STATE OF WASHINGTON
DEPARTMENT OF NATURAL RESOURCES
BRIAN J. BOYLE, Commissioner of Public Lands
ART STEARNS, Department Supervisor

DIVISION OF GEOLOGY AND EARTH RESOURCES
Raymond Lasmanis, State Geologist

REPORT ON GEOTHERMAL GROUND NOISE MEASUREMENTS IN WASHINGTON STATE

by

Robert S. Crosson

and

Ian R. Mayers

Washington Department of Natural Resources
Division of Geology and Earth Resources
Olympia, Washington 98504

Open File Report 72-1

March 30, 1972

Revised October, 1989

CONTENTS

Page
Introduction.. 1

Field Measurements.. 2
Data Reduction and Analysis............................... 4
  Discussion of Spectral Data............................. 5
  Klamath Falls Area...................................... 6
  Klickitat Area.. 7
  Tum Tum Mountain Area................................... 9
Conclusions... 9
Suggestions for Further Work.............................. 10

Acknowledgments... 10

References Cited.. 10

TABLES

Station Descriptions.................................... 12
Seismic Ground Noise Data Acquisition................... 18
Average Noise Power in Specified Frequency Band.......... 19

INTRODUCTION

The purpose of this report is to summarize the results of a field geophysical investigation made during summer 1971 to study seismic noise related to potential geothermal resources in Washington State. A major review of geothermal phenomena and its significance for energy production is given by Kiersch (1964). It is reasonable to expect at this embryonic stage of our understanding, that many geothermal anomalies exist in the earth's crust at depths accessible by drill, particularly in the volcanic regions of the western United States. However, only scattered surface evidence of subsurface thermal anomalies exist in the form of hot springs and other features. It is natural to turn to geophysical methods to assist in locating anomalies which may have no surface expression. A number of geophysical techniques have been applied to the problem of finding and delineating geothermal resources including gravity, magnetic, heat flow, and seismic methods [Bodvarsson, 1970]. No one method has proven universally applicable and the perfection of techniques for studying geothermal resources is still undergoing extensive research and development.

In making seismic measurements in known geothermal regions it has been found that micro-earthquakes frequently occur in large numbers [Bodvarsson, 1970; Lange and Westphal, 1969; Ward et al., 1968; Ward and Bjornsson, 1971; Ward and Jacob, 1971; Kasuga, 1967]. One mechanism for such occurrence is presumably excessive fluid pressure resulting from "hot spots", reducing effective stress levels to trigger fault slippage in much the same manner as currently believed to occur from fluid injection [Healy, et al., 1968]. Thus the presence of micro-earthquakes may be an indicator of a geothermal anomaly at depth. However, micro-earthquake activity may occur in many areas due to non-thermal tectonic activity [Westphal and Lange, 1970]. Also there is no assurance that all geothermal areas exhibit micro-earthquake activity.

A second seismic technique is based on observed changes in the seismic background noise field over geothermal anomalies as reported by Clacy (1968) and later Goforth et al. (1971). These studies indicate that there is an increase in noise power in the range from 1 to 10 Hz frequency over geothermal reservoirs. Although this report is concerned with the noise measurement method, much work remains to be done to fully verify and understand the nature and use of such data. The exact mechanism responsible for "noise" generation at hot spots in the earth's crust is not well understood although it presumably involves time dependent mechanisms of heat transfer such as suggested by Clacy (1968). The geothermal anomaly must be an active source of seismic noise energy to make the method valid and there are still uncertainties, to be discussed later, in making this connection. An aspect of the seismic noise measurements approach which has made it appear extremely attractive is the ease and rapidity with which measurements can be made. Thus noise measurements may potentially be useful not only for detailed investigations but also for regional reconnaissance.

The objective of the present study was to obtain a body of seismic noise data from a variety of geologic areas in Washington State, including regions which have potential for the existence of geothermal anomalies. The data was to be analyzed for the type of anomalies noted by previous investigators and for particular noise characteristics which might assist in understanding and improving the exploration technique. The study includes a suite of measurements made in the Klamath Falls region, Oregon, for the purpose of obtaining control information in a known geothermal area. All measurements were made during the period July to October, 1971.

FIELD MEASUREMENTS

Field measurements in the study were made at a number of sites in Washington, largely in, and west of the Cascade Range. Fig. 1 is an index map illustrating the location of all Washington stations. Most station locations were established on the basis of proximity to known thermal springs or other surface manifestation of geothermal activity. One wider-spaced profile of measurements was conducted across Stevens Pass for the purpose of establishing background levels of noise, to look for systematic variation in noise levels across the Cascades, and to field test the measurement equipment. The central to southern Cascades of Washington give abundant expression of recent volcanic activity and provide perhaps the best possibility for significant geothermal anomalies in Washington. Thorsen (1971) summarizes the principal features of this and other areas in a report on geothermal prospects in Washington. Campbell et al. (1970) have geochemically analyzed a number of thermal springs in the south Cascade region and found many of them to be of direct volcanic origin. Accordingly, a concentrated series of measurements was obtained in the Klickitat-Goldendale area of Klickitat County, where recent cinder cones, lava flows, and thermal springs attest to above normal temperatures at depth. The index map shown in Fig. 2 shows the detailed station configuration in the Klickitat area.

In addition, a series of measurements was made in the Klamath region of Oregon to obtain data from a known geothermal region. An approximately east-west profile of stations was established across the Klamath Hills geothermal region. The location and defining criteria for this anomaly are described by Peterson and McIntyre (1970). An index map of stations occupied in this area is given in Fig. 3.

The results of measurements made in each of these areas will be discussed in detail. Site descriptions and pertinent data are recorded in Table I for all stations from which usable data were obtained. In all, 98 stations were occupied of which 15 suffered equipment malfunction or other disturbance which made the data unusable. Only usable stations are listed in Table I.

Site selection is based on two levels of criteria. The first is regional and depends on general geologic features of interest as discussed in the introduction. The second is the local criteria which is applied while the survey is being conducted. The local criteria are accessibility, remoteness from spurious noise sources, goodness of seismic coupling, and appropriate station spacing. The noise measurement recording apparatus was not designed to be completely portable so the first restriction is access to a given site via four-wheel vehicle. A large number of possible spurious sources of noise is one of the chief difficulties of seismic background measurements and judgment must be applied in each case to minimize this effect. Examples are wind coupling to trees and directly to the ground, rivers, vehicle traffic, transformers, power stations, pumps, and logging activities. Observations were recorded at each site which might indicate spurious noise sources and these are tabulated in Table I. The seismic coupling aspect mainly concerns the type of soil the instrument is placed in. Humus-rich, highly organic soils and very loosely consolidated soils are extremely poor because of their low velocity characteristics and tendency to amplify surface motion. These types of soil were avoided where possible. A station spacing of 1 to 5 km was sought in most instances for regional coverage.

All measurements were made during daylight (or near daylight) hours and the duration of recording noise data at each station is of the order of 30 minutes to 1 hour. Since this mode of operation is a significant departure from that used by other investigators (e.g., Clacy, 1968; Goforth et al., 1971), some justification is in order. Night measurements were used, for example, by Goforth et al. (1971) to reduce the influence of cultural activity. In most of the regions investigated in the present study, cultural activity was not a major noise source due to remoteness. A far greater problem was the influence of wind, trees, and running water, which is not necessarily reduced at night. Longer recording intervals, up to 8 hours, were also used by Goforth et al. However, a fundamental assumption of the method is that the noise characteristics are stationary, that is, their statistical properties do not vary with time. Since we are interested in frequencies from approximately 1 to 30 Hz, the spectrum of the noise should, in principle be determined by a sample of data of the order of a minute in length. In practice, previous investigators have utilized only a small segment of the total recording time to determine the spectral characteristics of noise. Thus, if stationarity is a reasonable assumption, a 30 minute recording interval is sufficient to obtain a base noise-level segment for analysis.

A block diagram of the instrumentation required for measurement and analysis, from field recording apparatus through the digital processing, is shown in Fig. 4. The sensor is a 1.0 Hz natural frequency, velocity sensitive seismometer damped to 0.7 critical. Ground velocity response of the system is nominally flat from 1 to 30 Hz, the high frequency rolloff being determined by filters in the amplifier and discriminator systems. A relatively inexpensive cassette tape recorder is used with the tape speed compensation system shown in Fig. 4 to recover a dynamic range of better than 40 db. This dynamic range was sufficient to allow all recordings to be made at the same amplifier settings providing direct internal calibration among all stations in the survey. The

Develco Model 6202 seismic preamplifier was set at -30 db attenuation providing a nominal maximum voltage-out/ground-velocity magnification factor of 1 volt per .32 microns/sec. Without a shake table apparatus available, precise calibration was not attempted.

At each site the seismometer is buried 6 to 8 inches, leveled, and tamped for optimum coupling to the ground. A shallow, firm soil cover is desirable. The recorder is placed approximately 15 meters from the seismometer and provided with a foam rubber cushion to eliminate high frequency "hum" from the recorder motor. Recording was initiated when wind velocity and other possible extraneous sources of noise were observed to be at a minimum. Voice annotation at the beginning of each tape was used to record site description and other information. A short section of subcarrier was recorded with the seismometer unplugged at each station to ensure optimum baseline adjustment during playback. Field notes were written during the recording period which was nominally 25 minutes per station. Occasionally, two or more data tapes were made at a given station if a longer recording time was deemed necessary. The normal stations are numbered by month-day-sequence and additional data tapes are designated by (1) or (2) following the station number as appropriate. Typical site observations include time of day, general wind speed, weather conditions, soil condition, number and size distribution of trees, topography, rock exposures, proximity to rivers, and proximity to cultural features such as highways, pumping stations, and mills. In addition, the site environment was photographed whenever possible.

DATA REDUCTION AND ANALYSIS

The objective of data analysis was to obtain power spectral density estimates of the noise signals recorded at each site and compare these estimates qualitatively with the results obtained by Clacy (1968) and Goforth et al. (1971). The spectral estimation was ultimately carried out in a digital computer. However, initially data tapes were played back on a strip chart recorded to obtain a qualitative view of the data. Low noise level segments were noted for subsequent use. Obvious transient noise pulses were apparent on the strip chart record and it was assumed that the lowest amplitude record segments represent the true residual background noise level. All tape cassette playback was done through the Develco Model 6203 discriminator system with a model 6212 tape speed compensation channel attached.

The quiet portions of each record were then digitized according to the scheme illustrated in Fig. 4. The data were band-pass filtered from 0.1 to 25.0 Hz and sampled at a rate of 100 samples per second. Up to two minutes of data per station were digitized in this manner and written onto digital tape for later analysis.

Digital analysis consisted of estimating the power spectral density of the data from each station through the use of the fast Fourier transform method given by Welch (1967). Initially the data are read into the spectral analysis program in blocks of 1024 sample values and scaled by an arbitrary but fixed scale value. Constant bias is removed from the data by an averaging scheme. Next, the array of data values are tapered over the end 100 points using a cosine bell tapering function. The 1024-point array is Fourier transformed using an FFT algorithm and the spectral estimates calculated using the modulus of the Fourier transform. Four such estimates are calculated for each record of data and averaged to yield the raw power spectral density values. The spectrum is then smoothed using a 9-point smoothing operator for the final estimates. Finally the data are scaled and plotted as $\log_{10}$ of the power density in units of $[\mathrm{vel}^2/\mathrm{Hz}]$ vs. frequency. The cataloged plots of power spectra for the Klamath Falls, Klickitat, and Tum Tum Mountain stations are examples of the computer plotted output graphs produced by this method. The frequency scale for these plots is linear from 0 to 50 Hz, the folding frequency for the analysis. The vertical amplitude scale is arbitrarily chosen but uniform for all plots. From approximate calibration information the base level of the plot amplitudes corresponds to a ground velocity in the center of the pass band of 0.22 mu/sec. From this value the vertical amplitude of all plots can be scaled appropriately. In addition, the average power density in the bands 0-5 and 5-10 Hz was calculated and printed out with each plot for comparative purposes. The scale factors for the plots is not indicated due to limitations in the digital plotting system, however, they are identical for all plots and only relative comparison is important. The spectral plots cataloged in this report do not include all the data analyzed for this study. For reasons of conciseness, the plots presented are representative and are believed to include the most important observations.

Discussion of Spectral Data

Several important questions immediately arise concerning the significance of the spectra for various stations. For example, what are the effects of environmental factors such as wind velocity, running water, an trees? Are the spectral estimates truly representative of stationary phenomena, and do their detailed character differences reflect different geologic controls? The measurements obtained in this study are not ideally suited to answer all of these questions, however, we have made an attempt to determine obvious environmental correlations. For example, if weather conditions, temperature, cultural activity, etc., contributed appreciably to the noise spectrum, we might expect to see some correlation of the average noise power with observation time during the day. Fig. 5 shows a plot of average power density in the bands 0-5 and 5-10 Hz band which is probably fortuitous since many midday values for this band fall significantly below the clustered value and extraneous noise can only add to the spectral density. The 0-5 Hz band values average almost an order of magnitude lower than the 5-10 Hz band values, in part due to the fact that the normal tendency is for the spectrum to peak in the 0-5 Hz band and in part due to estimates which are probably too high near zero frequency due to inadequate removal of linear and high order bias. When the average noise power values for the same stations are plotted as a function of station elevations (Fig. 6) there appears to be a tendency for the maximum values to decrease slightly with increasing elevation, particularly in the 0-5 Hz band. This effect is not strong but could indicate a slight topographic element of noise control. Similarly, the data plotted vs. estimated wind speed ($<\sim 6$ m/sec) shows little obvious influence of wind velocity on the noise power in either the 0-5 or 5-10 Hz bands (Fig. 7). Insufficient data were obtained to estimate the influence of running water or trees on the noise spectrum. Similarly, the degree to which the data are stationary over the sample intervals used in this study is uncertain. However, two stations in the Klickitat area were occupied at different times and provide at least a minimal amount of data to test stationarity. Station numbers 9-9-3 and 9-22-2 represent the same site, as do 9-9-4 and 9-22-3. These are both low noise sites and the similarities of the two sets of measurements can be determined directly by comparison. 9-9-3 and 9-22-2 show great similarity in the spectrum below 13 Hz to the extent of reproducing small peaks. The 14 to 25 Hz band of 9-22-2 shows a higher level of noise power, however, even in this band a peak at 16 Hz is correlated between the two measurements. 9-9-4 has significantly higher noise power levels over the entire spectrum than does 9-22-3 which suggests non-stationarity. Despite the overall difference, however, several minor peaks are correlated from one measurement to the other and except for an overall vertical scaling, the spectral character between the two measurements is very similar. Clearly, the questions of stationarity and the fidelity with which detailed spectral character represents a given site need further investigation. In addition, to avoid the possibility of scaling errors, a reference signal for calibration should be recorded at each station. It is particularly difficult at this stage of investigation to assess the importance of minor spectral peaks that appear in virtually all the data and may be a function of site geology. Due to a higher data sampling rate, the frequency analyses presented here cover a broader spectrum than those calculated by Goforth et al. (1971). The results of Clacy (1968) cannot be directly compared with the present analysis since Clacy failed to present actual spectral plots and he omitted the details of his method of analysis.

The spectral plots for two areas in Washington, Klickitat and Tum Tum Mountain, and Klamath Falls in Oregon are presented as catalogs in this report. We will discuss the data from each of these areas in sequence.

Klamath Falls Area

Measurements of ground noise were obtained in the Klamath Falls, Oregon, region as control information from a known geothermal region. Although commercial power is not being produced from the Klamath Falls geothermal region, shallow wells drilled for space heating and other uses are numerous and serve to outline the extent of shallow thermal anomalies. On the other hand, apparently little is known of the possible extent of deeper, higher temperature anomalies. Peterson and McIntyre (1970) describe the geology of the region and discuss the general character of the known thermal regions. Fig. 3 shows the location of two major anomalous zones described by Peterson and McIntyre and characterized by surface water temperatures greater than 38°C and silicification of surface sediments. The dominant structure is an approximately northwest trending graben bounded by blocks consisting of late Cenozoic sedimentary rocks and volcanics. The downdropped blocks form alluvial valleys and the geothermal anomalies are in the valleys near the bounding faults.

A series of nine usable stations was established in a three-day period along and E-W profile normal to the dominant fault structure and across the Klamath Hills anomaly. Both bedrock sites, usually in the uplands, and valley sites were occupied. The southernmost anomaly was chosen to avoid high cultural noise levels in the vicinity of Klamath Falls. Bedrock of the Klamath Hills lies immediately to the east of the south geothermal zone shown on Fig. 3. The Klamath Hills are a horst-like feature of limited longitudinal extent in the middle of a larger graben complex. Two basic types of spectra are observed depending on whether the station was situated in the bedrock foothills or the alluvial valleys. The bedrock sites are characterized by low overall noise power and extremely steep falloff of noise power density above 10 Hz. Stations 8-25-1, 8-25-2, and 8-26-5 are in this category. The second class of stations, in the alluvial valleys, is characterized by considerable noise power up to and beyond 20 Hz and has much higher average noise power than the bedrock sites. Among the valley stations there are those exhibiting prominent noise power peaks below 5 Hz such as, for example, 8-27-2. Such peaks are of the type reported by Goforth (1971) and could be related to geothermal noise excitation. On the other hand, there is no obvious correlation of such prominent peaks with the location of the Klamath Hills geothermal zone and, furthermore, some of the valley sites are of questionable character and subject to possible extraneous noise excitation from cultural activity. For example, station 8-26-3 is about the highest average noise station recorded in the entire study, and although it shows a 3-4 Hz peak, the high noise levels above 20 Hz are very unusual and likely due to extraneous sources. We cannot be sure, of course, that some of the high noise levels and prominent low frequency peaks are not related to more extensive thermal anomalies at depth not necessarily with near-surface expression. Such a possibility is speculative at our current stage of knowledge. The effect of geologic control in amplifying and modifying normal residual background noise must clearly be investigated more thoroughly.

Klickitat Area

The most concentrated and extensive series of observations in this study was obtained in Klickitat County, Washington, near the towns of Klickitat and Goldendale. The locality is of interest because of abundant volcanic evidence of thermal activity as well as hot spring evidence. Fig. 2 shows the location of stations occupied in the area. Unfortunately, all stations were obtained during a concentrated period of field work before our analysis procedures were operational, hence, it was not possible to use the resultant analysis to correct or change the observation program. Such interaction would be desirable in future investigations.

Structurally, the region consists of a thick sequence of flows of Yakima Basalt interbedded locally with diatomite and tufaceous sandstone beds. The rocks have been deformed into gently E-W trending folds which have been fractured by NE-SW strike-slip faults. Geology of selected parts of the region has been described by Wise (1970), Sheppard (1967), and Luzier (1969). There is a strong need for additional regional geological investigation of the southern Cascades.

Unconformably overlying the Yakima Basalts are olivine basalt flows of late Cenozoic age which were apparently extruded through numerous vents penetrating the Yakima Basalt. Scoria cones are frequently associated with these vents. Locally, fluvial materials have been deposited by the Little Klickitat River.

Within the area covered by ground noise measurements, a number of interesting springs occur. The Klickitat Mineral Springs discharge cold, carbon dioxide charged water. Nearby wells have yielded CO_2 charged warm water indicating the possibility of deep origin. The Blockhouse Springs yield warm water in excess of 60^oF (15.5^oC) which was used for mineral baths. Most of the thermal springs suggest control by the major fault system which penetrates the Yakima Basalt. Thermal sources at depth are suggested although the existence of structures necessary for entrapment and production of geothermal steam is unknown.

The spectra calculated for stations in the Klickitat area are cataloged in this report. Most of the stations show low overall noise levels and are similar to the bedrock sites measured near Klamath Falls. On the other hand, a wide variety of detailed characteristics is apparent. Minor peaks are prevalent possibly indicating geologic structural control. Many of these peaks appear to bear harmonic relationships to one another suggestive of reverberation phenomenon in a layered medium. Simple theoretical models should be constructed to test this possibility. Structural information may be obtainable directly from noise data. In a few instances higher average noise levels were recorded. For example, 9-10-5 shows relatively high levels between 10 and 20 Hz, probably attributable to wind noise. 9-24-2 (1) shows a prominent low frequency peak at about 2 Hz. Gusting winds were noted for this station, however. 9-24-5 and 9-25-1 both show higher than average noise levels in the 0-10 Hz band. However, none of the Klickitat station approach the low frequency levels attained by the Klamath Falls observations. Near-surface geologic conditions likely account for at least part of this difference. For example, most of the Klamath Falls spectra do not show the fine structure of the Klickitat spectra, probably due to differences in layering structure and near-surface wave velocities. There appears to be no systematic association of high noise levels with the hot spring and well locations in the Klickitat area, a not surprising observation in view of the local and rather scattered distribution of surface hot water occurrence. In fact, one of the quietest stations, 7-27-1, lies close to the Klickitat Springs area.

Station 9-11-1 lies close to Blockhouse Butte, a young cinder cone, and exhibits an unusual broad spectral high between 20 and 30 Hz. The high frequency rolloff of this peak is slightly steeper than normal due to the 25 Hz low pass filter, but in any case the noise power level at 25 Hz for this station is comparable to the highest noise stations observed although the average noise level is very low over the entire spectrum.

Tum Tum Mountain Area

The last area for which detailed power spectrum data are presented is the Tum Tum Mountain area in northern Clark County, Washington. Geology of this area is similar to the Klickitat-Goldendale area. Tum Tum Mountain is a young cinder cone reaching approximately 450 meters above the surrounding terrain, suggesting very recent volcanic activity. A series of eight stations was occupied along and E-W profile near the cone to test for anomalous noise character possibly associated with volcanic activity. The spectra are included because several anomalously high noise levels were recorded, similar in total noise power to the Klamath Falls observations. Some of the high noise level stations are certainly due to spurious cultural noise. 8-17-1 and 8-18-1, for example, are both near logging roads with heavy truck activity. On the other hand, 8-18-2 and 8-18-3 are relatively high noise sites which are located remote from obvious noise sources. 8-18-2 exhibits sharp resonant peaks at 5, 10, and 15 Hz, harmonics which are strongly suggestive of structural control. The same peaks appear in 8-18-1 at even a higher intensity presumably due to artificial excitation. Station 8-18-3 shows a much broader peak between 10 and 20 Hz which is highly anomalous with respect to the other observations made during this survey. Such a pronounced peak is suggestive of a localized source of moderate bandwidth noise.

Conclusions

Any conclusions regarding the use of seismic noise measurements to locate and study geothermal anomalies must at this time remain speculative. The spectral character of data obtained in this study suggests the possibility of localized noise sources, particularly in the Klamath Falls and Tum Tum Mountain areas. Geologic control is strongly suggested by the character and variability of spectral estimates taken together with the fact that nearby stations often show similar character. It is reasonable to assume that the noise measurements we obtain at a particular station result from broadband noise excitation as observed through the filter of local geologic structure. Increase in amplitude level, without corresponding changes in the spectral shape, probably indicates and increase in the broadband excitation level. On the other hand, a localized narrow band source due perhaps to geothermal activity would significantly alter one region of the spectrum and be detectable on that basis.

Suggestions for Further Work

Detailed experiments should be carried out in control areas to investigate the stationarity and effect of geologic structure, wind, water, trees, topography, and cultural sources of noise or noise signals. In addition, theoretical models should be constructed to investigate the possibility that body wave noise reverberation may produce spectral peaks of the type observed. A denser grid of stations in a known geothermal area such as Klamath Falls is required to determine the detailed spatial extent of noise anomalies. Ultimately, other techniques must be brought in to verify the association of noise anomalies with geothermal anomalies.

ACKNOWLEDGMENTS

Vaughn E. Livingston, State Geologist, and Gerald Thorsen, Environmental Geologist, Department of Natural Resources, Division of Mines and Geology, Olympia, gave valuable advice on site selection and encouragement for this study. The Division of Mines and Geology provided partial salary support for the field investigations. Mr. Leland Bond assisted with development of the electronic recording equipment.

REFERENCES

Baldwin, E. M. (1964) The Geology of Oregon, U. of Oregon Press, Eugene, Ore., 165 pp.

Bodvarsson, G. (1970) Evaluation of geothermal prospects and the objectives of geothermal exploration, in Geoexploration, 8, 7-17.

Campbell, K. V., et al. (1970) A survey of thermal springs in Washington State, Northwest Science, 44, 1-11.

Clacy, G. R. T. (1968) Geothermal ground noise amplitude and frequency spectra in the New Zealand volcanic region, J. Geophys. Res., 73, 5377-5384.

Dibble, R. R. (1969) Seismic power recordings during hydrothermal eruptions from Ruapehu Crater lake in April, 1968, J. Geophys. Res., 74, 6545-6551.

Goforth, T.; Douze, E. J.; Sorrells, G. G., 1971, Noise measurements in a geothermal area [Abstract]: Geological Society of America Abstracts with Programs, v. 3, no. 2, p. 124.

Healy, J. H., W. W. Rubey, D. T. Griggs, and C. B. Raleigh (1968) The Denver earthquakes, Science, 161, 1301-1310.

Kasuga, I. (1967) Aspect on the relation of thermal water and Matsushiro earthquakes in Kagai Hotspring area, Nagano Prefecture, Chigaku Zasshi, Tokyo, 76, 16-26.

Kiersch, George A. (1964) Geothermal steam, origin, occurrence, characteristics, and exploration, AFOSR Report, Cornell University, Ithaca N. Y., 203 pp.

Lange, A. L., and W. H. Westphal (1969) Microearthquakes near the geysers, Sonoma County, Calif., J. Geophys. Res., 74, 4377-4378.

Luzier, J. E. (1969) Ground-water Occurrence in the Goldendale Area, Klickitat County, Washington (Map), U.S. Geological Survey.

Peterson, N. V., and J. R. McIntyre (1970) The reconnaissance geology and mineral resources of eastern Klamath County and western Lake County, Oregon, Bull. 66, State of Oregon, Dept. of Geology and Mineral Industries, 70 pp.

Sheppard, R. A., 1967, Geology of the Simcoe Mountains volcanic area, Washington: Washington Division of Mines and Geology Geologic Map GM-3, 1 sheet, scale 1:250,000.

"Thermal Waters of Washington" from Mineral Water, in Inventory of Washington Minerals, Part I, V. 1, Bull. 37 (1970), Washington Division of Mines and Geology.

Thorsen, G. W. (1971) Prospects for Geothermal Energy in Washington, from First Northwest Conference on Geothermal Power (May 21, 1971). 18 pp.

Ward, P. L., G. Palmason, C. Drake, and J. Oliver (1968) The microseismicity of Iceland and its relation to the regional tectonics, (Abs.), Trans. Am. Geophys. Union, 49, 293.

Ward, P. L., and S. Bjornsson (1971) Microearthquakes, swarms, and the geothermal areas of Iceland, J. Geophys. Res., 76, 3953-3982.

Ward, P. L., and K. H. Jacob (1971) Microearthquakes in the Ahuachapan geothermal field, El Salvador, Central America, Science, 173, 328.

Welch, P. D. (1967) The use of the fast Fourier transform for the estimation of power spectra: A method base on tie averaging over short, modified periodograms, IEEE Trans. on Audio and Electroacoustics, AU-15, 70.

Westphal, W., and A. L. Lange (1970) Mini-earthquakes . . . the noise can help map buried faults, Engr. Mining Jour., 171, 86-89.

Wise, W. S. (1970) Cenozoic volcanism in the Cascade Mountains of southern Washington, Bull. 60, Washington Dept. of Natural Resources, Div. of Mines and Geology, 45 pp.

Addendum to Report - December 1973

Recent advances in seismic ground noise studies make a brief addendum to our report appropriate at this time. Measurements taken in the Imperial Valley by Goforth, Douze and Sorrells suggest a positive correlation between peaks in the point measurement noise spectrum and known geothermal reservoirs. Iyer and his co-workers at the U.S. Geological Survey in Menlo Park, while not confirming the results of Goforth, et al., in the Imperial Valley have reported positive ground noise correlations with surface hot spring and geyser activity in the Yellowstone area. Thus there is an accumulating body of data that links ground noise anomalies with at least some geothermal reservoirs. Intensive further investigation of this phenomenon is thus warranted.

Virtually all previous noise measurements have been made with conventional seismographs designed primarily for earthquake recording. Hence the frequency and amplitude response properties of these instruments are not necessarily optimized to properly record low level noise information. To correct this situation we have constructed a highly accurate "digital" seismograph which is portable and designed specifically for analyzing a wide range of noise properties. Future research at the University of Washington will include utilizing this new system which will permit reliable, wide dynamic range data to be obtained. In particular, definitive research must be carried out on the properties of normal ground noise in non-geothermal regions and on the properties of different noise generating mechanisms as suggested in our report. This is necessary so that geothermal anomalies may be properly identified. Our future research plans include more extensive, higher quality measurements in known geothermal regions as well as in non-geothermal control regions. In addition, theoretical modeling of the earth as a transmission system for seismic waves as well as modeling of sources is feasible. We have already demonstrated that simple layering can cause sharp spectral peaks of the type observed at stations near Tum Tum Mountain in our report. The relative amplitude levels and the harmonic relationships of these spectral peaks agree quite well with a simple one-layer model. It is possible that other models may be used successfully in analyzing more complex spectra. Seismic noise measurements appear to hold promise in geothermal exploration; however, much research remains to be done before adequate interpretation of data can be carried out on a routine basis.

