Monitoring active volcanoes using a handheld thermal camera

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Abstract

Thermal imaging has recently been introduced in volcanology to analyse a number of different volcanic processes. This system allows us to detect magma movements within the summit conduits of active volcanoes, and then to reveal volcanic activity within the craters even through the thick curtain of gases usually released by volcanoes such as Mt Etna and Stromboli. Thermal mapping is essential during effusive eruptions, since it distinguishes lava flows of different age and concealed lava tubes' path, improving hazard evaluation. Recently, thermal imaging has also been applied to reveal failure planes and instability on the flanks of active volcanoes. Excellent results have been obtained in terms of volcanic prediction during the two recent eruptions of Mt Etna and Stromboli, both occurred in 2002-2003. On Etna, thermal images monthly recorded on the summit of the volcano revealed the opening of fissure systems several months in advance. After the onset of the flank eruption, daily thermal mapping allowed us to monitor a complex lava flow field spreading within a forest, below a thick plume of ash and gas. At Stromboli, helicopter-borne thermal surveys allowed us to recognise the opening of fractures along the Sciara del Fuoco, one hour before the large failure that caused severe destruction on the island on 30 December 2002. This was the first time ever that volcanic flank collapse has been monitored with a thermal camera. In addition, we could follow the exceptional explosive event of the 5th April 2003 at Stromboli from helicopter with a thermal camera recording images immediately before, during and after the huge explosion. We believe that a more extended use of thermal cameras in volcano monitoring, both on the ground and from fixed positions, will significantly improve our understanding of volcanic phenomena and hazard evaluations during volcanic crisis.

1. Introduction

Thermal imaging has recently been introduced in volcanology to analyse a number of different volcanic processes. In particular, heat distribution on volcanic surfaces can be used to: (1) recognise magma movements within the summit conduits and detect the upward movement of shallow feeder dikes, i.e. fractures in the ground suddenly filled by hot magma[1]; (2) distinguish active lava flows and lava tubes[2,3,4]; (3) analyse the evolution of fumarole fields[5] and active eruption plumes[6,7]; (4) obtain effusion rate for active lava flows[8]; (5) recognise storage of magma at shallow depth[9]; (6) discriminate between different lithological units[2]; (7) detect potential failure planes on recently formed cinder cones[10], or fractures developing just before flank collapse at active volcanoes[11]; (8) analyse active lava lakes[12].

Thermal IR surveys have been first performed on Mt Etna during the 1978 eruption using a NOAA 5 weather satellite[9], then during the 1981 eruption[13], just after the end of the 1989 eruption[2], and during the 1991-1993 eruption[14]. During the 1999 Etna eruption, the use of a handheld thermal camera[15] allowed us to recognise the hidden path of lava tubes growing some metres below the surface of the active lava flow field. This is of particular interest on Etna volcano, since it has been recently found that lava tubes promote greater lengthening of lava flow fields, with consequent higher potential hazard to the villages on the slopes of the volcano of being inundated by lava[16].

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2. Limits of the thermal measures and corrections

Thermal imagery data has been demonstrated as an important tool for volcano surveillance within the Istituto Nazionale di Geofisica e Vulcanologia (INGV) Section of Catania since 2001, when a handheld thermal camera became available. Our instrument is an uncooled microbolometer that detects emitted radiation in the interval between 7.5 to 13 microns waveband. Apparent temperatures recorded by infrared cameras are influenced by the temperature of the object being measured, its emissivity, and atmospheric attenuation. In turn, atmospheric attenuation is a function of the distance between the object and the camera, humidity, atmospheric temperature, dust, gas, snow, ice and aerosol concentrations in the air between the object and the camera, and reflection of solar radiation. During thermal measurements we generally measure atmospheric humidity and atmospheric temperature, and we use 0.88 for atmospheric transmission. For emissivity we use 0.99[17,18]. Field measurements made on Etna in August 2001 revealed that solar radiation increased apparent temperature by up to 20°C [10], and this needs to be taken into account when comparing temperatures collected at different times. Additionally, temperatures of individual pixels are mean values averaged over the total size of a pixel. Our thermal camera has a lens with a field of view of 24° x 18°, giving individual images of 320 x 240 pixels. At a typical viewing distance of 300 m, this results in a pixel size of 42 cm, which can therefore lead to a reduction in opponent peak temperatures. Additionally, in volcanic conditions the possibility of collecting thermal images perpendicular to the target surface is rarely applicable, then another correction for the inclination must be applied[7,19]. Our thermal camera has an internal calibration that, if distance to target, ambient temperature, humidity and emissivity are input, temperatures corrected for atmospheric and emissivity effects are output. This device thus produces digital data that can be rigorously used to determine temperatures of specific targets.

