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How the variety of satellite remote sensing data over remote volcanoes can assist hazard monitoring efforts

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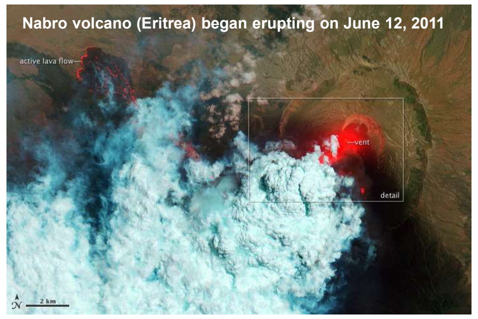
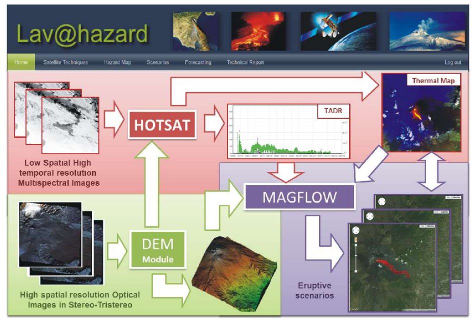
Introduction

Satellite remote sensing is becoming an increasingly essential component of volcano monitoring, especially at little-known and remote volcanoes where in-situ measurements are unavailable and/or impractical. Moreover the synoptic view captured by satellite imagery over volcanoes can benefit hazard monitoring efforts. By monitoring, we mean both following the changing styles and intensities of the eruption once it has started, as well as nowcasting and eventually forecasting the areas potentially threatened by hazardous phenomena in an eruptive scenario.

The diversity of remote sensing data over volcanoes and the mutual interconnection between satellite observations and numerical simulations can improve lava flow hazard monitoring in response to effusive eruption. Time-averaged discharge rates (TADRs) obtained from low spatial/high temporal resolution satellite data (e.g. MODIS, SEVIRI) are complemented, compared and fine-tuned with detailed maps of volcanic deposits with the aim of constraining the conversion from satellite-derived radiant heat flux to TADR.

Maps of volcanic deposits include the time-varying evolution of lava flow emplacement derived from multispectral satellite data (e.g. EO-ALI, Landsat, Sentinel-2, ASTER), as well as the flow thickness variations, retrieved from the topographic monitoring by using stereo or tri-stereo optical data (e.g. Pléiades, PlanetScope, ASTER). Finally, satellite-derived parameters are used as input and validation tags for the numerical modelling of lava flow scenarios. Here we show how our strategy was successfully applied to the first historic eruption of Nabro volcano (Eritrea), occurred in June 2011.





Methodology

The web-GIS Lav@hazard [Vicari et al., 2011], which integrates the HOTSAT satellite monitoring system [Ganci et al., 2016] and the physics-based MAGFLOW model [Cappello et al., 2016] has been extended with a new module able to produce DEMs in near real time starting from high resolution satellite data. The DEM module [Ganci et al., 2018], relying on the free and open source MicMac software (https://micmac.ensg.eu), has a double objective: (i) providing a pre-eruptive topography as input parameter for MAGFLOW; (ii) estimating syn-eruptive and post-eruptive bulk volumes and thickness distributions as input parameter for HOTSAT.

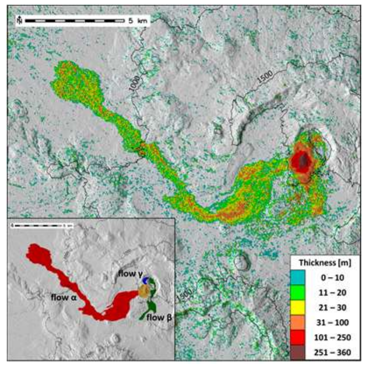
Our processing workflow so includes:

1) Pre-eruptive DEM production from high resolution stereo pairs;
2) Detection of thermal anomalies from multispectral satellite data;
3) Production of thermal maps;
4) Radiant heat flux estimation computed for thermally anomalous images;
5) TADR estimation by straightforward conversion of the radiant heat flux;
6) Production of lava flow scenarios using TADR and pre-eruptive DEM;
7) Syn-eruptive DEM production from high resolution stereo pairs;
8) Calibration of TADR using DEM-derived volume;
9) Refinement of lava flow scenarios using DEM-calibrated TADR;
10) Validation of lava flow scenarios by using higher resolution thermal map;
11) Improvement of lava flow scenarios through calibration of MAGFLOW inputs.

The 2011 eruption of Nabro volcano

Digital Elevation Model

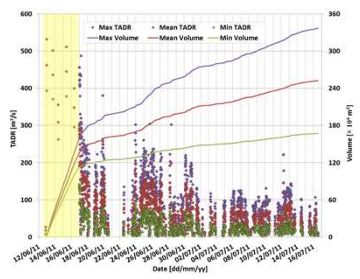
To map the deposits emitted during the 2011 eruption at Nabro volcano and provide an estimation of thickness distribution and volumes, we used a topographic approach relying on the difference of DEMs derived from stereoscopic ASTER and PlanetScope images. By differencing the pre- and post-eruptive DEMs, we were able to outline the four main deposits of the 2011 Nabro eruption, as well as to estimate a total bulk volume of about 580 millions of cubic meters, of which about 336 millions of cubic meters is the volume of the main lava flow that advanced eastward beyond the caldera.



Mapping of difference between pre- and post-eruptive DEMs. By using an adaptive local threshold we outlined the four main deposits of the 2011 eruption (inset): the longest lava flow, which initially travelled SW from the eruptive vent and then turned NW (flow a, in red); the two smaller lava flows erupted from vents around the inner caldera (flow b, in green, and flow c, in blue); and the new tephra and lava cone infilling the pit crater (in yellow).

