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GEOLOGICAL SURVEY

The use of soil-gas helium concentrations for earthquake prediction: Studies of factors causing diurnal variation

By

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This report is preliminary and has not been edited or reveiwed for conformity with U.S. Geological Survey standards and nomenclature

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Abstract

The diurnal variation in the soil-gas helium concentration was monitored at depths of 0.5-2 m. Barometric pressure, air temperature, wind speed, soil temperature, soil moisture, relative humidity, and precipitation were also monitored. The helium variation below a 1-m sampling depth usually did not exceed the analytical sensitivity limit of ±10 ppb helium. The meteorological parameters that had the greatest effect on the helium variation is wind speed and precipitation; another factor causing variations was the atmospheric pumping created by air-temperature changes and its associated effect on the near-surface soil moisture content. The absolute helium variation rarely exceeded 1 percent of the background helium concentration in air. This minor variation could be corrected because it followed a regular daily pattern. Diurnal changes in the soil-gas helium concentration did not impose any severe limitations on the use of helium soil-gas data collected for earthquake prediction purposes.

Introduction

The purpose of this study was to evaluate the usefulness of measuring the soil-gas helium concentration as a possible geochemical technique for predicting earthquakes. The initial investigation, presented in this paper, deals with the diurnal fluctuations observed in the soil-gas helium concentration and explores the mechanisms responsible for those variations.

Both helium and radon are inert gases produced by the radioactive decay of uranium and thorium. Fluctuations of radon concentrations associated with earthquake activity have been known for some time. (Ulomov and Mavashev, 1971; Shapiro and others, 1978, Sultankhodzhayev and others 1976). Although the analysis of helium has been used in some structural investigations (Bulashevich and Bashorin, 1974; Reimer and Adkisson, 1977), it is rather new for earthquake prediction. Helium has some physical advantages over radon; it is very mobile and is radioactively stable. However, for practical detection purposes, the concentration of helium must be much greater than that of radon.

The analytical equipment used in the course of this investigation has been developed by the U.S. Geological Survey (Friedman and Denton, 1975; Reimer, 1976). The equipment was primarily designed as a mobile technique for use in exploration for various types of energy "deposits" (Reimer and others, 1976a), but it is readily adaptable for making in-place, continuous helium measurements in either soil gas or water.

Study Parameters and Sampling Locations

This study evaluates the influence of various meteorological parameters on the helium concentration in soil gas. The meteorological parameters studied were barometric pressure, air temperature, relative humidity, wind speed, and precipitation. Also considered, to a lesser degree, were soil temperature and soil moisture. In some cases, the influence of all these parameters was evaluated as a function of sample-probe depth.

Sampling involved four geographic locations: Idaho Springs, Colorado (April 1978); Red Desert, Wyoming (December, 1977 and July, 1978); Mojave Desert, California (June 1978); and San Juan Bautista, California (June 1978). The first location, Idaho Springs, is a noted area of high soil-gas helium concentrations (Roberts and others, 1975). The next location, in the Red Desert area, contains a low-grade uranium deposit (Pacer and others, 1978) and the region experiences a great variability in wind. The third location is the Mojave Desert, California; it involved reconnaissance sampling of the Palmdale Bulge. The fourth location, near San Juan Bautista, is adjacent to the San Andreas Rift zone. The major portion of the study was conducted at the San Juan Bautista location. Figures 1 through 4 are the sampling locations corresponding to the four geographic locations. Table 1 indicates the parameters measured at each location.

Analytical and Sampling Equipment

The analytical equipment used for the helium analyses was the mobile helium analyzer developed by the U.S. Geological Survey (Friedman and Denton, 1975; Reimer, 1976; Reimer and Denton, 1978). The unit, which consists of a small mass spectrometer mounted in a 4-wheel-drive, 4-door pickup truck, is self-contained and can operate either as a mobile lab or at a fixed location where electric power is available. The inlet system of the mass spectrometer has been modified to accept gas samples collected in hypodermic syringes. All analyses for this study were performed within 4 hours of sample collection. All helium concentrations in this report are expressed as parts per billion (ppb) or parts per million (ppm) above the ambient air background of 5,240 ppb He, analytical precision of about ±10 ppb He. Samples were collected from hollow probes that had been driven into the ground.

Data

The daily helium variations of the Idaho Springs study are shown in figure 5. The barometric pressure is shown in figure 6, and cumulative precipitation is shown in figure 7.

Probes were permanently set at three stations 20 m north of Indian Springs resort lodge, each one at a different depth. The depth of station two was 0.5 m; station three, 0.75 m; and station four, 1.0 m. Samples were collected every 2-4 hours for the first 4 days of the 8-day study. The probes

