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CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES

TRIP REPORT

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DATE/PLACE: Colima, Mexico; Jorullo volcano, Mexico; and Parícutin volcano, Mexico; January 24 - February 11, 1994

AUTHOR: Charles B. Connor

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AUTHOR: Charles B. Connor

PERSONS PRESENT: Charles B. Connor, CNWRA
James Luhr, Smithsonian Institution
Mike Conway, Florida International University
Mitchell Ventura, Technical Field Assistant, Colima, Mexico

Background

This trip was undertaken to perform preliminary fieldwork at Parícutin volcano, Mexico, as outlined in the Field Volcanism Project Plan. The trip was planned to coincide with the Fourth International Volcanology Congress in Colima, Mexico. Connor presented three papers at this meeting. Also, the opportunity was taken to visit Jorullo volcano, a small-volume basaltic cinder cone located approximately 100 km from Parícutin and which formed in 1759.

The Field Volcanism project is designed to provide insight into the consequences of potential small-volume basaltic eruptions in the Yucca Mountain Region (YMR) to repository performance (Connor, 1993). Two areas of investigation that are critical to the determination of compliance are:

(i) the mechanics of cinder cones eruptions, including the entrainment and dispersive character of cinder cone eruptions, the duration of these eruptions, and the areal distribution of vents at active cinder cones

(ii) the secondary effects of volcanism, including the effects of diffuse degassing and thermal loading on geochemical transport, container performance, and groundwater movement.

In terms of its growth and development, Parícutin is clearly the most analogous historically active cinder cone in North America to those found in the YMR. Parícutin volcano (19.48 °N, 102.25 °W) is located in the Michoacán-Guanajuato volcanic field, Mexico, within the TransMexican Volcanic Belt (Williams, 1950; Hasenaka and Carmichael, 1985). There are well over 1,000 cinder cones in this region, in addition to several hundred monogenetic and polycyclic shield volcanoes, composite cones, and maars.

Cumulatively, this is probably the largest sub-aerial volcanic field on Earth. Parícutin is part of a cluster of approximately 120 cinder cone within the Michoacán-Guanajuato volcanic field. All of these cinder cones are believed to be less than 2 million years old and approximately 70 cones in the region are believed to be less than 40,000 years old, largely based on geomorphic evidence and eight ^{14}C dates (Hasenaka and Carmichael, 1985). Numerous young cinder cones are located in the immediate vicinity of Parícutin (Figure 1).

Parícutin formed as a result of eruptive activity that commenced in 1943 and continued through 1952. Details of the Parícutin eruption are summarized by Wilcox (1954). The Parícutin eruption began in February, 1943, when hot gases and pyroclastic rocks began erupting from a small fissure in a cultivated field. This pyroclastic activity was preceded by several weeks of seismic activity that was reported to increase in intensity and frequency up until the initiation of the eruptive phase (Wilcox, 1954). Although the eruption lasted nine years, most of the central cone was built in the first year of activity, during which time pyroclastic activity was fairly steady (Segerstrom, 1950). During October, 1943, a series of new vents formed on a NE -trending line. These vents, located NE and SW of the main cone, were the sites of vigorous explosive and effusive activity, and were alternately active and quiescent until the end of eruptive activity in 1952. According to Wilcox (1954), new satellite vents continued to form as late as 1947. Lava flow effusion ceased at Parícutin in February, 1952 and pyroclastic activity declined gradually until it also ceased in March, 1952. The cinder cone is now approximately 350 m in height and lava flows from the volcano cover an area of about 24 km^2. The nine year Parícutin eruption produced approximately 1.3 km^3 of lava and 0.7 km^3 of tephra and a total volume of 1.32 km^3 (dense rock equivalent) (McBirney et al., 1987).

The most energetic explosive activity occurred during March-August, 1943 (Foshag and Gonzalez, 1956). During this phase of activity, highly convective ash column heights were maintained at 6 to 8 km above Parícutin and blocks up to 15 m in diameter were ejected from the central crater. During the most energetic explosive activity ash accumulated to a thickness of 15 cm approximately 6 km from the central cone and ashfall was reported up to 250 km from Parícutin (Foshag and Gonzalez, 1956). Although the most sustained and intensive pyroclastic activity occurred during the first two years of activity, explosive activity continued through the end of the eruption in 1952.

As is the case with all cinder cone eruptions, volatile content is thought to have been an important control on eruption energetics at Parícutin. Several estimates of the volatile content in Parícutin magmas have been made previously (Fries, 1953; Eggler, 1972; Anderson, 1979). Fries (1953) estimated water content exsolved during the eruption by estimating the amount of gas released in the column above the volcano compared with the volume of material erupted. Fries calculated the volatile content to be about 1 weight percent using this technique. Eggler used phase relations among phenocrysts in Parícutin lavas together with experimental results to estimate water content at about 2.2 percent in Parícutin magmas. Anderson (1979), using melt inclusions in Parícutin lavas, found volatile contents of approximately 1.5 percent by weight. Volatile concentrations of 1-2 percent indicate that magmas were likely fragmenting at depths of more than 300 m and ascended as highly erosive gas-magma mixtures from those depths.

Wilcox (1954) reports that xenoliths of gabbro, quartz monzonite, and Tertiary silicic tuffs were common in the eruptive products during the first two years of activity. Parícutin lies on a section of Quaternary basalts of unknown thickness, but likely on the order of several hundred meters thick (Williams, 1950); the thickness of the underlying Tertiary silicic tuffs is also unknown, but is estimated by Williams (1950) to be over 300 m thick the Parícutin region, based on exposures along the Cupatitzio river about 30 km from Parícutin.

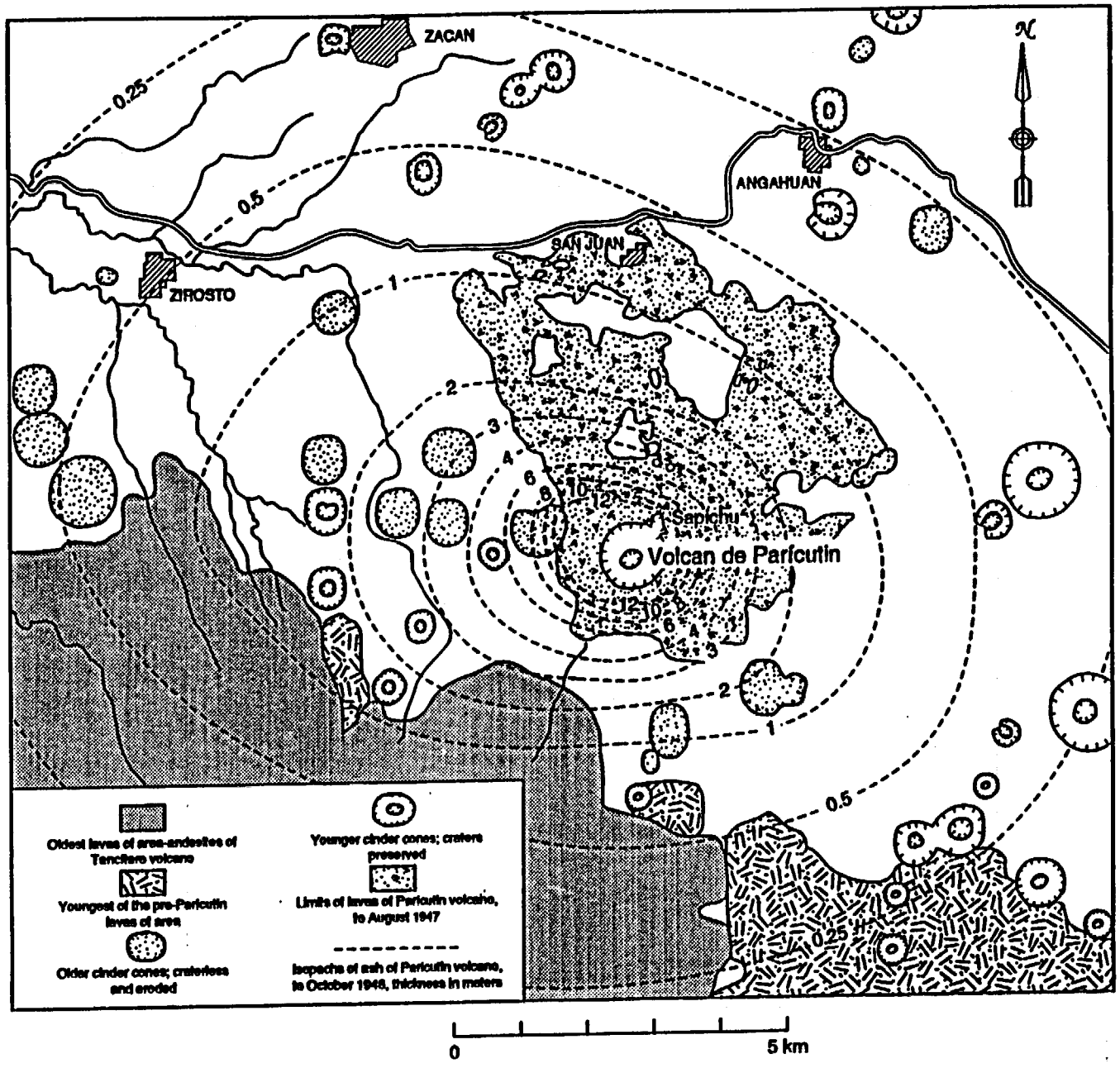


Figure 1. Cinder Cones near Parícutin (From Foshag and Gonzalez, 1956).

