Size and volume evaluation of the caldera collapse on Piton de la Fournaise volcano during the April 2007 eruption using ASTER stereo imagery

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[1] The scale of summit collapse during the April 2007 eruption of Piton de la Fournaise volcano, Réunion Island, western Indian Ocean, was evaluated using before-and-after differential digital elevation models (DEMs) derived from nadir and backward-looking images from the Advanced Spaceborne Emission and Reflection radiometer (ASTER) instrument. The dimensions of horizontal length and width, volume and depth of the depression were estimated as 1,100 × 800 m, 9.6 × 10^7 m^3 and 320 m, respectively. These estimates show excellent agreement with field survey data. A ring shaped thermal anomaly (diameter of about 500 m) was found at Dolomieu Crater during or just after the collapse on nighttime ASTER SWIR image. It may correspond to the high temperature areas associated with the cross section of a hydrothermal zone at a constant altitude inside the crater. Our analysis of ASTER orbital data documents topographic and related thermal changes as a result of the 2007 eruption and demonstrates the power of ASTER as a volcanological tool. **Citation:** Urai, M., N. Geshi, and T. Staudacher (2007), Size and volume evaluation of the caldera collapse on Piton de la Fournaise volcano during the April 2007 eruption using ASTER stereo imagery, *Geophys. Res. Lett.*, *34*, L22318, doi:10.1029/2007GL031551.

1. Introduction

[2] Piton de la Fournaise is a 2,632 m high basaltic shield volcano located on the southeastern part of Réunion Island, which is a French overseas department, in the western Indian Ocean. It is the youngest island related to the Deccan Trap hotspot and is one of the most active volcanoes in the world. For the last two centuries, the activity of Piton de la Fournaise has been quite regular with a mean period between eruptions of nine months (personal information from Observatoire Volcanologique du Piton de la Fournaise). Most of its recent activity occurred inside the Enclos Fouqué Caldera, which was formed 4500 years ago.

[3] The 2007 eruption began on March 30 with the emission of a small lava flow from the upper part of the southeast flank of Piton de la Fournaise (the western yellow dot on Figure 1). This was followed on April 2 by a new fissure eruption with lava fountains up to 200 m high occurring on the lower eastern flank (the eastern yellow dot on Figure 1). A large lava flow erupted from the lower fissure, covering the south part of Grand Brûlé and reaching to the coast of the Indian Ocean. Collapse of the Dolomieu Crater on the summit was recognized on April 6 by a camera of the volcanological observatory located at the summit of Piton de la Fournaise. Based on field observations [*Michon et al.*, 2007], the scale of the collapse was estimated to be 1,100 × 800 m in area, 330 ± 15 m in depth, and 1.0 – 1.2 × 10^8 m^3 in volume. The eruption ceased on May 1. The total volume of the erupted lava was estimated as 1.2 × 10^8 m^3 and it covered an area of 3.6 km^2 [*Michon et al.*, 2007].

[4] We submitted an emergency request to Earth Resource and Environmental Data Analysis Center (ERSDAC) for data acquisition with ASTER for Piton de la Fournaise on April 20 and ASTER successfully observed it four times in daytime and two times in nighttime until May 6. The results of the ASTER data analysis and the comparison with the field survey data are described in this paper.

2. Summary of ASTER Characteristics

[5] ASTER, which was launched on the NASA Terra platform in December 1999, is an imaging spectro-radiometer consisting of Visible to Near-Infrared Radiometer (VNIR), Short-Wave-Infrared Radiometer (SWIR) and Thermal Infrared Radiometer (TIR). The VNIR has a spatial resolution of 15 m and consists of a nadir and backward-looking telescope capable of producing pairs of stereo images with a base-to-height ratio of 0.6. Digital elevation models (DEMs) can be calculated from parallax between corresponding points on stereo images. The vertical accuracy of the DEM generated from the ASTER stereo images is about 20 m without ground control point [*Fujisada et al.*, 2005]. The SWIR has a spatial resolution of 30 m and is mainly designed for surface soil and mineral mapping, however, it can be used for temperature observations of very hot targets, such as a lava lake of an active volcano [*Yamaguchi et al.*, 1998]. The TIR, which has a spatial resolution of 90 m and has five spectral bands in thermal infrared region, allows more accurate determination of the land surface temperature up to 100°C. All ASTER daytime and nighttime images used in this paper are ortho-rectified using ASTER DEM and SRTM30 data, respectively. The location errors of all ASTER sensors in daytime, nighttime ASTER SWIR and nighttime ASTER TIR images are about 50 m, 200 m and 300 m without ground control points, respectively [*Fujisada et al.*, 2005; *Urai*, 2005].