Robert S. Crosson
Geophysics Program
University of Washington

December 1973

[Pagination continues on p. 17]

TABLE I - STATION DESCRIPTIONS

Station	Time	Lat	Lon	Elev (M)	Wind Vel. (M/S)	Regional Rock Type	Seismic Coupling	Site Photo	Comments
						Klickitat Area			
7-27-1	1000-1030	45°48.5'	121°06.5'	500	0-2	Basalt	Good	N	Grassland; 0.8 km S. of Klickitat River
9-8-3	1930-2000	45°49.5'	121°14.7'	690	4-7	Basalt	Good	N	30 m from small spring; some trees
9-9-2	0955-1025	45°48.3'	121°13.1'	510	4-7	Basalt	Good	Y	Near bluff on Klickitat Canyon; few trees
9-9-3	1120-1150	45°49.3'	121°03.4'	450	2-7	Basalt	Good	Y	High grassland site
9-9-4	1240-1310	45°49.6'	121°01.9'	480	0-3	Basalt	Good	Y	South of Little Klickitat River; high grassland
9-9-5	1555-1625	45°46.0'	121°09.2'	650	0-5	Basalt	Good	Y	High grassland; 0.3 km N. of gas pipeline station
9-9-6	1710-1740	45°47.1'	121°06.8'	575	0-5	Basalt	Good	N	High grassland; cattle as close as 0.2 km
9-9-7	1840-1910	45°50.8'	121°06.0'	480	0	Basalt	Good	Y	Wooded north slope of Klickitat River gorge
9-9-8	1950-2020	45°51.0'	121°08.5'	600	2-7	Basalt	Good	Y	Small clearing in Ponderosa Pine woods; lies on Warwick fault
9-10-1	0800-0830	45°49.6'	121°11.1'	550	0	Basalt	Good	Y	2 km from Klickitat; cultural noise audible; near woods
9-10-2	0930-1000	45°49.7'	121°13.1'	680	0-3	Basalt	Good	Y	Dry creek bed; dense woods
9-10-3	1155-1225	45°48.2'	121°0.0'	485	0-6	Basalt	Good	Y	High grassland
9-10-4	1336-1406	45°47.8'	120°56.8'	515	0-7	Basalt	Good	Y	High grassland
9-10-5	1555-1625	45°53.0'	120°56.8'	595	5-9	Basalt	Good	Y	Nearest woods 0.1 km; gusty winds
9-10-6	1717-1747	45°52.2'	120°59.2'	505	4-7	Basalt	Good	N	Nearest woods 0.3 km; gusty winds
9-10-8	1944-2014	45°50.8'	120°52.5'	515	4-8	Basalt	Good	N	High grassland
9-11-1	0730-0800	45°51.0'	120°56.3'	500	0-2	Basalt	Good	N	Near Blockhouse Butte cinder cone; road 0.8 km
9-11-2	0830-0900	45°50.1'	120°57.4'	480	0-2	Basalt	Good	Y	Open grassland; cultural activity 1.8 km
9-21-1(2)	1338-1408	45°42.3'	121°11.4'	460	2-7	Basalt	Good	Y	Scattered woods
9-21-2	1632-1707	45°43.8'	121°09.3'	610	2-4	Basalt	Good	Y	High grassland
9-21-3	1810-1840	45°43.2'	121°06.8'	615	2	Basalt	Good	Y	Edge of high prairie grassland; trees 0.1 km (closest)
9-21-4	1920-1950	45°45.2'	121°07.9'	660	0-2	Basalt	Good	N	High grassland
9-22-1	0755-0825	45°49.1'	121°06.0'	275	0	Basalt	Good	Y	0.7 km from Klickitat River; some trees (lies on Warwick fault)
9-22-2	1000-1030	45°49.3'	121°03.4'	450	0	Basalt	Good	Y	High grassland site
9-22-3	1118-1148	45°49.6'	121°01.3'	480	0-2	Basalt	Good	Y	South of Little Klickitat River; high grassland
9-22-4	1420-1450	45°47.4'	121°01.9'	525	2-3	Basalt	Good	Y	High prairie
9-22-5	1555-1625	45°46.9'	120°58.0'	570	2-5	Basalt	Good	Y	High prairie; in small dry valley
9-22-6	1735-1805	45°47.8'	120°51.5'	520	0-2	Basalt	Good	Y	Grassland; 3 km from Goldendale
9-22-7	1840-1910	45°52.3'	120°52.5'	585	0	Basalt	Good	N	Open field
9-23-1(1)	0907-0937	45°48.6'	121°14.5'	700	0-3	Basalt	Good	Y	Near power pylons; logging trucks in area
9-23-2	1055-1125	45°46.8'	121°14.3'	650	0-2	Basalt	Good	Y	North edge of large clearing
9-23-3(1)	1230-1306	45°45.4'	121°13.6'	490	2-7	Basalt	Good	Y	Bluff over Klickitat River; 0.7 km from river

Station	Time	Lat	Lon	Elev (M)	Wind Vel. (M/S)	Regional Rock Type	Seismic Coupling	Site Photo	Comments
8-6-1	1000-1030	47°32.4'	121°24.2'	330	0-2	Granitic	Fair/Good	Y	Logged clearing; humus rich soil
8-6-2	1536-1606	47°26.5'	121°25.4'	955	0-2	Granitic	Poor	Y	Small stream, 30 m; moist soil
9-3-2	1208-1238	47°39.3'	121°22.1'	520	0-2	Granitic	Fair	Y	Logged hillside; 0.5 km E. of Miller River

Garland Hot Springs

Station	Time	Lat	Lon	Elev (M)	Wind Vel. (M/S)	Regional Rock Type	Seismic Coupling	Site Photo	Comments
8-10-1	0900-0930	47°50.0'	121°29.7'	520	0-2	Granitic	Fair/Good	Y	Partially wooded hillside
8-10-3	1240-1310	47°54.9'	121°26.2'	490	2-4	Sand/Siltstone	Poor	Y	Steep recently logged hillside; 30 m W. of swift creek
8-10-4	1415-1445	47°55.6'	121°16.6'	760	2-4	Gneiss	Fair	N	Large trees (> 30 m); 0.4 km N. Snoqualmie River
8-10-5	1540-1610	47°54.5'	121°16.0'	970	2-4	Gneiss	Fair	Y	Logged hillside; 0.8 km to swift creek
8-10-6	1653-1723	47°53.2'	121°20.0'	485	2-4	Granitic	Fair	N	Alluvial flood plain of Skykomish River; 50 m from river
9-3-1	1025-1055	47°45.8'	121°27.3'	550	0	Metasediments	Fair/Good	N	Near logging activity; possible cultural noise
9-3-3	1225-1255	47°47.3'	121°16.7'	810	0	Metasediments	Poor	N	Steep, logged hillside; near bedrock
9-3-4	1545-1615	47°51.3'	121°19.0'	805	0	Metasediments	Poor	N	New growth; raining
9-3-5	1740-1810	47°53.7'	121°17.3'	915	0	Metamorphic	Poor	N	0.4 km south of swift creek; near bedrock

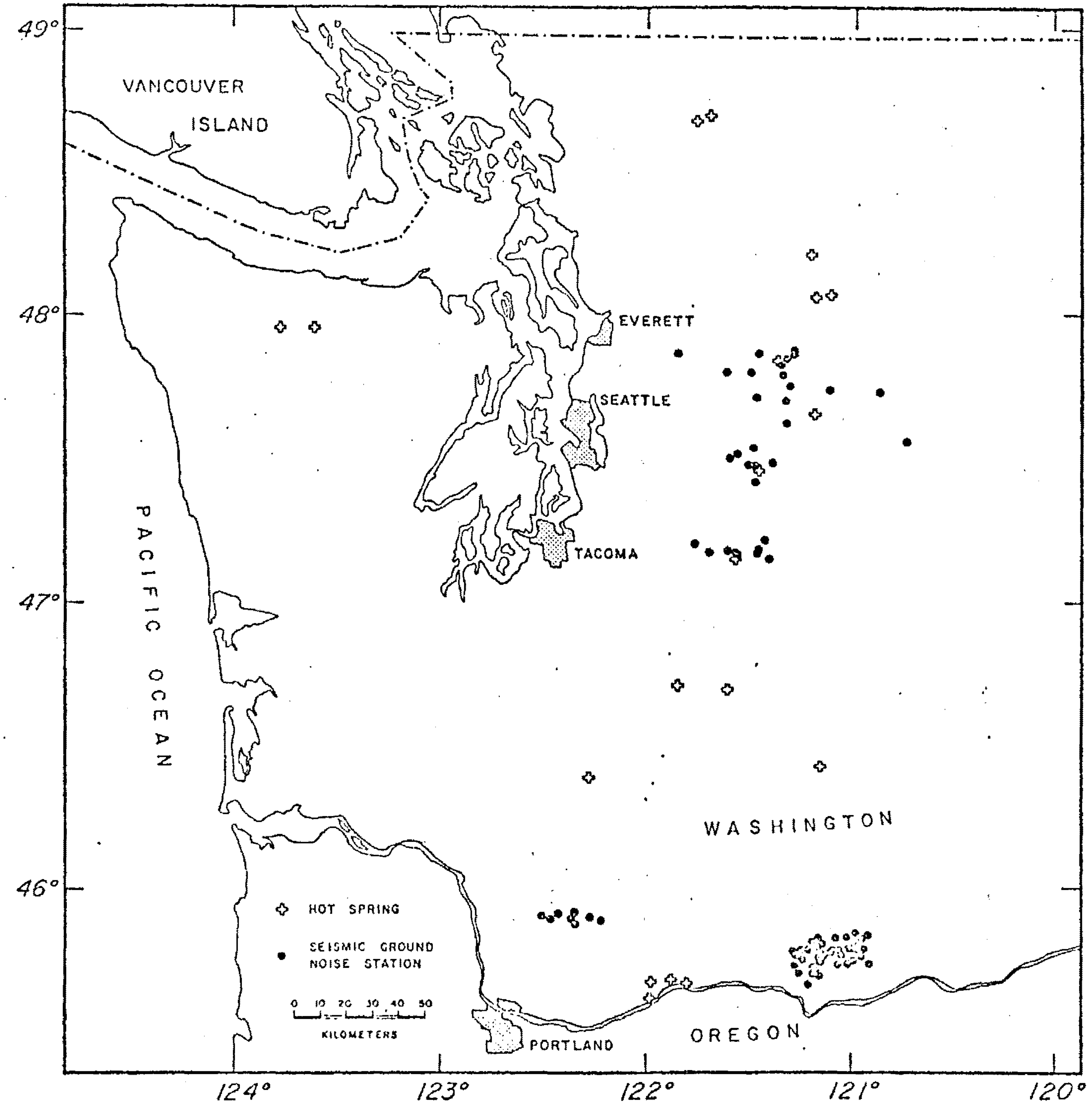
Green River Hot Springs

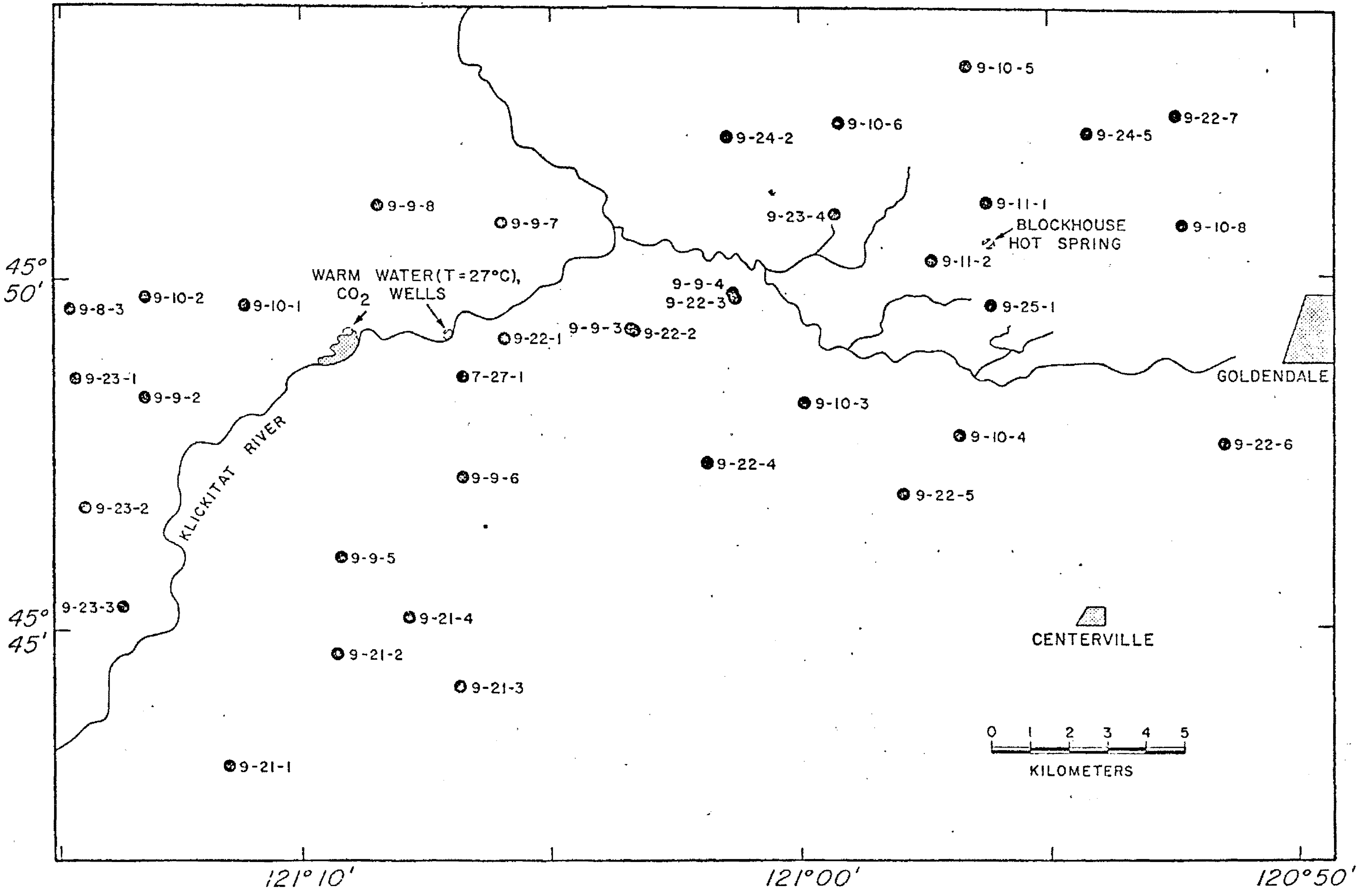
Station	Time	Lat	Lon	Elev (M)	Wind Vel. (M/S)	Regional Rock Type	Seismic Coupling	Site Photo	Comments
8-6-3	1800-1830	47°12.6'	121°31.7'	500	2-4	Andesite	Fair	N	Clearing; small creek 20 m distance
8-6-4	1910-1940	47°13.2'	121°34.9'	435	0-2	Andesite	Fair/Good	N	0.2 km N. of Green River
8-12-1	1145-1215	47°11.5'	121°22.7'	1070	2-6	Andesite	Good	Y	Logged hillside; vegetation in soil
8-12-2	1330-1400	47°16.3'	121°24.1'	830	4-6	Andesite	Fair/Good	Y	Numerous small creeks in area
8-12-3	1530-1600	47°13.0'	121°25.9'	615	2-4	Andesite	Good	N	Heavy woods; 0.4 km to Green River and large creek
8-12-4	1625-1655	47°12.9'	121°28.0'	510	2-6	Andesite	Fair	Y	N.W. end of airstrip; 70 m to Green River
8-12-5	1800-1830	47°13.2'	121°41.1'	635	0-4	Andesite	Very Good	Y	Logged hillside; near bedrock
8-12-6	1900-1930	47°14.9'	121°43.8'	360	0-2	Andesite	Good	Y	Near Green River (0.3 km)

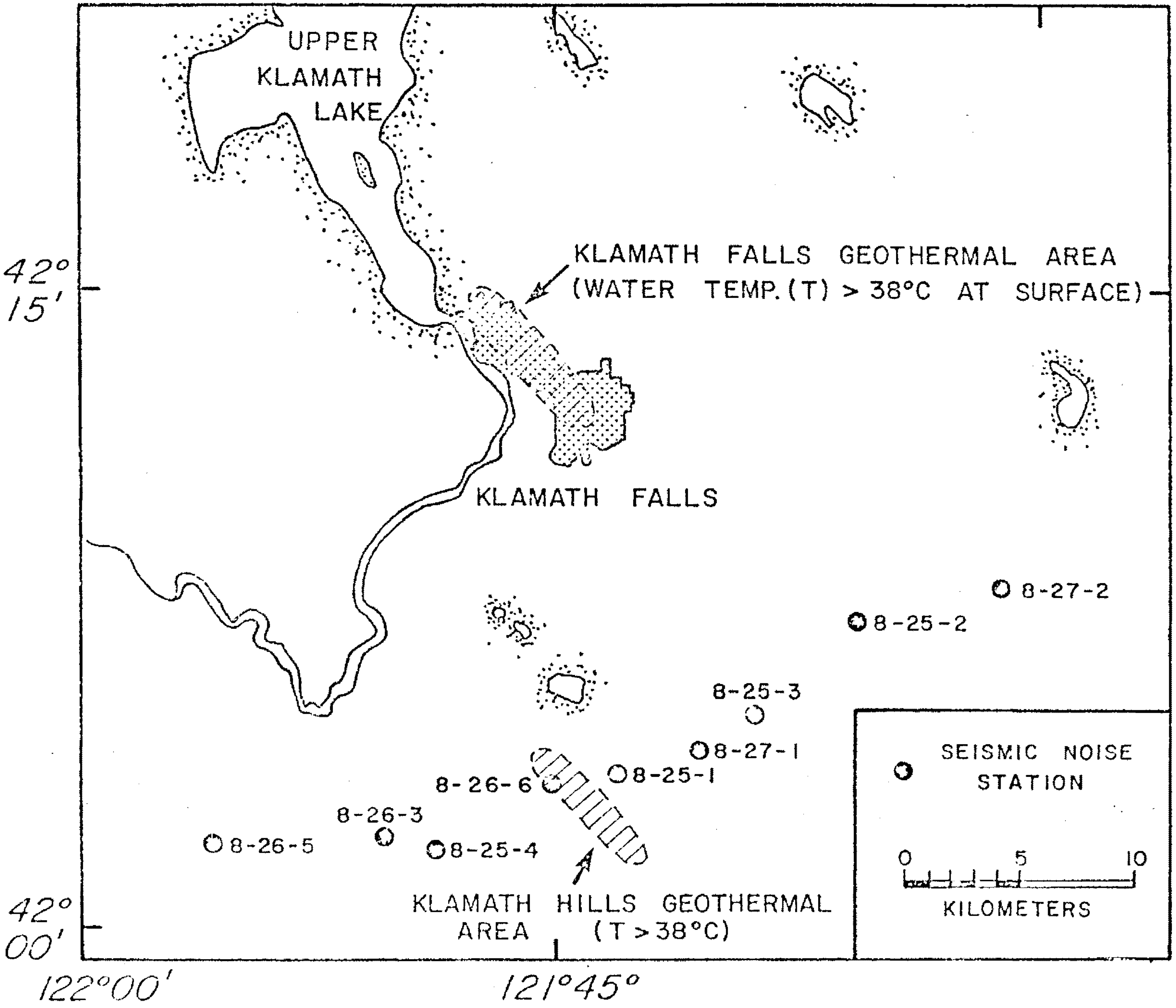
Stevens Pass Profile

Station	Time	Lat	Lon	Elev (M)	Wind Vel. (M/S)	Regional Rock Type	Seismic Coupling	Site Photo	Comments
7-23-1	0940-1010	47°53.6'	121°49.9'	60	2-5		Fair	Y	0.4 km N. of power line; cleared area
7-23-2	1105-1135	47°50.6'	121°36.4'	244	3-6	Granitic	Fair/Good	N	Wooded hillside; swift creek 30 m
7-23-3	1320-1345	47°44.4'	121°20.2'	455	2-5	Andesite/Basalt	Fair	N	Scattered trees; 0.6 km from river
7-23-4	1529-1548	47°46.2'	121°04.8'	1340	5	Granitic	Fair	Y	0.3 km from highway; swift creek 20 m from site
7-23-5	1645-1720	47°46.5'	120°49.8'	670	5	Gneiss	Fair	Y	Open field
7-23-6	1905-1940	47°36.5'	120°41.1'	610	0-2	Conglomerate	Fair	N	Irrigation pump 300 m east of site

Station	Time	Lat	Lon	Elev (M)	Wind Vel. (M/S)	Regional Rock Type	Seismic Coupling	Site Photo	Comments
9-23-4(3)	1740-1810	45°50.9'	120°59.2'	470	2-7	Basalt	Good	N	0.9 km from heavy highway traffic
9-24-2(1)	1204-1234	45°52.0'	121°01.5'	485	2-6	Basalt	Good	Y	Edge of cleared area
9-24-5	1913-1943	45°52.0'	120°54.3'	555	2	Basalt	Good	N	Open fields; power pylons 0.8 km north
9-25-1	0806-0836	45°49.6'	120°56.1'	490	0-2	Basalt	Good	N	Irrigation system 0.6 km S.E.
						Klamath Falls Area			
8-25-1	1052-1122	42°03.8'	121°43.4'	1385	0-2	Basalt	Fair	Y	In Klamath Hills; dry silt topsoil; sagebrush; ∿1 km from geothermal area
8-25-2	1450-1520	42°07.3'	121°35.7'	1445	0-5	Volcanic Breccia	Fair	N	Sagebrush; few pine trees; silty loam topsoil; near bedrock
8-25-3	1736-1806	42°05.0'	121°38.9'	1291	2	Sandstone	Fair/Good	Y	Grassland, near bedrock
8-25-4	2017-2045	42°01.9'	121°43.9'	1245	0-3	Alluvium	Poor	Y	Grassland
8-26-3	1200-1230	42°02.2'	121°50.5'	1245	0-5	Alluvium	Good	Y	Shallow water table; highway 2.3 km west
8-26-5	1835-1905	42°02.2'	121°55.8'	1430	0	Basalt/Breccia	Fair	N	Ponderosa Pine vegetation; bedrock near surface
8-26-6	2000-2030	42°03.3'	121°44.8'	1250	2-5	Alluvium	Fair	N	Open field near Klamath Hills geothermal area
8-27-1	0815-0845	42°04.0'	121°40.6'	1250	0	Alluvium	Good	N	Field, east edge of Klamath Hills, near bedrock
8-27-2	1030-1100	42°08.0'	121°31.2'	1253	0-3	Alluvium	Fair	N	Probably shallow water table; cultural activity
						Tum Tum Mt. Area			
8-17-1	1600-1630	45°57.2'	122°18.4'	220	0-4	Basalt/Andesite	Very Good	N	Wooded area; 0.6 km from active logging road
8-17-2	1750-1820	45°55.8'	122°11.2'	610	0-4	Basalt/Andesite	Fair/Good	N	Bottom of small steep valley; 2 m conifer growth
8-17-3	1920-1950	45°56.0'	122°14.7'	390	0-2	Basalt/Andesite	Fair	N	Hillside; 0.3 km north of swift creek
8-17-4	2040-2110	45°55.9'	122°20.0'	336	0	Diabase/Andesite	Poor/Fair	N	South slope of Tum Tum Mt.; wooded
8-18-1	0825-0855	45°56.3'	122°20.7'	220	0	Diabase/Andesite	Good	N	N.W. slope of Tum Tum Mt.; very near active logging road
8-18-2	0945-1015	45°56.8'	122°23.8'	214	0	Basalt/Andesite	Good	N	Small wooded hill; logging road with traffic 2.4 km south
8-18-3	1120-1150	45°56.4'	122°25.8'	342	0-2	Basalt/Andesite	Fair	N	Logged area; secondary growth of timber
8-18-4	1300-1330	45°56.5'	122°29.7'	320	0-2	Basalt/Andesite	Fair	N	Hilltop; grassland and scattered trees
						Goldmeyer Hot Springs			
8-3-1	1225-1255	47°29.3'	121°24.7'	490	0-2	Granitic	Poor/Fair	Y	Dense woods; 0.3 km N. Snoqualmie River; poor soil
8-3-2	1350-1420	47°31.2'	121°27.4'	420	2-4	Granitic	Fair	N	Dense wooded hillside; small waterfall 0.4 km to east
8-3-3	1500-1530	47°33.2'	121°31.5'	415	0-6	Basalt/Andesite	Good	N	Dense woods; 0.6 km from Taylor/Snoqualmie River junction
8-3-5	1800-1830	47°34.7'	121°26.6'	600	0-3	Granitic	Good	N	Steep, sparsely wooded hillside; 0.3 km to Taylor River
8-3-6	1945-2020	47°30.6'	121°21.3'	820	0-2	Granitic	Fair	Y	Logged hillside; 0.3 km to Snoqualmie River

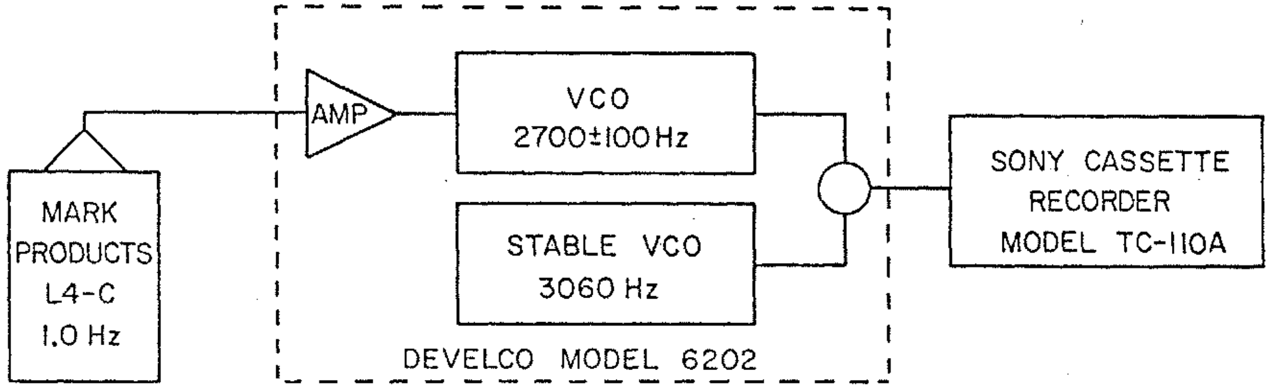

49°
48°
47°
46°
124°
123°
122°
121°
120°
VANCOUVER ISLAND
PACIFIC OCEAN
EVERETT
SEATTLE
TACOMA
PORTLAND
WASHINGTON
OREGON
HOT SPRING
SEISMIC GROUND NOISE STATION
0 10 20 30 40 50
KILOMETERS


9-10-5
9-24-2
9-10-6
9-24-5
9-22-7
9-9-8
9-9-7
9-23-4
9-11-1
BLOCKHOUSE HOT SPRING
9-10-8
9-11-2
WARM WATER (T=27°C), CO2 WELLS
9-9-4
9-22-3
9-25-1
9-8-3
9-10-2
9-10-1
9-22-1
9-9-3
9-22-2
GOLDENDALE
9-23-1
7-27-1
9-9-2
9-10-3
9-10-4
9-22-6
KLICKITAT RIVER
9-22-4
9-9-6
9-22-5
9-23-2
9-9-5
9-23-3
9-21-4
CENTERVILLE
9-21-2
9-21-3
0 1 2 3 4 5
KILOMETERS
9-21-1
45° 50'
45° 45'
121°10'
121°00'
120°50'

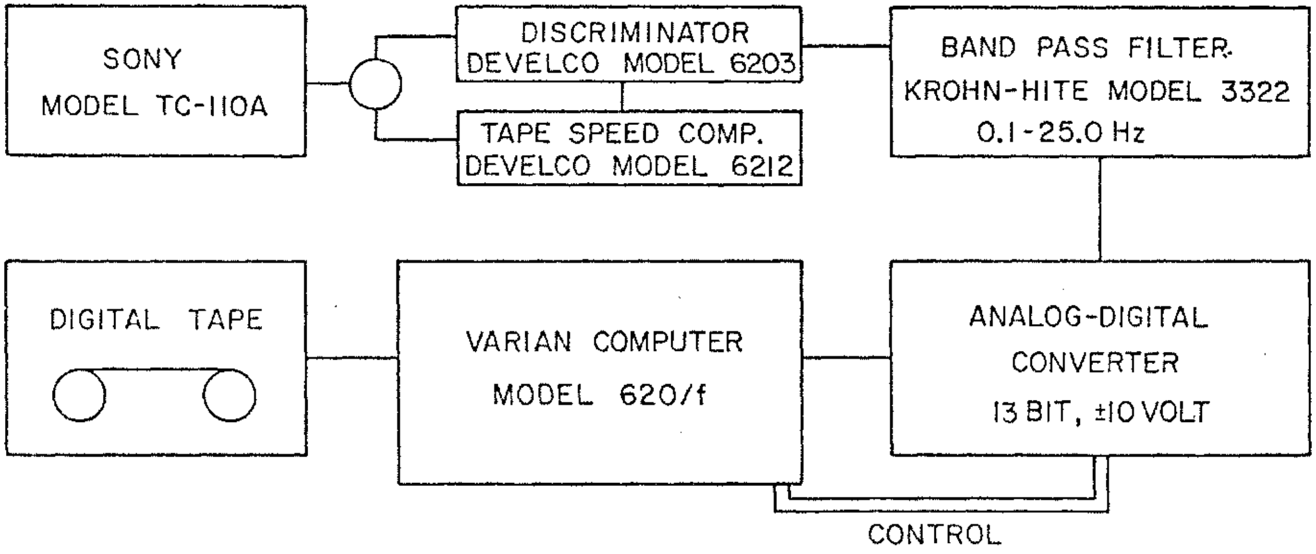

UPPER KLAMATH LAKE
KLAMATH FALLS GEOTHERMAL AREA (WATER TEMP. (T) > 38°C AT SURFACE)
KLAMATH FALLS
8-27-2
8-25-2
8-25-3
8-27-1
8-25-1
8-26-6
8-26-3
8-26-5
8-25-4
KLAMATH HILLS GEOTHERMAL AREA (T > 38°C)
SEISMIC NOISE STATION
0
5
10
KILOMETERS
42° 15'
42° 00'
122°00'
121°45°

