Lava Tube Fire Impact Study
El Malpais National Monument
New Mexico
Final Report

Kenneth Ingham
Kenneth Ingham Consulting

Diana E. Northup
University of New Mexico

Dr. W. Calvin Welbourn
The Florida Department of Agriculture and Consumer Services

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1 Introduction

This report is the final report for Order No. 1443PX700093892. It covers:

- background information on the products and effects of fire, especially in regards to invertebrates
- background information on prior research done on cave climate
- materials and methods used to collect the data
- over one year's worth of temperature and humidity data from the two caves studied
- analysis of the temperature and humidity data
- predictions about the effect of fire above or near a lava tube
- CO_2, water chemistry, particulate data
- maps of Lava Wall and Frozen Mat caves
- a listing of biota found
- problems encountered
- suggestions for future work.

Our original goal was to study the impact of a prescribed burn on Lava Wall (Peel Bark), a lava tube located in El Malpais National Monument, using a nearby lava tube, Frozen Mat, as a control. To accomplish this goal, we had the following objectives which were to be conducted pre- and post-burn:

- Monitor temperature continuously at appropriate sites in the sink, ceiling, and floor areas of the tubes.
- Monitor humidity continuously at one site in each lava tube.
- Measure carbon monoxide and carbon dioxide levels in the air in the lava tubes.
- Measure the dissolved solids, conductivity, and pH of standing water (in Lava Wall only drips were available).
- Measure particulate levels.

The original goal was not achieved because the burn was postponed indefinitely. To provide useful information to the park from the investment in the dataloggers, we turned our attention to the modeling of cave climate to better predict the factors in the lava tubes which may be affected by a nearby fire.

1.1 Description of the tubes

The experimental lava tube, Lava Wall (also known as Peel Bark), and the control lava tube, Frozen Mat, are located about 34°57′15″N and 108°06′30″W. Bob and Debbie Buecher mapped these lava tubes on 25-26 September 1993 and the maps are provided as an Appendix B to this report.

Lava Wall is the smaller of the two lava tubes. It has a large wide entrance about 6.5m x 1.5m, and gets narrower and lower as you go into the cave. The cave turns into a low muddy crawl just past the hygrothermograph, continuing for more than 24m. The crawl shows evidence of repeated flooding and organic input, and a slight breeze is detectable, implying a second entrance. Unfortunately, the cave is too low to continue to the other entrance. Checking the surface, it is likely that the second entrance is in breakdown in a low sink about 30m west of the cave. Unlike Frozen Mat, this cave is relatively level once you are inside the entrance.

Frozen Mat is the larger cave and consists of two rooms and a passage. The small (less than 1 meter square) entrance leads into a breakdown room. This entrance room is about 4m x 9m. Over a large breakdown pile, approximately to the southeast, is a room, 5m wide and at least 20m long containing an ice sheet about 5m wide by 6m long covered with up to 2.5cm of water. The ice sheet varies in extent and depth throughout the year and from year to year. The ice is about 3m-4.5m below the entrance and about 20m from the entrance. The room extends no more than about 7.5m beyond the ice.

On the left side of the entrance room in Frozen Mat is a low passage going to the left for at least 13m. We detected no airflow through this passage and it appeared to pinch out. This passage contains numerous bat bones.

2 Literature Review

This section provides references to prior research which helps set the stage for this report. In many areas covered by this report, we were unable to find any prior work.

2.1 Products and effects of fire

The major products of fire are heat, airborne particulates, carbon monoxide, hydrocarbons, water, and carbon dioxide ([42] and [10]). The smoke produced is composed of solid or liquid particulate material in the range of 0.001-10.0 microns ([10]). As compared to atmospheric carbon monoxide (0.05–0.2ppm), fire can produce carbon monoxide values in the range of 60ppm at the edge of the plot to as high as 1200ppm 30 feet over the center of the plot ([10], data from a

California fire of 30 acres with 160 tons of fuel/acre). The hydrocarbons produced by the burning of green brush are many and varied.

In addition to the products produced, fire produces an increase in air and soil temperature, lowers the relative humidity over time close to the ground due to loss of insulating vegetation and litter, and blackens the ground which produces increased solar absorbances ([25]). The effects of a fire may exist only during the time of the actual burn, or they may last much longer. For example, the heat of a fire dissipates soon after the fire is out. However, airborne particulates may enter a cave and settle out of the air, leaving a long-term record of the fire.

2.1.1 Heat

We begin by looking at the question of will the heat of a fire move by conduction down through the soil and underlying rock into the cave. To answer this question, we look at the thermal conductivity and specific heat of both the soil and underlying rock.

Tracy and Rodenbaugh ([37]) and Munn ([27]) both discuss soil thermal conductivity. Soil is composed of particles varying in size from 1 to 100 μ, has pores of various sizes which may contain air, water, or ice. The thermal conductivity of soil depends on the following factors:

- the thermal conductivity of the particles
- the size of the particles
- the particle size distribution
- the soil moisture content
- the compaction of the soil—the ratio of the volume between the particles to the total volume

Soils with a good distribution of particle sizes maintain a fairly constant thermal conductivity of 0.00239 to 0.00800 $\frac{\text{cal}}{\text{sec cm K}}$ until they get down to about 16% moisture content ([37], [27]), at which time their thermal conductivity begins to drop rapidly with dry soil being $\frac{1}{3}$ to $\frac{1}{4}$ as conductive ([35]). This means that soil is a fairly good insulator and will help prevent the heat of a fire from penetrating into the rocks below.

In addition to thermal conductivity, we also need to consider how much heat is needed to raise the temperature of soil. The more heat needed to raise the temperature, the shallower the high-temperature effects of the fire. Munn ([27]) points out that soil moisture is an important regulator of soil temperature, and that moist soil takes much more heat to raise its temperature than does dry soil.

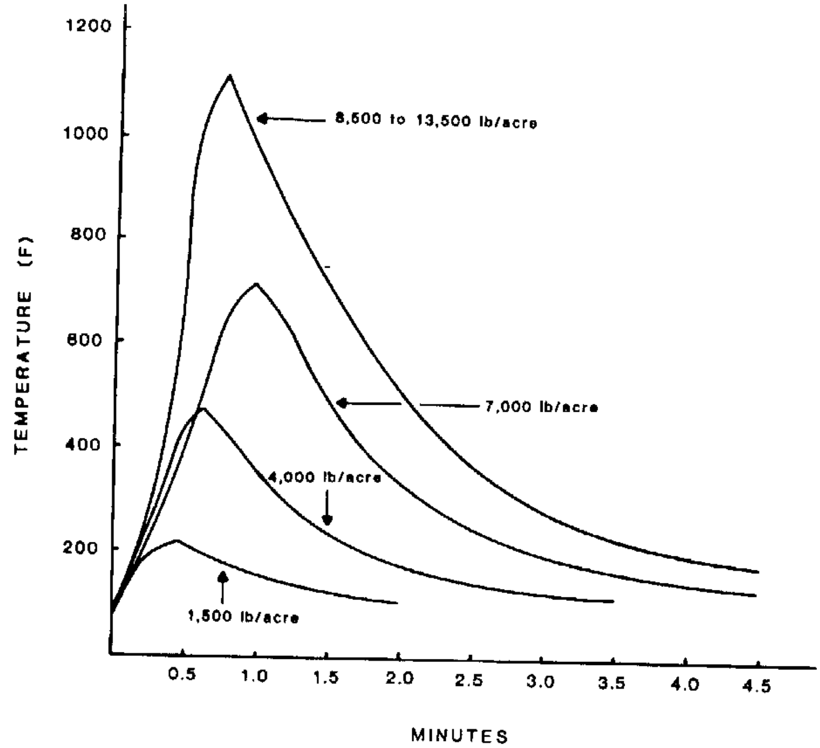

Figure 2.1: Time-temperature curves at the soil surface during prescribed grass fires for four amounts of fine fuel. At the time of burning, air temperature, relative humidity, and wind were 21°C to 27°C, 20 to 40 percent, and 13-24 km/h. (reproduced without permission from [42])

Therefore, recent rainfall will affect the specific heat and hence the possibility of the heat getting down to the cave below.

Given the insulative properties of soil and the specific heat of soil, we would not expect the thermal effects of fire to be felt deep in the soil. This result is exactly what Wright and Bailey[42] discovered and is illustrated in Figure 2.1. The elevated temperatures on and in the soil due to a fire are not long lasting. Majer[25] notes that a prescribed burn in a jarrah (eucalyptus) forest in Western Australia resulted in a temperature of 38° C down to 22-75mm, 45° C down to 10-57mm and 66° C down to 5-12mm.

However, we can look even further, into the conduction of heat through the basalt. Pohl and Vandersande ([29]), Krupka ([23]), Morgan and West ([26]) and the Excavation Engineering and Earth Mechanics Institute of the Colorado School of Mines all researched thermal properties of basalt. Their results show that the thermal properties vary depending on the specific basalt being measured. In any case, basalt is a reasonably good insulator. We will show this in Section 4.2 where we calculate how deep the effects of solar heating on lava would be felt.

Airborne particulates We found no papers that discussed the effect of airborne particulates on the cave or its environment. In general, they would be carried into the cave on air currents, with a relationship existing between the air velocity and the size of particle carried. Wherever the air slowed down, you would expect particles to be deposited ([31]).

2.1.2 Other effects of fire

We found no papers that discussed the effect of carbon monoxide or hydrocarbons on the cave or its environment.

We also found no papers that discussed the effect of water and CO_2 from fire on the cave or its environment. High CO_2 environments exist in several caves and there is evidence that cave-adapted organisms have evolved to exploit these highly saturated, high CO_2 environments ([20]). Thus, high CO_2 in and of itself, may not be a problem.

The cave atmosphere of single entrance caves or multiple entrance caves which have limited airflow is saturated or nearly so. Any additional water would extend this saturation zone toward the entrance.

The last two effects of fire, lowering of the humidity and darkening the soil, were not discussed in the fire literature found through our literature searching. One last item also not covered in the literature is rain washing into a cave the byproducts of a fire (e.g. ashes).

2.2 Fires inside of caves

With the exception of bat caves (such as Bat Cave), the lava tubes we have studied or visited at El Malpais National Monument are relatively devoid of combustible materials beyond the immediate entrance area or under skylights. Hence a fire would stop near the entrance due to the lack of fuel.

However, Gentles and Smithson ([13]) looked at fires *inside* of caves, and their paper provides data that might be used to help convince visitors that they do not want to build fires in caves. Smoke is a major problem in a single-entrance cave; only the lower 0.5m portion of the cave where they conducted their tests contained breathable air. People in such a cave with a fire are forced to lie down next to the fire to avoid smoke inhalation.

2.3 Cave climate

Understanding cave climate will allow us to make better predictions about the normal state of affairs in a cave which also them allows us to notice when conditions change. Such a change might be noticed after a fire, either a controlled burn or a wildfire.

2.3.1 Heat

We are interested in heat for two reasons. First, if we are to try to predict the temperatures inside of caves, we need to know where the heat comes from. Second, heat is sometimes responsible for airflow.

Heat in caves comes from three sources:

- the radioactive decay of elements in the Earth's core (geothermal heating).
- surface heat generated by the sun and transported by conduction through the soil and rock.
- surface heat generated by the sun and carried into the cave by air movement (advection).
- heat moved by a stream running through a cave (which does not apply to the caves at El Malpais).

Geothermal heating Atkinson, Smart, and Wigley ([3]) did the only research we found which mentioned geothermal heating as a heat source in caves. They use it to explain the difference between the mean annual temperature and the actual measured temperature deep in Castleguard cave in Alberta Canada. Most likely, geothermal heat is omitted from studies because the caves (especially the lava tubes we are studying) are not far below the surface, and the other factors dominate their temperature.

Solar heat transported by conduction Daily variations in temperature in the soil and rock below die out about 1m deep ([35]). Annual variations in temperature may be observed as deep as 20-24m ([35]) depending on the rock and soil types. At depths below below where the surface influence is felt, the temperature of a cave should be stable at the mean annual surface temperature ([14], [7], [35], [33]).

Heat transferred by advection Advection is the transfer of heat by air movement. In this case, rather than the heat which is being moved causing the movement (as in convection), some other factor is causing the air movement.

2.3.2 Airflow

To know about airflow, we must look at the factors that can cause air to move in caves:

- density differences in air caused by temperature variations
- the number of entrances a cave has and their relative elevation

- differences in air pressure from various factors considered below

The single most important factor affecting airflow is the number of entrances a cave has and the relative height of these entrances. A cave with multiple entrances where those entrances are not at the same level will nearly always have a breeze blowing through it. When the temperature inside is lower than the temperature outside (as it is in summer), the cool (and therefore denser) air will exit the lower entrance, and the outside, warmer air will enter at the upper entrance. Conditions reverse when the temperature inside is higher than the temperature outside (as it is in winter). During times when the inside and outside temperatures are nearly the same, no breeze may blow or other factors may dominate the airflow. The velocity of the air movement in this chimney effect is directly related to the temperature (and to some extent the humidity) differences between the air inside and outside of the cave. Airflow velocities will also be affected by the volume of the cave as well as the sizes of the entrances.

Wigley and Brown ([41]) as well as Atkinson, Smart, and Wigley ([3]), note that a cave may have extra "entrances" in terms of fractures leading to the surface which may be too small for humans to travel but are large enough to allow air to flow. These airflow routes will cause the chimney effect to occur even in what appear to be single entrance caves. An example cave on the monument where this effect is probably occurring is Lava Wall.

Given that the airflow in a multiple entrance cave is controlled by the temperature difference between the inside and outside of the cave, a fire will change the outside temperature and hence may affect the airflow through a multiple entrance cave. This airflow could bring in fire byproducts such as particulates as well as bring in heat, changing the temperature of a cave.

For caves with a single entrance, airflow is controlled by a complex collection of factors including:

- convection
- the current barometric pressure and how it is changing.
- wind blowing across or into an entrance.

Additionally, surface roughness, and the sinuosity of passage affect the airflow by making it more turbulent and hence slowing it down.

Since warm air is less dense that cool air, it will tend to rise or flow along the upper part of the cave. Similarly, cool air will flow along the bottoms of the passages. The slope of the cave and orientation of the entrance will determine if or how convection will cause air exchange with the interior portions of the cave ([41]). This convection was the primary air movement discovered at Altimira Cave in Spain by Villar *et al.* ([38]). It also is a part of the airflow at Glowworm Cave in New Zealand ([9]). Another example where convection is a major cause of the airflow was investigated by Smithson ([34]). He looked at vertical variations of temperature in Poole's Cavern U.K. and saw the effects of convective airflow.

Convection explains why single-entrance caves which slope downward are cold traps. In the winter cold air flows into the cave. In the summer it becomes stagnant, and hence remains cool and in some cases collects ice ([14], [5]). In upward-trending caves, the reverse would happen and cooler air would fall out the entrance when it was cooler in the cave than outside ([41]).

Other than convection, airflow also results whenever the barometric pressure outside is different from the pressure inside. When this difference occurs, the cave will inhale or exhale to equalize the pressure. Lewis ([24]) and Wigley and Brown ([41]) noted many factors which affect the atmospheric pressure outside and hence the breathing of a cave:

- weather patterns as high and low pressure systems move across, the cave lags the outside by a small amount as air flows to equalize the pressure.

- atmospheric tides are caused by the atmosphere absorbing heat directly from the sun and from the heat reflected from the earth's surface. A typical tidal curve has two maxima and two minima in 24 hours.

- gravity waves are the atmospheric equivalent of the waves we commonly associate with the ocean. They have periods from about three minutes to three hours.

- infrasound from sources such as the aurora, nuclear blasts, distant storms, waterfalls, the jet stream, volcanic explosions, earthquakes, waves on the ocean, large meteorites, supersonic aircraft

- cave resonance from wind blowing across an entrance, much like a bottle resonates when blown across its opening.

Wigley and Brown ([41]) note also that a cave with widely separated entrances which has a strong storm (such as a summer thunderstorm) over one entrance may have a notable difference of pressure between the entrances which causes airflow.

Wind blowing into an entrance can cause airflow as noted by Smithson ([34]). In multi-entrance caves, the wind may blow in one entrance and out another. Wind blowing across an entrance will lower the pressure at that entrance which will affect the airflow.

Any of the above mechanisms for airflow can act simultaneously to result in airflow which may be barely detectable (as in the flickering of a candle) all the way up to wind which moves gravel ([41]).

2.3.3 Temperatures in the cave

We now turn to predicting temperatures in the cave. Whenever the temperatures are different from the mean annual temperature, it is due to one of the other causes mentioned above. First, we note that the rock stores heat, and will release that heat to cooler air, or will absorb heat from warmer air ([40]).

Second, adding humidity to air cools it ([40], [11]) because of the heat needed to change liquid water to water vapor (about 540 calories/gram, depending on temperature). Therefore unsaturated air (from the surface) moving across a source of water (such as water percolating in from the surface) will cool as the water evaporates into it.

Taking these two factors into consideration, Wigley and Brown ([40]) develop the following formula to describe the temperature in the cave:

$$T = T_a + (T_0 - -T_a)e^{-X} + \frac{L_v}{c_p} w(q_0 - q_a)Xe^{-X}$$

where T_a is the deep cave rock temperature, T_0 is the temperature of the air entering the cave, X is the ratio of the distance from the entrance (x) and the relaxation length (x_0), L_v is the latent heat of vaporization, c_p is the specific heat of air, w is cave wetness which indicates the fraction of the cave wall which is wet, q_0 is specific humidity of the air entering the cave, q_a is the specific humidity of the outside air when it is cooled to T_a.

The relaxation length, $x_0 = 36.44a^{1.2}V^{0.2}$, where a is the radius of the cave in cm and V is the velocity of the air moving into the cave in cm/sec. It is the distance it takes the temperature T_a to decay to $\frac{1}{e}T_a$. In some caves it may be easier to calculate this distance rather than measure the airflow ([8]). Wigley and Brown ([41]) found relaxation lengths in the range of 10 to 500m.

Given the equation of Wigley and Brown along with data obtained from monitoring the cave, we can predict the temperatures in the cave based on temperature and humidity outside the cave, current airflow, and amount of moisture on the wall of the caves. Preceding a burn, the cave should be monitored, a plan suggested by Smithson and Wigley and Brown ([32], [41]). These predictions then should be compared with actual conditions observed to determine how the cave varies from predicted. During the burn, the cave can be monitored and any effects of the burn can be noted as divergence from the predicted values.

