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TECHNICAL AND REGULATORY BASIS FOR THE STUDY OF RECENTLY ACTIVE CINDER CONES

Prepared for

Nuclear Regulatory Commission
Contract NRC-02-88-005

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August 1993

ABSTRACT

Modern analogs provide a comprehensive and defensible means of assessing the impact of potential volcanism on repository performance. Two areas of investigation that are critical to the determination of compliance are into: (i) the mechanics of cinder cone eruptions, particularly as related to entrainment and dispersal of high-level waste (HLW), and (ii) the secondary effects of volcanism, including the effects of diffuse degassing and thermal loading on geochemical transport, waste container performance, and groundwater movement. These physical, chemical, and hydrologic effects can only be studied where modern analogs to Yucca Mountain region (YMR) volcanism exist, because these effects are dynamic and transitory. Evidence of the magnitude and duration of these processes is poorly preserved in the geologic record. Consequently, interpretations of the impact of volcanism on repository performance are ambiguous if based solely on studies of extinct western Great Basin volcanoes. The study of deposits, magma properties, current degassing, and thermal activity at modern analog cinder cones will provide the insight needed to bound numeric and conceptual models of potential volcanism at or near the candidate repository site. Field investigations at recently active cinder cones, coupled with detailed comparative studies at extinct western Great Basin volcanoes, will provide the only empirical data for the evaluation of performance assessment (PA) models and the reduction of Key Technical Uncertainties (KTU) related to volcanism. As a result, field investigations will provide support for several License Application Review Plan (LARP) activities related to volcanism (sections 3.2.1.9, 3.2.2.7, and 6.1).

As no modern analogs to YMR eruptions are located in the United States, it has been necessary to seek alternative sites. A literature review indicates that three analogous cinder cones are Tolbachik, Russia; Parícutin, Mexico; and Cerro Negro, Nicaragua. These cinder cones are more analogous to YMR cinder cones than any recently active volcanoes in the United States. Similarities include: cone morphology, eruption history, relationship to volcano clusters and vent alignments, occurrence of satellite cones and major element composition. These similarities suggest that eruptive and cooling processes at these analog volcanoes are broadly comparable to processes that have occurred at YMR volcanoes in the past and potentially could occur in the future. Small differences in major element composition between these volcanoes and those of the YMR have much less impact on magma properties (and consequently eruption mechanics), than factors such as volatile content, phenocryst size and distribution, and vesicle size and distribution. Differences in magma properties due to these factors will be explored in detail as the site selection process continues. These volcanoes are different than YMR volcanoes in that they have had well-monitored and documented eruptions and continue to degas today. Preliminary modeling of eruption mechanics indicate that a range of explosive activities and styles are represented by these volcanoes. Also, each of these volcanoes continues to degas from vents, and diffuse degassing over a broad area is occurring at Parícutin and likely at the other volcanoes. A preliminary heat- and mass-transfer model illustrates heuristically how the mass conservation, energy, and momentum equations will be used to investigate heat and mass transfer in cooling cinder cones using field observations. In view of the regulatory need for this investigation, it is auspicious to investigate these processes at multiple sites. These three analogs are ideal, because they represent a range of eruptive activity and because they have been cooling for varying lengths of time.

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ACKNOWLEDGMENTS

Useful discussions with B. Hill, R. Manteufel, and W. Murphy are gratefully acknowledged. Technical comments by S. Young and B. Sagar improved this manuscript. R. Martin was instrumental in preparation of the figures.

This report was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the U.S. Nuclear Regulatory Commission (NRC) under Contract No. NRC-02-88-005. The activities reported here were performed on behalf of the NRC Office of Nuclear Regulatory Research. The report is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the NRC.

1 INTRODUCTION

The Yucca Mountain region (YMR) has been the site of recurring small-volume basaltic eruptions during the last 10 million years (Crowe et al., 1983; Smith et al., 1990). This has led to the formation of numerous cinder cones, eight of which are less than 1.6 million years old. These volcanoes may represent a range of eruptive activity, from extremely explosive eruptions to comparatively gentle, effusive volcanic eruptions (e.g., Valentine et al., 1992; Amos et al., 1983, Walker, 1993). The technical objectives of the Field Volcanism project are to better characterize the impact of this type of activity on repository performance and, as a result, better constrain probability models of volcanic disruption of the repository. This will be possible through investigation of (i) the mechanics of mafic cinder cone eruptions, (ii) the extent and characteristics of shallow hydrothermal systems and diffuse degassing associated with small volume mafic eruptions, and (iii) the nature of mafic intrusive geometries at repository depths. Successful completion of the Field Volcanism project, which began in April 1993, will require study of Plio-Quaternary cinder cones in the western Great Basin, and comparison with modern, recently active cinder cones located elsewhere.

The Field Volcanism project utilizes a dual approach to the evaluation of the consequences of potential volcanic activity in the YMR. This dual approach includes both studies of extinct western Great Basin cinder cones and studies at modern analogs. Clearly, the range of volcanic activity in the western Great Basin, the duration of this activity, paragenesis of magmas, and geology of near-surface structures must be evaluated using detailed field studies in the region. However, much about the dynamic nature of volcanism in the YMR (e.g., eruption mechanics, extent and longevity of degassing, perturbation of groundwater flow) must also be learned from the study of analogous historically active cinder cones that have had well-documented and -monitored eruptions. Because no cinder cone eruptions have occurred in the western United States in the last one hundred years, it is necessary to investigate volcanic processes at analogous volcanoes elsewhere. Parícutin, Cerro Negro, and Tolbachik volcanoes are in many respects quite analogous to YMR volcanoes, but all of them have had recent eruptions that are were well monitored and documented.

It is the purpose of this document to describe the technical and regulatory basis for the study of recently active cinder cones as analogs to volcanism in the YMR. Investigations at these cinder cones will be critical in providing the most comprehensive and defensible basis for evaluation of compliance with 40 CFR Part 191 and 10 CFR Part 60.122(c)(15). Results of investigations at recently active cinder cones will directly support the License Application Review Plan (LARP) and reduce Key Technical Uncertainties (KTU) associated with volcanism. Without integration of investigations of analogous, recently active volcanoes with studies of ancient systems in the western Great Basin, consequence studies and their utility in probability model development will become unnecessarily tenuous.

The following sections provide details of the regulatory and technical basis for the study of Parícutin, Tolbachik, and Cerro Negro volcanoes, including a discussion of the degree to which these volcanoes are analogous to those of the YMR, given current information, the types of investigations that will be performed at these volcanoes, and the utility of this technical information in providing insight into volcanic processes in the YMR that cannot be otherwise attained.

2 REGULATORY BASIS FOR THE STUDY OF RECENTLY ACTIVE CINDER CONES

Young and Kovach[1] (1993) have pointed out that the goals of analog studies during the investigation of potential geologic hazards at the site are to reduce KTU and to help constrain initial and boundary conditions important to modeling repository performance. The investigation of recently active cinder cones in the course of the Field Volcanism project will provide a straightforward means of reducing KTU associated with volcanism and provide results that will be directly integrated into iterative performance assessment (IPA) studies. In fact, from a regulatory standpoint, adequate resolution of KTU and development of sufficient understanding to evaluate the probability and consequences of volcanic activity at or near the candidate repository site requires investigation of analogous modern cinder cones. Trapp and Justus (1992) showed that 10 CFR 60.122(a)(2) provides a basis for the evaluation of volcanic activity and that this activity must be investigated in order to demonstrate compliance with the overall system performance objective. Several probability models indicate that the likelihood of volcanic disruption by magma injection into the repository is very close to or exceeds 1 in 10,000 in 10,000 years (Ho et al., 1991; Ho, 1992; Sheridan, 1992; Connor and Hill, 1993). The probability of igneous activity within several kilometers of the repository during the next 10,000 years is much higher (Connor and Hill, 1993; Crowe et al., 1993). These probability models, although not finalized, strongly suggest that the consequences of volcanic activity must be considered in order to demonstrate compliance (Trapp and Justus, 1992).

Two areas of investigation that are critical to the determination of compliance are (Trapp and Justus, 1992; Young and Kovach,[1] 1993) 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

- Secondary effects of volcanism, including the effects of diffuse degassing and thermal loading on geochemical transport, container performance, and groundwater movement.

Field data are absolutely necessary in order to evaluate volcanism models developed in Performance Assessment (PA) (e.g., Ross, 1987; Barnard et al., 1991) and elsewhere (e.g., Margulies et al., 1992; Valentine et al., 1992) that attempt to describe these dynamic processes. The most relevant field data for the evaluation of eruptive and secondary volcanic processes can be gathered at analogous, modern cinder cones, where actual eruptions have been observed and where the secondary effects of volcanism can be monitored today.

Insight into the possible magnitude of volcanic eruptions likely to occur in the YMR in the event of future volcanic activity, the areas likely affected, and the likely duration of volcanic activity form an integral part of site characterization activities (evidence of igneous activity as a potentially adverse condition, LARP section 3.2.1.9, and impact of volcanism on groundwater movement, LARP section 3.2.2.7), and

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[1]Young, S.R. and L. A. Kovach, 1993. Volcanism/Tectonics working group summary. *The Role of Natural Analogs in Geologic Disposal of High-Level Nuclear Waste.* Editied by W.M. Murphy and L.A. Kovach. Center for Nuclear Waste Regulatory Analyses, in press.

the description of overall system performance (assessment of compliance with the requirement for cumulative releases of radioactive materials, section 6.1). Compliance Determination Strategies (CDS) for these LARP sections are currently under development. The CDS associated with evidence of Quaternary volcanism calls for independent research to evaluate KTU associated with volcanism, because volcanism poses a high risk of noncompliance with 40 CFR Part 191 as set forth by the Environmental Protection Agency (EPA) and 10 CFR Part 60.122(c)(15) as determined by the Nuclear Regulatory Commission (NRC). For example, until the characterization of the likely magnitude and duration of eruptive activity, and the impact of this activity on groundwater and geochemical transport is completed, it will be difficult to ascertain compliance with 40 CFR Part 191.

To date, three KTU related to igneous activity have been identified as a result of concern with evidence of Quaternary igneous activity. These KTU are:

- Low resolution of exploration techniques to detect and evaluate igneous features
- Inability to sample igneous features
- Development and use of conceptual tectonic models as related to igneous activity

Evaluation of these KTU will require detailed safety review supported by analyses and independent tests, analyses, and related investigations. Young and Kovach[1] (1993) noted that the potential physical, chemical, and hydrological effects of eruptions similar to those that have occurred in the YMR in the past can only be studied in regions where modern analogs to these volcanoes exist. Because of the inability to sample igneous features, it is important that modern analogs be used to investigate problems associated with eruption mechanics and the dynamics of heat and mass transfer in cooling cinder cones, following episodes of eruptive activity.

Because there are several KTU associated with volcanism, the investigation of volcanism has been identified as a research need by of the NRC Office of Nuclear Material Safety and Safeguards (NMSS). The following user needs have been identified by NMSS:

- Mechanisms that control igneous features (User Need 601)
- Spatial and temporal patterns in igneous activity (User Need 602)
- Effects of igneous activity on groundwater (User Need 603)
- Theories of multiple volcanic eruptions (User Need 604)
- Age-determination techniques in volcanic terrain (User Need 605)
- Coeval nature of basaltic volcanism and deformation in the Basin and Range (User Need 609)

User Needs 601, 602, and 603, in particular, can best be addressed through investigations at recently active cinder cones. This is primarily because these User Needs reflect a need to better understand the dynamic and transitory aspects of cinder cone volcanism (Trapp and Justus, 1992).