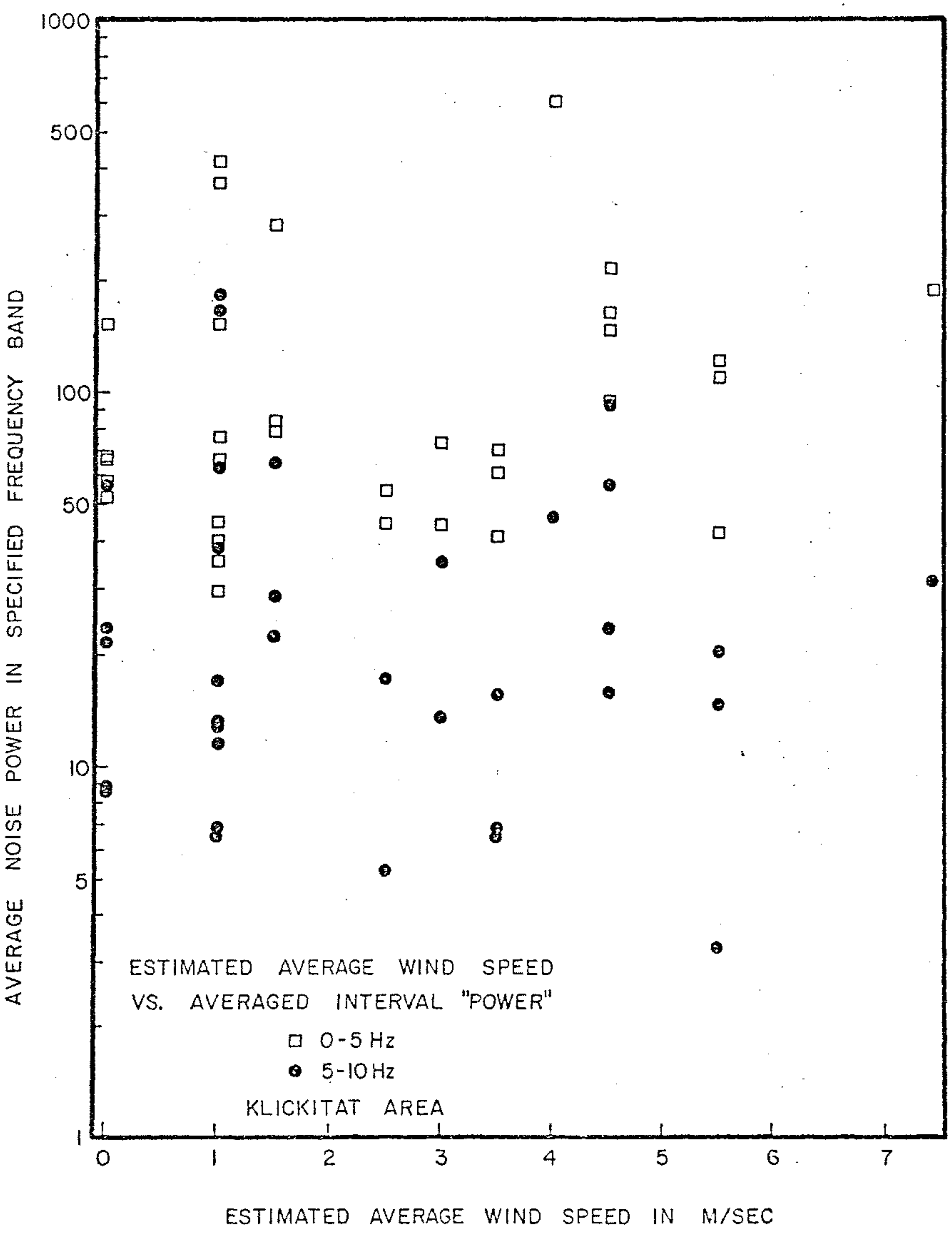
SEISMIC GROUND NOISE DATA ACQUISITION

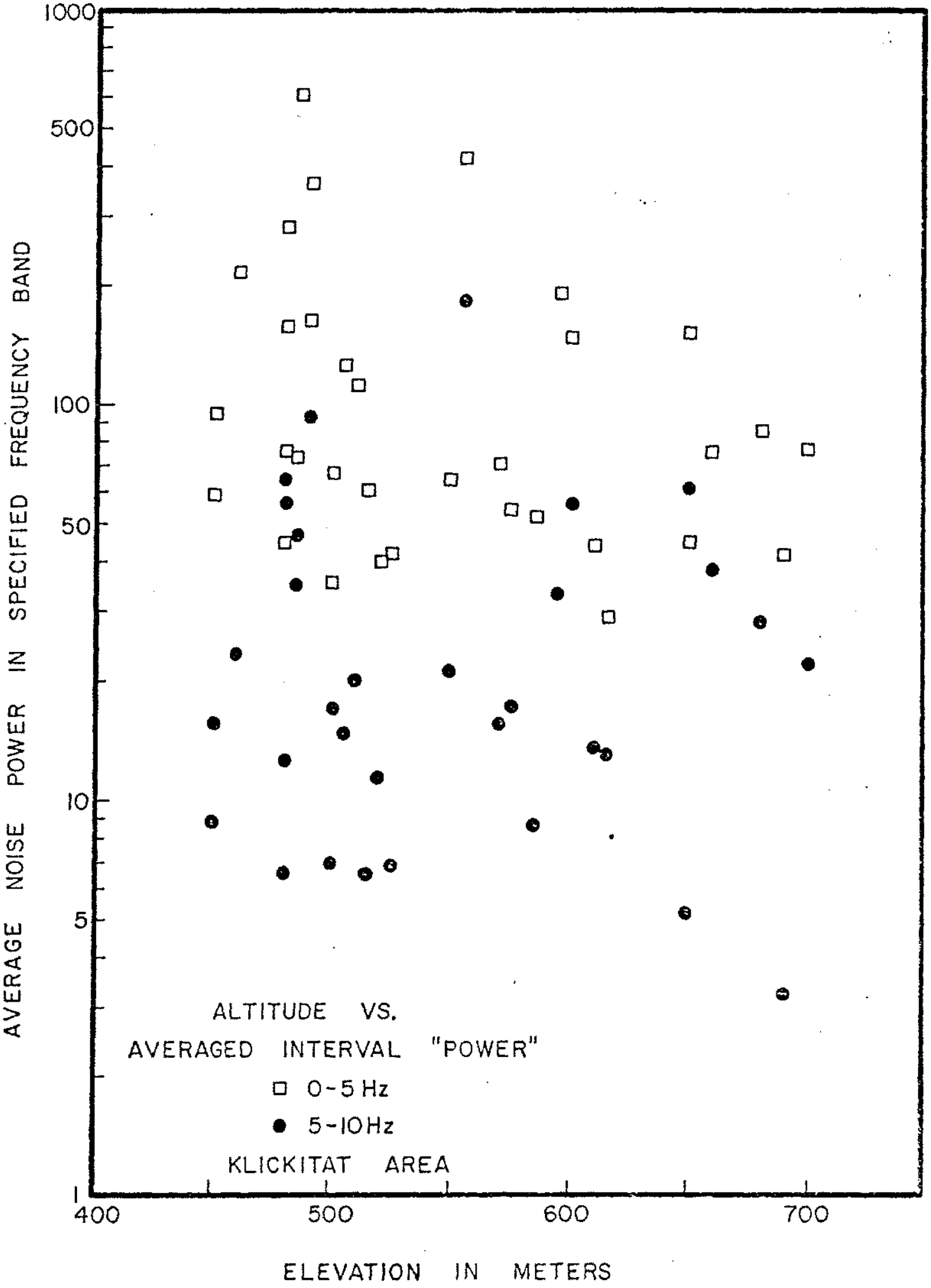
FIELD RECORDING

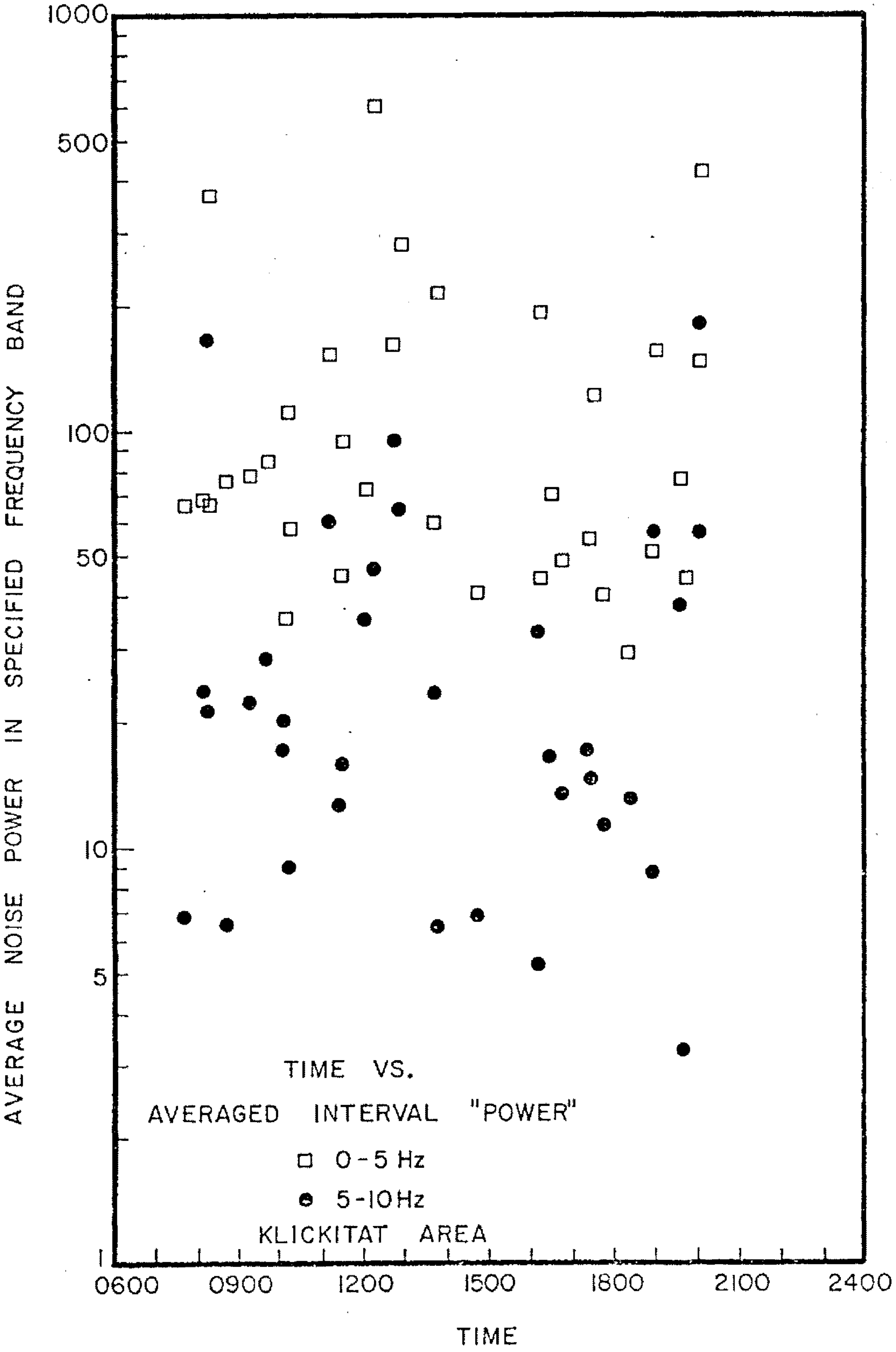


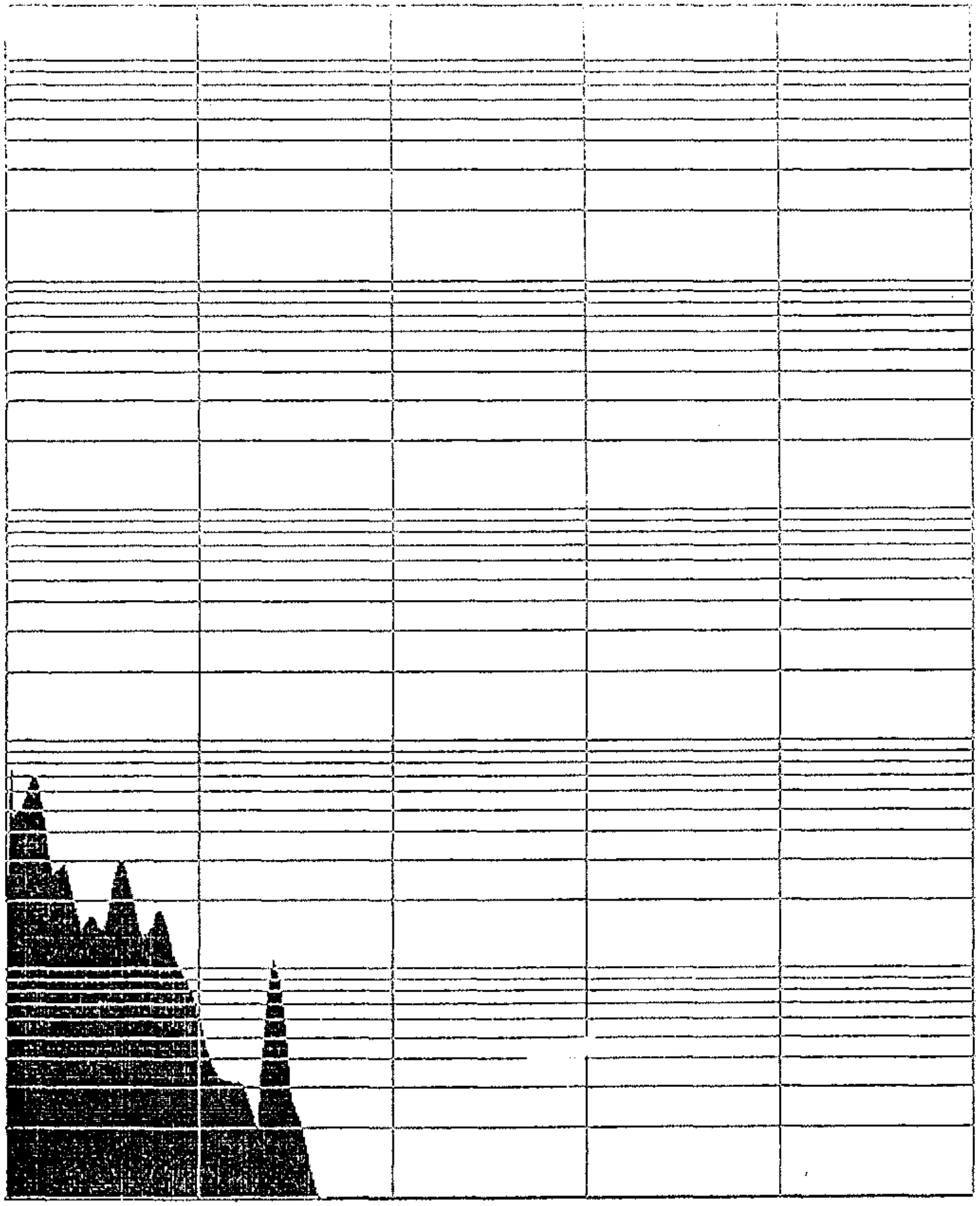
LABORATORY PLAYBACK



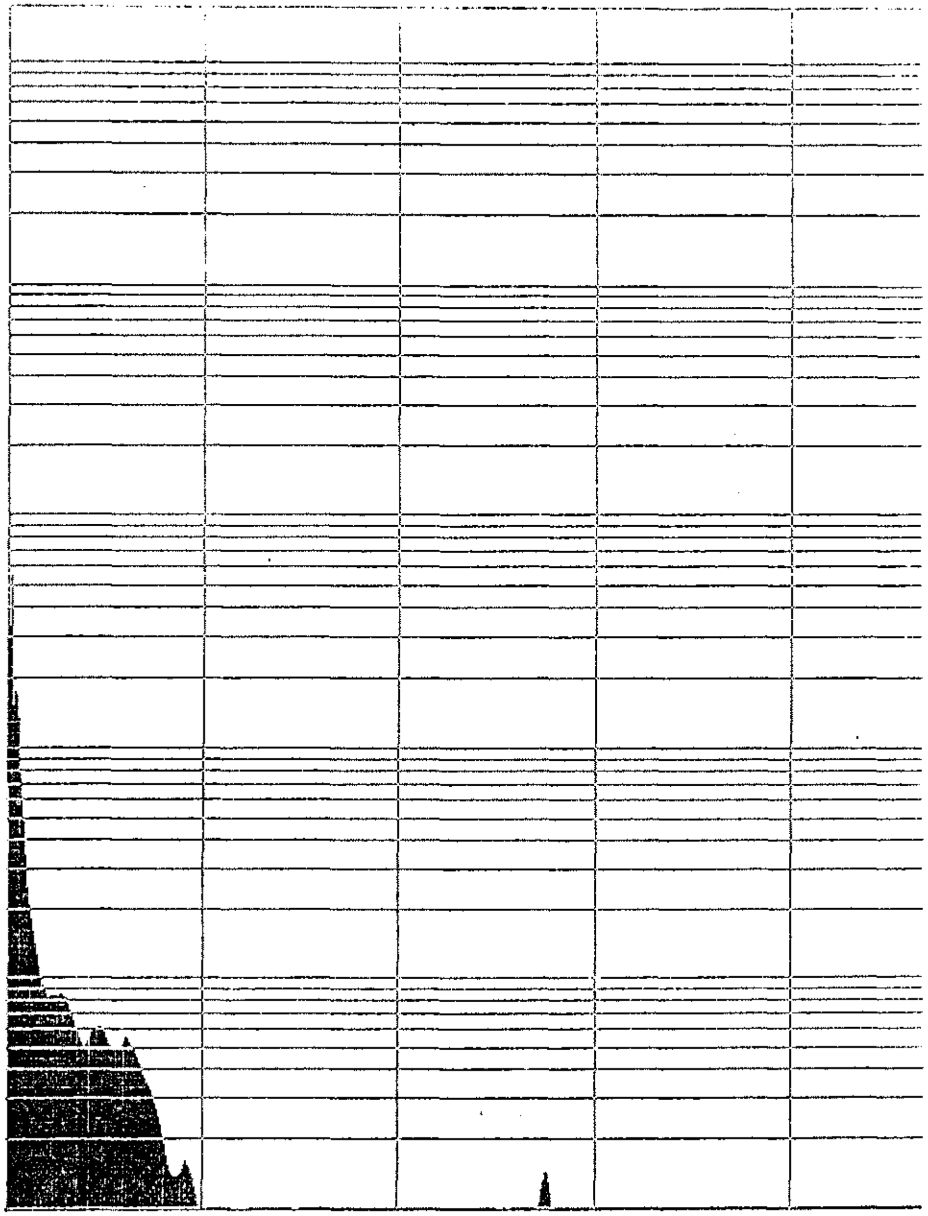

ESTIMATED AVERAGE WIND SPEED
VS. AVERAGED INTERVAL "POWER"
□ 0-5 Hz
● 5-10 Hz
KLICKITAT AREA
AVERAGE NOISE POWER IN SPECIFIED FREQUENCY BAND
1000
500
100
50
10
5
1
0
1
2
3
4
5
6
7
ESTIMATED AVERAGE WIND SPEED IN M/SEC


1000
500
100
50
10
5
1
400
500
600
700
ELEVATION IN METERS
AVERAGE NOISE POWER IN SPECIFIED FREQUENCY BAND
ALTITUDE VS.
AVERAGED INTERVAL "POWER"
□ 0-5 Hz
● 5-10 Hz
KLICKITAT AREA

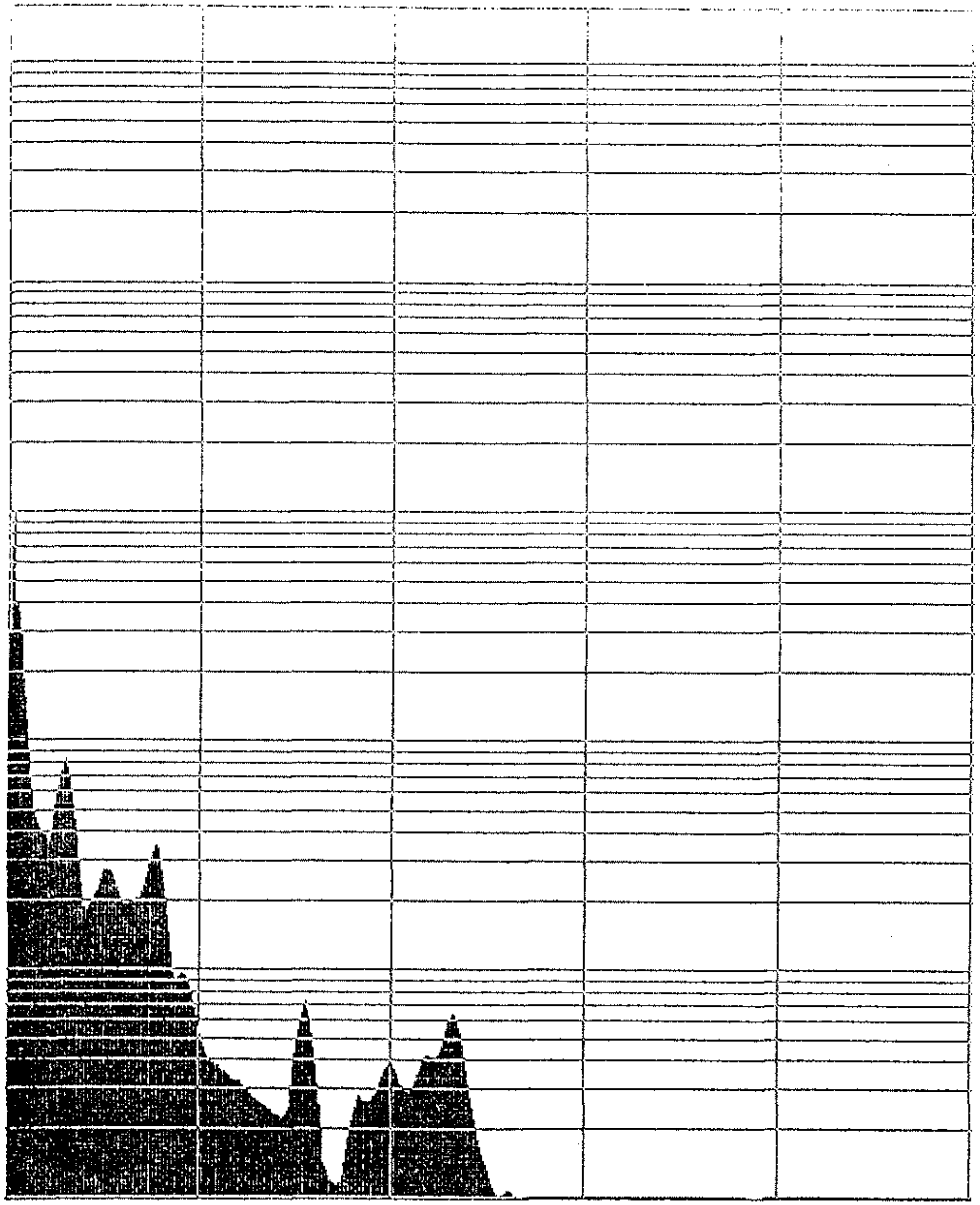

1000
500
100
50
10
5
1
0600
0900
1200
1500
1800
2100
2400
TIME
AVERAGE NOISE POWER IN SPECIFIED FREQUENCY BAND
TIME VS.
AVERAGED INTERVAL "POWER"
□ 0-5 Hz
● 5-10Hz
KLICKITAT AREA



