RADIATIVE HEAT POWER AND HYBRID EARTHQUAKES RECORDED CONTEMPORANEOUSLY AT UBINAS VOLCANO (PERU) DURING THE 2013-2014 ERUPTIVE ACTIVITY

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INTRODUCTION

The Ubinas stratovolcano (16°21 'S, 70°54'W, 5672masl) located in southern Peru and within the CVZ or Central Volcanic Zone of the Andes, is the most active of Peru, with25 minor eruptions(VEI 1-3)recorded since1550, with a frequency of 6-7 eruptions per century.The mostrecent eruption, VEI2, vulcanian, occurred from March 2006 to June 2009. After 4 years and 2 months of quiescence, the Ubinas volcano renewed eruptive activity which began with phreatic explosions occurring from 2 to 7 September 2013.After a brief calm, the explosive exhalations/explosions of ash and gase missions restarted on February 1, 2014. At the time of this writing (May 2014), this activity persists.

The Observatorio Vulcanológico de Arequipa (OVA) of the Instituto Geofísico del Perú (IGP) performs continuous geophysical monitoring of this volcano since 2006, mainly through the analysis of seismic records which are accessible in real time due to a telemetric system. In addition, from July 2013 this volcano is also monitored by the near real-time MIROVA system (Middle Infrared Observation of Volcanic Activity) of the Department of Earth Science- University of Turin (Italy) which detects thermal anomalies using MODIS satellite image. Here we present the results of Ubinas volcanomonitoringbetween September 2013 - May 2014, mainly based on these two tools: seismology, giving information associated to the movement of magmatic material very close to the surface, and satellite observation of hot spots which are associated with the arrival of fresh magma.

SEISMICITY AT THE UBINAS VOLCANO

The Ubinas volcano seismic network consists of 4permanentdigitaltelemetric stations (UB1, UB2, UB3andUB4) distributed overthe entire volcanic cone, between4850and 5000masl (Fig. 1).Two stations(UB1 andUB2) are equipped with GuralpCMG-40T, 3C broadband sensors, and the other two(UB3 andUB4) withLennartzLE-3Dlite short period sensors. All digitizers are RefTek.

The analysis and classification of seismic signals recorded by the network, the determination of the seismic energy, the location of events, etc., is performeddaily. During the current eruption alltypes of seismic events have been observed like Volcano-tectonic (VT), Long period (LP), hybrid (events having high and low frequencies), tremors, explosions and exhalations.During the stage of magmatic eruption, characterized by intense eruptions of tephra, the most important signals are earthquakes of the hybrid type, which have been detected and registered from the second week of February onwards (Figure3). Since these features have been associated with magma as centto the crater (White et al., 1998; White, 2011) we decided to conduct a surveillance of the eruption based primarily on the number and daily seismic energy of suchhybrid type earthquakes.

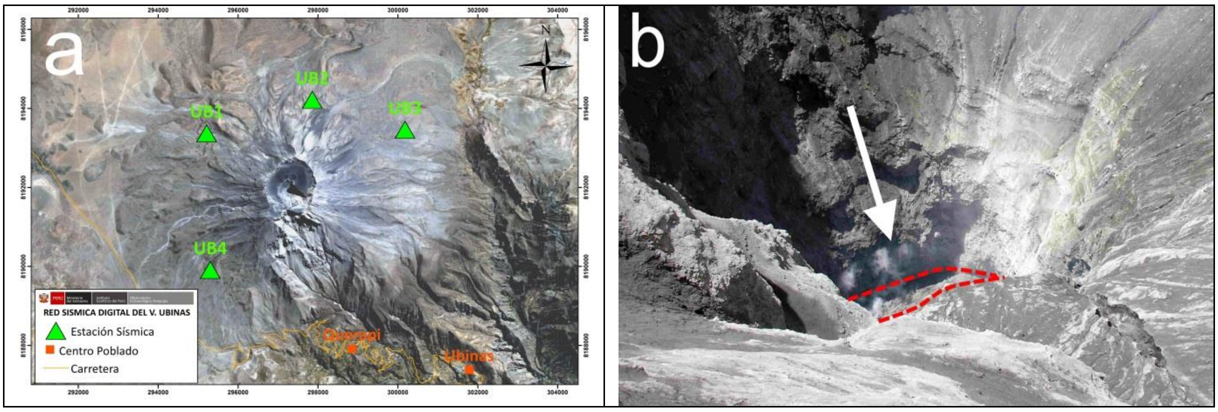

Figure 1.– (a) Network of 4 seismic stations of IGP around Ubinas volcano. Signals are transmitted in real time to Arequipa; (b) Lava body (30-40 m in diameter) observed at the bottom of Ubinas crater on 02 March 2012 (photo by IGP).