Field investigations at modern analogs, together with related investigations, will form an integral part of volcanism model development in PA. For example, the effective dispersion of waste in the accessible environment following eruption will best be predicted if models are assessed in light of observed eruptive processes at analogous, recently active cinder cones. Furthermore, current PA models do not include the effects of diffuse degassing and hydrothermal activity or estimates of the volume of surrounding country rock likely affected by such systems. This type of geological detail is critical to the development of more comprehensive PA models. In addition, analogs will help constrain probability models of volcanism in the YMR. For example, area terms are quite important in all probability models currently proposed. Therefore, probability models need to consider the extent of hydrothermal systems about cinder cones in area terms. This type of refinement of probability models will only be possible as a result of investigations using modern analog cinder cones.

3 PROPOSED STUDY SITES AND TECHNICAL BASIS FOR THEIR SELECTION

3.1 BRIEF DESCRIPTION OF THE SITES

Review of the literature indicates that three historically active cinder cones are broadly analogous to those of the YMR. These are Cerro Negro, Nicaragua; Parícutin, Mexico; and Tolbachik, Kamchatka (Figure 3-1). All three of these cinder cones have formed historically and eruptions at these volcanoes have been monitored and documented using modern volcanological techniques. The preliminary site selection process indicates that these cinder cones are analogous to YMR cinder cones in the following respects.

- All of these cinder cones have similar morphologies to YMR cinder cones, indicating that they have been constructed through similar eruption processes. Although the volume of total erupted tephra is not necessarily directly proportional to cone volume, the similarity in cone volumes, compared with other types of volcanoes, is indicative of broadly comparable pyroclastic activity.

- All of these cinder cones formed during comparatively brief periods of time and have simple eruption histories. In terms of eruption history, these volcanoes are much more analogous to YMR volcanoes than any other historically active volcanoes in the United States.

- Each of these cinder cones is part of a cinder cone cluster, within which activity has persisted throughout the Quaternary. Cinder cone clustering is a fundamental aspect of vent distribution in the YMR, and clustering may be indicative of broad similarities in magma supply rate.

- Each of these cinder cones is part of a vent alignment. Structural controls on vent formation and distribution may be similar to those of the YMR. However, the specific character of these alignments differ. At Parícutin and Tolbachik, vents within alignments were active simultaneously, whereas Cerro Negro is the only cinder cone in its alignment active historically. This range of activity within alignments encompasses the range of "structural" probability models proposed for the Crater Flat alignment (Crowe et al., 1993).

- Satellite vents are important features at each of these cinder cones. Lava flows and, in some cases, tephra issued from satellite vents during or following explosive activity at main craters at each site. Furthermore, in each case, structural control on the distribution of satellite vents is evident, as these satellite vents align. Satellite vent alignments might result from interaction with pre-existing structures or dike injection perpendicular to the minimum principle horizontal stress. Detailed mapping at Lathrop Wells and Red Cone (Smith et al., 1990) indicates that development of satellite vents is an important aspect of cinder cone volcanism in the YMR.

- Differences in major element composition between magmas erupted at each of these cinder cones, and those of the YMR, are minor in terms of their affect on the rheological properties of the magma, and consequently their affect on eruption mechanics. This important similarity will be discussed in detail in following sections.

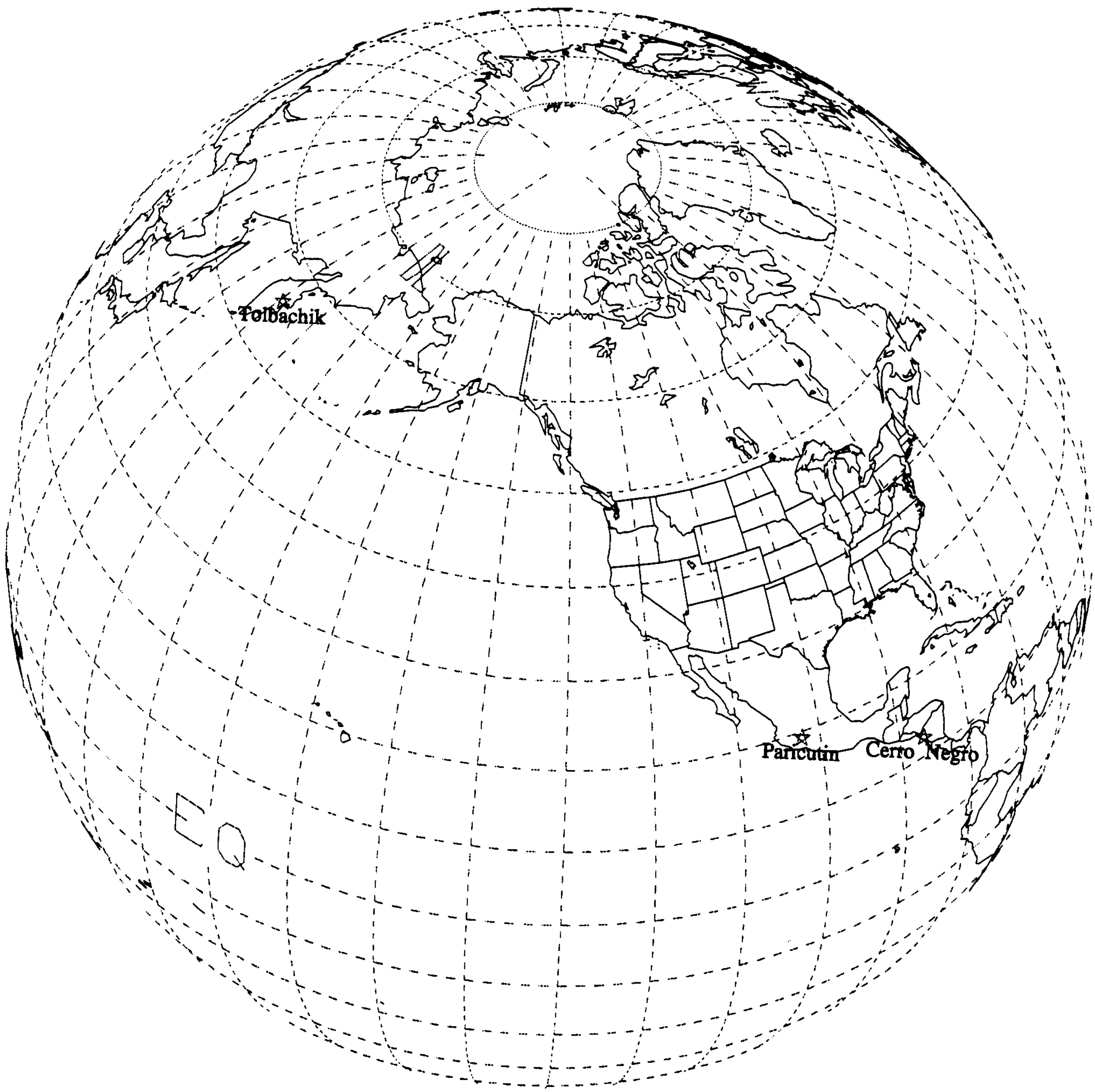

Figure 3-1. Locations of Tolbachik, Russia; Parícutin, Mexico; and Cerro Negro, Nicaragua

Major differences between these cinder cones and those of the YMR or other cinder cones in the United States are that:

- Eruptions at these volcanoes have been observed and well-documented by volcanologists using modern observational and measurement techniques. Consequently, the energetics and duration of activity at these volcanoes is well known or may be calculated. In contrast, no cinder cone eruptions have occurred in the United States recently enough to have been monitored, with the exception of eruptions along major Hawaiian rifts, where magma supply rates and rheologic properties are vastly different than those of the YMR.

- These volcanoes have active hydrothermal systems and are currently degassing. The development of these hydrothermal systems likely varies because of the time elapsed since each last erupted. No cinder cones in the United States erupted recently enough to continue to degas, or are known to sustain hydrothermal activity.

These differences suggest that field investigations at these three sites can provide important insight into eruption mechanics and into the secondary effects of volcanism, two areas of research that must be explored in order to determine compliance (Trapp and Justus, 1992). In order to explore the dynamics of YMR volcanism, it will be critical to describe processes that occurred during and following eruptions at each of these volcanoes in detail. In the following section each of the three cinder cones are described, focusing on their eruptive history and current state of activity. Technical details about volcanological issues that can be resolved through study of these volcanoes are provided following these descriptions.

3.1.1 Cerro Negro

Volcán Cerro Negro (12.5 °N, 86.7 °W) is a small cinder cone located 63 km NW of Managua, Nicaragua (Figure 3-2), in the Cordillera de los Marribios. Cerro Negro is a young cinder cone, first formed in 1850, and is part of the El Hoyo volcanic complex, a cluster of cinder cones and small shields (Figure 3-2). This complex is located midway between two large composite cones, Momotombo and Telica volcanoes, along the main trend of the Central America volcanic arc. Six Quaternary cinder cones, including Cerro Negro, and one maar form a 12-km-long, NNW-trending alignment across the west flank of the El Hoyo complex. Cerro Negro has erupted at least 19 times since its formation, with 13 of these eruptions occurring between 1947 and 1971, and is the site of the most recent small-volume basaltic eruption at a cinder cone in the western hemisphere, having last erupted in April, 1992 (GVN, 1992; Connor et al., 1993). Eruptive activity at Cerro Negro has been different than activity at Parícutin or Tolbachik volcanoes, because it has consisted of short phases of explosive activity, followed by periods of repose, during which activity is limited to light degassing from fumaroles. Dramatic variation in volcano morphology has occurred as a result of these successive eruptions. For example, 1971 activity resulted in the formation of a steep-sided cone with a crater diameter of approximately 100 m. The 1992 eruption reduced the volume of the cone substantially, resulted in a decrease in the maximum slope of the cone, and widened the main crater from 100 m to 400 m. No other volcanoes in this cluster have been active historically, although Las Pilas (Figure 3-2) may have been solfataric (Simkin et al., 1981).