[6] ASTER has observed more than 1,500 active volcanoes periodically under its Global Volcano Monitoring Plan

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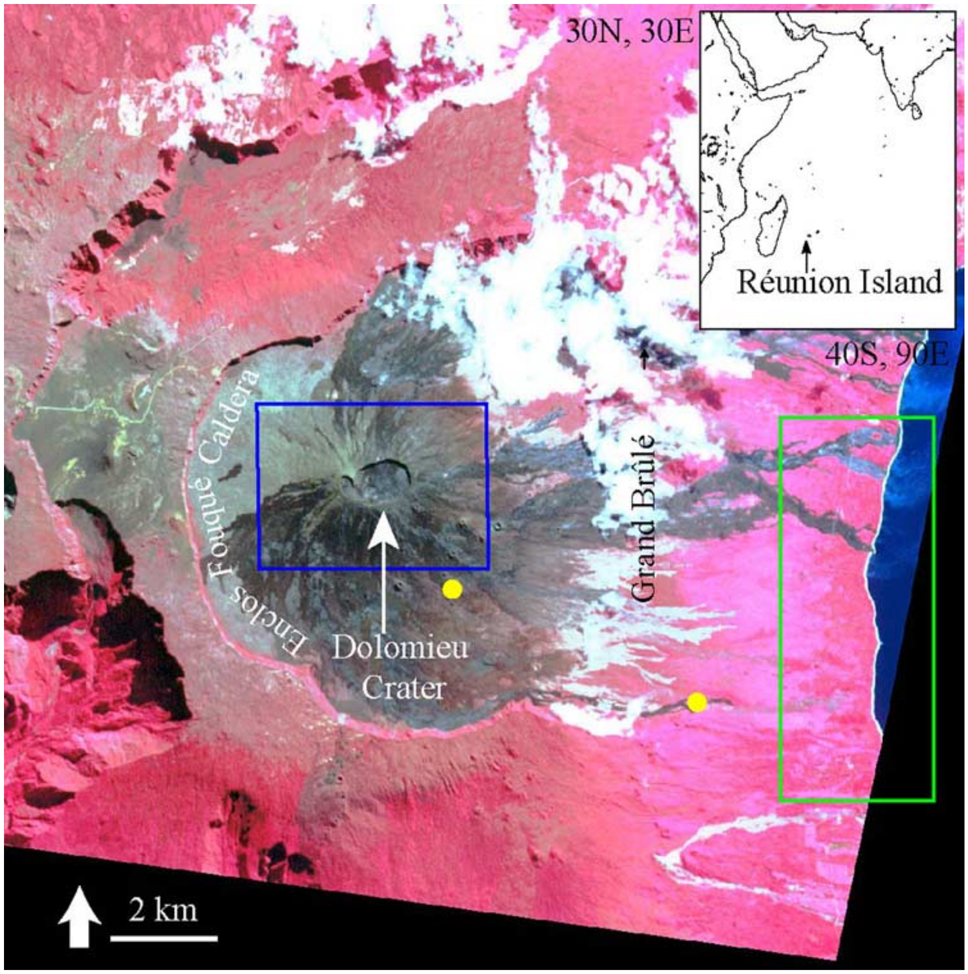


Figure 1. ASTER VNIR image of Piton de la Fournaise observed on June 8, 2005. The two yellow dots indicate the source locations of the lava flow on March 30 (west one) and on April 2, 2007 (east one). The blue rectangle indicates the area that DEM difference is calculated in Figure 2. The green rectangle indicates the extent of Figure 7. Light to dark gray indicates no vegetated area, red color indicates vegetated area, and white color indicates cloud. The thick arrow in the figure points north.

[*Urai et al.*, 1999] since 2000. ASTER images are stored in the ASTER Image Database for Volcanoes and open to the public at http://www.gsj.jp/database/vsidb/image/index-E.html and at the JPL ASTER Volcano Archive at http://ava.jpl.nasa.gov.

