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ESTABLISHMENT, TEST, AND EVALUATION OF A PROTOTYPE VOLCANO-SURVEILLANCE SYSTEM_/

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ABSTRACT

A volcano-surveillance system utilizing 23 multilevel earthquake counters and 6 biaxial borehole tiltmeters is being installed and tested on 15 volcanoes in 4 States and 4 foreign countries. The purpose of this system is to give early warning when apparently dormant volcanoes are becoming active. The data are relayed through the ERTS-Data Collection System to Menlo Park for analysis. Installation was completed in 1972 on the volcanoes St. Augustine and Iliamna in Alaska, Kilauea in Hawaii, Baker, Rainier and St. Helens in Washington, Lassen in California, and at a site near Reykjavik, Iceland. Installation continues and should be completed in April 1973 on the volcanoes Santiaguito, Fuego, Agua and Pacaya in Guatemala, Izalco in El Salvador and San Cristobal, Telica and Cerro Negro in Nicaragua.

The event counters developed for this use count earthquakes of four different amplitudes. An earthquake is assumed if 10 peaks of a full-wave rectified seismic signal exceed a given threshold in 1.2 seconds and no peaks had exceeded the threshold in the previous 15 seconds. This latter criterion inhibits the counters if the ground noise is high for long periods of time. Inhibit times are counted on separate counters. All data are printed on a unique printer in the counter that provides a check on the reliability of the DCS. The average power consumption is only 2 milliwatts, and the counters are now operating reliably in a wide range of environments. Standard seismometers are being placed near most event counters in this initial program in order to verify that the counters are discriminating earthquakes as anticipated. Local earthquakes are being recorded at nearly all sites.

The biaxial tiltmeters are 2 inches in diameter and fit in a hole 5 feet deep. They are proving easy to install and are operating stably with a sensitivity of about one microradian.

Since this project was not funded until one month before the launch of ERTS-A, much of the first year of satellite life has been

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spent building and deploying equipment. The data available to date show that the instruments are working quite reliably and show how the system can be tuned to improve the data and reliability. The primary objective--evaluating the effectiveness of the system--must await more data.

1. INTRODUCTION

A prototype volcano-surveillance system consisting of 23 multi-level earthquake counters and 6 biaxial tiltmeters is being installed and tested on 15 volcanoes in Alaska, Hawaii, the Cascades, Iceland and Central America. The data from the instruments are relayed via the ERTS Data Collection System to Menlo Park for analysis. Such rapid and routine collection of data from a variety of widely spaced volcanoes is a major breakthrough in the surveillance of potentially hazardous volcanoes. There are more than 500 historically active volcanoes scattered throughout the world, but only a few may be erupting at one time. Some volcanoes emit fume for years with no explosive eruptions, while other seemingly dormant volcanoes suddenly become violently active. Although visual evidence of an impending eruption may be detected too late to allow proper study, there are usually much earlier indications that an apparently dormant volcanic center is becoming active, such as increases in earthquake activity and the rate of ground tilting. Until now, routine observations have been logistically and financially feasible at only a few volcanoes. Very few volcano observatories exist, primarily because of the long-term financial commitment necessary. A devastating eruption may arouse interest in establishing an observatory, but by the time one can be developed, the volcanoes it was designed to study may have become inactive. Thus, there is a great need in volcanology for a method of monitoring large numbers of volcanoes with relatively simple instruments and with a minimum of manpower and other resources, for the purpose of identifying the most dangerous volcanoes. Once these are identified, studies aimed at predicting devastating eruptions can be started.

The ERTS Data Collection System offers an excellent opportunity to collect data from widely scattered instruments and to make them rapidly available for analysis at a central facility with minimal logistical expense. It eliminates the need to send observers in many different countries up the sides of rugged volcanoes, often in bad weather, to collect data routinely. It also permits rapid, simultaneous evaluation and comparison of observations from a large number of similar volcanoes by a single group of volcano specialists; thus new results from any volcano that does erupt are immediately available to aid in interpreting data from many others.

Two relatively easily measurable phenomena that have been observed to change most consistently prior to volcanic eruptions are the occurrences of large numbers of small earthquakes and small changes in the ground tilt, which are typically related to the swelling of the volcano (e.g. Eaton and Murata, 1960; Minakami et al., 1969; Minakami, 1960; Tokarev, 1971). Tokarev (1971) has even used the rate of increase in numbers of small earthquakes to predict the eruption of andesitic volcanoes in Kamchatka and Japan. The recent eruption of Helgafell volcano in Iceland, for example, was preceded by an intense swarm of small earthquakes on the previous day (Páll Einarsson, oral communication, 1973).

For these reasons, we have chosen to develop multilevel earthquake counters and biaxial tiltmeters for use with the satellite data relay system and are presently evaluating and testing the reliability and utility of the instruments under a wide variety of conditions.

2. DEVELOPMENT OF THE EARTHQUAKE COUNTERS

Standard methods for recording earthquakes produce data at the rate of about 4 million digital bits per 12-hour period. Yet the ERTS Data Collection System can only relay approximately 64 bits in a 12-hour period. Other satellite relay systems would not significantly increase this data rate and still keep the system economical enough to operate on a wide scale. Thus, substantial data compression is necessary.