Cerro Negro is unique in the western hemisphere because it is a young cinder cone at which three recent eruptions (1968, 1971, and 1992) have been studied in detail [(Dillard, 1968; Goldsmith,

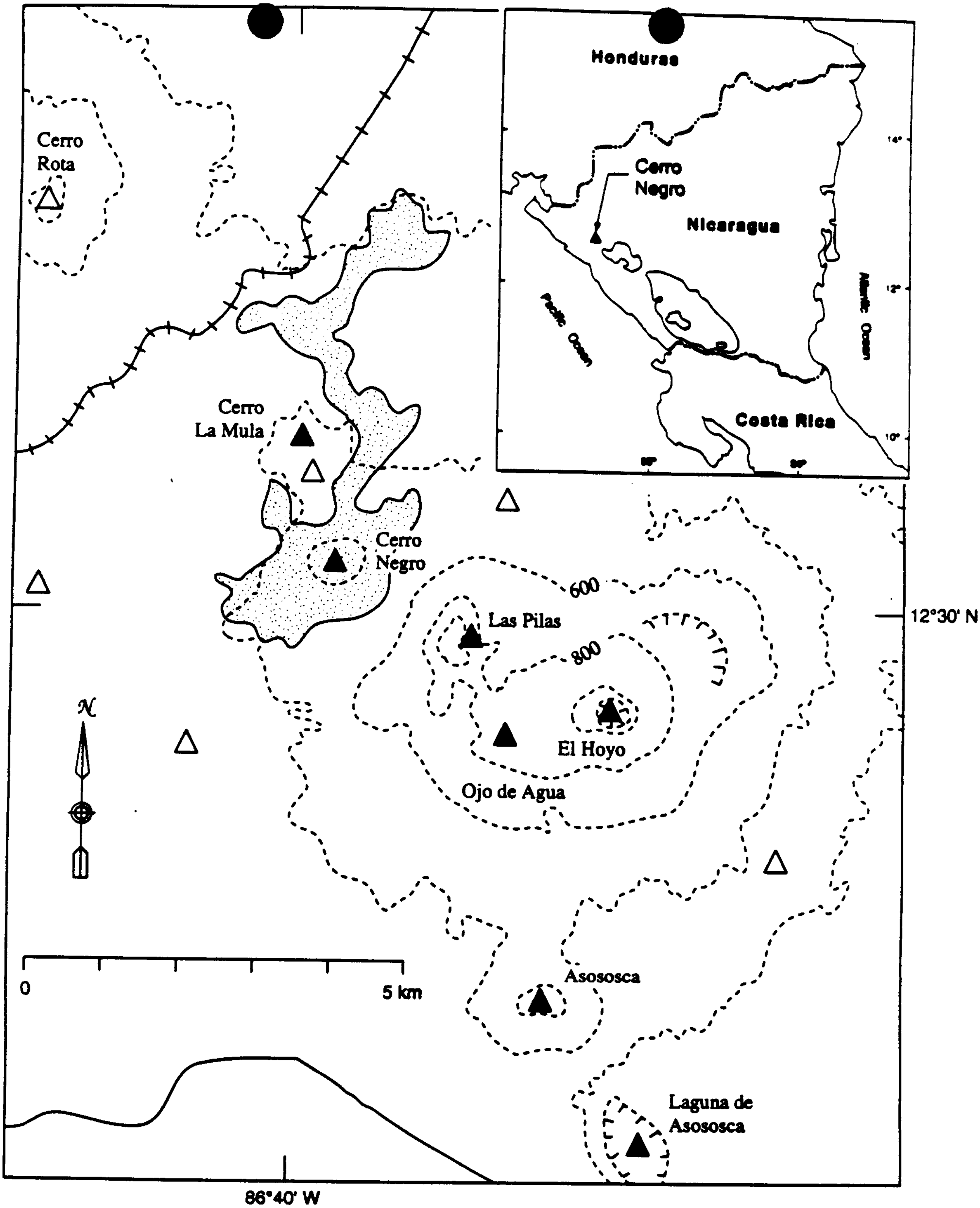

Figure 3-2. Location of Cerro Negro, Nicaragua. Late Quaternary cinder cones and maars of the El Hoyo complex are shown as solid triangles; older Quaternary(?) cones are shown as open triangles. The 1968 lavas of Cerro Negro are indicated by the stippled pattern.

1968; Taylor and Stoiber, 1973; Viramonte and Di Scala, 1970; Viramonte et al., 1971; Rose et al., 1973; Carr and Walker, 1987; Global Volcanism Network (GVN), 1992; Connor et al., 1993)]. Of these three, the 1992 eruption was the most energetic and dispersive. During the explosive phase of the 1968 eruption, convective ash column heights reached heights between 150 m and 1500 m above the cinder cone, and total erupted volume was approximately 1.7×10^7 m^3 of ash (Viramonte and Di Scala, 1970; Rose et al., 1973). This explosive activity took place over 46 days (Dillard, 1968; Goldsmith, 1968) and consisted of numerous strombolian and vulcanian bursts (Taylor and Stoiber, 1973). Explosive activity was followed by the effusion of lavas from the southern flank of the volcano. In contrast, 1992 activity took place over two eruptive phases of 17.75 hours and 19 hours duration. During these episodes, eruptive columns were maintained at a much greater height (3.5 - 7.5 km) than ever occurred during 1968 activity, and the resulting ash deposit was more voluminous (6.0×10^7 m^3) and widely dispersed than the 1968 deposit (Figure 3-3). Nearly all the ash that erupted during the 1992 eruption fell during the first phase of activity (GVN, 1992). Total ashfall in the city of Leon, for example, had reached 4 cm after 18 hours of eruptive activity, and only an additional 0.25 to 0.5 cm accumulated during subsequent activity. Eruption column heights were reported to be sustained at approximately 7.5 km during this initial 18-hour period.

Relative seismic energy release was monitored during the second, less voluminous eruptive phase in April, 1992 (Connor et al., 1993), using the real-time seismic amplitude method (Murray and Endo, 1989). These are believed to be the first data of their kind ever recorded for a cinder cone eruption. Seismic energy release was remarkably steady during the eruption, increasing rapidly from background immediately before the onset of eruptive activity and dropping to background levels following the eruption (Figure 3-4). This seismic energy release was largely a result of volcanic earthquakes associated with the movement of magma and hydrofracturing of rock at depths of less than 8 km (Connor et al., 1993). The seismic energy release pattern is very different than that expected if activity were characterized by a series of essentially instantaneous explosions, which would be characteristic of vulcanian or strombolian eruptive activity. During this phase of activity, magma apparently ascended from depth and flow was maintained in the conduit until activity rapidly waned.

Volatile concentration in erupting magma is believed to be a primary control on eruption style, energy release, and ash dispersion (Sparks, 1978; Wilson et al., 1978; Wilson, 1980; Wilson and Head, 1981). One of the simplest ways to learn about volatiles exsolved from magma during eruption is to monitor the chemistry of aerosols and salts adsorbed on ash particles in erupting columns. This can be done by collecting ash as it falls, or immediately after it falls, seiving the ash, and leaching the ash samples using a known amount of deionized water. The resulting ash leachate is then analyzed by ion chromotography for selected ions. Ion ratios, such as S/Cl, in leachates are indicative of volatile ratios in the erupting column (Taylor and Stoiber, 1973; Rose et al., 1973; Rose, 1977). Increases in S/Cl are indicative of increases in eruption magnitude and energy release (e.g., Menyailov, 1977; Nehring and Johnston, 1981; Rose, 1977). Ash leachate data collected from the April, 1992 eruption are shown in Table 3-1. In comparison with the 1968 and 1971 Cerro Negro eruptions, the S/Cl ratios in the 1992 ash samples are higher. This is consistent with the more dispersive character of the 1992 eruption and suggests that variation in magmatic volatile chemistry, and probably concentration, are a fundamental control on eruption character at Cerro Negro. Furthermore, there is a consistent change in S/Cl with stratigraphic position along the major axis of dispersion within the 1992 ash blanket (Figure 3-5). Early in the first eruptive phase, ash was less dispersive and S/Cl ratios were lower. Later, ash was more dispersive and S/Cl ratios were higher. This may be a result of overall change in magma chemistry during the eruption (c.f. Carr and Walker, 1987), rather than simply a change in volatile chemistry.

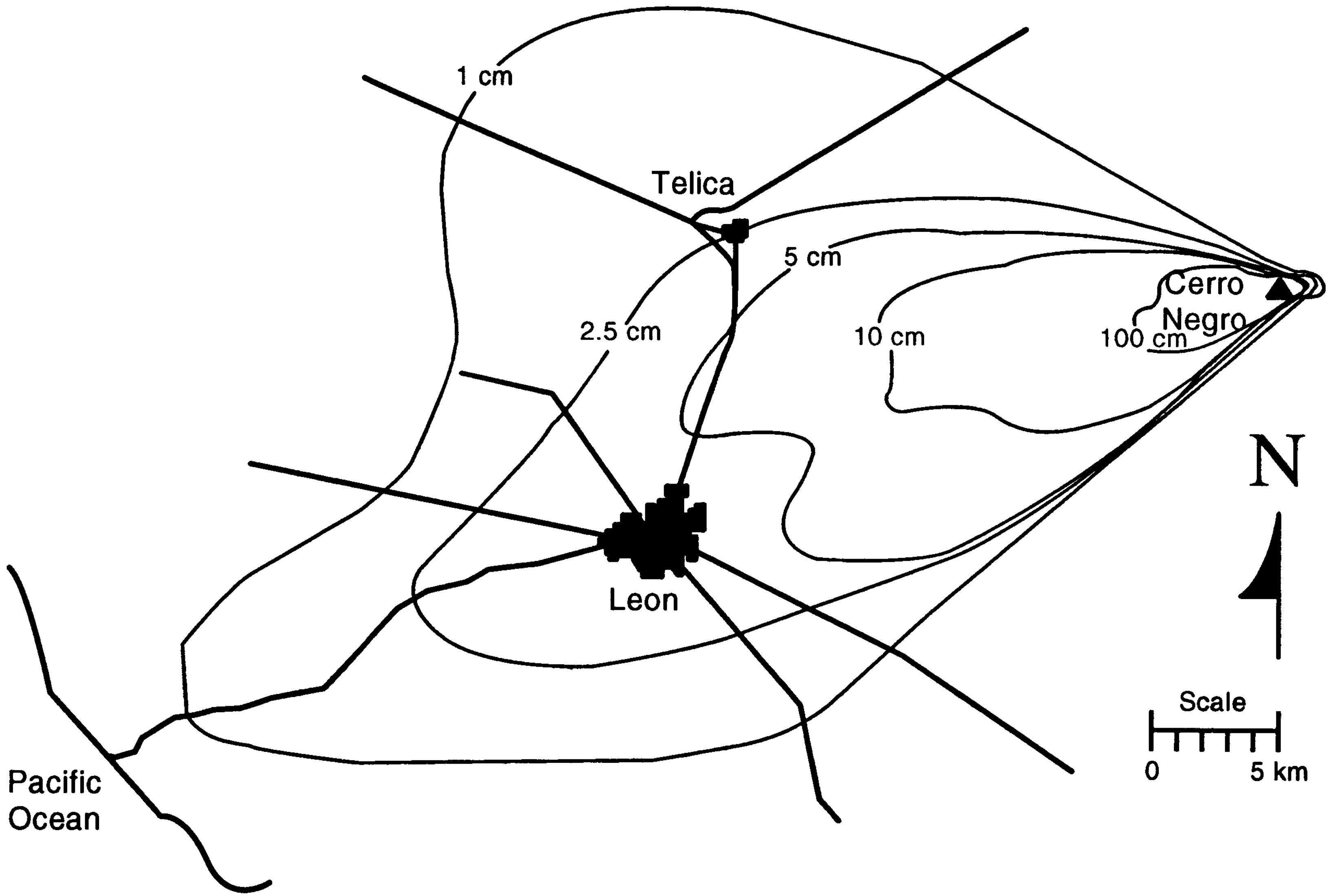

Figure 3-3. Isopach map of airfall from the April 1992 eruption of Cerro Negro. This eruption was voluminous and dispersive compared to 1968 or 1971 activity.

