ANNALI DI GEOFISICA, VOL. XXXIX, N. 2, March 1996

Development of an early-warning system for monitoring remote volcanoes

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Abstract
Many andesitic volcanoes are quiescent for long time periods: usually (but not always) an increase in seismic activity and in deformation precedes an eruption by a few months or a few days. A UNESCO panel has put forward the concept of an early warning system for monitoring dormant volcanoes in remote regions. Simple seismic or deformation measuring devices can in principle be built for monitoring remote volcanoes. These instruments are composed of two units: 1) a processor that measures the baseline «activity» of the volcano and decides when the activity increases above a certain threshold; 2) a transmitter for long distance communication. For slow parameters like tilt or extensometry, the signal can be transmitted every few minutes or hours. For seismology, signals include a large quantity of data and therefore they are usually not transmitted. The processing unit is not easy to design because a single seismic station can record noises that are very similar to «volcanic events». Average noise level on a given time interval, event detection counters and high amplitude ground motion counters are a simple (but not exhaustive) way to summarize seismic activity. The transmission of data from the field to a monitoring center is feasible by present and future satellite telemetry. We present our attempt to develop an early warning system for remote volcano monitoring with data transmission by satellite.

Key words *volcano monitoring – early-warning – satellite transmission – seismology*

1. Introduction

Many volcanic eruptions are preceded by some kind of precursory phenomena. Banks *et al.* (1989) summarize the techniques for detecting indicators of unrest of a volcano which can be observed by the populace or by instruments. Often, the first premonitory phenomena revealing the beginning of a phase of unrest are an increase in seismic activity and in deformation. This is why a seismic station is frequently the first geophysical device monitoring a volcano. A UNESCO panel (Yokohama *et al.*, 1984) proposed to establish «early warning» systems on remote volcanoes, «early warning» meaning the scientific detection of the onset of a volcanic eruption and the possibly dangerous development of an eruption. The UNESCO panel stressed the necessity to monitor volcanoes as follows:

– acquire long-term geological, geophysical and geochemical observations on as many volcanoes as possible;

– when a potentially dangerous crisis is detected by these networks, teams equipped with mobile equipment will be dispatched.

A group of European volcanologists recently published a report for the European Science Foundation on «Automated systems for volcano monitoring» recommending the same strategy (EVOP, 1994). An active volcano in an urban zone should be monitored by a permanent observatory staffed with specialists in various techniques. Measurements are telemetered in real-time to the observatory where the local staff analyses the data. This procedure is expensive and cannot be applied everywhere: a few laboratory volcanoes (Hawaii, Etna, Piton de la Fournaise, Merapi, Sakurajima, ...) are intensely monitored. These observatories are essential for improving our understanding of the physics of eruptions and in the long term for mitigating volcanic hazards.

2. Standard monitoring procedures

Let us summarize the standard procedures to monitor deformations and seismicity on a volcano (Banks *et al.*, 1989). For deformation studies, geodetic measurements are reiterated every several months or years (by leveling, Electronic Distance Measurement or Global Positioning System, ...). For real time monitoring, tiltmeters and extensometers are routinely deployed to follow the short term variations of local deformations. Real-time GPS is presently tested on several volcanoes. In any case, it is important to get long term data series to compare the data to their baseline level.

Seismological observation provides an efficient means to evaluate the «activity» inside a volcanic edifice. A presentation of the seismological techniques applied to volcanoes is given in Shimozuru (1971), Gasparini *et al.* (1992) or Siswowidjoyo and Djumarma (1989). The simplest seismological observation is a single vertical seismometer connected to a graphical recorder. When the seismometer is installed near the summit of the volcano, a radio link transmits the output from the seismometer to a recorder installed at the base of the volcano. An observer examines the records every day: he counts the number of earthquakes, evaluates their approximate distance and their type (volcanic or not). His objective is to pinpoint a temporal change in seismic activity within the volcano. When a single station is available, to determine if an earthquake is volcanic or not is more a question of comparison with past records or seismic sequences from other volcanoes than a precise quantified measurement. In case of an unusual earthquake (an event different from what has already been observed), a warning is given to the National Volcanic Survey which can decide to dispatch additional surveying equipment to get more information. The essential data given by a single seismic station on a volcano are:

- the number of shocks and their «type»;
- their magnitude;
- the approximate distance of an event to the station which is obtained from the time difference between the *P* wave and the *S* wave if it can be picked up on the seismogram;
- the amplitude and frequency of tremor sequences.