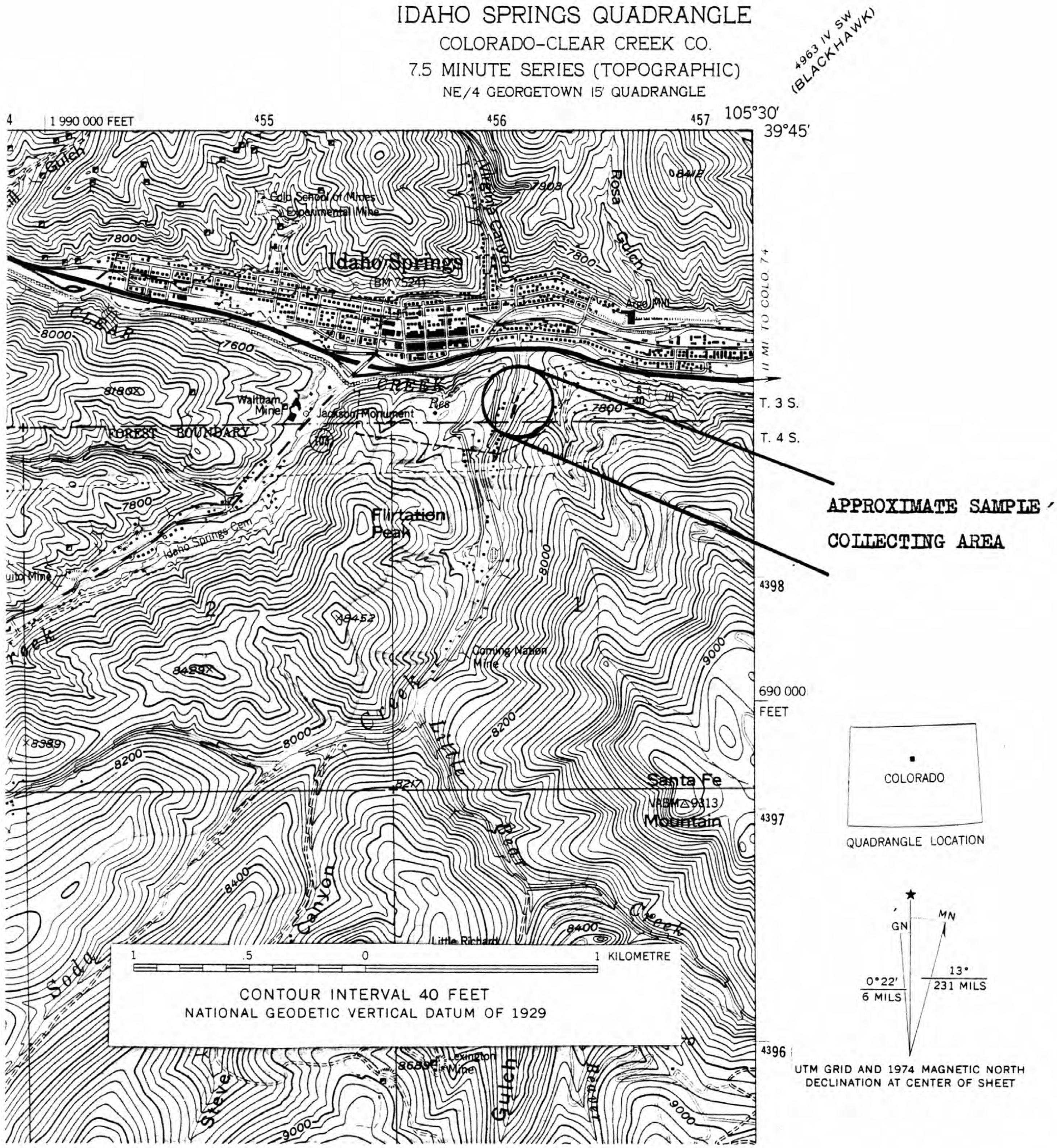


Figure 1.--Map of Idaho Springs, Colo., sample-collecting area. The probes were located in the northern trailer-park lot of the Indian Springs Resort.