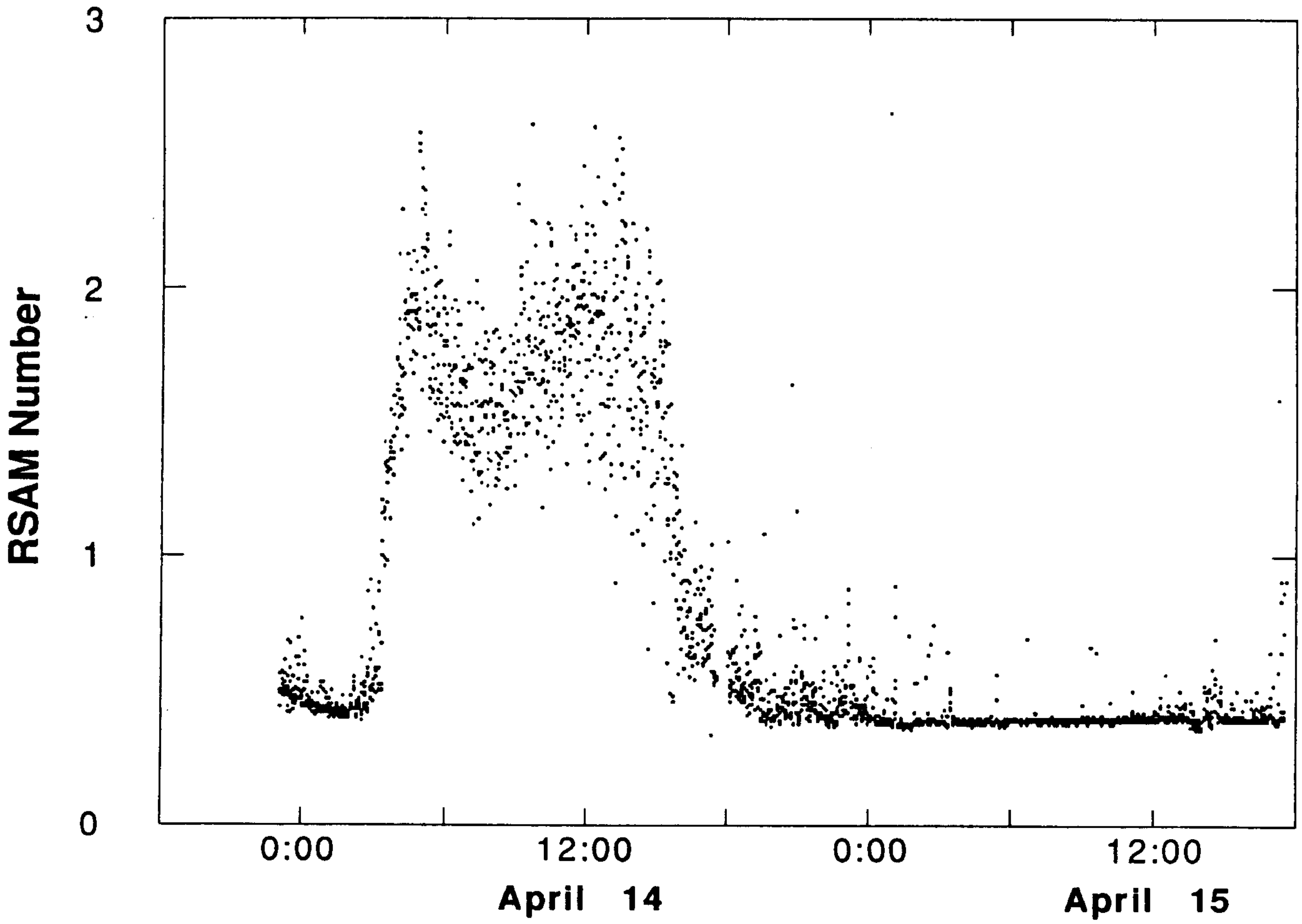

Figure 3-4. Real-time seismic amplitude measurements collected during the second phase of eruptive activity at Cerro Negro during the 1992 eruption. RSAM units are relative, calculated using the procedures of Murray and Endo (1989), and are indicative of total seismic energy release. Each sample point represents the root-mean-squared amplitude of the seismic signal collected at a site 5 km from the volcano.

Table 3-1. Leachate concentrations (ppm) in three eruptions of Cerro Negro

	Cl	F	SO_4	Na	K	Ca	Mg	S/Cl
1992, 71 Samples								
avg	88	8	457	17	2	148	175	1.7
max	703	221	3583	271	35	1138	1292	
1971, 53 Samples								
avg	777	14	541	146	20	257	23	0.2
max	1150	20	1240	230	180	510	48	
1968, 41 Samples								
avg	409	8	725	187	22	156	17	0.6
max	1200	22	2400	1500	86	650	54	

Fumaroles were established on the crater rim following the 1992 eruption. These fumaroles have low mass flows and temperatures between 250 and 350 °C (M. Navarro, pers. comm., 1993). Fumarole temperatures were monitored relatively consistently between 1980 and 1983 at Cerro Negro. During this time, high-temperature fumaroles were located on the crater rim, as they are today, and maximum temperatures varied between 300 and 500 °C (McClelland et al., 1987). This indicates that degassing and related hydrothermal activity continued for at least 10 years following the 1971 eruption (volcanoes were simply not monitored in Nicaragua between 1983 and 1990). This type of persistent activity is important to consider in models of the secondary effects of volcanism on repository performance, and also may have implications for models of polycyclic volcanism. Continued high heat flow long after the termination of eruptive activity would strengthen theoretical arguments for polycyclic activity at cinder cones (Fedotov, 1981).

3.1.2 Tolbachik Cinder Cones, Kamchatka, Russia

Probably the most powerful, monitored eruption to have occurred at a small-volume basaltic cinder cone was at Tolbachik, Kamchatka, Russia (55.93 °N, 160.47 °E), in 1975. During this activity a series of powerful basaltic eruptions created an alignment of cinder cones and fissure-fed lava flows. Ploskiy Tolbachik shield volcano is in an area consisting of numerous monogenetic cinder cones and spatter cones. Four other cinder cones in the area are thought to be less than 500 years old (Braytseva et al., 1983). Three cinder cones, Cones I, II, III, and a series of small vents formed an alignment during several weeks of activity, known as the Northern Breakout, at Tolbachik in July and August 1975. This activity was followed by a fissure eruption known as the Southern Breakout, 10 km south of the Northern Breakout and about 20 km from the summit caldera (Fedotov, 1983). A single cone formed as a result of Southern Breakout activity.

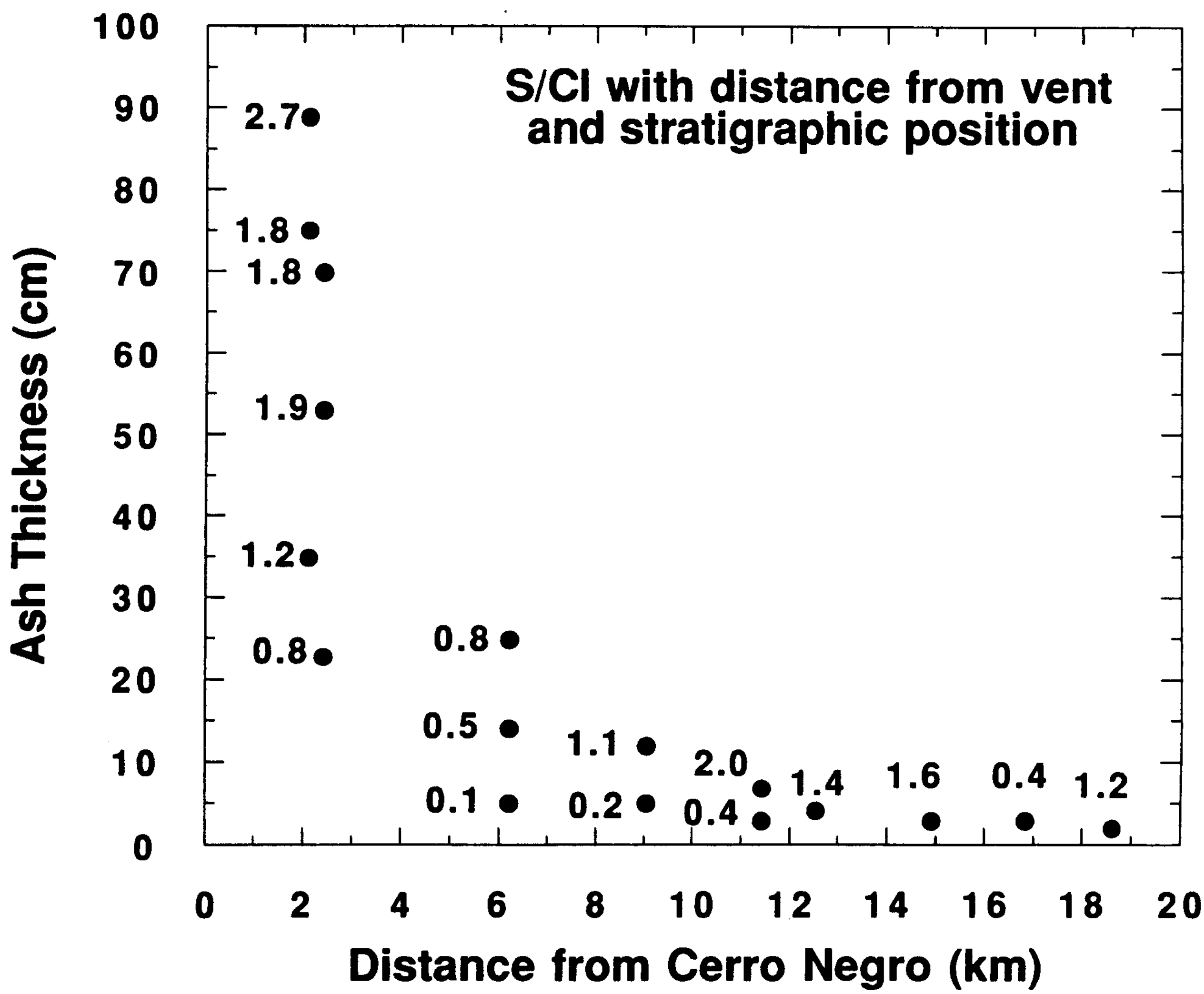

Figure 3-5. The thickness of the ash deposit varies exponentially with distance from Cerro Negro. Ash samples were collected during and immediately following the eruption at several stratigraphic positions along the major axis of dispersion of the deposit, and leachate S/Cl ratios were determined. A sample collected at 16.8 km is believed to have been altered prior to collection.

