Contrasting styles of volcanic activity as observed by remote sensing: The cases of Lascar, Llaima and Villarrica volcanoes, Chile

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INTRODUCTION

The most active volcano in Central Volcanic Zone (CVZ) is **Lascar Volcano** (23°22'S–67°44'W) (Francis & Rothery, 1987), a composite volcano formed by andesitic and dacitic lava and pyroclastic flows, and occasional basaltic andesites lava flows (Gardeweg *et al.*, 1998). Its historic activity have been explosive principally (vulcanian and subplinian eruptions) and is related to viscous lava dome growth and collapse cycles (Matthews *et al.*, 1997). The largest historical eruption took place in April 1993 (subplinian eruption), which produced eruptive column that extended up to 20 km and pyroclastic flows that extended up to 7.5 km of the summit (Gardeweg & Medina, 1994).

The more active volcanoes in Southern Volcanic Zone (SVZ) are Villarrica and Llaima volcanoes (Moreno & Fuentealba, 1994). **Villarrica Volcano** (39°25'S–71°57'W) is a stratocone built over two calderas, with more than 30 adventitious eruptive centers (Moreno, 1998), formed by basaltic and andesitic lava and pyroclastic flows (González–Ferrán, 1995). In its summit crater there is a small and continuously active lava lake (Ortiz *et al.*, 2003; Calder *et al*, 2004). Since 1558, 59 important eruptions have been reported (Petit–Breuilh, 1994), with hawaiian, phreatomagmatic, vulcanian and strombolian eruptions (Moreno, 1998). Villarrica Volcano eruptions have emitted lava flows as long as 18 km (Ortiz *et al.*, 2003) and important lahars (> 20 km) have been formed by glaciers melting (González–Ferrán, 1995). One of most important historical eruptions occurred in 1971 (González–Ferrán, 1995). **Llaima Volcano** (38°42'S–71°44'W) is a complex composite–shield volcano, with a buried caldera and 40 parasitic scoria cones, formed by basaltic and andesitic lava flows, andesitic pyroclastic flows and, dacitic surge and pumice fall deposits (Naranjo & Moreno, 1991). Since 1640, about 47 eruptions have been reported, with phreatomagmatic, strombolian and subplinian eruptions (Naranjo & Moreno, 1991; González–Ferrán, 1995). At least, 10 eruptions have emitted voluminous lava flows and pyroclasts, also lahars have been formed by glaciers melting (Moreno & Fuentealba, 1994), being the 1957 eruption the biggest historic eruption (Naranjo & Moreno, 1991).

In this work, are characterized the contrasting styles of volcanic activity of these three volcanoes, correlated the volcanic activity with satellite responses and determined the causes of thermal anomaly for each one, using radiance data from Landsat TM and ETM+ images, between December 1984 and December 2001.

CORRELATIONS BETWEEN RADIANCE DATA AND VOLCANIC ACTIVITY

In the case of **Lascar Volcano**, Matthews *et al.* (1997) characterized its volcanic activity as cycles of lava dome growth, collapse and completed by an explosive event, determining four cycles. The cycle 1 begin in

December 1984, although dome growth do not observed, and finalized with an explosive event in September 1986. Radiance data for this period show high values for December 1984 and later on radiance value descending progressively until 0 (zero) for band 5 and 1 for band 7 in August 1986 (the lowest radiance value in data set of Lascar Volcano), previously an explosive event (Figure 1a). The progressive descent of radiance signal has been related to dome collapse. The cycle 2 (February 1989–February 1990) and cycle 3 (February 1992–April 1993), where dome growth and collapse were observed, they coincide with radiance data behavior (Figure 1a). The radiance data for cycle 2 (November 1986–March 1990) begin with a low values in November 1986 and after a consistent ascent until October 1989, related to dome ascent. Between October–December 1989 there are nearly constant values with little variations, but after December 1989 a dramatic descent occur, reaching lower values in March 1990, related to dome collapse and explosive event in February 1990. In cycle 3 (March 1990–February 1993), after low radiance values in March 1990, the radiance line begin with a consistent and rapid ascent until April 1992 (the highest radiance value in data sets), related to dome growth, again. After, a dramatic descent occur reaching lower values in February 1993, directly related to dome collapse and explosive event in April 1993. There are no radiance data for correlations with cycle 4. After December 1993, there are no cycles defined, because the activity of Lascar Volcano does not show a clear pattern of behavior. This can be confirmed with Landsat ETM+ radiance data from February 2000–October 2001 period (Figure 1b), where are showed a simple but opposite trending lines for bands 5 and 7 and do not represent clearly a defined radiance cycle.