3. Dolomieu Crater Collapse

[7] ASTER has observed Piton de la Fournaise more than twenty times in the daytime since 2001, allowing us to generate DEMs from the least cloudy ASTER stereo images taken before and after the collapse of the Dolomieu Crater. Figure 2 shows the west-to-east DEM profiles through the center of Dolomieu Crater before and after the eruption calculated from the ASTER stereo images. The elevation of the crater floor was about 2,480 m before the eruption and is about 2,160 m after the eruption, having been depressed at most 320 m. Though slightly shallower, the ASTER result is nevertheless in excellent agreement with the field survey result of 330m. Since the parallax between corresponding points is calculated from correlated 9 by 9 pixel sub-images, each ASTER DEM point represents an area of 9 by 9 pixels

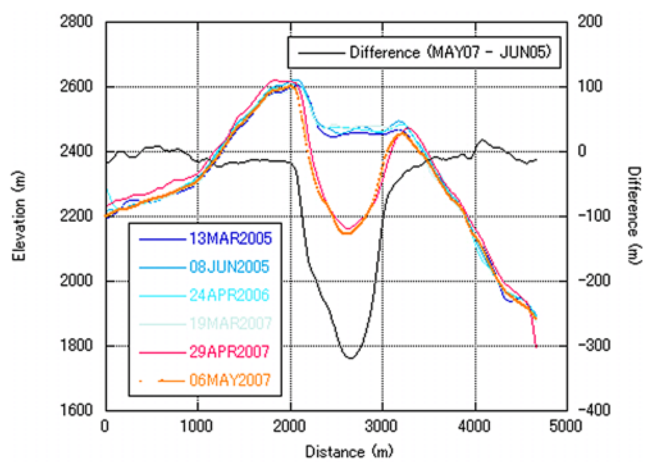


Figure 2. West to east ASTER DEM profiles at Dolomieu Crater. Blue to light blue lines indicate west to east DEM profiles before the eruption, and red and orange lines indicate DEM profiles after the eruption (left-hand side scale). Black line indicates the difference between DEMs that are calculated from the ASTER observations on May 6, 2007, and June 8, 2005 (right-hand side scale).