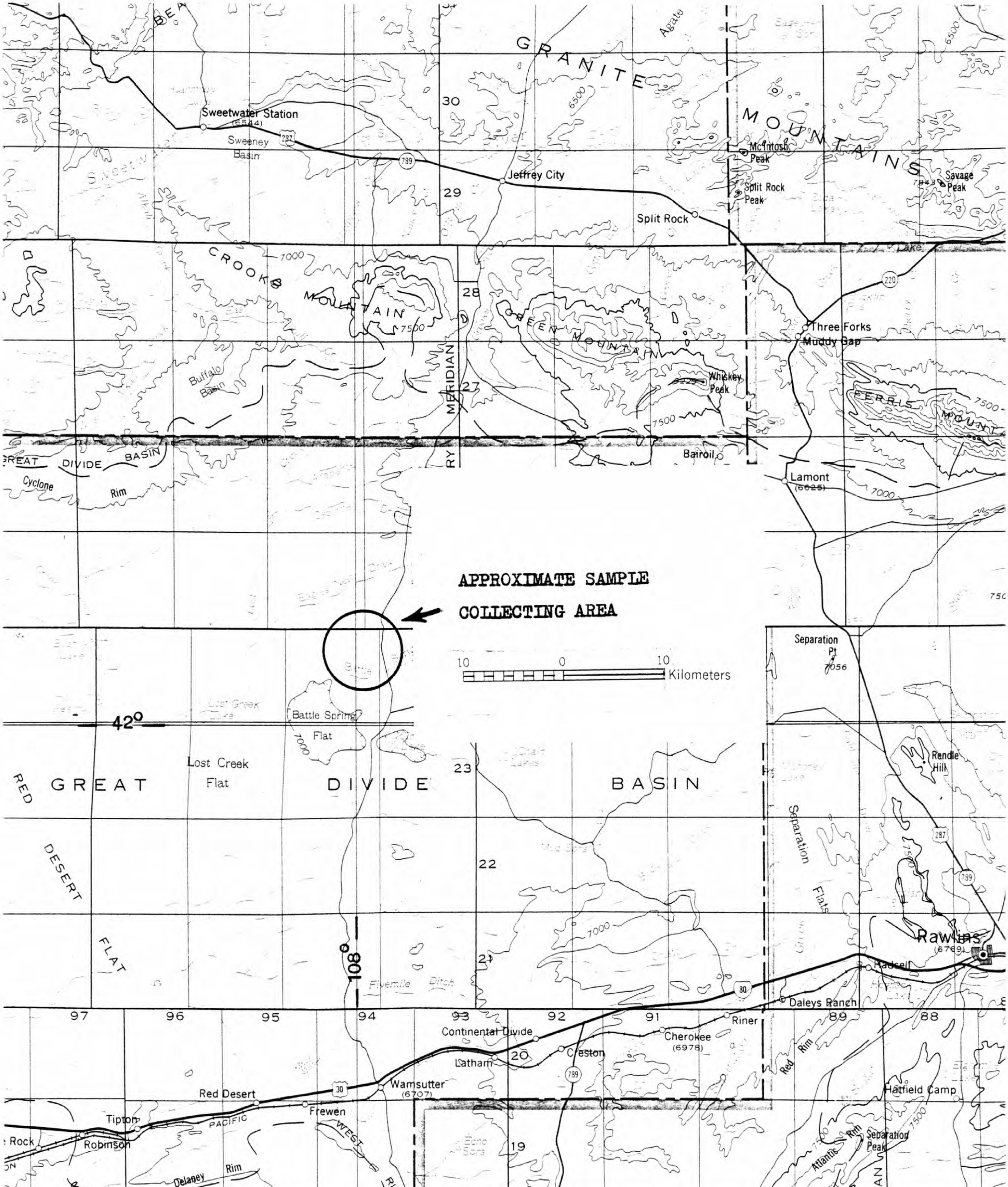


Figure 2.--Map of the Red Desert, Wyoming, sample-collecting area. The same area was sampled in December 1977 and July 1978.

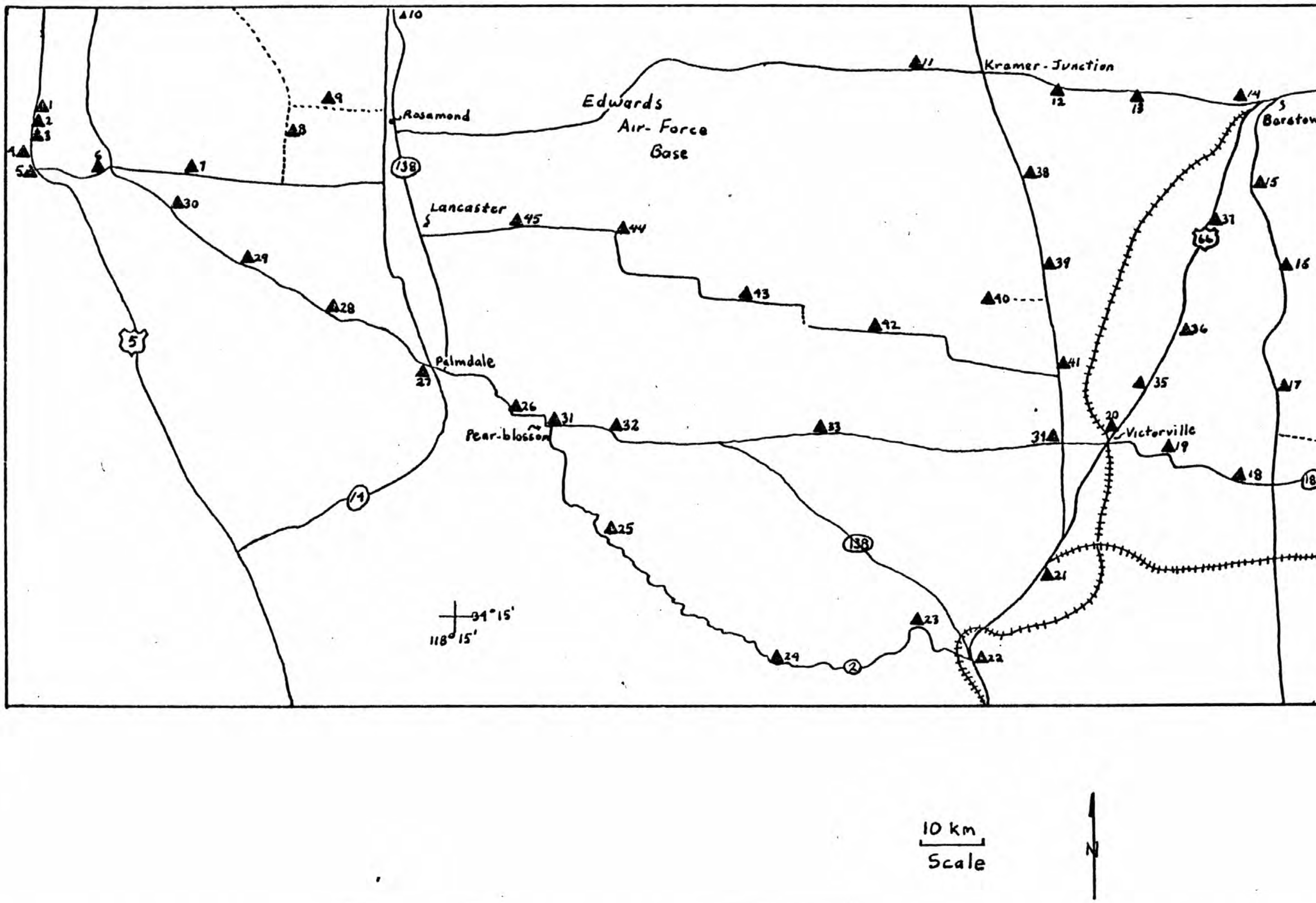


Figure 3.--Map of the Mojave Desert, California, sample-collecting area. The sample locations are indicated by solid triangles.