2.3.4 Humidity

Humidity is of interest because when water evaporates, it absorbs heat. Conversely, when it condenses, heat is released. So humidity is tied together with heat. Additionally, Howarth ([2],[18], [19]) states that the key environmental factor that determines the distribution of troglobites is the degree to which the atmosphere is saturated.

As you travel deeper into the lava tube (provided there are not additional entrances), evaporation decreases. Howarth ([17]) found that the rate of potential evaporation in the deep cave zone was only 8% of that of the twilight zone and hypothesized that the rate within the mesocaverns was much lower still. Cave organisms further take advantage of areas with low evaporation by moving into the small voids, which are often sites of accumulation of organic matter ([2]).

The degree of saturation of air in lava tubes is dependent on several surface factors and is a dynamic phenomenon. Climate on the surface influences the movement of air in lava tubes. When the temperature is lower outside than inside, as often happens at night in the winter, the vapor pressure of water is higher inside the cave than outside causing moist air to diffuse out of the cave. If the daytime water vapor pressure is still less than that in the cave, the water vapor will continue to diffuse out of the cave in the daytime, resulting in a winter drying of the cave known as the "wintering effect" (Howarth, 1980, 1982). When conditions reverse, the cave will gain moisture from the surface air.

The "wintering effect" does not seem to apply to the blind tubes at El Malpais. Frequent snowpacks that remain for days or weeks provide moisture for the lava tubes both in the form of atmospheric moisture and as melting water percolating through cracks. Ice in the lava tubes accumulates over winter, reaching a peak in early spring.

The deeper in to the cave you go, the longer the lag between changes in the surface conditions and the corresponding changes in the cave environment. Similarly, the amount of change becomes less with increasing distance from the entrance ([2]).

The lava tubes at El Malpais are similar to ones elsewhere in the world. A cave with multiple entrances is drier and more closely follows the surface temperature and humidity. Bat Cave is an example of this type of cave. It has several entrances, frequently has air blowing through the lava tube between entrances, and it is a dry lava tube (compared with other lava tubes in the Monument).

Caves with only one entrance become more thermally stable and moister the deeper you venture into the cave. Examples of this type of cave include Navajo Cave (with its perpetual ice and nearly constant 32.0° F temperature), Junction Cave (with the Mud Room at the end where humidity is quite high and the temperature remains around 40.0° F all year), and Braided Cave (which also becomes cooler and more humid farther from the entrance). The true troglobitic community exists in the deep zone in the lava tubes that have blind sections or other areas with restricted air flow to the surface. These areas represent the only areas that develop a high enough degree of saturation of the air by water ([2]). The presence of the temporary pools during the rainy season, represents an important resource for the cave-adapted species. The moss gardens also represent important areas of protected microclimate with abundant organic resources.

2.4 Water chemistry

We were unable to find any literature about water chemistry in lava tubes. We checked BIOSIS, GeoRef and Chemical Abstracts.

2.5 Biota

Fire plays important roles in ecosystems and can be a force in releasing nutrients that are tied up in plants and litter. Many studies have examined the impact of fire on above ground flora and fauna, but a search of the BIOSIS database back to 1969 revealed no studies that examined the effects of fire on caves or lava tubes. Only one study of fire in volcanic areas (other than the fire during volcanic eruptions) was found ([21]). We will review the literature on the effects of fire on surface invertebrates, and using this as a base will speculate on the effects of fire on the entrance and twilight zone biota.

The effects of fire on vegetation, mammals, and birds are reviewed by Wright and Bailey[42]. The effects of prescribed burns and wildfires on invertebrates are discussed by Bellido[4]; Force[12]; Hansen[15]; Majer[25]; and Sgardelis and Margaris[30].

Fire kills some invertebrates outright and influences surviving invertebrates by the degree to which resources on which they feed (plants, litter, etc.) are destroyed. Other factors which influence the impact on invertebrates include the destruction of structural diversity of their environment, which leads to a a decline in invertebrate abundance, diversity, and densities ([30]). Differences in mortality of soil and litter fauna are influenced by the intensity of the fire ([4]) and the season in which the burn occurs. During the rainy season there are more arthropods active on the surface to be killed than during dry or cold times when arthropods are further down in the soil ([30]).

Fire has immediate effects (mortality and survivorship) on invertebrates and long terms effects (recolonization from taxa that survive the fire and the immigration of fauna from surrounding areas). The immediate effect of fire may be an increase in diversity and richness followed by a decline of species richness, diversity, and abundance ([12]). Overall, some studies show no differences between burned and unburned plots (e.g.[1]), while other studies say that the arthropod fauna was destroyed ([36]). Looking at which particular taxa survive fires begins to reveal differences among different studies and habitats.

Studies vary in their determination of which taxa survive the best, but Buck[6], Force[12], Hansen[15], and Sgardelis and Margaris[30] are in general agreement that ants (Formicidae), Collembola, and various ground beetles (Staphylinidae and Carabidae) survive well.

Some fauna may escape the fire by being under rocks on the ground surface. Litter survives with them in this refugia and enhances their continued survival until other litter is generated ([30]). Over time, recovery of invertebrate fauna is tied to the recovery of the plants and hence the litter in which many invertebrates live and on which they may feed. Recolonization occurs from surrounding areas ([30] and[36]). Sgardelis and Margaris[30] and Abbott[1] show three to four years are necessary for recovery of invertebrate fauna.

The knowledge gleaned from these studies provides guidelines for the parameters to be studied during and immediately following the fire, and allows for a prediction as to the groups in which we expect to see survivorship.

3 Materials and methods

3.1 Introduction

This section provides information on the equipment and methods used to assess levels of carbon dioxide and particulates, temperature and humidity across time, water chemistry (pH, conductivity, and dissolved solids), and the diversity of biota in the lava tubes and surrounding area. We only took measurements of carbon dioxide, water chemistry, and particulates at the beginning of the study. These measurements were discontinued until a definite date for the prescribed burn was provided. Thus, more detail concerning temperature, humidity, and biota assessment is provided as these procedures were used throughout the year and a half of study.

3.2 Temperature and humidity

Onset Computer Hobo^{TM} dataloggers recorded temperatures and relative humidity in the two caves. These dataloggers were chosen for their low-cost, small size (1.5cm x 3.3cm x 4.3cm), and flexibility. Table 3.1 details their specifications. The temperature dataloggers have a 1.8m cable between the datalogger and the temperature probe allowing the datalogger to be placed nearby in a safe, convenient location. For the Lava Wall sink, this distance is extended by a cable 3m longer.

Datalogger	Range	Best Resolution
Sink temperature	$-37°$ C to $+46°$ C	0.26° C
Cave temperature	$-5°$ C to $+37°$ C	0.16° C
Relative humidity	0 to 100%	0.5%

Table 3.1: Specifications for Onset Hobo dataloggers used.

Figures 3.2 shows the approximate locations of the dataloggers in Lava Wall. The sink temperatures are recorded to provide a base from which to try to predict

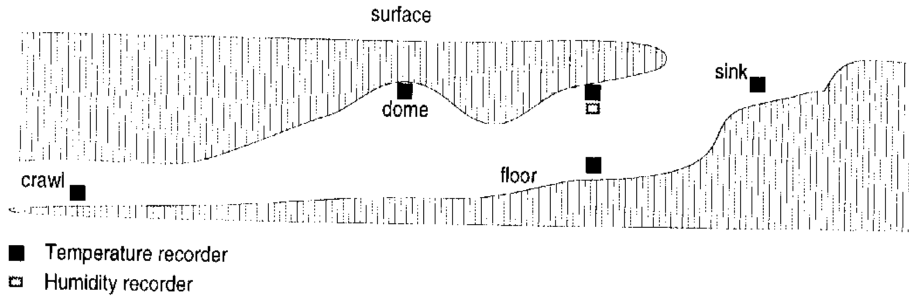

Figure 3.2: Approximate locations of dataloggers shown in a cross-section of Lava Wall.

the internal temperatures. The reasons for choosing the other locations are as follows:

- Floor and ceiling temperature measurements in the twilight zone record any breathing in and out the entrance.
- The dome is a location where the distance to the surface is minimized, and hence may be more likely to feel the effects of the fire.
- The crawl is a low area where the temperature should remain stable. If hot air from the fire blows through the cave, this datalogger will record it.

Frozen Mat has dataloggers located in areas detailed by Figure 3.3. It does not have any additional openings, so the floor and ceiling temperature measurements in the twilight zone record the cave breathing in and out the entrance. The ice sheet in the back will keep the temperature nearly constant as long as it remains a major portion of the floor in the back of the cave. Of note is the fact that the ice was down significantly in April 1995.

The dataloggers are capable of storing 1800 observations before the data needs to be downloaded. The interval between samples was chosen to maximize the observations recorded between the trips when the data could be downloaded. Therefore, the time interval between downloadings ranged from one week when we were visiting the site often, to four months in the winter (normal weather patterns prevent access to the lava tubes during winter).

Recording temperatures was not without incident. At Lava Wall, a rodent of some sort chewed on several cables. We noticed the first one when graphing the temperature in the sink; the removal of the temperature probe by the critter caused the temperature reading to drop to temperatures inconsistent with the Frozen Mat sink. When we investigated the erroneous readings, we discovered the missing cable. On the next trip, we discovered the rodent had severed two other cables.

As a result of these problems, the sink probe was encased in PVC pipe, the floor probes were withdrawn into the plastic containers protecting the dataloggers,

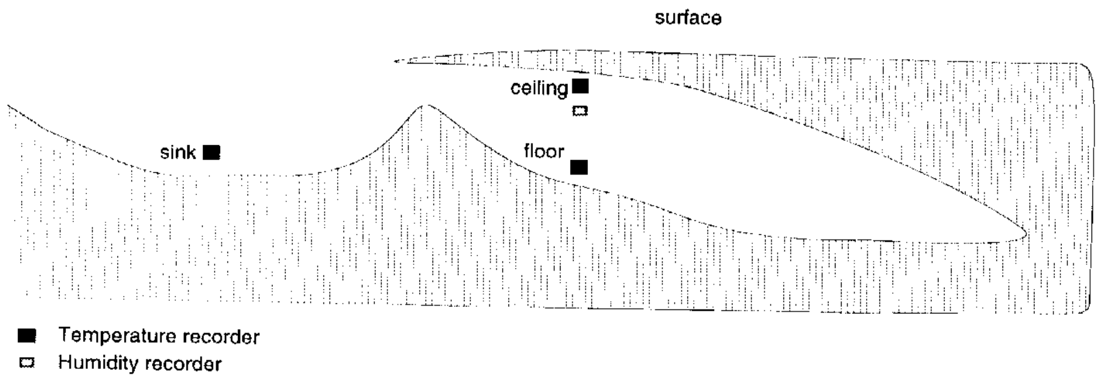

Figure 3.3: Approximate locations of dataloggers shown in a cross-section of Frozen Mat.

and the ceiling and dome dataloggers were moved to the ceilings rather than being on the floor as before. As a result of these changes, the reaction time of many of the thermistors will be slower than before. A test we did showed that the thermistor in the container took about 40 minutes to reach equilibrium with the outside temperature (a difference of about 35F), whereas Onset claims that the thermistor itself will only take two minutes (a claim which was backed up by our tests).

3.3 CO_2 and CO

Dräger tubes were used to measure CO_2 levels in both lava tubes. They are sealed glass tubes containing a substance which absorbs CO_2 and changes color. These tubes are calibrated for a specific volume of air to pass through the tube, supplied by a hand-operated pump. The percentage of CO_2 in the air is read by the distance the color exists in the tube after the air has passed through the tube. In theory it all works well. However, the color does not have a sharp line, but gradually fades out, making determination of the exact depth of the color difficult.

3.4 Water chemistry

25ml of water was collected from each cave. Since Lava Wall had no standing water, this water came from drips in the dome, collected by holding a sterile vial next to them. In Frozen Mat, the water was taken into a sterile syringe from beside the ice sheet in the back room of the cave. The caves were sampled 9/25/93 and 10/2/93, and Simon Santillanes at the City of Albuquerque analyzed the samples.

3.5 Particulates

Particulate traps, consisting of white sticky shelf paper approximately $0.09m^2$ were placed in each of the caves, at the back of the twilight zone on October 2, 1993. After intervals of 24 hours and 2 weeks, the traps were collected and covered with clear plastic wrap.

3.6 Biota

To inventory the terrestrial invertebrates present in the lava tubes and in the immediate vicinity of the two sinks, we used a combination of the following techniques:

Visual Inspection One of the primary techniques to observe and sample the invertebrate fauna is visual inspection of habitats using an OptiVisor™(a magnifier). We examined organic material in the lava tubes (leaf litter, wood, guano, feces, roots, etc.) as well as different substrates (soil, under rocks, cracks, crevices). Each cave was examined for invertebrates in August, September, and October of 1993, and October 1994.

Pitfall Trapping Another technique for sampling the invertebrate fauna is pitfall trapping, which uses small plastic cups (we used 16oz and 10oz) with funnel shaped inserts (used only on the 16oz cups). These are buried in the substrate up to the rim and were unbaited. The surface was sampled using two sets of twelve pitfall traps, one in the control plot near Frozen Mat and the other in the proposed burn plot near Lava Wall. All pitfall traps were set for a period of 24 hours in August 28-29, September 25-26, October 2-3, and 18 to 24 October 1993; and during 11-12 June 1994 and 12 October 1994. All pitfall samples were returned to OSU for arthropod extraction and identification.

Extraction of Soil Invertebrates The most efficient technique to sample invertebrates, especially the very small taxa (< 5mm) is to extract them from the organic matter and soil in which they live. The two primary methods of extraction are: Berlese [28] and flotation ([16], [22], and [39]). The advantage of flotation over Berlese is you do not need a large sample and it is much more efficient than Berlese; however, flotation will not work for the guano of insectivorous vertebrates. For the El Malpais soil fauna, we elected to use heptane flotation of litter samples collected from under vegetation in both sinks, under shrubs near the sink, and from soil in open areas surrounding the sink. Extraction was performed at The Ohio State University (OSU).

Samples were sorted by one of the authors (Welbourn) at The Ohio State University (1993-1994) and then at the Division of Plant Industry at the Florida Department of Agriculture (1994-1995). Mites were identified by Welbourn; other taxa were sent to appropriate taxonomic experts for identification.

4 Results

4.1 Introduction

The following sections detail the results of our mathematical investigations of heat conduction through the lava; the analysis of the temperature and humidity measurements from 1993-1995 (approximately 1.5 years of data) and graphs of the data from all 10 dataloggers; pre-burn measurements of carbon dioxide in the experimental and control lava tubes; preburn measurements of pH, conductivity, and total solids of drip water (Lava Wall) and standing water (Frozen Mat); preburn measurements of particulates landing in the entrance of both lava tubes; and a listing of biota found in both lava tubes, in a set of 10 pitfall traps around each entrance sink, and in a set of 12 pitfall traps in a line leading away from each sink.

4.2 Heat conduction through the lava

As heat diffuses into an object, it follows the equation of heat diffusion found in textbooks on partial differential equations:

$$DT_{xx} = T_t,$$

where x is the distance from the entrance or surface and t is time since the heat was applied to the outside of the cave, and D is a constant relating to how fast heat diffuses into lava.

Initially, we will assume that the forcing function (the sun heating the surface) for this equation is a sine function, not completely correct, but sufficient for a first order approximation. Doing the math, we end up with a model for the temperature in the cave of:

$$T(x,t) = Ae^{-x\sqrt{\frac{\omega}{2D}}}\cos[x\sqrt{\frac{\omega}{2D}} - \omega t],$$

where D, x, and t are as before, ω is the period of the forcing function (24 hours), and A is the amplitude of the forcing function (the difference between the maximum and minimum daily temperatures).

Let $A = 21.804$°C which is based on over 300 observations in the Frozen Mat sink. Values for D range from 0.67 to 4.18 $\frac{\mathrm{W}}{\mathrm{m\,K}}$ ([23]). Setting it (somewhat arbitrarily) at 2.75 and plugging all of these values into the equation leads to the graph in Figure 4.4.

4.3 Temperature and Humidity

Figures 4.5 through 4.14 show the temperature and humidity data collected for the caves. Figures 4.15 through 4.24 show a close up of the data, illustrating the diurnal cycles of temperature and humidity.

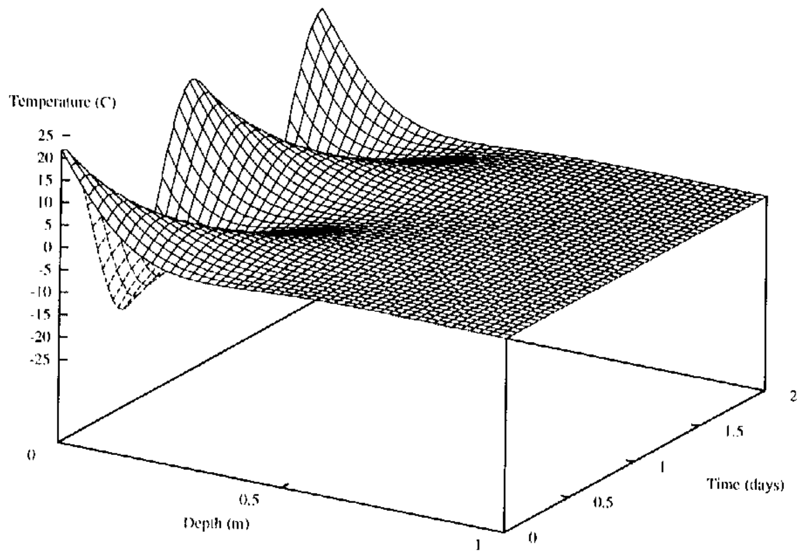

Figure 4.4: Plot showing temperature versus time and distance which illustrates the conduction of heat into the lava. This plot shows two days of solar heating. Distance is in meters, temperature is in C.