Parícutin continues to degas today, forty-one years after the cessation of eruptive activity. This degassing is extremely weak compared with that observed at many quiescent composite volcanoes, but is also quite sustained, with low mass flow, high-temperature fumaroles remaining stable since at least 1983 (McClelland et al., 1987). Connor (1989) mapped fumaroles and soil Hg anomalies around the main crater and Ahuan vent, located SW of the main crater, and the Taqui vent, located NE of the main crater. High-temperature fumaroles are restricted to the Ahuan and Taqui vents. Temperatures at the Ahuan vent have been monitored intermittently since 1983. During this period, temperatures have varied between 473 °C, recorded in November, 1985, and 303 °C, recorded in 1991. These fumaroles have low mass flows and the dominant components of the gas are water vapor, HCl, and Cl_2. Sulfur species are present in very low concentrations (R.E. Stoiber, personal comm., 1993). A single SP electrical traverse across the Ahuan vent , made in 1983, identified a 1.2 volt anomaly. These electrical data, although quite preliminary, may indicate the presence of localized zones of groundwater movement and vaporization in response to high heat flow.

Low temperature fumaroles (50-150 °C) are more widespread, occurring elsewhere on the lava flows, along flow levees, and along the rim of the main crater. Connor (1989) collected approximately 50 soil samples on the SW flank of the volcano, near and around the Ahuan vent. Soil Hg concentrations were found to be anomalously high over an area of at least 1 km^2 on the SW flank of the volcano (Figure 7), with soil Hg concentrations between 1200 and 11,000 ppb. These Hg concentrations are comparable to those found in active geothermal systems (e.g., Varekamp and Buseck, 1983; Lescinsky et al., 1987). Mean background concentrations in the Parícutin area, far from the volcano, are 30 $\pm$ 24 ppb. Based on Hg distributions, Connor (1989) concluded that convective upwelling of gas occurs over an area of at least 1 km^2 on and around the SW flank of the volcano. This diffuse degassing is far more widespread at Parícutin than is indicated by the distribution of high-temperature fumaroles or alteration zones, but its areal extent was not determined because of the limited extent of the Hg survey.

Specific activities planned for Parícutin fieldwork included:

- Collection of volcanic gases and fumarole temperature data at Parícutin.
- Collection of soil samples for soil Hg analysis over a broad area at Parícutin.
- Collect ash and volcanic bomb samples for volatile content determination.

These activities were carried out following the conference in Colima.

Colima Volcanology Conference (January 24 - 27)

An international volcanology meeting was held at the Universidad de Colima on January 24-28. This meeting consisted of approximately one hundred talks and posters, largely with the theme of reducing volcanic hazards. Connor presented three papers, one on diffuse degassing through soils on volcanoes, another on the 1992 eruption of Cerro Negro, Nicaragua, and a third on monitoring fumaroles and modeling mass flow from fumaroles.

Several talks of programmatic note include one by Dr. Gene Smith of the University of Las Vegas concerned with polycyclic cinder cone volcanism in the Yucca Mountain region. C.-H. Ho presented a Weibull-Poisson model for estimating recurrence rate of cinder cone volcanism in the YMR. Don

Hooper, a post-doc at SUNY Buffalo presented a model of cinder cone degradation based on the diffusion equation. He cited several areas in which he hopes to apply, including in the Pancake range of Nevada. Copies of these abstracts are attached.

The conference also included a discussion of the role of Colima as a Decade volcano - that is one that has been selected under the Decade for natural disaster reduction program.

Following the conference, Connor, Conway, Ventura, and Luhr traveled to Uruapan, Michoacán, Mexico, for studies at Jorullo and Parícutin volcanoes. The trip to Uruapan took one day by van.

Jorullo Volcano (January 29)

Jorullo volcano is located in southern Michoacán, about 100 km from Uruapan by road and near the city of Nueva Italia. Jorullo is a small volume basaltic cinder cone that formed during a single episode of activity that lasted from 1759 and 1778. No volcanologists witnessed the eruptions of Jorullo, but several geologists visited the cinder cone in the years following the eruption. Lyell wrote about the eruption extensively in his 1830 work, Principles of Geology.

The purpose of our trip to Jorullo was to collect samples of ash for analysis in order to characterize the rheology of the basalt, and to collect soil gas samples in and around the main crater of the volcano. Luhr, during field work five years ago, had found low-temperature fumaroles in the crater. This is intriguing because the persistence of thermal activity 200 yrs after the last eruption indicates that cinder cones may have a long-term impact on the hydrologic setting and possibly the geochemical setting of the repository, should a volcano form nearby.

The group hired a guide from the village of La Huacana and climbed the cone in about a one hour hike from the van. The cone is now densely vegetated and does not look much different than numerous other, older cinder cones in the area. We climbed to the NE rim of the crater, which was breached by a late stage lava flow. The inner walls of the crater are steep and unstable. An alteration zone is apparent on the SW crater wall, approximately 20 m above the crater floor. Connor and Ventura hiked to the alteration zone and found fumaroles over an area of approximately 40 m x 10 m. Temperatures ranges from 60 to 125 °C in this area. These fumaroles and the alteration zone are clearly related to inward dipping fractures along the crater wall, along which the crater wall is slumping. He, CO_2, and Hg samples were collected at the fumarole zone and on the floor of the crater. A second, more diffuse fumarole zone was found on the W wall of the crater. Fumarole temperatures within this zone were up to 125 °C. Additional samples were collected on an alignment of satellite cones extending SW of Jorullo. No fumaroles were identified on this alignment. A total of five CO_2 and He samples, and 10 Hg samples were collected at Jorullo.

Subsequent analysis of the He samples indicate that He concentrations at Jorullo are slightly higher than atmospheric. The most anomalous He samples were collected from soil on the crater floor of the main cone, and at the 125 °C fumaroles on the SW crater wall.

Ash samples were collected SE of the main cone, approximately 250 m from its base. Here, on a road that circles the cone on its east side, ash sections from the latest stages of the eruption are well exposed. Approximately 3 kg of sample were collected from these sections.

Parícutin Volcano (January 30 - Feb. 10)

Field work was carried out at Parícutin during a ten day period. The following activities were performed:

- Four fumaroles were monitored continuously during a four day period using a Campbell Scientific datalogger
- A total of 84 soil CO_2 samples were collected
- A total of 29 radon stations were established and monitored at intervals over a period of one week
- A total of 14 soil He samples were collected
- 93 soil Hg samples were collected
- An infrared CO_2 analyzer was tested for direct measurement of soil CO_2
- Gas condensates were collected from fumaroles for determination of H and O isotopic composition, and major element analysis
- Numerous ash samples were collect, primarily form a 2 m deep pit dug in the ash section approximately 800 m from the base of the cone.

Temperature data are shown in Figures 2-4. Temperatures were measured continuously in four fumaroles at the Ahuan vent, on the SW flank of the main cone. Temperatures in these fumaroles have been measured to be as high as 473 °C, in 1983, and have fallen steadily since that time. The highest temperatures recorded during this field work were about 220 °C (Table 1). These fumaroles are located in an alteration zone that measures approximately 100 m by 50 m. The fumaroles do not have a large condensable phase although flow is audible in these fumaroles. These comparatively high temperature fumaroles are surrounded by low-temperature fumaroles (40 - 85 °C) that cover a broad zone around the Ahuan vent, extending up onto the main cone, and to some of the surrounding lava flows. These fumaroles appear to emit water vapor. A second zone of higher temperature fumaroles is located at the Taqui vent, on the NE flank of the main cone. Fumarole temperatures of up to 280 °C were measured at the Taqui vent. Like the Ahuan vent, these fumaroles are in an extensive alteration zone and surrounded by low temperature fumaroles. The alteration and sublimate minerals around these fumaroles are: sulfur, hematitie, sylvite, magnetite, ilmenite.

Temperatures varied by as much as 40 °C during 24 hr periods during continuous monitoring and correlate well with atmospheric temperature in some fumaroles. Specifically, temperature variation in the lower temperature fumaroles correlates very well with atmospheric temperature variation. This correlation was not found in the highest temperature fumaroles located in the central part of the fumarole field (Figure 3). Barometric pressure fluctuations have a pronounced 12 hour cycle and no large barometric pressure fluctuations occurred during the sample interval. Fumarole temperature variations did not show a correlation with barometric pressure, as fumarole temperatures do at some volcanoes. A preliminary

Table 1. Temperature measurements at Parícutin.

	baro (mbar)	Air T (°C)	T1 (°C)	T2 (°C)	T3 (°C)	T4 (°C)
Minimum	744.0	10.8	190.2	182.6	163.9	136.0
Maximum	749.6	32.1	218.5	221.1	207.2	176.3
Range	3.6	21.3	28.3	38.5	43.3	40.3
Mean	746.0	18.4	204.0	203.3	188.8	153.8
Median	746.0	15.7	204.5	205.8	190.9	152.6
Std Deviation	1.2	6.4	3.8	8.9	8.7	7.6
Variance	1.5	41.1	14.9	79.7	75.4	57.5

interpretation of this is that air and gas flow in these fumaroles is driven by a Venturi effect, resulting in a good correlation with atmospheric temperature. It is clear from these preliminary results that Parícutin has an active hydrothermal system that is gradually cooling, but remains active 40 years after the end of eruptive activity.

