EMSEV[1]-PHIVOLCS[2] cooperation

1: http://www.emsev-iugg.org/emsev/
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Report - August 16, 2010

Summary on Electromagnetic and other geophysical data recorded on Taal volcano (Philippines) during March to July seismo-volcanic crisis

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1. Preliminary remarks

The following report is based on data recorded at the two telemetered multi-parameter stations, MCL and DAK, located in and outside the crater on Taal volcano (see report 1 on June 11, 2010).
These data are transferred every day to the PHIVOLCS server in Manila and the VEML server (http://virtual-electromagnetic-laboratory.com/). As well, the total magnetic field were recorded on-site on self-recording data loggers until June 2010.

2. Details of the two multi-parameter monitoring stations

a. Real time monitoring network

The real-time monitoring network consists of two continuous self-recording stations, DAK and MCL. Eight channels of data are recorded at 0.5 Hz sampling at each station and are radio-transmitted every 2 seconds to the local Buco observatory where a PC computer collects the data. Twice a day, data from the previous day are sent by internet to PHIVOLCS headquarter in Manila, and to the VEML remote server located in France for further analyses. In addition, tilt records are also sent to the USGS in Menlo Park, California.

In March 2010, a borehole tiltmeter provided by the USGS was installed at DAK station by Malcolm Johnston. Data are recorded on channels 1 and 2 of DAK telemeter station.

The configuration of the two multi-parameter stations is shown in figure 1.

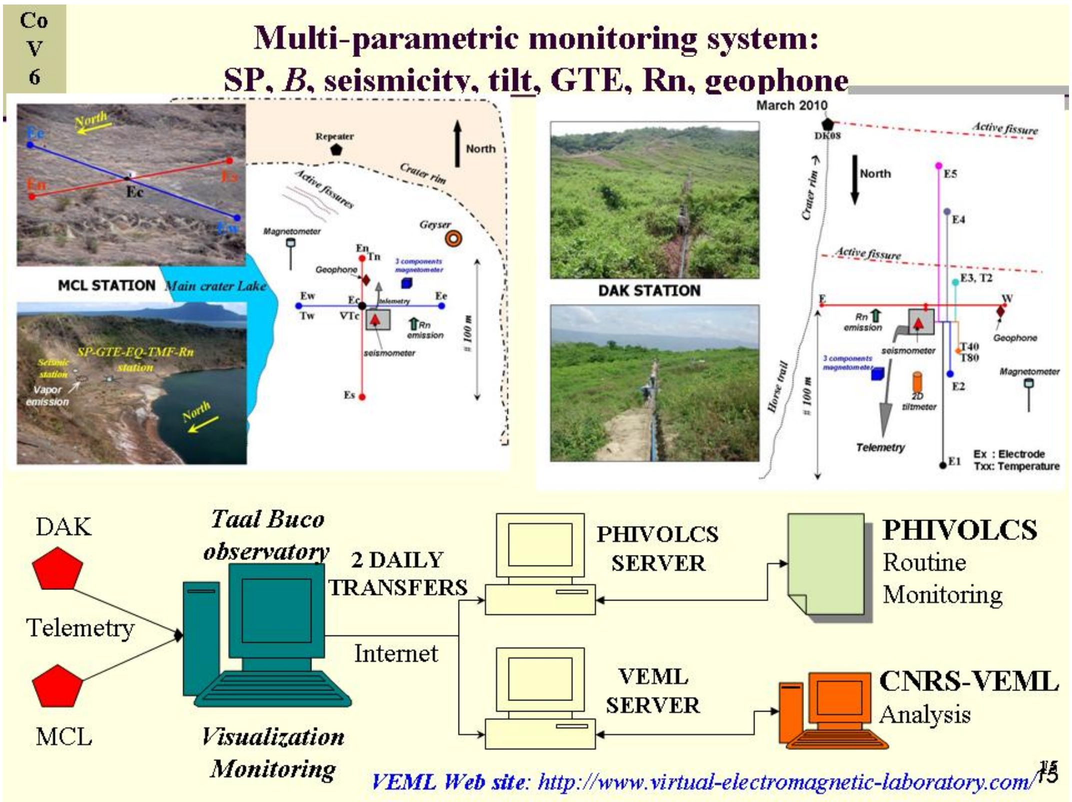


Figure 1. Upper part: Schematic representation of the two stations.
Lower part: Telemetry system and Internet link.

The parameters recorded at the two telemeter stations are the following (June 2010):

MCL station

Channel	1	2	3	4	5	6	7	8
Sensor	**N-S**	**D**	**E-W**	**H**	**Tpe N**	**Tpe W**	**Tpe C80**	**Tpe C40**

DAK station

Channel	1	2	3	4	5	6	7	8
Sensor	**TiltX**	**TiltY**	**n2-n1**	**E-W**	***Tpe 1***	**Tpe 2**	**Tpe 3**	**geophone**

b. Total magnetic field network

Two proton magnetometers record the total field at DAK and MCL. Data are sampled every minute and are stored on a memory card. Every month, data are recovered from the stations and processed by PHIVOLCS and the Japanese team directed by Y. Sasai (see paragraph 7).

3. Summary of the recent activity

After 2007, the volcano entered a phase of decreasing activity, as shown by the decline of seismicity, self-potential anomalies, magnetic field values (see Sasai reports), ground and water temperatures. The two geothermal fields were clearly restricted to the areas (1) of the fissures opened during the 1991-1994 seismic crises and (2) to the northern inner part of the crater.
In November 2009, the surface activity was at its lowest level since 2005.

The last joint field campaign on the volcano was completed in February-March 2010.
At that time, seismicity, as well as the surface activity, was very weak.

- The hydrothermal activity receded in the two specific geothermal areas described in several articles (Harada et al., 2005, 2008; Sasai et al., 2008; Zlotnicki et al., 2008; 2009).
- Temperatures at the bottom of the Crater Lake were low (less than 40 °C).
- Self potential surveys made between the northern rim of the crater and the northern tip of the active fissures opened in 1991-1994 indicated weak geothermal activity near the rim of the crater. In comparison, this section of about 170 m of the N-S extension was geothermally reactivated during past seismic crises (2005, 2006, and 2007).
- Ground temperatures in the geothermal area surrounding the 1991-1994 fissures were comparable to those measured in 2008 and 2009. Only the main active thermal outcrops were the seat of higher temperatures (up to 99°C in three locations).

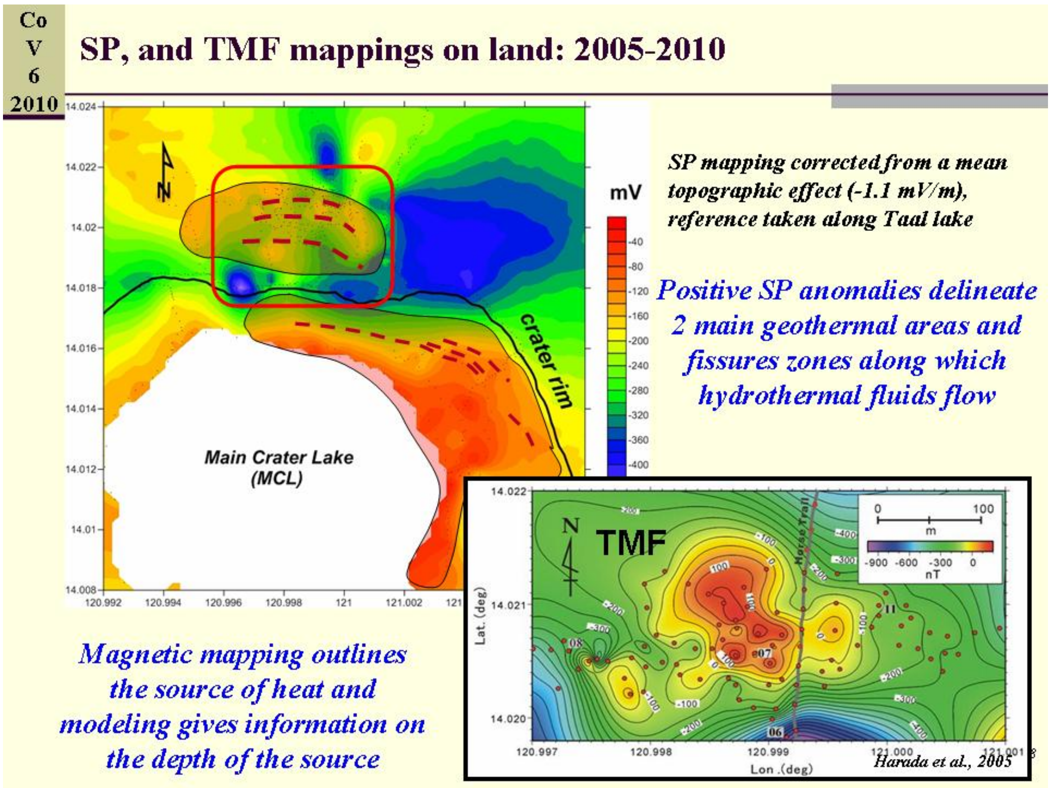


Figure 2. Location of the geothermal fields

4. April to July 2010 seismic activity

Seismicity started to increase in April 2010, reached a peak in early June, and receded at the end of July.
Alert 1 was raised to 2 by PHIVOLCS when the seismicity increased sharply. It was lowered back to level 1 on August 2.