Since the most important aspect of volcanic earthquakes to be monitored is a large increase in the rate of occurrence of local earthquakes, a multilevel earthquake counter was developed and tested in 1971 (Figure 1). This experience led to the development of a new counter in 1972 for the ERTS-A experiment. Twenty-three of these counters were built and are proving to operate very reliably in a wide variety of climates (Figure 2). The principal criteria for an event to be counted are as follows: 1) 10 peaks of the full-wave rectified seismic signal must be above a given threshold level during an interval of 1.2 seconds, and 2) there must have been no signal above the threshold during the previous 15 seconds. Each instrument contains four counters separated in threshold level by factors of four. This multilevel feature is an important improvement over the single level event counters used earlier by Decker (1968) because it allows the reliability of the data to be tested and gives a greater dynamic range. Each earthquake counter channel is inhibited by continuous high ground noise. The inhibit times are counted on separate counters. All counts are recorded on a small printer, as well as being relayed to the satellite. The printer has only one moving part, a solenoid, and records the data in a compact binary matrix. In this way 75 bits of information can be printed every 6 hours for 2 years on a reel of tape only 0.25 inches wide and 3 inches in diameter.

The design of the new event counters appears quite suitable and reliable for this use. One principal question to be answered is whether these criteria for data compression are indeed satisfactory. Thus, in the present experiment, standard seismometers have been set up near most of the event counters so that the compressed data can be compared directly with the more usual types of seismic recordings (Figure 3).

Other methods of compressing seismic data, but using digital computers and complex analog circuits, have been under development at the National Center for Earthquake Research for some time (e.g. Stewart et al., 1971). Such methods are still too complex to be used in a widespread system and are not yet sufficiently well developed and reliable for use in a volcano-surveillance network, although they hold considerable promise for the future.

3. DEVELOPMENT OF THE TILTMETERS

Eaton (1959), building on earlier work in Japan (Hagiwara, 1947; Hagiwara et al., 1951), developed extensively the use of watertube tiltmeters in Hawaii and demonstrated their great value in studying volcanoes. Since that time he and others have searched for ways to measure tilt more routinely and simply. This search culminated in the development of a pendulum-type borehole tiltmeter by Allen (1972) and others at the National Center for Earthquake Research. During 1972 an entirely different type of borehole tiltmeter was developed by suitably packaging an electronically monitored level bubble developed by North American Rockwell for use in the Minuteman Missile. The new instrument is a very low power biaxial tiltmeter only 2 inches in diameter and about 3 feet long (Figure 4). In tests alongside other types of tiltmeters operated by the USGS, this new tiltmeter has proved to be stable and sensitive enough to record earth tides. Furthermore, it is substantially cheaper and easier to install than the other tiltmeters tested.

Under the ERTS-A program one of these meters was installed in welded tuff on Mt. Lassen in California and one in sand in Hawaii, and two will be installed in Guatemala. Two others have been installed in Hawaii under a related program. We have found methods for installation in rock (Figure 5) and all types of soil using only tools that can be easily backpacked. Different designs of installations and different types of sites still need to be tried, however, to develop simple and reliable methods of placing these new meters in regions of maximum tilt changes on andesitic volcanoes.

4. ESTABLISHMENT OF A PROTOTYPE VOLCANO-SURVEILLANCE SYSTEM

The distribution of earthquake counters, standard seismometers, and tiltmeters installed or planned as part of this prototype surveillance system is summarized in Table 1. This program was funded less than a month before the launch of the satellite. As NASA continued to delay the start of this program, we realized that it was becoming impossible to develop the earthquake counters and install them in Alaska and the Cascades before winter. Thus, we began designing the counters in January 1972, and with the help of a loan from the EROS program, we were able to issue a subcontract in May to build the 23 counters. The first counters were delivered in late August 1972, and by late September the system was integrated and tested. The sites had already been selected where possible, and despite early snowfalls, installation in the Cascades was completed by late October. In Alaska, however, we could only install instruments at St. Augustine in September before winter set in. Owing to subfreezing temperatures, a second instrument was placed near Iliamna Volcano, rather than the planned sites on the volcanoes Redoubt and Spurr.

In December 1972, event counters and DCP's were installed in Hawaii and at a site near Reykjavik, Iceland, to test whether the range of the ERTS data transmission system is sufficient to reach these important volcanic regions. The Icelandic instrument will be moved to a volcano next summer when weather allows. During November and December, sites were selected in Central America, and the necessary permits were obtained. Installation was begun in Guatemala in February and should be completed in Nicaragua by April. An average of about 10 messages per day are being received from stations in the Cascades and 6 per day from Alaska, with all transmitters adjusted to transmit once every 3 minutes. In Hawaii and Iceland the transmitters send data every 90 seconds, and an average of about 6 and 10 messages per day, respectively, are received. These data rates are quite sufficient.

The final key link in the system will be a teletype from Goddard Spaceflight Center to Menlo Park for rapid data analysis. We hope this will be installed by April 1973.