In order to perform quantitative temperature measurements, a correction must be applied to measured radiance data to take account of absorption of radiation by atmospheric and volcanic species. The in-built software within the thermal camera we use permits a limited correction, in some way taking into account relative humidity, temperature and path length. It is not clear how this algorithm works or what accuracy the correction has. However, since atmospheric pressure and absorption due to volcanic gases are not accounted for, the level of accuracy may not be high for measurements carried out on Etna and Stromboli. A detailed analysis of the main parameters influencing thermal data collected with our instrument has been carried out by Sawyer[20]. Her main results are the following:

1 - the shorter the path length the less sensitive the system is to atmospheric conditions and therefore the more accurately we can calculate the source temperature;

2 - when considering the atmospheric conditions, we see that varying the path amount of water vapour has the largest effect on the integrated observed radiance. If we do not have an accurate estimate of the amount of water vapour between the source and the thermal camera, it can lead to large errors in the calculated source temperature;

3 - spectroscopically, atmospheric temperature and pressure have little effect on absorption coefficients. It is important to note however, that atmospheric temperature has a large impact on saturated vapour pressure which in turn has implications on path amounts associated with given relative humidity values. This is not the case for atmospheric pressure. Atmospheric pressure has a negligible effect on saturated vapour pressure and therefore for a given relative humidity, changing the atmospheric pressure does not significantly change the path amount;

4 - in order to perform an accurate atmospheric correction of measurements made by our thermal camera, it is necessary to have an accurate atmospheric temperature, relative humidity and path length or distance. The effect of pressure is negligible. Therefore, no significant error in the calculated source temperature results from the software of our thermal camera not accounting for atmospheric pressure.

Although thermal monitoring has been proved very useful in volcanic environment, caution should be used when considering object temperature from readings with the thermal camera, since the main parameter influencing the detection of temperature is distance from the object. Most of the times, due to difficult access to the sites during explosive and effusive volcanic eruptions, we have collected thermal images using the same portable instrument at different distances from the object, comparing thermal images taken from the ground at a few meters distance, with those collected during helicopter flights. When operative conditions were favourable, we have measured the distance from the object using a high-precision laser finder, and these values have been inserted in the camera's software for automatic corrections.

3. Incipient collapses

The surfaces and flanks of active volcanoes commonly present fractures and cracks on the ground along which frequently hot gases are released. Leakage of hot gases allows then detection of these structures using regular surveys with a thermal camera. A consequence is that monitoring the summit, and especially the crater rims and summit cones of volcanoes like Etna, allows to forecast the occurrence of major collapses in the volcano's summit. Here, the hottest zones and fractures bordering the craters' rims are the most liable of becoming the site of future failures. Collapses of the flanks and rims of the Etna's summit cones occurred a number of times during the 1999 eruption[21], seriously threatening the thousands tourists which visited the summit to observe the spectacular volcanic activity. More commonly, small landslides within the summit craters of the volcano, which has its top at about 3350 m above sea level, cause ash emission, and the ash is carried out up to tens kilometres height by the hot gases constantly released by the volcano. Detection of ash emission, and ability to forecast these events, are extremely important in the Etna's region, due to the presence of an important international airport in the outskirts of Catania, that during the 2001 and 2002-2003 eruptions has been severely affected by several months of ash fall from the volcanic activity[22,4].