Soil gas sampling stations were chosen using the following criteria:

- A base station was located far from the volcano, in an area thought to be beyond the influence of any hydrothermal activity or diffuse degassing. The base station was located at a campsite, 2 km NW of the main cone. The location of the base station was determined by GPS: 2159350N, 786820E

- Several stations were established on the main cone, at the Ahuan vent, and near the Taqui vent. Samples could not be located on the Taqui vent itself because this blocky vent lacks ash pockets or soil development.

- A sampling traverse was located along a NE survey line, extending southwest from the main cone. It was anticipated that soil degassing might be high along this line because of the preferred orientation of vents in a NE direction at Parícutin

- A sampling traverse was established trending NW, orthogonal to the apparent structural control on vent alignment in the area

- Other stations were established around the base of the cone, and extending south and southeast of the cone.

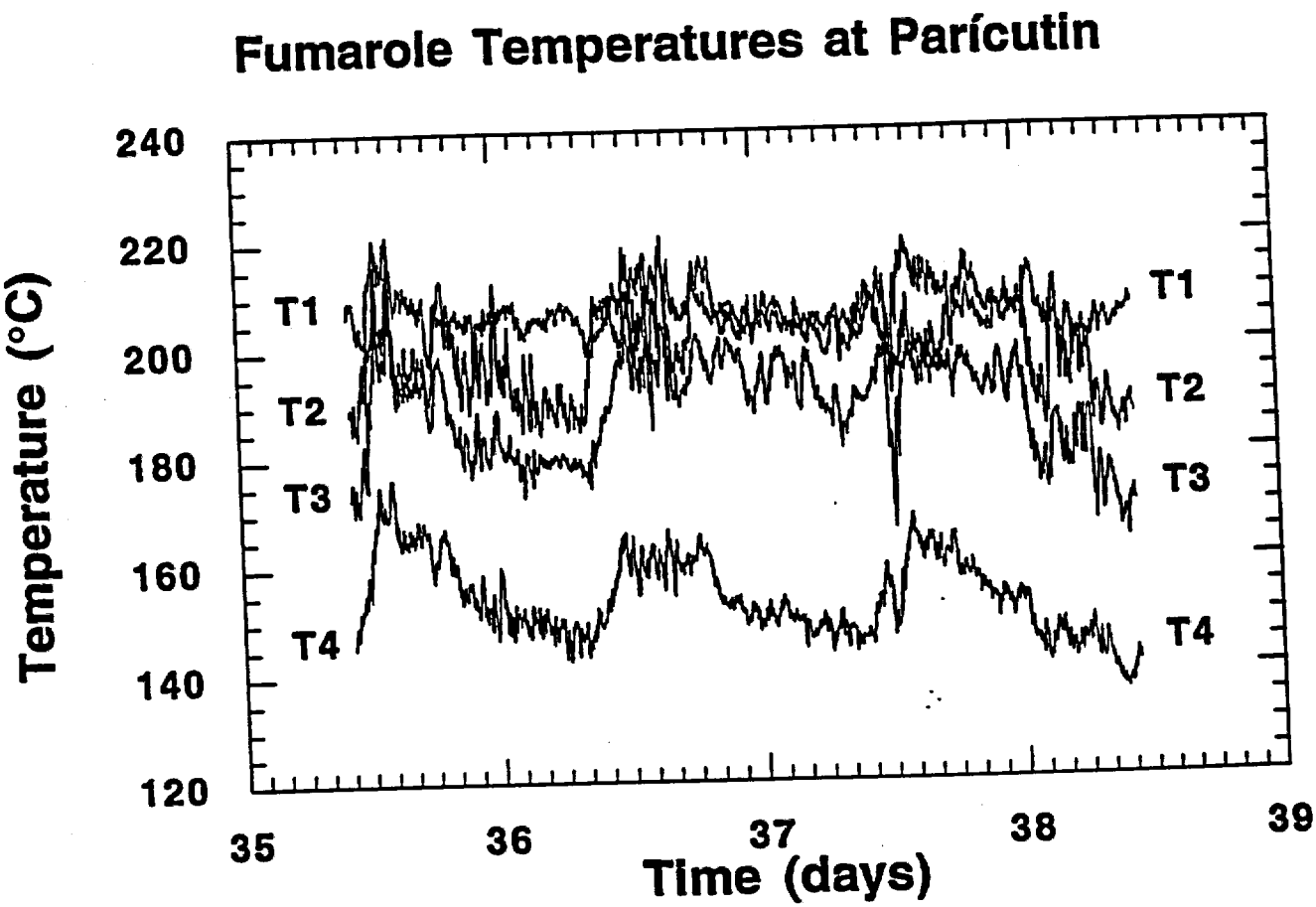


Figure 2.Temperature measurements in four superheated fumaroles at the Ahuan vent, Parícutin. Time in days since January 1, 1994.

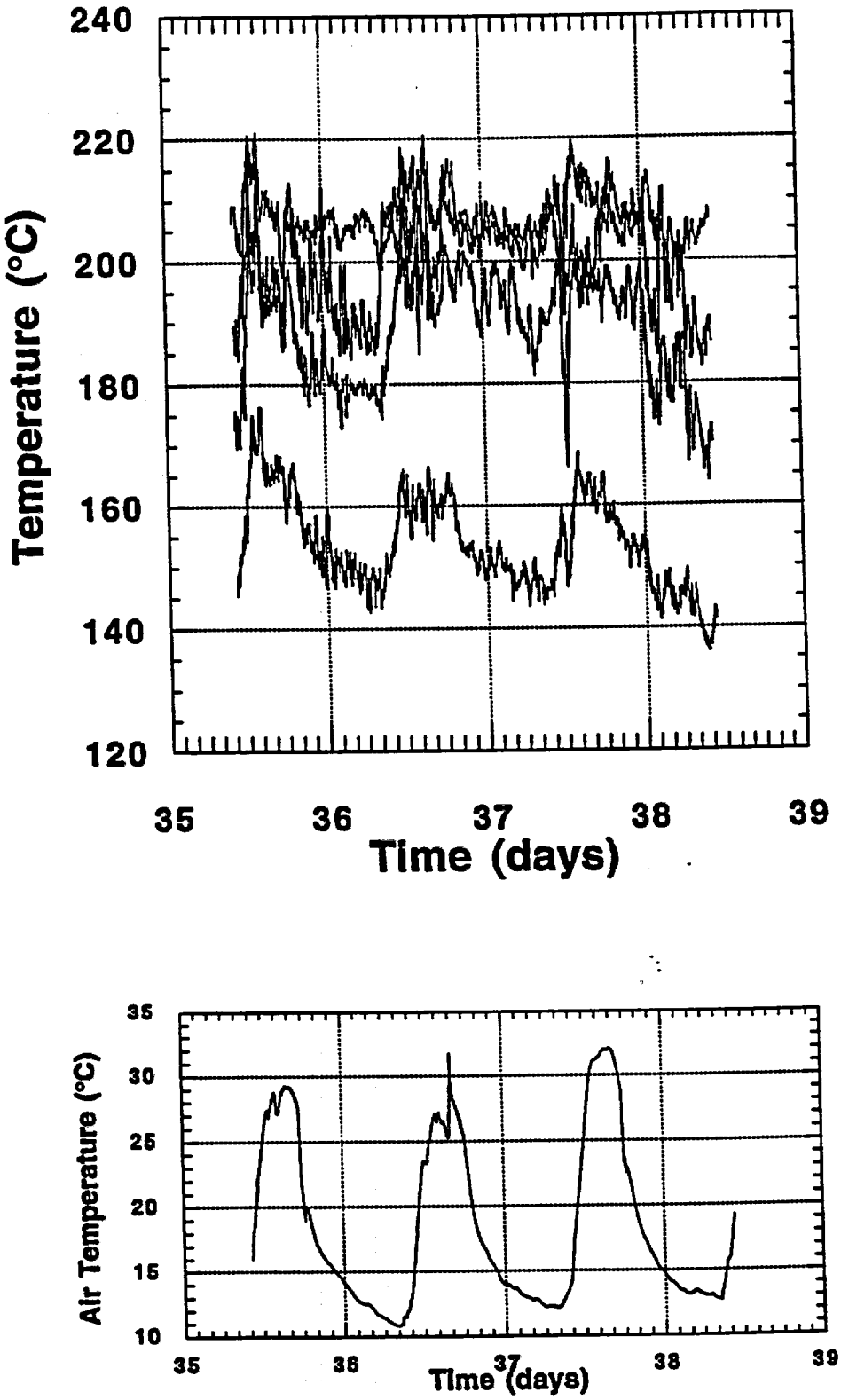
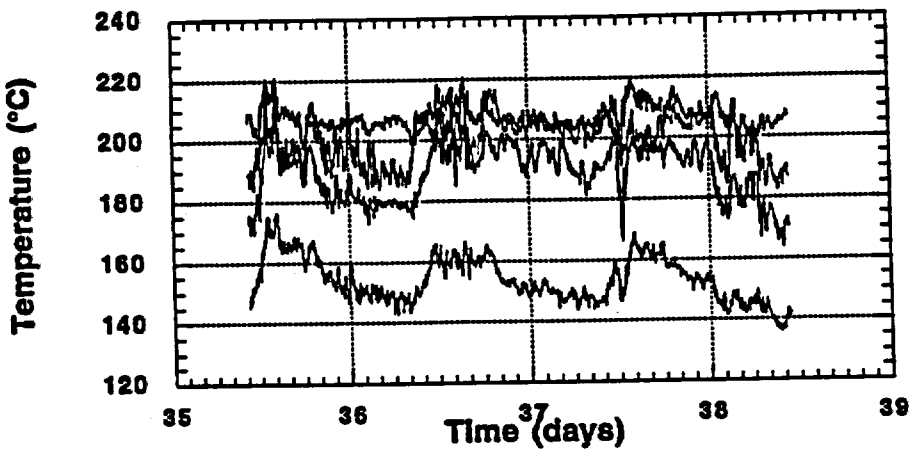


