Combined thermal and seismic analysis of the Villarrica volcano lava lake, Chile

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ABSTRACT

Villarrica volcano, a 2,850 m basaltic-andesite stratocone in southern Chile (39°25'S-71° 42'W), has had an active summit lava lake (30-60 m diameter) since the last eruption in 1984-85. Current activity is characterised by mild strombolian activity, continuous degassing, and periodic larger explosions. Between August-December 1999, Villarrica showed a significant increase in seismic activity. Lava lake activity increased and larger discrete explosions occurred destroying the lava lake crust on, at least, 4 occasions. Since February 1999, radiance data provided by the NOAA GOES 8 satellite via the University of Hawaii hot spot monitoring web-site served, as an additional real time monitoring method of the lava lake. Preliminary GOES data, for the period February-December 1999, have been correlated with seismic RSAM data and visual observations. Correlations exist between these data sets only for the most active periods. At Villarrica, the small dimensional and temporal exposure of the lava lake surface and the narrow crater coupled with a low satellite viewing angle generate a very subtle hot spot signature. Radiance variations can only provide reliable data where adequate constraining ground information exists and viewing conditions are optimal. However, the hot spot tool, once refined is considered a potentially important method of improving the monitoring capabilities.

Key words: Strombolian, Villarrica volcano, Radiance, Lava lake, Seismicity, GOES.

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RESUMEN

Análisis térmico y sísmico combinado del lago de lava del volcán Villarrica, Chile. El volcán Villarrica es un estrato-volcán andesítico-basáltico de 2850 metros de altura, que se ubica al sur de Chile (39°25´S-71°42´W). Presenta en su cráter un lago de lava, de 30-60 m de diámetro, que ha estado activo desde 1984-85, fecha en que se registró su última erupción. En la actualidad, este volcán presenta una actividad estromboliana moderada, permanente liberación de gases magmáticos y periódicas explosiones mayores. Durante los meses de agosto a diciembre de 1999, hubo un notable aumento de su actividad sísmica, acompañado con un aumento de la actividad del lago de lava: explosiones mayores destruyeron la corteza sobre éste en, al menos, 4 ocasiones.

Desde febrero de 1999, datos de radiancia proporcionados por el satélite NOAA GOES 8, han sido utilizados como un método adicional para observar la actividad del lago de lava en tiempo real. Los datos preliminares obtenidos durante el período comprendido entre febrero y diciembre de 1999 fueron contrastados con datos RSAM sísmicos y observaciones visuales. Es así como, correlaciones han sido encontradas entre estos conjuntos de datos, aunque solamente para los períodos de mayor actividad. La pequeña exposición temporal y dimensional de la superficie del lago de lava en un cráter angosto, junto con un bajo ángulo de visibilidad satelital, genera una incipiente señal en el volcán Villarrica. Las variación de radiancia puede solamente proveer datos confiables donde existe adecuada información de la superficie y las condiciones para la observación son óptimas. Sin embargo, la herramienta, una vez refinada, puede ser considerada un método potencialmente importante para mejorar las capacidades de monitoreo del volcán.

Palabras claves: Actividad estromboliana, Volcán Villarrica, Radiancia, Lago de lava, Sismicidad, GOES,

INTRODUCTION

Villarrica volcano (39°25'S-71°42'W, 2,850 m a.s.l.), in southern Chile, is an open system, basaltic-andesite volcano with a small, continuously active summit lava lake. Background activity is characterised by mild strombolian activity, continuous degassing and associated low level seismicity. Since the last eruption in 1984-1985, there have been several occasions where, for short periods of time, the activity has been at an elevated level with regard to the established 'background' but without culminating in an eruptive crisis (*e.g.*, Ortiz *et al.*, 2003). These episodes are important as they represent periods of critical decision making both by scientists and local authorities alike. An improved understanding of how and when they occur, and in particular determining whether they have the potential to develop into the next volcanic crisis, is paramount. One such period, between August and December 1999, is the focus of this paper. During this time, seismic activity increased substantially and several larger explosions occurred, generating a moderate level of concern for the authorities.

The Observatorio Volcanológico de los Andes del Sur (OVDAS), of the Servicio National de Geología y Minería, is located in the city of Temuco, 85 km WNW of Villarrica volcano. Direct observations of the lava lake activity are therefore limited to occasional ascents, opportunistic aeroplane over flights and reports from mountain guides and park rangers. The morphology of the crater, lava lake height, and intensity of strombolian activity can vary dramatically between successive observations of the crater. Systematic observations on a day-to-day time-scale cannot be made, and during the winter months, when cloud cover is low, are extremely limited.

The area around Villarrica volcano is a popular tourist resort with a summertime (December-February) population of up to 160,000 within 25 km radius of the crater. OVDAS monitoring facilities during 1999 were limited to two single component short period seismometers (Fuentealba, 1985; G. Fuentealba and P. Peña[1]) installed at 4 and 19 km from the vent respectively. Between January 2000 and February 2001, additional SO_2 monitoring using COSPEC was undertaken (Witter *et al.*, 2000a; 2000b; Witter and Delmelle, 2004; Witter and Calder, in press) and further expansion of the seismic network is currently in progress.

[1] 1998. Instalación y puesta en funcionamiento del sistema de monitoreo sismológico del volcán Villarrica, durante el Primer semestre de 1998 (Unpublished), *Servicio Nacional de Geología y Minería,* 13 p.