The use of a thermal camera to routine monitoring of Etna volcano has been applied since August 2001, when this device became available to the INGV Section of Catania. Routine measures from helicopter around the summit craters have shown the development of hot fractures on the inner crater walls. These fractures evolved into rock falls and ash emission, as well as instability of cinder cones recently developed on the upper reaches of the volcano. Apart from ash emissions and connected safety problems for the aviation, it has been also recently shown[10] the importance of thermal mapping to detect new cracks on the ground (Fig. 1).

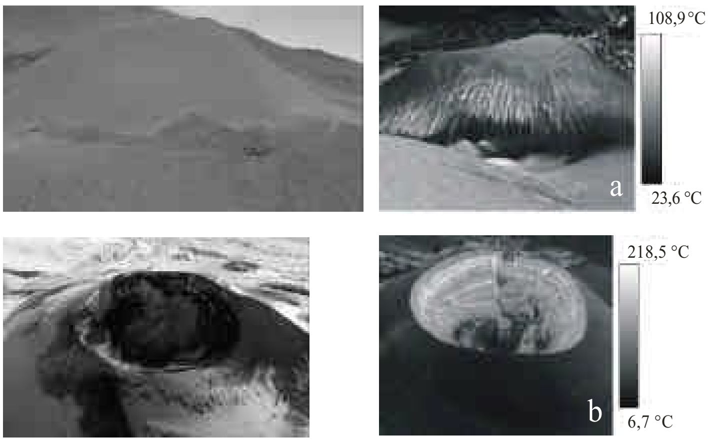

Fig. 1 – Photos (left) and thermal images (right) of fractures developing on the south flank (a) and inside the crater (b) of the "Laghetto" cinder cone (modified after Calvari and Pinkerton, 2004) that built up during the explosive activity of the 2001 Etna flank eruption.

During the formation of a new cinder cone that formed over a two week period of intense eruptive activity on the upper slopes of Mount Etna in summer 2001, arcuate cracks were developing on the flanks of the cone and inside the crater (Fig. 1). Detection of these cracks through a thermal camera anticipated of several weeks their direct observations at naked eye, allowing us to rise an alert to tourist operators daily visiting the summit of the volcano. In fact, these fractures can easily and suddenly evolve into landslides, such as those that affected the summit of Etna in 1999[21]. This was the first time that infrared thermography has been used to detect instability of volcanic structures. Results obtained during this test case demonstrated that thermal cameras are a very useful tool for studies of volcanic instability.
Again on Etna, between February and June 2002, helicopter-borne thermal images showed the opening of a field of fractures expanding from the NE-Crater to the SE-Crater, on the summit of the volcano, for a total length of about 4 km (Fig. 2). This field of fractures grew in the following months, eventually forming the 10-km-long fissure system feeding the 2002-2003 Etna flank eruption[4]. In this case, thermal mapping revealed essential to forecast the approach of hot magma through fractures on the surface. In fact, being the summit of the volcano already fractured by the previous flank eruption occurred just the year before[22], the seismic swarm preceding the 2002-2003 eruption[23] did not give a sufficient advice since it started just a few hours before ground fracturing and lava output.

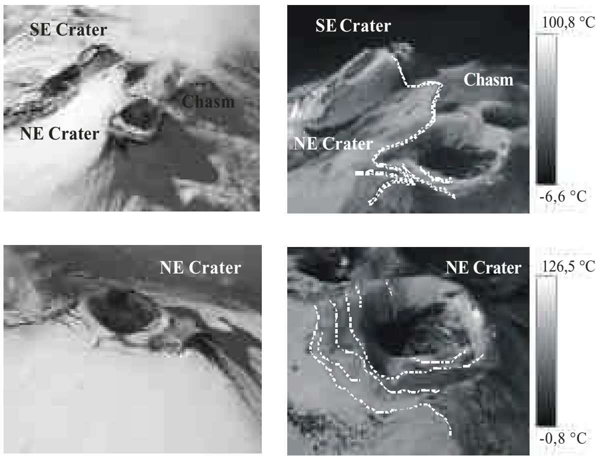

Fig. 2 – Photos (left) and thermal images (right) of fractures bordering the summit crater rims of Mt. Etna volcano detected in February 2002, several months before the 2002-03 flank eruption.