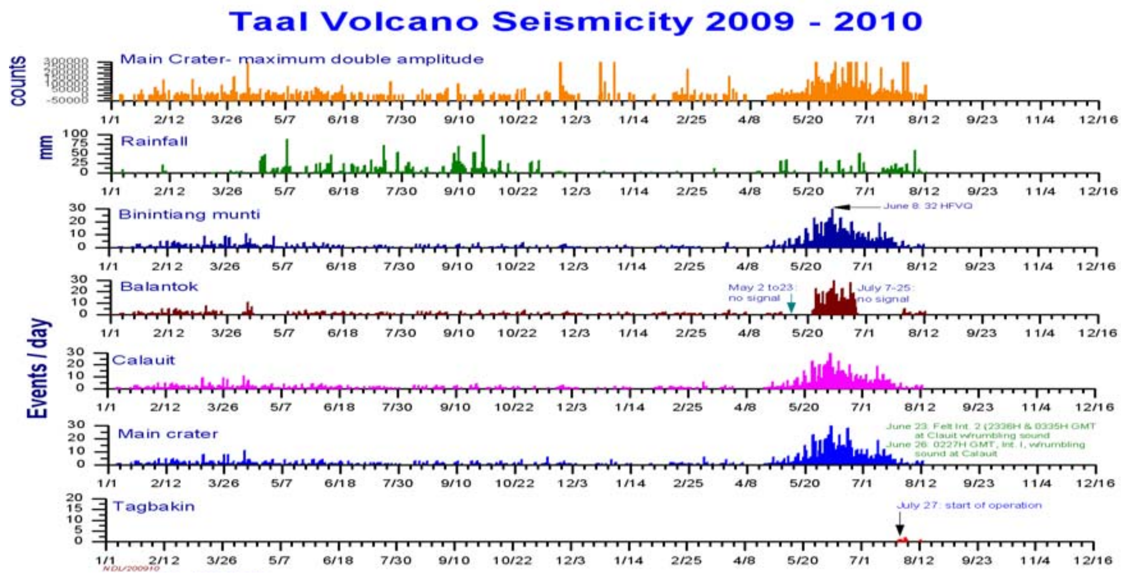


Figure 3: Seismicity at different stations located on the volcano (PHIVOLCS document)

5. Observations at DAK station

The data set is not complete. Radio-transmission of data has not been working correctly during the last month. This results in scattered values with some of the largest values in the daily files of spurious origin and do not represent actual geophysical data. These spurious data can be removed from the data files but the condition makes quick reading of activity difficult.

a. RMS Seismic level

RMS Seismic level at DAK is recorded by a geophone (figure 4). RMS starts to increase in March 2010 and reached a more or less steady level along which two sharp peaks of activity take place in mid-April, mid-May and in June 2010.

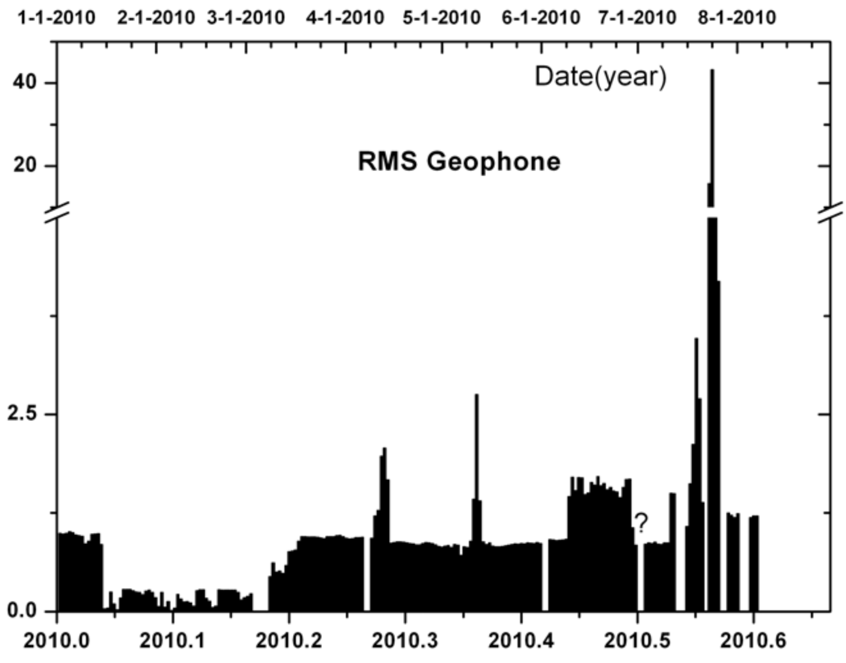


Figure 4. Seismic noise recorded at DAK station. Missing bars correspond to missing data.

This graph must be interpreted taking into account the following remarks:

- A low increase of the seismic activity with time seems to emerge,
- Bursts of higher seismic activity periodically appear as at the end of May, mid-May June,
- High values observed during July are partly due to bad records and heavy tropical rainfalls.

b. Evolution of the gradient of temperature in the ground

Since November 2005, ground temperature measured at 40 cm depth near the active fissures shows annual changes with amplitude of about 24°C. From 2006 to 2009, the maximum of temperature reaches about 53°C around mid-April. Different behaviour occurred in 2010 when the temperature increased continuously till the end of May (56°C) before finally recovering to a trend similar to that in 2007. Of course, this general pattern was affected by large rainfall on the volcanic massif which reduced the temperature by several degrees over a period of few days to some weeks.

Nearby DAK station, temperature records at 40 and 80 cm depth show a trend similar to that during 2009, with a constant gradient of about 6 °C/m, up to early 2010 (see report 1).
In January 2010, the temperature gradient (∇T) began to decrease in a regular manner, reaches a minimum in April when the seismicity activity starts on the volcano. It recovered the average value measured in 2009 after June (figures 5 and 6).
Finally, an increase of temperature at 80 cm depth of about 2°C can be observed between 2009 and 2010.

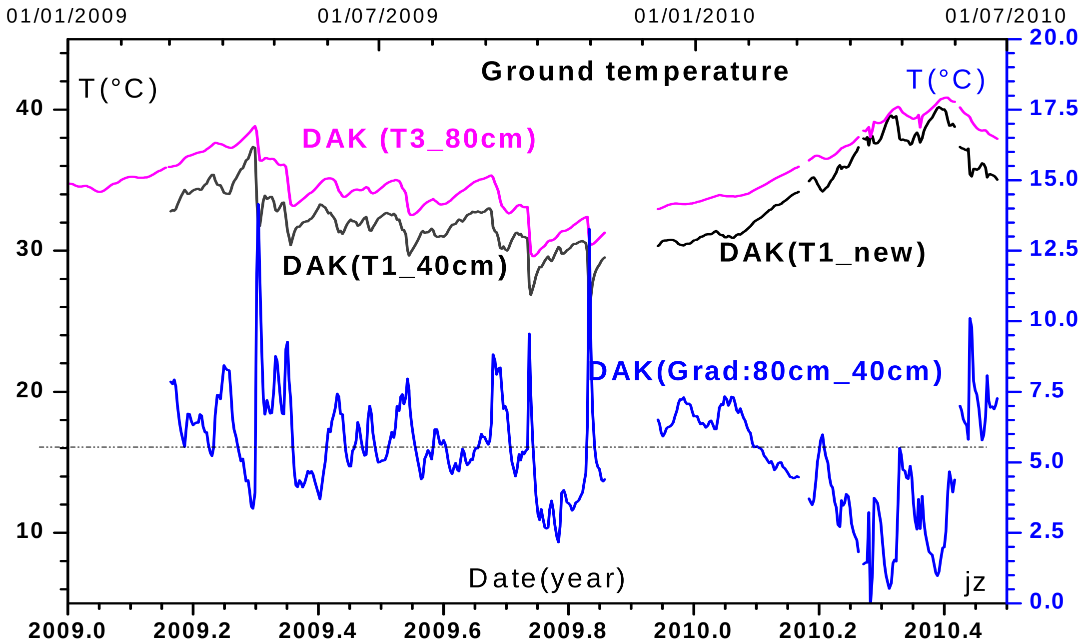


Figure 5. Time evolution of the ground temperature and the temperature gradient at DAK station.

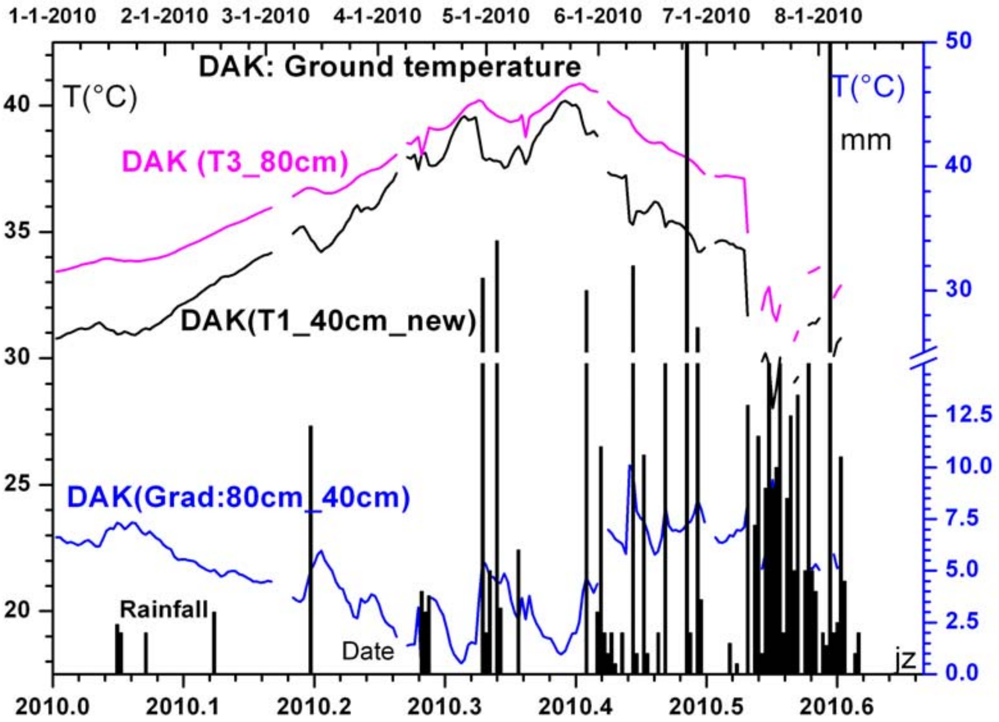


Figure 6. Time evolution of the temperature and gradient at DAK between 2009 and June 2010. Rainfall data, represented by black bars, are provided by PHIVOLCS.