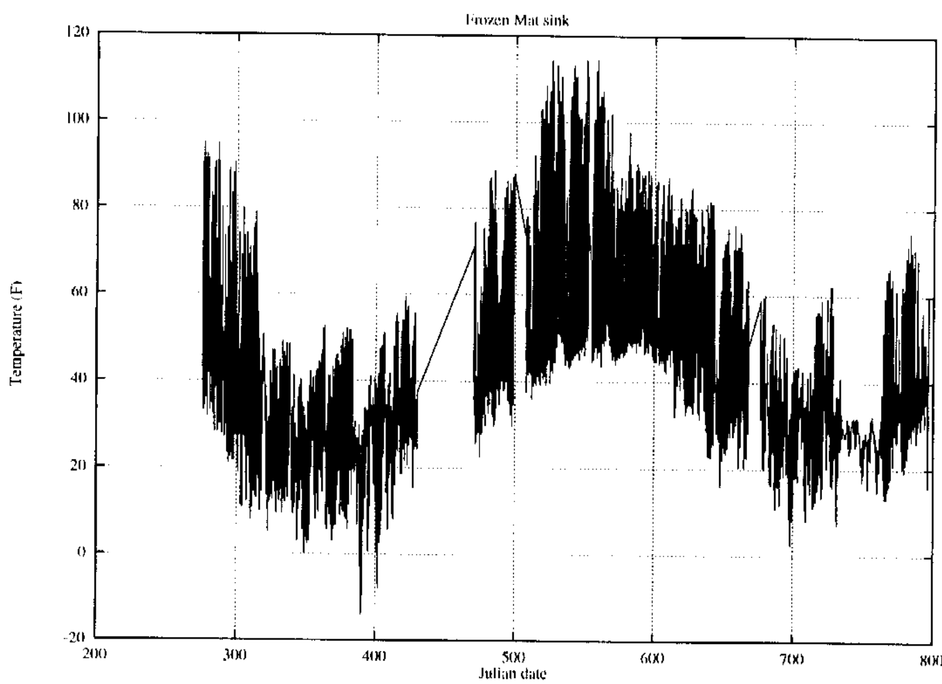

Figure 4.5: Temperatures for the Frozen Mat sink.

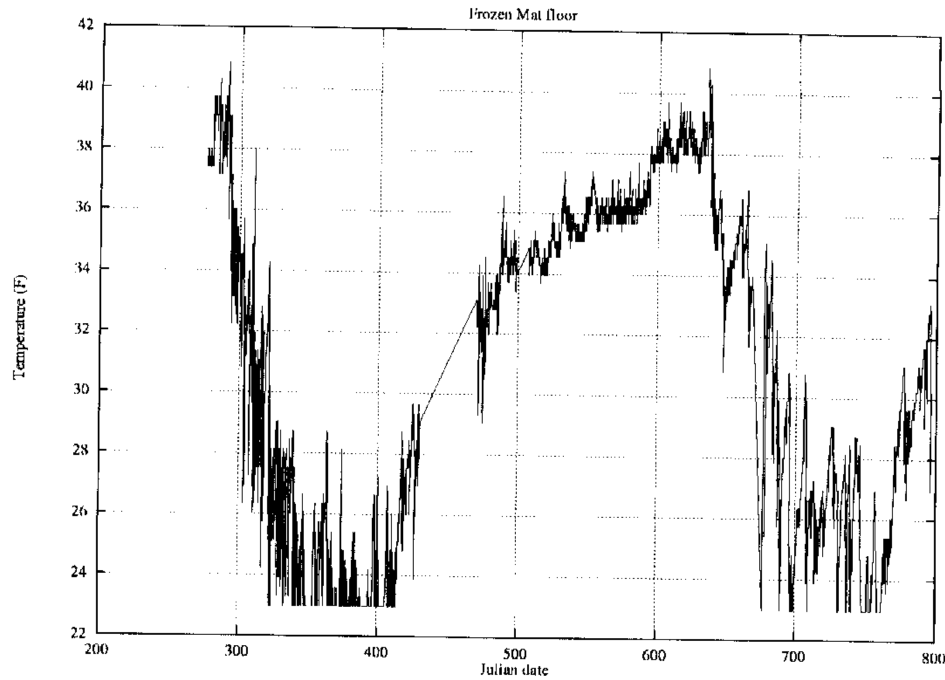

Figure 4.6: Temperatures for the floor in Frozen Mat.

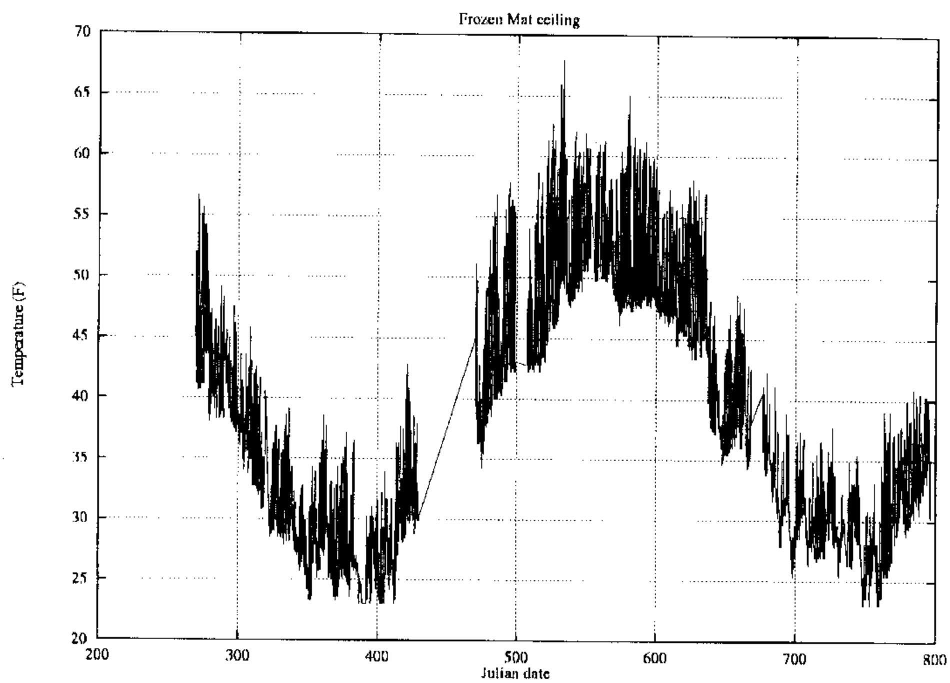

Figure 4.7: Temperatures for the ceiling in Frozen Mat.

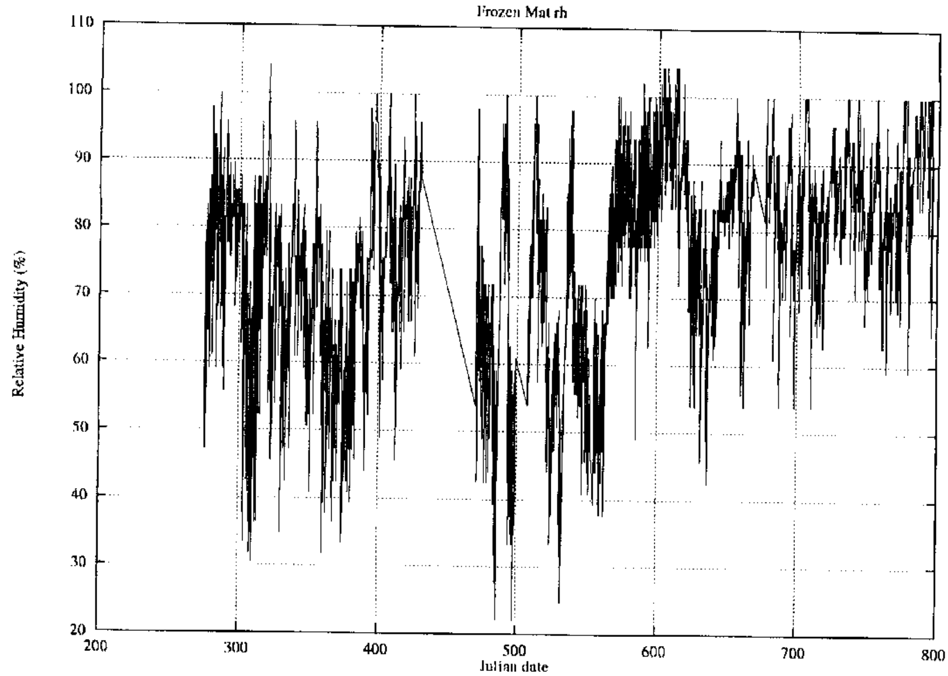

Figure 4.8: Relative humidity in Frozen Mat.

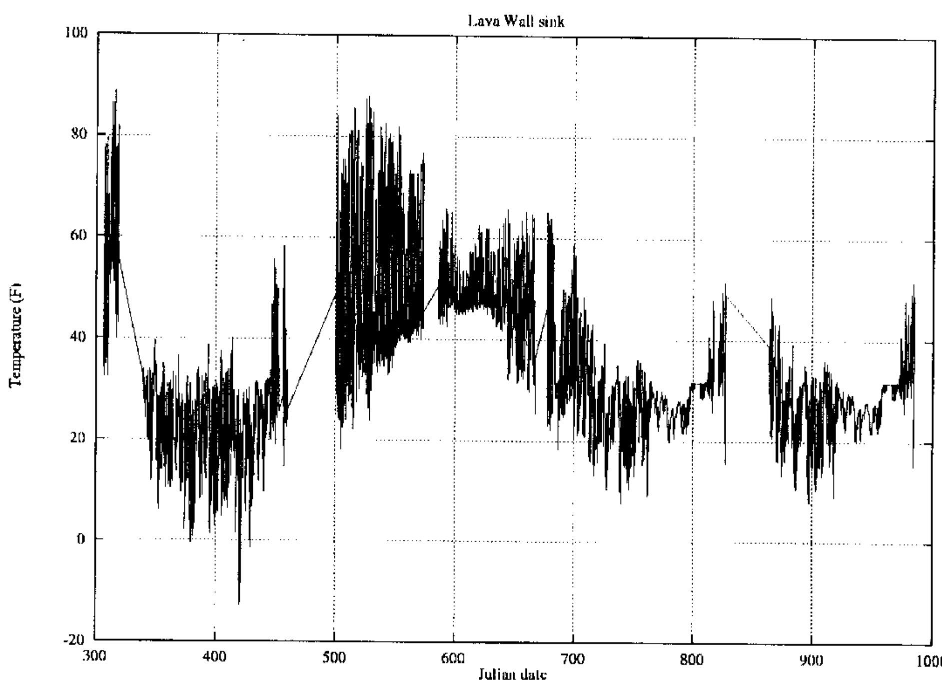

Figure 4.9: Temperatures for the Lava Wall sink.

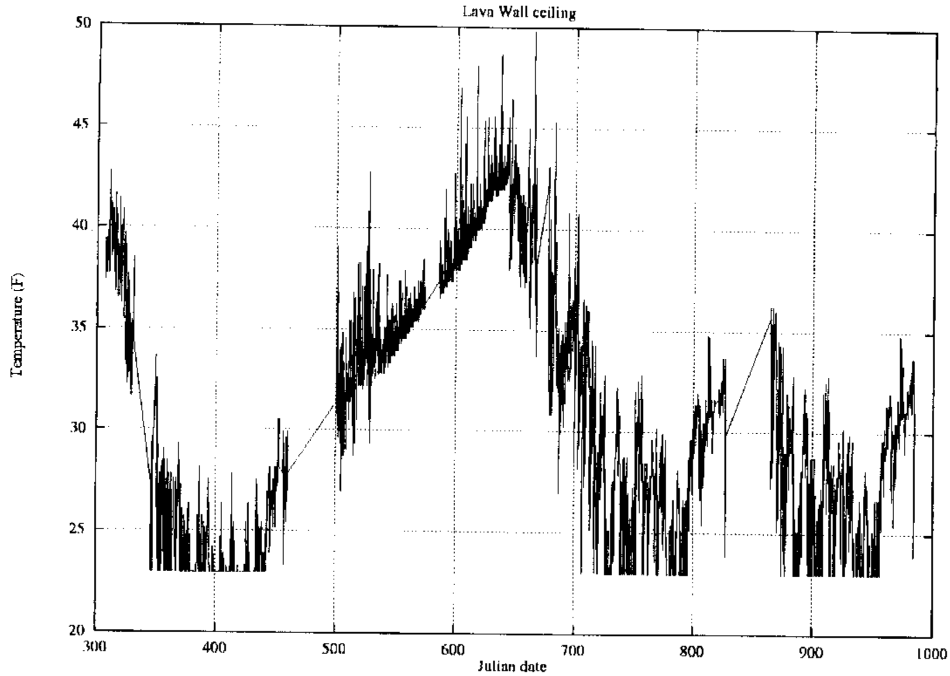

Figure 4.10: Temperatures for the ceiling in Lava Wall.

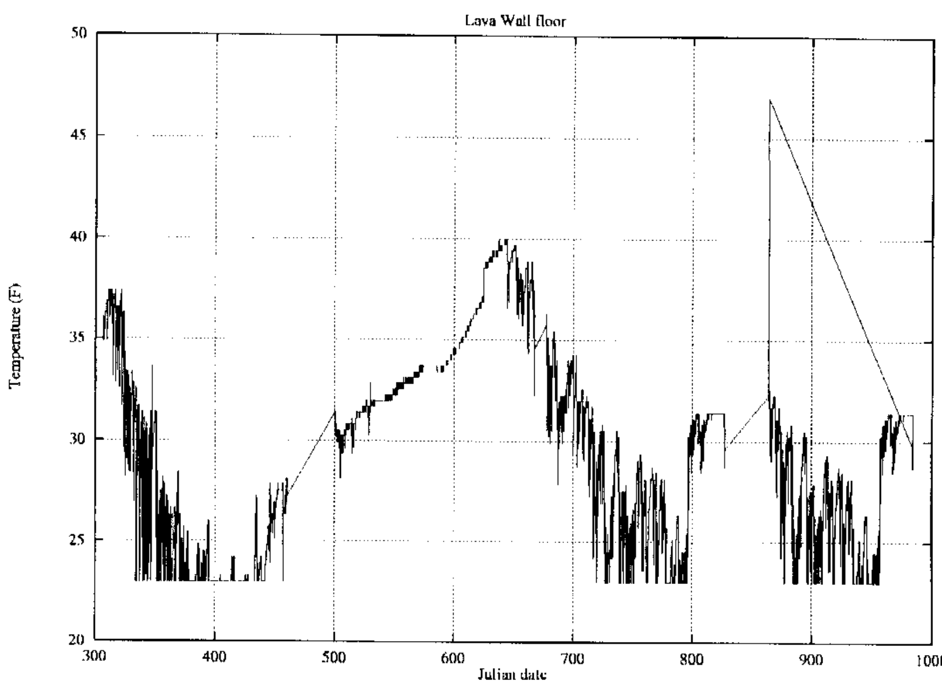

Figure 4.11: Temperatures for the floor in Lava Wall.

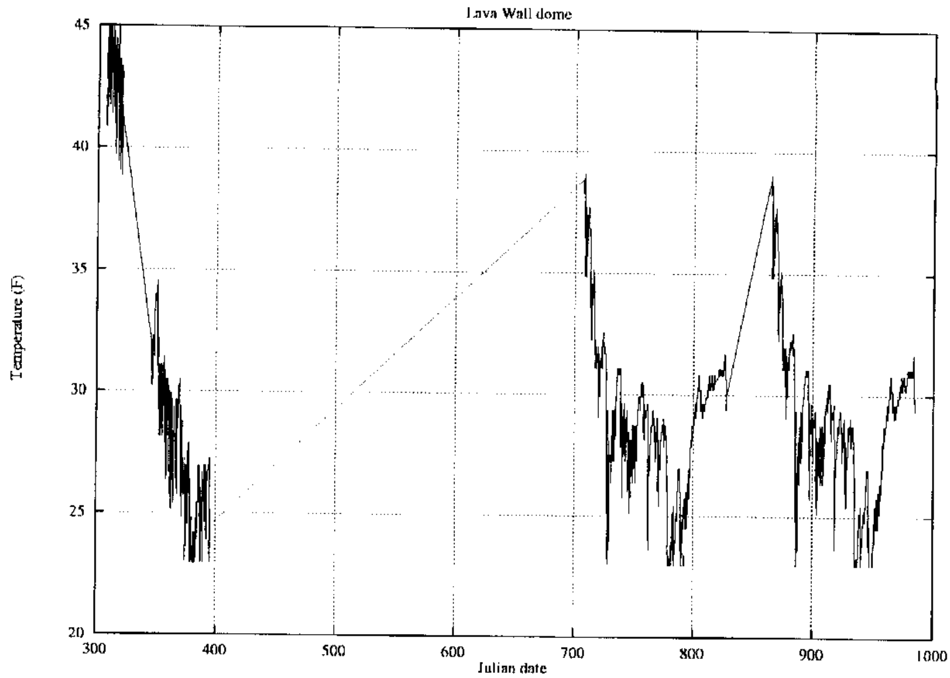

Figure 4.12: Temperatures for the dome in Lava Wall.

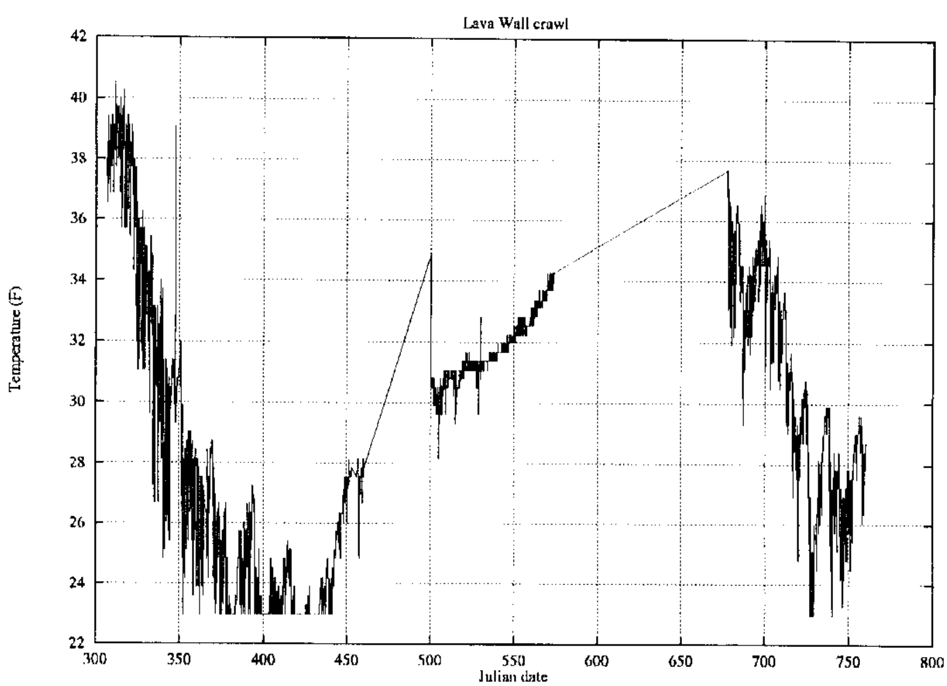

Figure 4.13: Temperatures for the crawl in Lava Wall.

