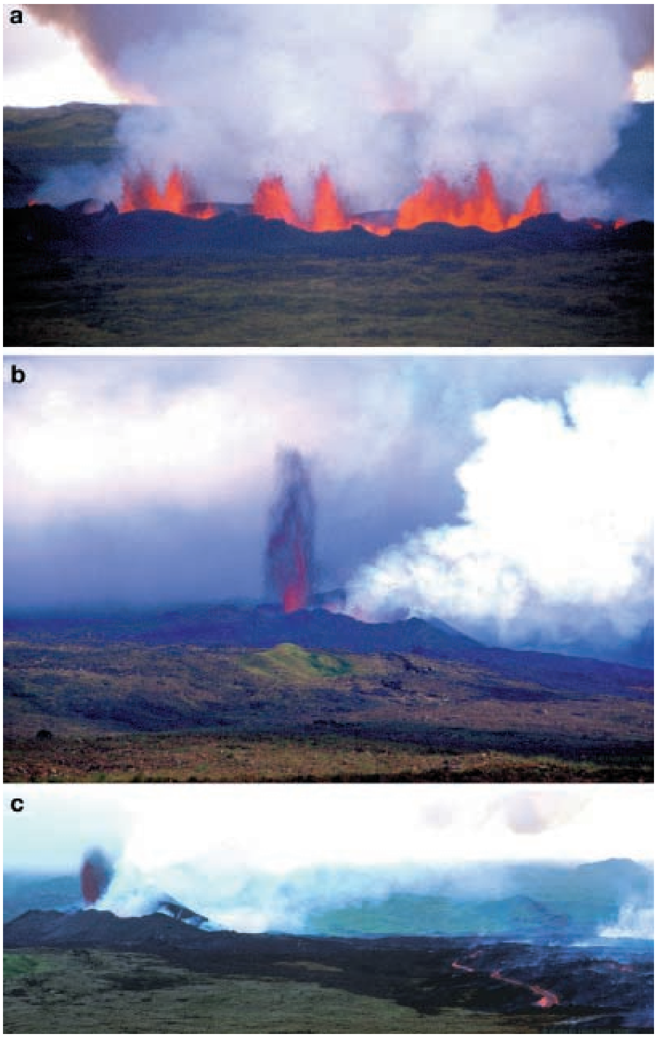

**Fig. 6** **a** Vent on SE flank of Cerro Azul, taken from the over flight on 17 Sept., approximately 36 h after onset of the flank eruption. Note the extended active fissure with "curtain of fire" activity and a broad smoke plume rising from the fissure. The height of these fire fountains is estimated to be ~200–300 m. View is looking upslope toward the west. **b, c** Ground photographs looking upslope at the vent on the SE flank, on 24 Sept. These images were taken at approximately 08:30 a.m. and are believed to be correlated with a large band-2 thermal anomaly on the flank detected by GOES. Lava fountain estimated to be ~70–100 m high. Note at right in **c** the active lava channel and the large amount of fume from the edge of the flow. Prolific amounts of fume from the cone and flow can also be seen these images. (All photos by H. Snell)

## End of the eruption

During the eruption considerable debate took place between our field and remote sensing investigators as to how to identify the end of the eruption. It was believed that field observations would be the only confident way in which the end of the eruption could be identified because, even when no new lava was being erupted, the hot lava flows would produce