Budnikov et al. (1983), Maleyev and Vande-Kirkov (1983), and Tokarev (1983) summarized the initial activity at Tolbachik during the Northern Breakout. Activity at the first cone (Cone I) was initially mildly explosive and strombolian. This evolved into sustained explosive activity, during which time a convective ash column was maintained at approximately 5 km elevation, and effusion rates were on the order of 1.25×10^5 kg/s (Budnikov et al., 1983; Tokarev 1983). This activity continued for 56 hours, during which time Cone I grew to a basal diameter of 700 m and relief of 135 m, roughly the size of Lathrop Wells. This phase was followed by a dramatic increase in eruption intensity. The convective ash column increased to 8-10 km and occasionally reached 13-15 km (Fedotov, 1983). During this period, the eruption column was incandescent to an elevation of 1-2 km above Cone I during daylight hours (Tokarev, 1983). This Plinian activity continued in a near steady-state through July 23, a period of 14 days (Budnikov et al., 1983), but did not add substantially to the volume of this cone. Explosive activity then gradually decreased through the end of July. Cones II and III were formed by strombolian and vulcanian activity during August. Following this activity the locus of activity shifted south. On September 18, fire fountaining was initiated over a 200-m-long zone that gradually lengthened to 600 m. This eruption was entirely effusive, with fountain heights never exceeding 100 m. Effusion rates during the Southern Breakout were estimated to average 25 $m^3\ s^{-1}$ between September and November 1975.

Cone I and Cone II deposits contain abundant Neogene sedimentary and volcaniclastic xenoliths (Shanster, 1983). These xenoliths effectively sample the stratigraphic section beneath the volcano between 1.8 km and the surface. Although the stratigraphic control is not good immediately beneath the volcano, it is known that the average thickness of Quaternary basalt at the volcano is approximately 500 m (Shanster, 1983). Therefore, it is very likely that all sedimentary crustal xenoliths at Cones I and II represent wall rock carried from greater than repository (300 m) depths. Size distributions and concentrations of xenoliths have not been determined.

3.1.3 Parícutin

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. Volcán Parícutin (19.48 °N, 102.25 °W) is located in 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, in terms of area and number of volcanoes, this is probably the largest sub-aerial volcanic field on Earth. Parícutin is part of a cluster of approximately 120 cinder cones 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 3-6).

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,

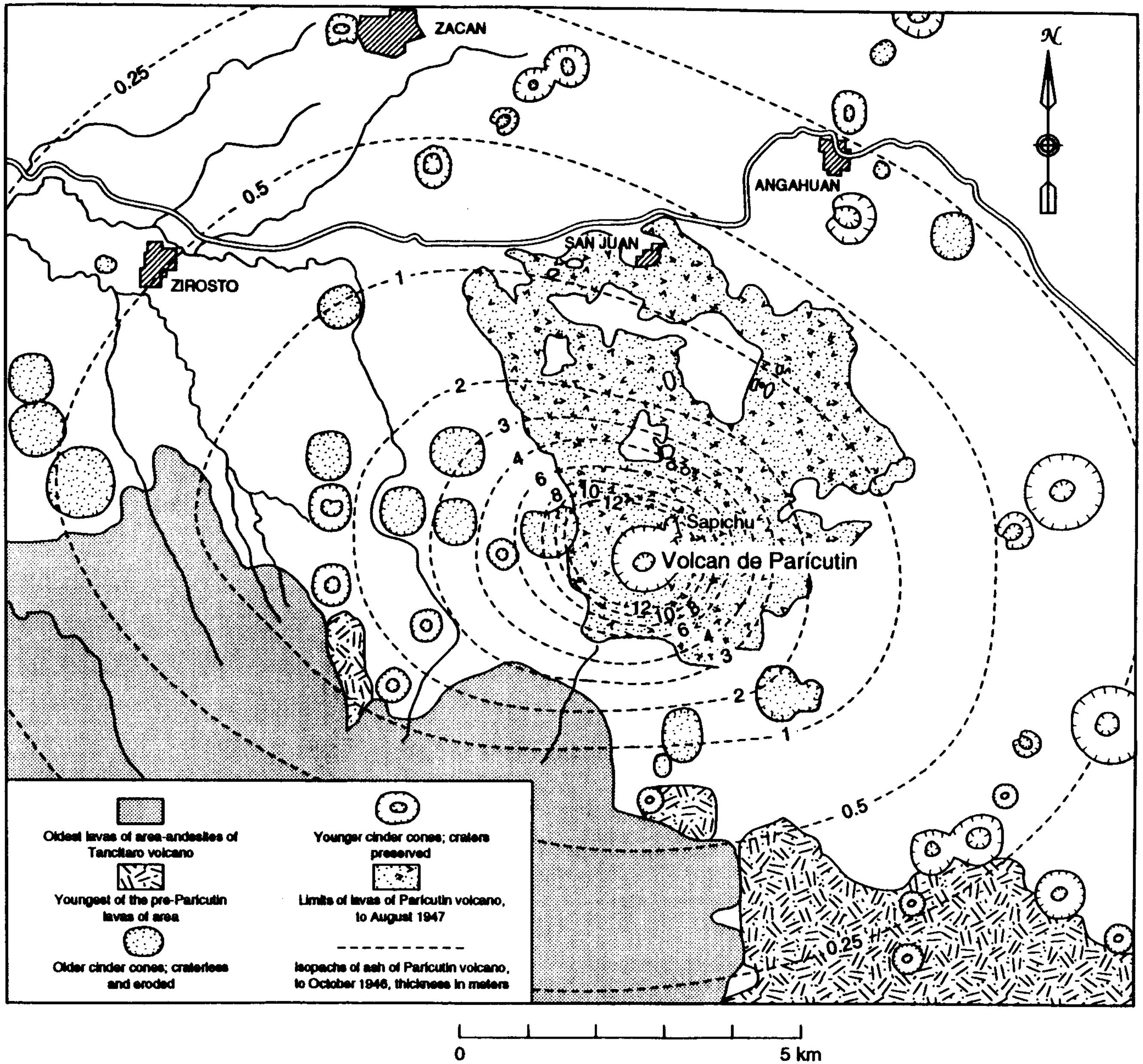

Figure 3-6. Volcán Parícutin is surrounded by numerous Quaternary cinder cones (modified from Williams, 1950)

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 to the volume of material erupted. Fries calculated the volatile content to be about 1 wt. 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 (Wilson and Head, 1981) 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 it is estimated by Williams (1950) to be over 300 m thick in the Parícutin region, based on exposures along the Cupatitzio river about 30 km from Parícutin.

Parícutin continues to degas today, 41 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 Sapichu vent, located NE of the main crater (Figure 3-7). High-temperature fumaroles are restricted to the Ahuan and Sapichu 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.

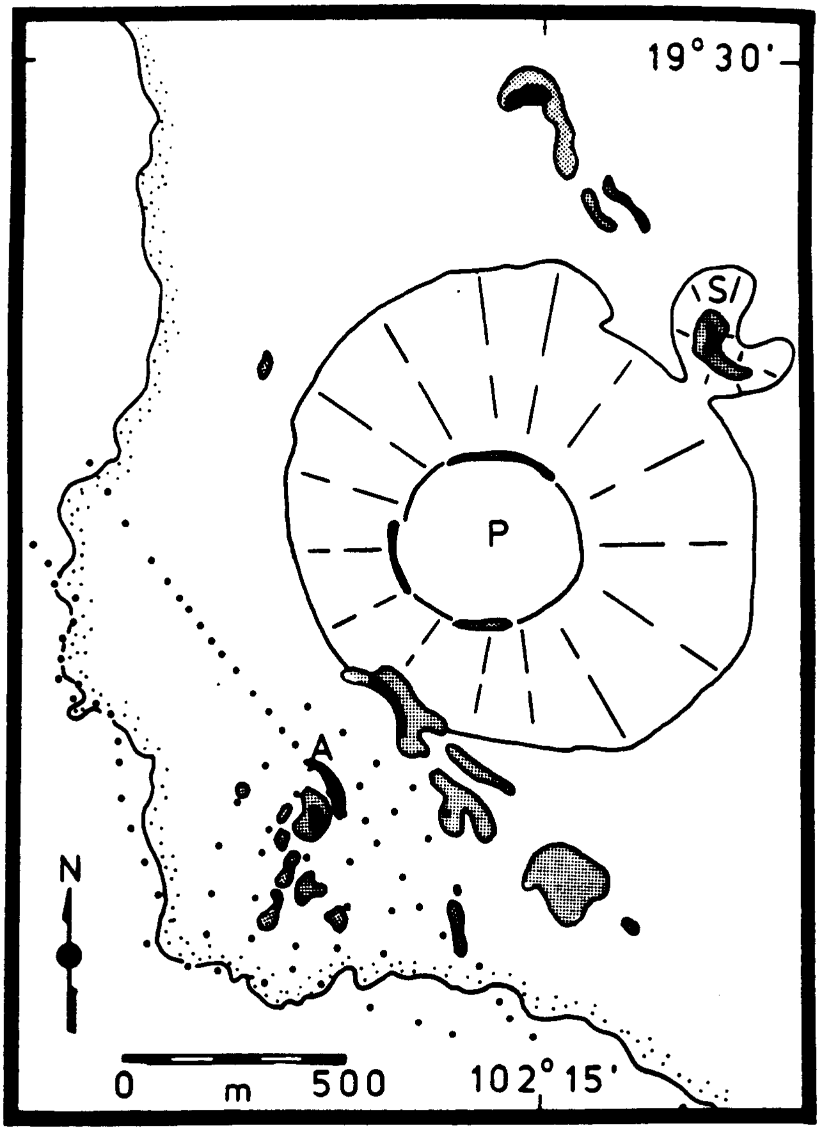

Figure 3-7. Soil mercury samples were collected by Connor (1989) on the SW flank of Parícutin. All soil samples (solid circles) had soil mercury concentrations in excess of 1,200 ppb. Three vents are labeled: Ahaun (A), the main crater (P), and Sapichu (S). The distribution of fumaroles is shown by temperature (solid pattern -> 100 °C; stippled pattern -< 100 °C). The west and southwest margins of the lava flows surrounding the cone are indicated by the stippled border.

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 3-7), with soil Hg concentrations between 1,200 and 11,000 ppb. These Hg concentrations are comparable to those found in active geothermal systems (e.g., Varekamp and Buseck, 1983; Williams, 1985; 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.