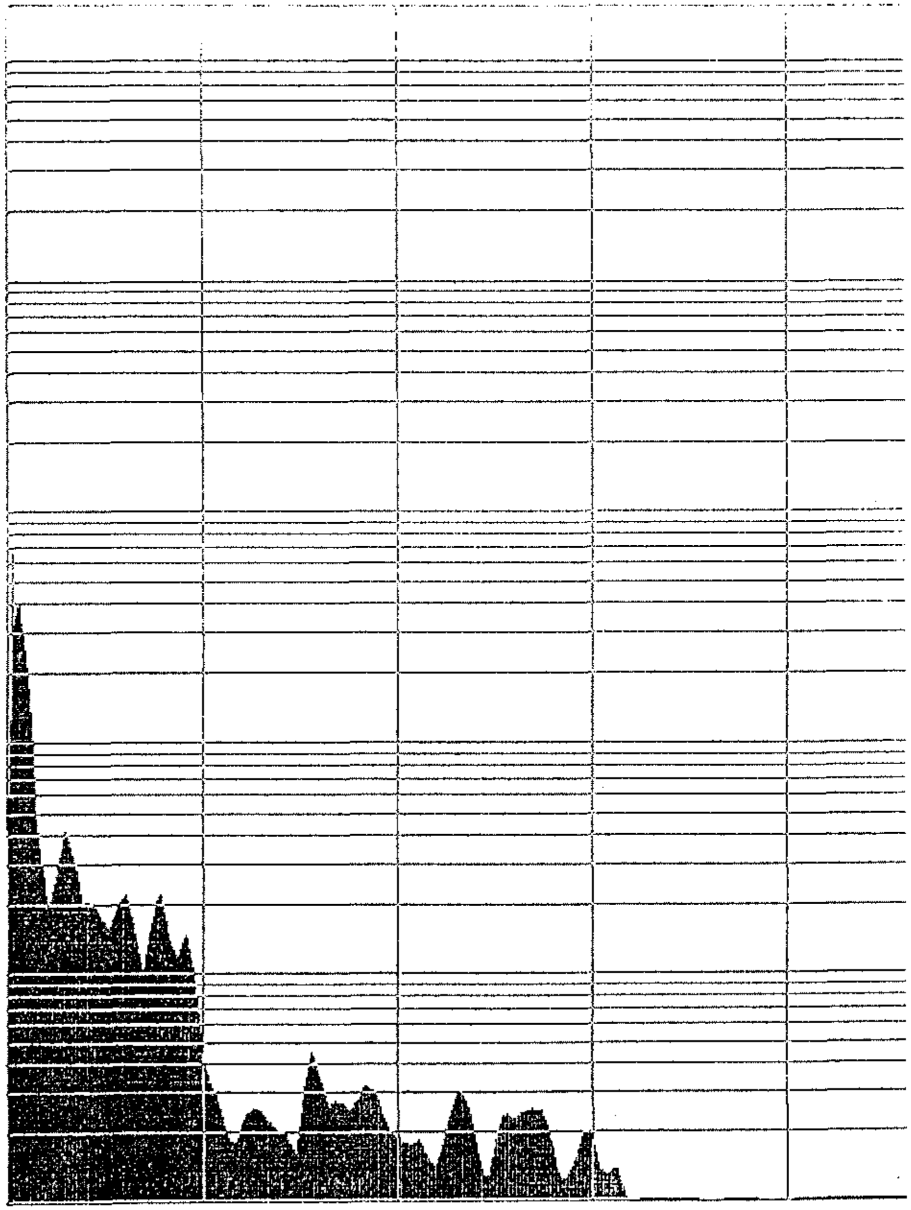
KLICKITAT 7-27-1



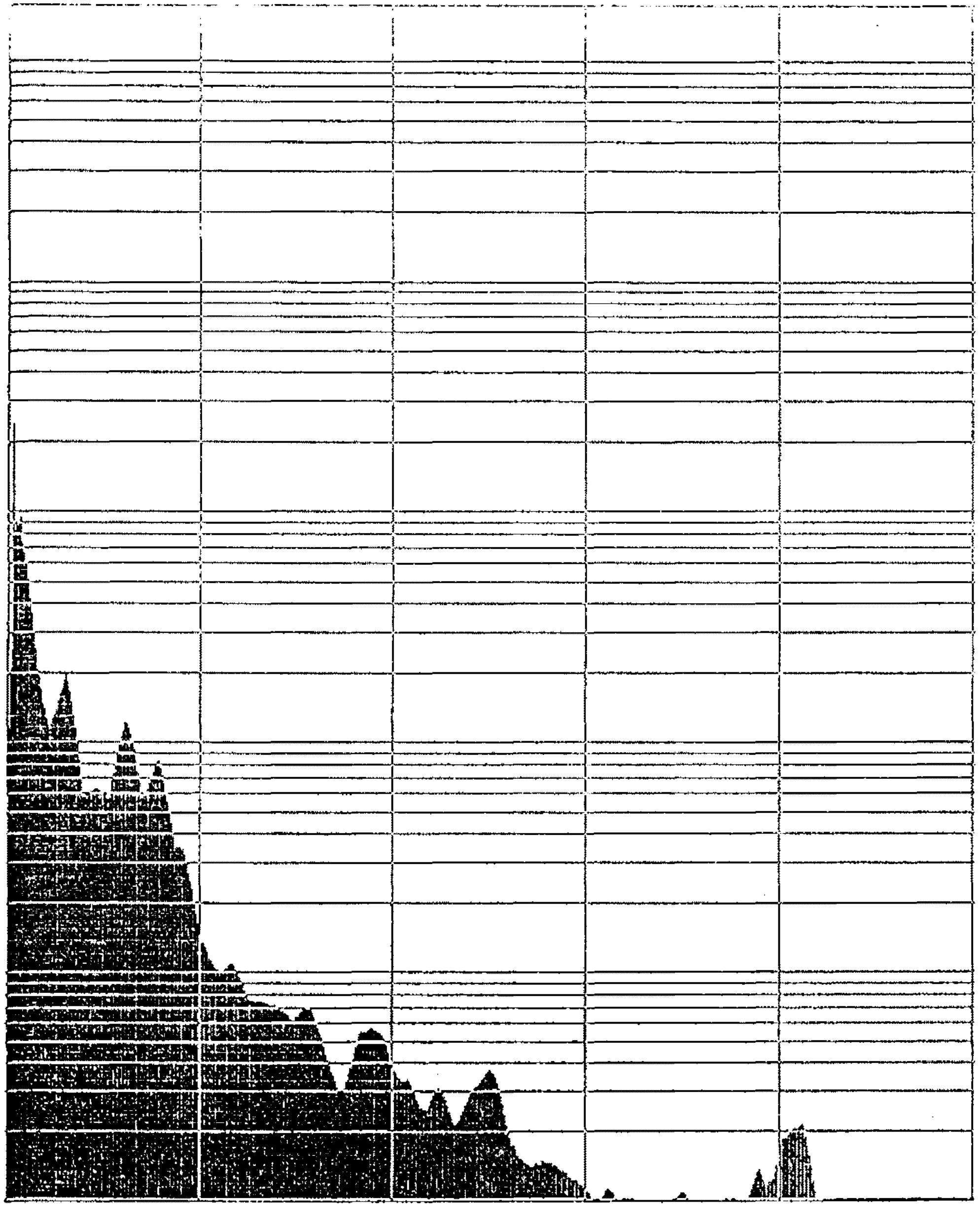
KLICKITAT 9-8-3



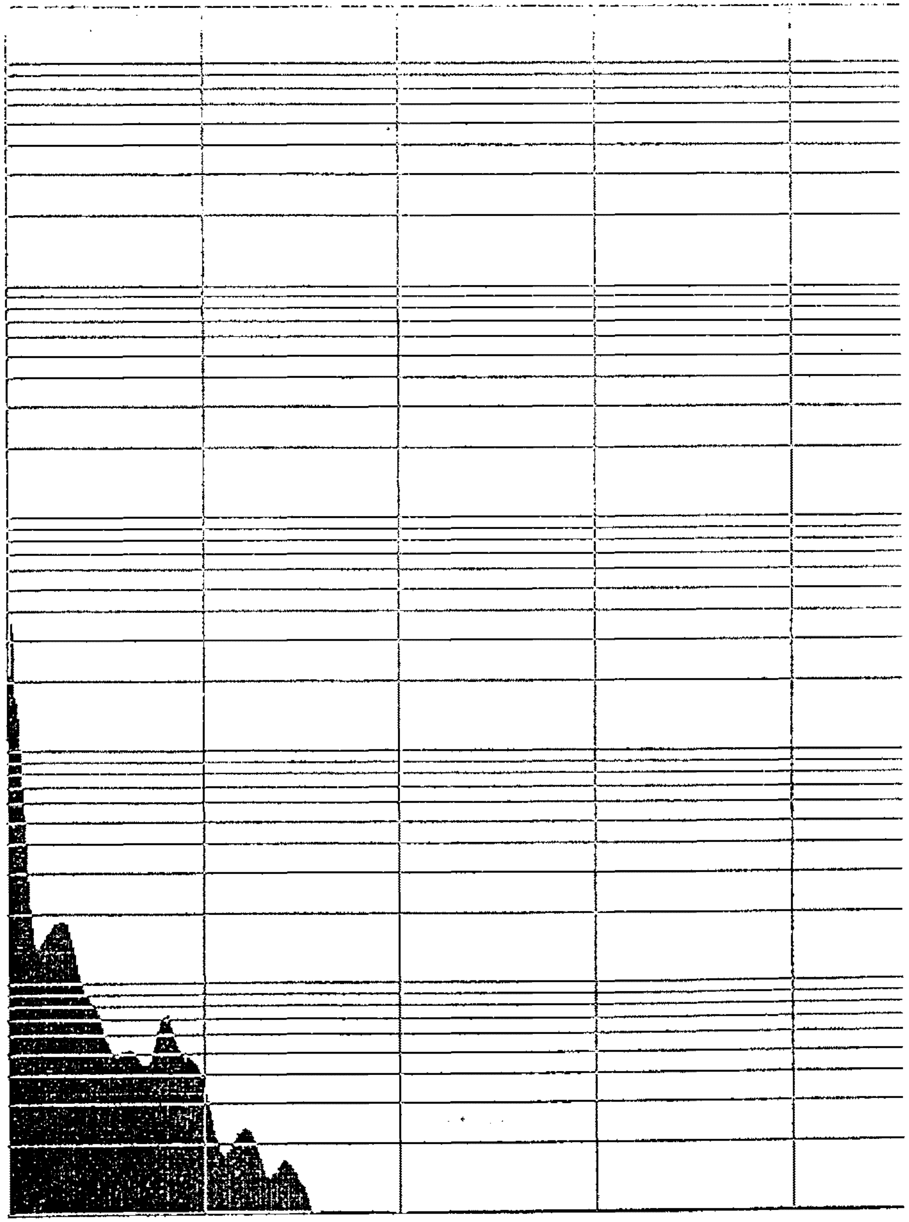
KLICKITAT 9-9-2



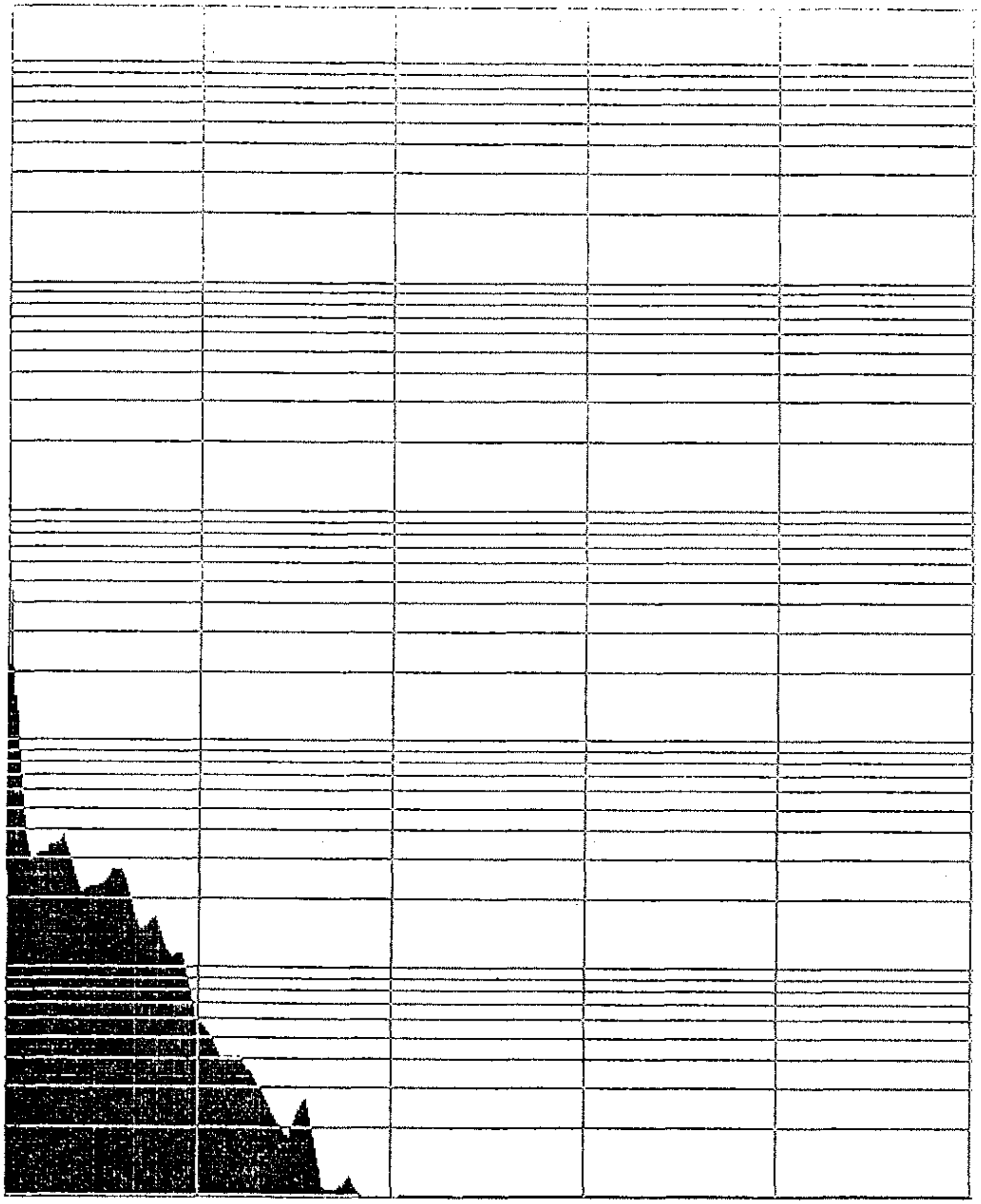
KLICKITAT 9-9-3



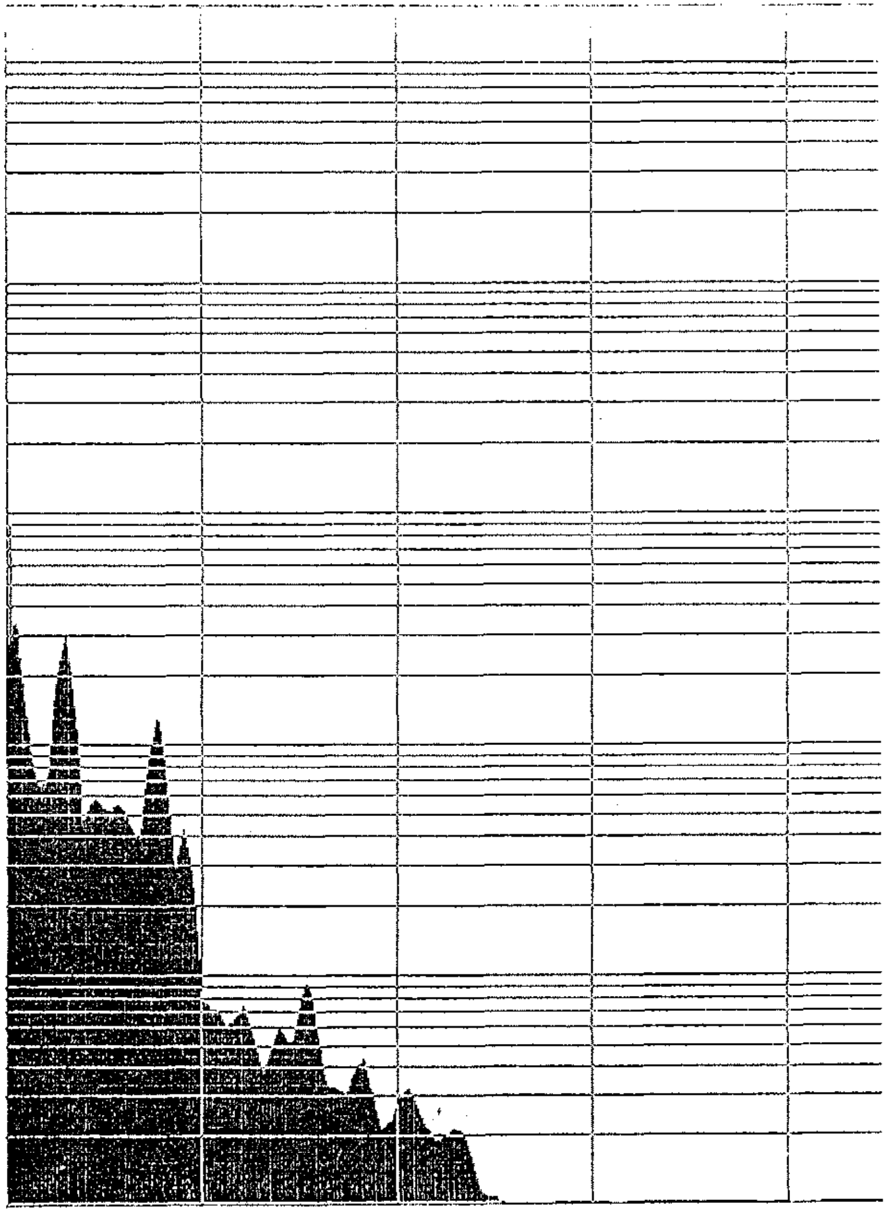
KLICKITAT 9-9-4



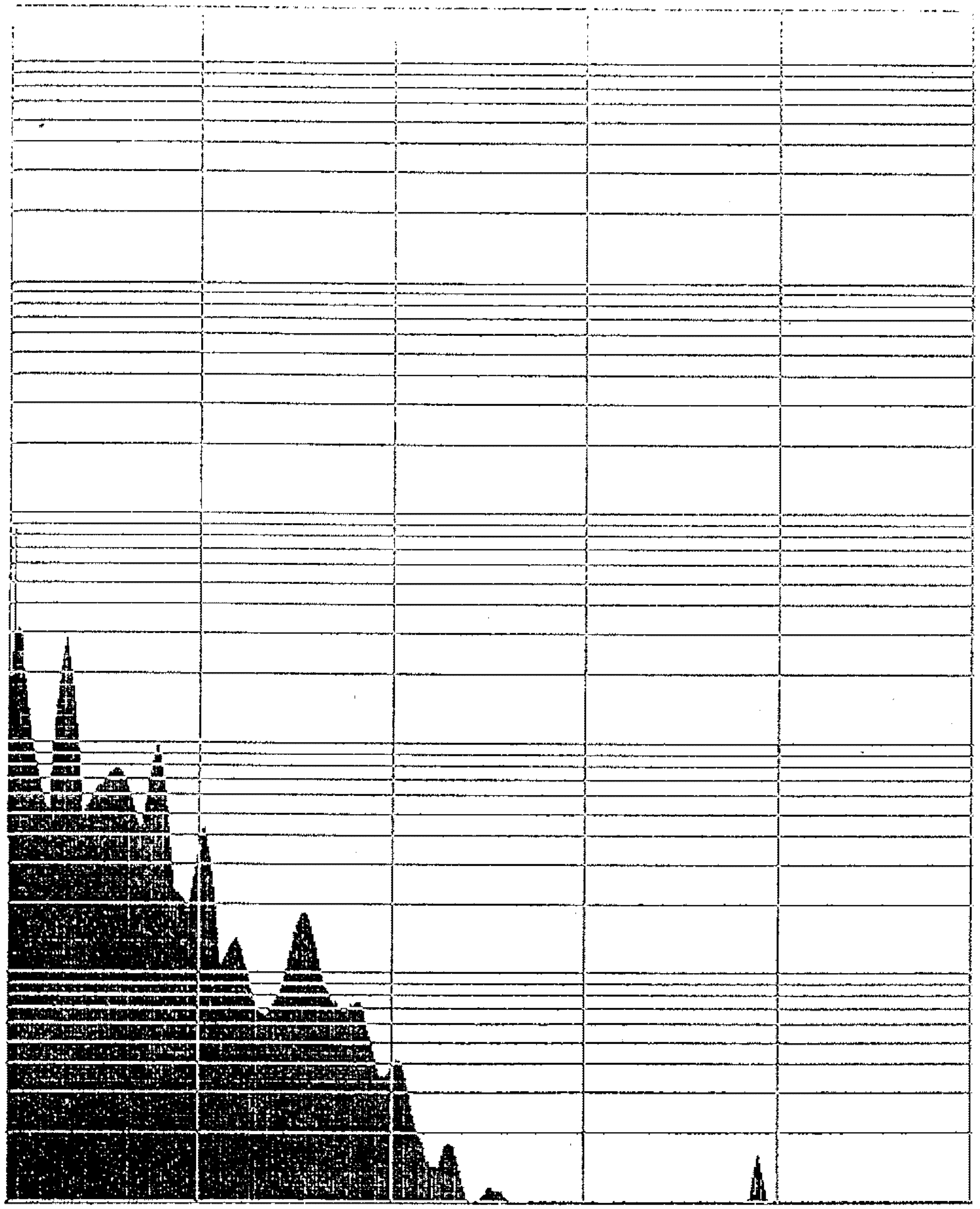
KLICKITAT 9-9-5



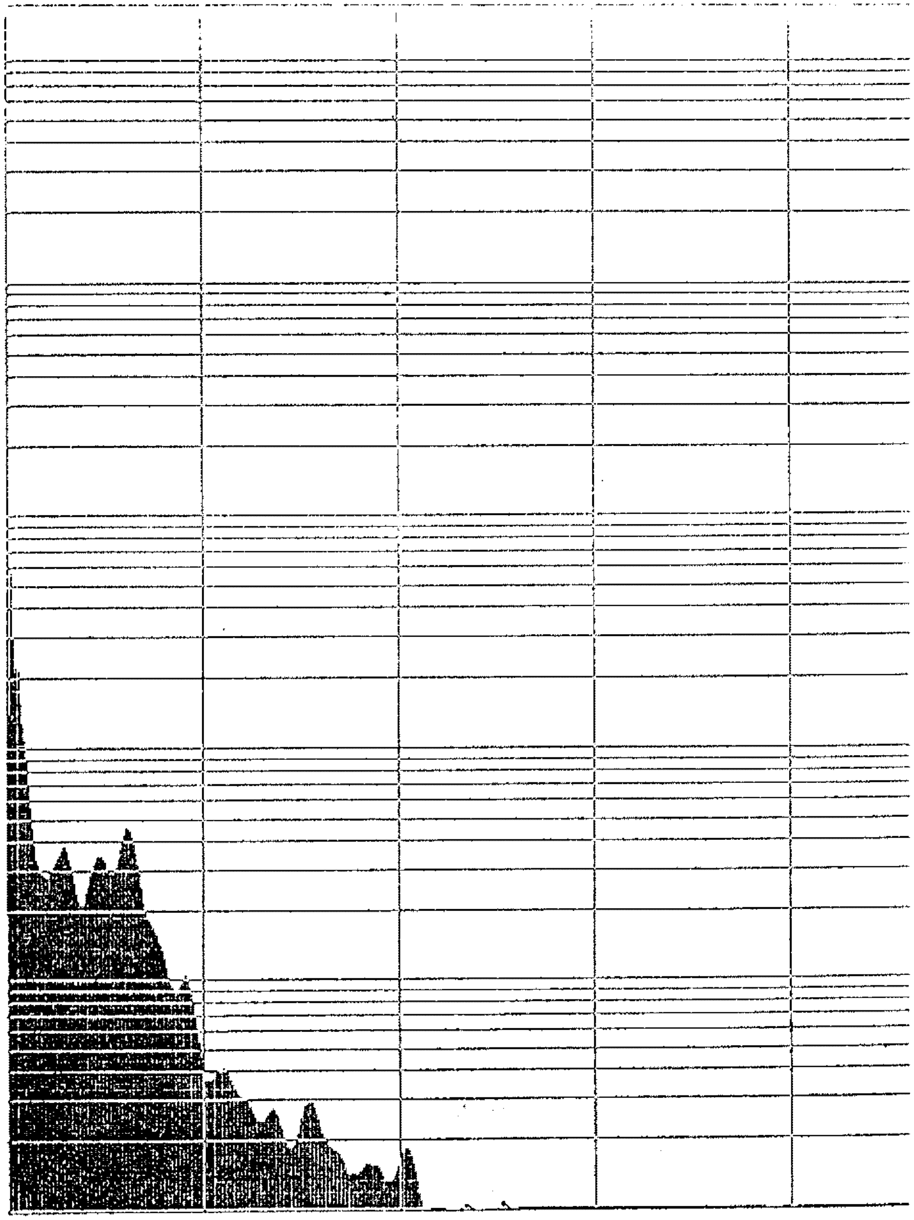
KLICKITAT 9-9-6



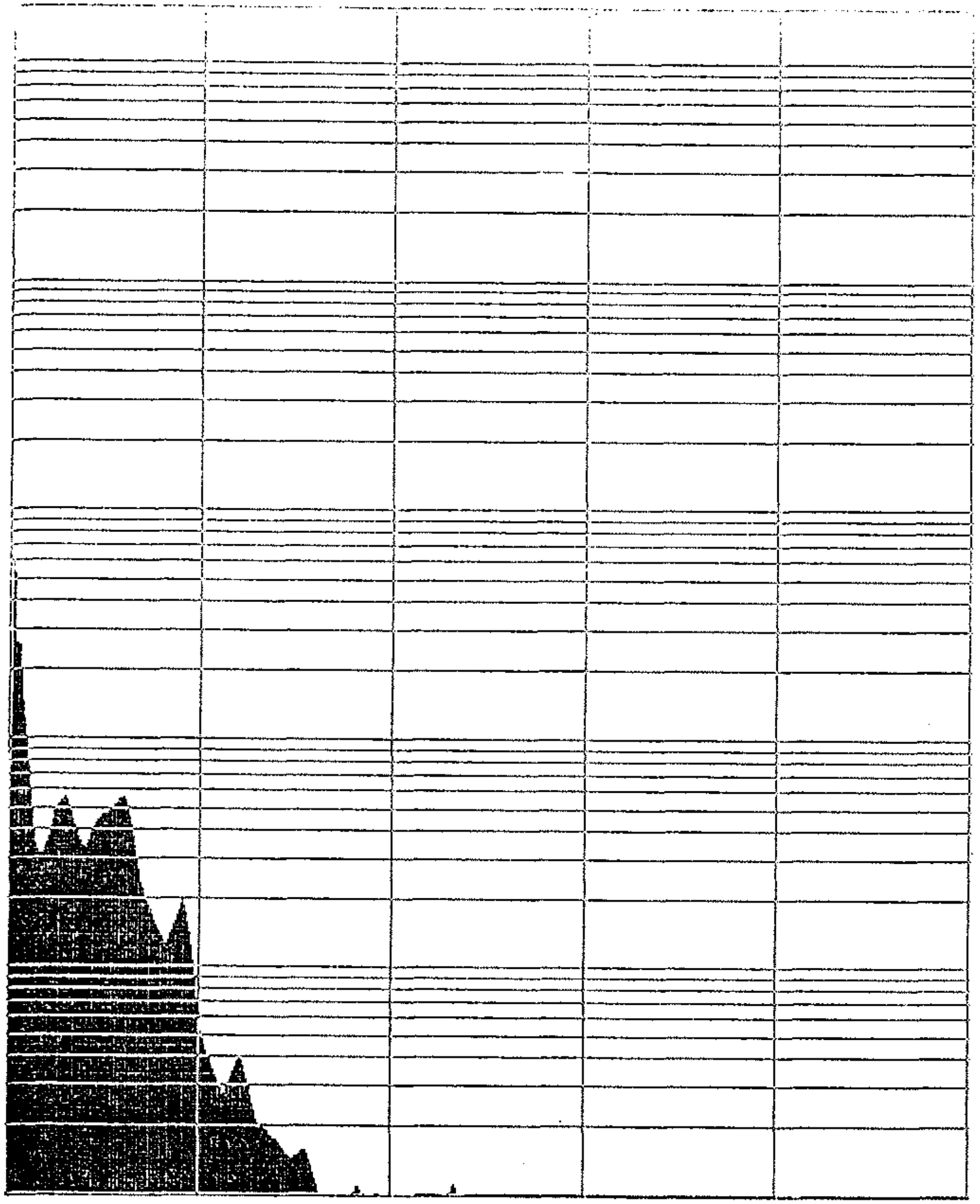
KLICKITAT 9-9-7



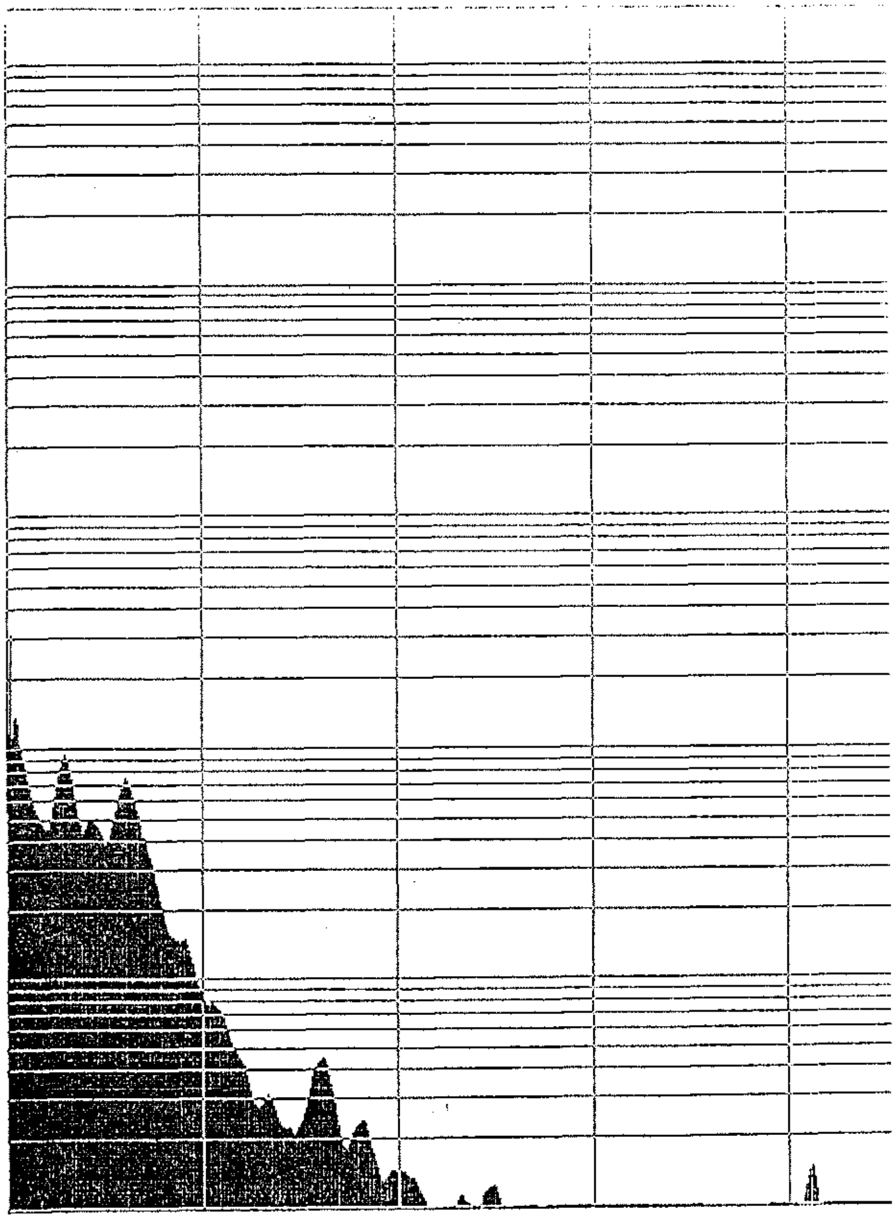
KLICKITAT 9-9-8