The most interesting results about development of fractures on the flanks of active volcanoes and failures detected with a thermal camera have been obtained during the flank collapse occurred on Stromboli on 30 December 2002 (Fig. 3).

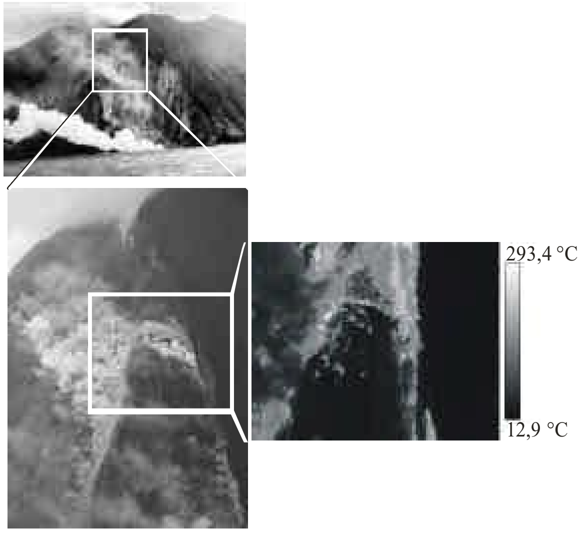

Fig. 3 – Stromboli, Italy, 30 December 2002. Photos (left) and thermal image (right) of the fractures developing along the north flank of the volcano, recorded just one hour before failure, flank collapse and tsunami (modified after Bonaccorso et al., 2003).

In that case we have been lucky enough to fly over the volcano for our usual thermal monitoring just one hour before the major landslide took place, and we could record the development and growth of hot fractures that eventually signed the boundary of the rock collapse. Thermal mapping from helicopter lasted that day about 40 minutes, giving us the time to record the propagation of these fractures along the steep northern flank of the volcano[11]. The fractures opened on the upper part of the volcano's flank and propagated downward, detaching an increasingly wider mass of rock. The landslide caused a highly destructive tsunami that devastated the eastern coast of the island up to an elevation of 10 m and a distance of 100 m from the coastline. This event demonstrated that thermal cameras, possibly continuously recording from a fixed position and with data transmitted to a volcano observatory, can be extremely useful to forecast major failures of the flanks of active volcanoes.

4. Explosive activity

Etna and Stromboli volcanoes have continuous gas emission from the summit craters, producing a thick curtain that constantly hides the inside of the craters to direct observation. It's only thanks to the images regularly obtained with a thermal camera that we can distinguish: (a) the morphology inside the craters; (b) the number of active vents on the crater bottom; (c) the kind of activity these vents show (degassing, explosive, effusive), as well as (d) the presence of obstructions. Obstructions of the active vents are commonly caused by frequent landslides interesting the inner crater walls. These are potentially very dangerous, since gas pockets accumulating below the landslide debris can be released with sudden explosions, throwing away blocks, ash and rock fragments. It is one of these explosions that caused 9 casualties in September 1979 on the summit of Mt. Etna[24] and this explains why it's so important to be able to forecast well on time the conditions that may lead to these events. Carrying out regular thermal surveys at Mt. Etna we managed to recognize new magma rising from the source through the summit conduits, gradually giving rise to explosive activity inside the craters. Explosions grew in intensity and led to powerful explosions and then to a new flank eruption[4].

Regular thermal surveys permitted to reveal the formation of cracks on the crater walls and to observe hot lava bombs being thrown away during explosive activity. There is probably no need to say that obtaining thermal images in these conditions is extremely useful to study processes occurring during explosive activity, and possibly also to distinguish between juvenile (hot) lava clasts and lithics (cold material coming from the conduit's wall). In addition, thermal images collected from helicopter during the 2002-2003 Etna flank eruption allowed us to distinguish the number of active vents within the crater (Fig. 4).