Figure 3. Relationship between fumarole temperature and air temperature.



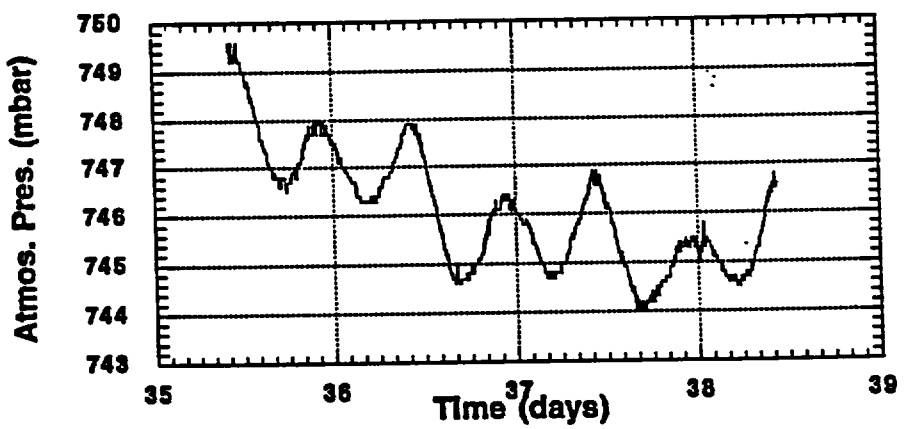


Figure 4. Relationship between fumarole temperature and barometric pressure.

- Sample locations were limited on the N and E sides of the volcano because there is little or no ash covering the late-stage lava flows there. This hinders soil gas sampling using our methods.

All sample locations were established using a GPS (relative error between stations of ±50 m). Sample locations were also determined using tape and compass techniques, with the exception of samples collected: (i) on the crater rim; (ii) on the North side of the cone; and (iii) the base station. Cross checking station locations indicates that these locations are known at worst to within ± 10 m and most have a relative error of less than 5 m. Sample locations and a base sketch map were subsequently digitized using the Arc/Info geographic information system.

Anomalously high He concentrations were identified in samples collected at the Ahuan vent and about 90 m from the Ahuan vent on the flanks of the main cone (Figure 5). Soil He concentrations are about 250 ppb in excess of atmospheric concentration; these concentrations are extremely high except in comparison to those observed at active volcanoes. For example, He concentrations at Kilauea volcano are up to 8000 ppb at sulfur bank. Other samples collected at Parícutin, mostly along a NE -trending traverse, average about 100 ppb in excess of atmospheric He. This indicates active convective upwelling of He in the area around the cooling cone. These He concentrations are normally thought to originate from decay of isotopes in the crust and indicate migration of excess He from depth.

Radon concentrations were greatest on the cone rim and in the area of the Ahuan vent (Figure 6). The highest radon concentration measured was 67 pCi/l, found on the northwest rim of the crater. Radon was found to be as high as 20 pCi/l at the Ahuan vent. High radon concentrations, in excess of 10 pCi/l, were also found along the traverse west of the cinder cone (Figure 6). Background Rn concentrations in the area are about 2.5 pCi/L. As was the case with the He concentrations, soil radon flux is high in a broad area around the cone and is very high on the main cone rim and at the Ahuan vent. Soil CO_2 concentrations were highest on the main cone (Figure 7) and were comparatively high throughout the survey area.

Hg samples collected at Parícutin are currently being analyzed. Isotopic composition of soil CO_2 and gas condensates is currently being determined.

In addition, a 2.3 m deep pit was dug at a distance of 1.5 km west of the main cone. Ash in this pit was sampled at 25 cm intervals for petrologic analysis, crystal size and vesicle distribution studies, and water content determinations.

Impressions and Conclusions

This survey at Parícutin provided an overview of current degassing at Parícutin. Several preliminary conclusions include the following.

- Fumaroles remain superheated at the Ahuan and Taqui vents. These vents are separated by a distance of approximately 750 m along a NE trend. Daily temperature variations in these vents are likely the result of atmospheric forcing. These superheated fumaroles have a minimal condensable phase and are surrounded by diffuse low-temperature fumaroles that emit water vapor.

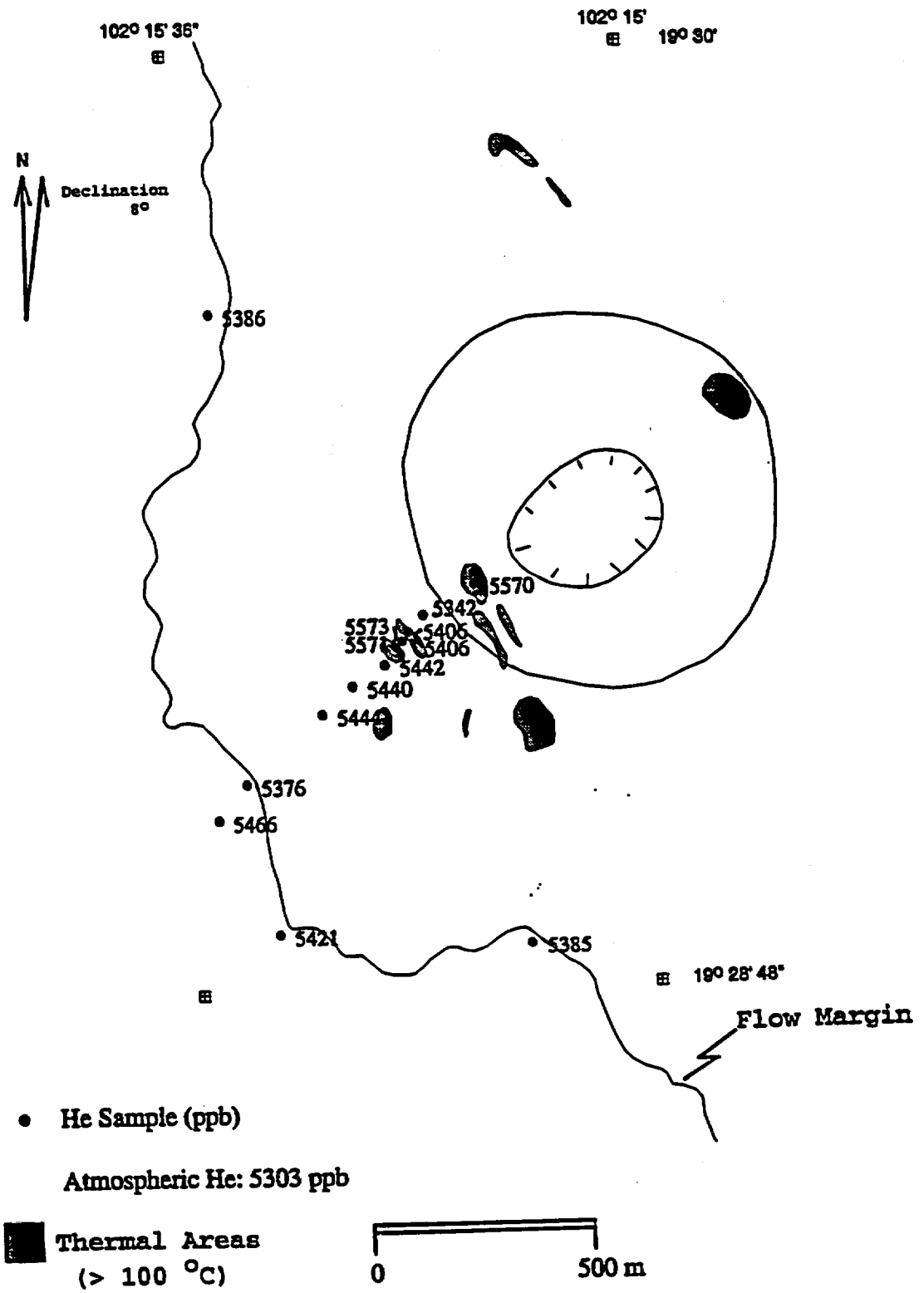


Figure 5. Helium measurements at Parícutin.