MIROVA SYSTEM

MIROVA (Middle InfraRed Observation of Volcanic activity) is a volcanic hot-spot detection system based on the analysis of multispectral images acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS). The MODIS instrument, aboard the Terra (EOS AM) and Aqua (EOS PM) satellites, offers a temporal coverage (~ 4 images per day), spatial resolution (1 km in the IR bands) and an adequate spectral coverage which enables monitoring of volcanic activity in different geotectonic contexts (Coppola et al., 2013). In particular, MIROVA uses the Middle InfraRed Radiation (MIR), in order to detect, locate and measure the radiative power sourced from volcanic activity (hereby called VRP).

MIROVA provides thermal maps (Fig. 2) and VRP estimates within 1-4 hours from each satellite overpass so that the location and intensity of a thermal anomaly may be tracked in near real time through a dedicated web-based interface (www.mirova .unito.it).

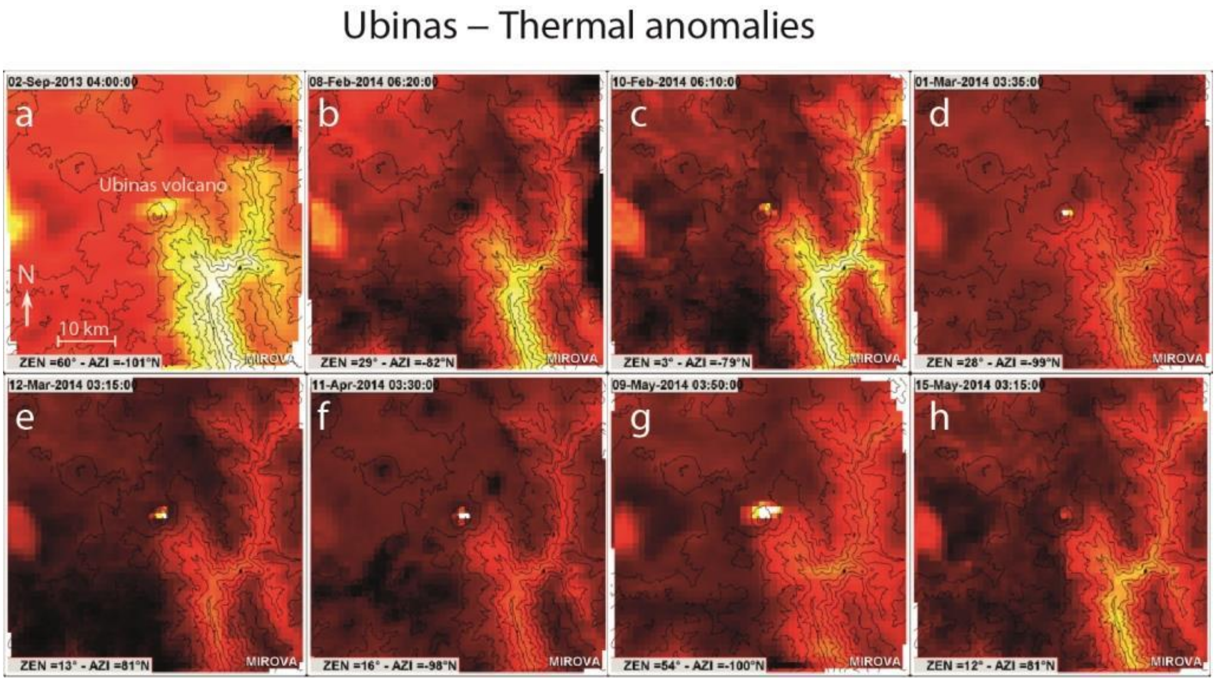

Figure 2 – Sequence of selected thermal maps showing the thermal activity at Ubinas volcano between September 2013 and May 2014. Note the hotspots at the summit of the volcano (particularly evident since 10 February 2014). The steep Tambo River Valley is also evident by the high temperature contrast between its bottom and the surrounding plateau.

RESULTS

Continuous near real-time MIROVA observations at Ubinas volcano began regularly in early July 2013. On September 2, at 03:46 UTC, the first of nine phreatic explosions that occurred at the volcano between September 2-7, 2013 generate ash plumes that rose 1.5 to 2 km above the crater. A few minutes after the explosion, at 04:00 UTC, the MIROVA system detected the first thermal anomaly (Fig. 2a). In the following months, Ubinas returned to calm and produced only occasional puffs of steam and gases, which, however, did not produce any evident thermal anomaly detectable by MIROVA (Fig. 2b). In 2014, during January 8-9 and 25 two earthquake swarms were registered below the volcano and preceded a general increase of seismicity recorded on January30-31. The following days, from February 1 to 8, numerous exhalations and explosions were observed. From February 9 to 14, we detected hybrid earthquakes increasing in number and energy.

