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# Infrared remote sensing techniques applied to the "Salinelle" mud volcanoes (Paternò, Sicily)

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## ABSTRACT

The Salinelle are the surface expression of over-pressurised sedimentary fluids hosted within clay sediments typical of compressive tectonic settings. Particularly at Paternò (lower SW flank of Mt. Etna), fluids are slightly thermalised and contaminated by magmatic gases (mainly $CO_2$), due to the nearby active volcanic system of Mt. Etna. Overall, the composition of the Salinelle gases shows temporal variations that have been correlated to the geodynamic activity of the area. Monitoring of mud volcanoes geochemical and thermal parameters has typically been performed by direct measurement techniques, thus implying long duration of the surveys. In order to speed up data collection and to simultaneously test the reliability of remote sensing techniques for studying the Salinelle activity, we carried out both ground-based thermal imagery and Fourier Transfer InfraRed (FTIR) measurements.

## 1. INTRODUCTION

The "Salinelle" mud volcanoes are the shallow manifestation - typical of compressive tectonic settings - of over-pressured sedimentary fluids in clayey sediments. In the south-western Etnean area, a few kilometers apart from each other, three groups of "Salinelle" (namely, Paternò Stadium, Vallone Salato and Simeto River) are active (Carveni et al 2012 and references therein).

The Salinelle dei Cappuccini, also known as Salinelle dello Stadio, are located on the western periphery of Paternò, on the northern slope of a hill named Conetto dei Cappuccini, where lava flows ascribed to the volcanic products of Piano Provenzana Formation outcrop (Branca et al 2011).

In such a geodynamic framework the emitted fluids generally consist of hydrocarbons (mainly $CH_4$) and salty water variably charged with mud. Particularly at Paternò (lower SW flank of Mt. Etna), fluids are slightly thermalised and contaminated by magmatic gases (mainly $CO_2$), due to the nearby active volcanic system of Mt. Etna. Overall, the composition of the Salinelle gases shows temporal variations that have been correlated to the geodynamic activity in the area, while that of the waters has been almost constant over time. Waters are strongly enriched in Na, Cl, B, As, alkaline (Li, Rb, Cs) and alkaline-earth (Sr, Ba) elements (Chiodini et al 1996; Aiuppa et al 2003; D'Alessandro et al 1995, 1996; Caracausi et al 2003; Giammanco et al 2007).

Historical notices of the Salinelle are known since Roman times being mentioned among others by the physician Galen. The archaeological remains of Roman baths and the prehistoric settlement, dated at the sixth millennium B.C., probably show the therapeutic use of the Salinelle waters since ancient times. Indeed, these waters were used for health-giving purposes by the inhabitants of the nearby city of Paternò, particularly for skin diseases, at least until the beginning of the twentieth century (Eredia 1931).

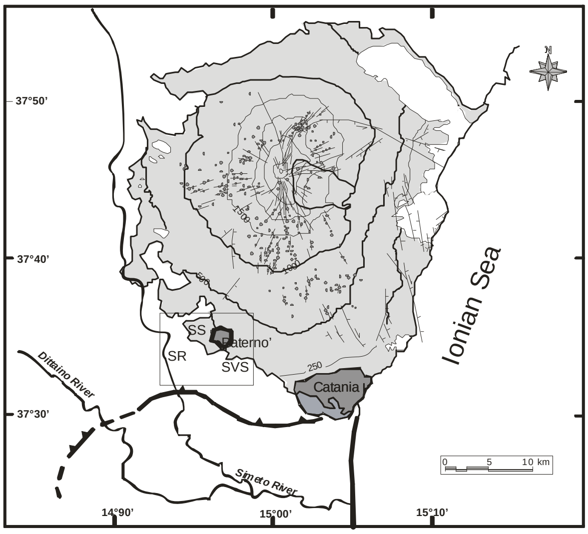


**Figure 1: Schematic geologic and structural map of Mt. Etna showing the boundaries of the volcanic products (grey area), the main volcano-tectonic features (modified from Catalano et al 2004), and the location of the Salinelle mud volcanoes. SS = Salinelle Stadium; SVS = Salinelle Vallone Salato; SR = Salinelle Simeto River.**