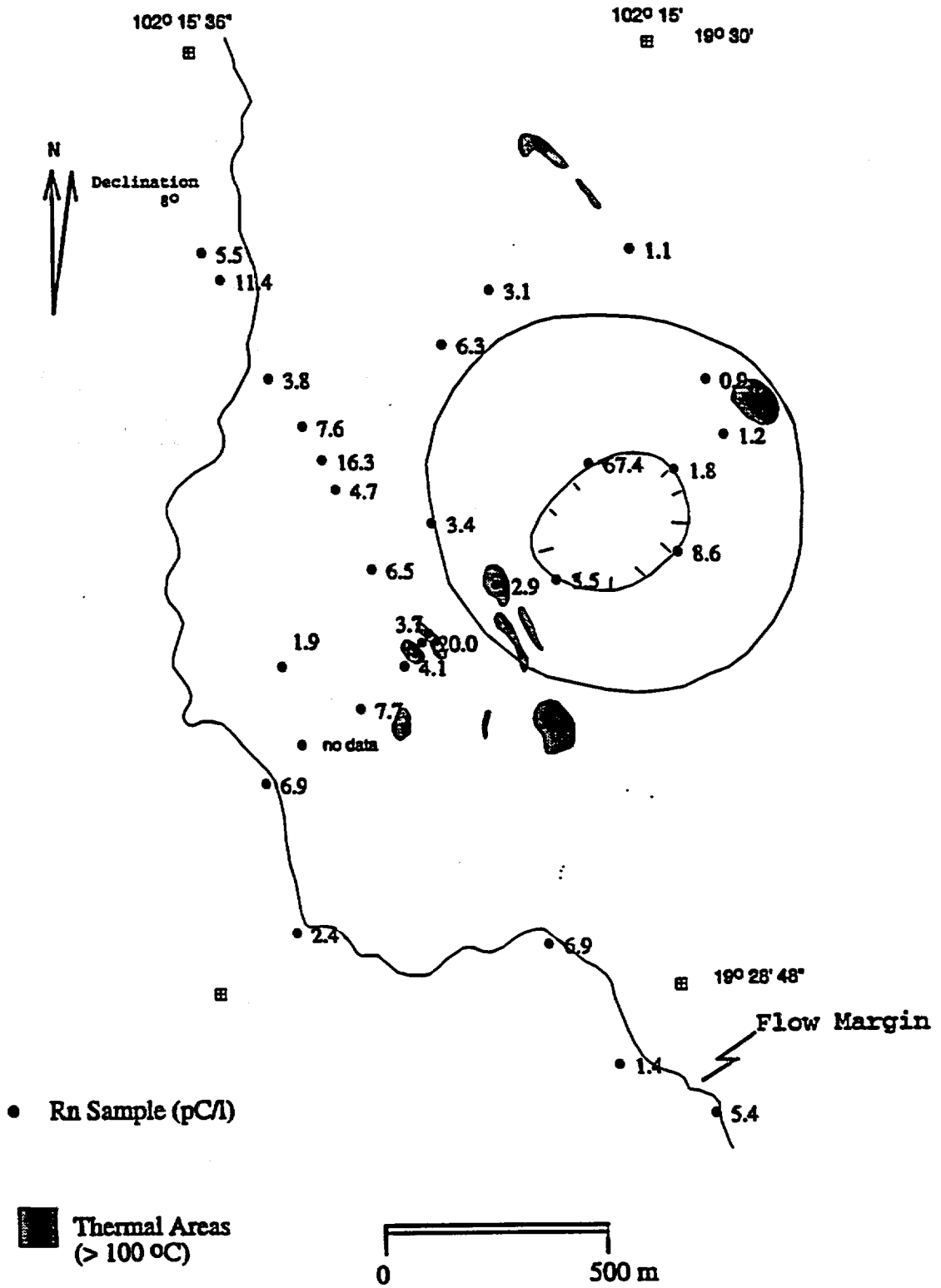


Figure 6. Radon measurements at Parícutin.

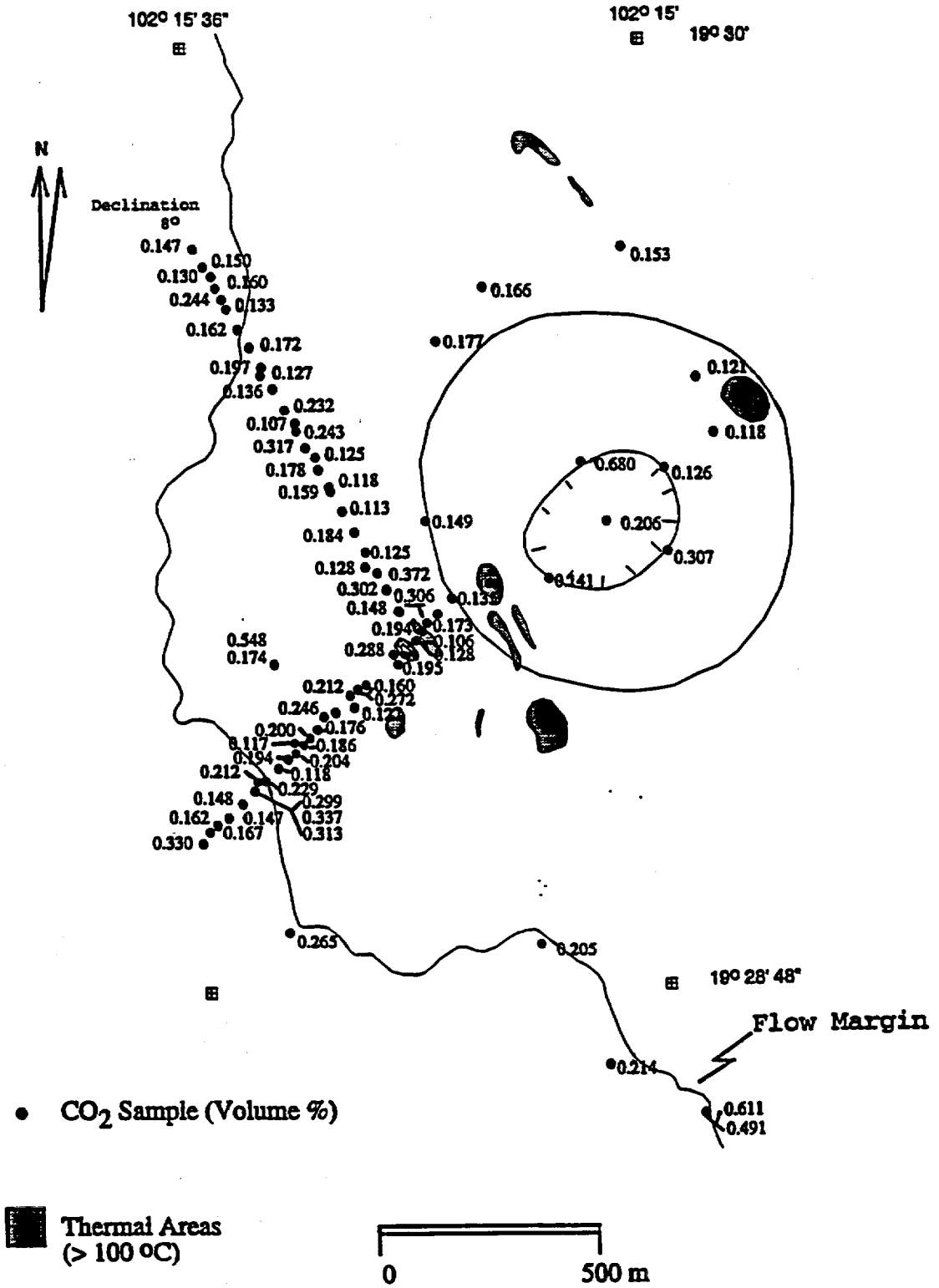


Figure 7. Carbon dioxide measurements at Parícutin.

- Low temperature fumaroles (45-85 °C) are found over a broad area at Parícutin, including the entire area between the Taqui and Ahuan vents, with the exception of the north rim of the main cone, and extending south and southwest of the Ahuan vent. These diffuse fumaroles emit water vapor.

- Excess He, Radon, and CO_2 flow occurs at Parícutin. Highest concentrations occur at the main cone and the Ahuan vent, suggesting forced convective flow of these gases in these areas.

- Elevated Radon and He concentrations are found over an area extending more than 500 m from the Ahuan vent.

- Fumaroles are currently superheated at Jorullo volcano. Excess He (130 ppb in excess of atmospheric He concentration) was found within the crater of the main cone of Jorullo.

Completion of the analysis of Hg data, condensate geochemistry and CO_2 isotopes is expected by the end of June, 1994.

Recommendations

Future field work at Parícutin should concentrate on several specific issues:

- Additional soil samples should be collected, concentrating on He sampling perpendicular to the NE-trending traverse already collected. This will provide an idea of the extent of the diffuse He anomaly.