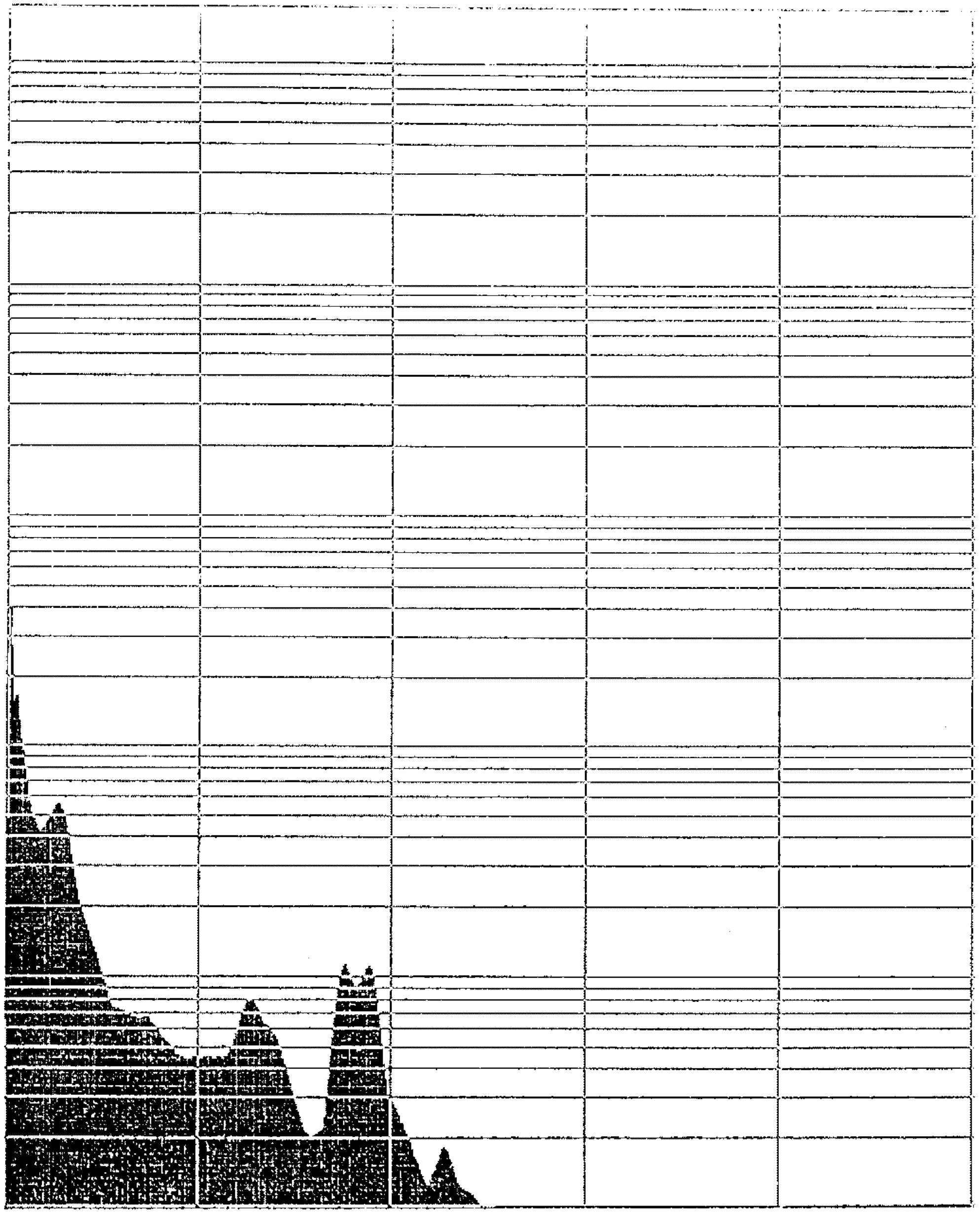
KLICKITAT 9-10-1



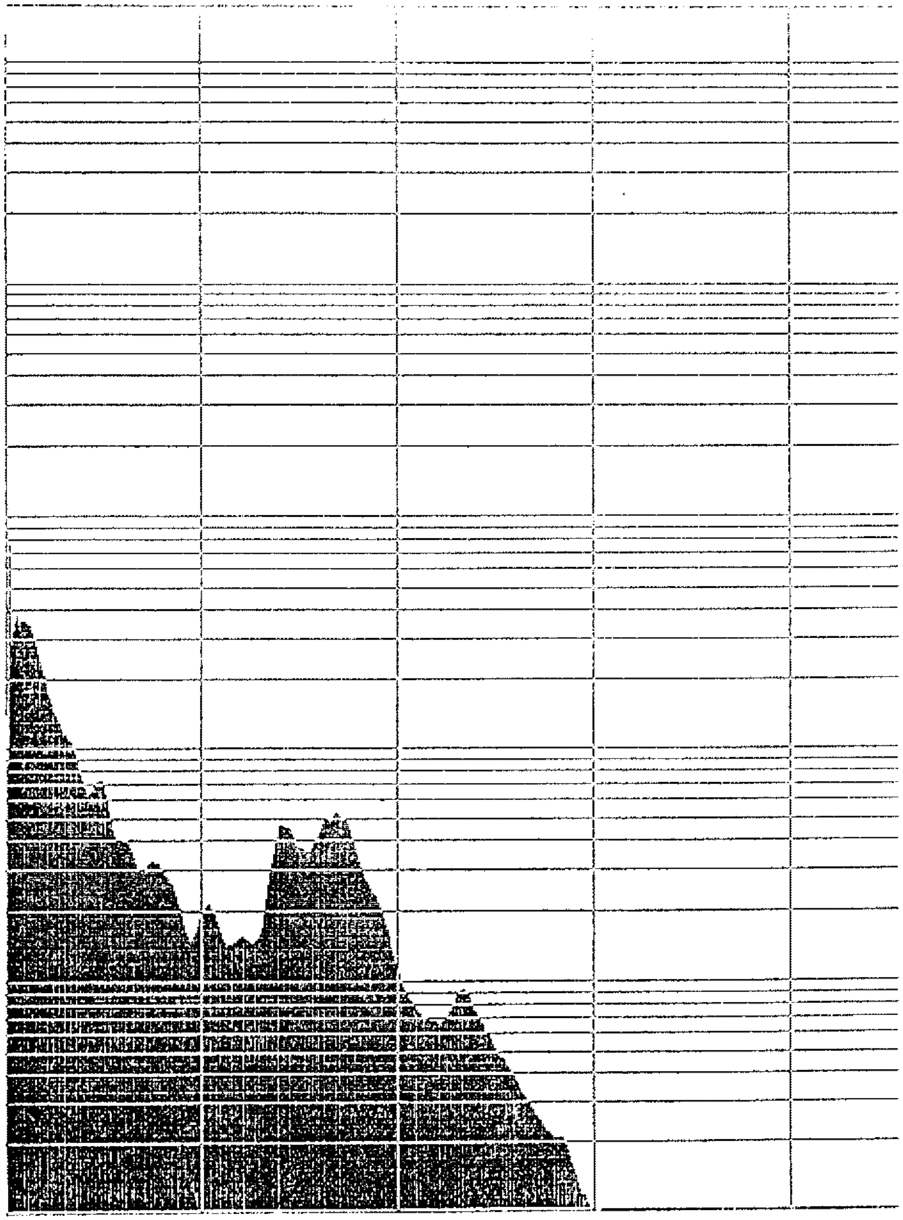
KLICKITAT 9-10-2



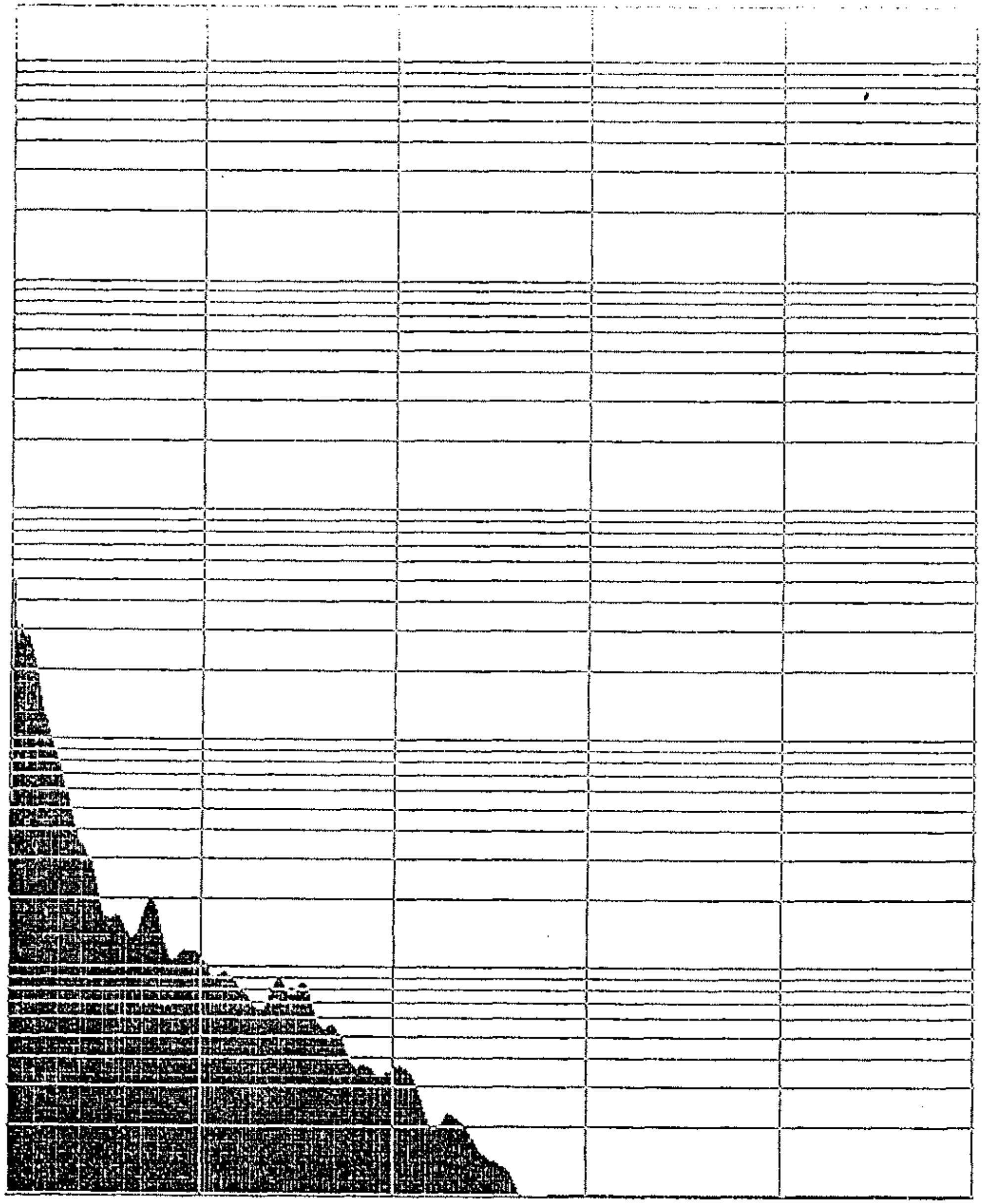
KLICKITAT 9-10-3



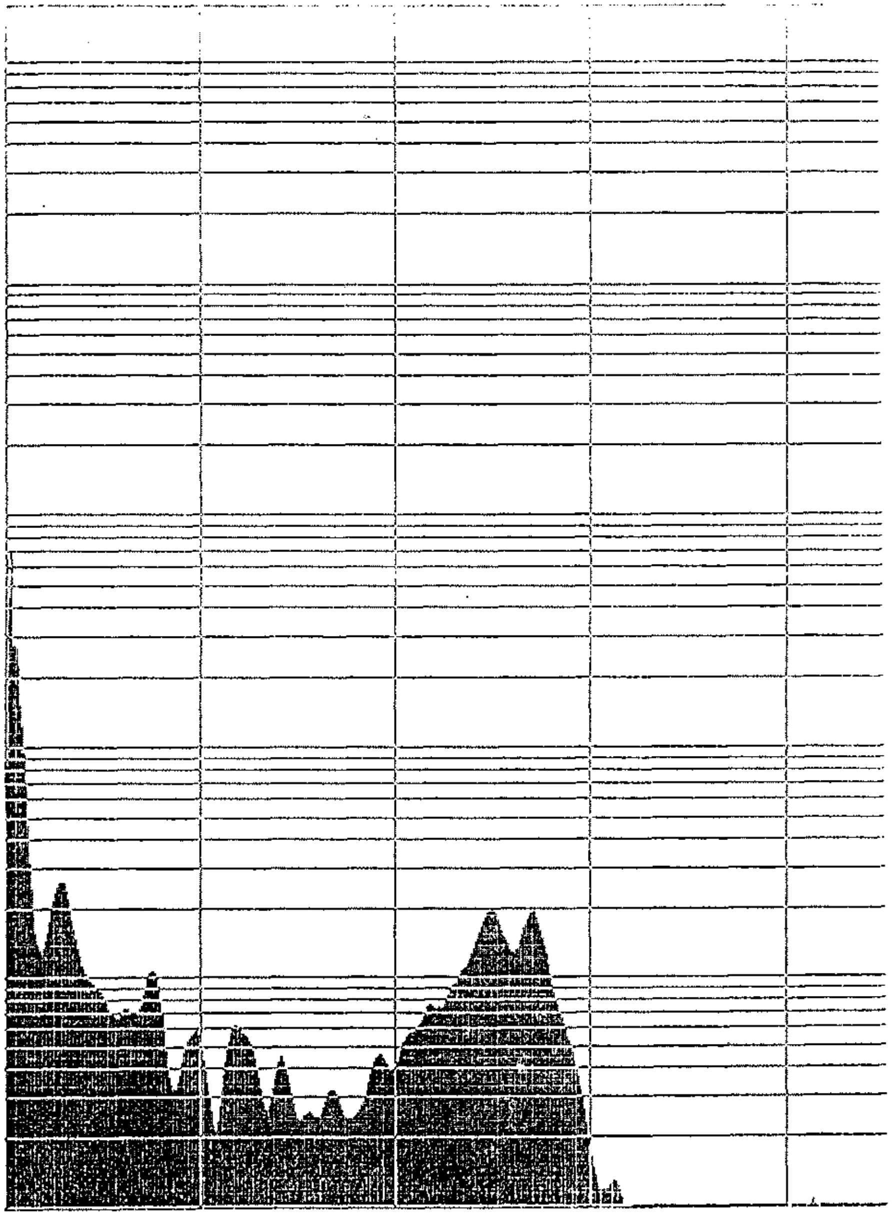
KLICKITAT 9-10-4



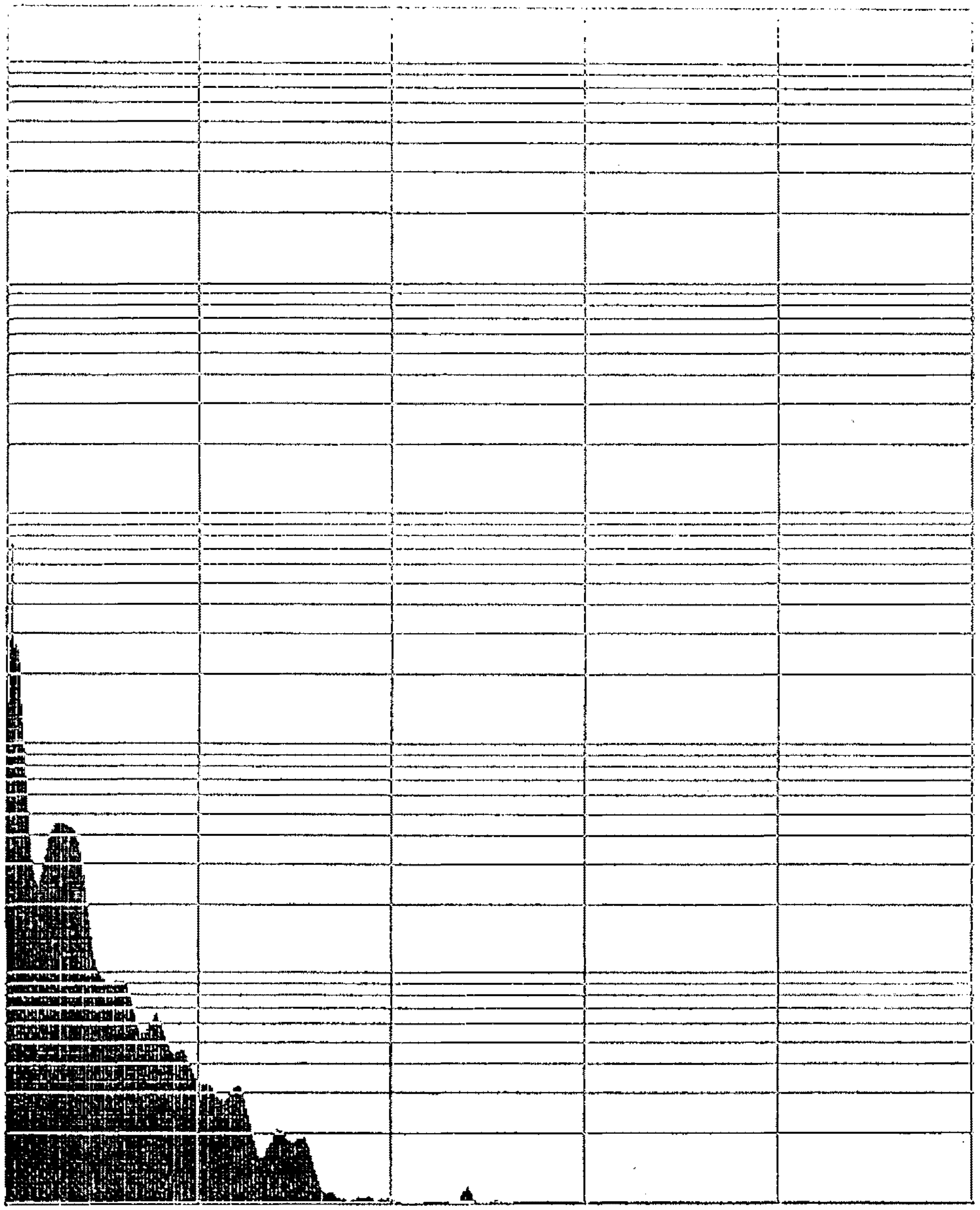
KLICKITAT 9-10-5



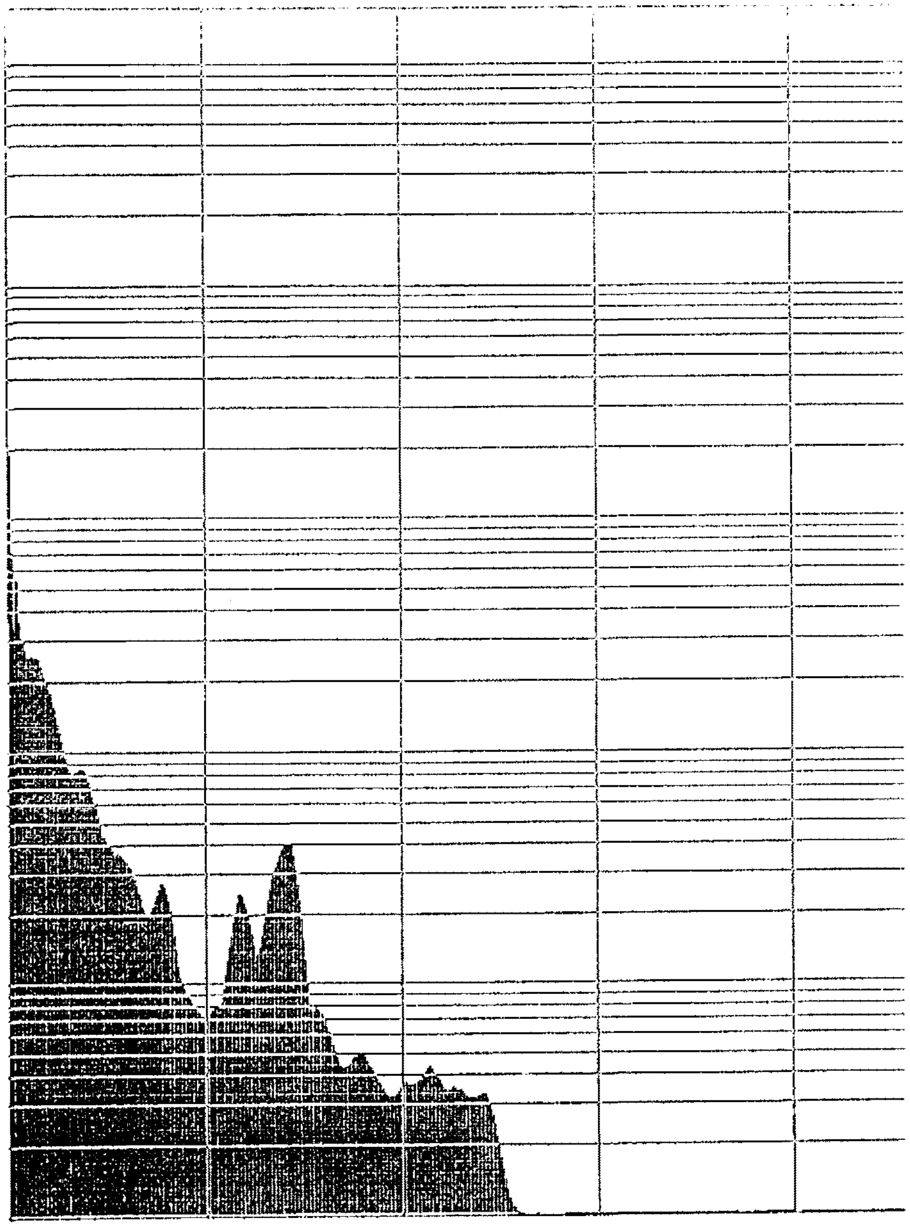
KLICKITAT 9-10-6



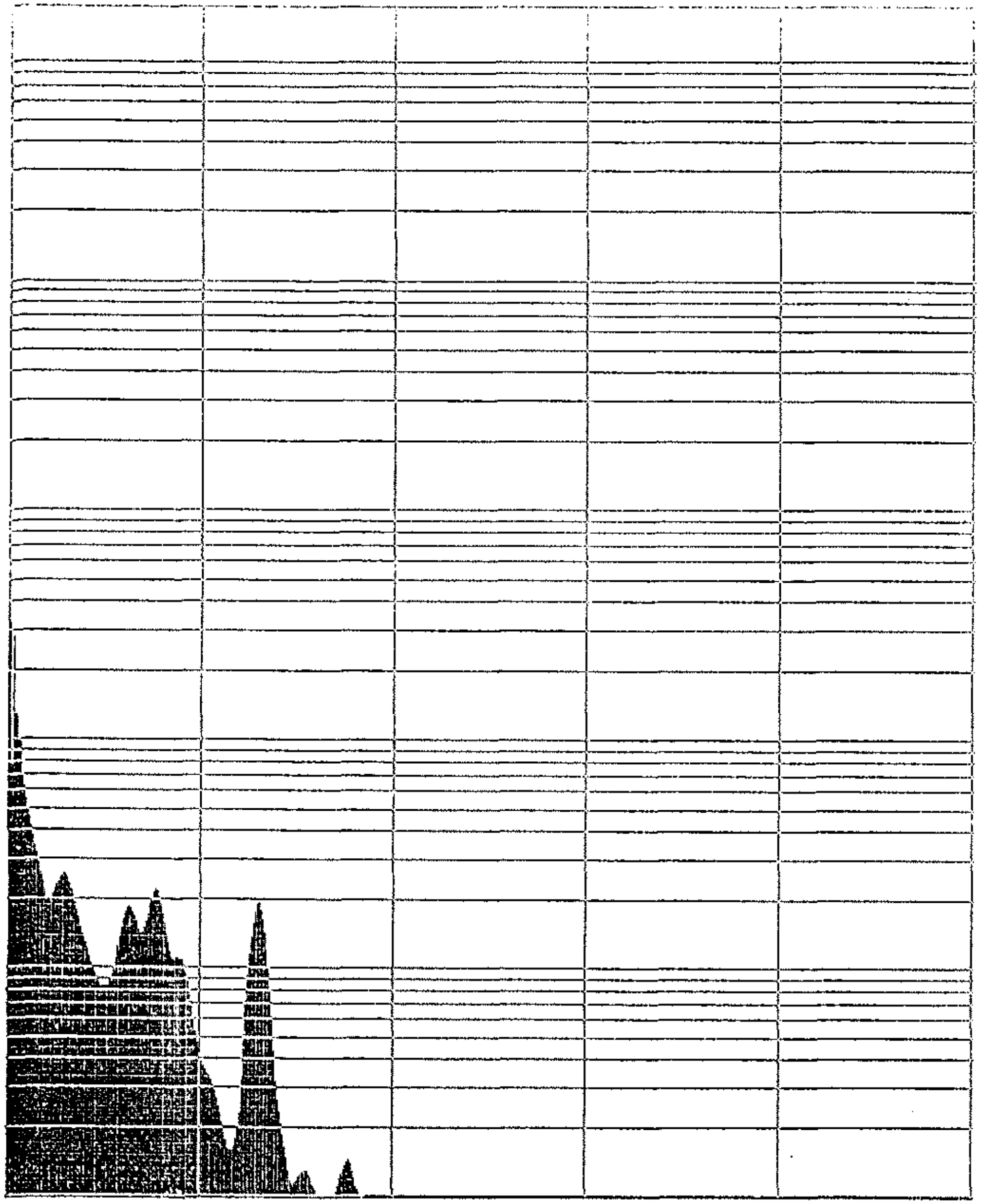
KLICKITAT 9-11-1



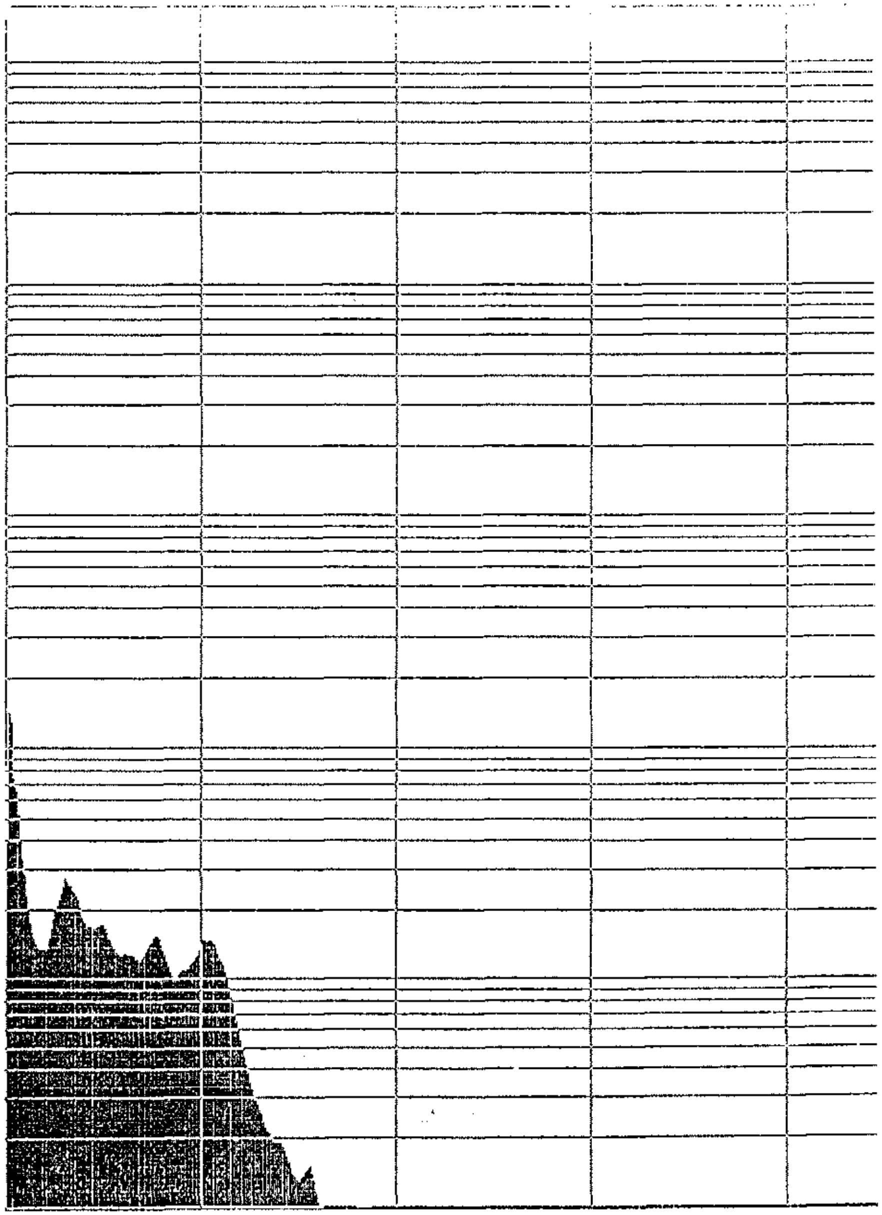
KLICKITAT 9-11-2



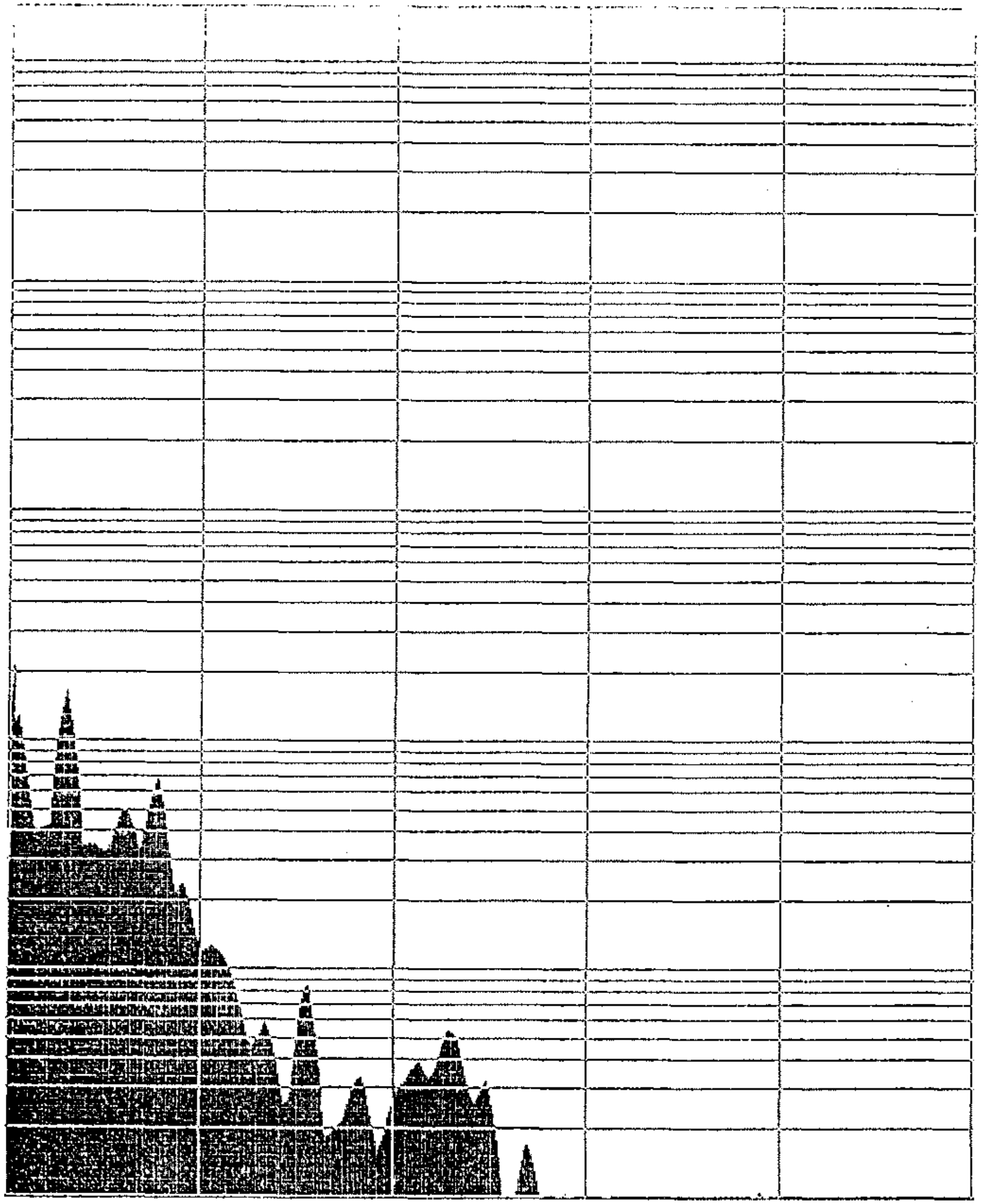
KLICKITAT 9-21-1(2)