Most of the pools and mud vents are ephemeral and show strong temporal variations in gas flow. Water outlet temperatures are normally between 10 and 20 °C, but occasionally increase to 40–50 °C. Such anomalous temperature values are always accompanied by increases in the gas efflux. Mud vent activity is presently characterised by alternating paroxysmal phases and quiescent periods The oldest reports of paroxysmal activity are found in Silvestri (1866, 1867, 1879), who reports - after a sequence of earthquakes felt locally - strong eruptive activities in early 1866 and late 1878. These included fountains of muddy water up to 3 m high with temperature up to 46 °C. During following eruptions, Cumin (1954) measured high water temperatures only at vents emitting hydrogen sulphide that, besides, was observed only during paroxysmal phases. In the past 15 years similar increases in degassing activity have also been recorded at the Salinelle. These events normally lasted few weeks to four months.

## 2. METHODOLOGY OF DATA COLLECTION AND RESULTS

### 2.1 Thermal imaging

Usually, monitoring geochemical and thermal parameters in the fluids emitted by the Salinelle mud volcanoes has been performed by direct measurement techniques, thus implying a long duration of the surveys due to the wide emitting area and the large number of active vents, typical of active geothermal zones (e.g., Shimozuru and Kagiyama 1978). In order to speed up data collection and to simultaneously test the reliability of remote sensing techniques for studying the Salinelle activity, on 30 October 2012 we carried out both ground-based thermal imagery and Fourier Transfer InfraRed (FTIR) measurements at the mud vents in the area next to the Paternò stadium.

Among the remote sensing techniques applied to volcanology, thermal imaging is one of the most used. In fact, this technique provides the opportunity of observation of wide thermal active areas, thus giving synoptic views and not just punctual measurements as such in the case for instance of infrared thermometers (e.g., Harris et al 2009; Spampinato et al 2011). For this reason, this is not the first time in which thermal imaging has been applied to study geothermal/hydrothermal phenomena. Particularly at geothermal areas, the use of infrared cameras especially during air-borne surveys, has allowed identification and mapping of thermally active areas, and tracking of the temporal and spatial changes of the targeted areas with estimation of the released heat budget (e.g., Benseman 1959; Yuhara et al 1981).

In order to collect thermal images infrared cameras are used, with the most recent models consisting of uncooled microbolometers. Particularly the instruments used at INGV-Osservatorio Etneo since 2001, are FLIR (Forward Looking InfraRed) thermal cameras with detector arrays of 320 × 240 and 640 × 480 pixels sensitive to the 7.5-13 μm waveband. FLIR cameras are able of recording radiometric images with more than one dynamic range (usually: – 40 to 120 °C, 0 to 500 °C, and from 350 to 1500 °C), and according to different sampling rates up to 60 Hz.

During our surveys at the Salinelle of Paternò, we collected radiometric data from fixed positions using a portable FLIR SC660 thermal camera (Fig. 2).

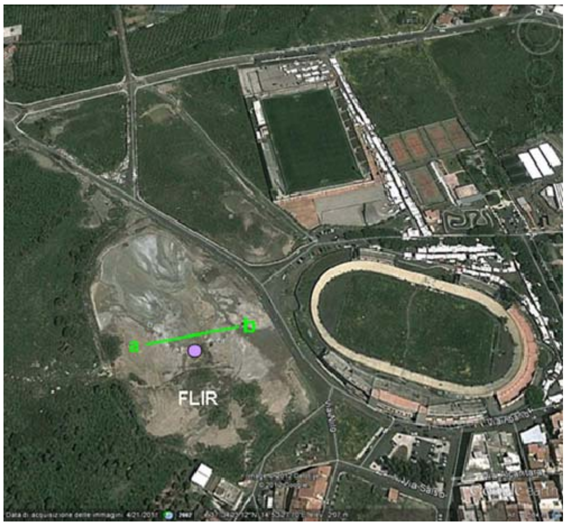


**Figure 2: Aerial view of the Salinelle mud volcanoes located next to the stadium of Paternò. The solid purple circle shows the site from which thermal images were taken. The a-b alignment (green line) indicates the thermal profile of Fig. 3.**