3.2 VOLCANOLOGICAL BASIS FOR STUDY OF ERUPTION MECHANICS (TASK 2)

Estimates of the amount of waste entrained by magmas erupting through the repository and the dispersion of this waste in the accessible environment must be made in order to characterize the expected performance of the candidate repository. As no cinder cones in the western Great Basin have erupted historically, it is necessary to infer the character of these eruptions from the geologic record and through the development of numerical models. Hence, U.S. Department of Energy (DOE) site characterization activities include the development of numerical models intended to simulate cinder cone eruptions and estimate their effect on repository performance (Valentine et al., 1992). The study of modern analogs to YMR volcanism provides an opportunity to evaluate these models in an unambiguous manner, because the energetics of these eruptions and their effects are known from direct observation. Eruptions at Parícutin, Cerro Negro, and Tolbachik have been well documented. Further investigation of the deposits resulting from these eruptions and the rheologic properties of the erupted magmas can, therefore, provide important insight into the utility and limitations of models used to describe YMR volcanism. This process of comparison will involve:

- Comparison of magma properties of YMR volcanoes and those of Parícutin, Tolbachik, and Cerro Negro magmas
- Comparison of near-vent deposits of YMR volcanoes and those of modern analogs
- Calculation of the energetics of cinder cone eruptions, the dispersion of ash, and related parameters at modern analogs using field observations
- Model validation studies using modern analogs to explore the adequacy of eruption models

These activities are needed because substantial uncertainty currently exists about the nature of cinder cone eruptions in the western Great Basin. Cinder cone eruptions are often characterized as low-energy Hawaiian, strombolian, or vulcanian eruptions (e.g., Crowe et al., 1993). These eruptions are not capable of wide dispersion of ash, or radioactive waste. However, historically active cinder cones frequently experience highly energetic sub-Plinian- or Plinian-style eruptions (Rose et al., 1973; Fedotov, 1983; Amos et al., 1983; Walker, 1991; Rowland et al., 1991; Walker, 1993, Connor et al., 1993). Based on geologic interpretation of deposits at Lathrop Wells and elsewhere in the United States

(Self et al., 1980; Valentine et al., 1992), cinder cones in this region may also experience this type of energetic eruption. A primary goal of the Field Volcanism project is to investigate this type of comparatively high-energy eruptive activity at modern, small-volume basaltic volcanoes and determine, through characterization of physical magma properties and volcanic deposits, whether or not this type of activity occurs in, or is characteristic of, western Great Basin volcanism.

3.2.1 Investigation of Magma Properties

In order to characterize magma rheology, the following properties will be estimated using field and laboratory investigations at both cinder cones of the western Great Basin and historically active cinder cones.

- Major element chemistry of lavas and pyroclastic material
- Phenocryst assemblage, volume fraction, and size distribution
- Initial volatile content in magmas, estimated from melt inclusions
- Vesicle size and distribution in pyroclastic material

Magma viscosity, density, and yield strength are strongly influenced by these properties, and, therefore, they are important controls on eruption mechanics (Wilson and Head, 1981; McBirney and Murase, 1984).

Major element compositions for each of the historically active cinder cones have previously been reported (McBirney et al., 1987; Carr and Walker, 1987; Fedotov et al., 1991). Consequently, it is possible to compare the effect of differences in major element chemistry on magma properties between YMR magmas and those erupted at historically active cinder cones. Magma viscosity, for example, may be estimated at a given temperature and volatile content from the major element chemistry (e.g., Marsh, 1981; McBirney and Murase, 1984). Assuming a volatile content of 1 wt percent and a magma temperature of 1,100 °C, the viscosity of Crater Flat and Lathrop Wells magmas is between 400 and 1,200 poises, based on the major element compositions provided by Vaniman et al. (1982). Using the same values for volatile concentration and temperature, viscosity of Parícutin magma is between 2,400 and 2,600 poises for magmas erupted in 1943 and 1944 (McBirney et al., 1987); viscosity of magmas of the 1971 eruption of Cerro Negro are between 800 and 960 poises; and the viscosity of magma from the early phase of the Northern Breakout of the 1975 eruption of Tolbachik are between 200 and 350 poises. Based on composition alone, viscosities of these recent eruptions are quite similar to those of Crater Flat and Lathrop Wells. However, in basaltic rocks, initial volatile content and crystal fraction have a much more profound impact on viscosity than composition. For example, recalculating the viscosity of Lathrop Wells magma for the same conditions as above, but with a 2 percent volume fraction of olivine (average diameter = 1 mm), results in an increase in viscosity from approximately 450 poises to 25,000 poises. In contrast, a 1943 Parícutin magma contains approximately 1.5-2 wt percent water, 2 percent phenocysts of olivine, and less than 1 percent phenocrysts of plagioclase (approximately 0.5 mm in diameter; McBirney et al., 1987). This magma, erupted at 1,050 °C, will have a viscosity of approximately 15,000 poises.

Differences in major element composition related to paragenesis and open-system fractionation between Yucca Mountain region volcanoes and historically active cinder cones are not nearly as important to determination of viscosity as initial volatile concentration and crystal fraction in the magma. This is true of other parameters that are important in eruptions mechanics as well, such as bulk density of magmas at shallow depths (Wilson and Head, 1981) and yield strength (McBirney and Muarse, 1984). As discussed in the Field Volcanism Project Plan, phenocryst composition, volume fraction, and size distribution will be determined systematically using heavy mineral separation and automatic point count techniques both at historically active cinder cones and western Great Basin volcanoes. Volatile concentrations will be estimated from melt inclusions and mineral assemblages. Vesicle size and distribution will be determined in thin sections using image analysis techniques.

In the event that magma properties are found to be broadly comparable between western Great Basin volcanoes and some or all historically active cinder cones, then it will be possible to apply observations of the range of eruptive activity observed at historically active cinder cones to those of the western Great Basin. In this case, the most defensible models of the consequences of potential YMR volcanism may come from simple comparison with analogous modern eruptions, rather than through simulation using numerical models. Should important differences in rheologic properties be identified, for instance, if there are broad differences in volatile content, then modern analogs will provide the only appropriate tests of eruption models.

3.2.2 Cinder Cone Eruption Energetics

Eruption energetics can be characterized using a broad range of measures if direct observations of the eruptions are made. Wilson et al. (1978), for example, described a method for estimating thermal energy release of Plinian eruptions based on ash column height. Assuming that density of basaltic magma is about 2,800 kg m^{-3}, integrating over the isopach map (Figure 3-3) indicates that the April 1992 Cerro Negro eruption rate during the initial phase of activity was on the order of 300-500 $m^3\ s^{-1}$. The steady release of thermal energy during Plinian eruption is given by (Wilson et al., 1978):

$$Q = \rho v s (T_m - T_a) F \tag{3-1}$$

where Q is the thermal energy in Watts, ρ is the magma density (2,800 kg m^{-3}), v is the average eruption rate (in this case 300-500 $m^3\ s^{-1}$), s is the specific heat of the magma (1.1×10^3 J kg^{-1} $°K^{-1}$), T_m is the magma temperature, T_a is ambient air temperature, and F is a factor describing the efficiency of heat transfer to the atmosphere as the magma cools (assumed to be between 0.7 and 1.0). Using this range of values, the average rate of thermal energy release during the initial phase of the eruption was 6.7×10^{11} to 1.6×10^{12} W, and the total energy release was between 4.3×10^{16} and 1.0×10^{17} J. The expected ash column height, given the range of estimated thermal energy release, can then be calculated using the empirical relation of Wilson et al. (1978):

$$H = 8.2 Q^{1/4} \tag{3-2}$$

where H is the column height in meters. Substituting in the calculated values for steady thermal energy release, Q, the expected column height is between 7.4 km and 9 km above the volcano. These calculations agree well with observed column heights for the April 1992 eruption of Cerro Negro (GVN, 1992; Connor et al., 1993). During the second episode of activity that lasted approximately 19 hr., column heights were observed to be on the order of 3.5 km and relatively sustained (Connor et al., 1993). Average eruption rate during this period was approximately 25 - 30 $m^3 s^{-1}$. Calculated column heights for this eruption rate are 4.0 to 4.5 km, again, in reasonable agreement with the observed maximum ash column height.

In comparison, ash column heights between 150 and 1,200 m were seen during activity at Cerro Negro between October 24 and December 10, 1968. This is consistent with the much lower energy and longer duration of the eruption and the less dispersive character of the ashfall deposit. Rearranging equation 3-2, the steady thermal energy flux associated with 1968 explosive activity was on the order of 1×10^6 W. This value is quite low compared to 1992 thermal energy flux and indicates that this eruption is more closely approximated by instantaneous explosions of a vulcanian nature (Viramonte and Di Scala, 1970).

Observations and empirical estimates of energy release indicate that the April 1992 eruption of Cerro Negro was Plinian rather than strombolian or vulcanian, styles of eruption that are characterized by instantaneous explosions. Both phases of activity maintained a convecting ash column, 7-8 km and 3.5-4.0 km in height, respectively, that resulted in ash accumulation rates and dispersion that are expected from Plinian activity. Based on seismic data from the second, less vigorous eruption, energy release was essentially steady during the eruption, again consistent with a Plinian model. Ash leachate data also suggest that there may have been a change in magma chemistry during the eruption, also consistent with Plinian-style activity. Using the volcano explosivity index (Newhall and Self, 1982), the 1992 eruption is classified as VEI 3, although the duration of both phases of the eruption was longer than expected for a VEI 3 eruption.

Energy calculations may also be made for the initial phases of the 1975-1976 Tolbachik fissure eruption. Based on column heights, the initial, less explosive phase of activity at Cone I (column heights sustained at 5 km) resulted in a rate of thermal energy release of approximately 1.38×10^{11} W . Using the mass flow from the cone during this period, estimated by Tokarev (1983) to be 220 $m^3 s^{-1}$, the rate of thermal energy release was 1.4×10^{11} W. Using a 10 km average column height, the rate of energy release during the following Plinian phase of activity was 2.2×10^{12} W. Total thermal energy release during Cone I explosive activity was 2.7×10^{18} J. This is about one-third the thermal energy release due to the 1883 eruption of Krakatau (Simkin and Fiske, 1983).

3.2.3 Implications of the study of recent cinder cone eruptions for volcanism models in the Yucca Mountain Region

Volcanic eruptions are often classified on the basis of dispersion and fragmentation of ash. All three Cerro Negro eruptions for which detailed information of this sort are available (1968, 1971, and 1992) and the Cone I eruption at Tolbachik are classified as phreato-Plinian field based on these criteria. Based on the dispersion and fragmentation within the ash blanket alone, it might seem that these eruptions would have had a significant phreatic (or hydromagmatic) component, although this is clearly not the case. Walker (1993) has observed a similar pattern of highly fragmented and widely dispersed ash blankets at Parícutin, Jorullo, and Xitle volcanoes, Mexico. A least at Parícutin and Jorullo, a significant hydromagmatic component can be ruled out. Walker (1993) has suggested that the dispersive and fragmented character of the deposits may be related to a high yield strength in the magmas. Yield strength does not so much suppress bubble nucleation as suppress bubble coalescence in the magma (Sparks, 1978). Nonetheless, this may have important implications for the depth of fragmentation and the ability of the magma to erode wall rock at varying stratigraphic levels. The Tolbachik eruption entrained a considerable volume of shallow crustal xenoliths (Shanster, 1983) and, although not searched for in a systematic way, crustal xenoliths do occur in Cerro Negro eruption products from the 1968 (Viramonte and Di Scala, 1970) and 1992 eruptions. Comparable entrainment of xenoliths may have occurred at Lathrop Wells, as abundant crustal xenoliths are present in near-vent facies at that cone (Crowe et al., 1983; Connor and Hill, 1993).

Monitoring of active cinder cones indicates that eruptions at these volcanoes can be explosive, highly energetic, and of long duration. Both the 1992 and 1975 eruptions of Cerro Negro and Tolbachik were considerably more energetic than suggested by the terms strombolian or vulcanian (e.g., Blackburn et al., 1976). Although these eruptions were small volume, and not Plinian in the strictest sense (Simkin et al., 1981), they do have many of the characteristics of Plinian eruptions. For example, eruption columns were sustained over a long period of time, during which significant changes in magma chemistry occurred, and total thermal energy release was large, comparable to some Plinian eruptions. Furthermore, muzzle velocities for the Cerro Negro and Tolbachik eruptions were approximately twice those reported for hydromagmatic eruptions (e.g., Self et al., 1980). Similar explosive activity may be a common characteristic of cinder cone volcanism in the southwestern United States (e.g., Amos et al, 1983). The extent to which this style of activity occurred during eruptions at Lathrop Wells, where strata of a highly fragmented character are common (Crowe et al., 1983), and other Quaternary cones in the western Great Basin will be addressed through analog studies. Characterization of volcanological features of near-vent facies, including sorting, grainsize, vesicularity, and xenolith concentrations, at historically active cinder cones will provide considerably more confidence in models of YMR volcanism than is otherwise possible.