5. SIGNIFICANT RESULTS

By February 1973, over 13,000 messages had been received from the satellite and analyzed. These data show clearly that the event counters and tiltmeters are working quite reliably and with incredibly few problems, considering the complexity of the system and the speed with which the instruments were designed, built, and installed. The only instruments to stop altogether are those on Mt. Baker, where a storm in January either destroyed the antennas or buried them too deeply in snow. Thus, we have succeeded in designing and building equipment that is reliable and stable at least over a short time period. We have also shown that the ERTS Data Collection System will operate satisfactorily over nearly twice the anticipated range. Naturally, our experience has led to many ideas for minor adjustments and improvements to tune up the system. These changes will be incorporated where feasible, but the main object now is to evaluate and test this volcano-surveillance system. Although too few data have been recorded so far to support a meaningful detailed analysis, it is clear that the event counters are discriminating earthquakes from most other seismic noises and that many small earthquakes are occurring at nearly every volcano studied, including Mts. Baker and Rainier in the Cascades.

Now we need to establish the background level of seismicity and tilt at these volcanoes so that abnormal activity can be rapidly identified.

The long-range objective of this project is to develop an automated global volcano-surveillance system utilizing relatively simple and inexpensive earthquake counters and tiltmeters on many volcanoes in order to detect which volcanoes are undergoing the most rapid internal changes and should be studied in detail to assess the danger of devastating eruptions. Thus, the most important objective is to observe the performance of these instruments before, during and after various stages of volcanic activity at a wide variety of volcanoes to prove whether the event counters, tiltmeters and data relay system do indeed work as planned to provide accurate, economical and timely information about the eruptive state of volcanoes. Now that the major hurdle of design and deployment has nearly been successfully passed, we feel the appropriate data can be collected in the next few years to meet this objective. The odds of observing eruptions seem quite good. The volcanoes Kilauea, Pacaya and the Fuego-Acatenango complex have been erupting in the past few months. The odds could be substantially increased, now that the range of the Data Collection System has been proven, by extending this surveillance system into Costa Rica, where there are several very active volcanoes. Otherwise this program as now formulated gives a good test of the event counters, provided the system functions for many years.

More tiltmeters, however, should be installed to give them a proper test. Only a few were included in this original program because during the planning stage inexpensive borehole tiltmeters were not proven. Now that we have shown the feasibility and practicality of these tiltmeters, we need to test their long-term reliability and stability under a wide range of conditions and to further develop techniques for deploying them on the many types of volcanoes.

In summary, installation of the prototype volcano-surveillance system being developed and tested by the U.S. Geological Survey under the ERTS-1 program is nearly finished. The equipment is working well. As the data begin to accumulate and evaluation begins, it should become more and more apparent that this network will make a major breakthrough in the surveillance of potentially hazardous volcanoes made possible primarily by the data-collection capability of the ERTS-1 satellite.

TABLE 1: PROTOTYPE VOLCANO-SURVEILLANCE NETWORK

COUNTRY OR STATE	VOLCANO	EVENT COUNTER + DCP	VISIBLY RECORDING SEISMIC SYSTEMS	TILTMETER + DCP	INSTALLED 1972-1973
ALASKA	ST. AUGUSTINE	1	1 existing		SEPTEMBER
	ILIAMNA	1	U.S.G.S. network		SEPTEMBER
WASHINGTON	BAKER	1	1		OCTOBER
	RAINIER	1	1		OCTOBER
	ST. HELENS	1	1		OCTOBER
CALIFORNIA	LASSEN	1	1	1	OCTOBER
HAWAII	KILAUEA	2	U.S.G.S. network	3	JANUARY
ICELAND	NEAR REYKJAVIK	1	1 existing		DECEMBER
GUATEMALA	PACAYA	1	1	1	FEBRUARY
	AGUA	1	-	-	FEBRUARY
	FUEGO	1	1	1	FEBRUARY
	OFF VOLCANIC AXIS	1	1	-	FEBRUARY
	SANTIAGUITO	2	1	-	MARCH*
EL SALVADOR	IZALCO	1	1		MARCH*
NICARAGUA	SAN CRISTOBAL	1	1		MARCH*
	TELICA	1	-		MARCH*
	CERRO NEGRO	1	1		MARCH*
	OFF VOLCANIC AXIS	1	1		MARCH*
		20	12 new		*planned

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Figure 1: The multilevel earthquake counter with the satellite transmitter on the left and batteries for operation for one year on the right. The seismic sensor is in the foreground. The event counter weighs 25 pounds and measures 10 by 14 by 12 inches.

Figure 2: A typical field installation of the seismic event counter. The dome on the antenna is to insulate the antenna's active elements from snow. This instrument is located in Alaska on the flank of Mt. Iliamna.

Figure 3: The standard seismic station on Mt. Lassen. The electronics and batteries are in the box in the left foreground. The signal is transmitted in the FM mode to Menlo Park for recording using the VHF antenna shown.

Figure 4: The biaxial borehole tiltmeter used in this project.

Figure 5: Drilling a four inch in diameter hole in welded tuff on Mt. Lassen. The drill frame is bolted to the rock.