Fig. 4 – Mt. Etna, Italy. Photo (left) and thermal image (right) of fire fountaining and ash column rising from a new cinder cone formed at 2750 m elevation on the south flank of the volcano during the 2002-2003 flank eruption.

Routine thermal monitoring of Stromboli has been carried out since August 2001 with the aid of a thermal camera, which has become essential because it is the only system allowing detection of the volcanic activity through the curtain of gases that usually obscures the craters. Figure 5 shows an example of the view of the summit craters, with thermal image showing strong explosions and lava jets from the NE-crater (or Crater 1, right of the image) and an active vent inside the SW-crater (or Crater 3, left of the image). During the 2002-2003 eruption at Stromboli, a daily thermal monitoring of the summit craters allowed us to plot changes in temperature at the crater bottom versus time, thus giving insights into the movements of magma in the feeder conduit[25], as well as allowing daily calculation of effusion rate from the active vents[8].

Fig. 5 – Stromboli, Italy. Photo (left) and thermal image (right) of explosive activity with vertical jets of hot lava from the NE-crater (or Crater 1, right) and an open vent (left) at the bottom of the SW-crater, or Crater 3. Images collected during the 2002-2003 flank eruption.

5. Lava flow fields

Since July 2001, Mt. Etna's activity has been monitored with a handheld thermal camera. During the 2002-2003 flank eruption at this volcano, helicopter-borne thermal mapping was carried out on a daily basis. The eruption started on 27 October with the opening of a field of fissures from the north to the south flank of the volcano. Abundant ash emission from the whole length of the 10 km long fissure covered the lava flow field, making it impossible to approach the active lava even with helicopters. Additionally, the northern lava flows were spreading into a forest, causing fire and impeding routine measures in field and lava flow mapping from the ground. This situation continued for several days. The only way to obtain an approximate mapping of the flow field was to use a thermal camera from helicopter, obtaining inclined images of the lava flow field. This allowed: (1) an estimation of the speed of the spreading lava and (2) of the position of the lava flow fronts, (3) evaluation of effusion rate, (4) daily covered area, and (5) organisation of evacuation plans for people living close to the area affected by flows. All these information were essential for civil protection purposes. Emission of lava flows from the north fissure stopped on 5 November 2002. During the following phase of the eruption, when lava flows spread for over two months only on the southern flank of the volcano, little ash emission from the craters allowed us a better view of the lava flow field. However, since the active flows were spreading on a limited surface, flanking and overlapping each other several times, location of new effusive vents (Fig. 6) and distinction between active and inactive lava flows (Fig. 7) was possible only using a thermal camera. This device allowed us to distinguish active lava flows, inflating flow fronts, lava tubes and ephemeral vents, giving us a comprehensive view of the evolution of the lava flow field. It also helped us discover new vent opening from the base of the cinder cone (Fig. 6), in a way to advice the civil protection authorities about the future path of new lava flows.

Fig. 6 – Mt. Etna, Italy. Photo (left) and thermal image (right) collected during the 2002-2003 flank eruption. The thermal image shows details of the volcanic activity taking place whitin the cinder cone, as well as location of the new vent just opened at the base of the cone. Note also as the left lava branch results more fed (higher temperature) than the right lava flow, that died off in a few hours.

Fig. 7 – Mt. Etna, Italy. Photo (left) and thermal image (right) collected during the 2002-2003 flank eruption. The thermal image shows details of the lava flow field, allowing us to distinguish between active (bright) and inactive (grey) lava flows. Inactive lava flows, in this case, are just two days old, and this is why it is extremely difficult to distinguish them from the active flows at the naked eye.

The use of a thermal camera from helicopter allowed us to distinguish the number and position of active vents on the lava flow field, and this in turn was immediately applied to lava flow model in order to forecast the area that will be inundated by lava[4]. Flow mapping with the aid of this device allowed daily calculation of the area covered by new lava flows. All these data, integrated into theoretical models of calculation of maximum lava flow length[16]

and lava flow simulation models using cellular automata[26], are used for civil protection purposes to predict what areas will be invaded by lava in the near future.
Routine volcanic monitoring at Stromboli volcano also benefited of the use of a thermal camera during daily surveys from helicopter. The effusive and explosive flank eruption that took place at this volcano between 28 December 2002 and 22 July 2003 was followed employing this technique, which allowed us to identify all details of the summit craters (Fig. 5) and of the lava flow field (Fig. 8).