3.3 VOLCANOLOGICAL BASIS FOR INVESTIGATION OF DEGASSING FROM COOLING, SMALL-VOLUME BASALTIC SYSTEMS (TASK 3)

Volatile concentration in magmas and interaction with shallow groundwater are important parameters governing eruption mechanics. After the cessation of eruptive activity, heat and mass transfer to the surface and through rock surrounding shallow intrusions continues through convective degassing and heat conduction. This type of degassing activity may have an important impact on repository performance in several ways. First, direct effects of volcano degassing include the movement of gas through the repository block. This activity may result in accelerated rates of container corrosion and deterioration of the waste package itself. Direct effects of volcano degassing would likely accompany direct magmatic disruption of the repository, but could also occur if magma intruded rocks near the repository without actually intersecting the repository itself. Therefore, the probability of this type of activity occurring is high compared to the probability of direct magmatic disruption. Second, indirect effects of degassing may also impact repository performance. Indirect effects may include change of partitioning of radionuclides between aqueous and solid phases, and changes in sorption of radionuclides. Finally, change in movement of groundwater and gas phases in the geologic environment, and changes in the mechanical properties of the rock, may also result from degassing and thermal loading of rock by conductive and convective heat transfer. All of these possible effects raise compliance issues. Observation of heat and mass transfer at actively cooling cinder cones will provide a basis for evaluating conceptual and numeric models that address these processes. Study of cooling cinder cones is needed in this context because very little is known about the rates of degassing of small-volume systems, the duration and area affected by this activity, or the relationship between degassing rates and alteration.

The effects of degassing on repository performance are different than those associated with eruptive activity for the following reasons.

- Volcanic degassing is a long-term process. Preliminary data from Parícutin, Tolbachik, and Cerro Negro indicate that cinder cones generally cool and degas over long periods of time. Vigorous, high-temperature degassing persists at some cinder cones for decades. Low-temperature and less vigorous degassing may continue for more than 100 years. Low-temperature fumaroles are found at Jorullo volcano, Mexico, for example, more than 200 years after that volcano's eruption (J.F. Luhr, pers. comm., 1992). As a result, a broad range of time scales must be considered in developing models of how volcanic degassing influences repository performance.

- Volcanic degassing is capable of influencing an area much greater than is disturbed by eruptive activity. This is important because most probability models for volcanic activity are area dependent; the probability of volcanic gases interacting with the repository and surrounding geological environment is much higher than the probability of direct disruption by magma transport. The areal extent of degassing and the nature of variation in degassing is uncertain and will need to be assessed through field investigation, coupled with the development of heat and mass transfer models.

- Volcanic degassing does not result in the fragmentation, transport and dispersion of rock and repository waste, as direct disruption of magma would. Instead, volcanic degassing has long-term effects on the geochemistry of the repository and surrounding rock. Volcanic gases are generally acid solutions, with pH in the range of 0.1 to 2. Gas temperatures commonly range from magmatic (800 to 1000 °C) near vents to ambient far from vents. Dominant species in the gases are water, carbon dioxide, sulfur dioxide, hydrogen chloride, and trace compounds, including trace metals like mercury and noble gases. Because of their composition, influx of volcanic gases into the repository would accelerate corrosion of waste containers, alter transport rates in the geologic environment, and alter the mechanical strength of the rocks in and around the repository block. These effects are different than simple thermal loading, such as that resulting from the repository itself, because in addition to enhanced thermal effects, mass flow of volcanic gases through the geologic environment will occur.

3.3.1 Conceptual Model for Cinder Cone Degassing

After the cessation of flow of magma, either because eruptive activity has ceased or because intrusion stagnates at shallow (< 1 km) depths, some percentage of magma remains in the subsurface. Volatiles and heat are released into the geologic environment as this magma cools and crystallizes. A simplified conceptual model of the heat and mass transfer process in illustrated in Figure 3-8. Heat and mass transfer take place through forced convection through fractures and free convection in the surrounding rock. Heat is also transported through the surrounding rock by conduction. At cooling cinder cones these are mixed processes. Forced convection takes place where rock is significantly fractured and as long as the pressure difference is large enough to drive flow. Fractures may result from deformation due to the intrusion process, or might be pre-existing faults or joints. Above the dike, flow is by free convection in the rock (or alluvium) and by forced convection through fractures. At cinder cones, fractures often concentrate around the crater rim and near satellite vents (e.g., Cerro Negro and Parícutin)

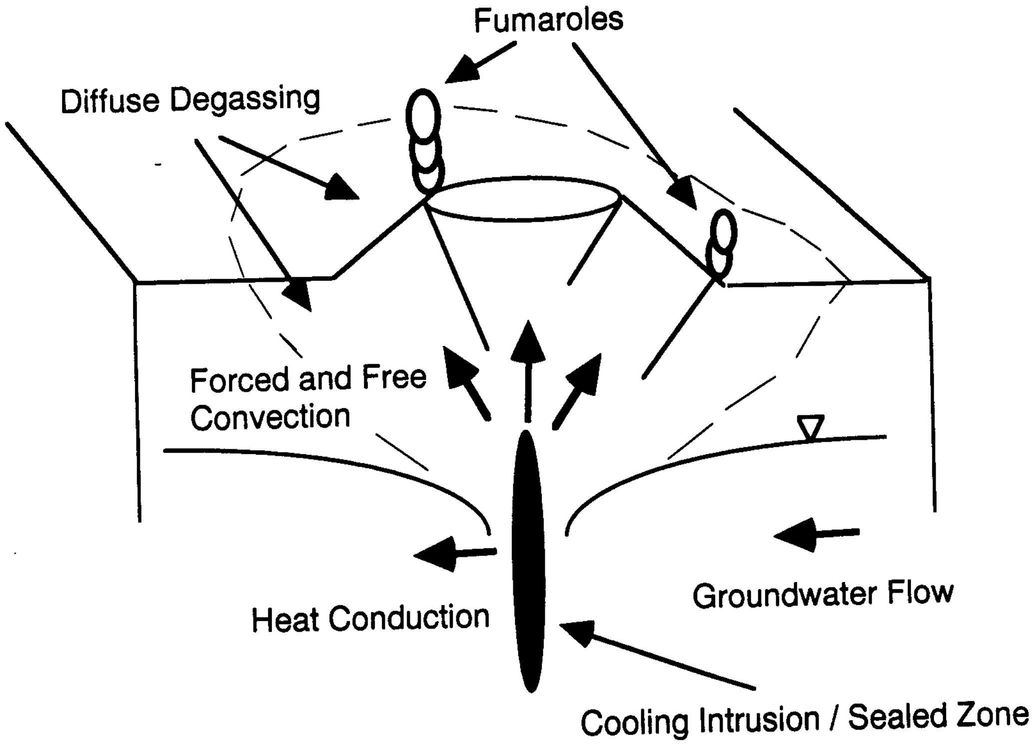

Figure 3-8. Schematic diagram illustrating one conceptual model of heat and mass transfer at a cooling cinder cone

and consequently these areas are the location of high-temperature fumaroles. Because of vaporization, the dike acts as a groundwater sink and there is a net movement of groundwater toward the dike.

3.3.2 Learning About Degassing at Cooling Cinder Cones Through Direct Observation of Active Systems

Direct observations at cooling and degassing cinder cones will provide information that cannot otherwise be attained. These data will greatly refine conceptual models of degassing and cooling. Three areas of investigation that can only be pursued through observations at recently active cinder cones are studies of: chemistry and physical properties of gas, variation in heat and mass transfer through time and duration of degassing activity, and the areal extent of degassing.

- *Chemistry, temperature, and mass flow of gases.* Characterization of the chemistry of gases emitted at the surface will greatly help constrain the impact of volcano degassing on repository performance. Typically, volcanic gases are mixtures of water vapor, carbon dioxide, sulfur dioxide, chlorine, hydrogen chloride, and numerous other compounds in trace abundances. These gases would likely influence repository performance given a long period of exposure. Studies of volcanic gases, as described in the Field Volcanism Project Plan, will include monitoring of mass flow and temperature at active fumaroles, and collection of gas samples for chemical analyses. Chemical analysis will include determination of major ions, and isotopic studies to determine the meteoric and magmatic fractions of the gases and residence time of the meteoric fraction. These data will provide critical information about the likely effects of volcanic gases on waste containers and transport in the geologic environment.

- *Duration of anomalous heat and mass transfer.* Little or nothing can be learned about the duration of degassing and cooling from study of ancient cinder cones. Most theoretical models for dike emplacement and solidification indicate that individual dikes cool rapidly to near ambient temperatures within hours or days of the cessation of rapid mass flow (Delaney and Pollard, 1982). However, the occurrence of high-temperature fumaroles at recently active cinder cones indicates that heat and mass transfer in the entire volcanic system remains elevated for considerably longer periods of time. The persistence of fumaroles with temperatures in excess of 400 °C at Parícutin, for example, indicates that gas at shallow depths remains super-heated for decades following eruptive activity, at temperatures far above those associated with normal vapor-dominated geothermal systems. Conditions responsible for the persistence of this activity must be better understood in order to determine the long-term impact of volcanism on repository performance. Two mechanisms that may account for the persistence of high temperatures are (i) long-term magma degassing at sufficient depths to prevent rapid quenching, or (ii) the presence of a sealed zone, within which gas pressures and temperatures are elevated, and from which gas escapes only through fractures.

  Field studies at cooling cinder cones will provide information about the longevity of heat and mass transfer in these cinder cones because of the varying time elapsed since the end of eruptive activity at each of the three sites. It is anticipated that differences in the rates of mass and heat flow, and changes in the chemical composition of the gases, will likely correlate to the time since eruptive activity.

- *Areal extent of degassing.* Alteration zones resulting from volcanic degassing can be mapped in ancient systems that have been exhumed by erosion. However, evidence from Parícutin indicates that diffuse degassing occurs over comparatively large areas. This diffuse degassing, which is known to be commonplace at active composite cones, rarely leads to the kind of pervasive alteration that is preserved in the geologic record. However, diffuse degassing may have an important impact on gas transport in the geologic environment and result in changes in groundwater flow. Determination of the areal extent of degassing at the surface will constrain models of the volume of rock influenced by degassing at depth. As the project develops, these surface studies will be coupled with electrical surveys that will provide additional insight into flow paths at depth.