Although, one might suspect that the decrease of ∇T during the first 3 months of 2010 was related to a faster response of the superficial ground temperature to seasonal rainfall and temperature changes (figure 7), a similar response did not occur in 2009 (figure 5).

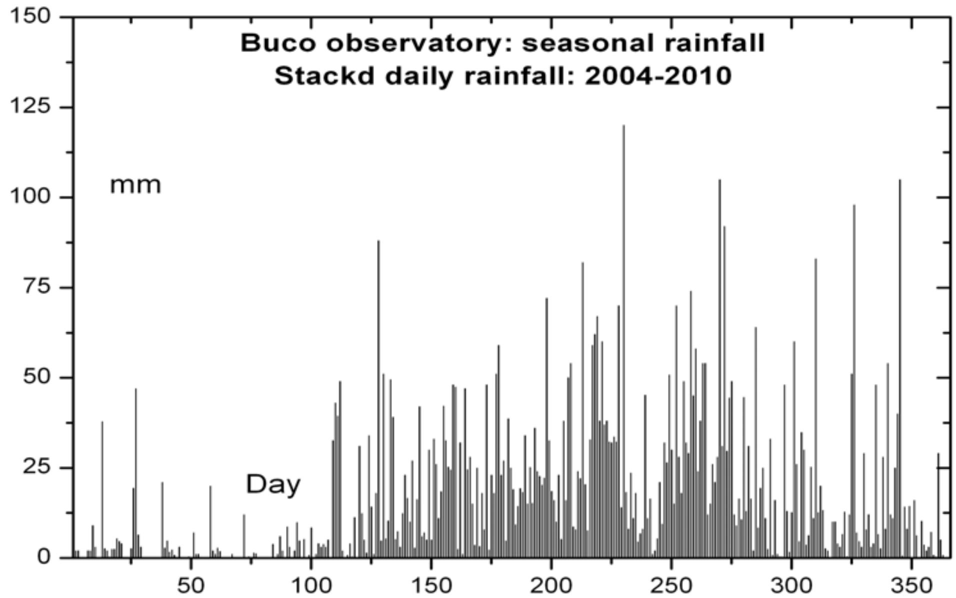


Figure 7. Average seasonal rainfall at Buco Observatory between 2004 and 2010. (PHIVOLCS document)

Seismicity also induces changes in the ground temperature. Several earthquakes are accompanied by ground deformation, electric signals, and a decrease in the ground temperature at 40 cm depth (i.e. days 119, 160, 16 …)(see figure 10).

For instance on June 10, the gradient jumps from 6.3 to 10.1°C/m. This event is accompanied by a steep change in the tilt and in the electric field. The change in the electric field reaches 140 mV/km and lasts about 10 hours.

c. Ground deformation: Borehole tilt records

In March 2010, a borehole tiltmeter was installed by M.J.S. Johnston nearby DAK station with the usual globally accepted tilt convention, positive X tilt means tilt down to the East and positive Y tilt means tilt down to the North. Data from March 8 to August 10 are shown in Figure 8. These data are scaled using Earth tide calibrations and spikes from telemetry malfunctions are removed. The data are detrended using just the tilt rate from March 8 to April 20 in order to isolate the response since April 20.

<u>Features of these data are</u>:

- Earth tidal tilts are evident on both components, more so as should be expected on the EW component.
- A tilt transient corresponding to tilt down to the SE on April 29 was detected and the information was sent to PHILVOCS on May 20. At this point, we were unaware of the increase in seismicity following April 29.
- Tilt increased in a positive sense on both components (i.e. down to the NE) after May 1 in correspondence with the cumulative seismicity as shown on Figures 8 and 9.
- The rate of positive tilt decreased after early June and has really flattened out after early July, again in correspondence with the seismicity.
- Following early July, seismograms from large teleseismic earthquakes (e.g. M7.7 Sumatra eq., M6.9 Qinghai eq. and many others) are evident throughout the data.

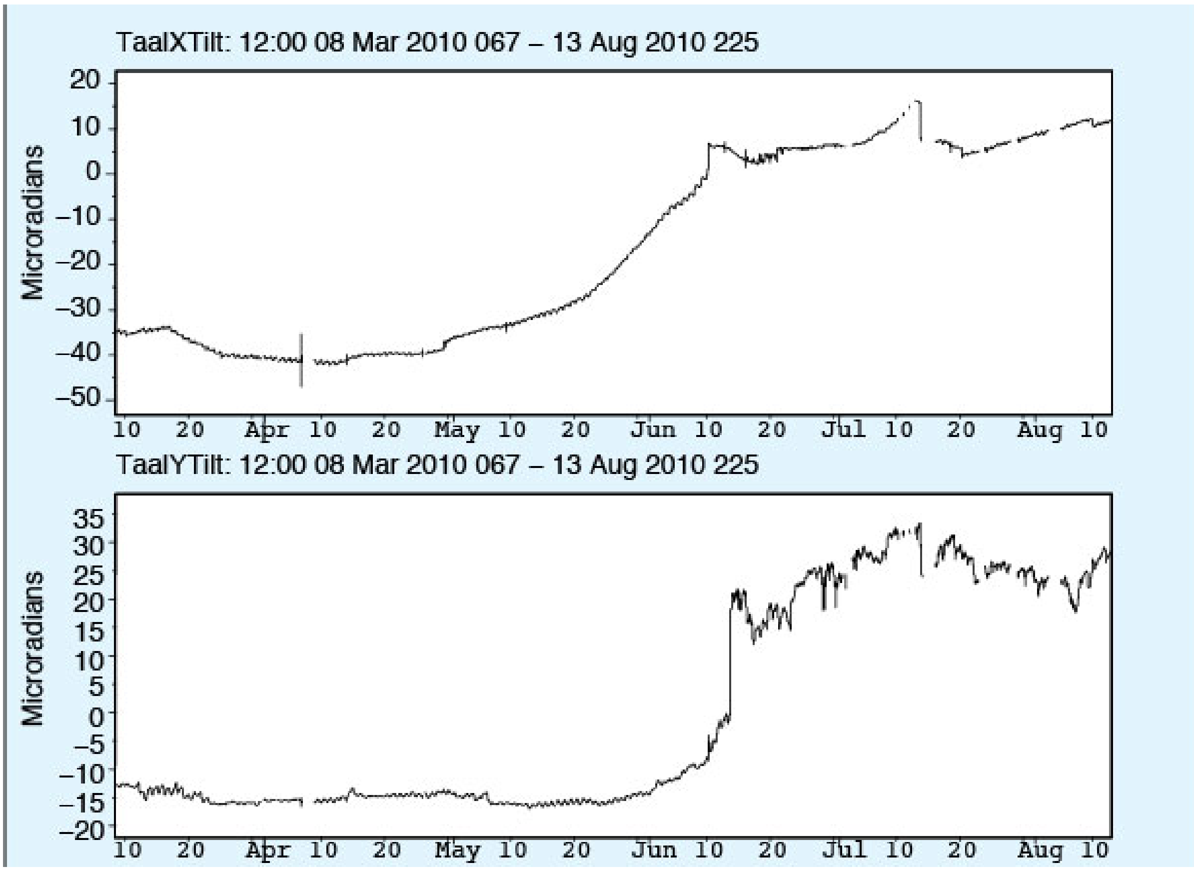


Figure 8. Comparison of time change of the horizontal tilt components from the borehole tiltmeter at DAK.