Measurements were deployed early in the morning, from 5:56:17 to 7:16:53 GMT, so as to avoid sun reflection and soil heating (e.g., Spampinato et al 2011).

We recorded thermal images at sampling rates of 0.5 and 10 seconds using the lowest dynamic range of the camera (-40–120 °C). Moreover, in order to apply a first-order corrections for the errors due to the atmospheric effects, we also measured the air temperature and relative humidity (%). These parameters were used as inputs for the internal software of the thermal camera operating the correction, together with the measured camera-object distance and object emissivity (we used 0.99).

Despite the leaning ground, thermal imagery provided an overview of the study area, allowing for the detection and mapping of the active mud volcanoes (Fig. 3).

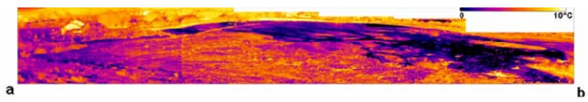


**Figure 3: Thermal profile of the Salinelle of Paternò Stadium area. Images were collected from the site shown in Fig. 2.**

Post-processing of the thermal images collected (more than 1100) at the most active and stable vents located in the southern portion the area showed that maximum apparent temperatures increased while moving from the topographic higher sites (next to the solid purple circle of Figure 2 to the lower ones (Fig. 4).

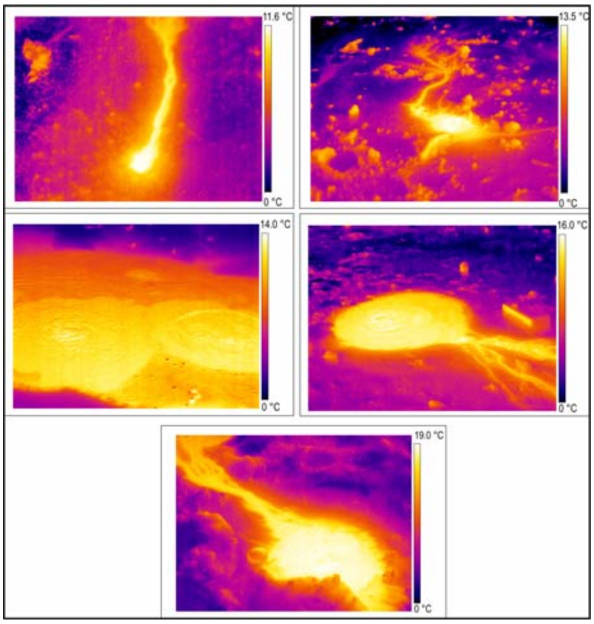


**Figure 4: Thermal images of the most active mud volcanoes in the Salinelle of Paternò Stadium area.**

Moreover, high frequency thermal imagery allowed characterisation of the dynamics of each of the targeted mud volcanoes, enabling the discrimination between each of the gas bubbles bursting at the water surface, and the assessment of the very shallow geometric relationship between neighbouring vents.