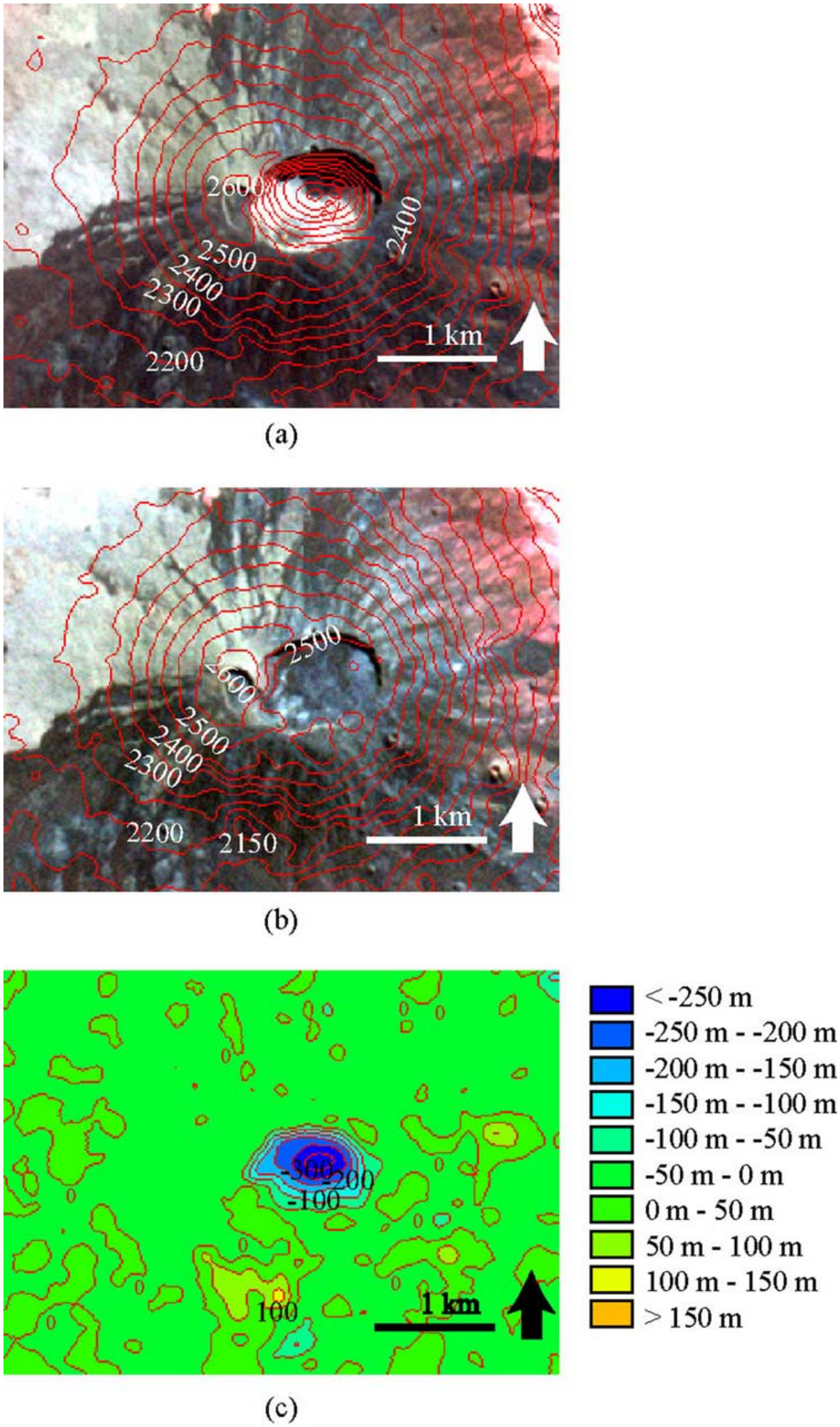


Figure 3. ASTER DEMs observed before and after the collapse of Dolomieu Crater. (a) ASTER VNIR image with 50 m contours observed on May 6, 2007 (after eruption), (b) ASTER VNIR image with 50 m contours observed on June 8, 2005 (before eruption), and (c) DEM difference between the observations.

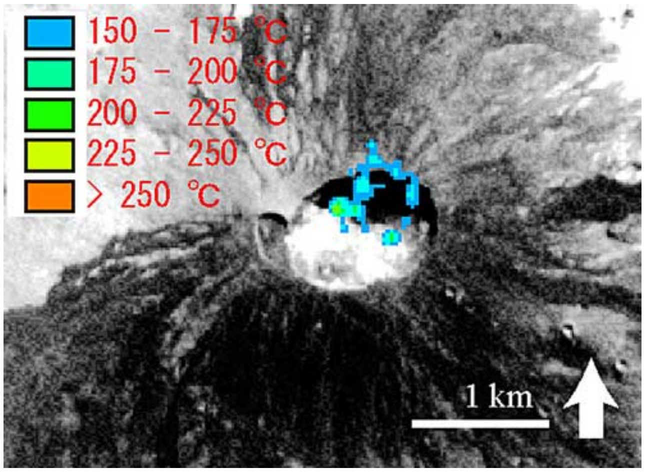


Figure 4. Color-coded surface temperature anomalies that have more than 150°C derived from nighttime ASTER SWIR band 7 observed on April 9, 2007. Background is ASTER VNIR band 3 daytime image observed on May 6, 2007.

or 135 by 135 m. If the deepest area of happens to be less than 135 by 135 m, the ASTER DEM (based on a 9 by 9 pixel average) may indicate a shallower elevation.

[8] Figures 3a and 3b show the DEMs after and before the eruption and observed elevation difference (Figure 3c). An oval shaped depression is recognized at Dolomieu Crater in Figure 3c. Likewise, a new uplift up to 100 m is seen at 1 km south of Dolomieu Crater in Figure 3c, however, we believe it may be DEM calculation error in shadowed area. A low elevation anomaly that is seen at the uplift area in contour map observed on June 8, 2005 (Figure 3b) may cause the DEM calculation error. The depression volume is estimated as 9.6×10^7 m^3, which agrees with the field survey value of $1.0 - 1.2 \times 10^8$ m^3. Dolomieu Crater today looks brighter than before the collapse in ASTER VNIR images (Figures 3a and 3b). Based on field observations, before the collapse it was covered by fresh dark pahoehoe lava flows and it is now covered by broken rock, blocks and gravel, which appear much brighter in ASTER VNIR images at these wavelengths.