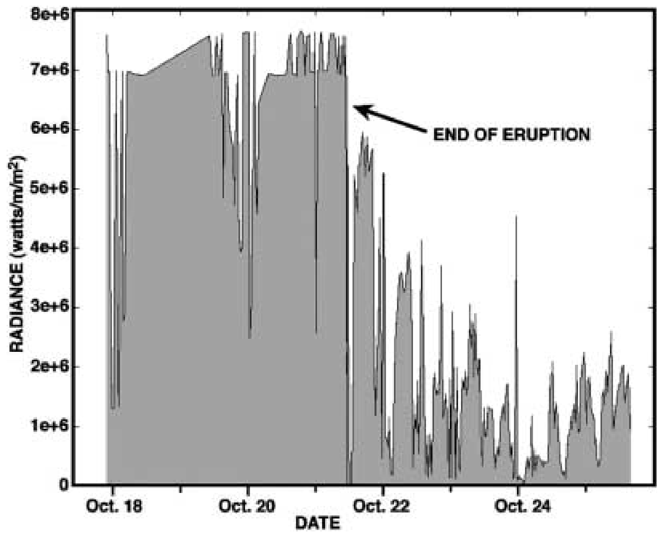


**Fig. 7** The termination of the eruption was abrupt, but the exact timing is difficult to determine due to cloud cover, as shown by this band-2 radiance plot. Sometime between 05:28 and 07:58 on 21 Oct. the eruption of new lava ceased and almost immediately the surface of the flow started to cool. This cooling continued smoothly until the early hours of 24 Oct., when a slight increase in radiative flux took place

anomalous band-2 GOES pixels. As it transpired, the high cost of field activities meant that no field observations were being made when the activity ended in late October, although occasional sightings from offshore of smoke near edges of the flows continued through mid-December.

Experience with the termination of activity at Kilauea volcano Hawaii (Harris et al. 1997; Harris and Thornber 1999) suggests that a marked decrease in the radiative flux from the lava flow would be detected by GOES almost immediately after the end of the eruption. Even if the lava flow continued moving, thereby exposing fresh hot material from the interior of the flow, the net radiative flux from the Cerro Azul flow should decrease as the lava crusts thicken and cool. This indeed proved to be the case (Fig. 7).

The period 20 to 26 Oct. had several periods of almost 100% cloud-free conditions over the flank eruption, so that these observations could be used to confirm the end of the flank eruption (Table 1). The last saturated band-2 pixel (i.e., radiance $\sim 7 \times 10^6$ watts/m per square meter) was observed at 05:28 on 21 Oct., which we interpret to be the end of the eruption. Decreasing radiance values were observed over the next 3 days (Fig. 7). Clouds masked the flow early on 23 Oct., but a less intense thermal anomaly ($\sim 1.3 \times 10^6$ watts/m per square meter) was detected when the clouds cleared. By 24 Oct. no distinct daytime anomaly could be seen in cloud-free images and the band-2 radiance had dropped to $\sim 1.0 \times 10^6$ watts/m per square meter. Comparable information was obtained from nighttime scenes that show no obvious clouds over the vent and flow areas. A persistent, low-intensity, band-2 thermal anomaly ($<5 \times 10^5$ watts/m per square meter) was observed on nighttime data collected after 26 Oct., indicating that the vent was now inactive but that the flows were still warm. We note that we can also rule out a change in the style of the eruption, including the formation of active tube-fed flows, because there was no high-temperature anomaly at the distal end of the flow such as the one observed at Kilauea volcano using GOES-9 data (Harris et al. 1997, in press).

## Lessons for the identification and monitoring of new eruptions using GOES

The use of GOES data to monitor the Volcan Cerro Azul eruption shows that investigators many thousands of kilometers away from an eruption site can provide timely information to local officials, as well as document critical aspects of the eruption before (and after) field parties reach the eruption site. In particular, the GOES data allowed five important aspects of the 1998 Cerro Azul eruption to be determined: (a) the timing of the initial eruption; (b) the lateral dimensions and dispersal patterns of the eruption plumes; (c) the confirmation that the first activity was within the caldera rather than on the flanks of the volcano; (d) the timing of the onset of flank activity; and (e) the date and time of the end of the eruption. Consistent with studies of other eruptions using GOES data (Glaze et al. 1989; Harris et al. 1997; Davies and Rose 1998), our analysis shows that the most important attribute of the GOES data was the high temporal resolution of the satellite observations, since many of these events were transient in nature. Neither the adverse weather conditions during parts of the eruption, nor the low spatial resolution of the data, precluded useful information being collected.