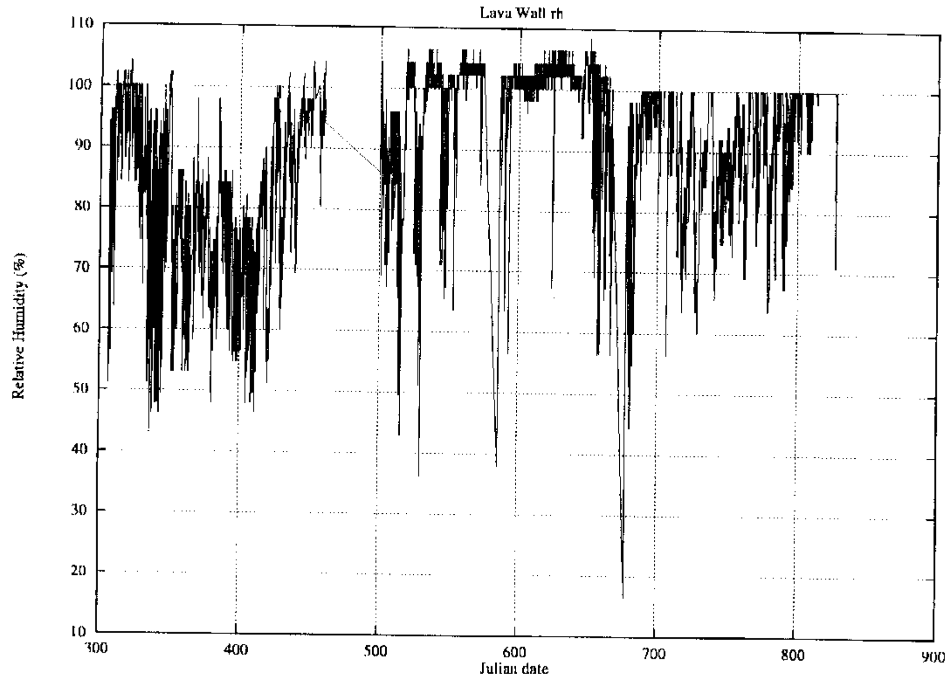

Figure 4.14: Relative humidity in Lava Wall.

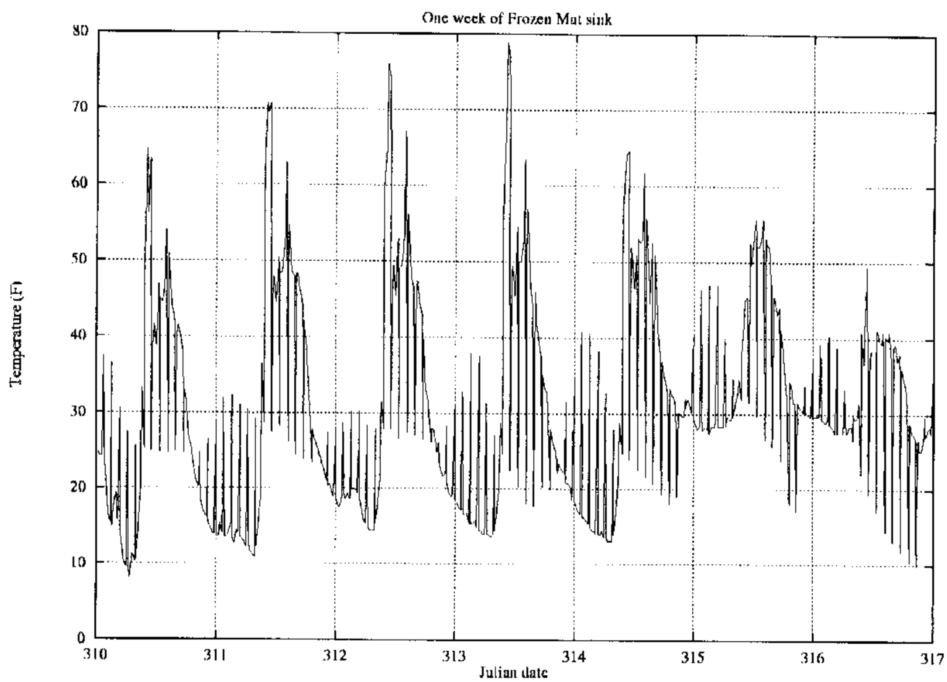

Figure 4.15: One week of temperatures for the Frozen Mat sink.

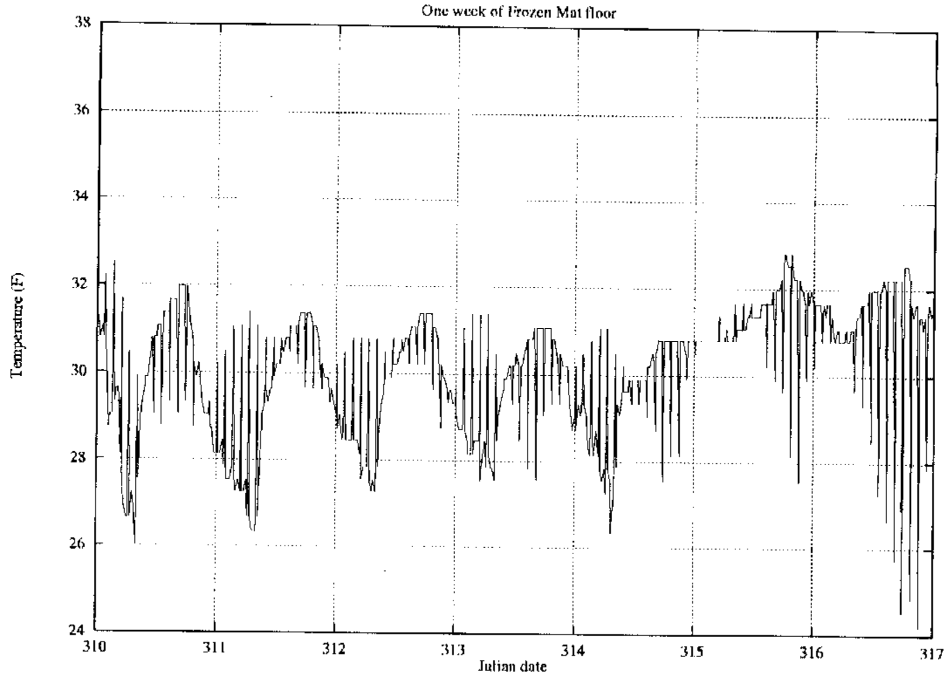

Figure 4.16: One week of temperatures for the floor in Frozen Mat.

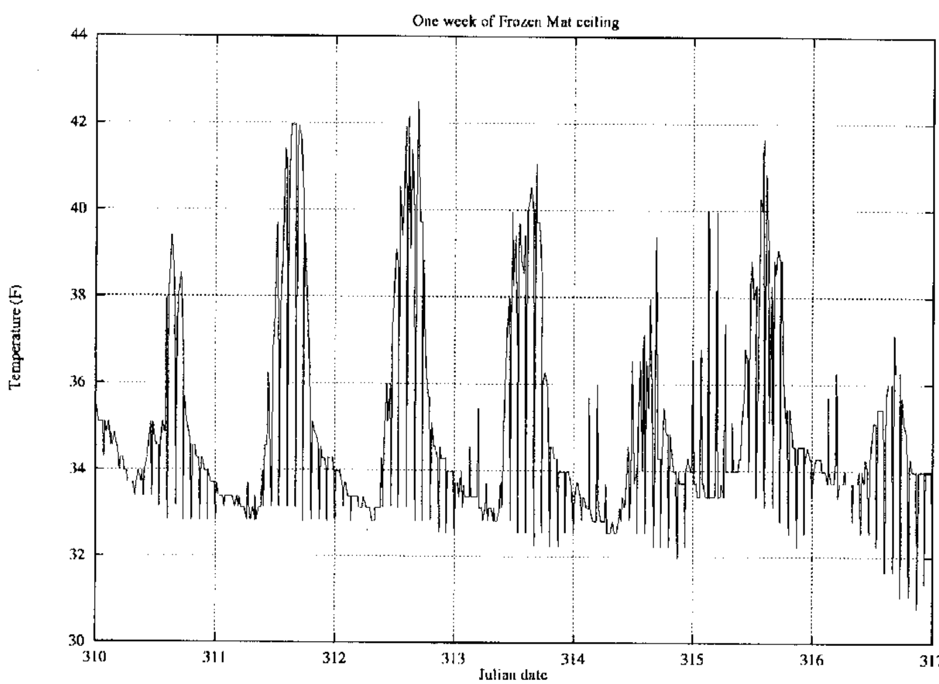

Figure 4.17: One week of temperatures for the ceiling in Frozen Mat.

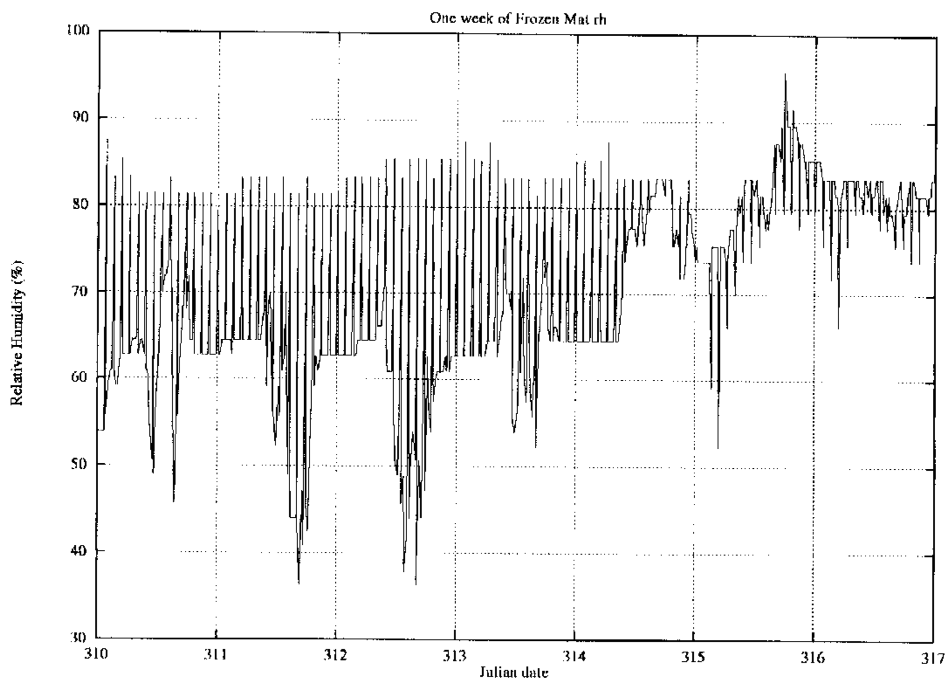

Figure 4.18: One week of relativehumidity in Frozen Mat.

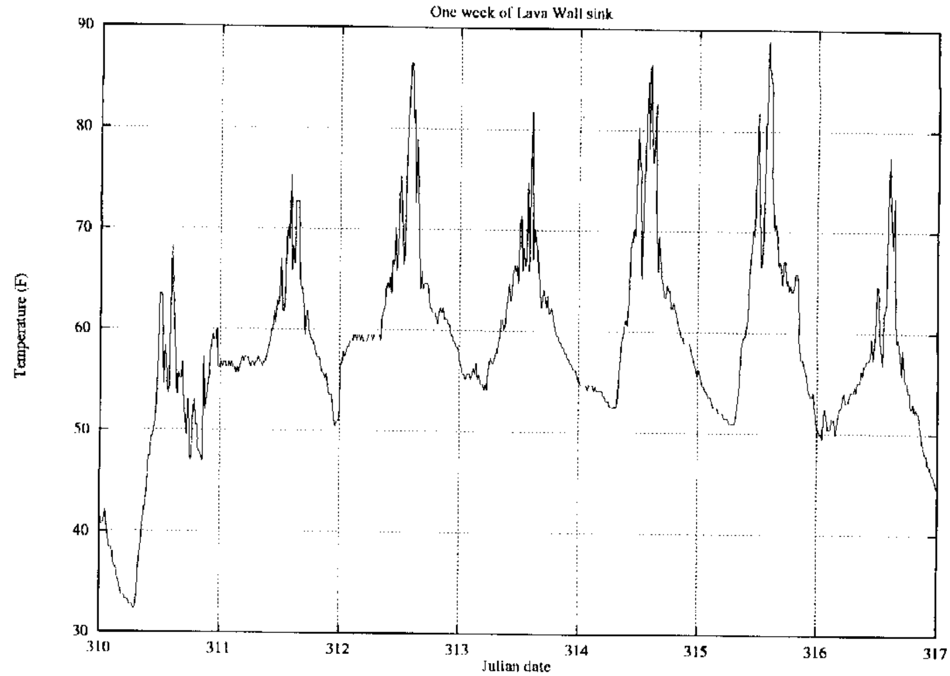

Figure 4.19: One week of temperatures for the Lava Wall sink.

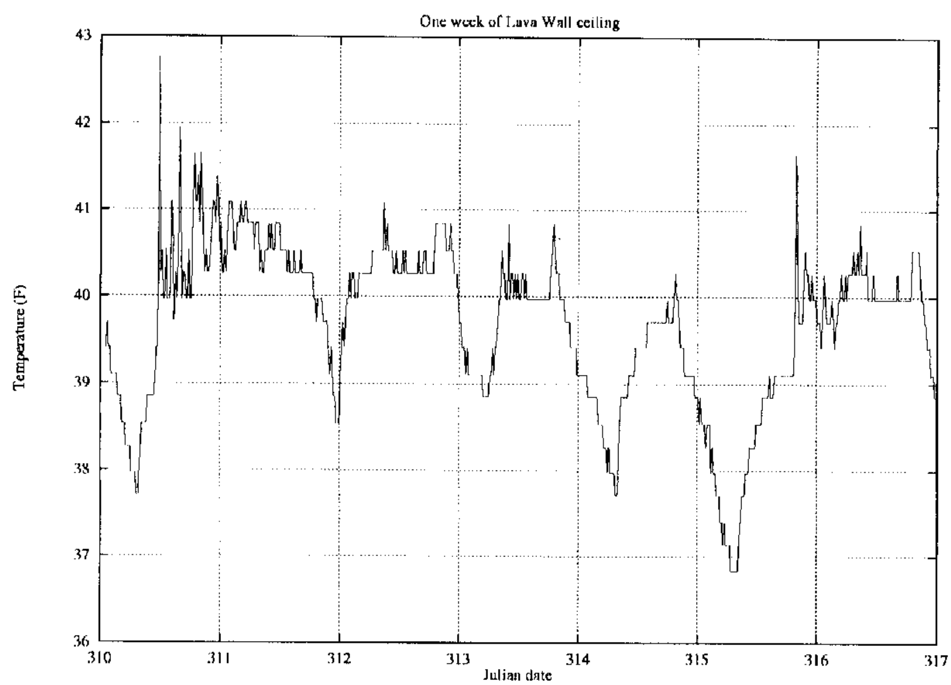

Figure 4.20: One week of temperatures for the ceiling in Lava Wall.

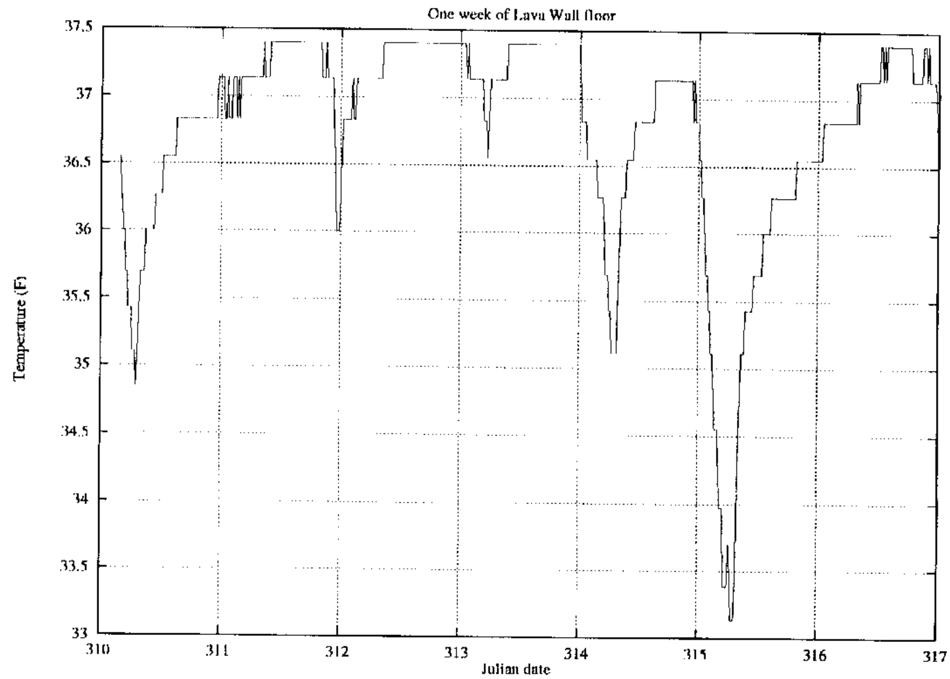

Figure 4.21: One week of temperatures for the floor in Lava Wall.