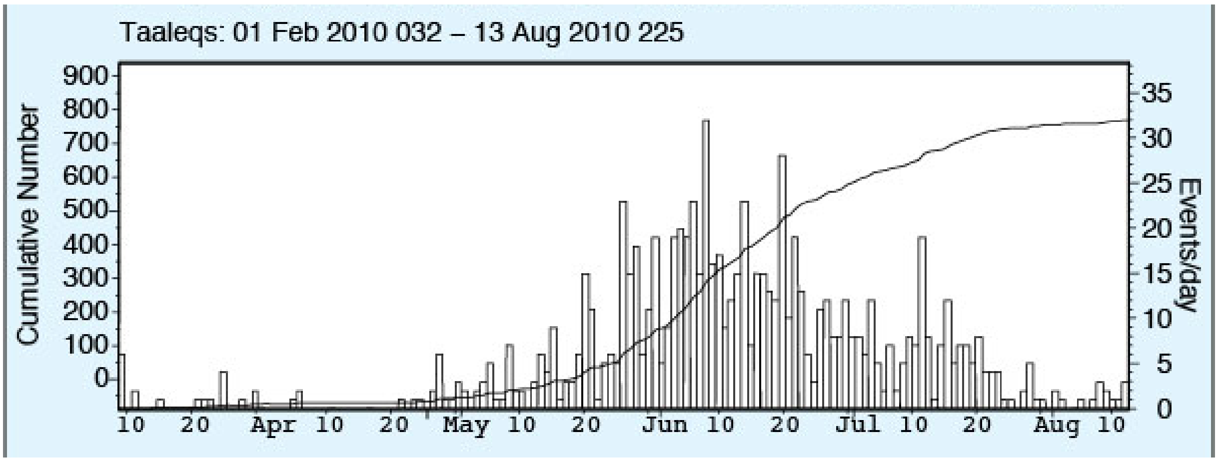
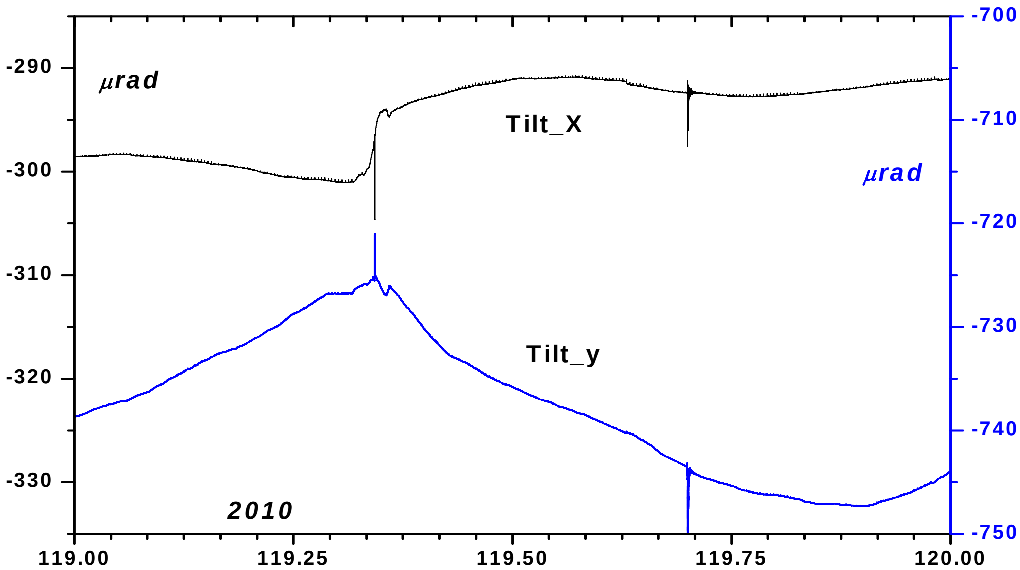


Figure 9. Seismicity at MCL (kindly provided by PHILVOCS).

<u>Interpretation:</u>
After mid-April, both components start to show positive variations, corresponding to a tilt to the NE. This variation is consistent with inflation located to the SW of the station (i.e. under the north side of the main Crater Lake). The interpretation is supported by the levelling surveys done by PHIVOLCS.

If the source of inflation is under the Main Crater and is very shallow (i.e. less than 4 km deep), a tilt node would occur between the tiltmeter and the source, and the Y tilt component, in particular, should have an opposite sign. Therefore, the inflation source, if it is under the Main Crater, is likely to be no less than, and probably greater than, 4 km deep. We note that the likely location of the inflation source can be easily and independently checked by investigating the precise distribution and depth of microseismicity under MCL.

<u>Tilt, Electric Field and Temperature:</u>
Coseismic tilt offsets with aseismic tilt transients of some weeks duration are observed, as on April 29 (figure 10). Transient signals in the electric field, in the ground temperature are often simultaneously observed.



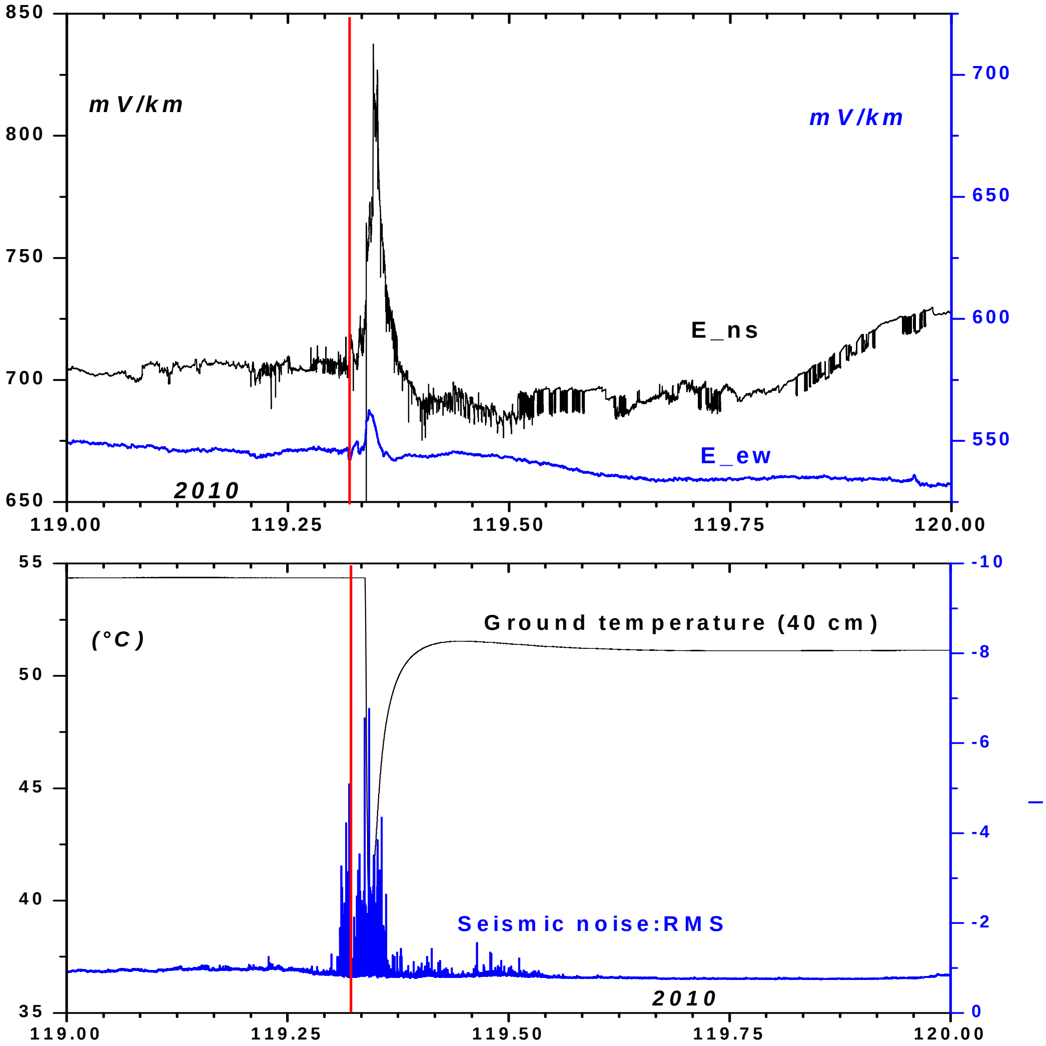


Figure 10: Raw variations recorded at DAK multi-parametric station on April 29, 2010. Upper plot: Variations in the horizontal components of the tiltmeter (X: EW, Y: NS); Middle plot: Variations in the horizontal components of the electric field; Lower plot: Variations in the ground temperature near the 1991-94 active fissure and in RMS seismic noise.

d. Evolution of the electric field

The following figure (figure 11) shows the changes in the electric field along two orthogonal directions; E5-E1, E4-E1, E3-E1, E2-E1channels are along the North direction and Ee-Ew one is along the East direction.

Although the SP values remain constant on average between 2008 and August 2009, seasonal changes are superimposed to the long term trend. Near the active fissures, the SP values drop down with an amplitude of about 300 mV/km when heavy rainfalls occur in September on the volcano. At E3, and E4 sites, the SP values rapidly recover a seasonal variation.