GOES radiance data has been providing a thermal time series for Villarrica at a resolution of ~33 data points *per* day since 9 February 1999. Thermal images acquired by the NOAA geostationary GOES 8 and GOES 10 satellites are automatically processed by the Hawaii Institute of Geophysics and Planetology at the University of Hawaii. This system provides a space-based volcano monitoring capability to support hot spot observations (Harris *et al.*, 2002a, 2002b). Data are processed on reception and displayed automatically in near real-time (20-35 minute data acquisition to display lag time) via the web (http://goes.higp.hawaii.edu/). An automated e-mail notice containing links to the image of interest is triggered by thermal events such as the eruption of new lava flows and sent out to the relevant monitoring bodies. The GOES hot spot monitoring capability has provided reliable real-time alerts to several major effusive events (*e.g.*, Harris *et al.*, 2000, 2001; GVN 2000a) and is now being tested at volcanoes which generate less intense hot spots. The subtle thermal anomaly due to fumarolic activity at Lascar (S. Matthews, oral communication, 2000), for example, has shown that GOES can provide reliable, ancillary information for low magnitude thermal features if ground-based data are available to guide interpretations (Harris *et al.*, 2002b).

The GOES hot spot tool thus provides an important additional monitoring capability that is currently being tested at Villarrica. Remote sensing of active volcanoes also has major advantages where accessibility is problematic (*e.g.,* Roach *et al.*, 2001). Validation and refinement of the GOES data is being, and must be, carried out to improve viability of this tool as a secondary real-time monitoring method. This paper reports on preliminary findings, highlighting successful aspects and noting a few method- and location-based limitations. It addresses the role that satellite remote sensing can play in real-time volcano monitoring, and provides an example of the experience of a small volcano observatory utilising satellite-based monitoring tools available in near-real-time through the internet.

VOLCANIC ACTIVITY

STROMBOLIAN ACTIVITY

Strombolian activity is characteristic of many basaltic volcanic systems (*e.g.,* Masaya, Nicaragua; Villarrica, Chile; Stromboli, Italy, Blackburn *et al.*, 1976). Episodic, explosive gas emissions occur when large gas pockets, rise up the conduit and rupture at the magma column surface. One model for strombolian activity requires that some of the ascending gas remained trapped as foam at some location in the conduit system. On reaching a critical volume, collapse of the foam layer causes a gas slug to rise up the conduit to generate a strombolian explosion (Jaupart and Vergniolle 1988, 1989; Vergniolle, 1996). Such strombolian systems are usually associated with convecting open systems and shallow level reservoirs (Vergniolle, 1996; Harris and Stevenson, 1997; Ripepe *et al.*, 2002) and often display some form of cyclic activity.

VILLARRICA LAVA LAKE

Since the last important eruption of Villarrica in 1984-1985, the magma column surface has remained at a high level within the volcano (varying between 90-180 m below the crater rim, Fig. 1a). Regular, small-scale, strombolian explosions occur as the quasi-continuous flow of large gas bubbles reaches the surface. The strombolian activity comprises well collimated jets of gas, laden with spatter, which burst in short eruptions lasting approximately 30 s and which occur at a typical rate of 10 events per hour (Calder *et al.*, 2000; Fuentealba *et al.*, 2000). The lava lake (30-60 m diameter) is commonly heavily crusted over with the lava only visible through a ~40 m^2 opening (Fig. 1b). Occasionally, when sections of the crust have been destroyed, the free surface of the lava lake is exposed to a