3.3.3 Numerical Models For Heat and Mass Transfer in Cooling Small-Volume Basaltic Systems

Data gathered at cooling cinder cones will be essential in the development of steady-state and transient numerical models of changes in heat and mass flow associated with intrusive and extrusive activity. These numerical models will be developed to explore the relationship between heat and mass transfer around dikes and cinder cones as they cool through time, and to help explain the relationship between surface features and likely flow paths at depth, in a manner quite similar to thermo-hydrologic investigations currently under way at Yucca Mountain. Ultimately, generalized models of the thermal and geochemical effects of degassing will be developed for the YMR, taking into account the range of activity observed at modern analogs and geologic variation in the YMR.

Here, a simple boundary-value problem is developed in order to heuristically illustrate the utility of these types of models and their relationship to data collected in the field. Heat and mass transfer are coupled processes in high-temperature hydrothermal systems. Heat drives flow due to natural convection and heat is advected through rock by forced convection in fractures and free convection. Heat and mass transfer in such situations are thought to be well described by the conservation of mass, energy, and momentum equations. Using these equations, it is comparatively simple to model single-phase, steady-state heat and mass transfer as a boundary value problem. By introducing a similarity variable for temperature,

$$\theta = \frac{T - T_0}{T_1 - T_0} \tag{3-3}$$

where T is the temperature at a point, T_1 is the temperature of this gas at the intrusion, T_0 is the temperature of the gas at the surface far from the intrusion, and Ψ is the stream function, these equations reduce to:

$$\frac{\partial^2\theta}{\partial x^2} + \frac{\partial^2\theta}{\partial z^2} = \frac{\partial\psi}{\partial x}\frac{\partial\theta}{\partial z} + \frac{\partial\psi}{\partial z}\frac{\partial\theta}{\partial x} \tag{3-4}$$

$$\frac{\partial^2\psi}{\partial x^2} + \frac{\partial^2\psi}{\partial z^2} = Ra\frac{\partial\theta}{\partial x} \tag{3-5}$$

where x and z are horizontal and vertical Cartesian coordinates, respectively, and Ra is Rayleigh's number. In this formulation, the Bossinesq approximation is used to accommodate the effects of thermal expansion of the gas, and subsequently change in gas density. These equations are solved as a boundary value problem using finite differences to explore flow patterns and distribution of heat that might result from dike intrusion. Solutions based on this approach do not capture the complexities of the heat and mass transfer processes. However, solutions based on equations 3-3 to 3-5 are useful for demonstration of the viability of the approach.

One solution calculated using this approach is illustrated in Figure 3-9. Here, boundary conditions similar to those shown schematically in Figure 3-8 are assumed. Specifically, gas is assumed to be emanating from a hot intrusion or partially sealed zone at depth. In this case, gas flow from the intrusion is assumed to be high compared with the inflow of meteoric water vapor. This inflow of meteoric water vapor is assumed to occur because the intrusion acts as a sink by vaporizing groundwater close to the intrusion. Assuming symmetry, a no-flow condition (for both heat and mass) is assumed to exist on the left-hand boundary immediately above the intrusion. Outflow at the surface is assumed to be uniform, except in a fracture zone along which flow is enhanced, and no flow occurs at the base of the model, at depth, except from the intrusion itself.

The distribution of heat in this model is quite different than that predicted by simple conduction. High-temperature gradients exist around the dike and heat is advected away from the dike by both magmatic gas and meteoric water vapor. Heat is also advected very efficiently in fracture zones and this, in turn, elevates temperatures in the surrounding rocks. Flow paths are complicated by the temperature distribution and by the Rayleigh number, which in this case is considered to be low, and the relative input of magmatic and meteoric gases. Although this model is clearly limited in its application to natural systems, it illustrates the point that a knowledge of flow and temperature distribution from field data (e.g., monitoring flow volume, temperature, and chemistry at the surface, mapping fracture zones, and electrical studies of the subsurface) can be of tremendous assistance in constraining likely temperature distributions and flow paths at depth. This type of information is important to constraining the likely impact of volcanic activity on repository performance (Trapp and Justus, 1992).

During the course of Task 3 of the Field Volcanism project, this type of model will be improved upon by (i) recasting the governing equations for a time-dependent initial value problem, (ii) taking into account the effect of temperature on the thermodynamic properties of the gas, using measured gas compositions, (iii) taking into account phase transformations, such as the vaporization and condensation of groundwater, and (iv) using measured mass flow and temperature distributions to bound model solutions at the surface. Thermo-hydrologic models, such as VTOUGH code, will be adapted to better model the complexities of these natural systems using an integrated finite difference approach (Crawford et al., 1987; Green et al., 1992; Manteufel and Green, 1993).

3.4 NEED TO STUDY MULTIPLE SITES

Reduction of KTU and the development of robust PA models require that geologic models be comprehensive and defensible. In the context of the licensing environment, very little is known about

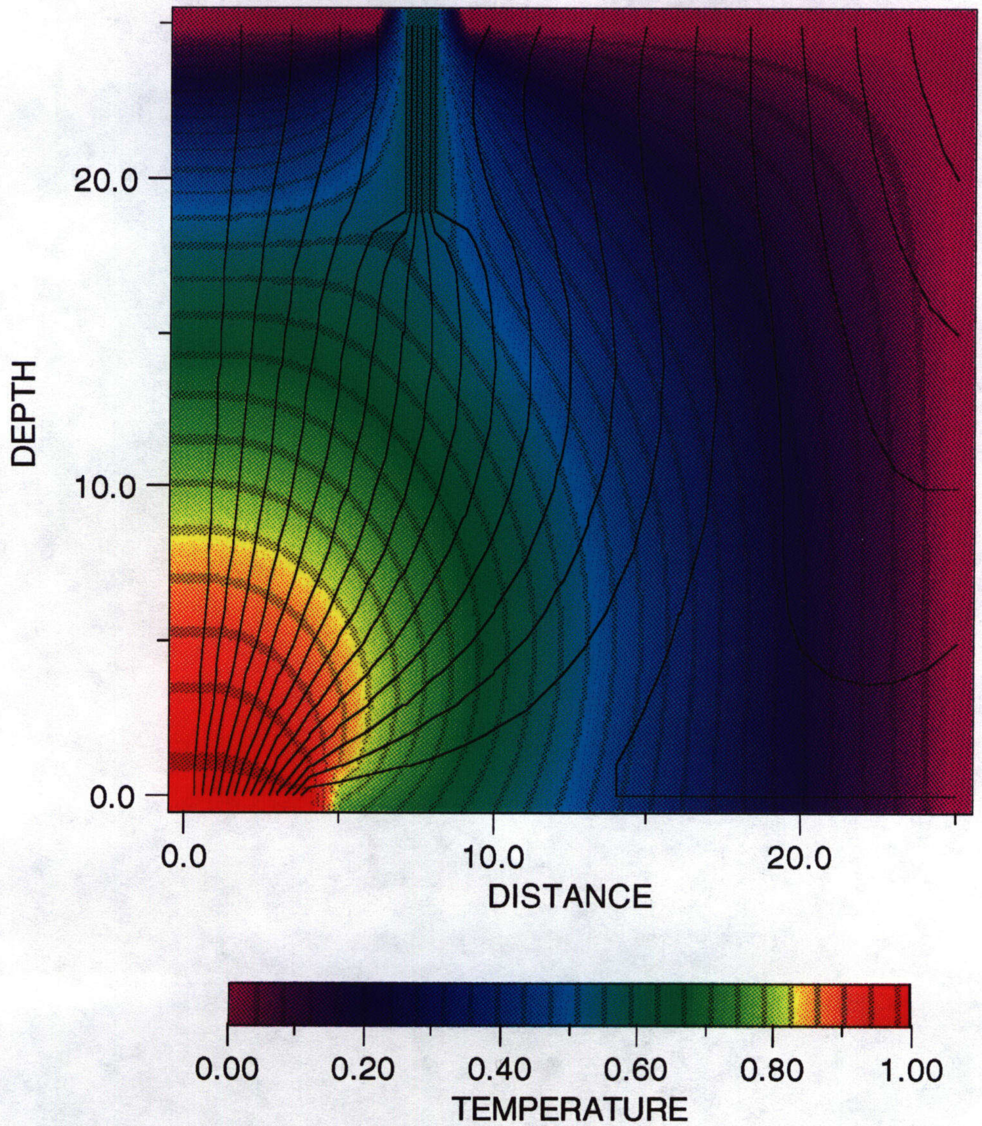

Figure 3-9. A boundary value heat and mass transfer problem solved using equations 3-3 to 3-5. Streamlines, Ψ, are indicated by solid lines. Temperature distribution, θ, is indicated by the color bar (cool, meteoric water vapor is shown in blue, hot magmatic gases in red). Gas escapes from a cooling and crystallizing magma (lower left corner) and rises by by free and forced convection to the surface, advecting heat along flow paths. A fracture extending part way to the magma (illustrated by increased streamline density) creates a thermal anomaly. Boundary conditions are similar to those illustrated schematically in Figure 3-8. Distance and temperature scales are relative.

eruption mechanics in small-volume basaltic systems and less is known about the way in which these systems cool through time. The research program outlined in the Field Volcanism Project Plan involves the use of innovative techniques to explore these technical issues. In view of the regulatory need to fully investigate volcanic processes, it is auspicious to apply these techniques at multiple sites. Each of the analogs in this study deserve careful investigation in order to characterize and bound the variation of these volcanological processes.

Observations indicate that Parícutin, Tolbachik, and Cerro Negro represent a range of eruptive behavior. It is likely, given the variation in eruptive behavior, that magma volatile content, phenocryst content and related factors will vary among the eruptive products of these volcanoes. The degree of this variation relative to the western Great Basin should be determined. Any development of numeric models of eruption mechanics should encompass the range of rheologic properties and eruptive styles observed at each of these volcanoes.

These three cinder cones have been cooling and degassing for different periods of time. Specifically, eruptive activity ceased 40 years ago, 17 years ago, and 1.5 years ago at Parícutin, Tolbachik, and Cerro Negro, respectively. Only the study of all three of these systems can provide a sense of how mass flow, temperature, and gas chemistry are likely to vary over long periods of time. The time scales of heat and mass transfer in these systems, and geochemical changes in gases through time, are important aspects of consequence scenario development. The study of a single modern analog, of course, cannot be used to quantify this variation.

3.5 RESEARCH PLAN

Specific methods for the study of these cinder cones are outlined in the Field Volcanism Project Plan. However, it is reiterated here that several factors make study of these analog sites practical from a logistical standpoint. Foremost of these is that CNWRA staff have extensive experience working at Parícutin and Cerro Negro. Because of this experience, there is a high probability of successful investigations being carried out in a timely manner at these sites. Yuri Doubik of the Kamchatka Volcano Institute has expressed an interest in cooperating with CNWRA staff in the investigations at Tolbachik. Dr. Doubik has conducted field work at Tolbachik since 1975 and his participation will also increase our ability to plan and implement an effective research program at that volcano. Scientific activities at each these sites are planned in stages in order to create a flexible and responsive research design. Initial investigations will include sampling for determination of magma properties, and gas and soil sampling. Results of these initial site surveys will provide important constraints on volcanism models. Later visits will include areally extensive surveys, mapping, and detailed stratigraphic sampling. This research design will provide the opportunity for extensive interaction with NRC staff concerning appropriateness of analog studies at specific sites, survey design, and the level of detail required to explore specific regulatory issues and resolve KTU.

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