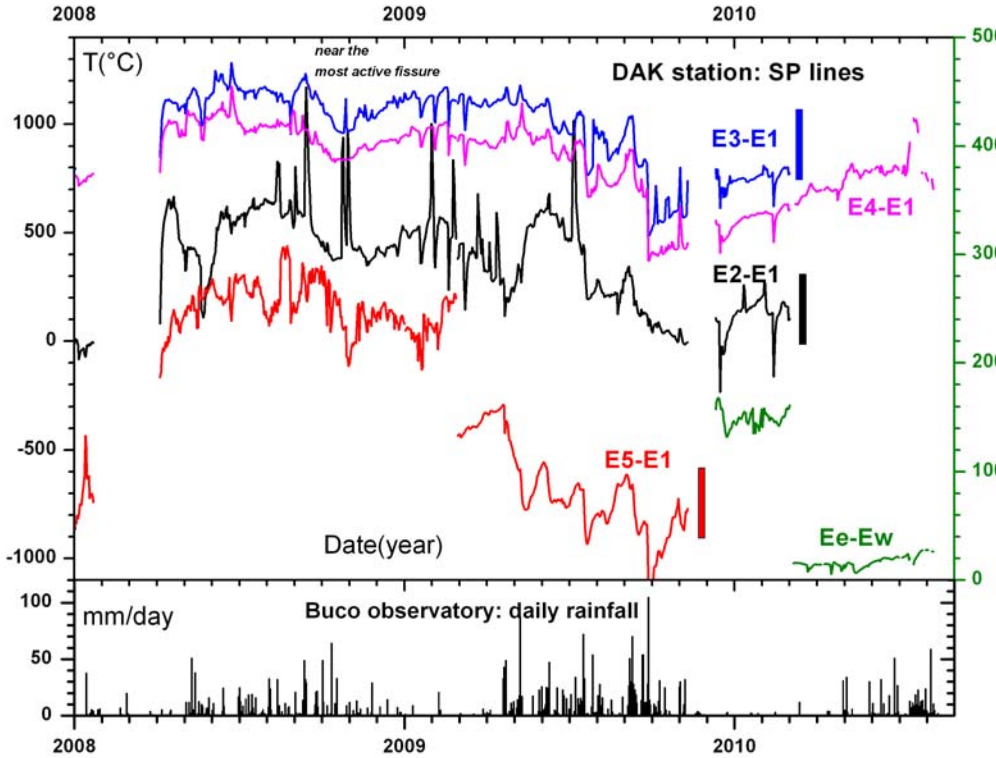


Figure 11. SP variations at DAK station (upper cartoon) and daily rainfall between 2008 and August 2010.

The general pattern of the SP variations is perturbed after mid-April 2010 during increased seismicity (figure 12). The E4-E1 (NS) and Ee-Ew components show opposite variations which reach 100 and -80 mV/km. These variations relate to signals generated by the onset of the seismic activity. These changes may indicate an increase of the hydrothermal activity to the South-West of DAK station.

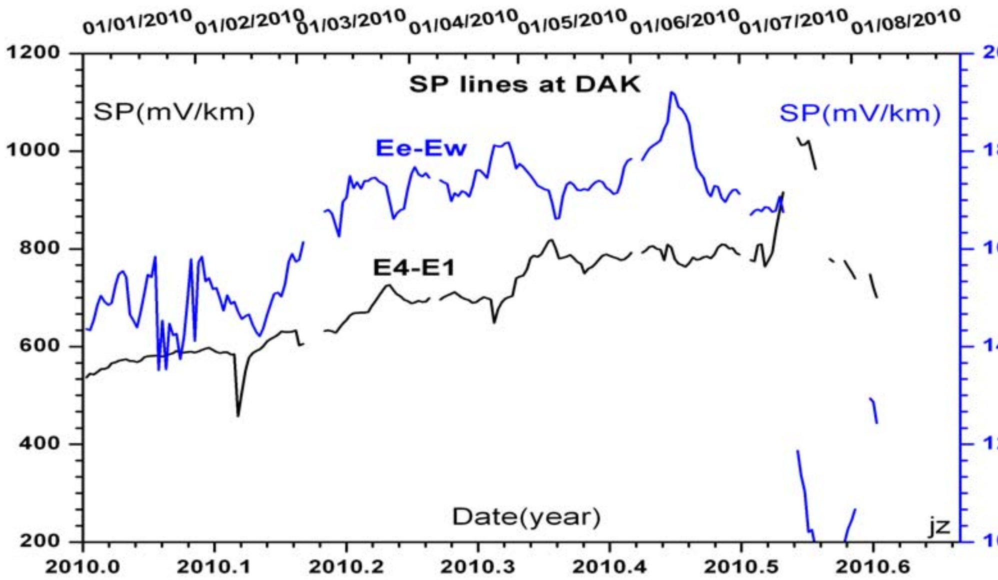


Figure 12. Time evolution along the NS and EW components of the electric field in 2010.

It is also noteworthy that the amplitude of the Ee-Ew component is maximal during the highest peak of seismicity and then sharply decreases when the seismicity recedes. This

behaviour is also observed on E4-E1 component with a delay of about 3 weeks. The maximum decrease reaches about 900 mV/km.
After July, E4-E1 recovers pattern similar to that seen in 2006.

6. Observations at MCL station

a. Evolution of the gradient of temperature in the ground

At MCL station temperatures in the ground are measured in the same way as at DAK station (figure 13). From March 2007 till April 2010, the gradient of temperature (∇T) slowly decreases step by step, from 11.3° to 3.5°C/m. This long term decrease matches the decline of the activity of the volcano (see EMSEV reports; http://www.emsev-iugg.org/emsev/).
On April 19, 2010 the decrease of the gradient stops when the seismic activity starts.
In 2010, the four increases and the recovery periods observed on figure 14 are due to rainfall. The interpretation can be as follows: Rainfall induces a more significant decrease in the ground temperature at 40 cm than at 80 cm, inducing a transient increase in the temperature gradient (Figure 14).

After, April 19, 2010, the gradients of temperature at MCL and DAK show similar behaviour, showing that the renewal of activity affects – at least – the northern inner part of the Main Crater, as well as the outer northern crater rim to the most northern active 1991-1994 fissures (figures 5 and 13).
At most, during the April to July volcano-seismic crisis, the temperature at 80 cm depth shows an increase of about 2°C at DAK between 2009 and 2010.

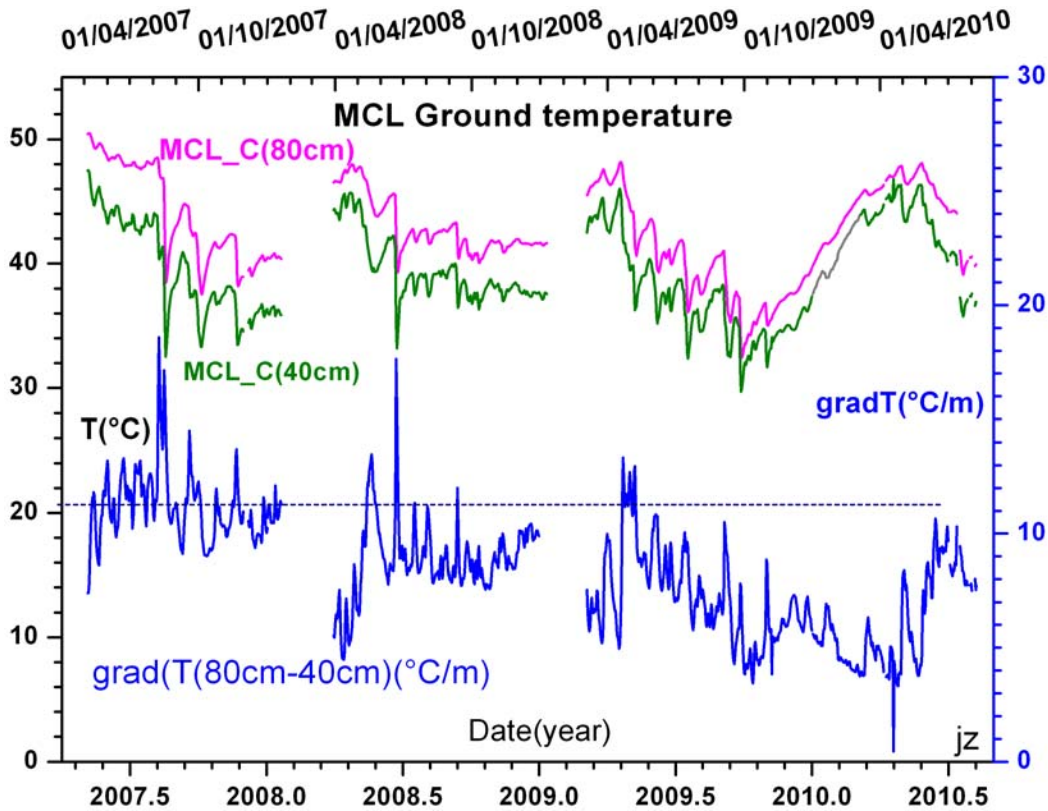


Figure 13. Time evolution of the temperature and gradient at MCL between 2007 and June 2010.

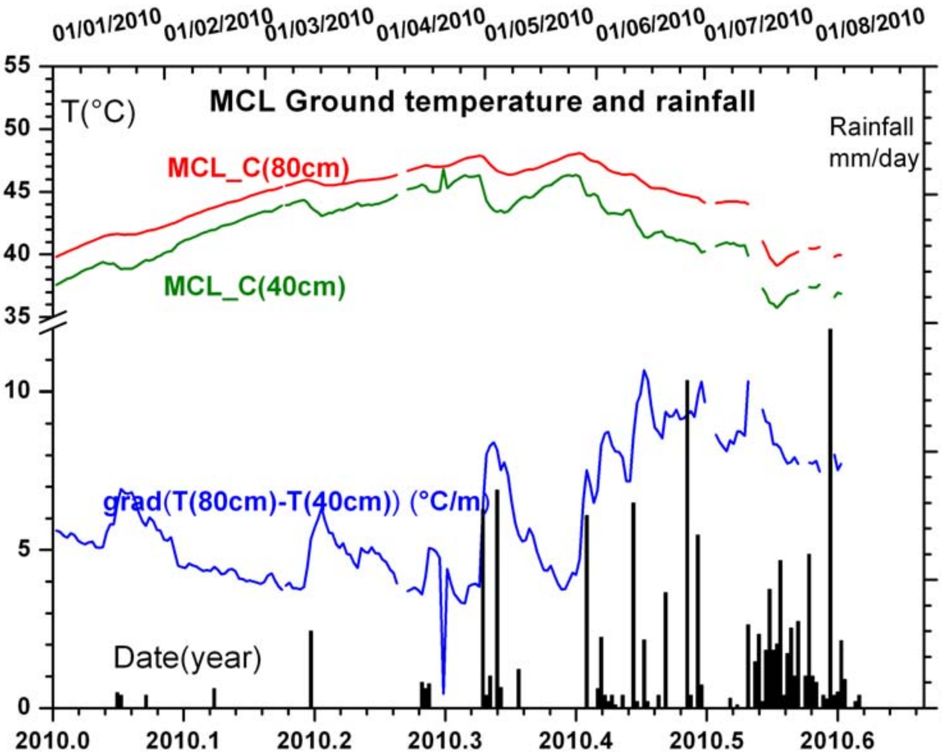


Figure 14. Time evolution of the temperature and gradient at MCL in 2010. Bar chart represents the daily rainfall (provided by PHIVOLCS).

b. Evolution of the Electric field

Since April 2007, both horizontal EW and NS SP components show a continuous increase, on which negative spikes of several days to weeks duration correspond to periods of rainfall.