Indeed, even on well-monitored volcanoes, field observations may not always be available so that the temporal coverage provided by GOES is a valuable addition to monitoring capabilities. Without the detailed chronology of the Cerro Azul eruption provided by the GOES satellite observations, it is likely that the first phase of effusive activity would have been misinterpreted to be on the SE flank. Reports from the town of Villamil suggested this location and the overflight the next morning confirmed an active fissure on the flank. Prior to 15 Sept., the lack of field observations and seismic data meant that there was no indication of an impending eruption of Cerro Azul; however, the automatic eruption system developed for the analysis of the GOES data sets (Harris et al. 2000) provided a rapid indication that an event was underway. Retrospectively, it appears that excessive caution was used in using the GOES data as an eruption alert, since the initial phases of the activity were very pronounced. However, the possibility that the thermal anomaly and plumes were due to fires (Flynn and

Mouginis-Mark 1995) was also high on this part of Isla Isabela. For example, in April 1994 the crew of a Space Shuttle observed a fire's smoke plume on the western side of the adjacent Volcan Sierra Negra that they first interpreted to be an eruption plume (T. Jones, pers. commun.). Comparable caution was also used in the identification of the end of the eruption. To assist in the analysis of future eruptions studied with GOES data, we list the criteria that we used for eruption detection, and for the identification of the cessation of activity, in the Appendix.

Finally, because GOES-8 is a geostationary satellite, the images acquired throughout the day have a wide range of lighting geometries. For the Cerro Azul eruption, observations made just after sunrise (06:00) or just before sunset (17:50) were found to favor the detection of small plumes over the vent or from burning vegetation, because the low-lighting geometry near the terminator illuminated the high clouds while keeping the ground in twilight (Fig. 2). Solar reflection off of the ocean near local noon, and solar warming of inactive flows, increased the difficulty of observing the smaller eruption plumes over the ocean or smaller thermal anomalies due to active flows. From inspection of the GOES images, it was evident that the local weather patterns during the eruption favored less cloudy conditions toward mid-afternoon, with daytime band-1 observations between 12:28–16:58 generally less cloudy than between 06:28–10:58. Thus, it was easiest to use the GOES data collected during the late afternoon to observe the distribution of low-altitude plumes and haze. Such features might well have been missed at other times of day when sun glint affected image contrast.

## Implications for future real-time observations of eruptions

For several aspects of the Cerro Azul eruption, the GOES satellite observations were one of the primary sources of information about the activity and they complemented well the field observations. Thus, the methodology developed here may aid in the analysis of future eruptions using GOES. Particularly important was the development of working collaborations between the remote sensing specialists and local scientists prior to the eruption. The display and analysis of the GOES data took place in near real-time, which provided important context information for the field investigations. The high degree of caution developed here for the identification of the start and termination of activity (see Appendix), as well as temporal variations in the ongoing activity (Harris et al. 1997; Harris and Thornber 1999), reflected our concerns for the release of misleading information. A similar level of caution will almost certainly contribute to the successful satellite monitoring of future eruptions in the Galápagos Islands and elsewhere.

This collaboration between different groups enabled the release of information concerning the eruption by individuals in the Galápagos Islands, and it prevented potentially conflicting information reaching the media. The collaboration also enabled local ecological issues to be included in the media releases at the earliest opportunity. Communications between Hawaii and the Galápagos depended completely on electronic communication and the Internet. Information extracted from the GOES images, field observations, and communications with volcanologists knowledgeable of Galápagos eruptions allowed the Galápagos National Park Service and the Charles Darwin Research Station to respond quickly by airlifting a rare subspecies of Galápagos tortoise out of the area when the lava flows threatened the animals' nesting habitat. The GOES data also enabled the ongoing eruption to be monitored by collaborators at the University of Idaho in order to plan the field activities.

The high temporal resolution of the GOES data was essential for the analysis of this eruption, and this fact has important implications for the general use of satellites to study active volcanoes in the future. Several of the plumes from Cerro Azul were visible for less than 8 h, implying that they may not have been seen by sensors on polar-orbiting satellites. Each AVHRR instrument (on the NOAA satellites) obtains only one daytime image per day, and the Landsat Thematic Mapper (TM) obtains one daytime image every 16 days. The implication is that high spatial resolution satellite sensors may have missed much of the activity at Cerro Azul. Analysis of the GOES images, and field observations of the distribution of clouds made throughout the day, also indicate that the eruption site was often cloudy between 09:30–10:30 when high-resolution sensors, such as the TM, acquire data.