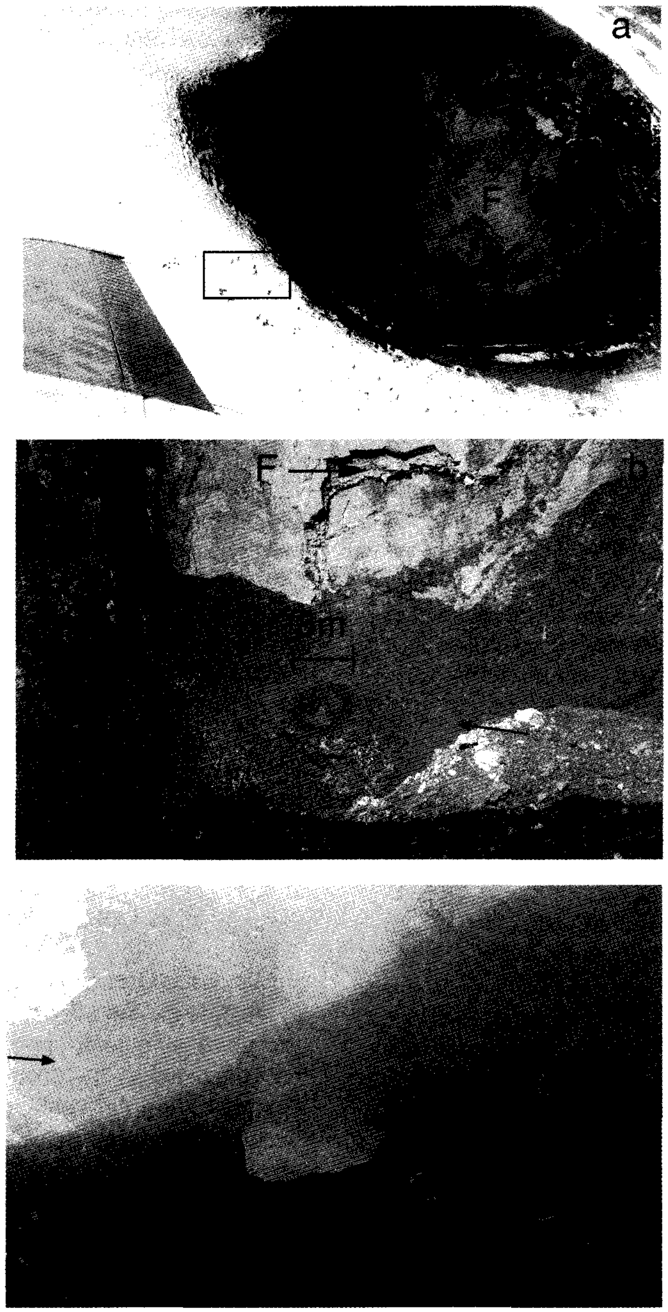

FIG. 1. **a-** summit of Villarrica volcano on November , 1999 (Julian day 315), showing crater rim (inner rim ~ 250 m diameter, inset box highlights people for scale) and crater floor ~160 m below. A small conical 'hornito' can be seen on the crater floor through which periodic bursts of spatter ascended. Photograph by H. Moreno; **b-** crater floor on January 22, 2000, showing lava lake covered with a well developed crust and a small (4-8 m diameter) central opening. Conspicuous fractures in the southern crater wall, marked 'F' on the photographs can be identified in both a) and b) for scale comparison; **c-** Crater floor on March 31, 2000, showing partially destroyed crust with vigorously convecting lava lake below. The opening in the crust has a diameter of ~ 30 m and the lava free surface is estimated to be 20-40 m below the crust shelf. Photographs b) and c) were taken from the same position at the same magnification and thus scales are directly comparable. The crater floor margins, indicated by the pairs of arrows in each photograph, are ~ 100 m diameter.

greater degree (*e.g.*, February 14, 2000; 31 March 2000 Fig. 1c). Thus, activity, as visible from the crater rim, is largely dependant on the degree to which the lava lake is encrusted. During periods when the lava lake is largely open, activity alternates between periods of fairly vigorous fountaining to heights of ~30 m, and periods characterised by more gentle surface 'roll-over' (convection) with occasional brief moments (5-10 s) of no activity, where the lake begins to crust over almost immediately. Occasional larger explosions send spatter ~60 m above the lake level. More commonly however, the lava lake has a well-formed crust (estimated to be 4-10 metres thick) with only a small central opening (Fig. 1b). The opening is characteristically round during periods of elevated activity (*e.g.*, 11 November 1999; 6-8 m diameter) and may even be built into a small spatter cone (*e.g.*, September 1996). When the opening is constricted in this manner, occasional explosions within the underlying lava lake produce narrow jets rising through the opening with spatter reaching > 200 m in height above the crust surface.

VILLARRICA SEISMIC ACTIVITY

Background seismic activity is well established (Fuentealba and Peña, 1998; Fuentealba *et al.*, 2000; Ortiz *et al.*, 2003), and is dominated by low frequency events which are associated with the continuous, open system degassing of the volcano. The seismic signals have been categorised into the following types: tremor, strombolian explosion signals, discrete larger explosions, and long-period, hybrid and volcano-tectonic earthquakes (G. Fuentealba and P. Peña, 1998[1]; Fuentealba *et al.*, 2000; Ortiz *et al.*, 2003). Tremor commonly has a frequency between 0.9 and 3.5 Hz with a dominant peak at 1.4 Hz, and is continuous for extended periods (up to months), but can exhibit frequent changes in amplitude and frequency content (Fig. 2a). Amplitude variations and frequency shifts have been attributed to variations in volcanic activity (Ortiz *et al.*, 2003) but also, on occasion and especially during the winter months, can be generated by climatic noise. Strombolian explosion signals or 'gas piston events' (*e.g.*, Chouet *et al.*, 1974; Blackburn *et al.*, 1976) have durations of less than a minute and when they exist, they occur continuously for periods of days to weeks at a characteristic rate of 10 events/hour (Fig. 2b). Seismic signals of these explosions, collected from the most proximal seismometer (VNV), correlate with pulse-like releases of gas from the vent, and the source region of these signals is inferred to be shallow (Fuentealba *et al.*, 2000). In the period leading up to the August-December 1999 crisis the activity was characterised by tremor and strombolian explosion signals were absent. Discrete larger explosions comprise relatively infrequent events that are considered significantly different from the normal strombolian activity. These signals occur as isolated events and generally have high frequency contents and sudden onsets. High amplitude tremor, if occurring concurrently, can mask these events so some such explosions are only know to have occurred through direct observations or evidence of fresh deposits. The authors consider these events important markers in defining the activity cycles of the volcano. Hybrid and volcano-tectonic earthquakes are rarer, and although event location with any accuracy is beyond the limitations of the network, their frequency of occurrence is considered important from a forecasting perspective. Volcano-tectonic events are generally uncommon, occurring only 1-3 times per month in recent years (Fuentealba *et al.*, 2000). Similar events have been located in a confined zone directly under the volcano using broad band seismometers (Bataille, personal communications, 2000), and are inferred by these authors to be associated with circulation of magma and/or pressure increases within the deeper structure. Long-period and hybrid earthquakes usually occur < 10 times per month with a recent maximum of 17 events in November 1997 (long-period earthquakes) and 12 events in April 2000 (hybrid earthquakes). Routinely, the level of seismic activity is measured in terms of real-time seismic amplitude measurements (RSAM) (Endo and Murray, 1991) and varies between 8-20 RSAM units.