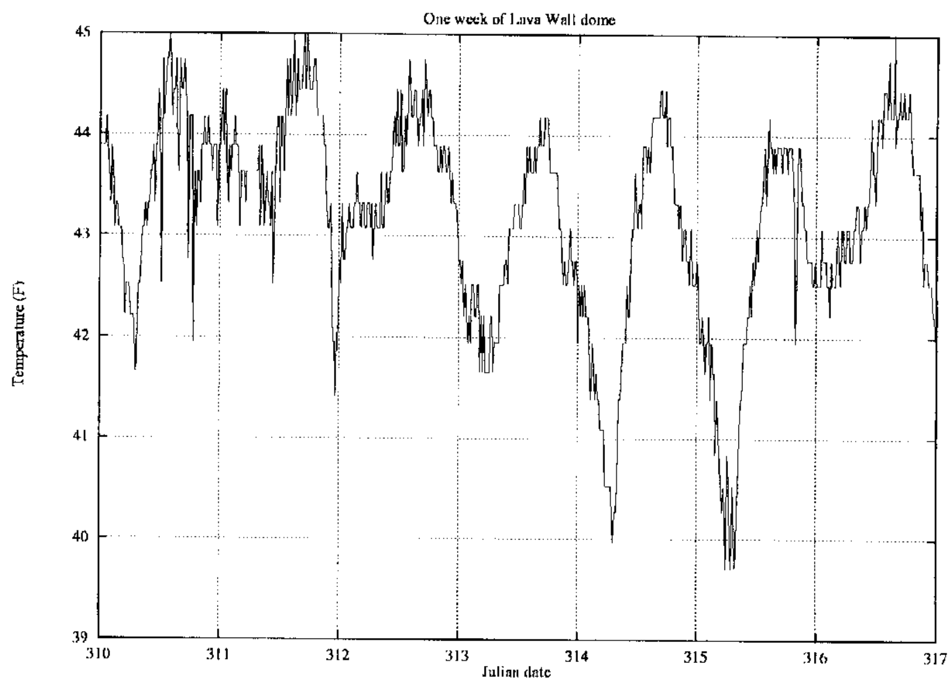

Figure 4.22: One week of temperatures for the dome in Lava Wall.

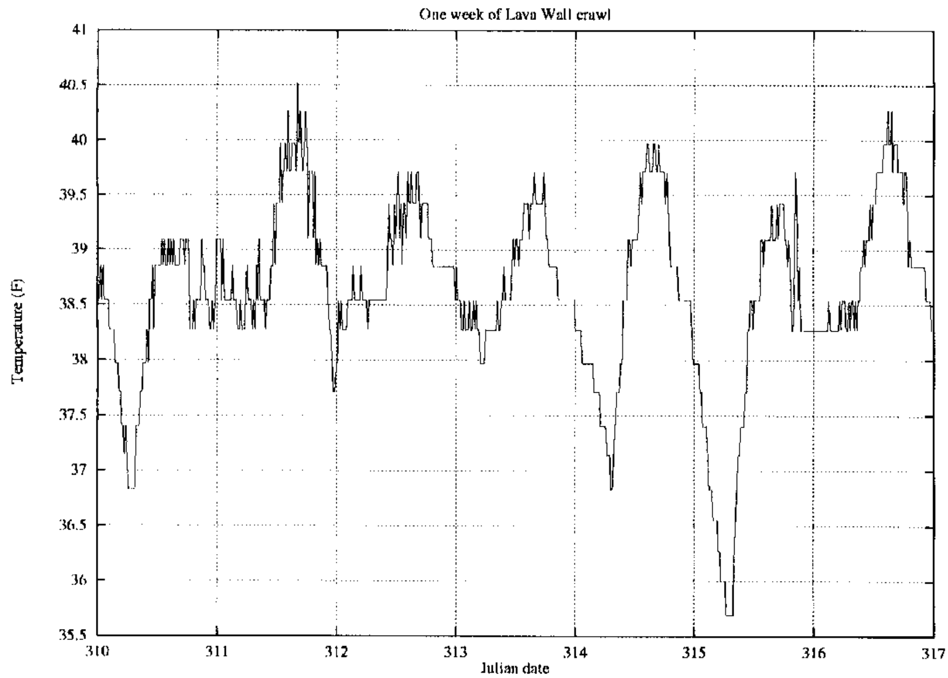

Figure 4.23: One week of temperatures for the crawl in Lava Wall.

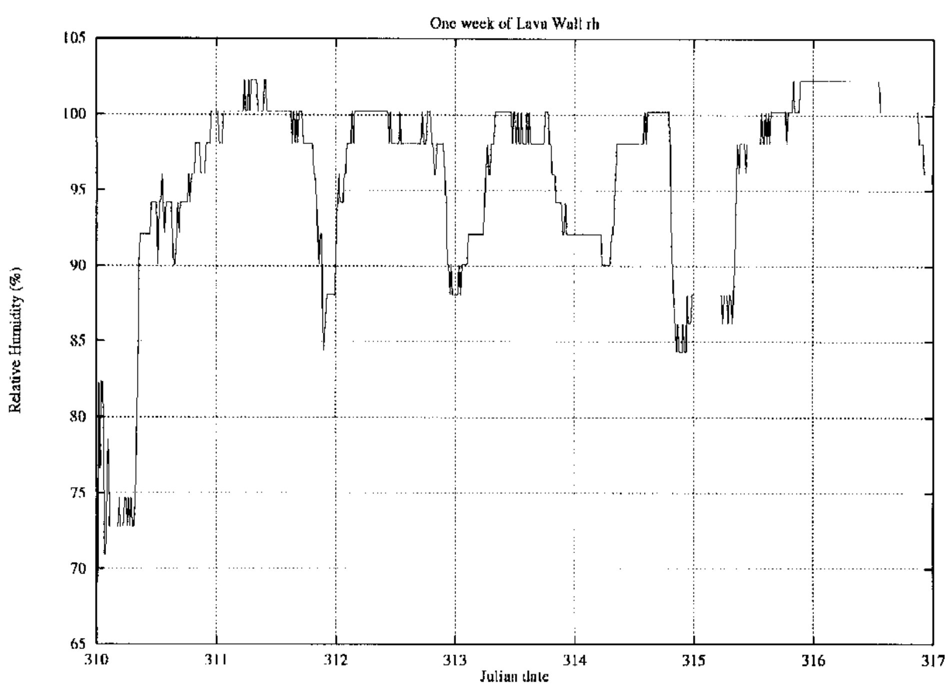

Figure 4.24: One week of relativehumidity in Lava Wall.

To look for cycles in the data, we ran the data through a Fourier transform. We were unable to use a Fast Fourier Transform (FFT) because our sampling interval was not uniform. The results are in Figures 4.25 through 4.34. Since we have cycles lasting over one day, Figures 4.35 through 4.44 present the data for these cycles.

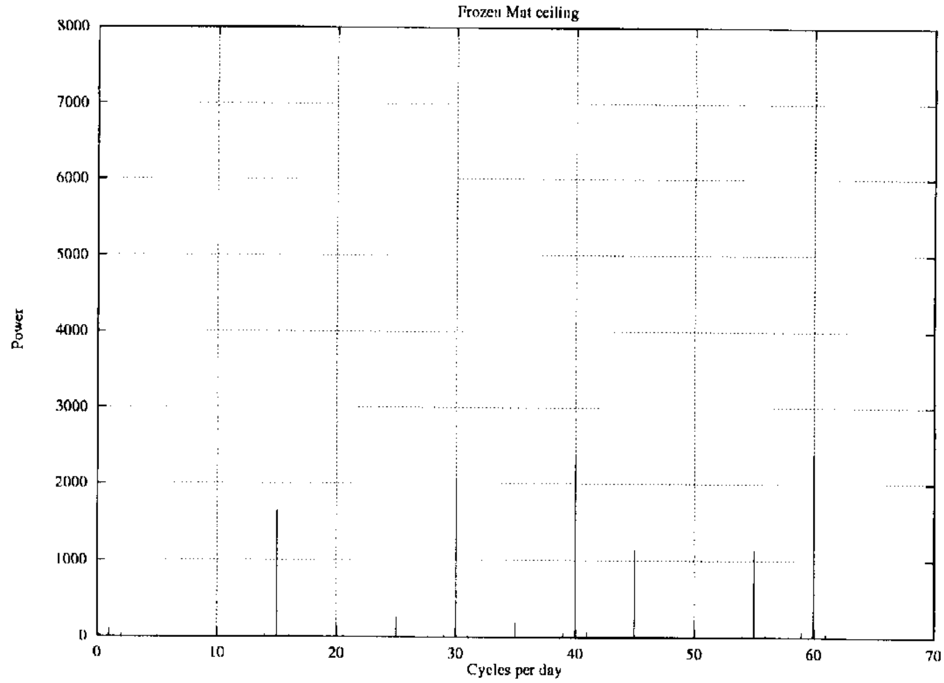

Figure 4.25: Power spectrum for the Frozen Mat ceiling temperature.

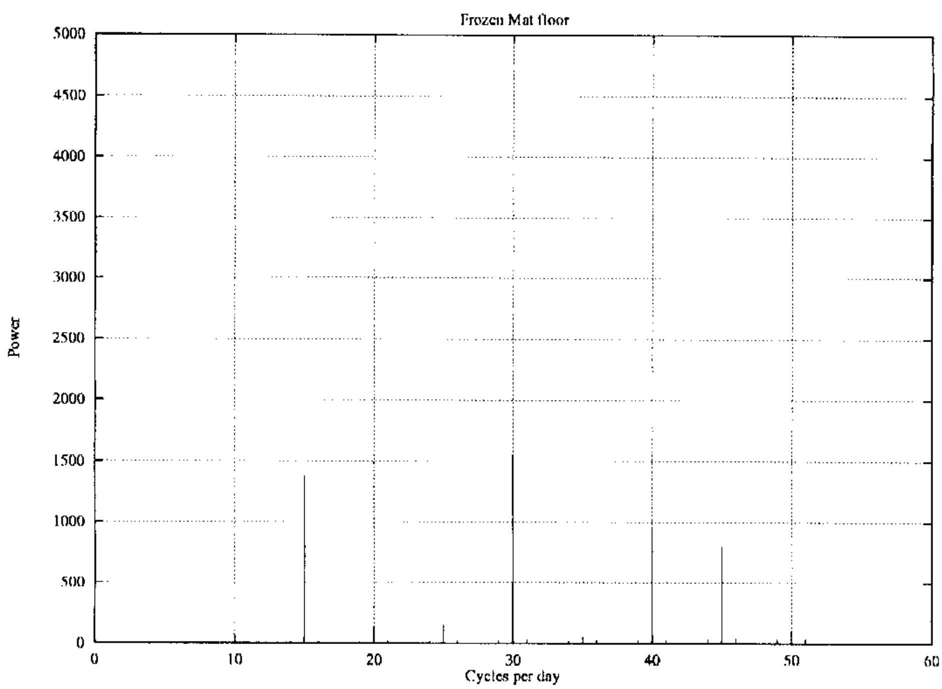

Figure 4.26: Power spectrum for the Frozen Mat floor temperature.

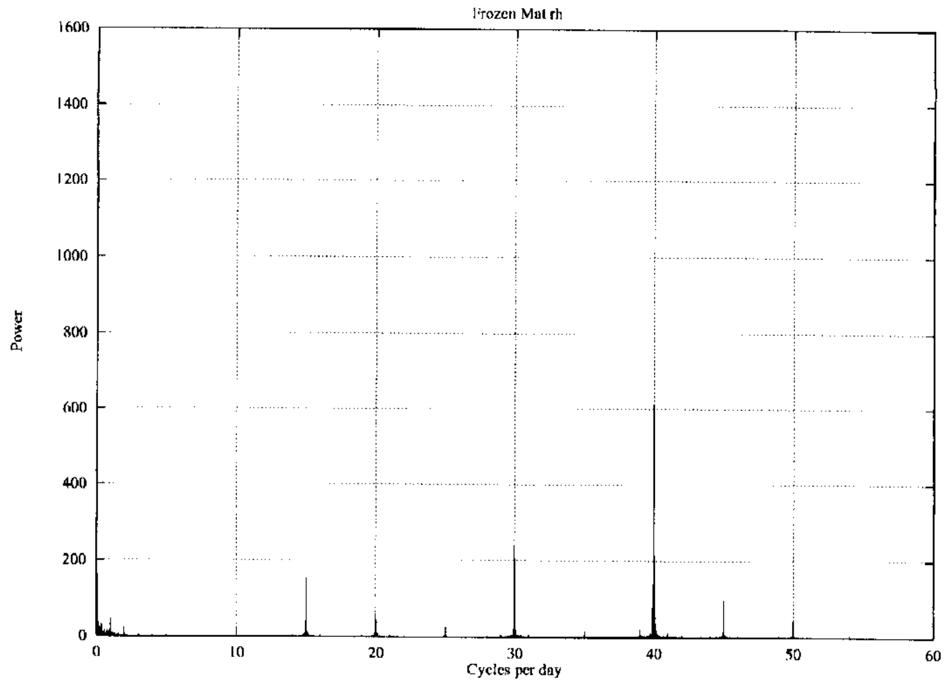

Figure 4.27: Power spectrum for the Frozen Mat relative humidity.

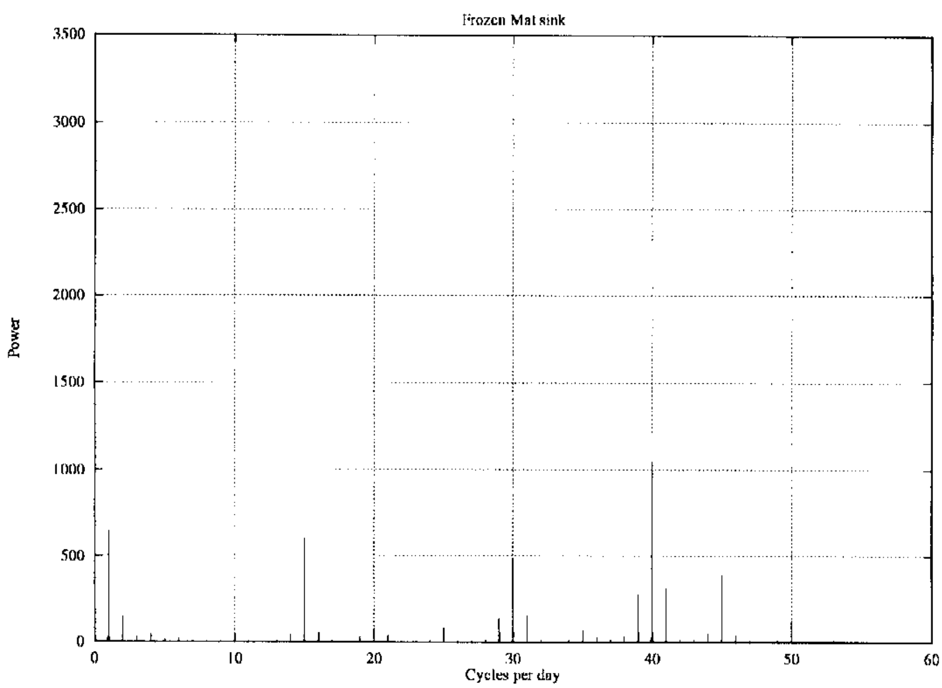

Figure 4.28: Power spectrum for the Frozen Mat sink temperature.

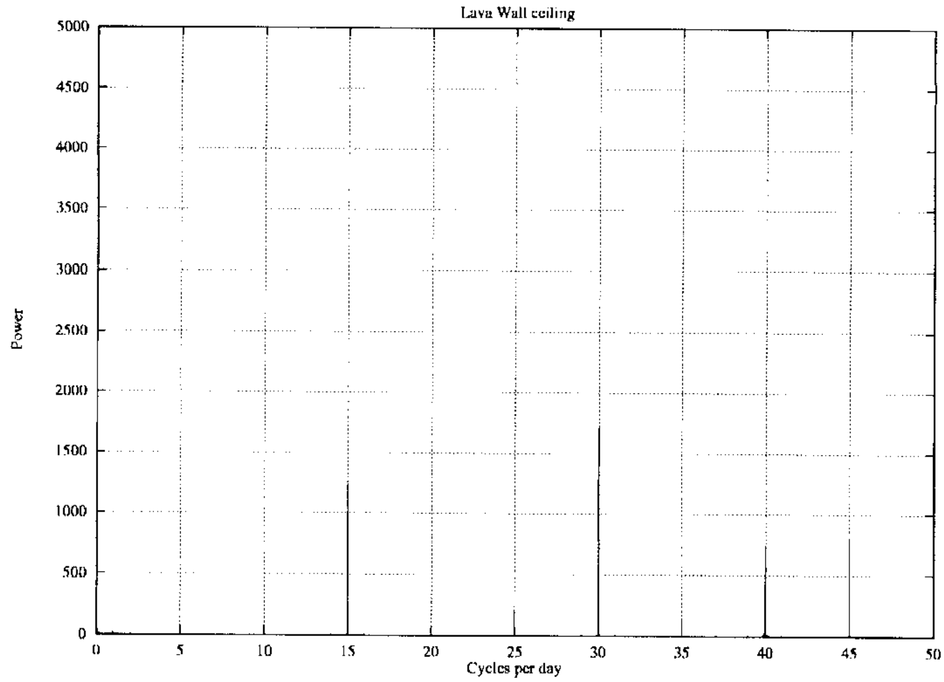

Figure 4.29: Power spectrum for the Lava Wall ceiling temperature.

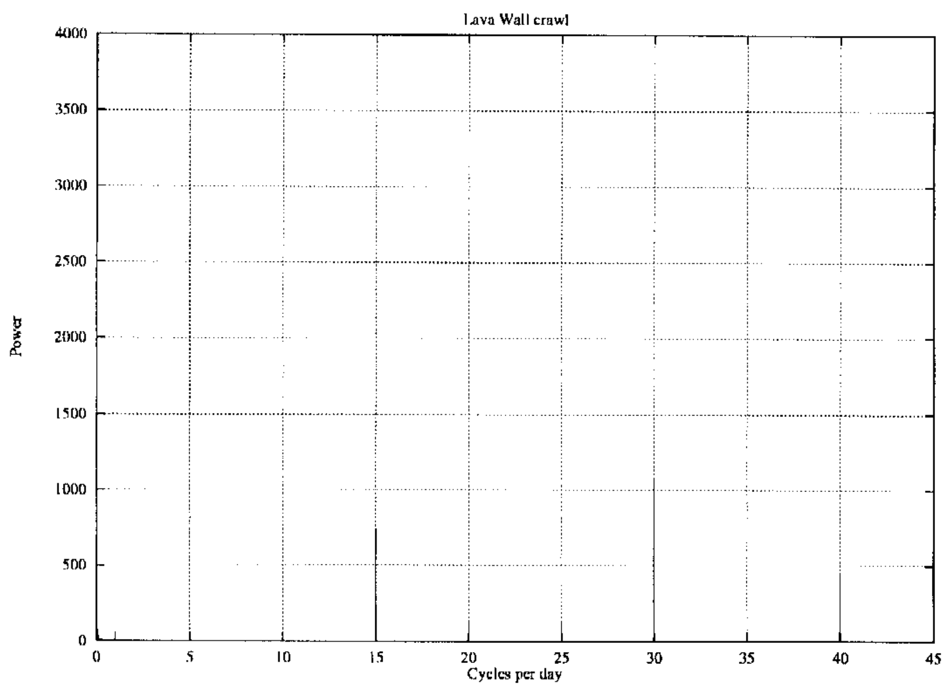

Figure 4.30: Power spectrum for the Lava Wall crawl temperature.