- Determination of the depth to the water table beneath Parícutin. This should be done through collaboration with local scientist and an effort to determine its depth and variation using drillhole data.

- The map distribution of thermal anomalies is poorly known at this volcano. The U.S.G.S. maps of Parícutin were made in 1946, prior to the end of eruptive activity, and as a result are not accurate. The Ahuan and Taqui vents, for example, had not yet formed in 1946. A topographic map, should be made of the main cone and the Ahuan and Taqui vents, extending out approximately 200 m from these areas. The simplest approach would be a plane table and alidade survey. As the topography is shot in, alteration zones, fumaroles, and soil temperature profiles can be plotted. The dry out zones associated with high temperature fumaroles and the areal extent of low temperature fumaroles can then be determined with confidence. This topographic base and geologic map will be very important for accurately modeling the cooling of the cinder cone, especially if flow in the system is related to Venturi effects.

- Perhaps the most interesting effect observed at Parícutin was the rapid flow of heated water vapor over a broad region at the volcano. This flow should be quantified. A similar experiment, although on a more limited scale, should be pursued at Jorullo.

- Future work needs to concentrate to a greater degree of systematic ash sample collection and the mapping of ballistic features and xenoliths on and around the cone (Walker et al., 1991; Rowland et al., 1991; Walker, 1993). The "hydromagmatic" deposits at Jorullo deserve further attention, given the concern with hydromagmatic activity in the YMR.

- Additional gas sampling should be done during the rainy season in order to quantify the change in the system in response to change and rechange.

Problems Encountered: None significant.

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SENSITIVITY IN RISK ASSESSMENT FOR THE YUCCA MOUNTAIN HIGH-LEVEL NUCLEAR WASTE REPOSITORY SITE: THE MODEL AND THE DATA*

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In the ongoing national debate on nuclear power as a source of electricity in U.S.A., a key issue is the disposition of the high level radioactive wastes produced in the process. At an earlier stage on this debate, Congress, aware of the importance of the waste issue, passed the Nuclear Waste Policy Act of 1982. This legislation required the federal government to develop a geologic repository for the permanent disposal of high level radioactive wastes from civilian nuclear power plants. This waste consists primarily of spent nuclear fuel. Congress designated the Department of Energy (DOE) to implement the provisions of the act. The Department of Energy established the Office of Civilian Radioactive Waste Management (OCRWM) in 1983 in response to the legislation and set about to identify potential sites. When OCRWM had selected three potential sites to study, Congress enacted the Nuclear Waste Policy Amendments Act of 1987, which directed the DOE to characterize only one of those sites, Yucca Mountain, in southern Nevada.

To characterize the site, the DOE must study in detail the natural environment and the various natural processes to which a proposed deep geologic repository might be subject. For a site to be acceptable, these studies must demonstrate that the site could comply with regulations and guidelines established by the federal agencies that will be responsible for licensing, regulating, and managing the waste facility. The regulations, which were promulgated to ensure the safety of the public, require that radiation will not be released above some established safe limit, determined by the Environmental Protection Agency (EPA), for at least 10,000 years after the repository is permanently sealed.

Both advocated and critics disagree on the significance and interpretation of critical geological features which bear on the safety and suitability of Yucca Mountain as a site for the construction of a high-level radioactive waste repository. Recent volcanism in the vicinity of Yucca Mountain is readily recognized by both geologists and others with a knowledge of nuclear regulatory requirements as an important factor in determining future public and environmental safety. We regard basaltic volcanism as direct and unequivocal evidence of deep-seated geologic instability. Direct disruption of a repository site by basaltic volcanism is therefore a possibility. In this talk, sensitivity analysis of volcanic risk assessment for the Yucca Mountain site is discussed, taking into account some significant geological factors raised by experts.

Three types of models are considered in the sensitivity data analysis. The first model assumes that both past and future volcanic activities follow a homogeneous Poison process (HPP). The second model uses a Weibull process (WP) to estimate the instantaneous recurrence rate based on the historical data at NTS. The model then switches from a WP of past events to a predictive HPP. The third model assumes that the prior historical trend based on a WP would continue for future activities. Risks (at least one disruptive event over the next 10,000 years) using both classical and Bayesian approaches are evaluated based on the data for the following two observation periods: Pliocene and younger, and Quaternary. Combinations of various counts of events at volcanic centers of controversy and inclusion (or exclusion) of the youngest date at Lathrop Wells Center (= 0.01 Ma) generate 90 different data sets. Risk analysis is performed for each data set and the minimum and the maximum risk for each model are summarized. We conclude that the estimated overall probability of at least one disruption of a repository at the Yucca Mountain site by basaltic volcanism over the next 10,000 years is bounded between 2.02×10^{-5} and 6.57×10^{-3}

MONITORING CHANGES IN SOIL MERCURY CONCENTRATION IN RESPONSE TO WANING VOLCANIC ACTIVITY: VOLCAN COLIMA, MEXICO.

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Soil mercury (Hg) concentrations were monitored with the avalanche -type caldera (Playón) of Volcán Colima between May, 1991 and May, 1992. Soil Hg concentrations are used to indicate the presence of diffuse, convective upwelling of gases from cooling and crystallizing magma. At Volcán Colima, we began collecting soil Hg samples during the warning stages of the most recent episode of effuse activity, which lasted from approximately March through the end of May, 1991, and continued monitoring soil Hg concentration for one year.

Samples were collected at fixed locations (near deformation stations) throughout the Playón. These samples were collected from soil depths of 25 to 30 cm and stored in glass vials. During analysis, ampules were sieved using a #80 (180 micrometer diameter) sieve and 0.5 grams of the sieved fraction placed in 10 ml glass ampules. The sample is then digested using a 1 ml 5% HCl and 2 ml concentrated nitric acid solution. Following digestion, 0.5 ml of digested material is added to 20 ml of 1% HCl solution and analyzed by atomic fluorescence spectrometry. In the case of high concentration samples, further dissolution was necessary. Analysis of soil standards indicate that this procedure is accurate to ±4 ppb (1 part in 109) at 60 ppb Hg concentrations.

Samples collected on the summit dome near active, high-temperature fumaroles in May, 1991 varied between 8100 ppb and 13,400 ppb. Concentrations on the summit of Volcancito varied from 1810 to 2720 ppb and concentrations in samples collected on the Playon varied from 500 to 4630 ppb during this same period. All of these values are indicative of a high convective flux of Hg through soil. During the following three surveys, soil Hg

concentrations in samples collected within the Playon varied fell steadily. This trend is seen in the geometric mean and standard deviation of Hg concentration, and also in threshold values. Threshold values are calculated using log - probability plots and are indicative of anomalously high Hg concentrations (Table 1; Figure 1). These anomalously high concentrations were found consistently in the central part of the Playon, between the summit dome complex and a large dike located in the caldera wall.

These data indicate that soil Hg concentrations in the Playon vary in response to volcanic activity. Soil Hg and radon measurements at Colima may be a particularly effective means of monitoring diffuse degassing in response to changing volcanic activity, because this degassing does not appear to be buffered by a substantial two-phase (saturated) hydrothermal system. This approach has advantages because data may be collected frequently and with comparative ease and safety. Anomalous Hg concentrations in the central part of the Playon may be related to structural control on degassing in the Playon, rather than simple free convection.

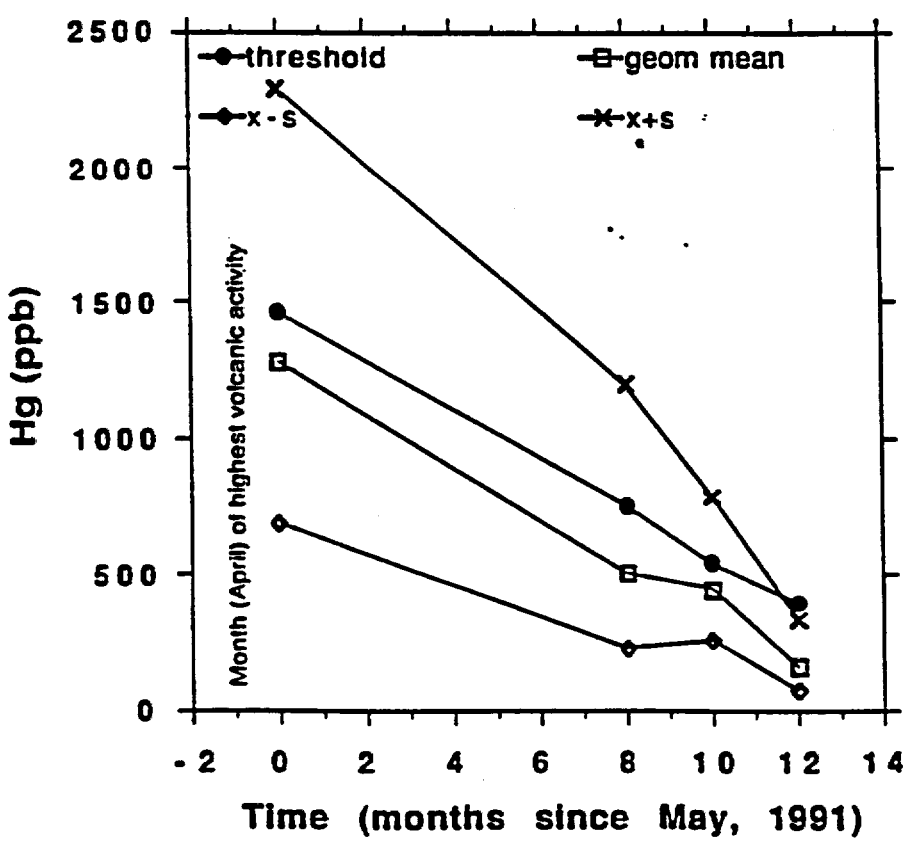
Comparison of the goemetric mean, standard deviation, background and threshold values of soil-Hg concentrations in the avalance caldera at Volcán Colima.