Almost simultaneously thermalanomaliesappeared (Figure 3). On February 10, 2014 at 06:10 UTC, the second small thermal anomaly (3 MW) was detected by MIROVA (the first after September 2013) suggesting a renewal of thermal activity at the summit of the volcano (Fig. 2c, Fig. 3). During the following days, several thermal anomalies were detected, increasing in energy over time and reaching about 6-7 MW on March 2 (Fig. 2d, Fig. 3) when a new elongated body of incandescent lava (30-40 m) was observed for the first time at the crater floor (fig. 1b). Thermal activity sourced at Ubinas's crater continued to increase in the following days, and, by March 12, the VRP reached 12 MW (Fig. 2e, Fig. 3). Indeed, the seismicrecordsindicated thepersistence ofhybridtypeseismiceventsassociated withlava extrusionbetweenMarch10-11, along with rising emissionsof sulfur dioxidemeasured duringthe same period (Krotkovetal,2014). In the following three weeks persistent thermal emissions of 2-7 MW were recorded over the summit of the volcano and preceded a new period of increased thermal activity that had begun on April 1, when more than 15 MW were registered. Also, from March 27 to April 5 the daily energy of hybrid earthquakes increased significantly (Fig 3); these values then decreased, butstill remained high up to April 14. Between April4 and 15 several thermal anomalies reached more than 20 MW, even up to 37 MW, a radiative power representing the highest thermal emission recorded during this eruption (Fig. 2f, Fig. 3). This phase was accompanied by increased seismicity and eruptive activity, which in turn produced multiple explosions ejecting incandescent tephra and blocks. After this energetic phase, the thermal anomalies lowered abruptly, and the detection of lower thermal anomalies (about 1 MW) became more sporadic (Fig. 3). Thisphase of decreasingthermal anomalies was accompanied by a general reduction of seismic activity, especially concerning the hybrid earthquakes, as well as lower explosive activity observed since late April 2014. On May 9, at 03:50 UTC, an isolated thermal anomaly of 30 MW was detected (Fig. 2g, Fig. 3) and probably resulted from the hot material ejected during a coeval explosion. At the time of this writing we observe weak seismic activity, while few and low thermal anomalies (about 1 MW) are detected.

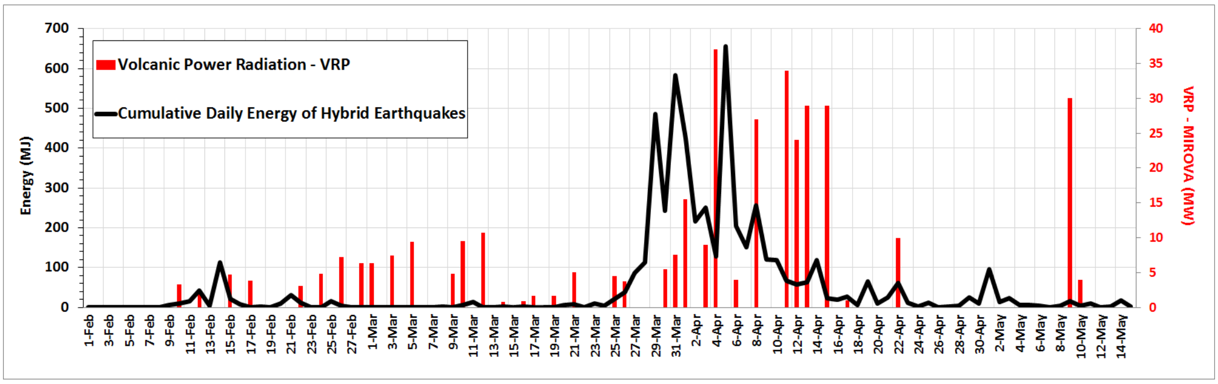

***Figure 3**.-Cumulative daily energy of hybrid earthquakes (dark line, OVA) and Volcanic Power Radiation (VRP, red bars, MIROVA) determined between February 1 and May 15, 2014.*

DISCUSSION

Between February 10, 2014 (when the first thermal anomaly had been detected) and mid May 2014 (the time of this writing), the MIROVA system detected a total of 53 thermal anomalies, spanning from less than 1 MW to more than 35 MW.

During the first month of registrations, thermal anomalies were detected on a daily basis and increased gradually from 3 MW to 12 MW. This thermal activity was most likely related to the appearance and growing of a new lava body, observed for the first time on March 1-2, 2014 (Fig 1b). Since mid-March 2014, a large number of thermal anomalies accompanied the phase of more intense seismic and explosive activity which possibly can be related to the continuous disruption of the lava body extrusion as well as the source ofenergeticearthquakes. In these cases, we suggest that the manifestations of such thermal anomalies are most likely associated with hot incandescent material ejected during the explosions thatoccurred, for example on September 2 and May 9 (Fig. 2a and 2g).

It is important to note that during the monitoring time of the eruption we observed a very good correlation between thermal and seismic data. Firstly initial detection of hybrids earthquakes and thermal hotspots occur almost simultaneously (March 9-10) and secondly, the period of strongest anomalies (late March through the first two weeks of April) also coincide in time, even though there is a shift on interval of maximum values. This could be due to masking of thermal anomalies caused by the presence of low temperature fumaroles and ash emissions in the atmosphere near the crater.

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