### 2.2 FTIR measurements

Open-path Fourier transform infrared (OP-FTIR) spectrometry is a powerful tool for volcanic research and monitoring. Gas detection and quantification using OP-FTIR is based on the infrared spectroscopy principles. Considering light propagating through a medium, the intensity observed after its interaction with the medium will be a function of emissivity ε, reflectivity r and absorptivity α of the medium. Kirchoff's law states that $\alpha = \varepsilon$. The transmittance, τ, of the system is defined as $1 - \alpha$.In the case of dilute gases, the reflectivity is essentially zero and the transmittance follows the Beer-Lambert law:

$$\tau = \frac{I}{I_0} = \exp(-\alpha \cdot c \cdot l) \qquad [1]$$

where I and $I_0$ are the intensity of the incident and the transmitted light, respectively, α is the absorptivity of the substance, c the speed of light and l the path length through the medium.

Therefore, in the collected spectra, spectral absorption lines, characteristics of every molecule of the gaseous mixture will be present (Fig. 5).

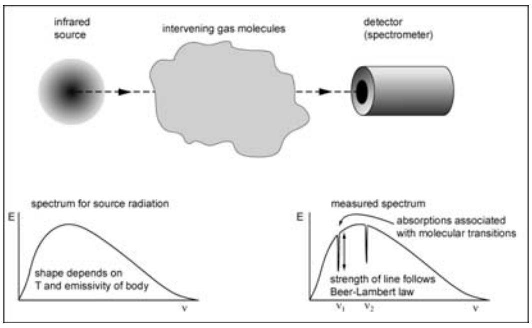


**Figure 5: Sketch showing the basic principles of FTIR, the Beer-Lambert law, and the basic geometry of sampling.**

The nature of the measurement by FTIR methodology is such that all wavelengths are measured simultaneously, in this way it is possible to discriminate between each of the gas bubbles bursting at the water surface and to determinate the gas composition in each bubble.

Measurements at the Salinelle mud volcanoes were performed in bistatic active mode using the Midac M4406-S spectrometer and an infrared lamp placed 1 m from the spectrometer and acting as source of radiation. The infrared lamp consists of a high emissivity 6-volt Scitek IR-12K infrared source (http://www.scitec.co.uk) that operates at a temperature of 975 °C, and it is positioned at the focal point of an 2-inch parabolic reflector (Fig. 6).

**Figure 6: The geometry of sampling used for FTIR measurements at the Salinelle of Paternò Stadium.**

Spectra from OP-FTIR systems were evaluated using a non-linear least-square fitting algorithm and a forward model in order to calculate the radiative transfer in a two-layer model atmosphere (Burton 2009; La Spina et al 2010).

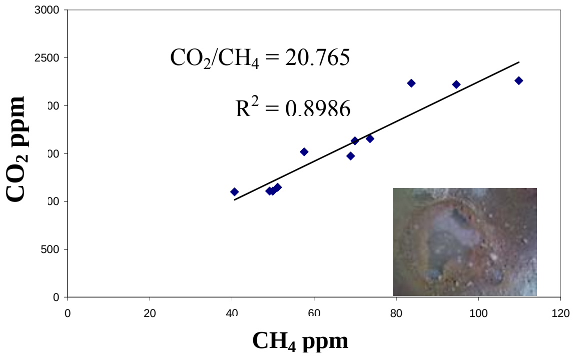


**Figure 7: Scatter plot between $CO_2$ and $CH_4$ amounts retrieved from FTIR measurements at one of the vents (shown in the inbox picture) of the Salinelle of Paternò Stadium.**

Figure 7 shows the $CO_2/CH_4$ ratio determined by linear regression between the retrieved amounts of the two gas species.

## 3. CONCLUSIONS

The results obtained from the application of remote sensing techniques to the measurement of fluid emissions at the Salinelle mud volcanoes are undoubtedly promising. Measurements are relatively fast and allow for a reliable and easy determination of the heat emission and gas composition from bubbling gas vents. In fact, consistently with previous measurements of water temperature and gas bubbles composition during non-paroxysmal phases, maximum apparent temperatures ranged from ~10 to 20 °C and the $CO_2/CH_4$ ratio was steady around 21. In the future this combined measurement technique might include routinely campaigns for better characterisation of the Salinelle parameters and activity.

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