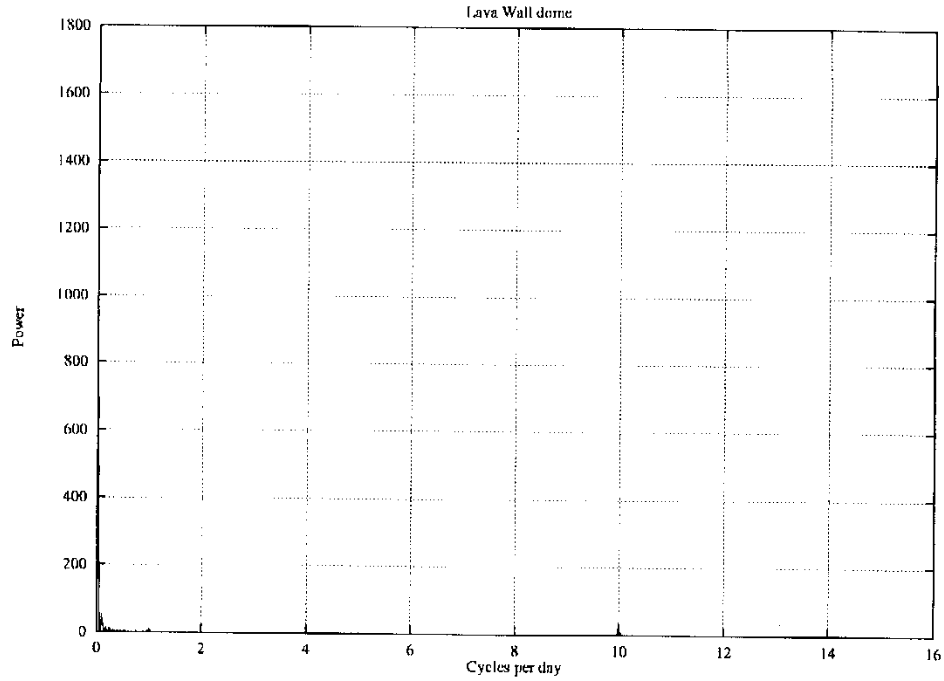

Figure 4.31: Power spectrum for the Lava Wall dome temperature.

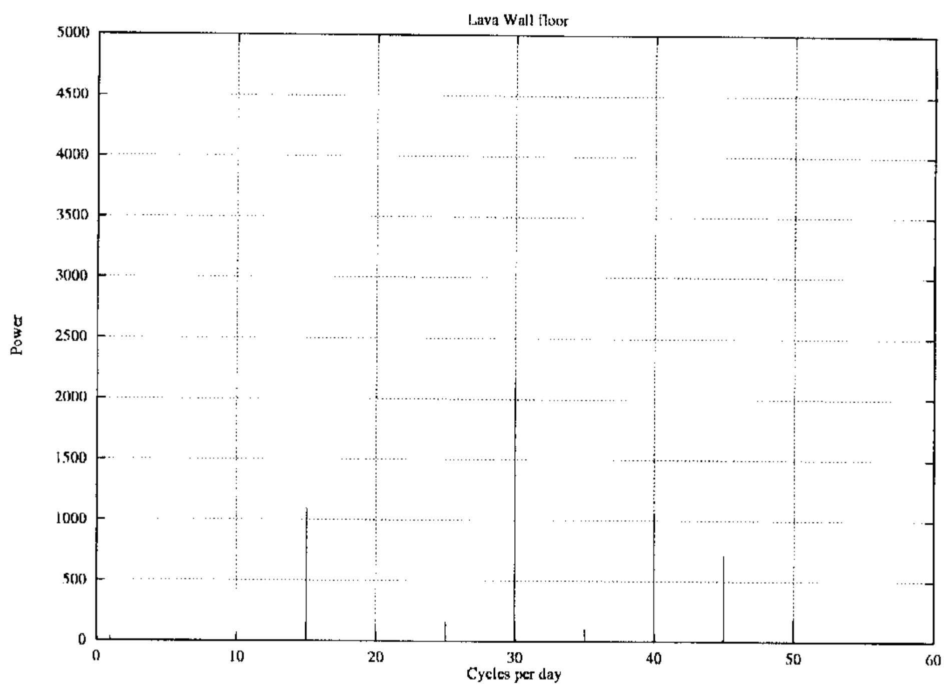

Figure 4.32: Power spectrum for the Lava Wall floor temperature.

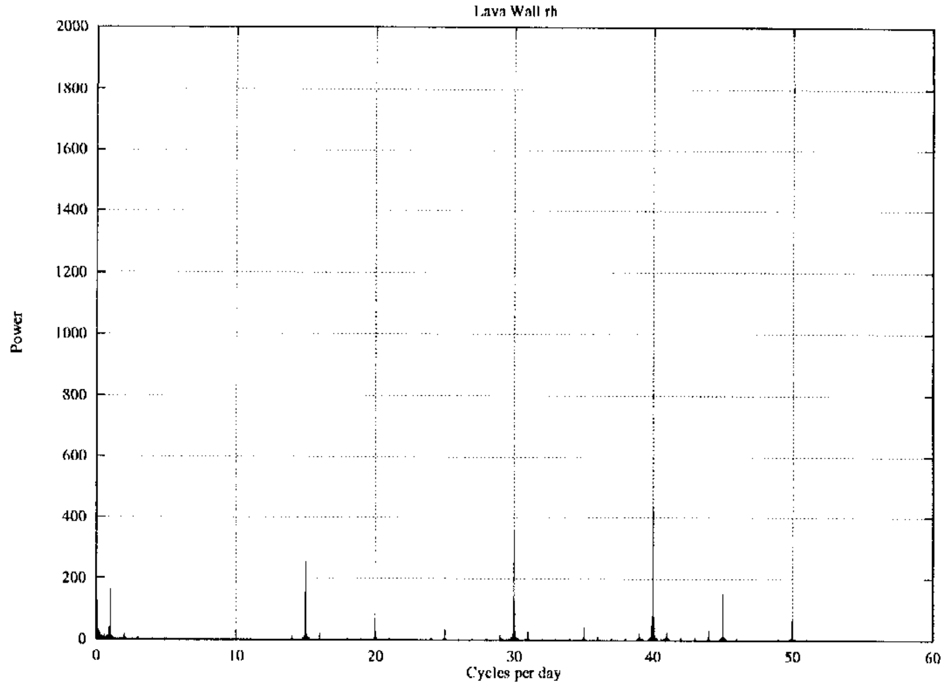

Figure 4.33: Power spectrum for the Lava Wall relative humidity.

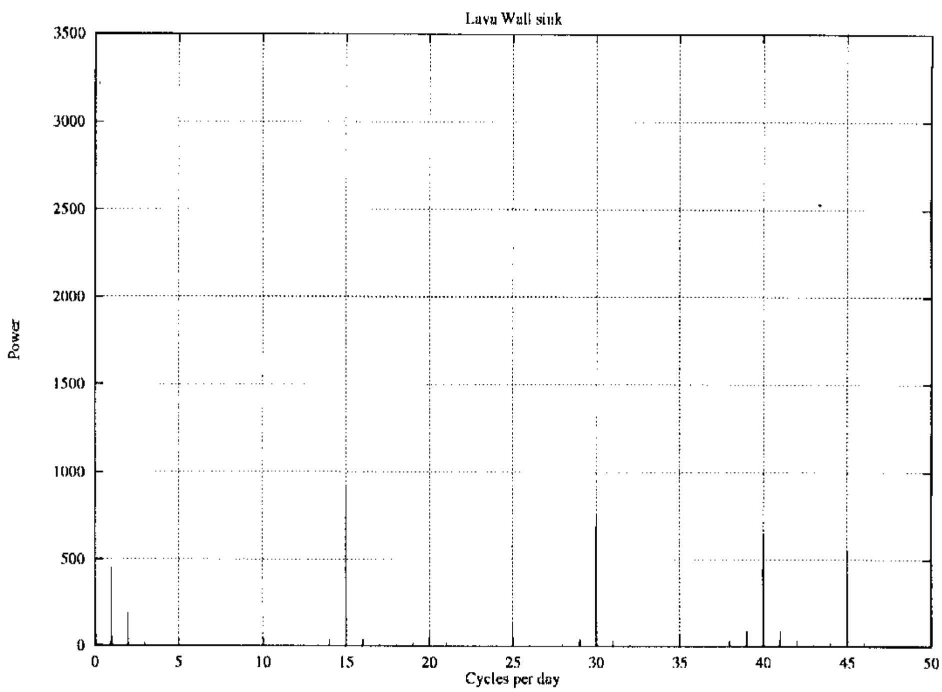

Figure 4.34: Power spectrum for the Lava Wall sink temperature.

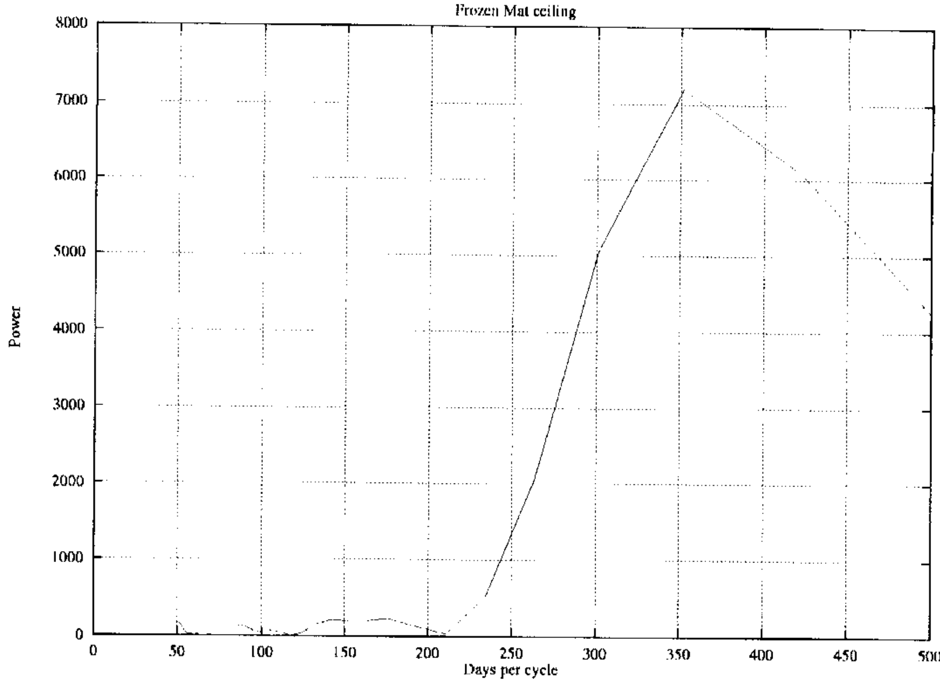

Figure 4.35: Power spectrum for cycles longer than one day for the Frozen Mat ceiling temperature.

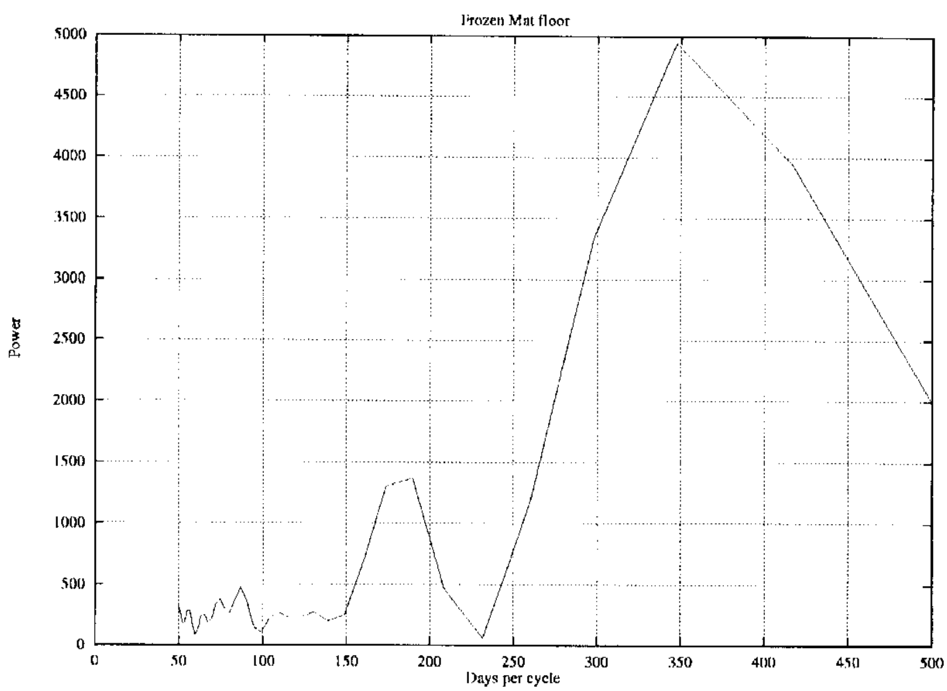

Figure 4.36: Power spectrum for cycles longer than one day for the Frozen Mat floor temperature.

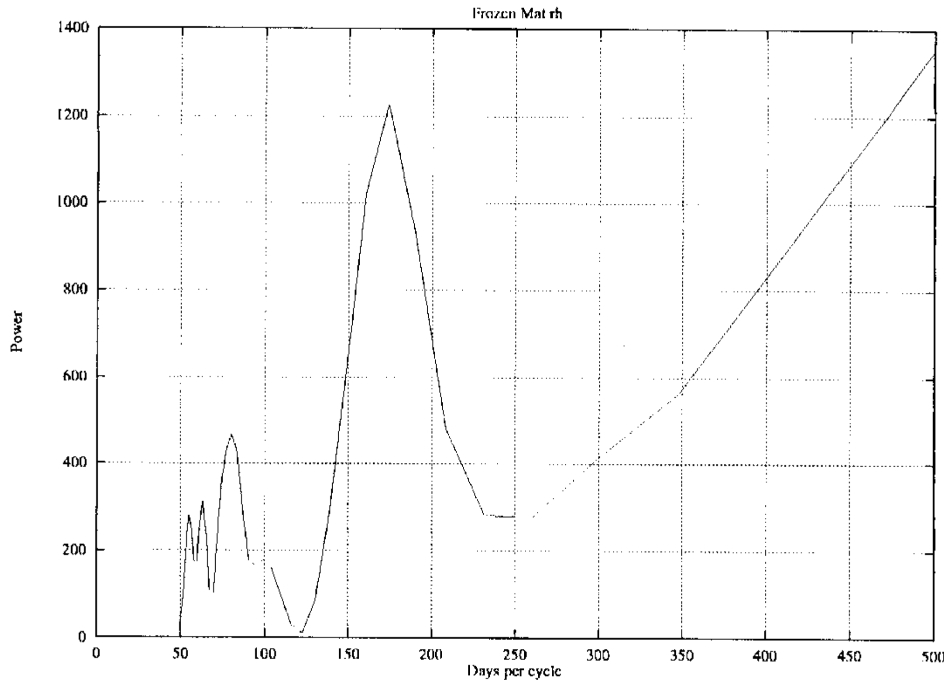

Figure 4.37: Power spectrum for cycles longer than one day for the Frozen Mat relative humidity.

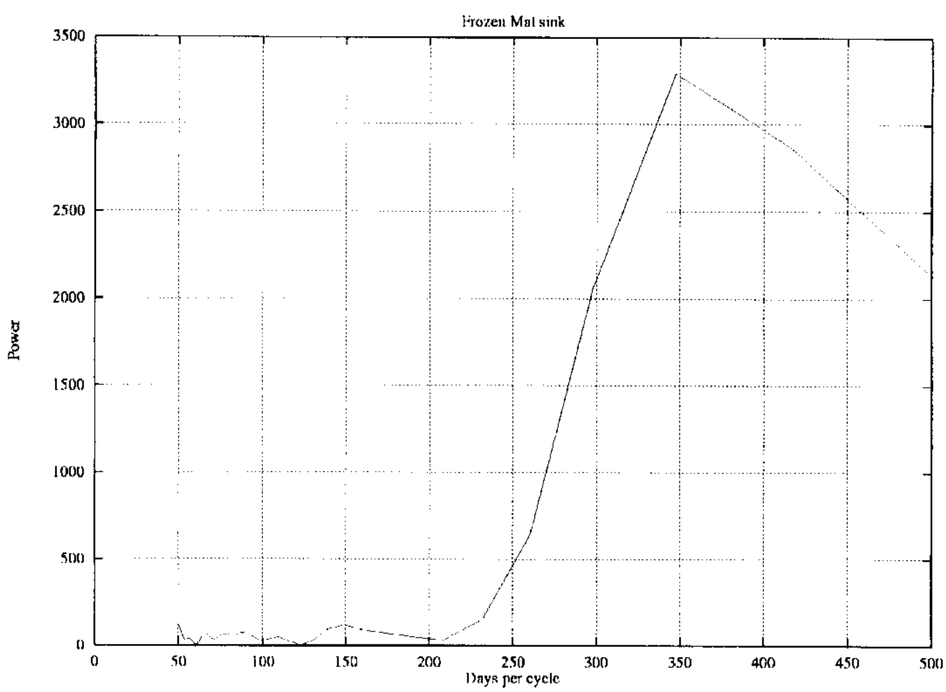

Figure 4.38: Power spectrum for cycles longer than one day for the Frozen Mat sink temperature.