However in 2009, heavy rainfall stops in September, which leads us to suppose that the drastic decay observed in December 2009 on the NS component may be due to a change of activity in the hydrothermal system. It also should be noted that after that period, both components show variations of opposite sense. The largest amplitudes are observed on the NS component.

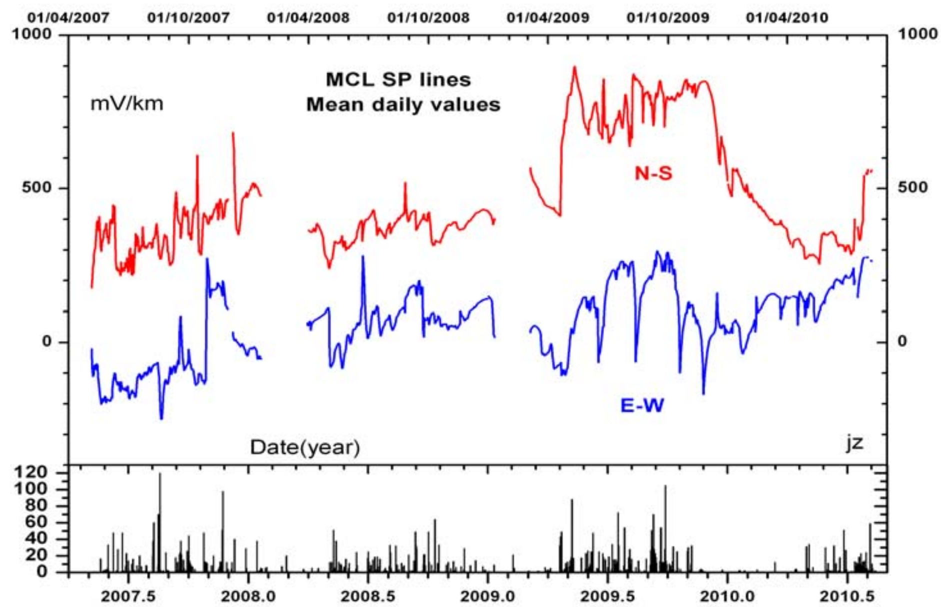


Figure 15. Evolution of the components of the electric field between 2007 and 2010.

Figure 16 shows that there is no large change in the electric field due to rainfall during the first five months of 2010. Therefore, noticeable changes in the electric field appear to be generated by the volcanic activity. After April 2010, the two components seem to recover the same 'positive' trend. These may be related to the volcanic activity.
Short terms transient signals are apparent after May 15 and 21. These changes mark an increase of hydrothermal activity in the crater, most probably to the North of the station.
The amplitude of these SP variations is an order of magnitude smaller than at DAK: a few tens of mV.
After July 2010, the SP components appear to be strongly disturbed by numerous rainfall episodes occurring on the volcano.

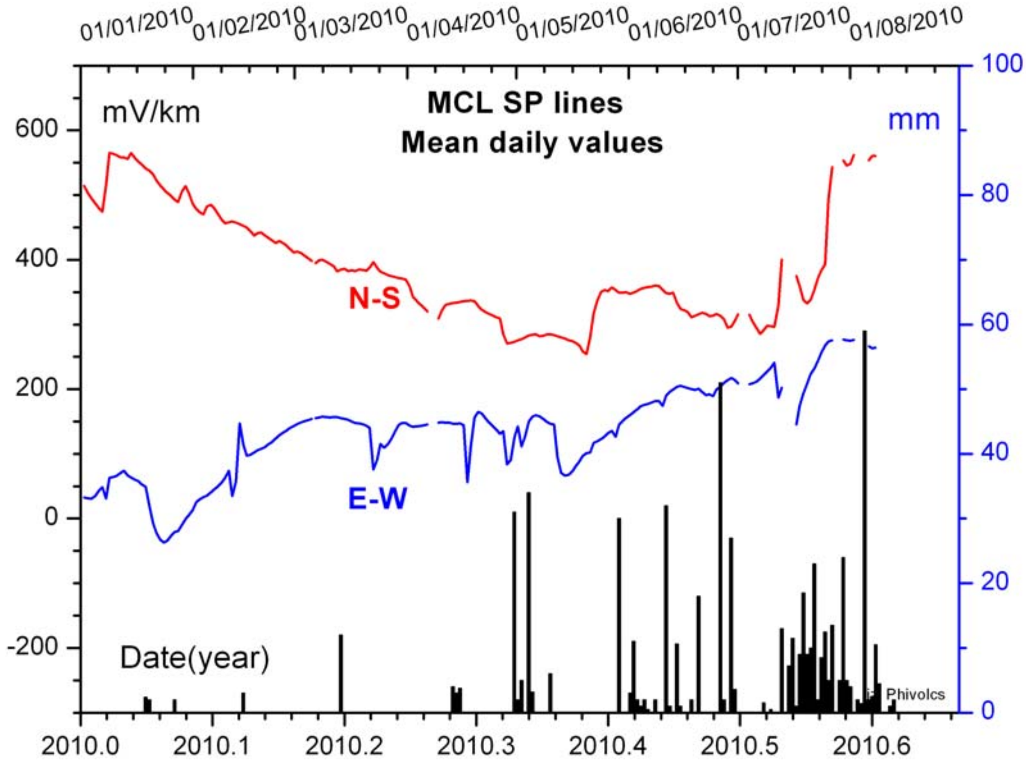


Figure 16. Evolution of the components of the electric field in 2010. Rainfall is shown with a bar chart.

7. Magnetic observations in Main Crater and Daang Kastila areas

The 13th repeat survey of TMF (Total Magnetic Field) was conducted from February 28 till March 5, 2010. This is the summary of our survey. Figure 17 shows the location map of repeat survey points. Simple differences of TMF values between each point and the temporary reference station DKT are averaged over 15 minutes and named as DF_DKT. The TMF difference δF between DKT and the reference station MUT (Muntinlupa) was calculated using data from both stations for the period from February 11 till February 28. Finally, the TMF value at each point is calculated by adding delta F to DF_DKT, namely

$$DF\_MUT = DF\_DKT + \delta F$$

where δF = Average of simple differences (F_DKT - F_MUT), and δF is estimated as 112.0 nT.

a. **Repeated magnetic network of benchmarks**

TMF changes in the area A (Main Crater East and Calauit) are shown in Figure 18(a). In relation to the previous survey (November, 2009), a decreasing trend near along MCL shore has continued. This is also evident in the continuous data at MCE (see figure 19). The southernmost two points (TA20 and TA21), which could not be found during Survey 12 owing to thick vegetation, were again discovered.

TMF changes in the area B (Daang Kastila) are shown in Figure 18(b). In the previous survey, TA23 was not measured. We found that a wooden hut near the bench mark was damaged probably due to typhoons and was abandoned. This could be the cause of the large change at TA23 between Survey 11 (March, 2008) and 13. TA09 A and B are located along the northern boundary of the geothermal area. The data from these seem relatively stable. TA17 shows relatively large changes at Survey 12 or 13. We could not find any likely causes for such changes. Points in the geothermal area TA11, TA08, TA07 and TA06 as well as TA25 outside the geothermal area show little changes.

TMF changes in the area C (Main Crater West and Alas-As) are shown in Figure 18(c). We could not find the benchmark TA27 this time again, where it should be buried in mud owing to heavy rains during typhoons in 2009. Changes at points along the western shore of MCL, i.e. TA 15, TA14, TA12, TA13 and Ta26 are small. TA16 is stable for the recent period, between Survey 12 and 13. Although a new route along the pass on the western cliff of the crater wall was developed, it does not affect the survey point very much. We can not find the possible cause of large changes between Survey 11 and 12. A large change at TA22 is ascribed to construction of a new wooden hut. The ground soil may have been dug and readjusted.