AUGUST-DECEMBER 1999 CRISIS

On August 23, 1999, there was a significant increase in seismic activity (Fuentealba *et al.*, 2000). Tremor increased in amplitude and periods, 3-48 hour long, of high amplitude tremor alternated with periods, 1-8 hours long, of low amplitude tremor. A high amplitude long-period event occurred on 15 September and between 24-25 September a

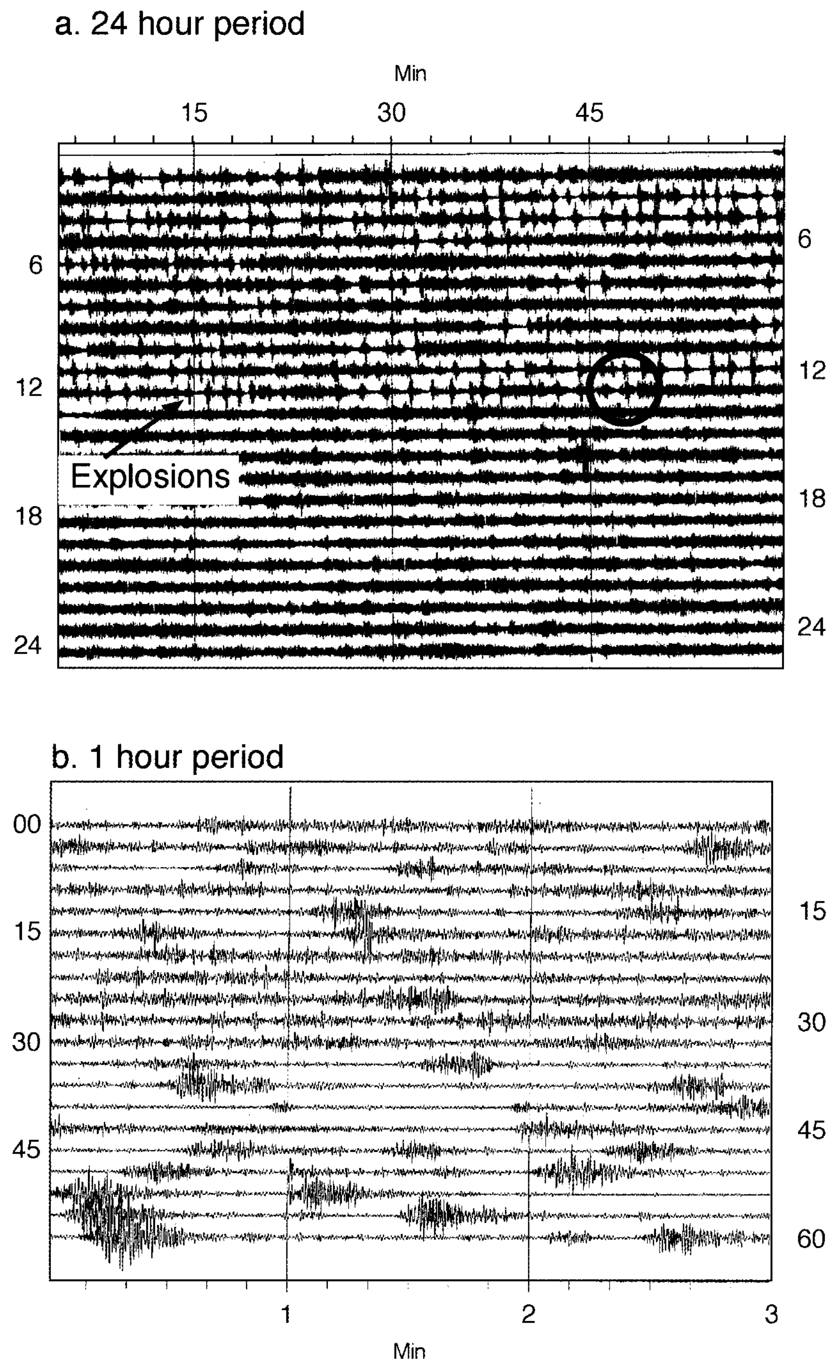

FIG. 2. Seismic signals for March 5, 2000 from VNV short-period station 4 km from the crater; **a-** strombolian explosion signals or 'gas piston' events (marked 'Explosions' on figure) interspersed with periods of tremor. The figure displays data for a 24-hour period with each line representing one hour. Ticks on the horizontal axis are 3 min apart, note the first minute of each line has been cropped. After the last strombolian explosion at 0903 LT (circled on figure), explosions ceased and continuous tremor occurred for the following 20 hours; **b-** strombolian explosion signals or gas piston events between 0700-0800 local time on 5 March 2000 (each line represents 3 minutes).

significant ash and scoria fall occurred on the ESE flanks of the volcano with the deposits clearly extending up to 5 km from the vent (Figs. 3, 4). A further increase in seismic activity occurred on October 3, with new ballistics (20-60 cm diameter) observed on October 4, on the NNE upper flanks of the volcano, ~200 m from the crater rim. No visual observations of these explosions were possible due to the persistent low cloud cover during that period. The OVDAS alert level for Villarrica, based on the 'Sistema Semáforo' (De la Cruz Reyna, 1996), was raised to Green-level 2 on October 11 (GVN October 1999). Between August 23 and November 20, when activity began to subside, at least 4 explosions occurred destroying the lava lake crust and emitting bombs outside the confines of the crater (Fig. 4). These explosive events are substantially more violent than the normal strombolian activity that occurs during 'background-level' activity as deposits from the latter are generally confined to the crater floor. During the period August-December 1999, seismic RSAM levels reached up to 40 units with the highest RSAM peaks corresponding to periods when the tremor had an increased high frequency component. Elevated RSAM levels were associated with at least three occasions when the lava lake crust was known to have been destroyed ('CD' in Fig. 4). From late December 1999 to January 2000, the style of seismic activity gradually changed. Tremor amplitude decreased, and seismicity became increasingly characterised by discrete small amplitude 'gas piston' events separated by periods of low amplitude tremor. These signals evolved gradually into the larger gas piston or strombolian explosions seen in figure 2b.