[9] Just after the collapse (April 9), a ring shaped thermal anomaly that has a diameter of about 500 m was observed inside the Dolomieu Crater in nighttime ASTER SWIR observation (Figure 4). Since nighttime ASTER SWIR images have location errors of up to 200 m [*Urai*, 2005], the anomaly actually may be at the center of the crater, even it appears at the northeastern edge of the crater on ASTER SWIR image. Sometimes, thermal anomalies have been observed in nighttime ASTER SWIR images to be located inside the Dolomieu Crater, however, the ring shaped one is not observed until after the collapse on April 9. Based on field observations, small lava flows had been observed some tens of m below the eastern crater border from eastern and southeastern plateaus, which were still present on April 6, but also collapsed next days [*Michon et al.*, 2007] and a small "lava lake" was observed on the crater floor on April 6. We believe that these were old lava from the August 2006 to January 2007 eruption inside of Dolomieu crater and which were stacked beneath the ~30 m thick lava flow that deposited before August 2006. On April 7 and 10, no lava was observed any more but up to 200°C hot areas were detected by a FLIR PM695 infrared camera about 200 m below the crater rim, which could most probably correspond to cross section of a hydrothermal zone of Piton de la Fournaise (Figure 5). These hot areas still exist at a constant altitude inside the depression, even though temperature decreased. The hot areas look like a ring when viewed from high altitude and may correspond to the ring shaped thermal anomaly on nighttime ASTER SWIR observation.

4. Lava Deposit Area

[10] Thermal anomalies associated with new lava flow in the Grand Brûlé, which started on April 2, were detected both on nighttime ASTER TIR and ASTER SWIR images on April 9 and afterwards. Large surface thermal anomalies that were 4 km long, 1.5 km wide and represent an area of 3.85 km^2 were detected in cloud free nighttime ASTER TIR

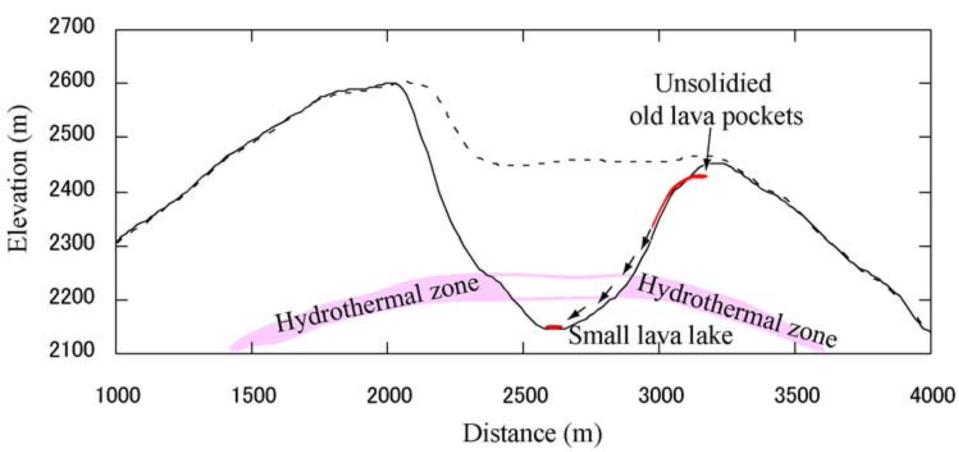


Figure 5. Schematic diagram to illustration the thermal anomalies detected by nighttime ASTER SWIR. The solid and dashed lines indicate west to east DEM profiles before and after the eruption, respectively. The red and pink areas indicate un-solidified old lavas and hydrothermal zones, respectively.