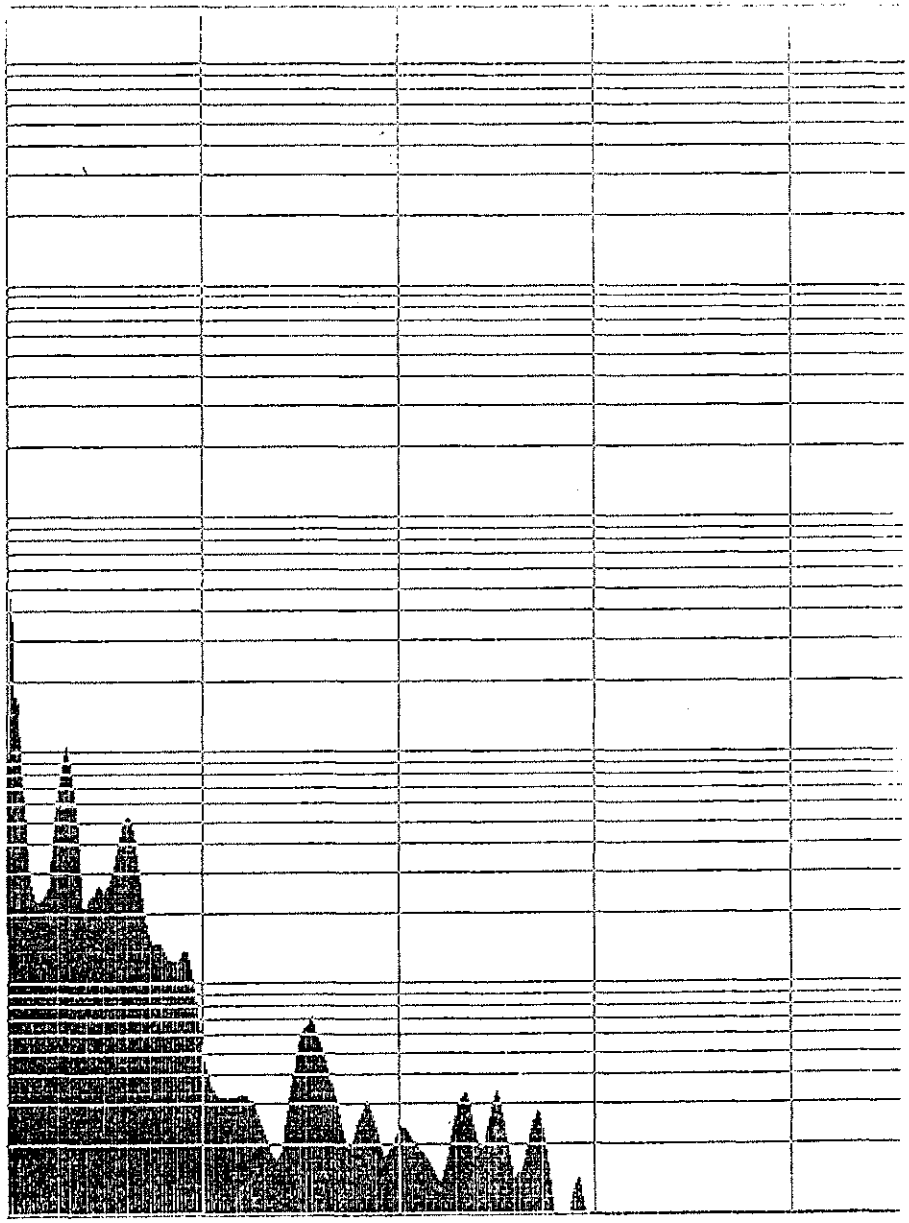
KLICKITAT 9-21-2



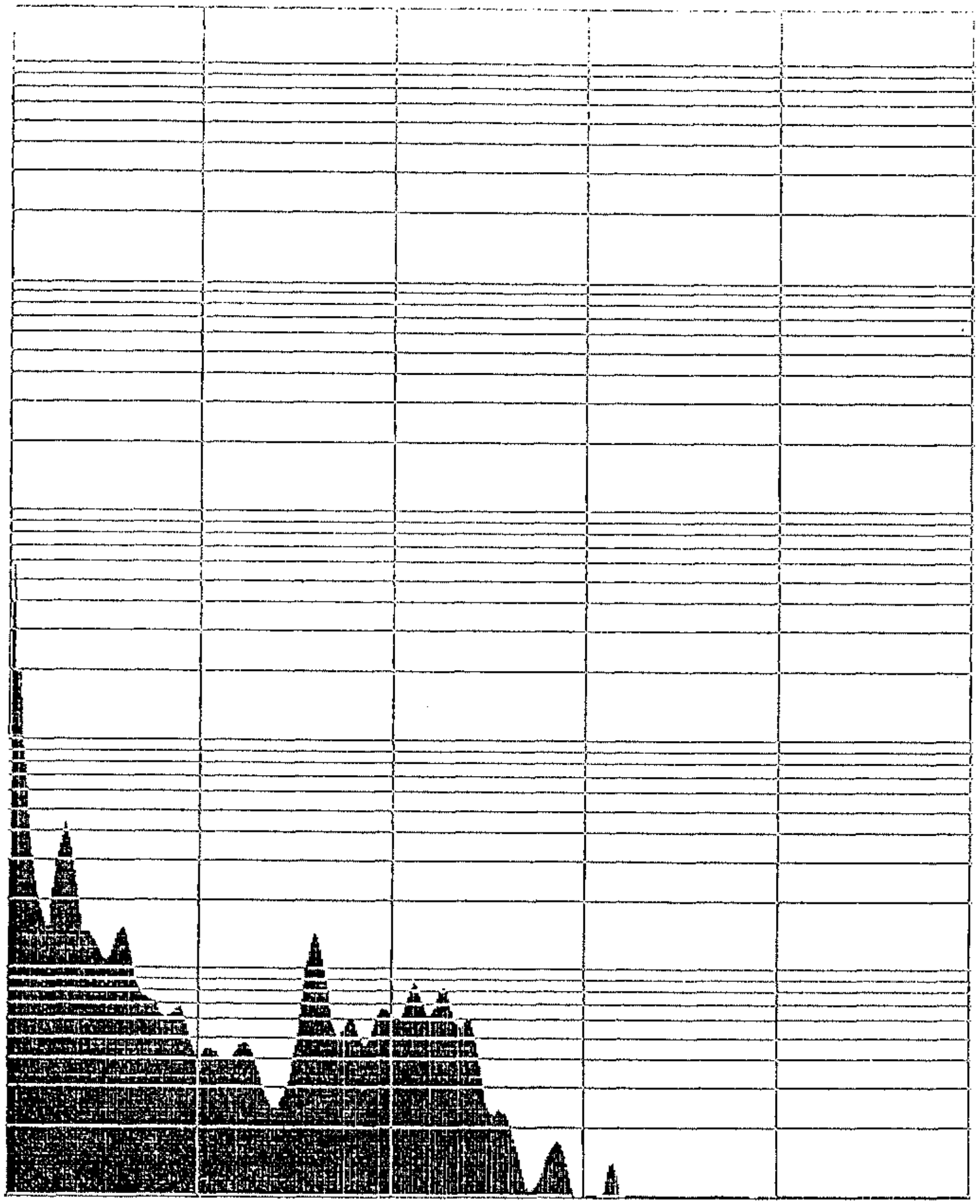
KLICKITAT 9-21-3



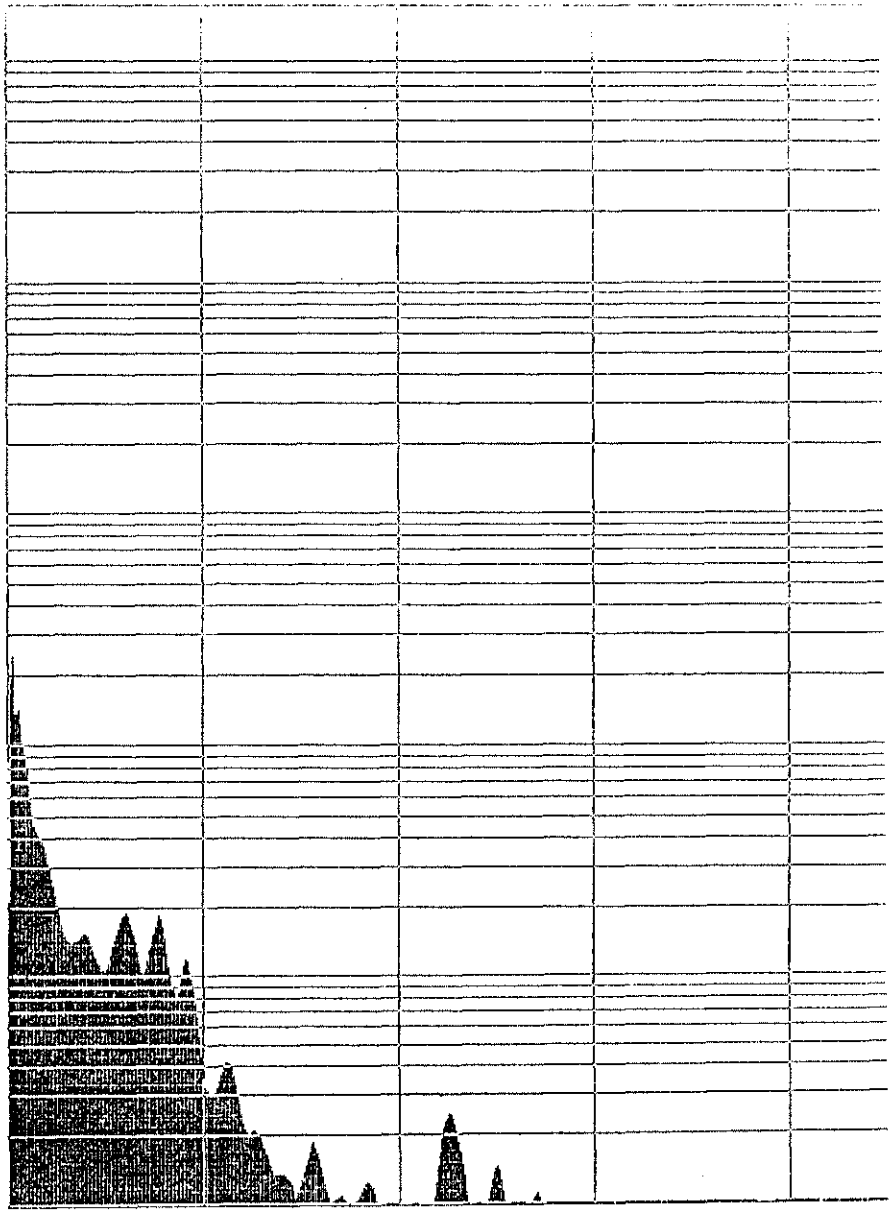
KLICKITAT 9-21-4



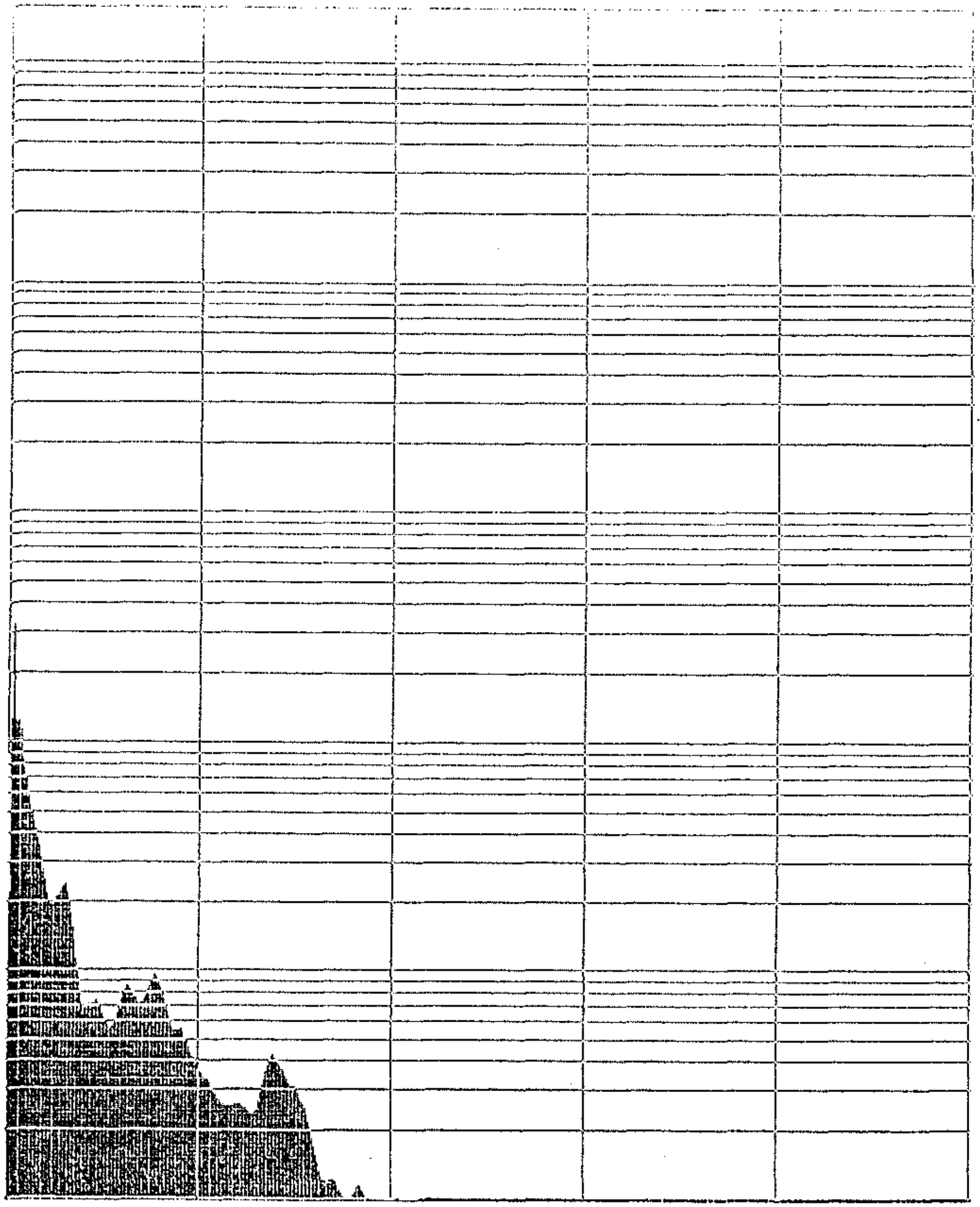
KLICKITAT 9-22-1

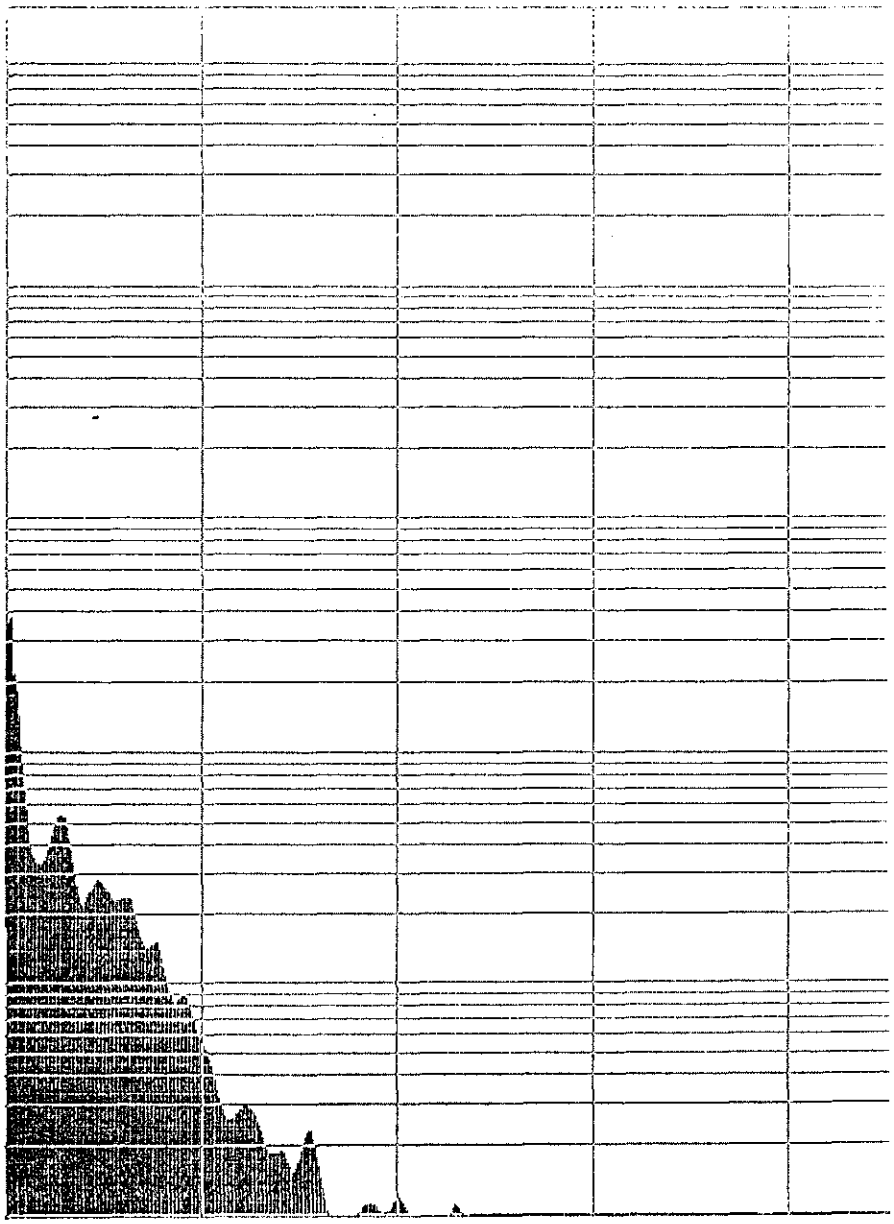


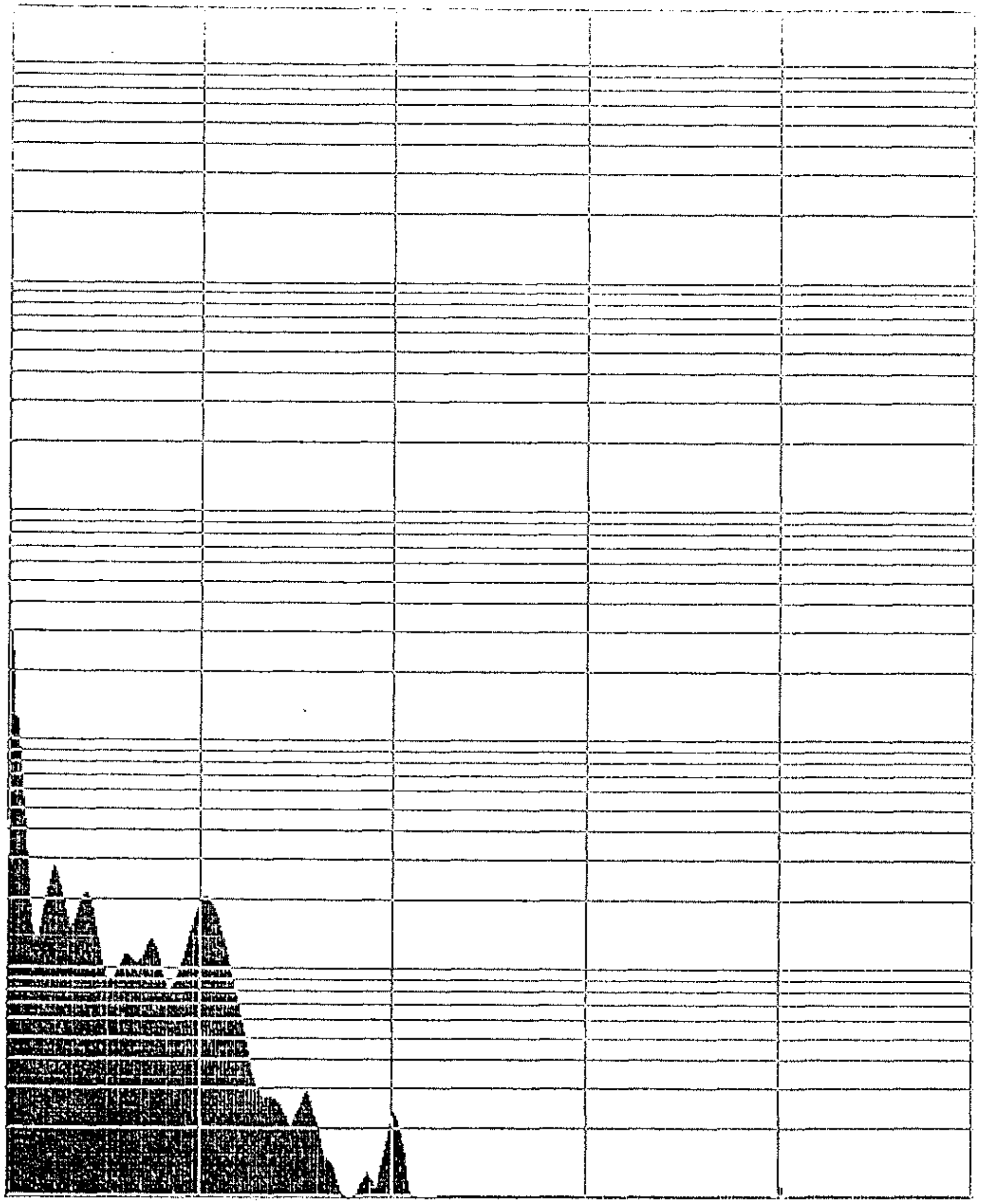
KLICKITAT 9-22-2



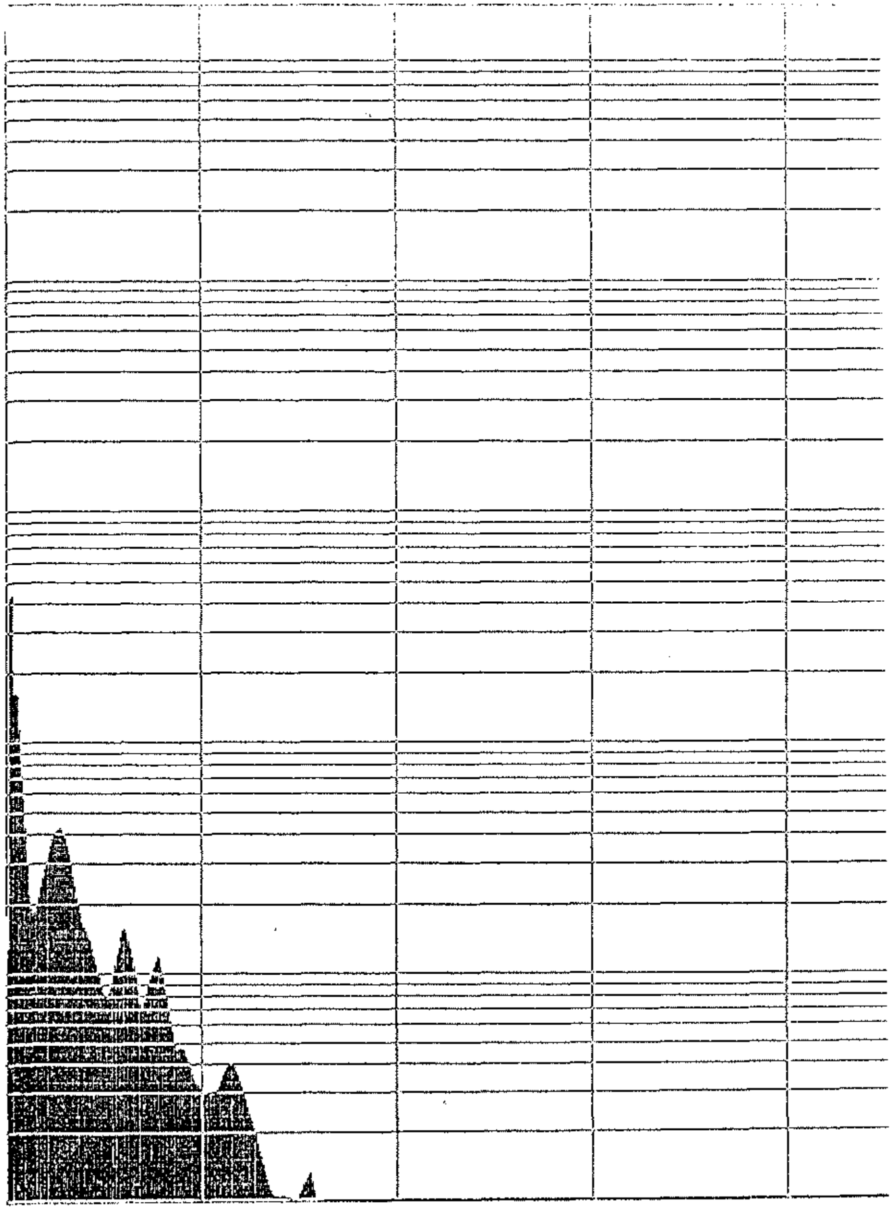
KLICKITAT 9-22-3


KLICKITAT 9-22-4

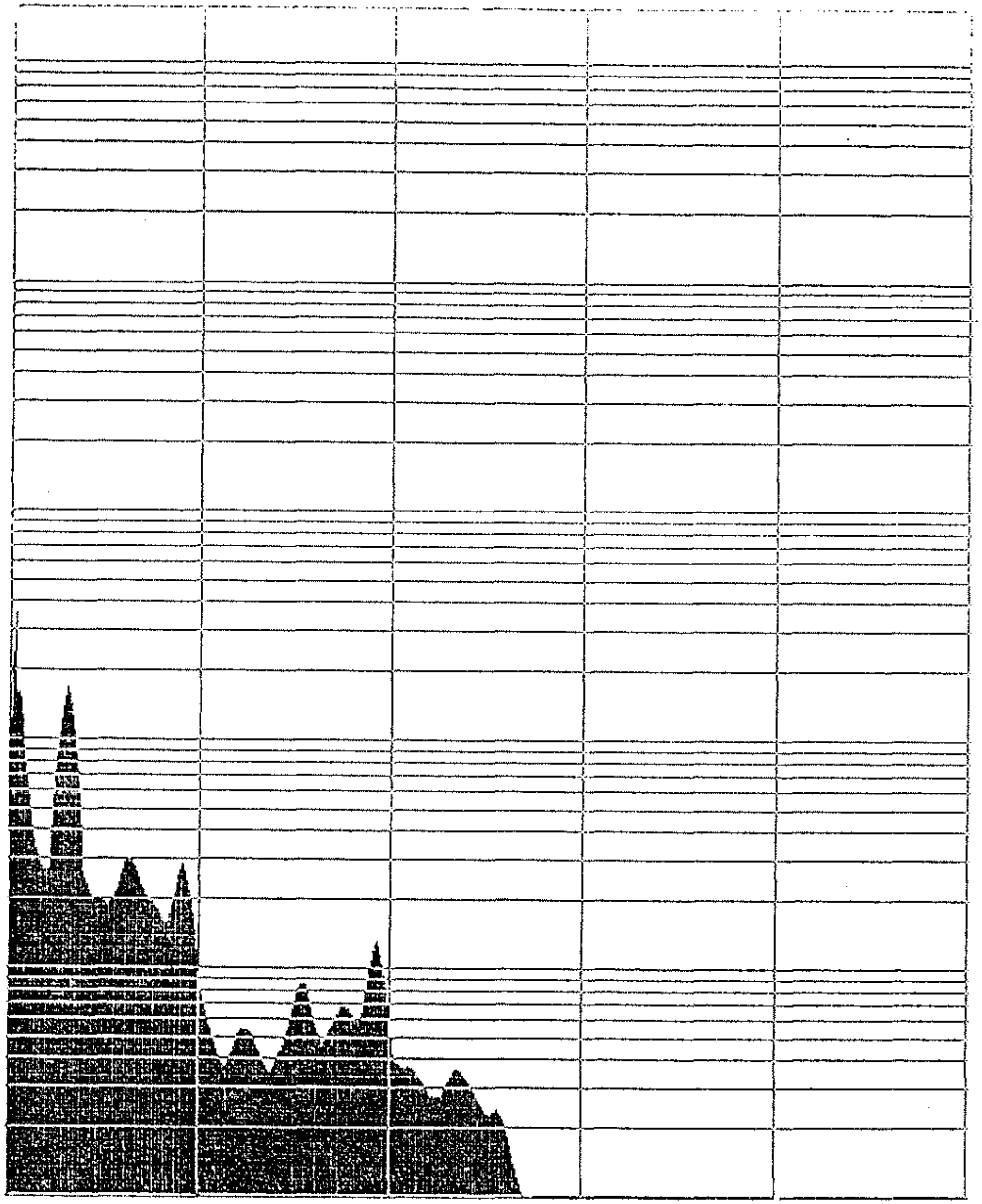

KLICKITAT 9-22-5



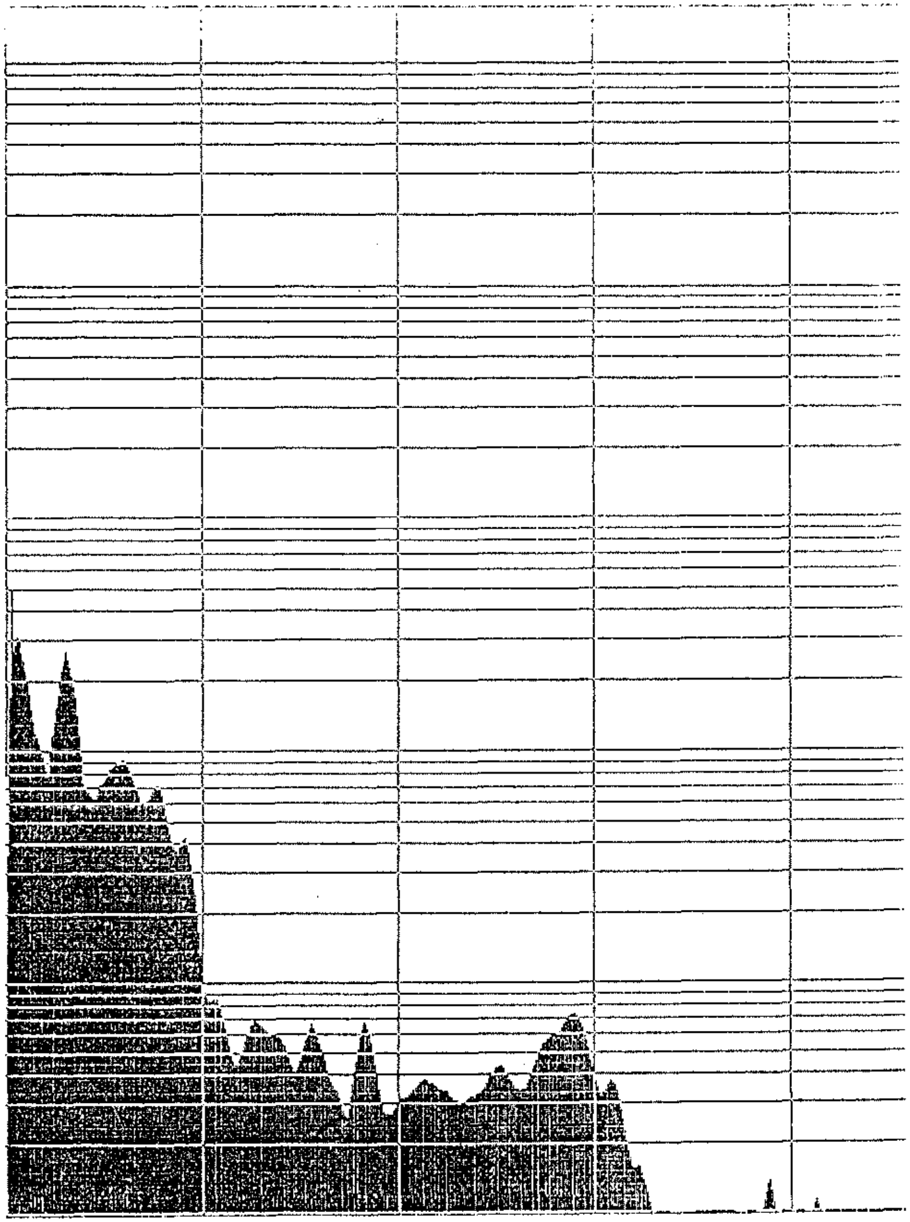
KLICKITAT 9-22-6



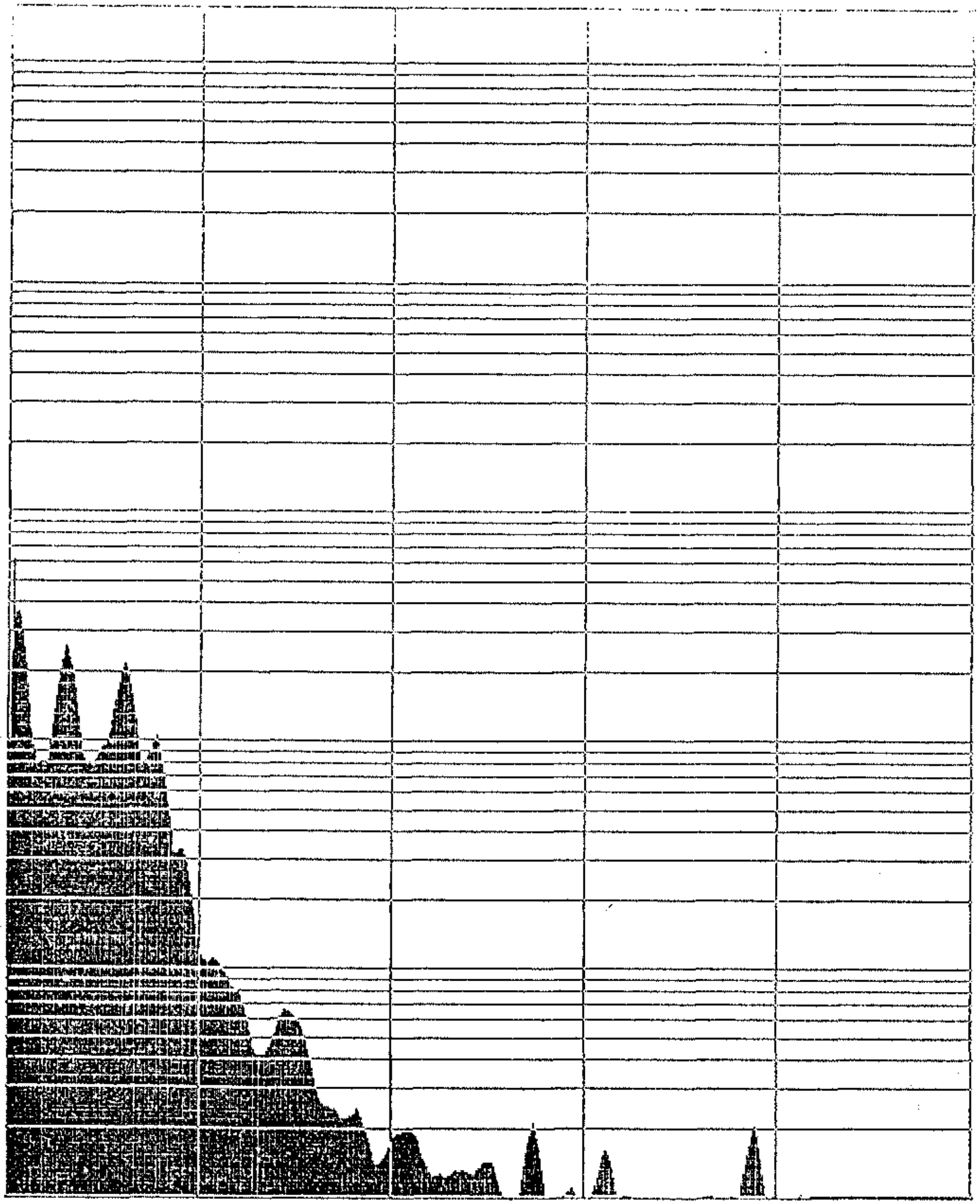
KLICKITAT 9-22-7



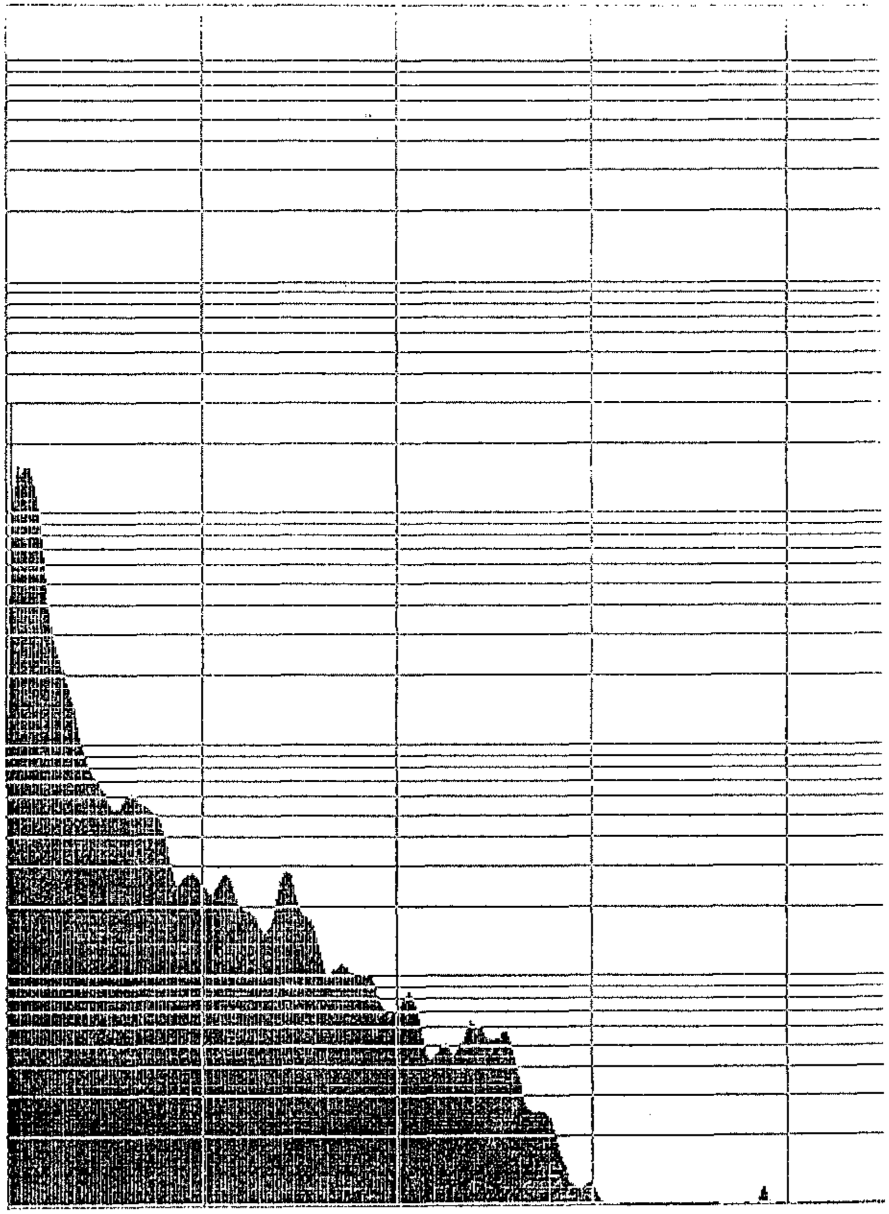
KLICKITAT 9-23-1(1)



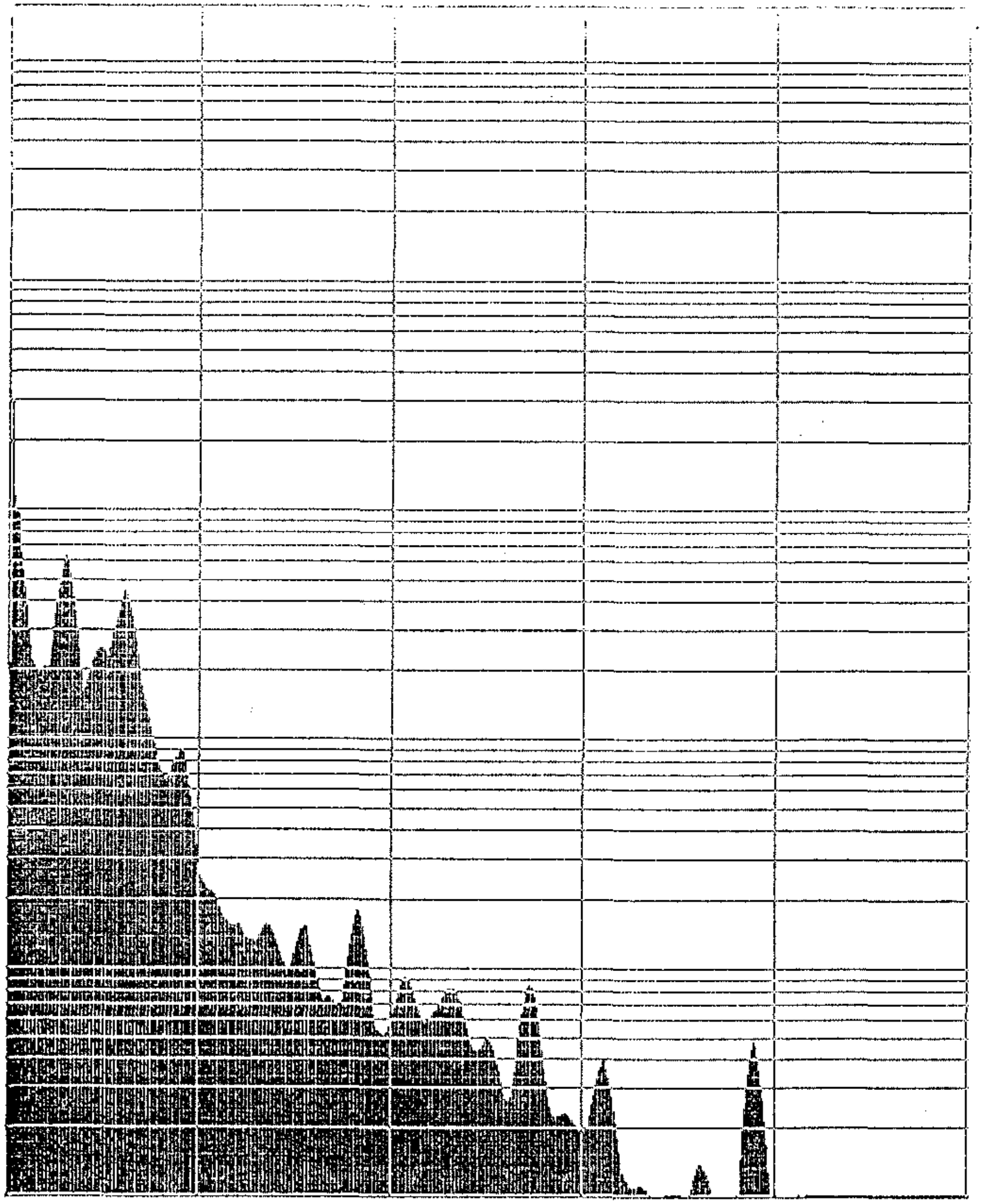
KLICKITAT 9-23-2



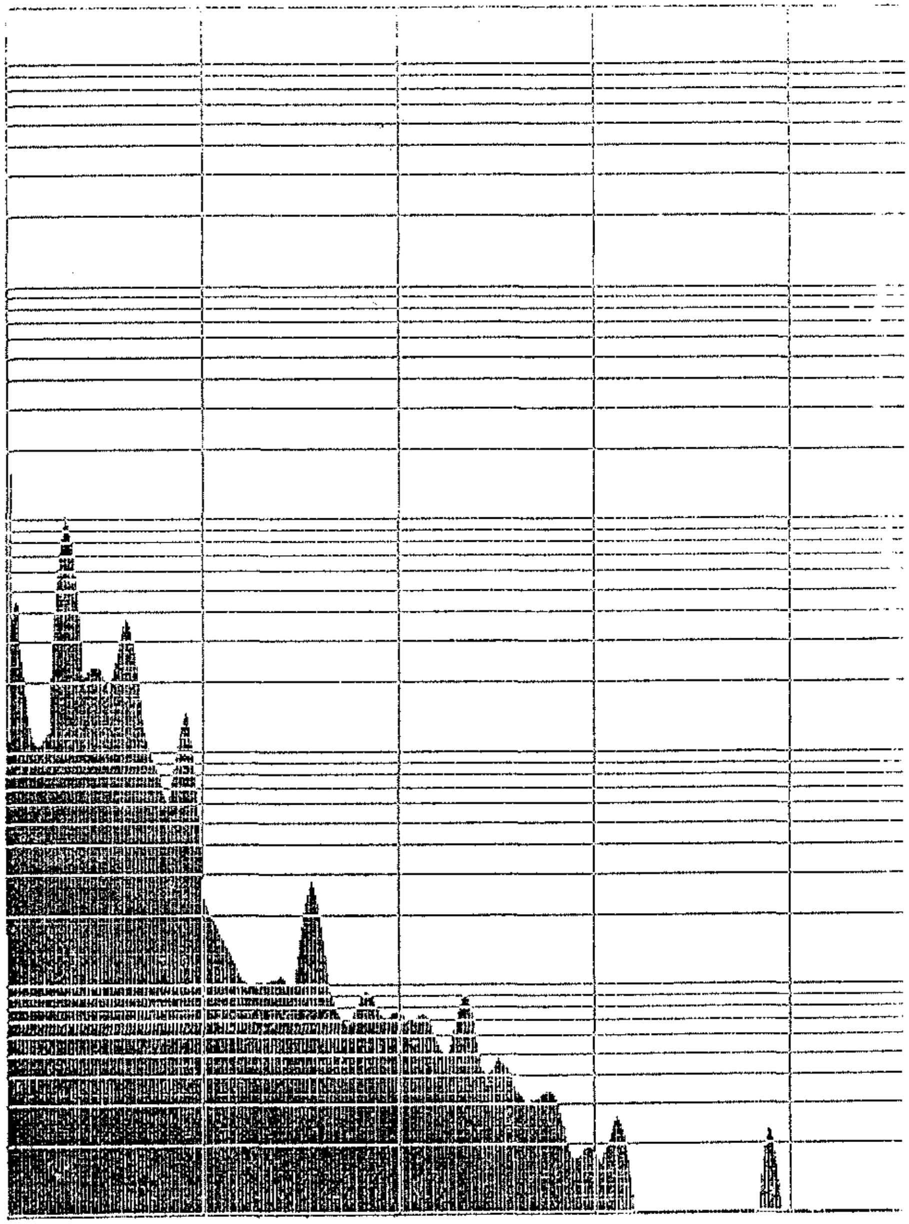
KLICKITAT 9-23-3(1)