PRELIMINARY GOES RESULTS

The GOES target site for Villarrica, is 500 x 500 pixels (where pixels are about 4 km across in the thermal infrared) and also contains the sub-sites of Concepción (for forest fire generated hotspots), and Llaima, Callaqui, Copahue and Planchón volcanoes. The Villarrica sub-site from which the quantitative thermal data are automatically extracted has a size of 10 x 10 pixels. GOES radiance data has been acquired for Villarrica at a resolution of ~33 data points *per* day since 9 February 1999, where the data set is up-dated as each new image is acquired. The images are based on data collected in three wavebands (Harris *et al.*, 2002a). Band 1 data are collected in the visible portion of the spectrum, at a waveband of 0.55 to 0.75 μm, and then converted to albedo (a measure of reflectance). Band 2 data are collected in the mid-infrared portion of the spectrum, at a waveband of 3.80 to 4.00 μm. Band 4 data are collected in the thermal infrared portion of the spectrum, at a waveband of 10.00 to 10.20 μm.

As described in detail in Harris *et al.* (2002a), various images are posted on production, of which the most straightforward to interpret is the 'rgb' colour image. This colour scheme results in upper level clouds appearing bluish, lower level clouds appearing greenish and land appearing various shades of red depending on temperature. Any visible lava or fire hotspots will be bright shades of red and yellow. The site also illustrates graphically the time series (in Julian days) of radiance, albedo and alerts means data (a probability-based alerts threshold) and projects any hot spots located by the software onto a map.

The authors have carried out a pilot study to determine whether GOES radiance data can provide reliable data for the current style of activity at the Villarrica lava lake. Analysis of the February-December 1999 thermal time series revealed four different radiance periods (Fig. 5). These are: (1) relatively high-to-moderate, but declining levels between 11 February (Julian day 42) and 18 April (Julian day 108) followed by (2) a sharp drop to lower but moderately stable levels until 12 August (Julian day 224). This is followed by period (3) between 14 August (Julian day 226) and 22 October (Julian day 295) when the data were processed in temperature rather than radiance format, so are not currently comparable in this plot, but showed correlation with RSAM data. The year ends with (4) a steady increase to higher radiance levels once more. The use of residual radiances is intended to remove diurnal and seasonal heating effects from the thermal signal and isolate the volcanic signal

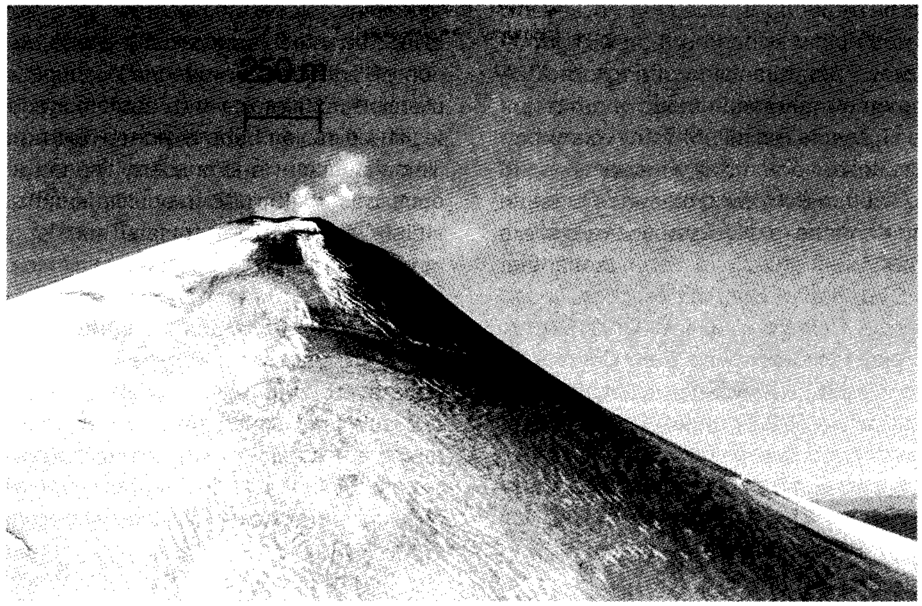

FIG. 3. Photograph of scoriaceous lapilli and bomb deposits on the ESE flanks of Villarrica volcano produced by an explosion that occurred sometime between September 24 and 25, 1999 (Julian day 267-268). The deposits on the south east flanks could be easily traced over the fresh snow to extend ~5 km from the vent (photograph by H. Moreno).