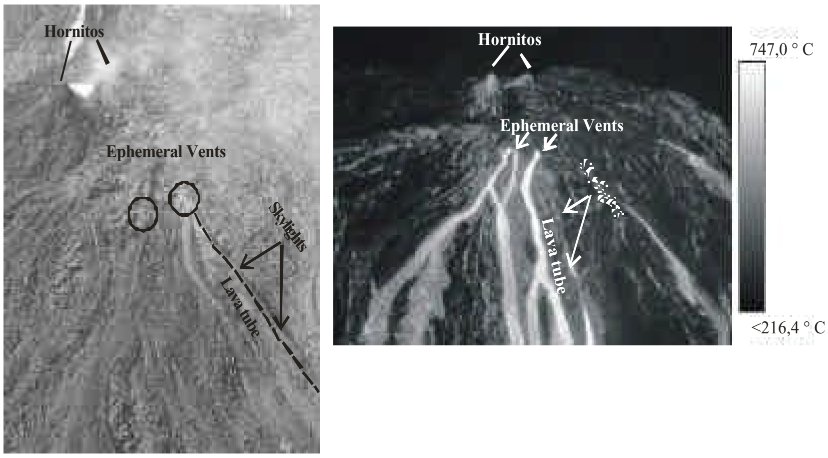

Fig. 8 – Stromboli, Italy. Photo (left) and thermal image (right) collected during the 2002-2003 flank eruption. The thermal image shows details of the lava flow field, allowing us to distinguish between active (bright) and inactive (grey) lava flows, hornitos, ephemeral vents, skylights and lava tubes. See text for further explanations.

As an example, Figure 8 shows details of this lava flow field as recorded in May 2003. Comparison between photo and thermal image reveals a number of interesting features, such as: (a) hornitos, (b) ephemeral vents, (c) active lava flows (white in the thermal image), (d) lava tubes and (e) skylights. The presence of hornitos, steep moulds of lava produced by splashing of lava blebs by low-energy explosions from an active vent, indicates that gas-rich magma is coming out from a vent. This has important implications in terms of volcanic processes occurring within the feeder conduit, as well as in terms of volcanic prediction and forecast. The presence of ephemeral vents, lava tubes and skylights is extremely important since they, all together, show the hidden path of lava tubes. Lava tubes are volcanic features worldwide recognised for being able to increase the maximum length a lava flow can reach. They have then important implication for lava flow hazard[16].

Another important process occurring during lava flow emplacement is flow front inflation[27]. This is very common during emplacement of smooth, thin lava flows at Kilauea volcano, and causes the propagation of lava tubes down slope and the opening of ephemeral vents or breakouts that elongate the final flow. Figure 9 shows a sequence of thermal images recorded at this volcano in July 2003, and reveals the hottest points of the active lava flow field as the margins of these flows.

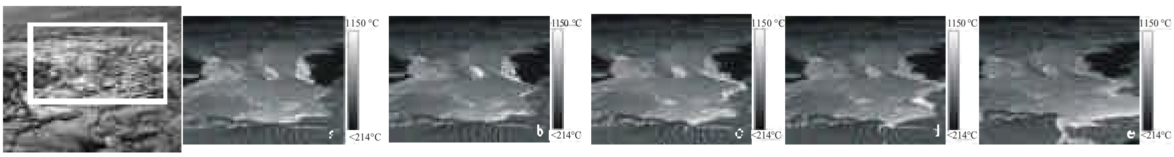

Fig. 9 – Kilauea, Hawaii. Photo (left) and thermal images collected during a field trip in July 2003. The thermal image shows details of the inflation of the lava flow field.