TADR estimation

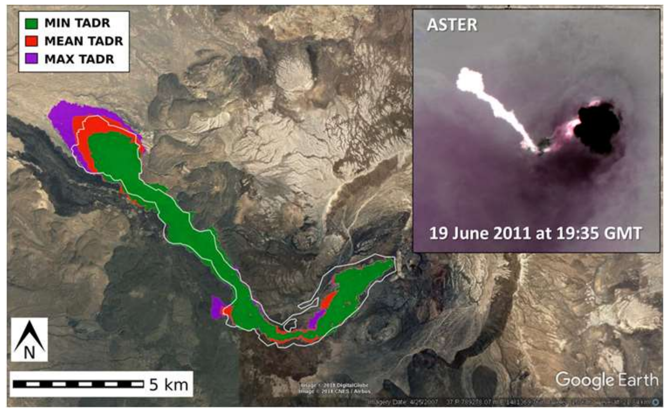
Time-averaged discharge rates (TADRs) were estimated via the HOTSAT thermal monitoring system [Ganci et al., 2011] from 12 June with SEVIRI and from 14 June with MODIS data. Since during the first three days, Nabro emitted a thick plume that prevented the thermal anomalies associated with the active lava flow to be detected from satellite, we constrained HOTSAT TADRs using satellite-derived estimates of the SO_2 flux [Theys et al., 2013] and the volume from DEM difference. We thus obtained a DRE volume associated to the lava flows ranging between ~170 and ~340 millions of cubic meters.



TADR values (diamonds) and cumulative lava volumes (lines) with the minimum (green), mean (red), and maximum (violet) estimates computed from MODIS and SEVIRI data. The yellow bar marks the approximately 3 days of explosive behavior

Lava flow scenarios

We reproduced the longest lava flow erupted during the 2011 Nabro eruption with the physics-based MAGFLOW model using the pre-eruptive DEM derived from ASTER images, and the minimum, mean and maximum TADRs estimated by HOTSAT



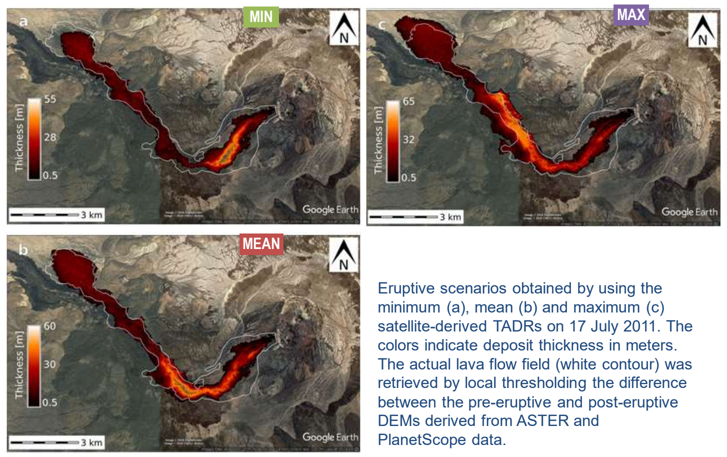
	19 June 2011			16 July 2011		
Actual length [km]	15.50			15.80		
Actual area [km^2]	16.07			17.84		
	MIN TADR	MEAN TADR	MAX TADR	MIN TADR	MEAN TADR	MAX TADR
Simulated length [km]	15.08	15.11	16.08	16.16	16.88	17.01
Simulated area [km^2]	12.43	14.67	16.99	13.36	16.83	19.73
Fitting	0.62	0.70	0.65	0.62	0.69	0.60

Visual comparison between the actual area of the main lava flow of Nabro eruption and the three simulated scenarios on 19 June (left) and at the end of the eruption (right).

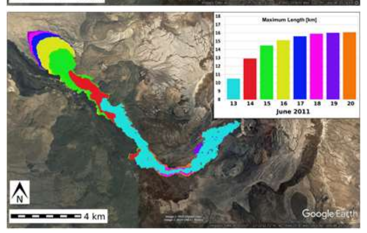
Real lava flow dimensions, and simulated lengths, areas and average thicknesses on 19 June and 16 July.

On 19 June the real flow-field had attained almost 100% of its final length, as clearly shown by the ASTER image in the inset. After 19 June, the flow a continued to thicken and widen along its length, while the front advanced about 300 meters, reaching a maximum distance of 15.8 km from the main vent.

The goodness of fit between the actual and MAGFLOW-simulated areas was quantified through the intersection over union areas of the simulated and actual lava flows. A fitting score equal to 1 corresponds to a complete overlap, i.e., the simulated area coincides totally with the actual lava flow field. On the other hand, a fitting score equal to 0 indicates the maximum error, i.e., lack of common areas between the simulated and actual lava flows. We found that the actual lava flow field is consistently well reproduced by the MAGFLOW model, with the fitting score always higher than 0.60. However, the actual lava flow is better fitted by the simulation driven by the mean TADR with scores of 0.70 and 0.69 on 19 June and at the end of the eruption, respectively. Lava flow simulations driven by satellite-derived parameters allow building an understanding of the advance rate and maximum extent of the main lava flow showing that it is likely to have reached 10.5 km in one day with a maximum speed of ~0.44 km/h.



Eruptive scenarios obtained by using the minimum (a), mean (b) and maximum (c) satellite-derived TADRs on 17 July 2011. The colors indicate deposit thickness in meters. The actual lava flow field (white contour) was retrieved by local thresholding the difference between the pre-eruptive and post-eruptive DEMs derived from ASTER and PlanetScope data.



MAGFLOW scenarios with the mean TADR during the first 8 days of eruption. Colors represent the scenario at the end of each day. The inset shows the maximum length reached at each day.

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