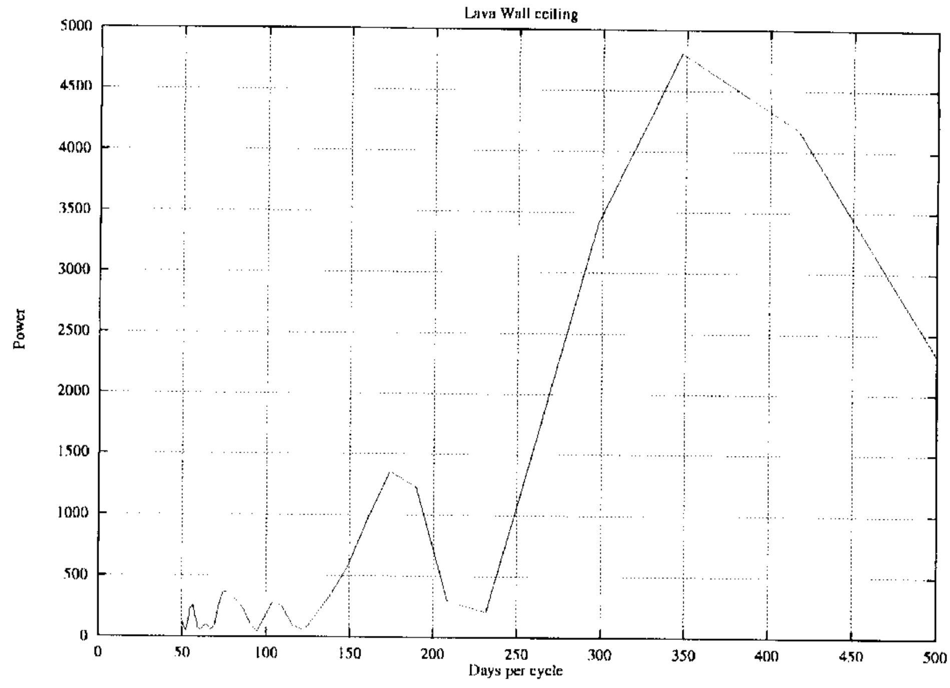

Figure 4.39: Power spectrum for cycles longer than one day for the Lava Wall ceiling temperature.

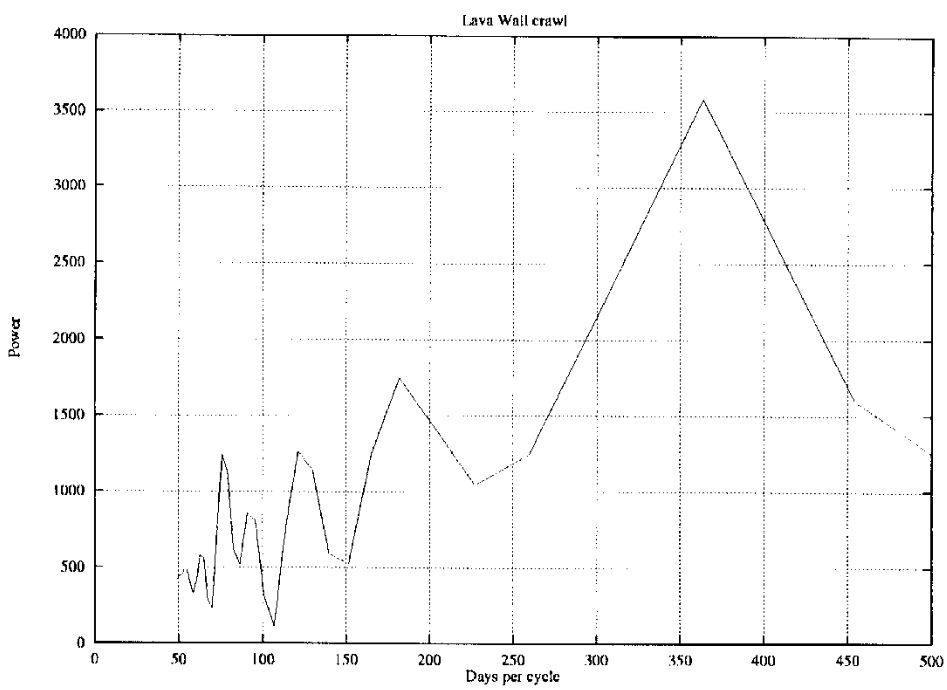

Figure 4.40: Power spectrum for cycles longer than one day for the Lava Wall crawl temperature.

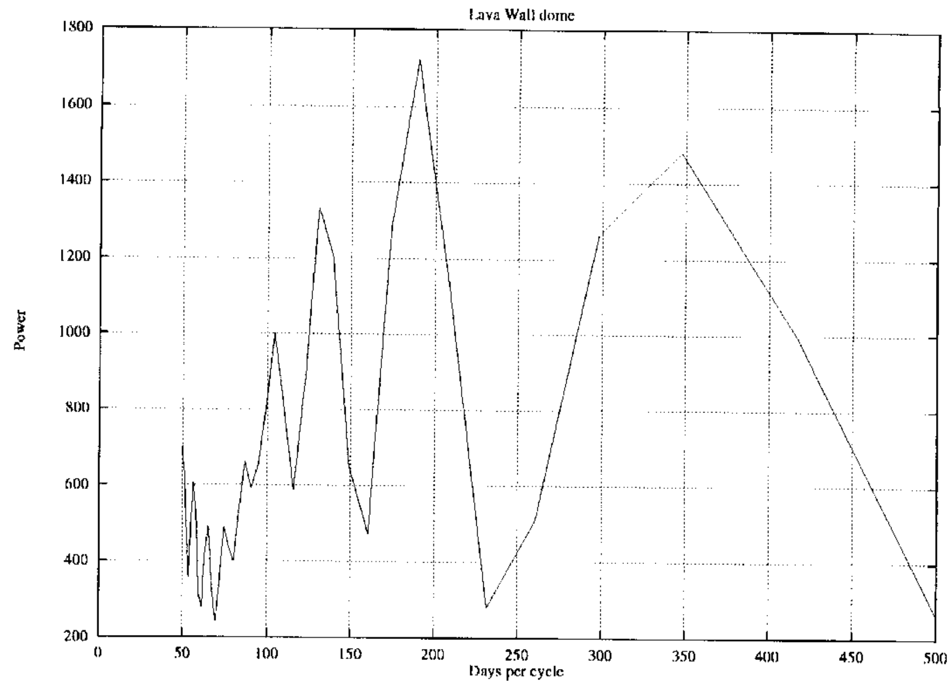

Figure 4.41: Power spectrum for cycles longer than one day for the Lava Wall dome temperature.

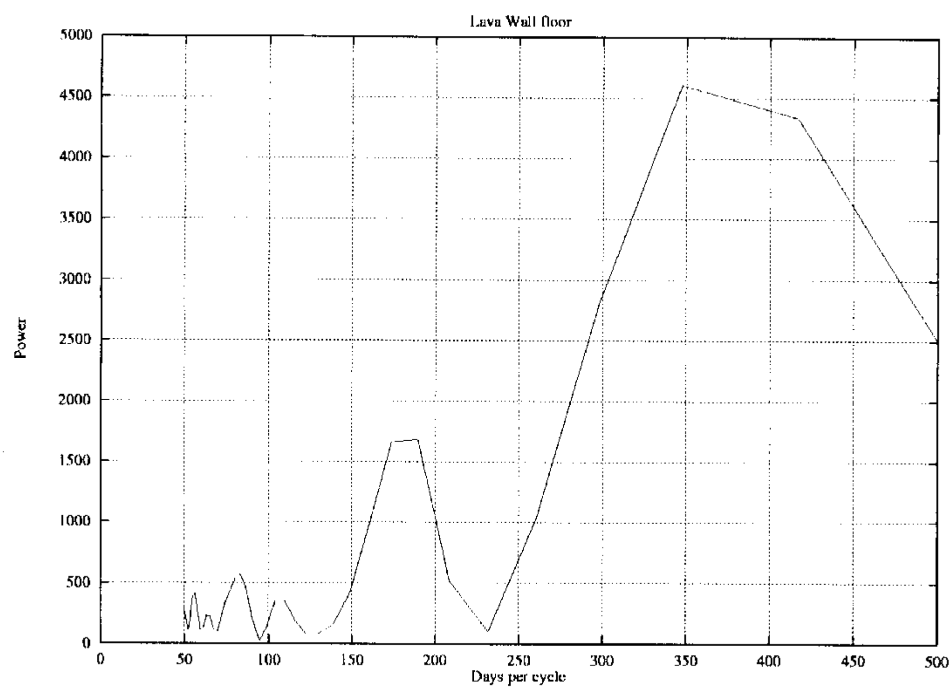

Figure 4.42: Power spectrum for cycles longer than one day for the Lava Wall floor temperature.

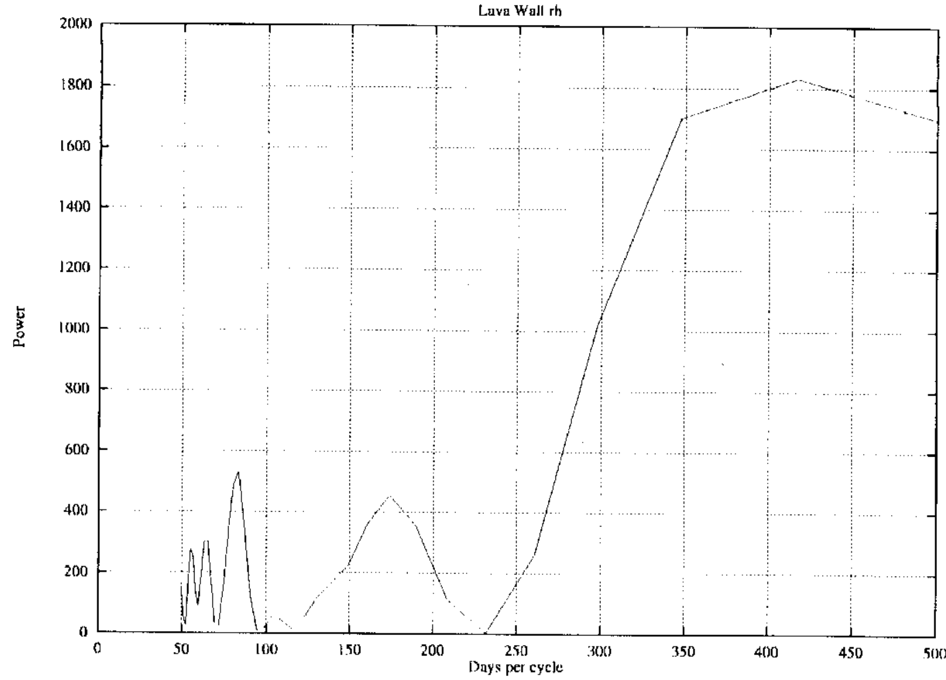

Figure 4.43: Power spectrum for cycles longer than one day for the Lava Wall relative humidity.

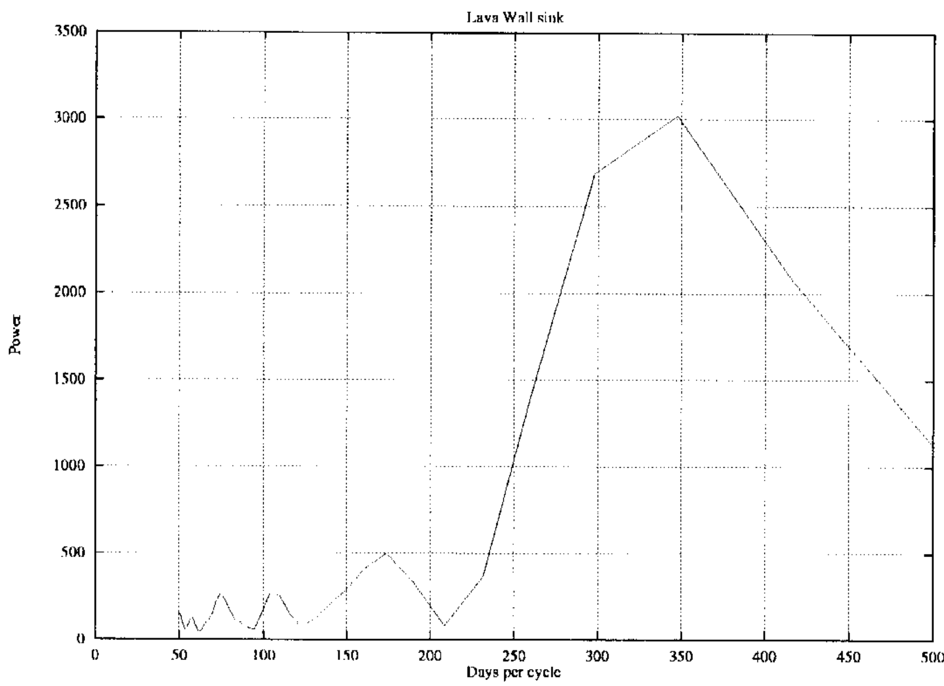

Figure 4.44: Power spectrum for cycles longer than one day for the Lava Wall sink temperature.

We also took a different approach and tried fitting an annual sine and daily sine curve to the data. The results are presented in Tables 4.2 and 4.3. Note the confidence values for each parameter of the equation which indicates how well it fits.

ceiling	$T(t) = 0.0(\pm 0.0) + -8.430573(\pm 0.012779)\cos(\frac{t2\pi}{365.24}) + -20.716593(\pm 0.011610)\sin(\frac{t2\pi}{365.24}) + -0.368887(\pm 0.012041)\cos(t2\pi) + 0.136714(\pm 0.012025)\sin(t2\pi)$
sink	$T(t) = 0.0(\pm 0.0) + -23.819973(\pm 0.015790)\cos(\frac{t2\pi}{365.24}) + -22.008461(\pm 0.013915)\sin(\frac{t2\pi}{365.24}) + -3.382733(\pm 0.014441)\cos(t2\pi) + -0.264057(\pm 0.014429)\sin(t2\pi)$
floor	$T(t) = 0.0(\pm 0.0) + -8.482291(\pm 0.015796)\cos(\frac{t2\pi}{365.24}) + -17.615507(\pm 0.013921)\sin(\frac{t2\pi}{365.24}) + 0.014079(\pm 0.014441)\cos(t2\pi) + -0.054044(\pm 0.014440)\sin(t2\pi)$
relative humidity	$T(t) = 0.0(\pm 0.0) + -5.646605(\pm 0.015349)\cos(\frac{t2\pi}{365.24}) + -38.756611(\pm 0.013631)\sin(\frac{t2\pi}{365.24}) + 0.471688(\pm 0.014182)\cos(t2\pi) + 0.210453(\pm 0.014171)\sin(t2\pi)$

Table 4.2: Results of least-squares fit to the general function $T(t) = a_1 + a_2\cos(\frac{t2\pi}{365.24}) + a_3\sin(\frac{t2\pi}{365.24}) + a_4\cos(t2\pi) + a_4\sin(t2\pi)$ for Frozen Mat data.

ceiling	$T(t) = 0.0(\pm 0.0) + -10.843922(\pm 0.016795)\cos(\frac{t2\pi}{365.24}) + -14.900744(\pm 0.015138)\sin(\frac{t2\pi}{365.24}) + -0.147362(\pm 0.015631)\cos(t2\pi) + -0.261526(\pm 0.015624)\sin(t2\pi)$
floor	$T(t) = 0.0(\pm 0.0) + -7.237748(\pm 0.016262)\cos(\frac{t2\pi}{365.24}) + -15.836785(\pm 0.013960)\sin(\frac{t2\pi}{365.24}) + -0.129653(\pm 0.014451)\cos(t2\pi) + -0.361877(\pm 0.014440)\sin(t2\pi)$
crawl	$T(t) = 0.0(\pm 0.0) + -1.427401(\pm 0.033754)\cos(\frac{t2\pi}{365.24}) + -10.884780(\pm 0.025210)\sin(\frac{t2\pi}{365.24}) + -0.261690(\pm 0.020269)\cos(t2\pi) + -0.531103(\pm 0.020291)\sin(t2\pi)$
sink	$T(t) = 0.0(\pm 0.0) + -19.417273(\pm 0.016925)\cos(\frac{t2\pi}{365.24}) + -13.317093(\pm 0.016707)\sin(\frac{t2\pi}{365.24}) + 0.625014(\pm 0.016633)\cos(t2\pi) + 0.546246(\pm 0.016627)\sin(t2\pi)$
dome	$T(t) = 0.0(\pm 0.0) + 31.512697(\pm 0.054709)\cos(\frac{t2\pi}{365.24}) + -25.051178(\pm 0.054308)\sin(\frac{t2\pi}{365.24}) + -0.198811(\pm 0.052696)\cos(t2\pi) + -0.744981(\pm 0.052707)\sin(t2\pi)$
relative humidity	$T(t) = 0.0(\pm 0.0) + -16.574255(\pm 0.016254)\cos(\frac{t2\pi}{365.24}) + -36.632496(\pm 0.013953)\sin(\frac{t2\pi}{365.24}) + -1.820918(\pm 0.014438)\cos(t2\pi) + -0.763961(\pm 0.014441)\sin(t2\pi)$

Table 4.3: Results of least-squares fit to the general function $T(t) = a_1 + a_2\cos(\frac{t2\pi}{365.24}) + a_3\sin(\frac{t2\pi}{365.24}) + a_4\cos(t2\pi) + a_4\sin(t2\pi)$ for Lava Wall data.

Location	% CO_2
Outside Lava Wall	0.014
Lava Wall twilight zone	0.012
Lava Wall near hygrothermograph	0.014
Frozen Mat northeast corner of entrance room	0.01
Frozen Mat near large ice sheet	0.01

Table 4.4: CO_2 percentages of air at various locations in Lava Wall and Frozen Mat.

Data not taken for this study, but which shows the relationship between distance into the cave and relative humidity is the humidity measurements taken in Braided Cave. A sample of this data is in Figure 4.45.

4.4 CO_2 and CO

Table 4.4 lists the CO_2 percentages recorded.

No CO measurements were taken since the burn was postponed.

4.5 Water Chemistry

The results of Santillanes' analysis are presented in Tables 4.5 and 4.6.

4.6 Particulates

The two week particulate counts are:

Lava Wall	331
Frozen Mat	1584

From these data we can see that Frozen Mat appears to suck in a greater number of particulates.

4.7 Biota

Tables 4.7, 4.8 and 4.9 show the results of pitfall trapping.The pitfall traps were flooded on two occasions, August 28-29 and October 19, 1993. The rains resulted

Sample location	pH	Temperature °C	Conductivity uS/cm	Total Solids dg/L
Lava Wall	5.4	24	19.82	< 1
Frozen Mat	6.0	24	111.00	1

Table 4.5: Water quality results for sample collected on 9/25/93.