6. Continuous monitoring with fixed thermal cameras

The use of hand held thermal cameras during monitoring of eruptive phases at the Italian volcanoes Etna and Stromboli has shown the importance of these instruments in volcanic surveillance. At Stromboli, we believe for the first time in the world, a network of visual, infrared and thermal cameras has been installed in October 2003. The position of the cameras allows two points of view (Fig. 10), with a continuous observation of the south-east crater slope from station 1 (Fig. 10), and of the inside of the summit craters from station 2 (Fig. 10). This system allows a continuous record of the volcanic activity, with automatic counting of the number of explosions occurring every day, day and night, and with the effect of weather conditions minimized. The good results already obtained with this network at Stromboli pushed the Italian Civil Protection to fund a project for the installation of a similar network also on Etna volcano. We believe that a greater knowledge of volcanic processes could be obtained only with a more widespread use of these instruments on active volcanoes and in different volcanic conditions.

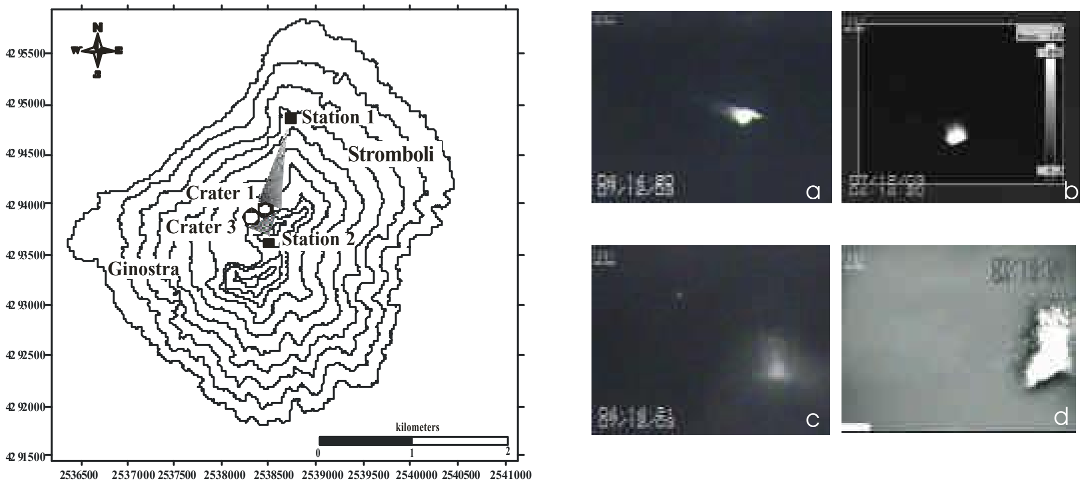

Fig. 10 – Stromboli, Italy. Sketch map of the volcano (left) with location of the two stations where visual, thermal and infrared cameras are located. (a) visible image from station 1; (b) thermal camera from station 1; (c) visible image from station 2; (d) infrared image from station 2. Images from these cameras, both live and fixed, are visible on the INGV-CT website at www.ct.ingv.it.

7. Conclusive remarks

Important results have been obtained during the last decade with application of thermal remote sensing to volcano monitoring. Using a hand held thermal camera during the latest flank eruptions at Stromboli, Etna and Kilauea volcanoes allowed us to detect a number of processes extremely important for volcano hazard. The growth of a lava flow field, and the development of several volcanic features, allowed us to keep under control the eruption and to promptly rise issues with civil protection purposes. Surveys with a hand held thermal camera from helicopter also revealed important in detecting volcano instability, with development of hot cracks on the flanks of active volcanoes. Continuous monitoring of the summit of active volcanoes allows a routine mapping of the distribution, number, morphology and kind of volcanic activity at the summit vents, as well as detection of obstructions within the craters that might trigger sudden and unpredictable gas explosions. We believe that even more interesting results will derive from a widespread instalment of thermal camera networks on the slopes of active volcanoes. A greater spread of these instruments among the volcanological community will significantly help to improve our understanding of volcanic processes and prediction of volcanic phenomena.

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