Although the GOES data greatly enhance the capability of observing eruptions in North and South America (Harris et al. 2000), the monitoring described herein cannot currently be conducted on a global scale. Only the GOES-8 and GOES-10 geostationary satellites have the 3.9-μm band which is required for the hotspots to be detected and monitored. Thus, this type of thermal monitoring cannot be carried out in the western Pacific, because the only data set of this area provided by a geostationary satellite (the Japanese GMS-5 spacecraft) lacks the appropriate mid-infrared coverage. Similarly, coverage of Europe and Africa by the European METEOSAT satellite does not include mid-infrared data. Other spacecraft, such as the polar orbiters flown by NOAA, carry instruments that can extend the area of coverage. However, the NOAA polar orbiters only make observations of any particular area of the Earth once every 4–12 h depending on the latitude. In addition, the geometry is different for successive images, so that the automated detection of the initial eruption becomes a more difficult task. Our experience with the Cerro Azul eruption shows that a new set of geostationary satellites located at additional longitudes around the equator would be needed to provide comprehensive near-global monitoring of volcanoes for rapid changes during an eruption. Whereas the GOES band-2 (4 km/pixel) data were adequate for studying this eruption, any increase in spatial and temporal resolution (to ~1 km/pixel every 5–10 min) from future satellites would further enhance this system without causing a prohibitive increase in the transmitted data rate. Data would have to include observations in the mid-infrared (3.9 μm) portion of the spectrum to enable the volcanic hotspots to be uniquely identified. These satellite data would have to be provided over the Internet in almost real-time in order for the remote sensing community to provide the best assistance to field volcanologists monitoring the volcanoes. Efforts to provide such information for additional parts of the world are currently underway within the remote sensing community.

## Appendix: Criteria for eruption detection

The following criteria were applied to the 15 Sept. GOES data for the Cerro Azul eruption in order to avoid a "false eruption alarm":

1. The thermal alert had to remain at the same geographic location in several GOES frames to ensure that there were no random sensor errors producing false high radiance values. Five successive images were checked prior to the confident identification of the eruption. Because the GOES satellite collects data for the Galápagos Islands every 30 min, this criterion had the effect of delaying the provision of eruption notification to the local authorities by more than 2 h.
2. The shape of the GOES band-2 thermal anomaly had to be similar to that of previously observed eruptions. In particular, the distribution of saturated "alerted" pixels associated with a new active lava flow had to be either a point source or tightly confined to a small area.
3. Confidence was increased that a real eruption had been observed at Cerro Azul because two large distinct plumes (plumes 1 and 2) were seen in band-1 images. These plumes both formed over the summit caldera and had different altitudes soon after the detection of the first band-2 thermal anomaly. Smoke plumes from fires could therefore be discounted because it is expected that a fire smoke plume would not form two well-defined discrete plumes in such a short interval of time between the initial GOES observations at 13:28 and 13:59. The sustained duration of these two distinct plumes in the band-1 GOES images collected at 13:59, 14:28, and 14:58 (Fig. 4b–d) also increased our confidence of an eruption.

### Criteria for the identification of eruption termination

The following characteristics of the GOES data were used to identify the end of the Cerro Azul eruption:

1. There had to be cloud-free conditions over the eruption site during the daytime in order for a real decrease in radiance to be confirmed. Nighttime band-2 data were not sufficient to confidently preclude the undetected occurrence of thick cloud cover over the active site.
2. The decrease in radiance had to be long-term (several days) so that the trend in decreasing activity could be confidently identified. Radiance values (in watts/m per square meter) were automatically calculated by the University of Hawaii GOES website so that changes in the energy emitted by the active flow could be quantified. A decreasing trend in band-2 radiance from the pixel-saturated value of $\sim 7 \times 10^6$ watts/m per square meter could be identified after only two or three observations, but because of our criterion for a long-term trend, the end of the eruption was only identified retrospectively after three additional days. We note that this criterion would have meant that we would have missed any short pause in the eruption had one occurred.
3. The thermal anomaly, which at times was more than six saturated thermal (band-2) pixels, had to show a decrease in spatial extent as well as a progressive decrease in intensity around a central "core." This criterion was applied in order to ensure that tube-fed flows were not still active.