To obtain more information from earthquakes, an array of at least 6 seismic stations should be set up. The arrival-times of *P* waves (and eventually of *S* waves) are picked up and associated in order to compute the hypocenter of each event. Focal mechanisms for individual events can be computed. Spectral analyses are performed on digital seismograms: a study of the spectra of body waves gives the size and the stress drop of each source.

2.1. *Computer-aided monitoring of volcanoes*

Other parameters should be monitored in complement to seismic activity. Slow parameters like temperature, tilt, extensometry, distance measurement, geochemical measurements (COSPEC, radon, ...) are plotted as a function of time. Tilt contains tidal harmonics and a meteorological component due to daily temperature variations and to rainfalls. These effects have no direct relationship with the evolution of the volcano and the data should be corrected for such perturbations. As a practical way for forecasting eruptions, Voight (1988) proposed to plot the inverse of a significant measurement as a function of time: an acceleration in the time gradient of a curve and an extrapolation of this curve may indicate the probable date of occurrence of an instability. This procedure is standard for monitoring landslides or rock failures. However, no short term precursor was observed before the eruption of Mt. St. Helens on May 18th 1980, so that even for major events, this technique is not always reliable. With our limited understanding of the physics of a volcano, it is however a «quantitative» help for assessing the probability of an eruption.

During a volcanic crisis, parameters like the duration and level of tremor sequences, the number and type of earthquakes are essential data. Depending on the volcano, some typical sequences may repeat and help the forecast. Unfortunately, precise geophysical and geochemical observations before an eruption remain limited, particularly for andesitic volcanoes. Taking into account their experience in monitoring eruptive crises, several scientists have developed programs analyzing seismic signals on personal computers. The amplitude level and duration of tremor sequences is a key indicator preceding an eruption: a system that continuously monitors the amplitude of the envelope of the seismic signal is very helpful (Schick *et al.*, 1982; Endo *et al.*, 1991). Brüstle *et al.* (1992) have built an electronic device that computes so-called Volcanic Activity Parameters (VAP) by counting the number of times the envelope of the seismic signal overtakes a threshold. In the Real-Time Seismic Amplitude Measurement system (RSAM) (Endo *et al.*, 1991), the average amplitude of the envelope of the seismic signal is computed during fixed time windows and plotted as a function of time. In the case of the Mt. St. Helens late eruptions, the increase of the seismic envelope is correlated with deformations before several eruptions. In another version, a spectral analysis is performed (Nishi, 1987), or the signal is filtered in various frequency bands and the amplitude of each envelope plotted. These procedures provide information that is fast to grasp and easy to understand for scientists coping with a volcanic crisis, and advising their local authorities. Computer graphics systems combining condensed information from seismology and from other disciplines are essential tools in a modern volcano observatory.