In Figures 18, we notice a long gap between Survey 11 (March, 2008) and 12 (November, 2009). Actually we did conduct the survey in February-March, 2009. However, during this period, the ROM reader for magnetometers at MCE and DKT mal-functioned causing us to lose data. Moreover, MUT magnetometers (both proton and flux-gate types) were not working well. We are forced to discard the repeat survey data because of the absence of reference data.

a. **Continuous magnetic network**

Results of continuous TMF observations are shown in Figure 19 for the period from Dec. 2007 to Dec. 2009. Unfortunately, ROM's retrieved from MCE and DKT magnetometer were sometimes found to have errors, likely resulting during the period in the first half of 2009 when the ROM reader mal-functioned. In Figure 19, we find that MCE magnetometer suffered some disturbances at the end of Dec. 2009. We could not identify the cause of such disturbances. A possibility is that the wooden fence was damaged by cows. TMF values at MCE decreased by 2 nT since November 2009. The amount of TMF changes is consistent with the overall decrease in TMF at survey points surrounding MCE, which is clearly seen in Figure 18(a). On the other hand, DKT showed little changes during the last several months.

Unfortunately, the magnetometer at MCE has some problems with its recording system and batteries, and only DKT data are available for the past 4 months (from March to June). Also, MUT magnetometer has sometimes mal-functioned.

However, TMF values at DKT show no remarkable changes since March, which implies that no drastic changes in the underground temperature had occurred during this period. We also notice that TMF values at MCE remained stable until early May, which suggests that the ground temperature at a depth of a few to a few tens of meters remained at the same level which had been slightly cooled down owing to heavy rains (typhoons) in 2009.

We should notice that the tiltmeter and precise levelling data clearly indicate that the inflation source should lie beneath around the western coast of the Main Crater Lake, where no geothermal activity exists. However, we have no continuous stations nor enough number of repeat survey points there. We intend to install a new continuously recording proton magnetometer with telemetry system there as soon as possible.

Acknowledgement: Geomagnetic data at Muntinlupa Magnetic Observatory were provided by NAMRIA via OHRC(ERI)-JAMSTEC under MOA among NAMRIA, PHIVOLCS, OHRC(ERI)-JAMSTEC, EMSEV and Tokai Univ.

Reference

Sasai, Y., Changes in the total magnetic force (TMF) on the east coast of Main Crater Lake in the latter half of 2009, A technical report to PHIVOLCS, Dec. 19, 2009.

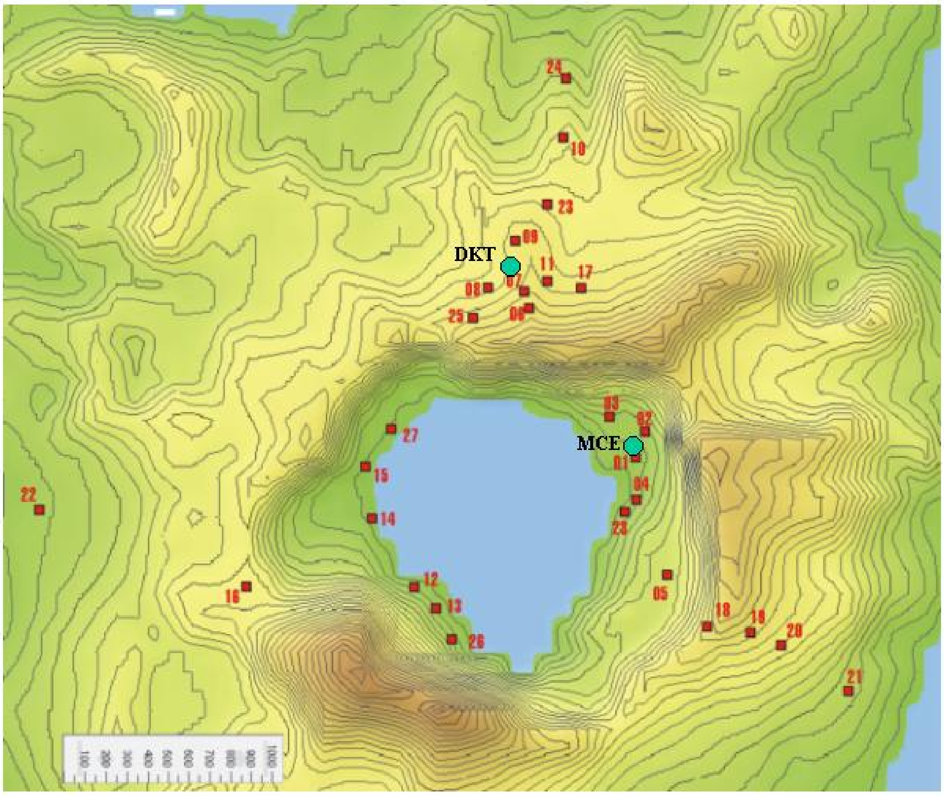


Figure 17. The distribution of repeat survey points (red square with station number) and continuous TMF stations (green circle with station name) on Volcano Island. Note that the point at the southeastern shore of MCL is labeled as TA23, which should be renumbered as TA28.

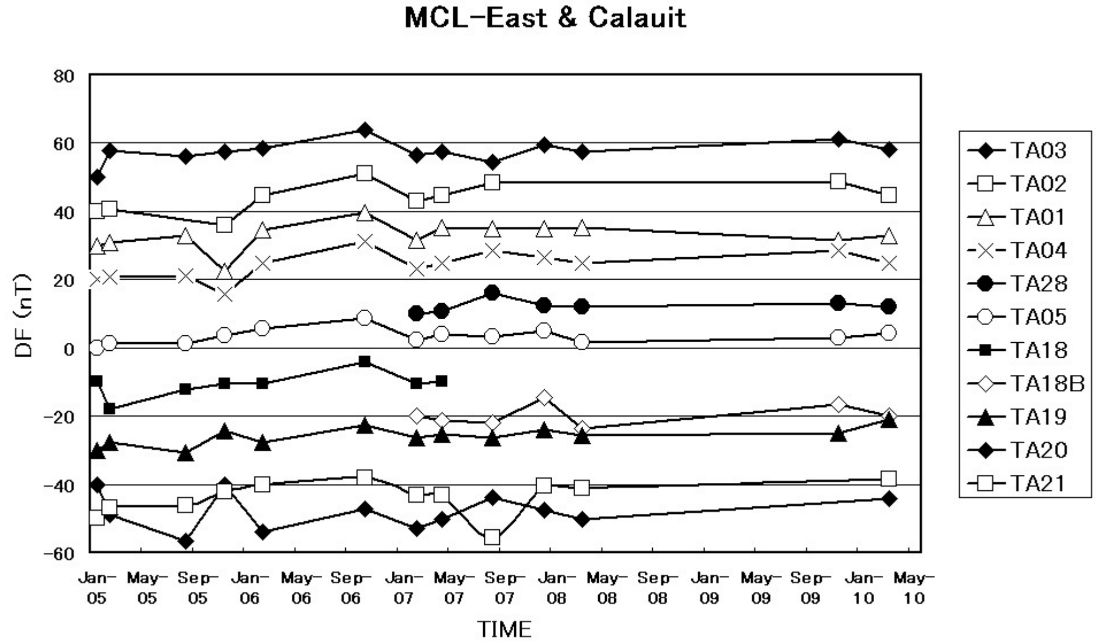


Figure 18(a) TMF changes in the area A (Main Crater East and Calauit).

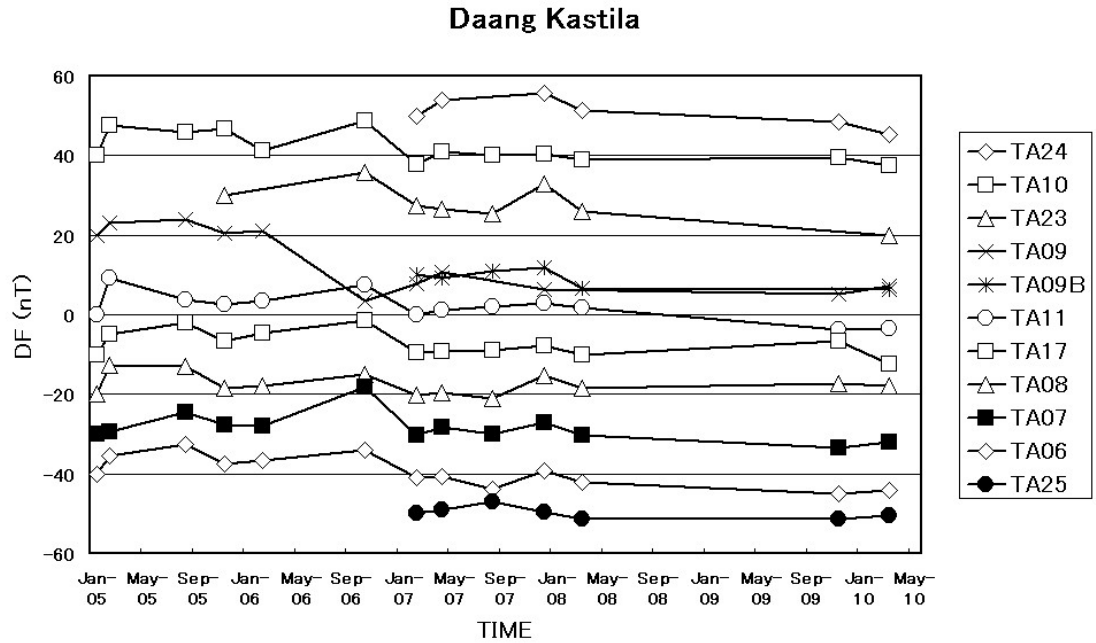


Figure 18 (b). TMF changes in the area B (Daang-Kastila).