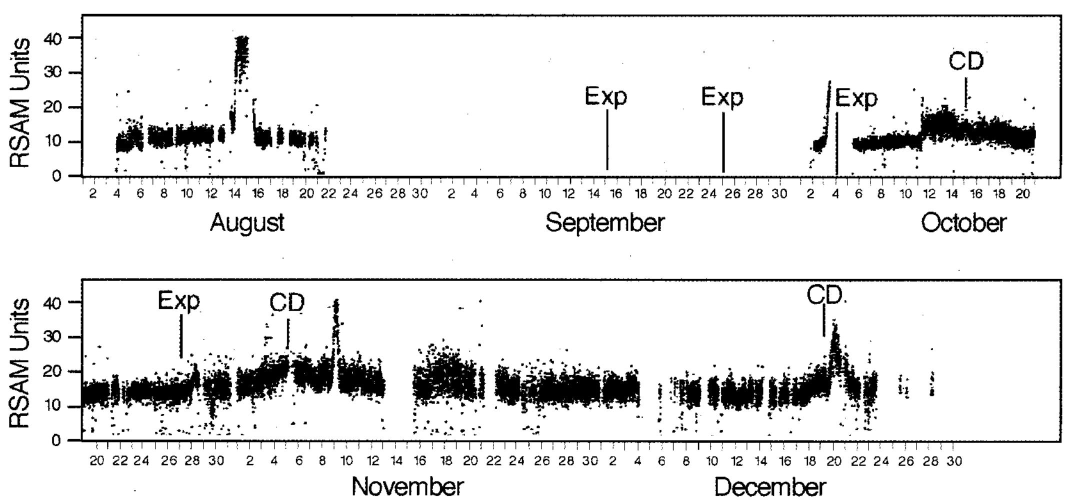

FIG. 4. Real time seismic amplitude measurements (RSAM) from VNV seismic station located 4 km from the crater for the period August 1 (Julian day 213) to December 31 (Julian day 365) 1999. Gaps in the data set represent periods where seismic data from this seismometer was unavailable. Explosions (Exp) and lava lake crust destruction events (CD), inferred from combined seismic data and observations of the crater or the appearance of fresh deposits, are indicated on the time line.

(Harris *et al.*, 1997; Harris and Thornber, 1999). The trends in figure 5 however, may indicate the influence of a seasonal effect that has not been completely removed. Further investigation will attempt to constrain this effect by comparison of the data with that of a neighbouring non-volcanic area.

Period (3) ties in with dates of heightened activity between August 14 (Julian Day 226) and September 13 (Julian Day 256) 1999. These data were compared with seismic RSAM data and ground based observations in order to better understand the radiance variations. Before and after the high activity period, no correlation was found between the GOES and RSAM data (Fig. 6a-b). During August and September, however, peaks and troughs in the two data sets are reasonably correlated (Fig. 7a), where lack of correlation prior to 29 August can be explained by persistent cloud cover masking the GOES signal. Lower radiance levels occurred after the 15 September (not shown). Further correlation between the GOES and RSAM data during October 6-16 (Fig. 7b), just precedes a second cycle of activity between October 24 and November 11, before the two signals become decoupled in December (Fig. 6a). Night-time observations of glowing above the volcano depend on atmospheric conditions as well as height of lava column within the crater, exposed lake surface and height of spatter fountains. Strong glowing episodes reported on September 25, October 13 and 26, and November 5 do, however, coincide with periods when the lava lake crust was inferred to have been partially destroyed. This provides additional evidence that elevated GOES radiances around these times and variations in seismic tremor have a dominantly volcanic source (*e.g.,* October 13 Fig. 7b).

LAVA LAKE DYNAMICS

Between August and December 1999, the lava lake crust was destroyed and then regenerated on at least 7 occasions. Destruction of the crust can occur by rupturing during the larger explosions but also by sequential inward collapse along fractures formed by the continuous pounding during lesser activity and collapse generated by instability when the lava lake height subsides. Crust regeneration is thought to occur rapidly, with the lake becoming covered in the order of <48 hours (observed from successive visits). In comparison, exposed lava flow surfaces in Hawaiian basalts exhibit temperature declines of 30°C *per* second in the first 5-10 seconds following exposure. Over the first minute temperatures decrease from molten down to about 550°C but then cooling begins to tail off, following an exponential decline (Hon *et al.*, 1994). Given the observations at the Villarrica lava lake, we would anticipate that widespread core exposure after a crust destroying event would lead to radiance spikes with decaying tails. These spikes, in theory, would last as long as the crust was disrupted and the tail would develop once crust formation and thickening began to force a cooling trend. Crust destroying events are known to have occurred on 14 February and 09:10 LT on 5 March 2000, and coincided with clear weather conditions and good visual observations. Preliminary analysis of the radiance for these dates suggests that neither of these events left a resolvable signal or radiance spike that can be attributed to the short-term core exposure. This may be due to the thermal event being spatially too small, or temporally too short, to be evident in the GOES data.

DEVELOPMENT OF THE GOES TOOL

The GOES hotspot monitoring method currently has several limitations in its use at Villarrica volcano:

- Southern Chile (~ 39° S) has a relatively wet climate and persistent cloud cover for periods of days to weeks during the winter months which means radiance data cannot provide a continuous data set.
- The Villarrica lava lake provides a heat source that has a relatively small dimension.the authors calculate that the 40 m^2 vent in a 4 km pixel will cause a 0.2 or 1.4°C anomaly if it is at 500 or 1000°C, respectively. Additionally, for such subtle anomalies, the influence of ambient variations, clouds and daytime solar reflection may also generate false trends that will mask volcanic trends. These need to be efficiently filtered from the data set.
- The relatively narrow, deep, crater poses a morphological constraint. GOES views Villarrica volcano at an angle of ~44° producing a shadow zone on the crater floor the coverage of which varies with fluctuations in crater floor height. The central part of the crater floor is therefore only visible by the satellite when the crater floor is < 90 m below the