3. Early attempts to monitor remote volcanoes

The U.S. Geological Survey experimented a volcano monitoring station that telemetered its data through EOLE (Endo *et al.*, 1974). It included a seismic event counter and a tiltmeter. About 15 volcanoes were instrumented from Alaska to Central America. Later, a very low-power multichannel data transmitter was tested on Etna for slow rate measurements like temperature, spontaneous potential and seismic activity (Argos Newsletter, 1987). It included a seismic events counter. This instrument was also deployed on Piton de la Fournaise (Réunion), Hunter and Matthews Islands, Soputan (North Sulawesi). Ten seismic event detectors that transmitted *P*-arrival times through Argos were deployed on Etna from 1983 to 1987. The hypocenters of the earthquakes were computed daily in Grenoble, 1000 km from Etna (Glot *et al.*, 1984; Argos Newsletter, 1987). A multiparameter acquisition system using a microcomputer has been developed by Institut de Physique du Globe de Paris and installed on Piton de la Fournaise. The acoustic activity and the temperature in the crater lake of the Kelut (Indonesia) was measured and transmitted by Argos until a few hours before the eruption of 1990 (Van de Meulebrouck *et al.*, 1990; Sudrajat, 1991). These systems use the Argos satellite system which is installed on the NOAA satellites following polar sun-synchronous orbits at an average altitude of 850 km. Every ground platform emits a message of 32 bytes every 200 s on 401.65 Mhz. A message received by the satellite is stored on a magnetic recorder and retransmitted to the ground in 3 receiving stations. Data are also accessible on a direct read-out station in view of the satellite. The data are accessible through data phone lines. Argos is a worldwide system. Its performance increases with the latitude of the transmitters, up to 28 messages being collected at the poles.

Transmission of data can also be performed as easily on a meteorological satellite like Meteosat, GOES or GMS with a simple transmitter. Many multiparameter data collecting platforms use GOES (USGS tilmeters in California for example) or Meteosat. Telecommunication satellites are accessible with a Very Small Aperture Terminal, but this system requires more power for transmission than environmental satellites: seismological data are transmitted in real-time by satellite in several countries. Within a few years, multinational companies (Motorola and Microsoft for instance) intend to deploy a worldwide phone satellite system which should cover the globe. These systems will certainly replace current data collecting systems.

4. Experimenting an early warning system for volcanoes

An early warning monitoring station should have the following characteristics:

– it should be easy to install on any volcano and not power-hungry;

– maintenance cost should be low;

– the electronics and transmitter package should be robust, resisting low and high temperatures, heavy rain and wind, acidic fumaroles;

– data should be accessible in near real-time from far away;

– the cost of operation and transmission should be low, in order to obtain continuous measurements over long time periods in many different sites.

This short list of requirements is nearly impossible to meet. Based on the past experiences described earlier, TAD, an electronic firm specialized in environmental data recorders, has developed two electronic systems, one for slow rate measurements and the other for seismological monitoring. Both systems share the same architecture: data are analysed by a microcontroller, stored on a removable Flash memory and stastistics are transmitted through Argos.

Fig. 1. Photograph of the extensometer installed across a fracture on the summit of Merapi (Java, Indonesia). The box contains a one channel electronic system and the battery. The Argos antenna and the solar panel are fixed on the box. The wire of the extensometer is protected by a plastic tube.

4.1. *Slow rate sensor monitoring*

The TAD 808 recorder has up to 8 channels recorded locally, among them up to 4 channels can be transmitted on Argos. The input is adaptable to various types of sensors: voltage or current in different ranges, resistance, frequency, RS232 ... The signal is digitized with a voltage-to-frequency converter (11 bits) which automatically filters the spurious signals and is stored on a removable Flash memory. Standard sensors like a tiltmeter, an extensometer, a temperature gauge and a radon sensor can be connected to the TAD 808 recorder. An extensometer has been installed on a fracture on the summit of Merapi (Indonesia) (fig. 1). An example of data transmitted through Argos is presented in fig. 2. This recorder is similar to many such electronic systems, except that the local Flash memory storage is complemented by an Argos transmission.

4.2. *Seismological monitoring*

TAD has conceived a seismological event detector – Sismo1 – that stores seismograms and transmits through Argos statistics on the seismic noise and on the number and size of earthquakes. Sismo1 is a one channel seismic recorder equipped with a removable Flash memory. It has all the functions of a standard seismological recorder and it also performs a statistical analysis of the seismic signal that can be transmitted through Argos. Sismo1 is also used for local seismicity studies and for teleseismic recording (lithospheric tomogra-