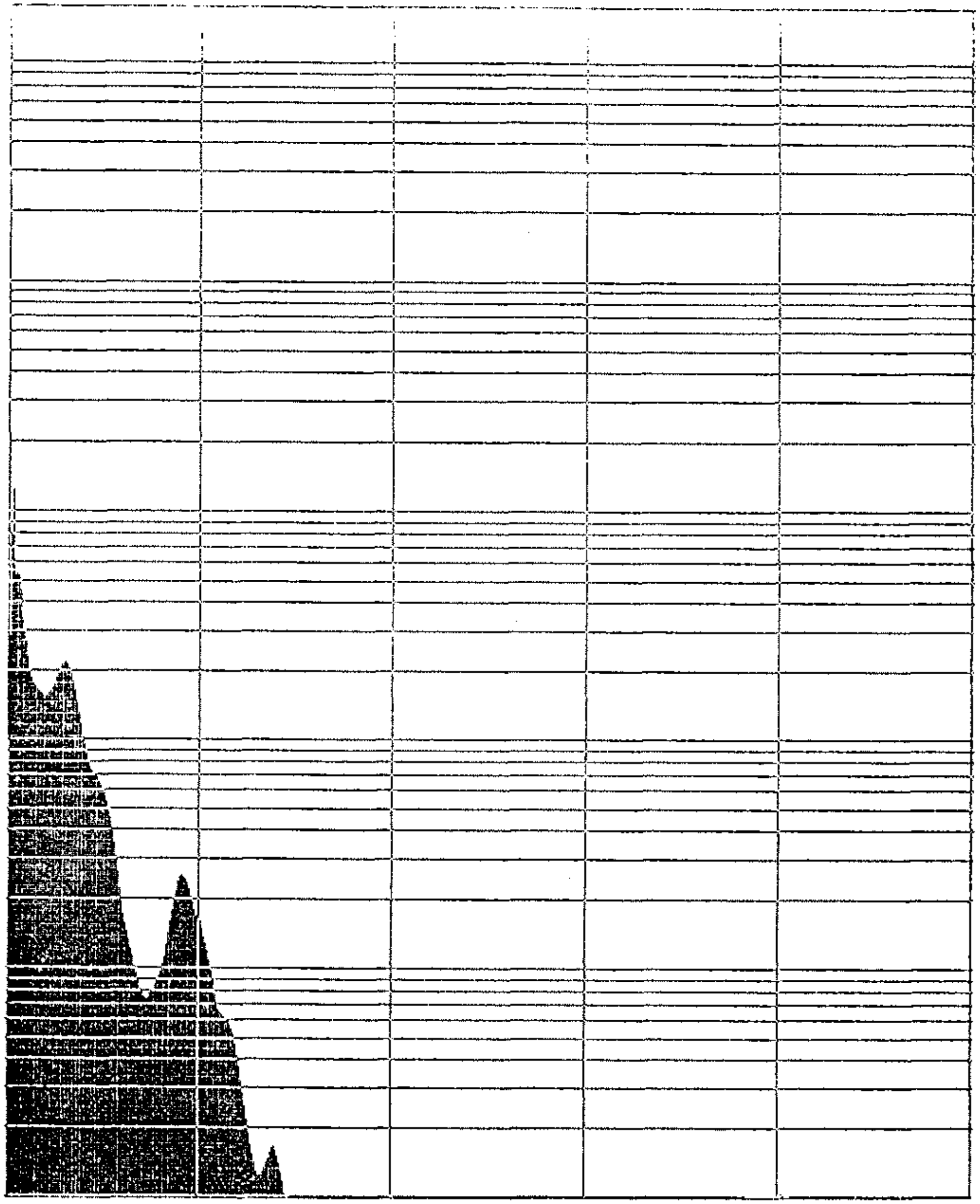
KLICKITAT 9-24-2(1)