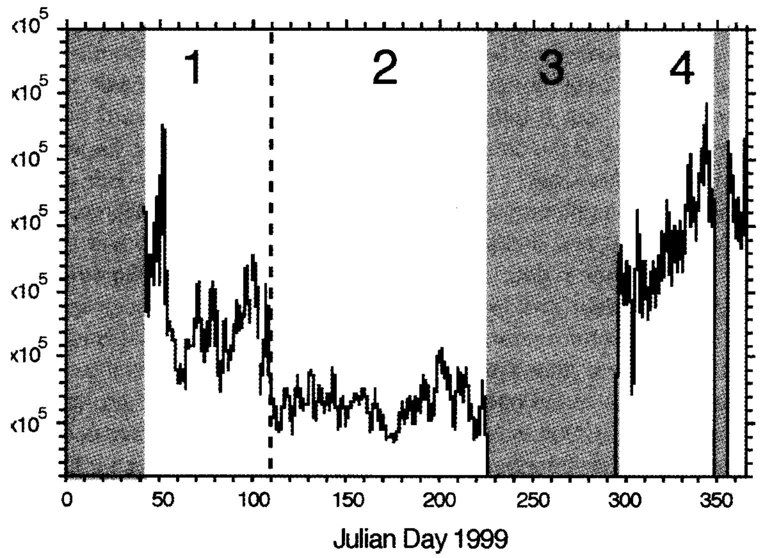

FIG. 5. Residual GOES band 2 radiance (peak pixel minus background) from the 10 x 10 pixel Villarrica analysis zone. All currently available radiance data for 1999 are plotted with a 1-day-long running mean applied. Grey boxes indicate periods when radiance data are not currently available. Four distinct periods are identified in the data, 1-4, these are referred to in the text.

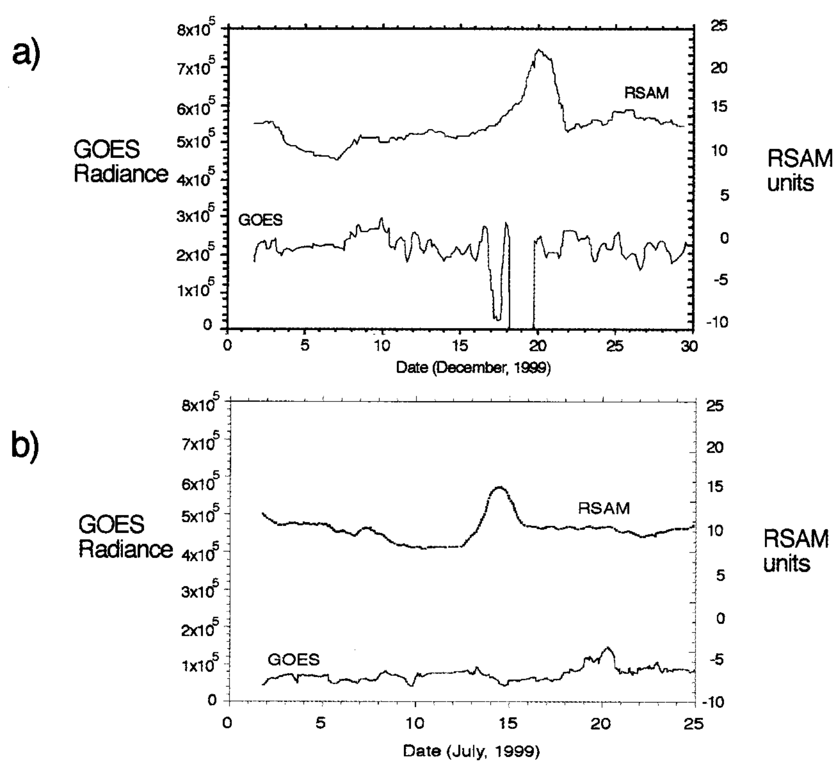

FIG. 6. Smoothed residual GOES band 2 radiance and RSAM data for two periods of relatively low activity; **a-** (December 1-31, Julian day 335-365) and **b-** (July 1-25, Julian day 182-206) at the Villarrica lava lake during 1999.