The last big eruption of **Villarrica Volcano** was between October 1984–January 1985, when lava flows were emitted and lahars were generated (SEAN 9:11; SEAN 10:01). After this event, only a minor activity has occurred. Between 1986–1990 period there are no reports of explosions or important activity in Villarrica Volcano. This period is showed in Figure 1c, where thermal radiance of bands 4, 5 and 7 show a important descent, specially between December 1986 (the highest radiance value in data sets)–February 1987. In March 1990, thermal radiance show very low values, reached zero in band 4. This behavior probably reflects the cooling of system after October 1984–January 1985 activity, and consequently, a descending activity in the crater lava lake. The February–December 2001 period (Figure 1d), the radiance data show a upward trending between February–November and downward trending between November–December. This behavior has direct relation with activity of volcano. GVN 27:02 report, indicate that between January–February incandescent lava was observed in the crater and explosions occurred, accompanied by degassing sounds. However, more intense activity occurred between September 2001–January 2002, with incandescent lava in the crater and explosions occurred every 1 to 10 minutes. GVN 27:02 report, also show de Monthly Incandescent Index (MII) quantitative estimate of incandescence carried out during the night. The MII show low values for February and high values for November and December, although December value is lower than November. The thermal radiance behavior for this period is very similar to activity reports, where low values for February can be related to low activity in crater lava lake and low values of MII, and high values of radiance for November and December can be related to explosions, lava lake activity and high values of MII. In fact, the lower values for MII and thermal radiance correspond to February data, followed by December data and higher values for November data.

Important activity in **Llaima Volcano** between 1986–1990 not occurred, only a fumarolic activity observed in 1988 and 1990, and small explosions in February 1990 (SEAN 13:04; GVN 15:01 and 15:03). The most important activity near to this period was in April 1984, when dense columns of dark ash were emitted. Thermal

radiance data of December 1986–March 1990 show similar behavior of Villarrica Volcano for same period, where is showed a simple pattern of radiance behavior (Figure 1e), showing the highest value in December 1986 and rapid descent during December 1986–February 1987 period. Finally, in March 1990 the radiance reaching the lowest values, being near zero for bands 5 and 7. The cause of behavior Llaima radiance data be the same of Villarrica Volcano, descent of thermal emission after the eruption period, April 1984 activity for Llaima Volcano. Radiance data from February and November 2001 (not showed) gave zero values for bands 5 and 7, and it coincides with absent of activity.