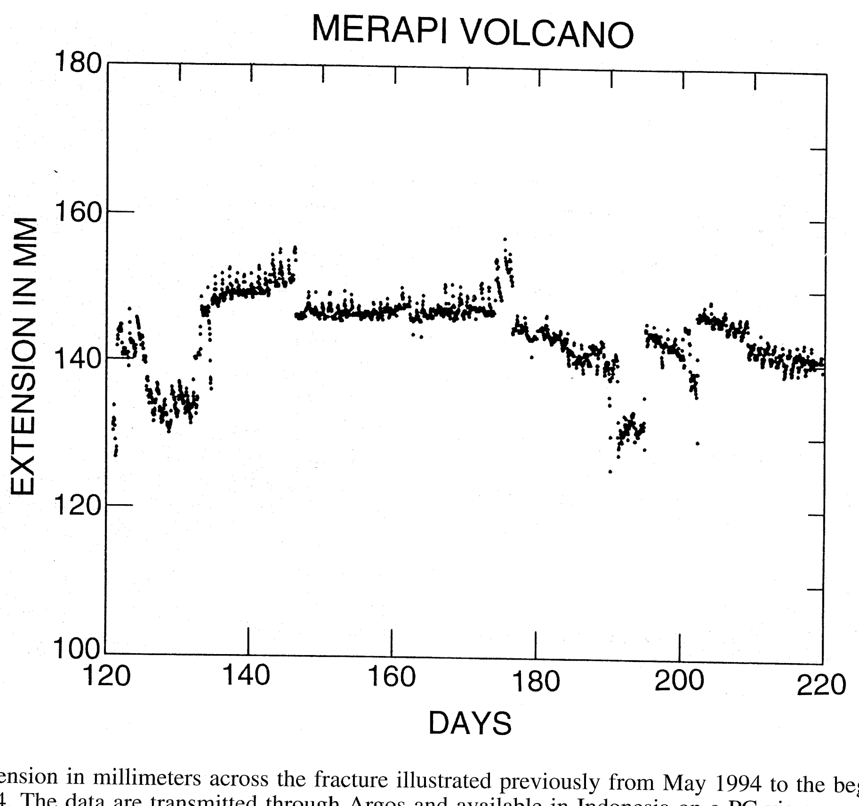

Fig. 2. Extension in millimeters across the fracture illustrated previously from May 1994 to the beginning of August 1994. The data are transmitted through Argos and available in Indonesia on a PC via a non-dedicated phone connection to the Argos Centre. A daily component related to temperaure is observed in the data.

phy). The input board is a programmable low noise preamplifier allowing gains from 1 to 2048. The analog to digital converter performs through a continuous integration of the signal during a time window of at least 5 ms. The digitization range is 11 bits plus sign and the sampling rate is chosen between 200 and 12.5 points per s. Events are detected by a Sta/Lta algorithm (short term average on long term average). The sampling rate, Sta duration, Lta duration, trigger level, length of the stored waveform are programmed by connecting a PC to the station, either in the laboratory or in the field. In the stand-alone version, a time synchronization signal is input to the station and stored in a table of comparison between the internal clock and the external time signal. When using Argos, the internal time is transmitted at the beginning of each message and compared to the time of reception of the message in the satellite. Thus, the drift of the clock is monitored with respect to the satellite clock which is precise. Event waveforms are on removable Flash cards with a maximum length of 16000 samples. The maximum storage capacity of a Flash card is actually 20 Megabytes and will increase to 64 Megabytes. The Flash card is read on a standard PC equipped with the appropriate reader. A retrigger mode is available.

The Argos message contains a statistical summary of «seismic activity». A time window of length T = 3, 6 or 12 h is selected for the computation of the various statistics:

– the average seismic noise per time window of $T/6$ h;

– the number of earthquakes per range of size (equivalent to magnitude);

– the number of minutes during which the signal overtakes some prefixed thresholds;

– the trigger time for the largest event;

– the time of the station when the message is transmitted to Argos;

– the percentage of Flash card memory space used.

Seismic recorders entirely devoted to volcanic signal processing, for instance the RSAM (Endo and Murray, 1991 or Brüstle *et al.*, 1992) electronic systems, could be connected to an Argos or Meteosat transmitter. However, for a seismologist, it is important to visualize the seismic signals that are considered precursors to an increase in activity of the volcano. Waveforms are very complex and difficult to characterize by present low power field electronics.