Month/Year	N	$\bar{x}$	$\bar{x} - S$	$\bar{x} + S$	t_1	t_2
May 1991	40	1280	690	2292	-	1460
January 1992	36	509	234	1200	-	757
March 1992	44	451	264	792	274	546
May 1992	69	167	80	341	63	395

N - number of samples $\bar{x}$ - geometric mean S - standard deviation

t_1 - background value t_2 - threshold value

Figure 1 Soil-Hg concentrations over months decrease with decreasing activity of the volcano.



THERMAL AND PHYSICAL STRUCTURE OF POR TIONS OF THE SUMMIT DOME COMPLEX OF VOLCAN VOLIMA, MEXICO.

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The three-dimensional thermal and physical structure of high-temperature (350°-550°C) fumarole areas on Volcan Colima are revealed through ground magnetic surveys, conducted in December 1990 through March 1992. Short-wavelength, -900 to -2000 nT anomalies are spatially related to prevalent fracture systems located on the dome, from which degassing occurs (Figure 1,2). Anomalies are modeled assuming that rock adjacent to these fractures is heated to temperatures above magnetic unblocking temperatures. Rock magnetic measurements of samples yield mean susceptibility of 4.23 x 10-5 mass corrected SI, and mean remenant magnetization of 3.2 A/m. The magnetizations also exhibit very discrete unblocking spectra, with 90% of the magnetization unblocked between 500° and 580°C. The Hopkinson effect causes a 20% susceptibity increase in some rocks at elevated temperatures, but is ignored in models because this accounts for a maximum of 0.5% of the total magnetization contrast.

Meteoric fluids heated near shallow magma move with magmatic gas by forced convection through fractures in the summit dome. The thickness of a thermal boundary layer around fumaroles is dependent on conductive heat transfer through rock and varies as a function of depth. Boundary layers of this type are typically 2 m to 10 m thick on the summit dome. Comparison of magnetic and thermal models indicates that convective transfer of meteoric and magmatic gas to the surface occurred over a long period prior to the 1991 eruption. Continued forced convection of gases along these fractures, and mixed convective and conductive transfer in rocks around these fractures, will likely result in alteration and further destabilization of the dome.

COMPUTER-SIMULATION MODELS OF SCORIA CONE DEGRADATION AND THE GEOMORPHOLOGIC DATING OF SCORIA CONES OF THE COLIMA VOLCANIC COMPLEX, MEXICO.

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A computer model for simulating the erosion of scoria cones (cinder cones) has been formulated to investigate their degradational evolution. This model can utilize either a linear or a nonlinear diffusion-equation algorithm expressed in finite-difference form to operate upon a three-dimensional scoria cone input as a matrix of elevation values. The linear model assumes that downslope movement is directly proportional to surface gradient (to the first power) and simulates erosion by rainsplash, soil creep, freeze-thaw movements, and bioturbation. A linear plus cubic model incorporates erosion by nonlinear power-law creep and turbulent overland flow. A third version of the computer model is nonlinear and simulates erosion by slope wash with gullying.

Assuming an initial conical form, modifications of scoria cone morphology commence with rounding of the crater rim, decrease in cone height, crater infilling, and development of debris aprons to enlarge the basal diameter or width of the cone. Progressive modifications include a decrease in maximum and average cone slope angle, complete crater infilling to leave a scoria mound, and a continuing increase in cone width at the expense of cone height as eroding material continues downslope transport. Further erosion reduces the cone to a shield-like hill with a low height/width ratio. Age is the significant factor distinguishing the progressive transformations exhibited by a group of these landforms, and the systematic change with increasing age provides a basis for relative dating of scoria cones by comparing their morphometric parameters.

Morphometry for thirteen scoria cones around the Colima group volcanoes was calculated by field measurements, field photographs, and 1:50,000-scale topographic maps. The cone height/width

ratio (Hco/Wco) and maximum slope angle were determined for each cone, and the resulting values were then ranked or ordered. The sum of the rankings and degree of erosion determined the relative ages (or geomorphologic dating) of the cones. Using this simplistic scheme, each cone was placed into one of three groups. Group 1 encompasses youthful cones that have not completely lost he crater to infilling from erosion and have high height/width and maximum slope values. Cones that have lost the crater to erosion and have low height/width and maximum slope values comprise the oldest cones (group 3). Cones with intermediate morphometric parameters are classified as group 2.

Scoria cones in the semi-arid climate of the San Francisco volcanic field of Arizona generally lose their crater to infilling in less than 700,000 years. However, Colima has greater rainfall and a savanna-like climate which contributes to stronger chemical weathering and more rapid erosion. Any cones dated by radiometric, paleomagnetic, or other chronometric techniques would provide a method for calibration and improve the dating scheme.

GEOMORPHOLOGIC DATING OF SCORIA CONES OF THE COLIMA VOLCANIC COMPLEX, MEXICO

Name/Relative Age (ordered)	H_{co}/W_{co}	Order	Max. Slope	Order	Crater
Group 1 (Youngest)					
Volcán La Erita	0.176	3	34.5°	2	yes (breached)
V. Apaxtepec	0.141	5	35.5°	1	yes
V. Telcampana	0.186	1	32.0°	5	yes
El Carpintero Norte[1]	0.170	4	33.7°	3	yes
V. Comal Grande	0.183	2	29.5°	6	yes
V. El Comal Chico	0.132	8	33.2°	4	yes
Group 2 (Intermediate)					
Sayula[1]	0.140	6	22 8°	10t	no
V. San Isidro	0.129	10	26.6°	7	breached, heavily infilled
El Carpintero Sur[1]	0.131	9	25.6°	8	no
Group 3 (Oldest)					
Usmajac[1]	0.137	7	21.5°	13	no
V. Tezontal	0.094	13	24.6°	9	no (?)
Cuauhtemoc[1]	0.111	12	22.8°	10t	no
Cerro Los Olotes	0.123	11	21.8°	12	no

Explanation: H_{co}/W_{co} = cone height/width ratio; and Max. Slope = maximum cone slope angle (measurement of the maximum slope angle as an assumption that the steepest slope angle is the initial angle of repose).

[1]Informal name (see also Luhr and Carmichael, 1981, Contrib. Mineral. Petrol., v. 76, p. 127-147)

THE APRIL 1992 ERUPTION OF CERRO NEGRO VOLCANO, NICARAGUA.

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The six-day eruption in April 1992 continued the very short but active history of the Cerro Negro Volcano. The volcano was born in 1850, and at least 24 eruptions have been recorded to the present, therefore it can be considered a living example of the initial stage of volcano generation.

The 1992 eruption consisted of two discrete eruptive phases. Phase I began on April 9 (23:20 local time) after a period of seismic activity accompanying conduit opening. The opening stage was characterized by explosive blasts of accidental material. The deposit formed during the opening stage has a volume of about 3000 m3 and maximum thickness of 30 cm. It consists primarily of oxidized scoria and blocks of slightly altered basalts, and contains up to 5 vol.% of sublimates. The climactic eruption started on April 9 (23:50) and lasted until April 12 (18:00), and in the first few minutes reached its paroxysmal level. During this phase a series of explosions occurred at intervals of a few seconds. The eruptive column reached a height of 7.5 km. Eruptive phase II began after a break of 20 hours on April 13 (22:00), and ended on April 14 (17:30). It was dominated by rhythmic explosions with intervals of 2-3 sec at the beginning, and 8-10 sec at the end of the eruption. Maximum height of eruptive column was 3.5 km. The final stage of seismic activity continued for 10 days.

The greatest volume of erupted material is represented by volcanic ash. Throughout the area of ash fall the deposit consists of two units (I and II) that correspond to the two eruptive phases. Unit I samples are coarse and show stronger fines depletion than the associated Unit II samples. This fact is consistent with the relative intensity of the corresponding eruptive events. The ash from both units has the same modal composition, although Unit I is relatively enriched in crystals. In general, the 1992 Cerro Negro ash is composed of 40-50 vol.% of phenocrysts, 40-45 vol.% of groundmass, and only less than 10 vol.% of material is represented by tachylite pyroclasts. Tachylite pyroclasts are highly vesiculated in both units, but are charac-

terized by irregular surfaces in Unit I, and by plastic shapes and smooth surfaces in Unit II, pointing to higher temperature and lower viscosity of the material that was erupted during Phase II. Solid products of the eruption (bombs, scoria) also are characterized by high crystallinity (up to 45 vol.% of phenocrysts). Phenocrysts in products of Phase I have more evolved crystallization trends than do those from Phase II. Analysis of profiles along the axis of the fall indicates a strong influence of sedimentation processes on the granulometry, modal and hence chemical composition of the tephra. Median diameter of tephra and concentration of denser phases (olivine, pyroxene) decreases exponentially away from the source.