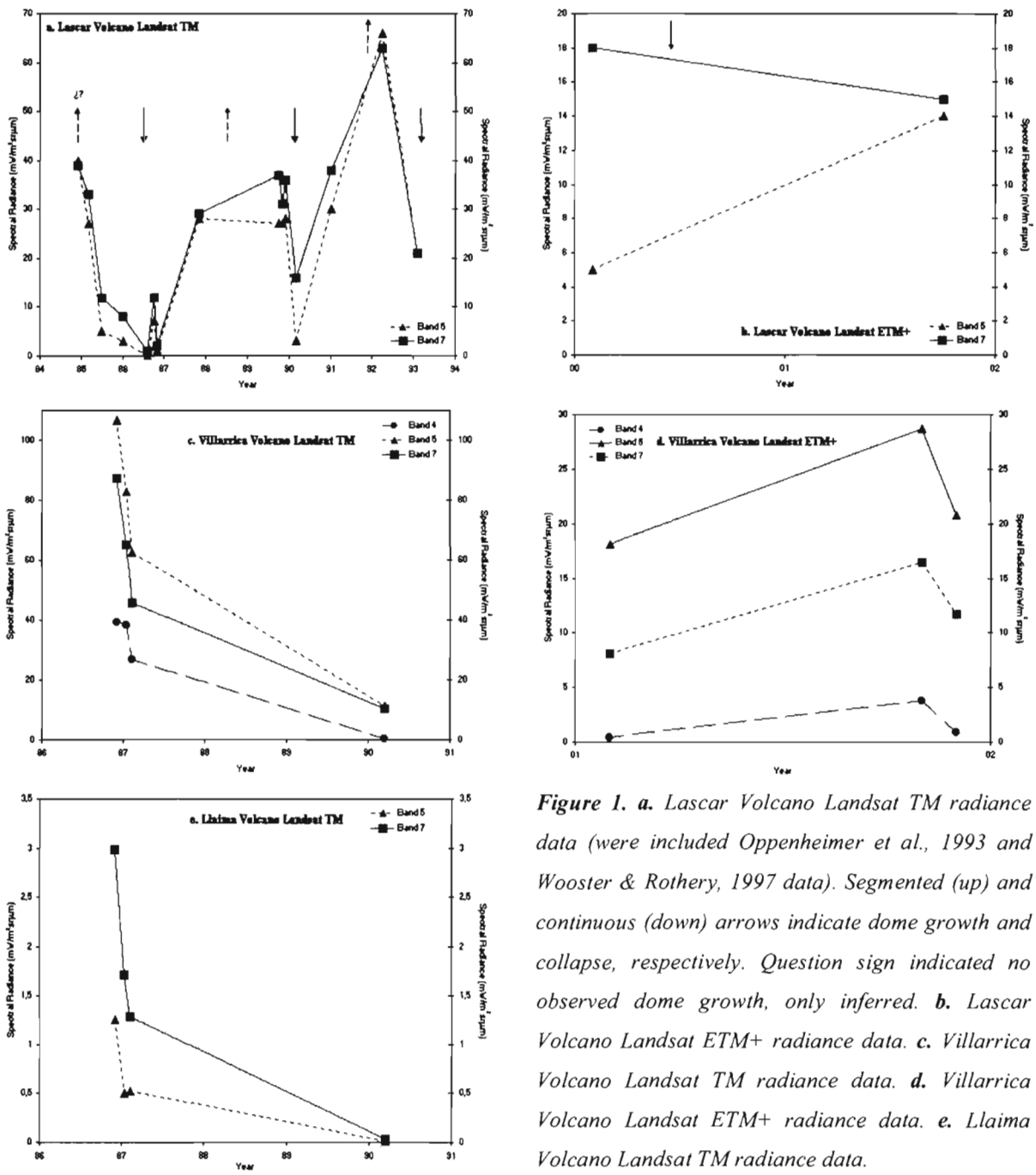

Figure 1. a. *Lascar Volcano Landsat TM radiance data (were included Oppenheimer et al., 1993 and Wooster & Rothery, 1997 data). Segmented (up) and continuous (down) arrows indicate dome growth and collapse, respectively. Question sign indicated no observed dome growth, only inferred.* ***b.*** *Lascar Volcano Landsat ETM+ radiance data.* ***c.*** *Villarrica Volcano Landsat TM radiance data.* ***d.*** *Villarrica Volcano Landsat ETM+ radiance data.* ***e.*** *Llaima Volcano Landsat TM radiance data.*

CONCLUSIONS

The causes and behavior of thermal anomaly, and quantity of energy (radiance) emitted by the volcano are directly related to style of activity, type of magma and area occupied by the body that generate the anomaly.

The thermal anomaly in **Lascar Volcano** is caused by extrusion and collapse of dacitic dome in its central active crater. Its thermal anomaly is captured only by bands 5 and 7, because the temperature and energy emitted by dacitic lava dome is lower than andesitic and basaltic magmas, which emitted more energy and have higher temperatures. Finally, the quantity of radiance emitted by lava dome is increased by area of lava dome, being the area of this body greater than the bodies that generate the anomaly in Villarrica and Llaima volcanoes.

In **Villarrica Volcano**, the thermal anomaly is caused by activity of lava lake in its crater. Its thermal anomaly is captured by bands 4, 5 and 7, because the temperature and energy emitted by basaltic magma in the lava lake is high. Perhaps that the area of lava lake are not greater than lava domo in Lascar Volcano, the lava lake emit very high levels of radiance, reaching temperatures sufficiently high for that band 4 capture thermal radiance from volcanic activity.

In **Llaima Volcano**, the thermal anomaly is caused by activity of basaltic magma in its conduit. Its thermal anomaly is captured only by bands 5 and 7. Perhaps that the temperature of this magma is high, the area of vent is small, and is probably that the magma activity in its conduit is low and not continuous.

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