**Acknowledgements** The efforts of J. Hawkins (Marine Meteorology Division, Naval Research Laboratory, Monterey, Calif.) are gratefully acknowledged in providing the GOES-8 data used herein. A. Gillespie and T. Naumann provided formal reviews. The University of Hawaii's GOES thermal alert web page is partially supported by the EOS Volcanology Team and NASA's Virtually Hawaii project under grants NAG5-4395 and NAG5-2695. The GOES Team at UH includes L. Flynn, E. Pilger, A. Harris, C. Okubo, and H. Garbeil. A. Harris is thanked for his many stimulating discussions of this eruption based on his review of a previous draft of this manuscript. We thank H. Snell (Charles Darwin Station) for use of her photos in Fig. 6. Funding for R. Ellisor's fieldwork was provided by NSF grant EAR-9612110 to D. Geist (Univ Idaho). Research in the Galápagos was supported by grants from The Charles Darwin Foundation, the Galápagos Conservation Trust, and the Special Expeditions Galápagos Fund. The ecological monitoring team at the CDRS includes S. Rea, W. Llerena, C. Marquez, H. Vargas, and H. Snell. This is HIGP contribution 1095 and SOEST publication 5006.

## References

Davies MA, Rose WI (1998) GOES imagery fills gaps in Montserrat volcanic cloud observations. Eos Trans Am Geophys Union 79:505–507

Flynn LP, Mouginis-Mark PJ (1995) A comparison of the thermal characteristics of active lava flows and forest fires. Geophys Res Lett 22:2577–2580

Glaze LS, Francis PW, Self S, Rothery DA (1989) The 16 Sept. 1986 eruption of Lascar volcano, north Chile: satellite investigations. Bull Volcanol 51 : 149–160

Harris AJL, Thornber CR (1999) Complex effusive events at Kilauea as documented by the GOES satellite and remote video cameras. Bull Volcanol 61 : 382–395

Harris AJL, Swabey SEJ, Higgins J (1995) Automated thresholding of active lava flows using AVHRR data. Int J Remote Sensing 16 : 3681–3686

Harris AJL, Keszethelyi L, Flynn LP, Mouginis-Mark PJ, Thornber C, Kauahikaua J, Sherrod D, Trusdell F, Sawyer MW, Flament P (1997) Chronology of the Episode 54 eruption at Kilauea volcano, Hawaii, from GOES-9 satellite data. Geophys Res Lett 24 : 3281–3284

Harris AJL, Flynn LP, Dean K, Pilger E, Wooster M, Okubo C, Mouginis-Mark P, Garbeil H, Thornber C, Cruz-Reyna S de la, Rothery D, Wright R (2000) Real-time monitoring of volcanic hot spots with satellites. In: Mouginis-Mark PJ, Crisp JA, Fink JH (eds) Remote sensing of active volcanoes. American Geophysical Union Monograph, No. 116, Washington, DC, pp 139–159

Harris AJL, Pilger E, Flynn LP, Garbeil H, Mouginis-Mark PJ, Kauahikaua J, Thornber C (in press) Automated, high temporal resolution, thermal analysis of Kilauea volcano, Hawaii, using GOES satellite data. Int J Remote Sensing

McClelland L, Simkin T, Summers M, Nielsen E, Stein TC (1989) Global volcanism 1975–1985. Prentice-Hall, Englewood Cliffs, New Jersey

Rowland SK (1996) Slopes, lava flow volumes, and vent distributions on Volcán Fernandina, Galápagos Islands. J Geophys Res 101 : 27657–27672