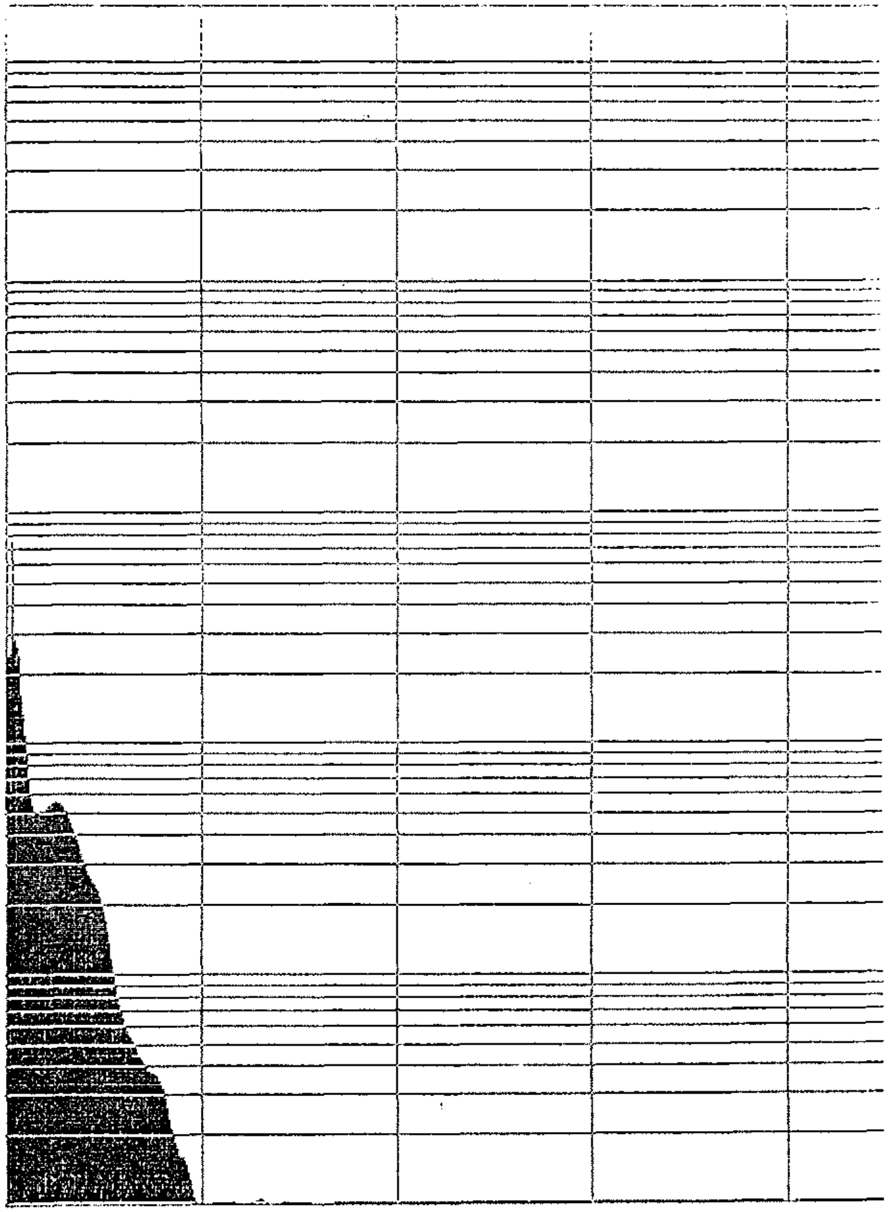
KLICKITAT 9-24-5



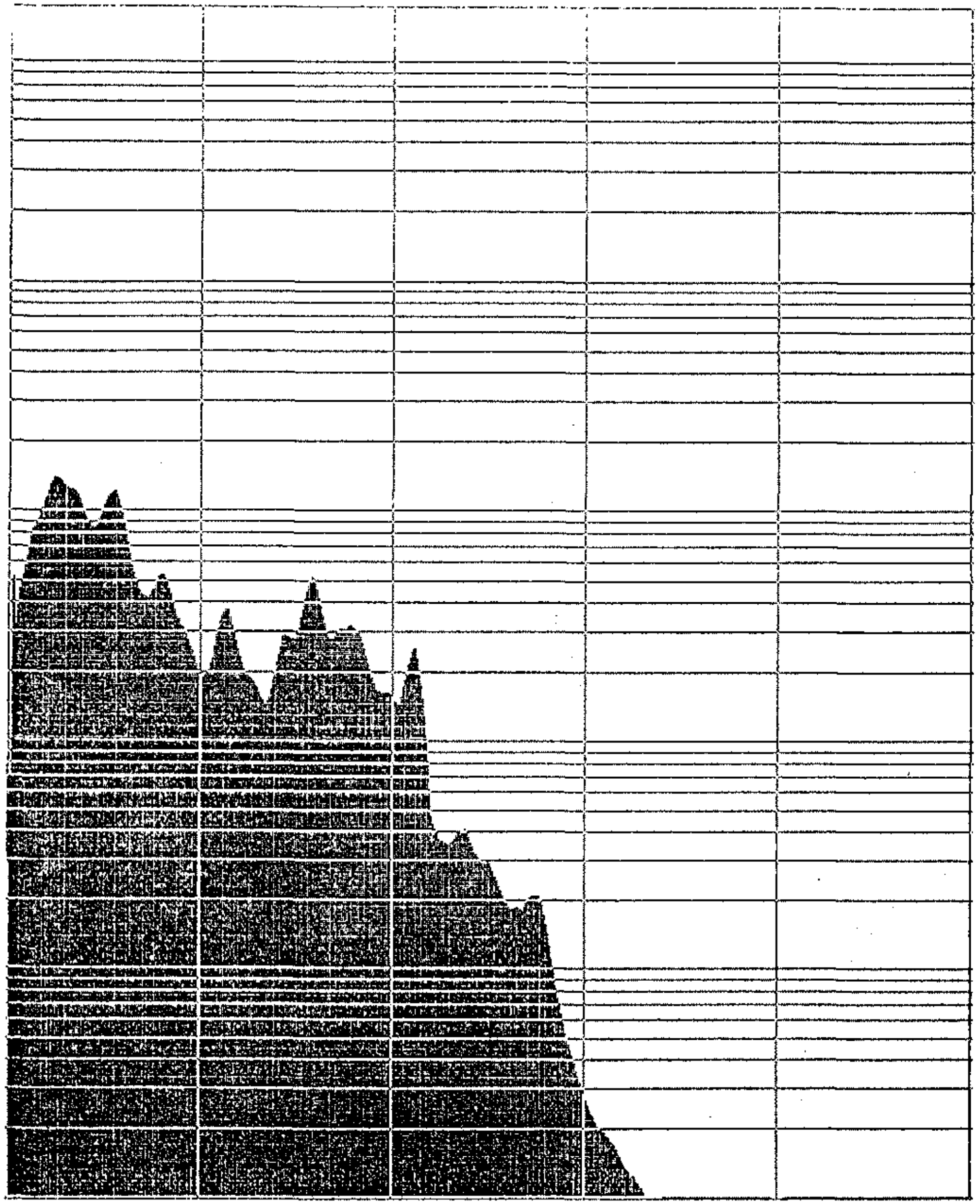
KLICKITAT 9-25-1



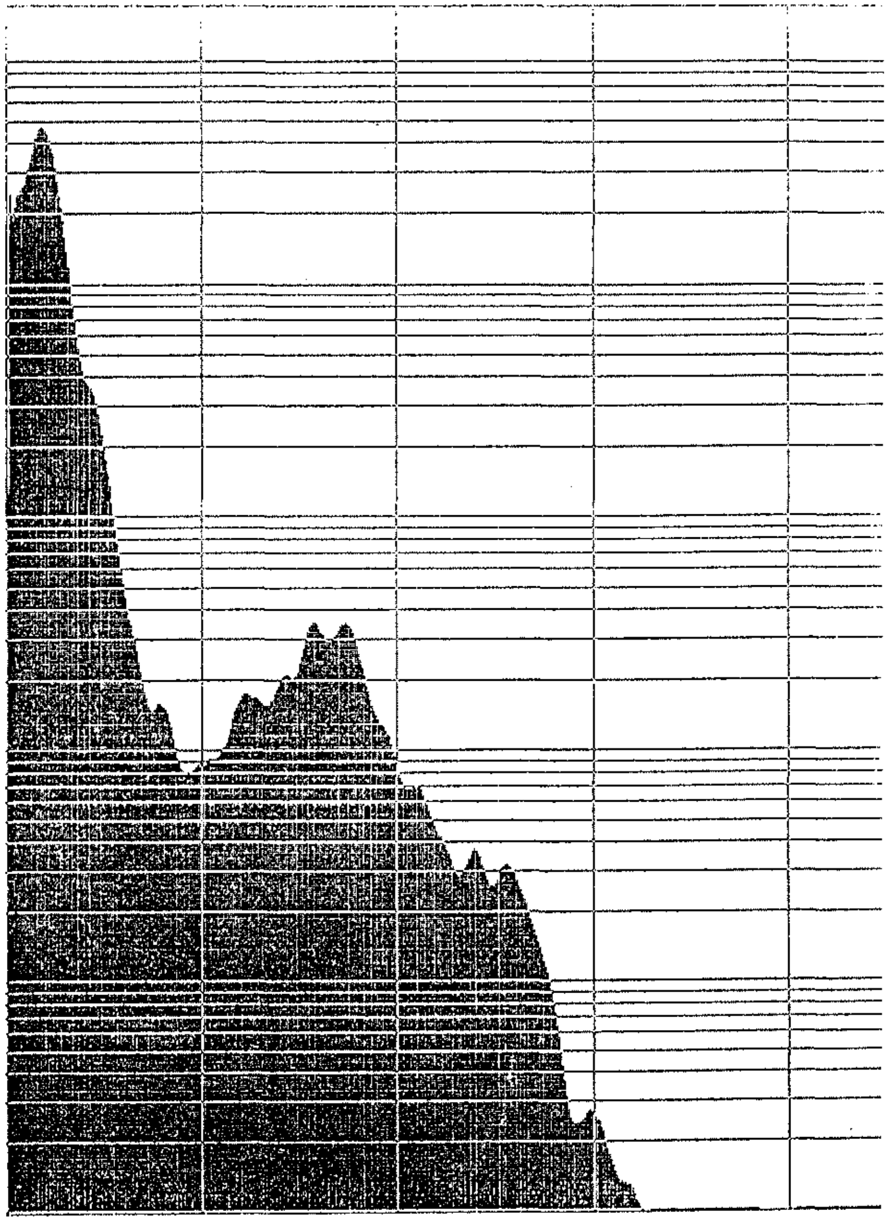
KLAMATH FALLS 8-25-1



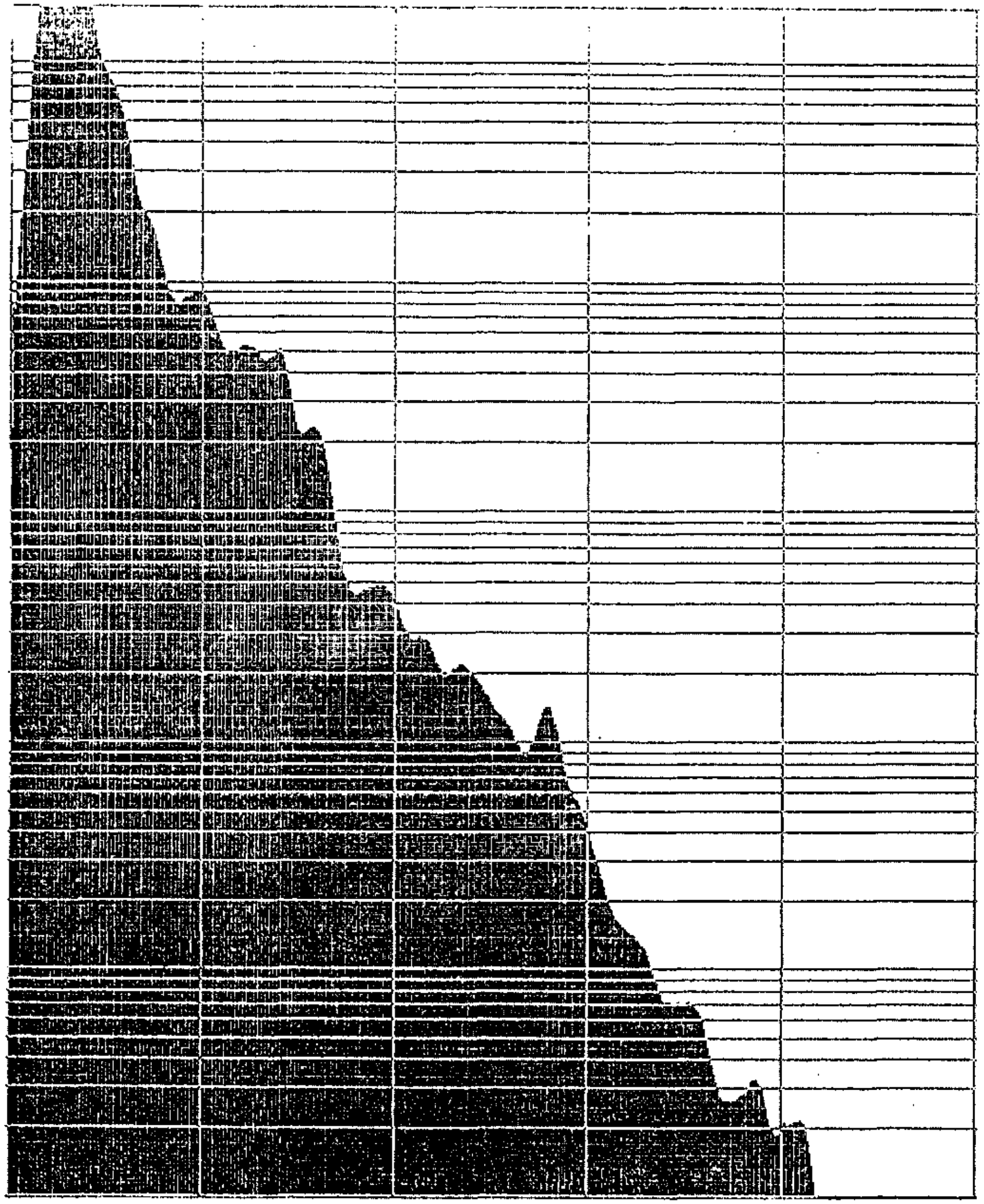
KLAMATH FALLS 8-25-2



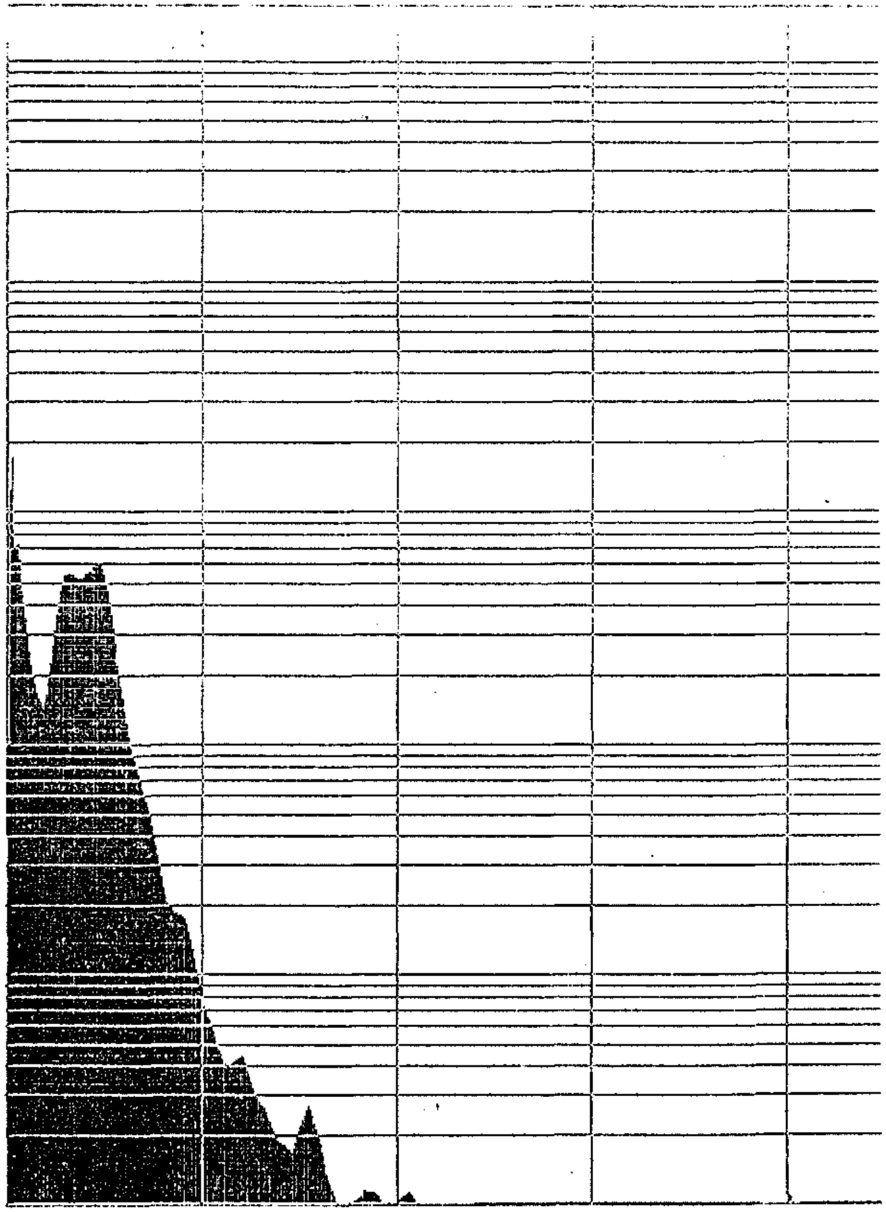
KLAMATH FALLS 8-25-3



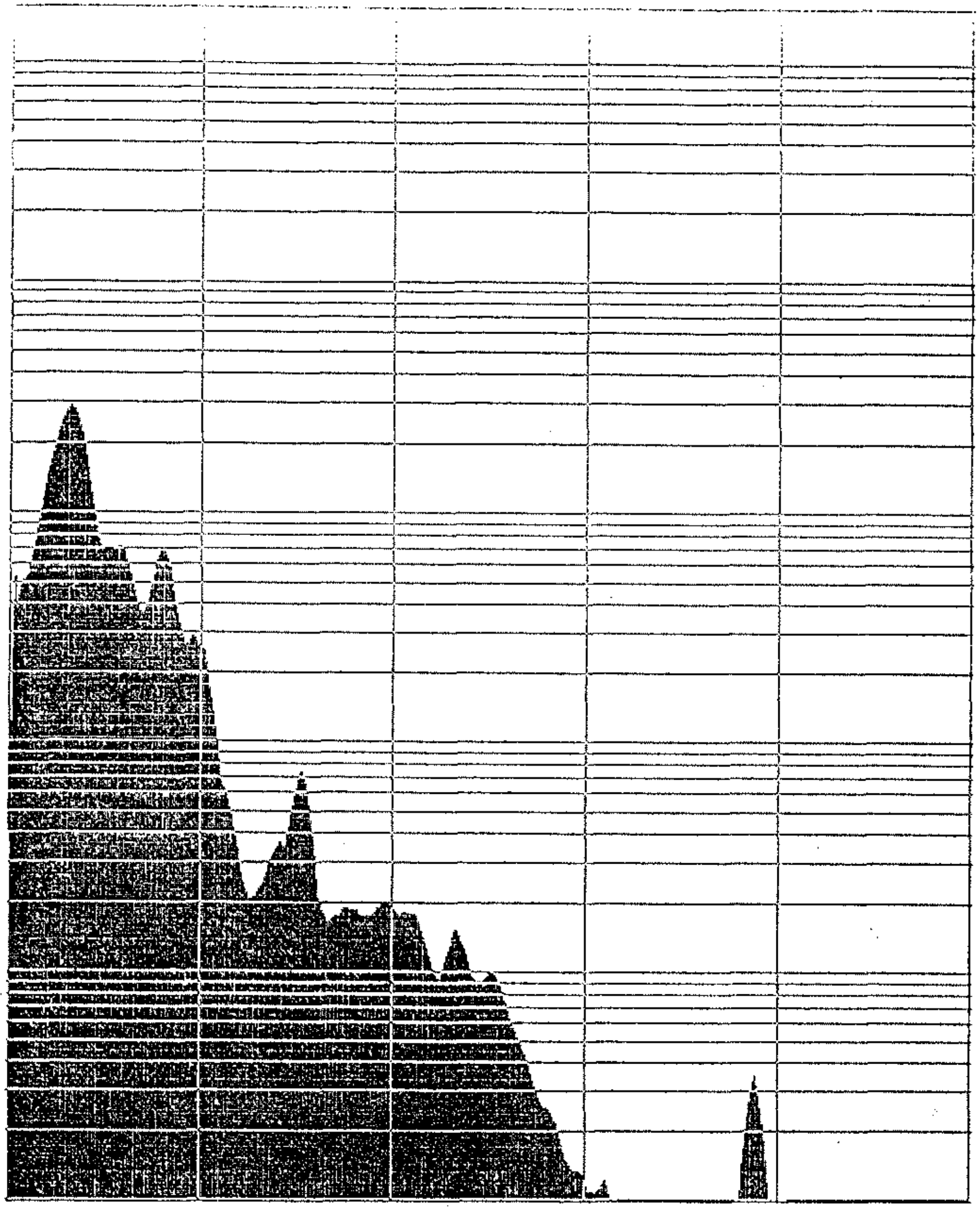
KLAMATH FALLS 8-25-4



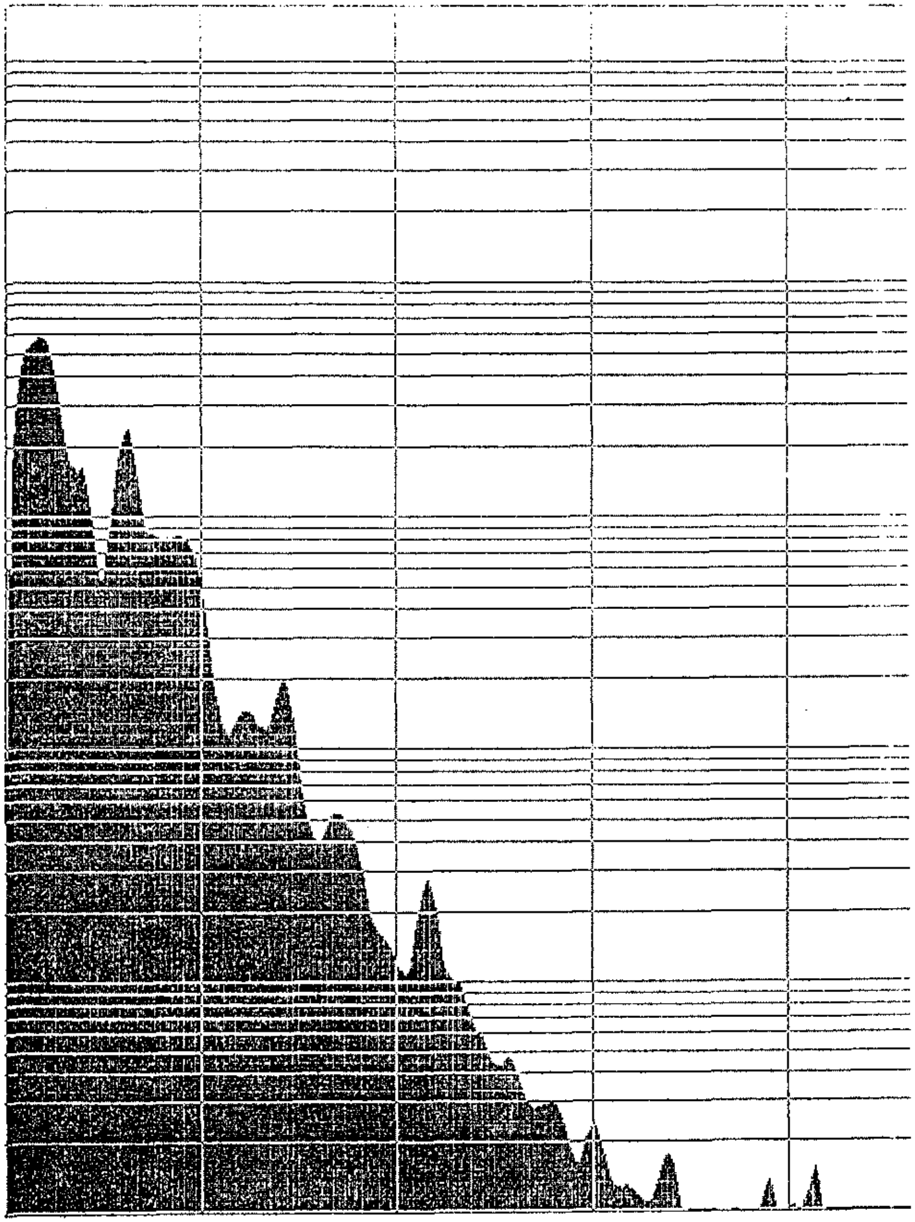
KLAMATH FALLS 8-26-3



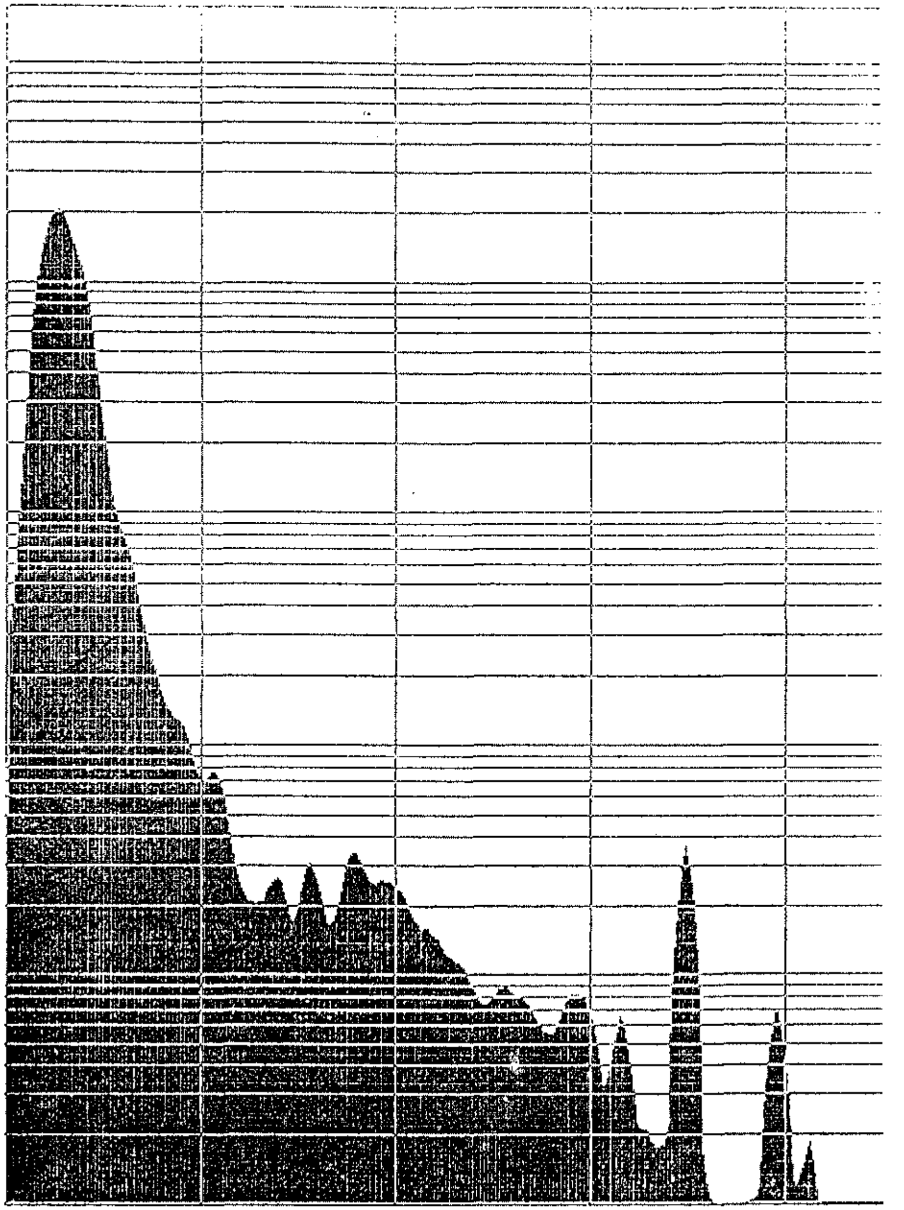
KLAMATH FALLS 8-26-5



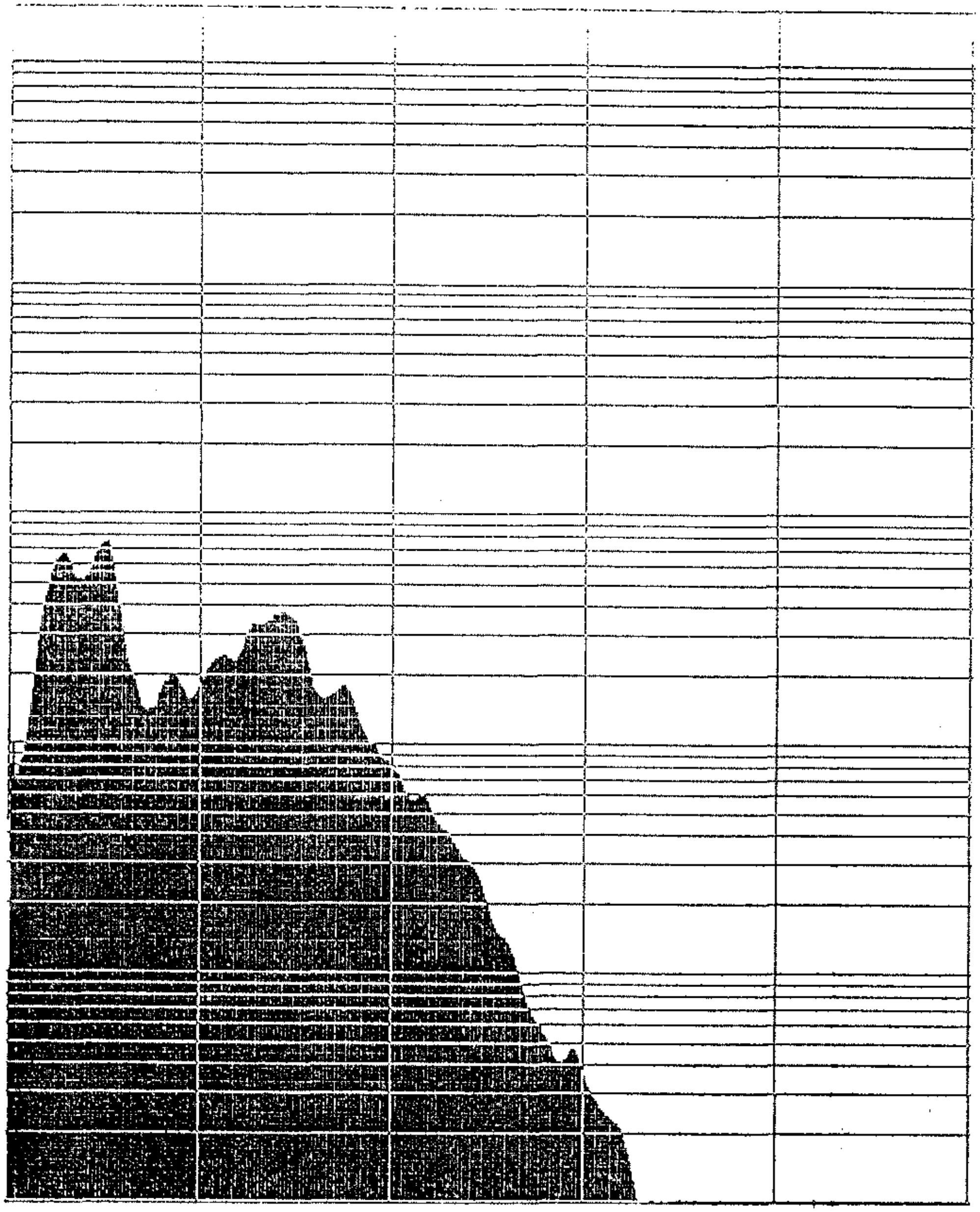
KLAMATH FALLS 8-26-6



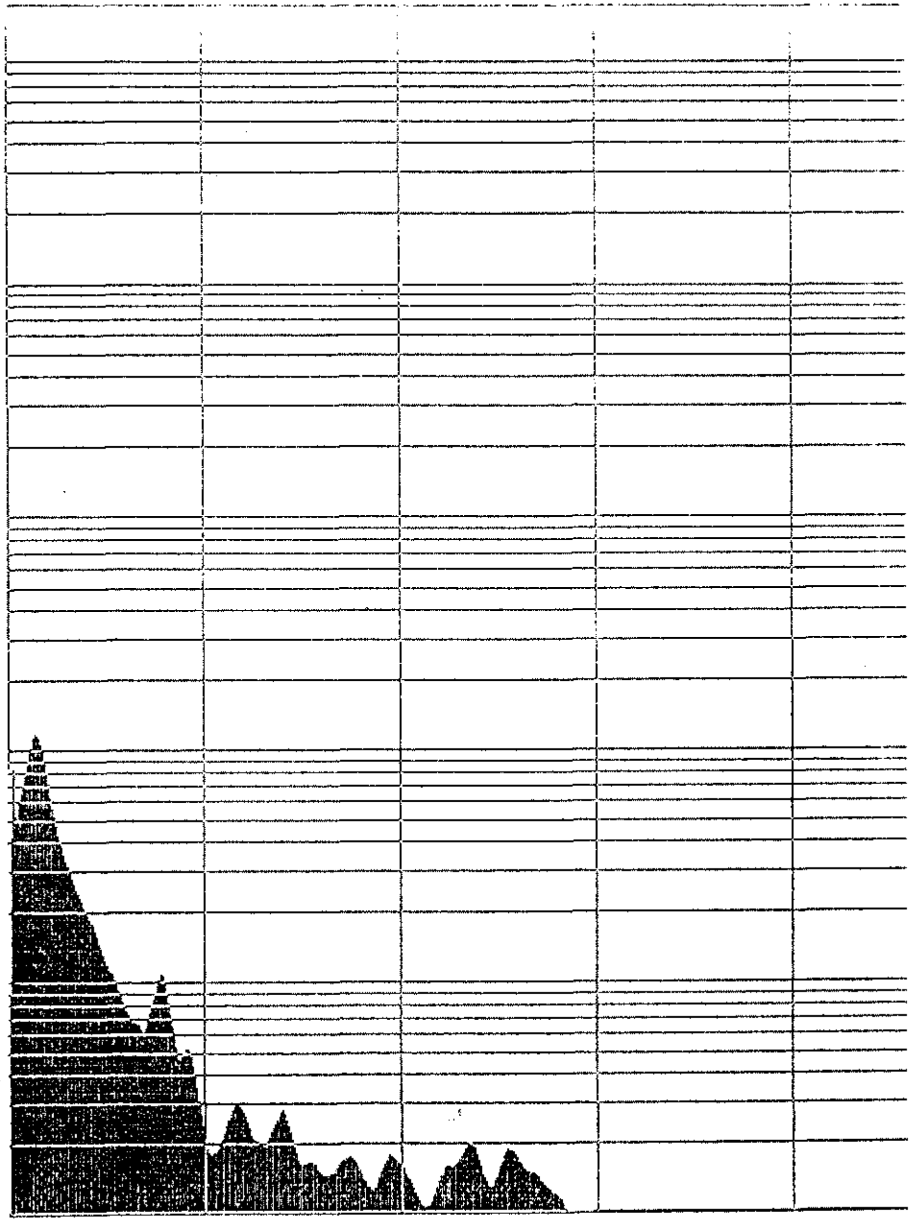
KLAMATH FALLS 8-27-1



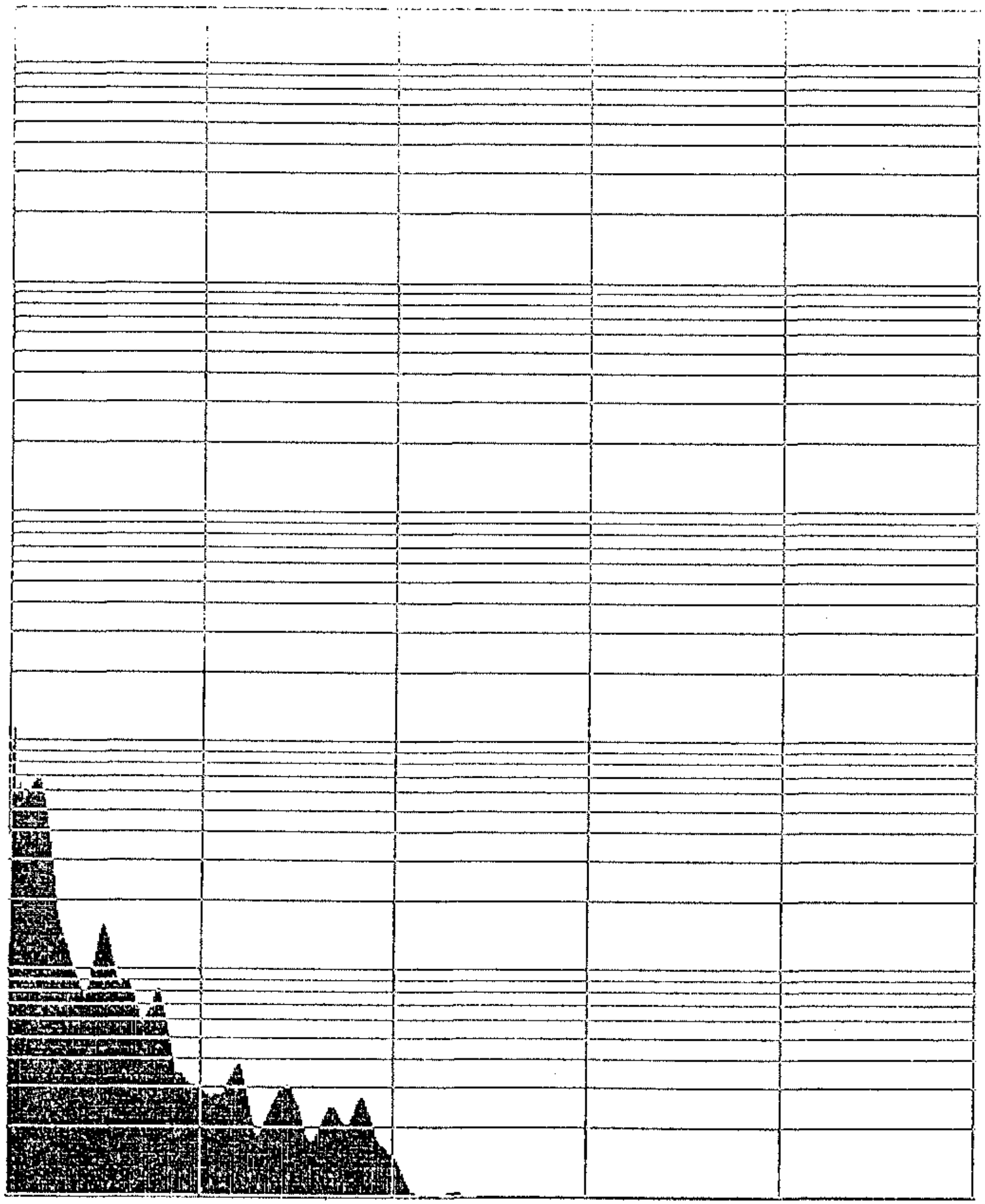
KLAMATH FALLS 8-27-2

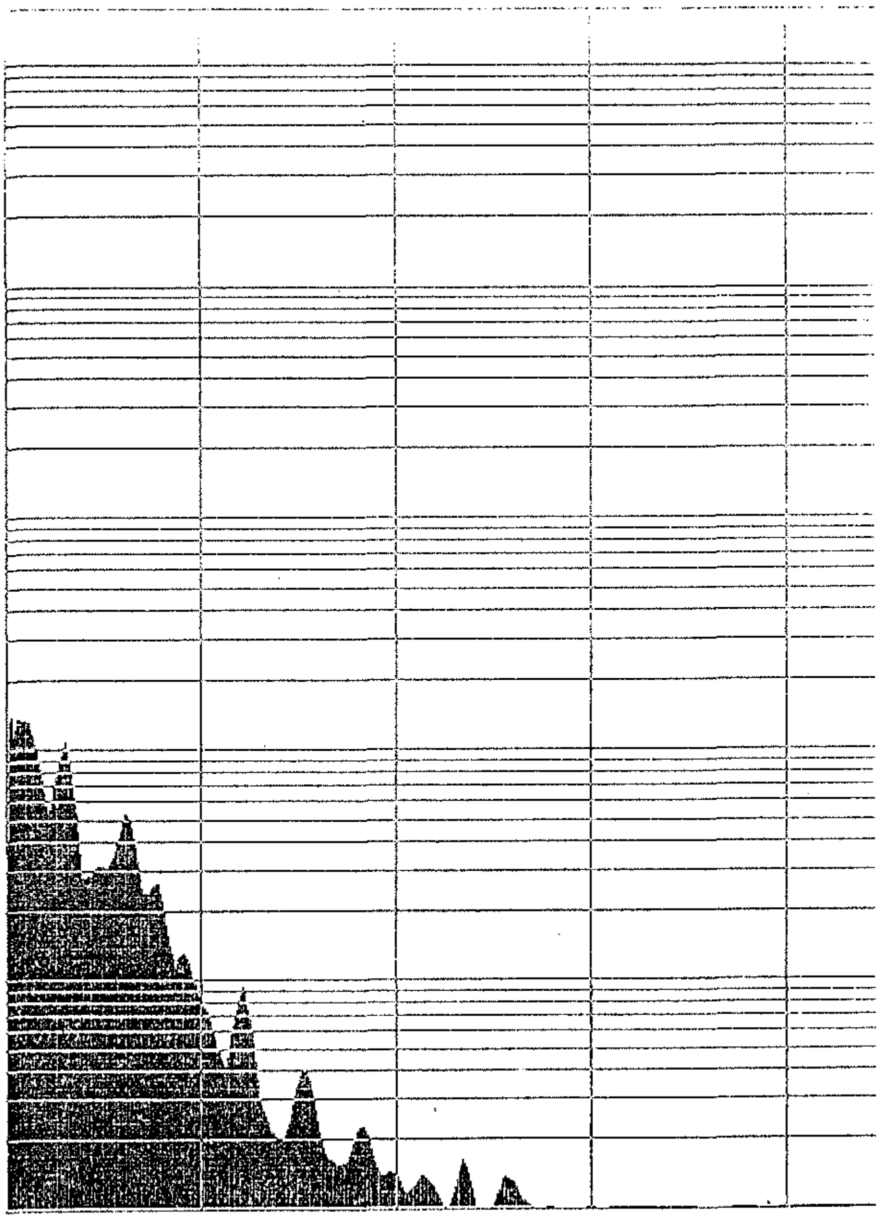


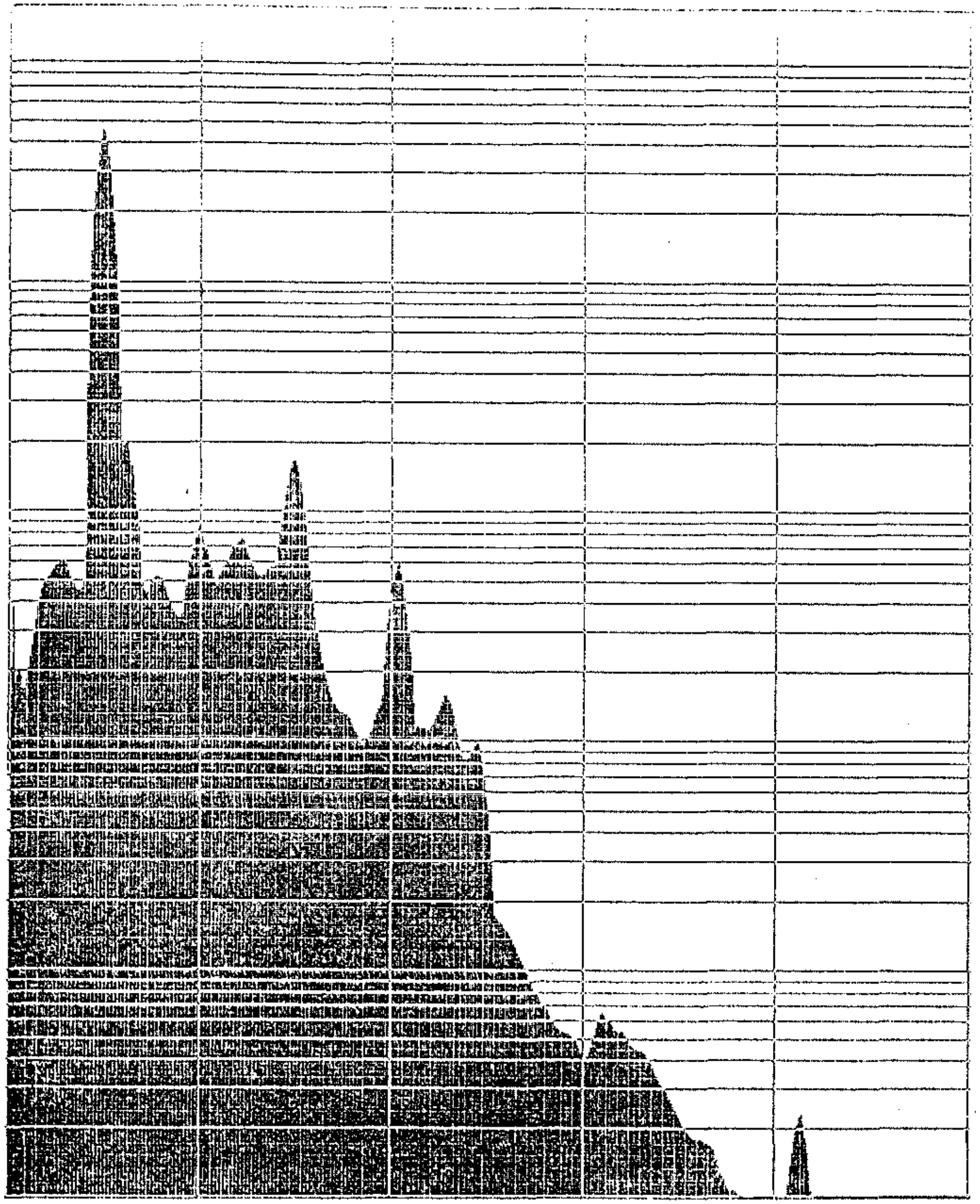
TUM TUM MT. 8-17-1



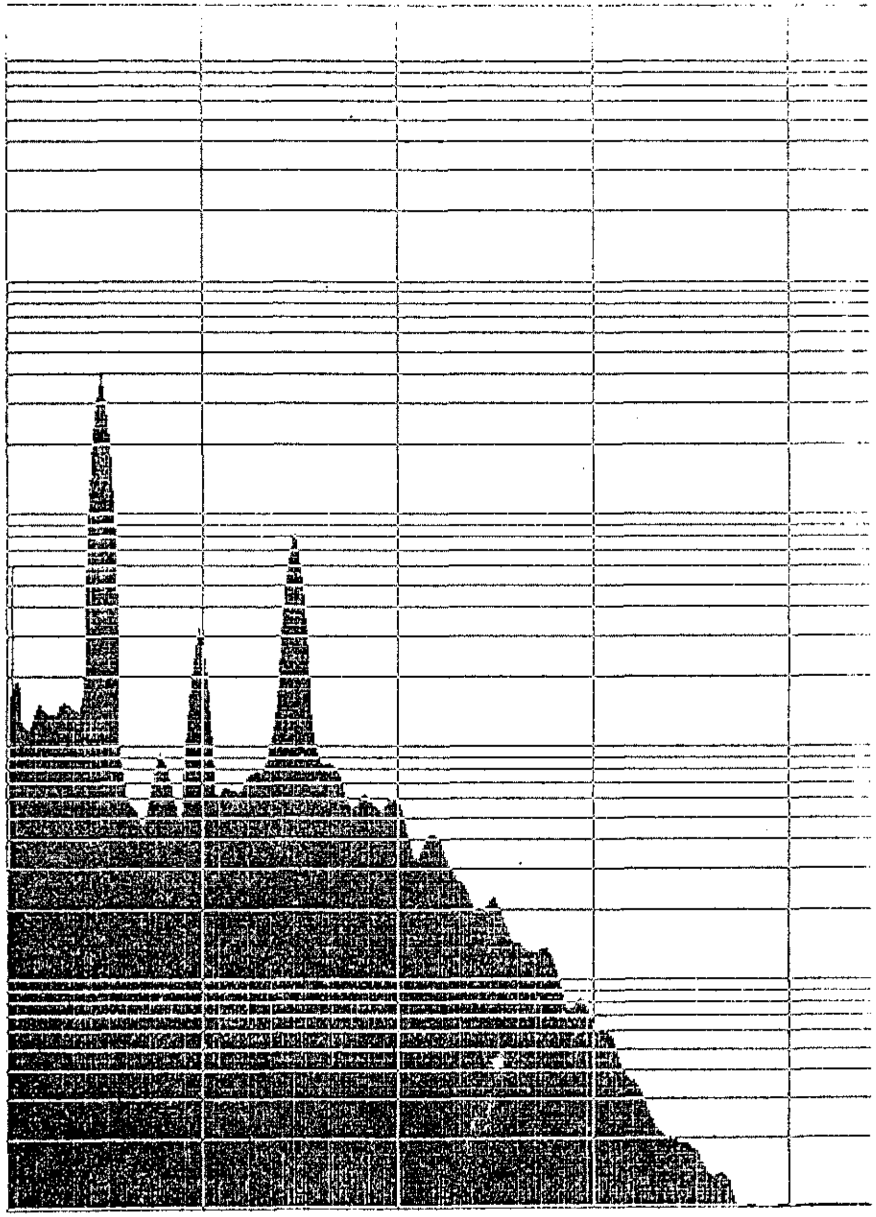
TUM TUM MT. 8-17-2


TUM TUM MT. 8-17-3

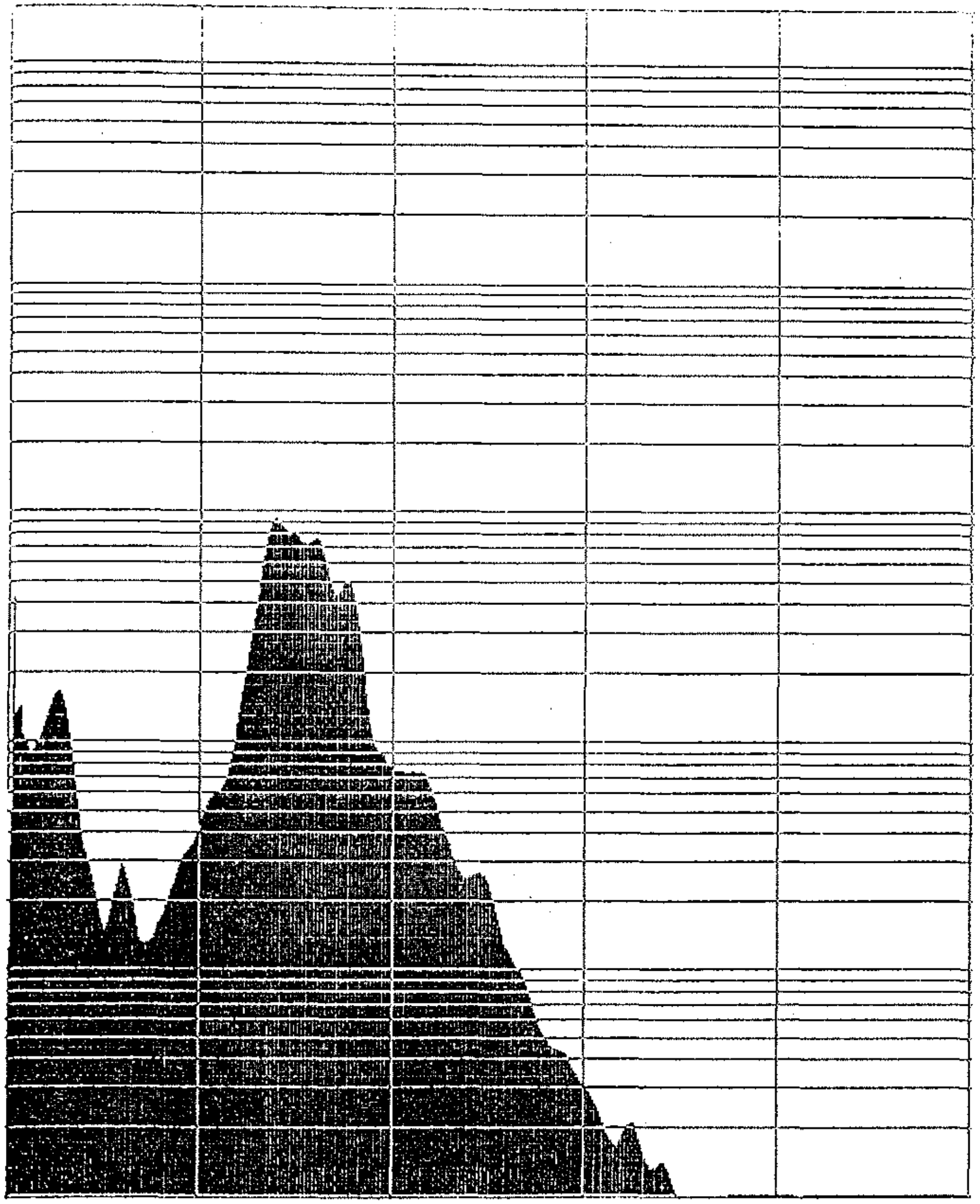

TUM TUM MT. 8-17-4



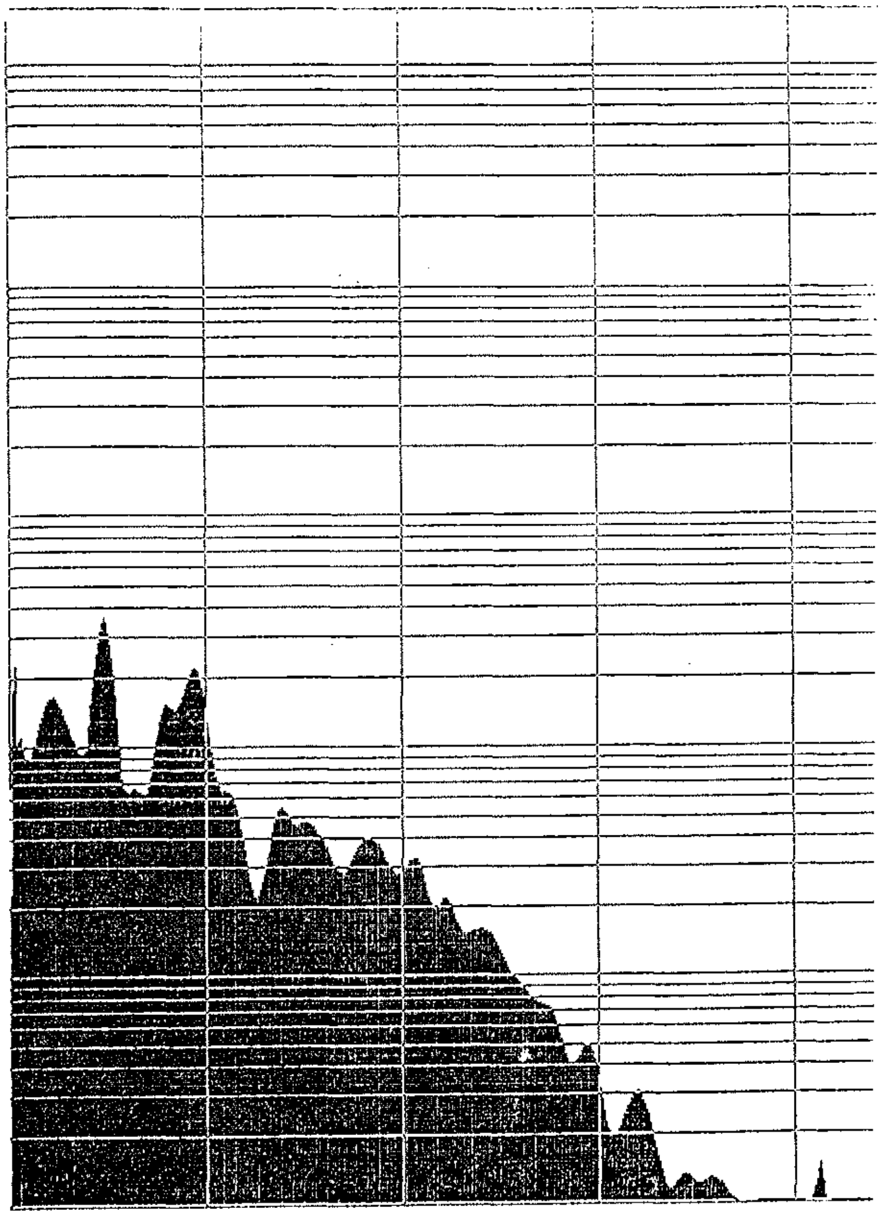
TUM TUM MT. 8-18-1



TUM TUM MT. 8-18-2



TUM TUM MT. 8-18-3



TUM TUM MT. 8-18-4