The Sismo1 electronic systems installed on Merapi is shown in fig. 3. Seismograms recorded on the Flash memory and processed later on a PC with the Sismalp software (Fréchet and Thouvenot, 1993) are presented in fig. 4. The data transmitted on Argos for two counters giving the number of earthquakes in two amplitude range are plotted in fig. 5. This information corresponds to 4 bytes in the 32 byte Argos messages.

Fig. 3. Photograph of a Sismo1 seismic event detector installed on the summit of Merapi (Java, Indonesia). The sensor is a Mark Product L4C 1 Hz seismometer. The Sismo1 electronics is protected by the box close to the antenna which is fixed on top of a small mast. A solar panel recharges a car battery.

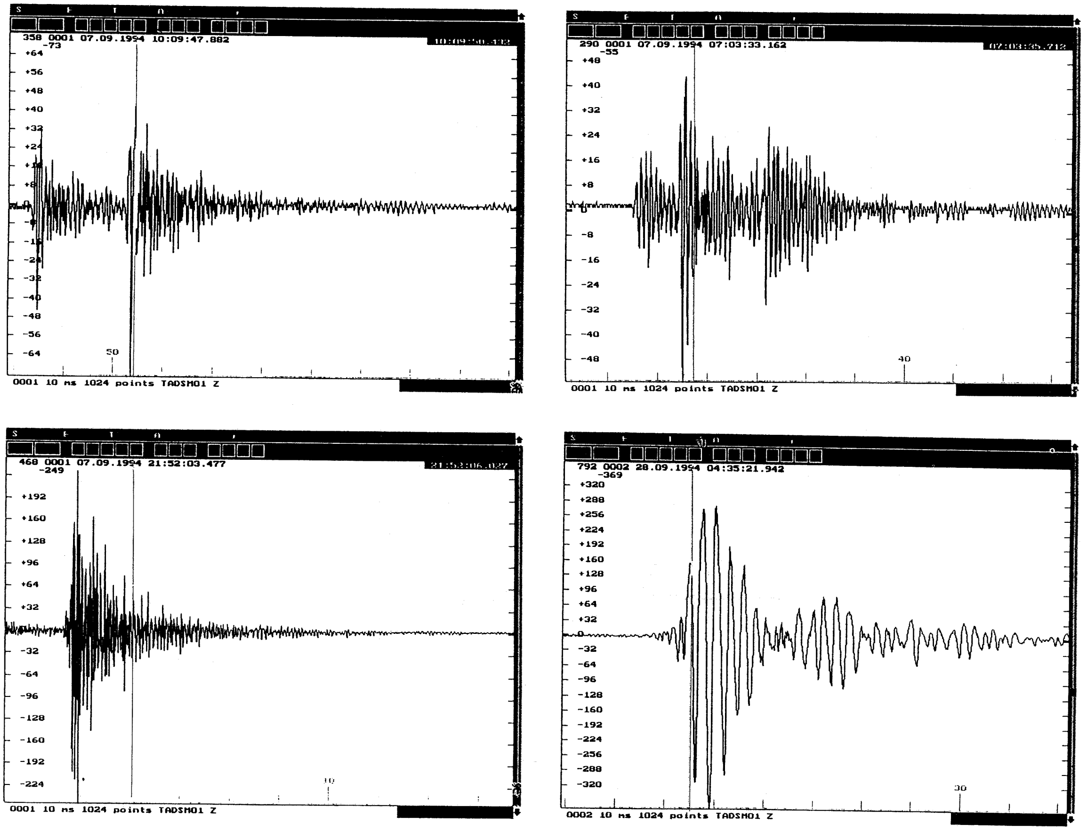

Fig. 4. Examples of short period seismograms recorded on the removable Sismo1 Flash memory installed on Merapi. The data are transferred on a PC and processed with the Sismalp software.