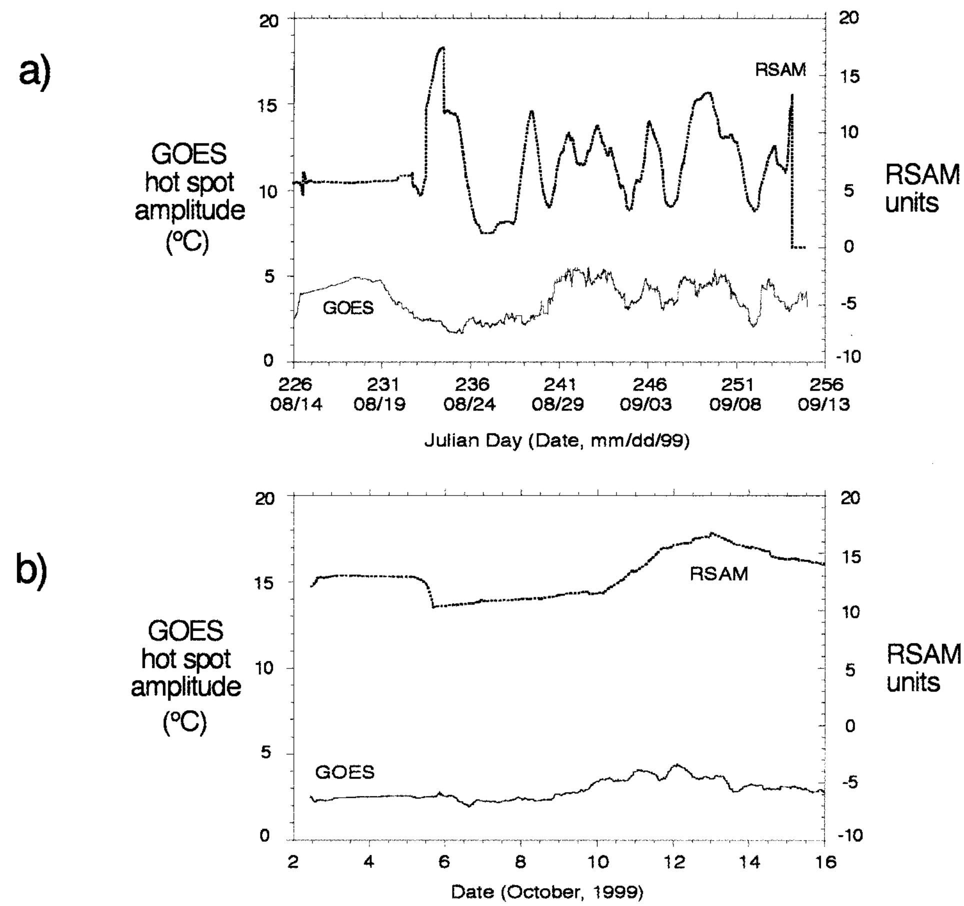

FIG. 7. Smoothed GOES hot spot amplitude (peak pixel minus background converted to centigrade) and RSAM data for two periods characterised by relatively high activity; **a-** (August 14-September 13, Julian day 226-256) and **b-** (October 2-16, Julian day 275-289) at the Villarrica lava lake during 1999. The small vertical arrow indicates a time when the lava lake was reported to be more active, and was followed by a crust destruction event (Fig. 4).

crater rim. During the period under study it is estimated that the central part of the crater floor was therefore only visible by the satellite for a total of a few weeks.

For certain periods, seismic data (including RSAM data) are effected by climatic noise, such as wind and rain. These periods are usually, but not always straightforward to identify. This source of uncertainty in the seismic data constitutes a further limitation in our ability to constrain the origins of thermal variations. However, for periods where good correlations with radiance data exist it is unclear how common fluctuations can be anything but volcanically derived.

Further analysis is required to determine the correlation between the GOES signal and that due to external ambient (cloud, diurnal, seasonal induced variation) and that due to internal volcanic influences (variations in the size and temperature of the lava lake). Currently, the subtle variations in activity exhibited by the lava lake, cannot confidently be tracked as it may simply be too small a feature to be resolvable. Should a major effusive event begin, however, then our experiences at other volcanoes (*e.g.*, Pacaya (GVN, 2000a); Cerro Negro (GVN, 2000b; Harris *et al.*, 2002a) show that unambiguous hot spots will occur and e-mail notification will be tripped within an hour of event onset.

Development of ground-based thermal monitoring instrumentation, examination of high spatial resolution satellite data (*e.g.*, ETM+ images) and refinement of current GOES data processing and analysis techniques are required in order to confidently define radiance trends at Villarrica volcano. If GOES proves to be a viable secondary data source, then thermal and seismic data sets may be used together to assess and define activity cycles of the lava lake and, as has been done at other volcanoes (Harris *et al.*, 2001), constrain variations in mass flux.

CONCLUSIONS

This work attempts to identify how the remotely sensed hot spot data can be most usefully incorporated into real-time, ground-based monitoring schemes. GOES alerts are known to be effective for large effusive eruptions (*e.g.*, GVN 2000a; 2000b) but it is becoming increasingly apparent that, with careful examination, detailed information can also be extracted from GOES data to define subtle variations at less intense hot spots.

Villarrica volcano entered a phase of increased activity in August 1999, which lasted until mid-November 1999. Variations in observed and seismic activity appear to have been reflected, when climatic conditions allowed, in GOES radiance data (Fig. 7a). For this period, ground based observations supported GOES-derived inferences. The style of seismic activity that began to occur in late November 1999 probably reflected a change in degassing style to that of a more periodic release of larger gas slugs. Radiance data did show increased values during November and December 1999 although seasonal variations cannot yet be fully excluded.

Activity cycles at Villarrica need to be defined. Change in magma column height occurs on short-period time scales. An efficiently functioning ground or space based thermal monitoring system may be able to track these variations, and also provide notice of crust destroying events such as explosions, which are not always visually observed nor evident from the unfiltered seismic data.

GOES has the potential to provide an important complimentary monitoring method for this dynamic system where volcano alert levels currently have to be determined largely on the basis of limited seismic data. Seismic activity at Villarrica however, is dominated by signals inferred to be produced at a shallow level and associated with degassing and lava lake dynamics. Thus, monitoring of parameters such as heat flux, whose variation may, in part, reflect deeper level processes may be important to our improved understanding of the system.

The University of Hawaii's Hotspot package displayed via internet currently has some limitations in it use at Villarrica volcano, largely due to the small heat source and morphological constraints of the narrow crater. During the 1999 period of increased activity, when the magma column was at a relatively high level within the crater, correlations between thermal and seismic data are considered to be volcanically derived. Further investigations, such as using ground-based thermal studies, are now needed to better constrain these relationships.

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