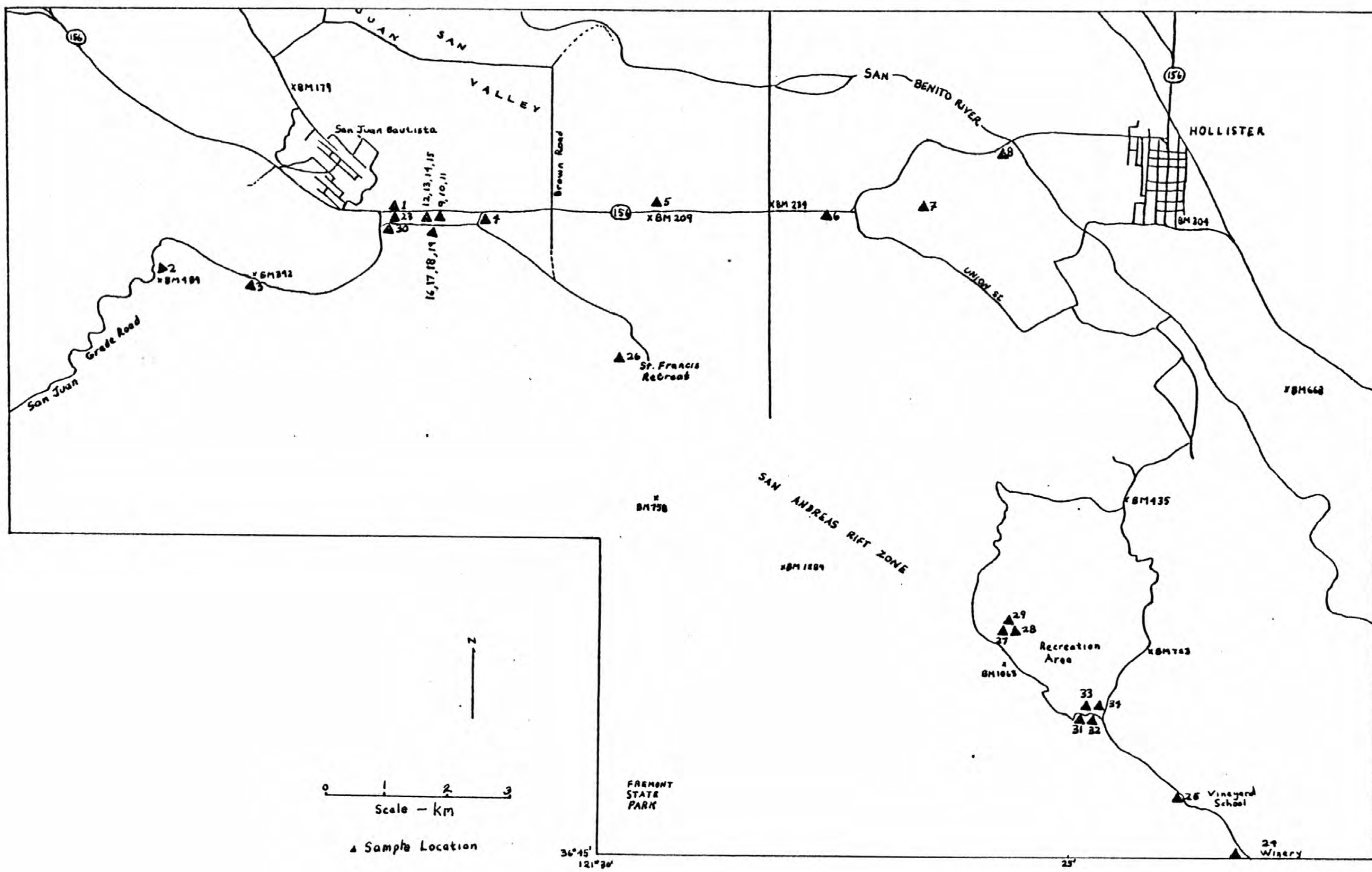


Figure 4.--Map of the San Juan Bautista, California, sample-collecting area. The sample locations are indicated by solid triangles.