5. Conclusions

In countries where many volcanoes are spread over large areas, the UNESCO panel on mitigating volcanic hazards (Yokohama *et al.*, 1984) suggested a two-step strategy: an early warning system and a mobile array for monitoring emergencies. For long-term monitoring, low-cost instruments should be deployed for giving early warnings when signs of unrest are detected. Various groups have developed volcano monitoring devices connected to meteorological data collecting systems. These instruments can be installed almost anywhere on the globe, and measurements are centralized in regional or national centers. Satellite telemetry is adapted for monitoring volcanoes during the long time periods in between the phases of unrest. The pre-processing of seismological data and the recognition of seismic signals that are the sign of an unrest phase, is not easy. However, a system that gives information on the average noise level, the number of earthquakes per magnitude range and the duration and frequency of tremors, performs an analysis which is similar to that of an operator. Usually before an andesitic volcano awakes, there have been no or just a few previous records of volcanic quakes that may allow classification of the events; therefore a local storage of the events and the possibility to visualize waveforms seems to be the best solution because of our

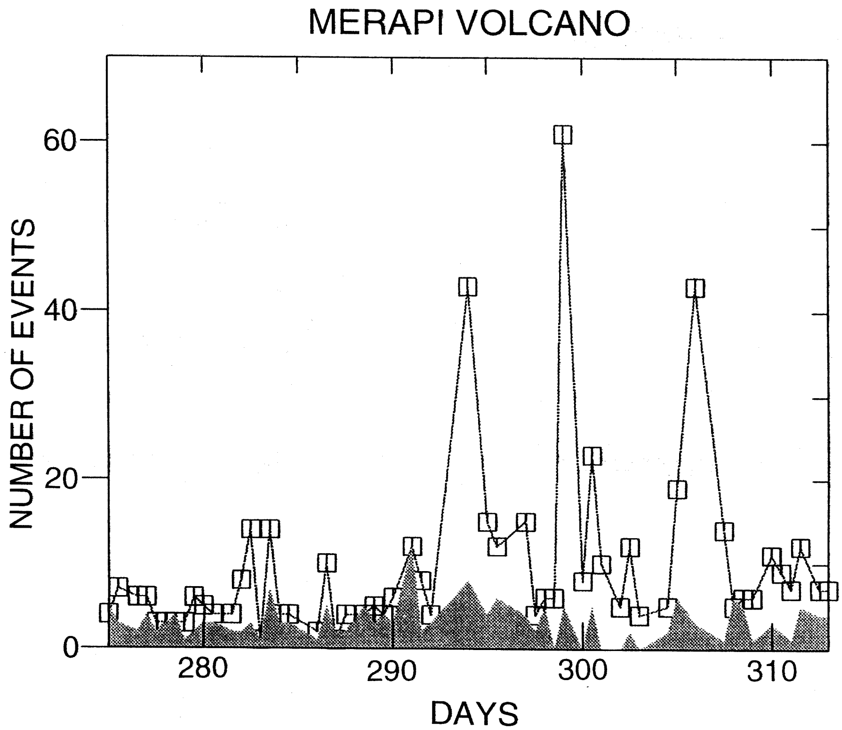

Fig. 5. Example of statistical data on seismicity transmitted through Argos. The two curves are the number of earthquakes per day for the amplitude ranges 128-256 and 256-512 (in digitization units).

limited knowledge of precursory events. Sismo1 is an early warning station that transmits via Argos statistics on the seismic noise level and on the number and size of earthquakes and that also retrieves seismic waveforms that can be analyzed in more detail at a later time by specialized personnel.

Acknowledgements

The development of this equipment has been funded by CLS-Argos. The tests of these instruments in Indonesia are funded by Délégation aux Risques Majeurs from the French Ministry of Environment within the frame of the French-Indonesian project in volcanology. We thank M.lle R.-M. Chevrier and the French Embassy in Jakarta for helping to solve administrative difficulties. We thank Dr. Wimpy Tjetjep and Dr. R. Sukhyar from the Volcanological Survey of Indonesia for their continuous support; François Beauducel and Michel Dejean for implementing this project in Indonesia; Michel Lambert and Denis Hatzfeld for their help.

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