. Based on the character of the eruptive events, petrology of the products, and analyses of volcanic gases (low Cl/S ratio) we suggest that hypabyssal, highly evolved basaltic material took part in the eruption. In this most recent stage of its history the Cerro Negro Volcano is in transition from effusive/explosive to explosive types of eruption. It is influenced by increasing silica content, and by low hypsometric level of the top of magmatic column (and/or intermediate chamber) that creates favorable conditions for crystallization and differentiation of the magma.

bserved elsewhere.

THE 1992 ERUPTION OF CERRO NEGRO, NICARAGUA: AN EXAMPLE OF PLINIAN-STYLE ACTIVITY A T A SMALL BASALTIC CINDER CONE

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Introduction.- The 1992 eruption of Cerro Negro, Nicaragua, provided a unique opportunity to learn more about the energetics of cinder cone volcanism. Here, we describe several aspects of the eruption including:

- .physical volcanology
- .seismicity
- .ash leachate chemistry

Cumulatively, these data indicate that the 1992 explosive eruption of Cerro Negro was more energetic and sustained than previously monitored eruptions in 1968 and 1971. Although small in volume, the eruption is better described as Plinian (VEI 3), rather than strombolian or vulcanian. Ongoing investigations of the petrology, geochemistry and melt inclusions of the ash blanket should provide further clues as to the magma properties controlling this explosive activity.

The April 1992 eruption followed a 22 year period of quiescence. The eruption occurred during a 5 day period in two explosive phases. The first phase lasted 67 hours on April 11 - 13, and the most energetic activity occurred during the initial 18 - 20 hours of this first phase. Following this first phase, the volcano was completely quite. A second phase began on April 14 and lasted 17 hours. This phase was less explosive than the first. The second phase was followed by a seismic swarm on April 17, but no further eruptive activity occurred

Physical Volcanology

Eruption energetics can be characterized using a broad range of measures if direct observations of the eruptions are made.

.observed column height (first 18 hr):7 - 8 km

.observed column height (2nd phase):3.5 - 4.0 km

.sustained ash column

.ash accumulation in Leon (20 km from C.N. after 18 hr):4cm

total ash volume: 0.06 km3 (about 0.03 km3 DRE)

Assuming that the density of the magma is about 2800 kg m-3 and accumulation rates in Leon are representative, the effusion rate during the initial 18 hr of 1992 activity was 300 500 m3s-1.

Given this effusion rate, steady thermal energy release is calculated based on a simple, empirical approach (Wilson et al., 1978):

$Q = pvs(Tm - Ta)F$

$p = 2800$ kg m-3

$v = 300 - 500$ m3s-1

$Tm = 1050$ °C

$Ta = 0$°C

$F = 0.7 - 1.0$ (efficiency of heat transfer)

$Q = 6.7 \times 1011$ to 1.6×1012W during the initial phase of the eruption.

Given Q, column height is estimated by:

$H = 8.2\ Q0.25$

or H = 7.4 to 9 km, in excellent agreement with observed column height. A sustained column and steady energy release describes the initial phase of the eruption well.

Seismicity

Relative seismic energy release was monitored during the second, less voluminous phase, using the real-time seismic amplitude method (Murray and Endo (1989). Seismic energy release was remarkably steady during the eruption, increasing from background immediately before the onset of eruptive activity and dropping to background levels following the eruption. This seismic energy release is largely the result of volcanic earthquakes at depths of less than 8 km, based on hypocenter locations. During this phase of activity, magma rapidly ascended from depth, and flow was maintained in the conduit until activity rapidly waned. This pattern of energy release is different than that expected from a series of instantaneous explosions, which would be characteristic of strombolian or vulcanian-style activity.

Ash Leachates

One of the simplest ways to learn about volatiles in erupting magmas is to monitor the chemistry of aerosols and salts adsorbed on ash particles in erupting columns. This is done by collecting ash as it falls, or immediately after it falls, sieving the ash, and leaching the samples with a known amount of deionized water. The resulting leachate is analyzed by ion chromatography.

S/Cl ratios are higher in 1992 ash samples in comparison with 1968 or 1971 ash samples collected and analyzed by Taylor and Stoiber (1973) and Rose et al. (1977). This is consistent with the more dispersive character of the 1992 eruption and suggests that magmatic volatile chemistry is a fundamental control on the eruptive character of this cinder cone. There is a consistent change in S/Cl ratio along the major axis of dispersion in the 1992 ash blanket. S/Cl ratios are highest in the most widely dispersed ash. This may correlate with an overall change in magma chemistry during the eruption, rather than simply a change in volatile chemistry.

Implications

Observations and empirical estimates of energy release indicate that the 1992 eruption of Cerro Negro was more nearly Plinian than strombolian or vulcanian. The first phase of activity maintained a convecting ash column at 7.5 to 8.0 km at effusion rates of 300-500 m3s-1, greater than occurred during explosive eruptions in 1968 and 1971. During the second phase, a column was maintained at 3.5 - 4.0 km and seismic energy release was remarkably steady. S/Cl in 1992 ash leachates are higher than those of 1968 and 1971 eruptions, indicating that volatile chemistry and magma rheology are important controls on differences in eruptive behavior at this cinder cone. The 1992 eruption is best characterized as VEI3, although the duration of the both phases is longer than normally expected for a VEI 3 eruption.

This type of explosive activity has been observed at numerous cinder cones, including Tolbachik, Kamchatka, Russia, and Paricutin, Mexico, and may be a common feature of small-volume basaltic cinder cone volcanism.

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POLYGENETIC QUATERNARY VOLCANISM IN THE WESTERN USA: AN EXAMPLE FROM CRA TER FLAT, NEVADA.

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Crater Flat lies in the Great Basin of southern Nevada and is situated approximately 140 km northwest of Las Vegas. Crater Flat is bounded on its east side by Yucca Mountain, the site of a proposed high-level nuclear waste repository. Quaternary volcanism within Crater Flat consist of five cinder cones arranged in a northeast trending chain. These are from south to north: Little Cone, Red Cone (0.95-1.01 Ma), Black Cone (1.09 Ma) and Northern Cone. Black Cone is the largest center and has a volume of about 0.067 km3 with lava flows covering about 4 km2. Red Cone is slightly smaller and sits on a lava field covering about 3 km2. The other centers are much smaller in size, therefore our discussion below is limited to Black Cone and Red Cone.

Alkali basalts erupted during the Quaternary at Crater Flat record a complex history of both polycyclic and polygenetic volcanism. Magmas from Black Cone and Red Cone define end-member magma types. The Black Cone type (depleted) has lower Sr (1300), Ce (220 ppm), Ba (1700 ppm) and Th (15.5 ppm) than the Red Cone magma type (enriched) (Sr-1800 ppm), Ce (280 ppm), Ba (2000 ppm) and Th (15.5 ppm). At Red Cone, there is a complete range of compositions for these elements. The youngest samples have the most elevated values. However, there is only limited variation in the compatible trace elements (e.g., Sc and Ni). High trace element concentrations, low Nb/La and high Zr/Y ratios indicate that both end-member magma types were derived by small degrees of partial melting of the lithospheric mantle. The array of compositions at Red Cone cannot be reproduced by changes in the degree of partial melting, or by fractional crystallization. Rather, a model of magma mixing is proposed between relatively enriched and depleted end-members. The cluster of Black Cone analyses falls consistently at the least-enriched end of the Red Cone sample array, suggesting that Black Cone magma represents one of the mixing end members. Sr and Nd isotopes of basalts from Crater Flat define an unusual positive array on a plot of 87Sr/86Sr vs. Nd with the deple-

ted Black Cone magma type having 87Sr/86Sr = 0.70691 and ¯Nd = 9.6 and the enriched Red Cone Magma 87Sr/86Sr = 0.7071 and ¯Nd = 8.6. The isotopic composition of the Black Cone end-member may be explained by adding up to 3% isotopically depleted lower crust to the Red Cone magma type.

This modeling may indicate that the magmatic plumbing systems of the two centers were linked, at least during the early stages of volcanism. Thus suggesting that volcanic activity was not restricted to a single center during an eruptive phase, but that a number of sites were active along the length of the magmatic feeder zone. A reconstructed sequence for the magmatic history of Crater Flat resembles the following:

1- Eruption of the Black Cone compositional type at Red Cone and at Black Cone.

2. A new magma batch with elevated trace-element concentrations erupted at Red Cone and mixing occurred with the earlier magma type. The range of compositions at Red Cone is a result of this mixing event.

3. Volcanism ceased at Red Cone while activity continued at Black Cone.

These conclusions could have significant implications for volcanic hazard assessment about the proposed high-level nuclear waste repository at Yucca Mountain, Nevada. This study raises the possibility that renewed eruption at an existing center may be accompanied by activity at other localities along the magmatic feeder zone, thus forming a volcanic chain and potentially having a direct effect on the proposed nuclear repository.