Table 1.--Parameters considered at various sampling locations

[All parameters, except probe depth, soil temperature, and soil moisture were measured using recording instruments. X, parameter was measured, -, parameter was not measured]

	Idaho Springs	Red Desert	San Juan Bautista
Barometric pressure	X	-	X
Air temperature	X	X	X
Soil temperature	X	-	X
Wind speed	-	X	X
Relative humidity	X	-	X
Precipitation	X	-	X
Probe depth	X	-	X
Soil moisture	X	-	-

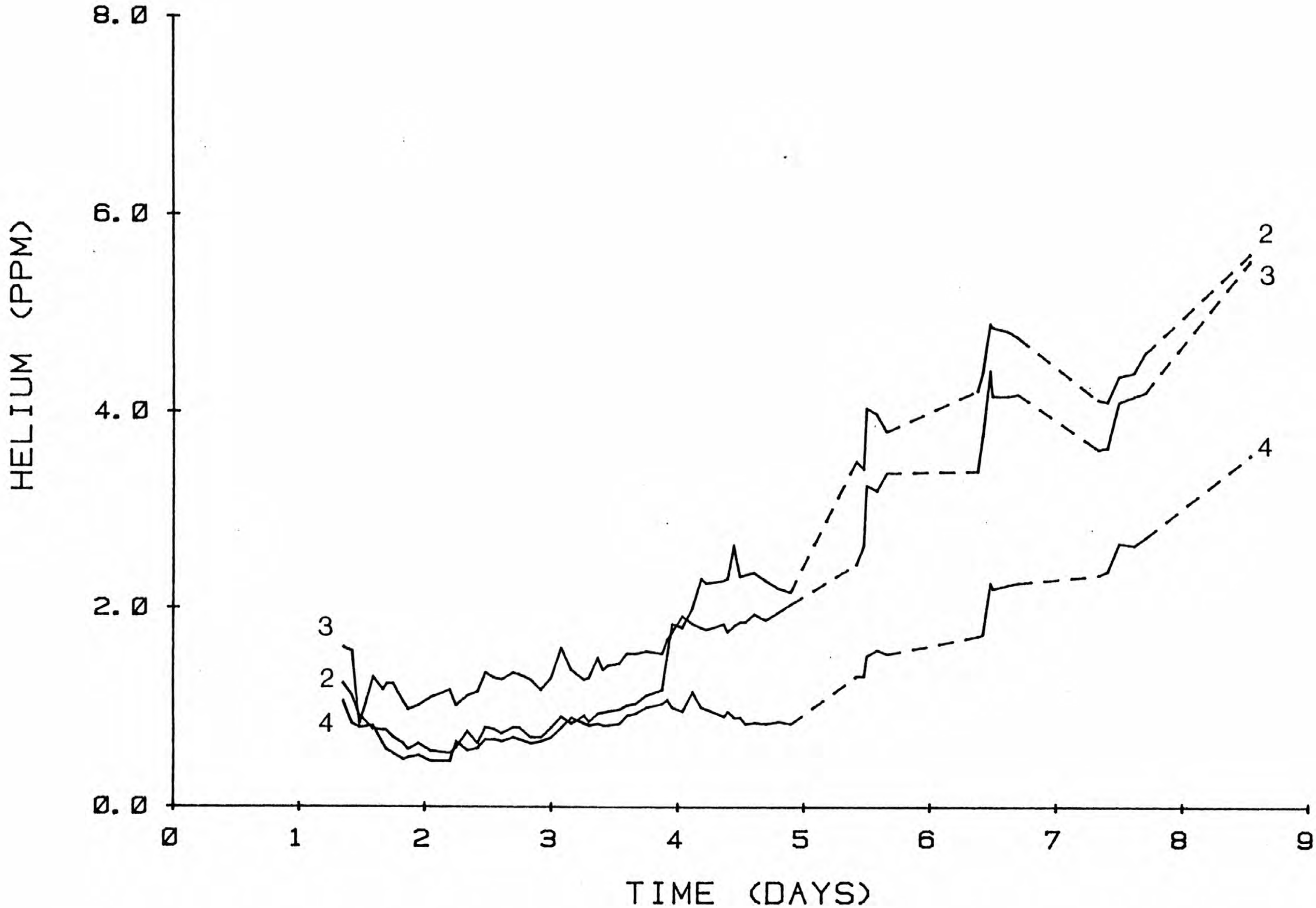


Figure 5.--Graph of the soil-gas helium variations for the Idaho Springs study. Probes at stations 2, 3, and 4 were at depths of 0.5, 0.75, and 1.0 m, respectively. Precipitation caused the soil-gas concentrations to increase more rapidly for the shallowest probe than for the deepest. Helium concentrations are expressed as parts per million above ambient air at 5.24 ppm helium.