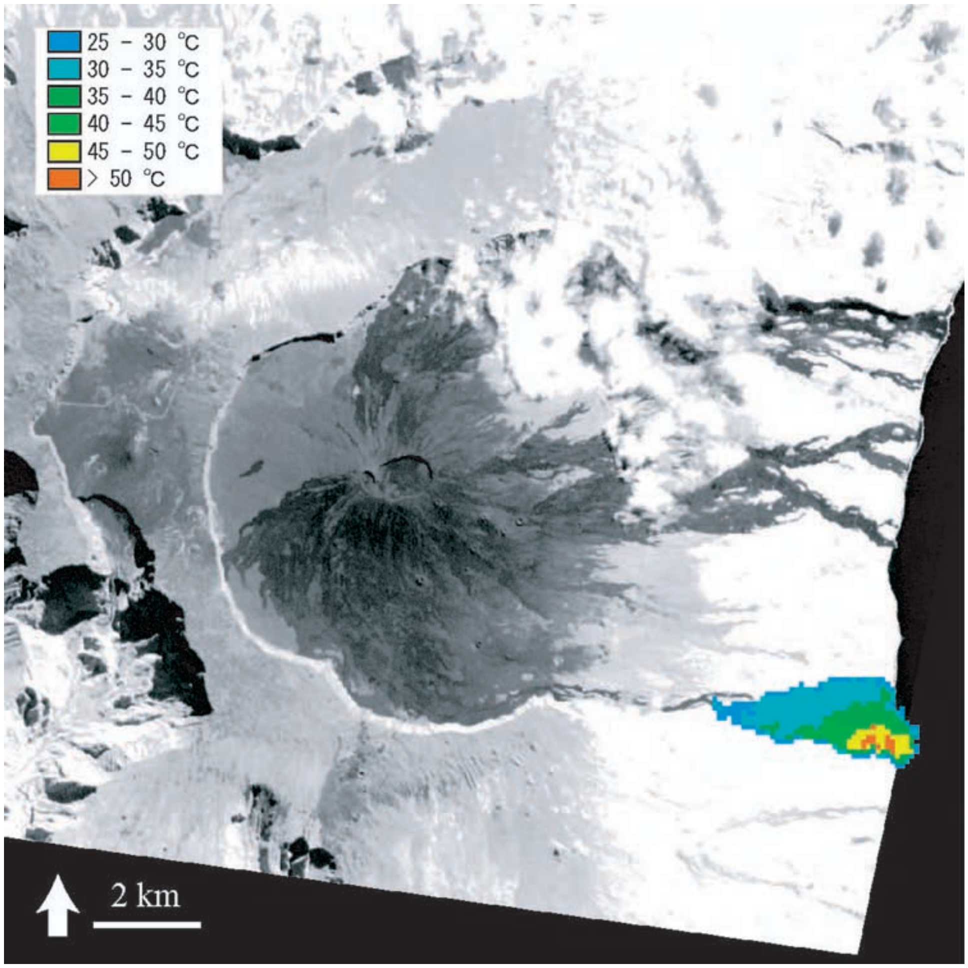


Figure 6. Color-coded surface temperature anomalies that has more than 25°C derived from nighttime ASTER TIR band 13 observed on May 4, 2007. Background is ASTER VNIR band 3 daytime image observed on June 8, 2005.