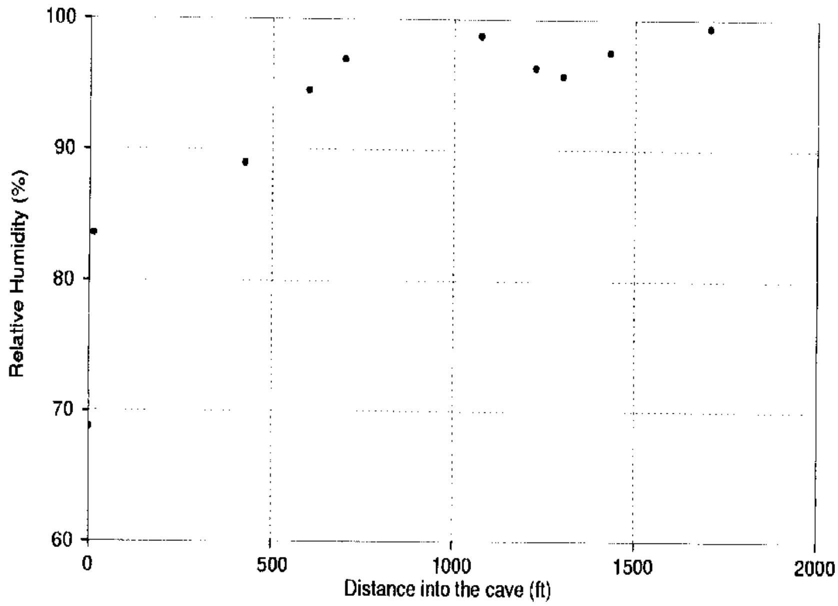

Figure 4.45: Distance vs Humidity in Braided Cave, El Malpais National Monument on August 16, 1995.

Sample location	pH	Temperature °C	Conductivity uS/cm	Total Solids dg/L
Lava Wall	5.4	24.16	16.00	1
Frozen Mat	5.8	23.60	109.30	1

Table 4.6: Water quality results for sample collected on 10/2/93.

in little or no usable information in August and a longer trapping period (5 days) in October. Results of the collections in the two caves are given in 4.10.

	Burn Plot	Control Plot
Myriapoda		
Diplopoda (millipedes)		
Identification not complete	X	X
Chilopoda (centipedes)		
Scolopendromorpha		
Identification not complete	X	X
Insecta (insects)		
Collembola (springtails)		
Entomobryidae		
Identification not complete	X	X
Poduridae		
Identification not complete	X	X
Sminthuridae		
Identification not complete	X	-
Coleoptera (beetles)		
Carabidae (ground beetles)		
Identification not complete	X	X
Scarabaecidae (scarab beetles)		
Identification not complete	X	-
Staphylinidae (rove beetles)		
Identification not complete	X	-
Tenebrionidae (darkling beetles)		
Eleodes sp.	X	X
Hemiptera (true bugs)		
Identification not complete	X	X
Homoptera (leaf & plant hoppers)		
Identification not complete	X	X
Hymenoptera (bees, wasps and ants)		
Formicidae		
Identification not complete	X	X
Identification of other not complete	X	X
Lepidoptera (moths & butterflies)		
Identification not complete	X	X
Microcoryphia (jumping bristletails)		
Identification not complete	X	X
Orthoptera (grasshoppers & crickets)		
Rhaphidophoridae		
Ceuthophilus nr. *utahensis*	X	X
Siphonaptera (fleas)		
Identification not complete	X	-
Thysanoptera (thrips)		
Identification not complete	X	-

Table 4.7: Comparison of surface collected invertebrates in the Lava Wall and Frozen Mat area (Part 1: Myriapoda and Insecta).

	Burn Plot	Control Plot
Arachnida (arachnids)		
Acari (mites)		
Adamystidae		
Adamystis sp.	X	X
Anystidae		
Chausseria sp. (new species)	X	X
Bdellidae		
Bdella sp.	X	X
Caeculidae		
Caeculus sp.	X	-
Cunaxidae X	-	
Identification not complete	X	-
Erythraeidae		
Abrolophus sp. (new species)	X	-
Balaustium sp. (new species)	X	X
Erythraeus sp. (new species)	X	X
Lasioerythaeus sp. (new species)	X	X
Leptus sp. (new species)	X	X
Eupodidae		
Eupodes sp.	X	X
Linapodes sp.	X	-
Laelapidae		
Geolaelops sp.	X	X
Microtrombidiidae (velvet mites)		
new genus C	X	-
Nanorchestidae		
Nanorchestes sp.	X	X
Neothrombiidae (velvet mites)		
Ceuthothrombium sp. (new species)	X	X
Pygmephoridae		
Pygmephorus sp.	X	X
Oribatida		
identification not complete	X	X
Rhagidiidae		
Poecilophysis (probably new species)	X	-
Smarididae		
Fessonia sp. (probably new species)	X	-
Tetranychidae (spider mites)		
Tetranychus sp.	X	-
Trombidiidae		
new genus D	X	-
Allothrombium sp.	X	X
Tydeidae		
Identification not complete	X	X
Araneae (spiders)		
Linyphiidae (sheetweb spiders)		
Lepthyphantes sp.	X	X
Salticidae (jumping spiders)		
identification not complete	X	X
Theridiidae (combfooted spiders)		
Steatoda sp.	X	X
Opiliones		
Phalangiidae (harvestmen, daddy longlegs)		
Leiobunum townsendi Weed	X	-
Scorpiones		
Vaejovis sp.	X	-

Table 4.8: Comparison of Surface Collected Invertebrates in the Lava Wall and Frozen Mat area (part 2).

	Lava Wall	Frozen Mat
Insecta		
Collembola (springtails)		
Entomobryidae		
Identification not complete	X	X
Poduridae		
Identification not complete	X	X
Sminthuridae		
Identification not complete	X	-
Coleoptera (beetles)		
Staphylinidae		
Identification not complete	X	-
Tenebrionidae		
Eleodes sp.	X	X
Diptera (flies)		
Phoridae		
Identification not complete	X	-
Hymenoptera (bees, wasps & ants)		
Formicidae		
Identification not complete	X	X
Orthoptera (grasshoppers & crickets)		
Rhaphidophoridae		
Ceuthophilus nr. *utahensis*	X	X
Arachnida (arachnids)		
Araneae (spiders)		
Linyphiidae (sheetweb spiders)		
Lepthyphantes sp.	X	X
Pholcidae (cellar spiders)		
Identification not complete	X	X
Acari (Mites)		
Anystidae		
Chausseria sp. (new species)	X	X
Bdellidae (snout mites)		
Bdella sp.	X	X
Eupodidae		
Eupodes sp.	X	X
Linopodes sp.	X	-
Erythraeidae		
Balaustium sp. (new species)	X	-
Leptus sp.(new species)	X	-
Laelapidae		
Geolaelops sp.	X	X
Nanorchestidae		
Nanorchestes sp.	X	X
Neothrombiidae (velvet mites)		
Ceuthothrombium sp. (new species)	X	X
Oribatida		
Identification not complete	X	X
Rhagidiidae		
Poecilophysis sp. (probably new species)	X	-
Trombidiidae (velvet mites)		
Allothrombium sp.	X	-
Tydeidae		
Identification not complete	X	X
Opiliones (harvestmen)		
Phalangiidae		
Leiobunum townsendi Weed	X	X

Table 4.9: Comparison of Invertebrates from the Lava Wall and Frozen M at Sinks.

	Lava Wall	Frozen Mat
Insecta		
Collembola (springtails)		
Entomobryidae		
Identification not complete	X	-
Orthoptera (grasshoppers & crickets)		
Rhaphidophoridae		
Ceuthophilus nr. *utahensis*	X	-
Lepidoptera (moths & butterflies)		
Identification not complete	-	X
Arachnida (arachnids)		
Araneae (spiders)		
Linyphiidae (sheetweb spiders)		
Lepthyphantes/ sp.	X	X
Acari (Mites)		
Bdellidae (snout mites)		
Bdella sp.	X	-
Eupodidae		
Eupodes sp.	X	-
Oribatida		
Identification not complete	X	-
Rhagidiidae		
Poecilophysis sp. (probably new species)	X	-

Table 4.10: Comparison of Invertebrates from the Lava Wall and Frozen Mat.

5 Discussion

5.1 Introduction

Because no burn occurred to provide actual data for the assessment of the impact of fire on lava tubes and their inhabitants, we can only hypothesize about the probable effects, which we will do in this section. Additionally, we will point out the potential pitfalls that future researchers will encounter when they assess the impact during a real burn; we will interpret the climate data, providing information on what we have learned about the climate of these two lava tubes; and we will inform the reader of the significance of the biota inventories in the two lava tubes.

5.2 Conduction and Radiation of Heat Into Lava

We believe that conduction is not a significant factor in transporting heat from a fire into lava tubes. Studies of transportation of heat into soils examined by the authors show that heat can be conducted up to 1 m into the ground. However, the results in Section 4.2 show that the diurnal heating cycles die out (are less than 0.1 C) at 0.75m. This depth is less than what was predicted by the literature search (Section 2.3.1). We speculate that this difference is due to the insulative nature of basalt. Because the literature is often ambiguous about the nature of the material for which the thermal conductivity values are given, it is impossible to know for sure. But, overall, we feel that it is unlikely that the thermal effects of a fire will be transmitted via conduction to the cave below.

Fire lowers humidity and darkens the soil. Drying the soil will make it a better insulator as mentioned in Section 2.1.1, adding support for the assertion that heat will not be conducted very far into the soil. Darkening of the soil and the resulting increase in solar radiation absorption will warm the soil. However, due to the depth of the caves, and the increased insulation of the dry soil this darkening is not likely to have much effect on the temperature of the cave since the daily variations in temperature die out quickly.

We have shown that the heat of a fire is unlikely to penetrate the rocks down to the cave itself. Any effects of a fire will be carried into the cave by direct radiation, air, or water movement. The only effects of direct radiation would be from a fire in the entrance, and these effects would be confined to the entrance area ([13]).

Direct radiation would not be significant further in than a few meters unless air movement took hot air into the cave due to a chimney effect. An entrance fire could melt nearby ice and could be detrimental to entrance organisms to a limited extent. Many of these organisms, however, live under rocks and in crevices and would be shielded from such radiation.

Since no water moves through the caves on the monument except during rainstorms, we are left with air movement and more generally cave microclimate.

5.3 Temperature and Humidity

The data graphs of temperature and humidity demonstrate several interesting features of cave climate. Diurnal cycles are strongly evident at the fine scale in all the temperature graphs. Oscillations are diminished as one travels further into the cave. There are also a few irregularities in the graphs.

The long straight section in the temperature graphs (especially in Lava Wall) is probably due to a mass of ice melting and getting further away from the data logger. Melting ice is a heat sink, and it remains at a constant temperature until it has melted. Given that a winter ice mass exists in Lava Wall, and it melts late spring through summer, this theory is consistent with observed data.

The diurnal humidity cycle is backwards from the expected high at night and low during the day. The researchers have not been able to come up with an explanation for this phenomenon.

Seasonal temperature variations in the sinks can be modeled by a pair of superimposed sine curves as shown in Tables 4.2 and 4.3. This information may be useful to future researchers.

5.4 CO_2 and CO

Due to the difficulty reading the Dräger tubes, the error is probably as big as the differences noted, since the light available affects the ability to read the tube. Our preliminary investigations lead us to believe that much more sophisticated equipment is needed for an accurate assessment of CO_2 and CO. Literature searches have indicated that CO is a more notable byproduct of fire due to its toxicity, so future researchers should more thoroughly investigate this area and more precise measuring devices for both CO and CO_2.

5.5 Water Chemistry

The pH of the water is somewhat acidic probably due to the pine needles in the soil above the cave.

The water chemistry samples were very limited in volume due to lack of water in the caves at the time of sampling. This had two implications. Total solids, for this type of sample, is usually measured in mg/L instead of dg/L. However, with the limited amount of sample, the detection limit had to be raised.

The Frozen Mat sample had a small colloid of dirt that burst upon releasing the sample from the syringe. This may be the reason for the marked differences in total solids and conductivity between the two samples. Another possible reason for the difference in conductivity may be the high surface tension noticed in this sample. There was not enough sample to perform a duplicate test with. Another sample could be recollected for comparison purposes in order to confirm or refute this data so that a true baseline might be achieved.

5.6 Particulates

The use of sticky paper for assessing the number and size of particulates is time-consuming and error-prone. When the burn does proceed, a more accurate method of measuring particulates should be used. Measurement of particulates, and analysis of the chemical content, during and after the burn could be quite useful in predicting the biota response.

5.7 Biota

5.7.1 Significance of Biota Found

The pitfall data suggest the Acari (mites), are the dominant arthropod group with 17 families (Tables 4.7, 4.8). The Collembola (springtails) and Araneae (spiders) are a distant second and third with three to four families each. The pitfall data also imply the surface area around Frozen Mat has fewer species than the area around Lava Wall. This difference could be due to differences in vegetation and soils.

The composition of animal species in the two sinks is different (Table 4.9). The Frozen Mat sink had fewer species than Lave Wall sink. This reduction in species may result from one or more of the following:

- The Frozen Mat sink is only partially shaded by large ponderosa pines (*Pinus ponderosa*) depending on the season and time of day, and has a small juniper growing in the bottom of the sink;
- Most of the Frozen Mat sink is covered with a thick mat of pine needles and is much drier on the surface.
- The Lava Wall sink has several small shrubs (*Ribes* sp.) growing in it which extensively shade the surface and provide soil and leaf litter.
- The Lava Wall sink has steeper sides and a smaller diameter.
- The Lava Wall sink has moss growing on the rocks and soil, implying a higher moisture content.

The cave fauna in each cave is limited (Table 4.10). The lack of invertebrates is probably due to the low temperatures, lack of organic matter beyond the moss and some limited leaf litter at the entrance, and the lack of moisture especially in the entrance area of Frozen Mat.

5.7.2 Potential Effects of a Fire on the Lava Tube Biota

Although heat from a fire overtop the lava tube would have little effect, a fire in the entrance area of the lava tube, especially at Lava Wall, might lead to some melting of the ice in the entrance and twilight zones. This would provide more moisture for the biota. During a dry time of the year this could enhance conditions for biota.

Although it is impossible to predict whether CO or CO_2 would be drawn into Lava Wall without a test fire, it is unlikely that there would be a longterm effect due to the small second entrance in Lava Wall which would eventually flush the cave of the gases. Additionally, levels of CO_2 are generally higher above the fire than at ground level (Dieterich[10]), leading to less CO_2 being drawn into the cave. It's possible that CO and/or CO_2 could accumulate is small crevices and even enter the mesocavern and microcavern areas. There is evidence in the literature (Howarth 1990) that high CO_2 levels in caves may actually lead to the evolution of cavernicoles adapted to these high levels. Knowing whether animals that are adapted or preadapted to such levels exist in Lava Wall is beyond the scope of this project. However, the authors feel that the effects of CO or CO_2 on the biota in Lava Wall would be minimal.

Other byproducts of fire, particulates and smoke/particulates might enter the cave, probably after the fire as the particulates settle out. The second entrance in Lava Wall might lead to a chimney effect, pulling smoke/particulates into the entrance area of the lava tube. If bats were present this would be very detrimental. In fact, fire is a method used by vandals to kill bats in caves. Increased particulates (depending on their chemical/carbon content) could lead to increased microbial growth, providing increased food resources for some biota. However, this scenario is limited by the extreme cold in the entrance area of Lava Wall, which limits the presence of biota. We saw very little biota five feet beyond the dripline in Lava Wall.

One of the more likely outcomes of a fire would be that surface biota would take refuge in the lava tube entrances. They could possibly then become prey for lava tube residents. Most invertebrates that survive a fire shelter under rocks or other moist areas. The lava tube entrances provide many such shelters.

The Big Tubes fire provides anecdotal data concerning the effects of fire on the plants and animals. The areas around Fern Pit burned and a burning tree trunk fell into Fern Pit. The following summer we investigated the bottom of the pit, finding that the trunk, which had fallen in a rocky area had only burned an area about three feet in diameter. There was evidence of another spot fire in the center of the pit in a area of heavy vegetation. This spot fire also burned an area about 1 m in diameter before extinguishing. The increased moisture of the sink led to a quick extinguishment of the fire. The biota in the sink the following summer were diverse and numerous, showing no major effects of the small burn in the sink and the major burn on the surface.

Based on the anecdotal data from Fern Pit and our suppositions concerning how the byproducts of fire will behave we believe that the effects of fire over the surface of a lava tube will be minimal. The major event will be the use of the lava tube as a refuge by surface biota.

6 Future research

Future avenues of investigation that should be considered include:

- Investigate how human visitation affects the ice in the ice caves.
- See if Wigley and Brown's formulas for predicting temperature and humidity in a cave apply to the caves at El Malpais.
- Obtain pressure and wind velocity dataloggers. Install them in Bat cave for a day and compare the observed chimney effect to the predicted chimney effect.
- Using a pressure datalogger and a wind velocity datalogger, further investigate the possibility that Frozen Mat is an acoustic resonator.

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A Floppies containing data

The floppy disks accompanying this report are DOS formatted disks. The directories `froznmat` and `lavawall` contain one file for each datalogger with the entire collection of data from that datalogger. The data consists of a date and time of observation along with the value (temperature in Fahrenheit or relative humidity).

B Maps

The maps provided with this report were drawn by Bob Buecher based on survey data collected by Bob and Debbie Buecher.

C Trips and Personnel

- 20-21 August 1993: Cal Welbourn, Diana Northup, Mike Reid, Kenneth Ingham; Collection, Photography
- 25-26 September 1993: Bob and Debbie Buecher, Diana Northup, Kenneth Ingham; Collection, Mapping
- 2-3 October 1993: Kenneth Ingham, Diana Northup; Collection
- 16 October 1993: Mike Wester, Cal Welbourn, Kenneth Ingham, Diana Northup; Climate, Particulates
- 13 November 1993: Kenneth Ingham, Diana Northup, Don Fingleton; Photography, Climate
- 19 November 1993: Kenneth Ingham, Diana Northup; Probe repair
- 21 May 1994: Kenneth Ingham, Diana Northup; Data Downloading
- 11-12 June 1994: Jill DesJardins, Diana Northup; Collection
- 8 July 1994: Diana Northup, Kenneth Ingham; Data Downloading
- 8 October 1994: Kenneth Ingham, Diana Northup; Data Downloading
- 12 October 1994: Cal Welbourn, Diana Northup; Lava Wall; Collection
- 7 November 1994: Kenneth Ingham, Diana Northup; Data Downloading
- 6 April 1995: Kenneth Ingham, Charlie Winckless; Data Downloading
- 8 July 1995: Pulled data loggers
- Total analysis and report writing hours = 100 volunteer person hours
- Total of 39 person days at approximately 6 hours/day = 234 volunteer person hours

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