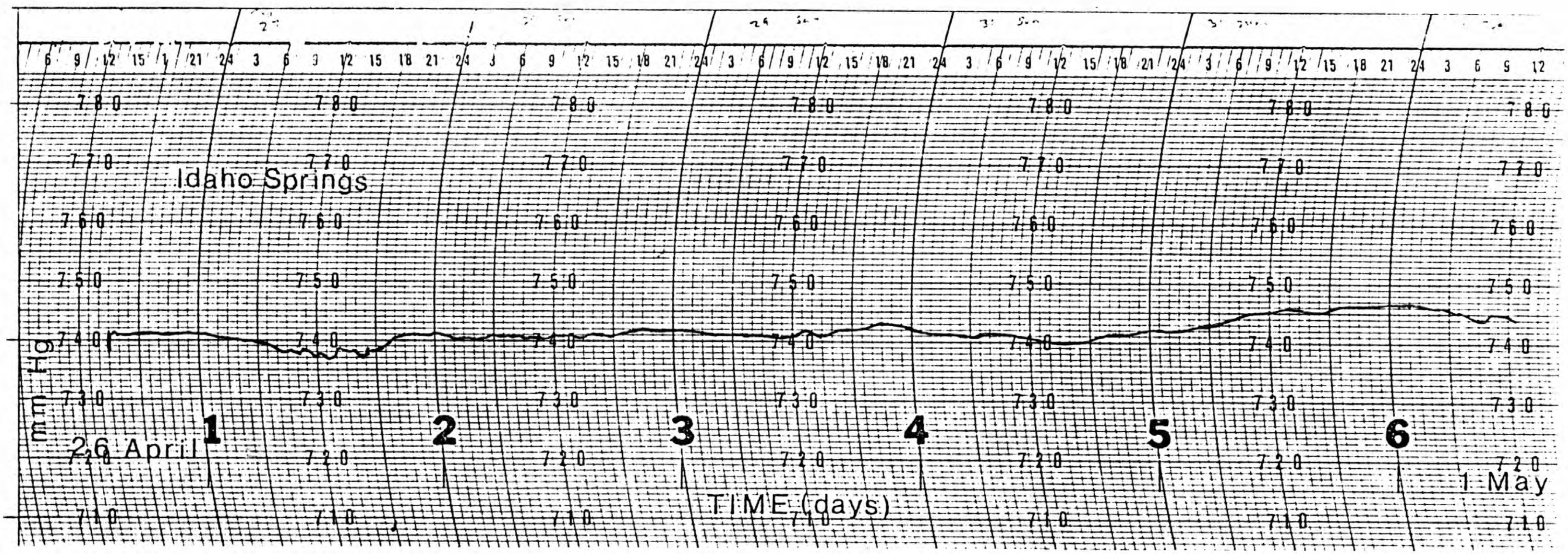


Figure 6.--Graph of Idaho Springs barometric-pressure variations. Fluctuation on day 1 (27 April) was during a windy period.

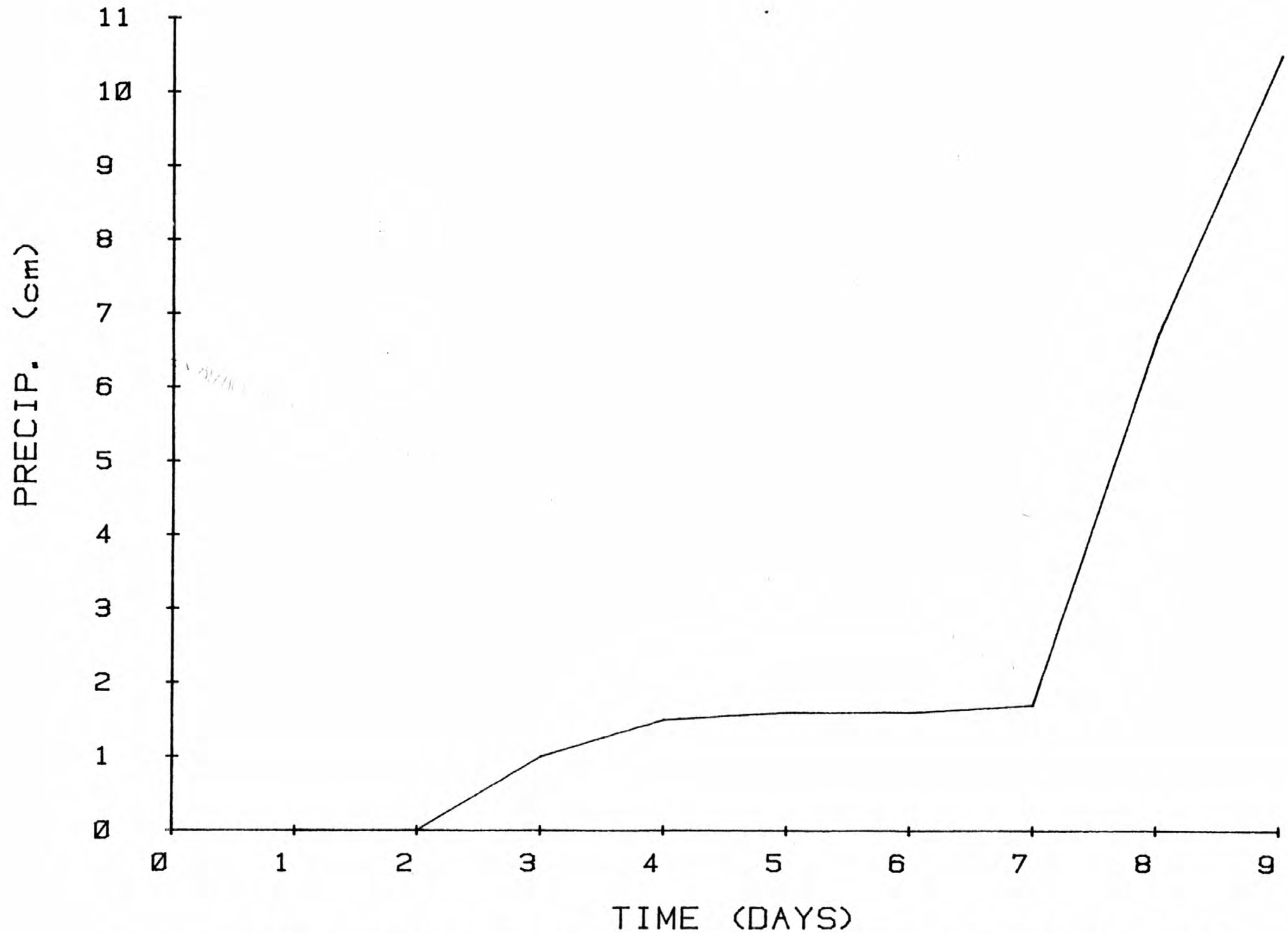


Figure 7.--Graph of the cumulative precipitation at Idaho Springs.