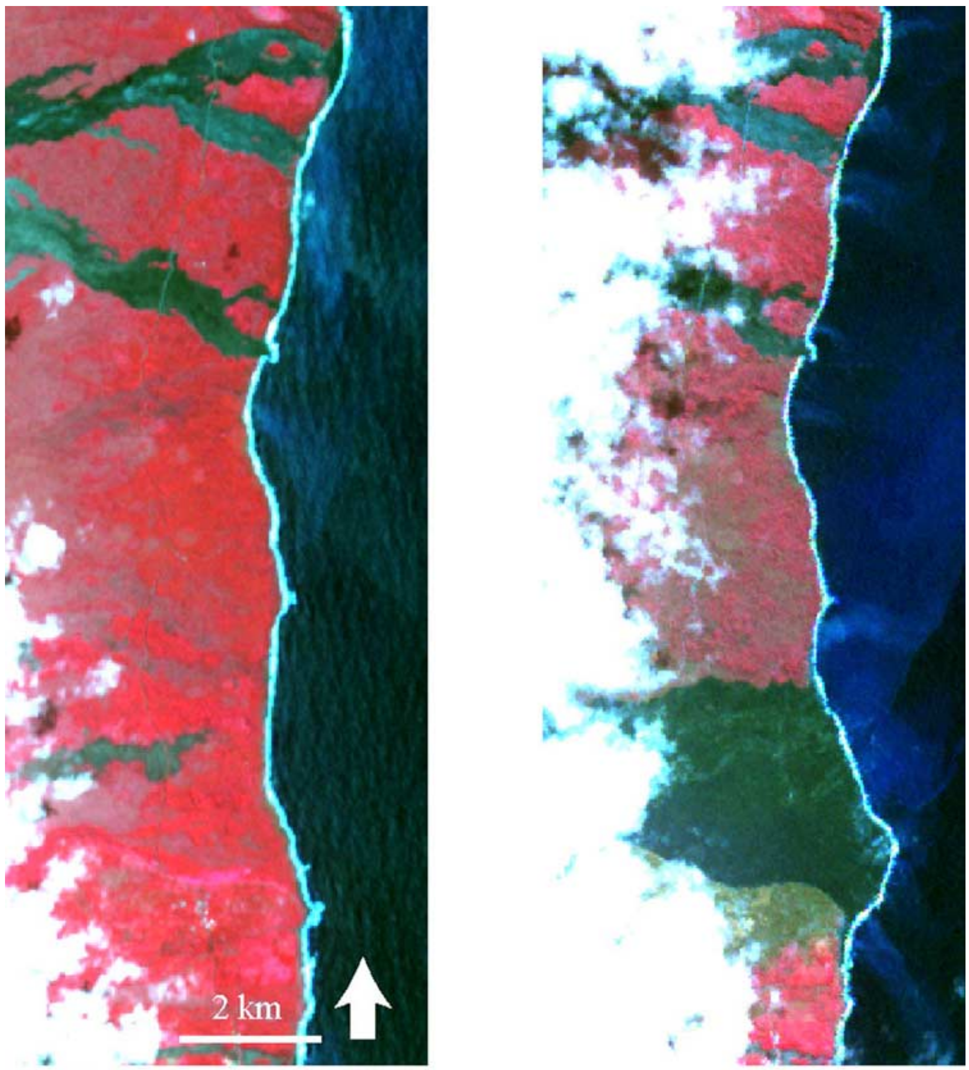
observations on May 4, just after the eruption ceased on May 1 (Figure 6). This evaluation using satellite sensor data agreed with the surface area of the lava flow of 3.6 km^2 estimated from field survey data. The total lava flow volume from this eruption could not be explicitly estimated using ASTER data because no cloud-free ASTER VNIR images have been acquired as of this time to estimate the thickness of the lava flows. ASTER could not observe earth's surface in cloudy weather. This is a disadvantage to optical sensors like ASTER. Even with cloud-free ASTER VNIR data, however, it may be difficult to measure the lava thickness of 30–40 m using an ASTER DEM that has an accuracy of 20 m. The DEM accuracy depends on the pixel size. The PRISM, which dedicates to DEM generation and was launched on January 2006, has a pixel size of 2.5 m that is six times finer than ASTER VNIR. The DEM generated from PRISM may have the accuracy that can estimate the lava thickness of 30–40 m.

[11] The lava flow in the Grand Brûlé reached the east coast of the island and built a new platform seaward. The area of the platform of 0.52 km^2, as calculated form ASTER VNIR images taken before and after the lava flow emplacement (Figure 7). An earlier lava flow occurred on March 30 is 1.13 km long and 150 m wide at most, and is visible in daytime ASTER VNIR images. However, no thermal anomaly associated with this earlier flow was detected in ASTER TIR or ASTER SWIR images.

5. Conclusions

[12] The combined analysis of thermal images and DEMs obtained by the ASTER satellite sensor revealed the area, depth and volume of the Dolomieu Crater collapse and lava deposit area of the 2007 eruption on Piton de la Fournaise volcano. A ring shaped thermal anomaly was found at Dolomieu Crater during or just after the collapse. Our analysis demonstrates that ASTER instrument is a powerful tool for semi-real time monitoring of active volcanoes because ASTER has a wide spectral range, stereo imaging allowing DEM generation, thermal anomaly detection capability and the ability to classify land cover characteristics.

[13] **Acknowledgments.** We thank the Earth Resource and Environmental Data Analysis Center (ERSDAC) for conducting ASTER emergency observations and providing ASTER data and we thank the members of ASTER Science Team for helpful comments. This paper was improved greatly by two anonymous reviewers.



(a) (b)

Figure 7. ASTER VNIR images of the east coast of Réunion Island. (a) March 19, 2007 and (b) May 6, 2007. The green rectangle in Figure 1 indicates the location of the image.

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