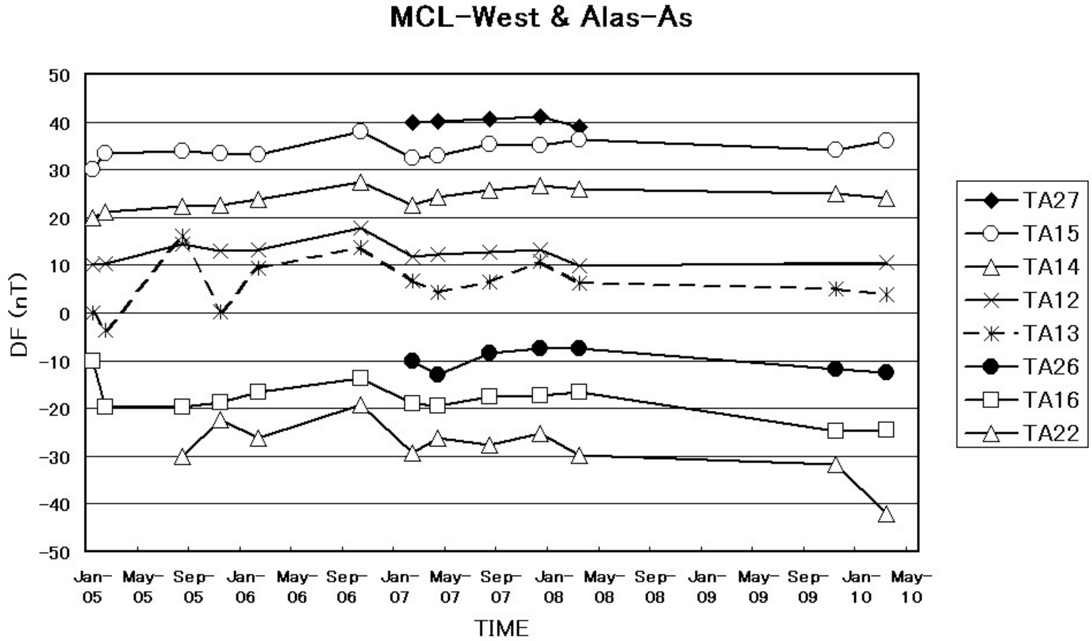


Figure 18(c) TMF changes in the area C (Main Crater West and Alas-As).

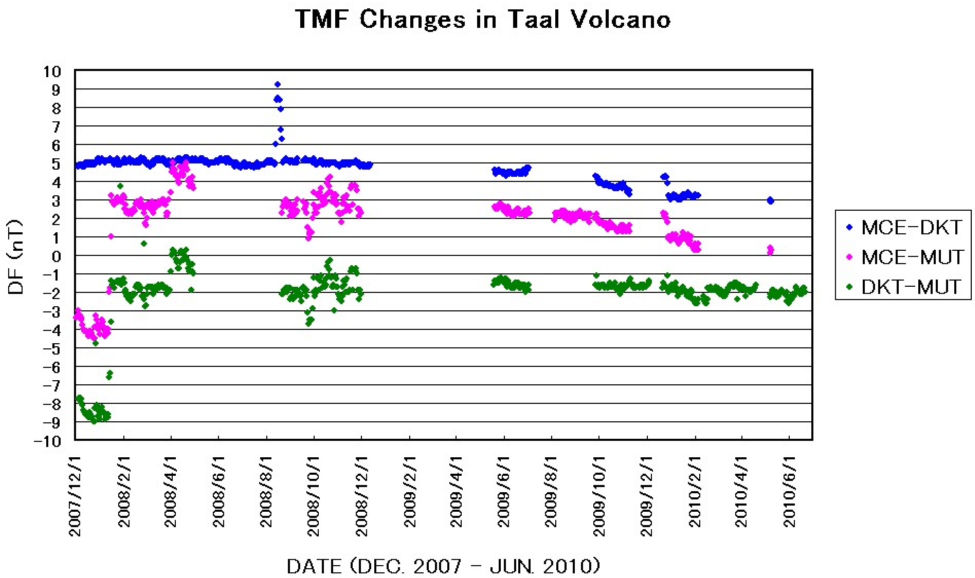


Figure 19. TMF changes at MCE, DKT relative to MUT for the period from Dec. 2007 to June 2010.

8. Preliminary synthesis

a. Multi-parameter analysis

From 2005 to 2010, the seismic activity has slowly decreased, although seismic crises of a few weeks duration have occurred almost every year (2005, 2006, 2007, 2008, and 2009).

During these past 5 years, self-potential, magnetic, ground temperature and CO2 soil degassing mappings have clearly shown that two geothermal fields are mainly active, forming a large hydrothermal system located in the northern part of the Main Crater to the northern end of the fissures that opened during the 1991-94 seismic crisis.

Repeated surveys and measurements in different locations show that the activity was at its lower level at the end of 2009. Several implications arise from these observations. One interpretation might be that the thermal source at depth is becoming less powerful during 2005-2009,

suggesting a decay of Taal activity. A second interpretation might be that the thermal source is still active but tropical rainfall and mineralization of rocks have progressively clogged up the superficial part of the volcano during this period.
The second possibility seems to be more plausible, but it means that thermal fluxes and gas cannot escape to the surface, increasing pressure and thermal stress at depth.

Anomalous changes in the ground temperature occurred in April 2010 simultaneously with the increase in the seismic activity. The comparison of the temperatures and the gradients at MCL and DAK shows that the larger changes in the temperature have occurred in DAK area. If seasonal changes can be considered, as a first approximation, to be similar at DAK and MCL it means that the thermal activity was larger in the Main Crater than outside after January 2010.
Between April and July 2010, short term temperature anomalies were clearly recorded during earthquakes, tilt variations, and transient changes in the electric field. Most often, these changes correspond to a negative drop in the superficial temperature near the 1991-94 fissures. It could be interpreted as small re-opening of these fissures.

After December 2009, large and continuous self-potential variations appear in MCL which morphology change after April 2010. The amplitude of the decrease of the NS component is huge: 575 mV/km. After April 2010, smaller variations of different types are observed. One type corresponds to variations up to a ten of days; the amplitude can reach 100 mV/km. The second type of SP signals is observed during seismic activity and tilt variations.
At DAK station the SP changes are less important before the onset of seismic activity, variations same a similar pattern to the seasonal variations. But during the seismic crisis, SP variations become large, about 100 mV/km, like the signal observed on the NS component during the peak of seismicity (June).
The large variations observed during the second half part of July are due to the heavy tropical rainfall.

Tilt records accurately contribute to a continuous understanding of deformation within the volcano, even though the equipment was installed only one month before the onset of activity. Inflation of the northern part of the volcano appears in April 2010 when seismicity starts and the maximum of tilt was reached in June. Since this time, inflation appears to have stabilized. Although only one tilt station is operating on the volcano, it seems that the source of inflation is likely to the South-West of DAK. The depth of the source is difficult to determine, but simple deformation considerations indicate a source's depth could be at 4 km or deeper. The up and down variation in the tilt observed during June could be due to inflation perturbations and/or local mechanical readjustments of fissures located near the station.

Until January 2009, the magnetic network of benchmarks has shown that that the magnetic field has decreased along the MCL border. This is consistent with other surveys: self-potential, ground and water temperature surveys. New surveys should indicate whether larger-scale changes of the magnetic field are occurring on the volcano.
Continuous magnetic records at MCL and DAK indicate a decrease of the magnetic field during the second part of 2009. This decrease may be related to the decrease of thermal activity in the area as shown by the ground temperature measurements. Further data collection will help us understand the magnetic changes during the seismic crisis.

From these data, we would conclude that the multi-parameter stations are a very powerful tool for real-time monitoring of the volcanic activity and can detect signals related to the on-going activity. However, new efforts should be made to improve the reliability of the data transmission, internet data transfer, and data processing. Daily graphs are now available on VEML server (http://virtual-electromagnetic-laboratory.com/). Another parameter can be easily added to the reception at Buco observatory: Rn emission is ready to be transferred to Buco, only an upgrade of the software is required.

b. General comments

When one considers the background of seismicity on the volcano, it is clear that seismic crises appear abruptly and are accompanied by rapid ground deformation as observed on many similar volcanoes. High levels of activity can be quickly reached. Real time monitoring and data analysis systems are a necessity for anticipating the level of hazard expected.

Earthquakes during this current crisis have again re-activated the 1991-94 fissures, which might unconsolidate the northern outer rim of the crater. Many data indicate that the region beneath the northern Crater Lake is still active. The hydrothermal activity appears to contribute continuously to generating features like the 1991-94 fissures whose roots are, at least, few hundred meters deep.

During this crisis, the near-surface activity in MCL is apparent, and one may consider that the general hydrothermal activity will again be similar to that observed in 2007 or before.

Taking into consideration all the available data, it seems that is new crisis is serious although the details of the deep activity and its potential are not clear. Magmatic intrusion, together with hydrostatic overpressure, could be reactivating the region below the northern part of the volcano. Under this hypothesis, any depressurization, resulting from faulting triggered by teleseismic or local earthquakes, landsliding, etc, could destabilize the system and lead to a phreatic explosion on the volcano.

The crisis has been a good opportunity to improve the communication and information between EMSEV and PHIVOLCS. EMSEV would like to warmly thank all PHIVOLCS members who have contributed to communicate and given information on the on-going activity. On the other hand, EMSEV teams has made its best for contributing to understand the activity on the volcano, and to inform PHIVOLCS on the analysis based on the real time multi-parametric network.

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