were sealed to the atmosphere and purged by drawing 10-cm^3 of gas through the probe before the 10-cm^3 sample for analysis was collected. For the first 4 days of the study, the barometric pressure did not vary more than ±1.5 mm of Hg. The only exception to pressure stability was for a 6-hour period during the first sampling day, when winds were gusting to 40 km/h. Light rain began to fall on the second day and continued as drizzle and snow until the seventh day when heavy snow began falling. Samples of the soil were taken near the probes and the soil-moisture content was determined by drying the samples in an oven at 90°C for 24 hours. Table 2 presents the results of the analysis of soil-moisture content.

The contoured helium content of soil gas for the Red Desert, Wyoming study is shown in figures 8 and 9 for the December 1977 study and the July 1978 study, respectively. A routine sampling plan used for helium surveys (Reimer and Otton, 1976) was employed in this study. Samples were collected from a depth of 1 m in both studies, and the sampling and analyses were completed within one day. Winds were 80-100 km/h, with gusts to 120 km/h for the December study. Winds did not exceed 30 km/hr for the July study.

The contoured concentrations of helium in soil-gas for the Mojave Desert study are shown in figure 10. This June 1978 reconnaissance sampling survey was made in the vicinity of the Palmdale Bulge and took two days to complete. Forty-five samples were collected over a 12,000-km^2 area. The samples were collected at a 1-m depth. This study provides a picture of the regional distribution of the soil-gas helium concentration.

The most detailed study comparing meteorological changes to soil-gas helium concentrations took place near San Juan Bautista, California. Observations were made for 10 days at 34 permanent sampling staions. Five areas had probes installed to different depths; three of those areas were

Table 2.--Moisture content of soils taken near Idaho Springs, May 1978

[Samples 2-9 were collected from a depth of 2-3 cm. Samples 1 and 10 were collected from a depth of 10-11 cm. Moisture content is reported in grams as weight loss per gram of sample after drying at 90°C]

Sample	Day	Moisture content ($g\ H_2O/g$ soil)
1	1	0.0012
2	1	.0034
3	2	.0029
4	2	.0069
5	3	.0082
6	4	.0324
7	5	.0367
8	6	.0589
9	7	.0897
10	7	.0072

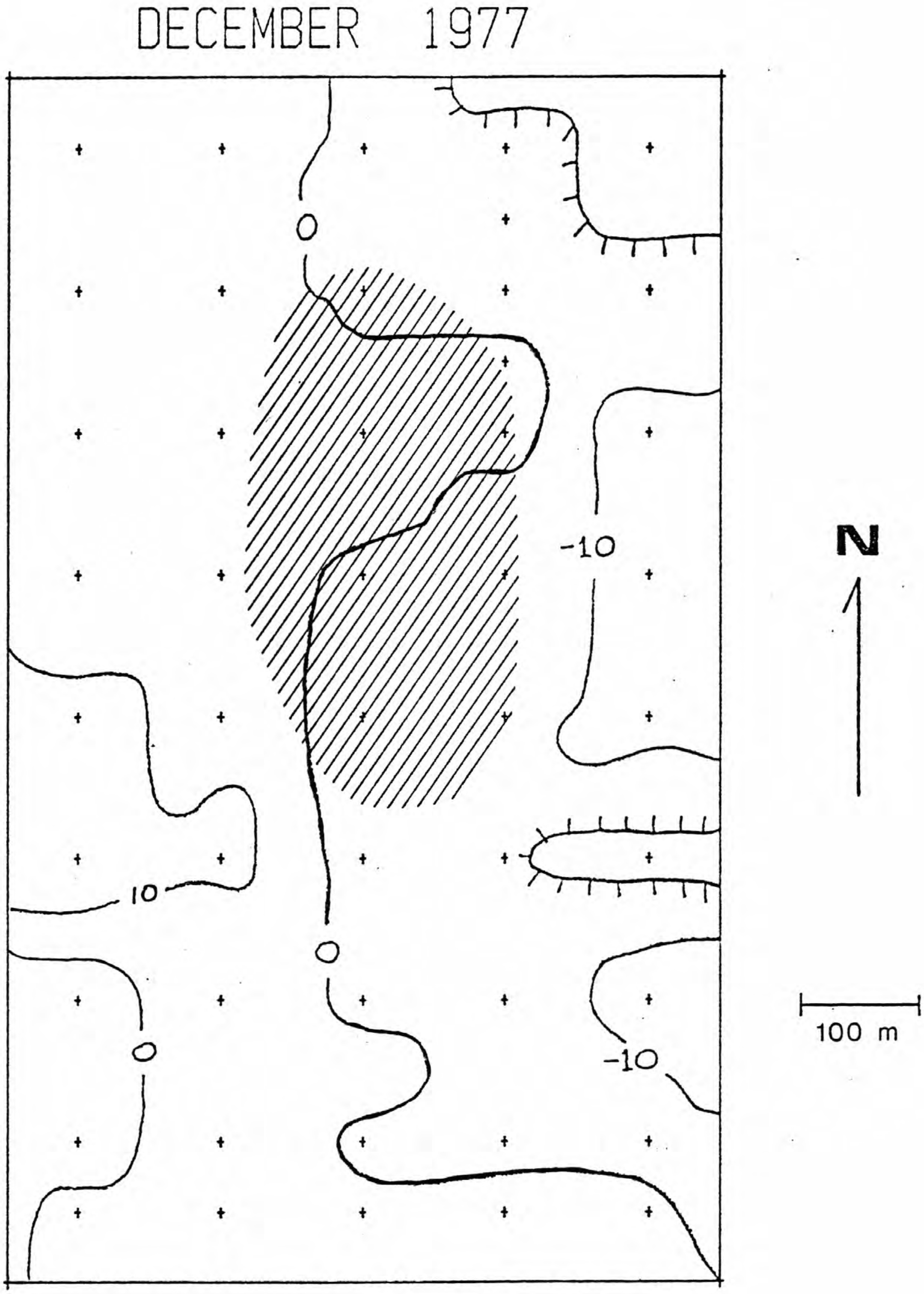


Figure 8.--Contour map of the helium concentrations for the December 1977 Red Desert study. The crosshatched area represents the approximate location of the uranium deposit. The contour interval is 10 ppb He. Helium concentrations are expressed as parts per billion with respect to helium in air at 5,240 ppb.

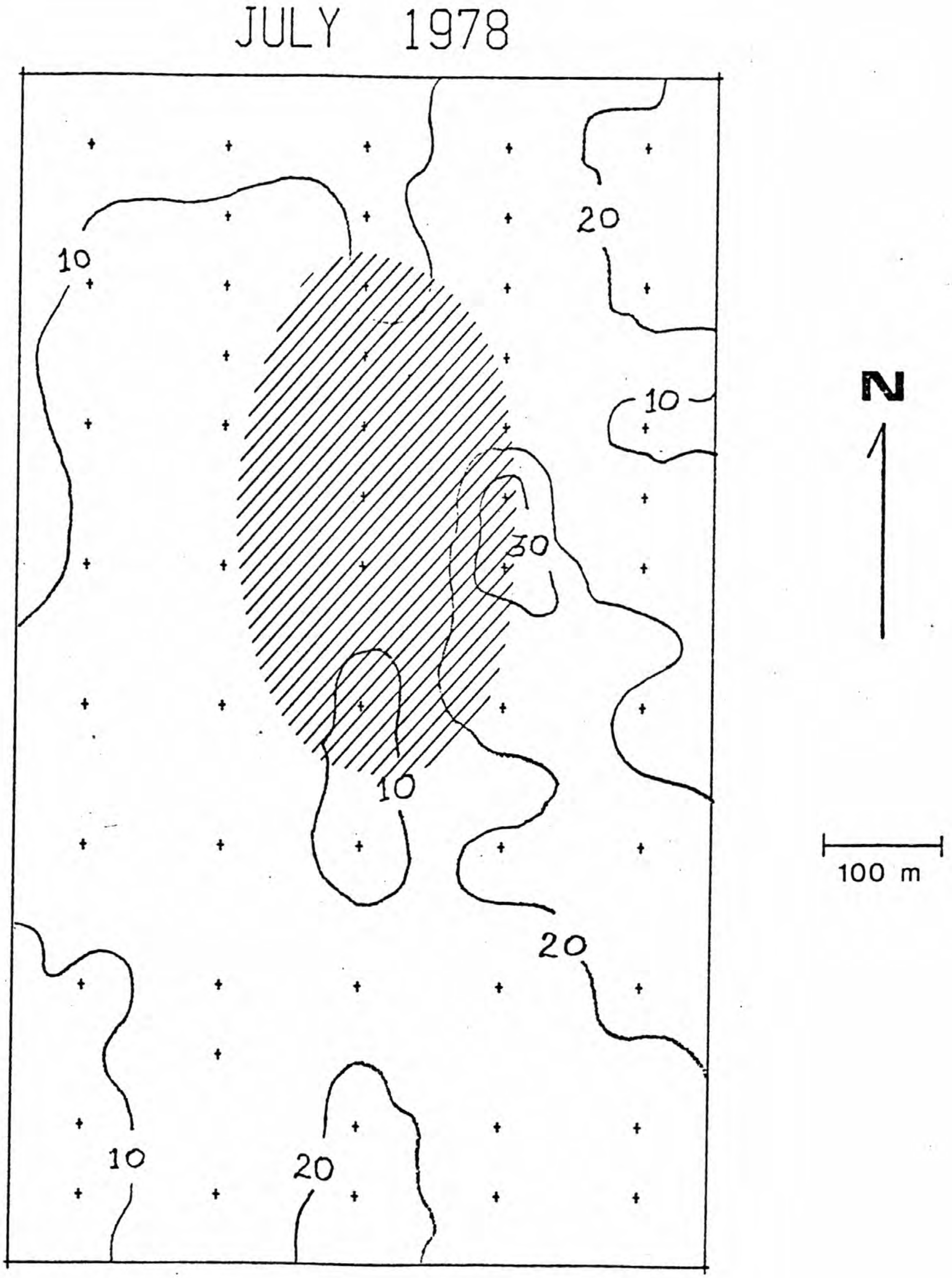


Figure 9.--Contour map of the helium concentrations for the July 1978 Red Desert study. The crosshatched area represents the approximate location of the uranium deposit. The contour interval is 10 ppb. Helium concentrations are expressed as parts per billion with respect to helium in ambient air at 5,240 ppb.

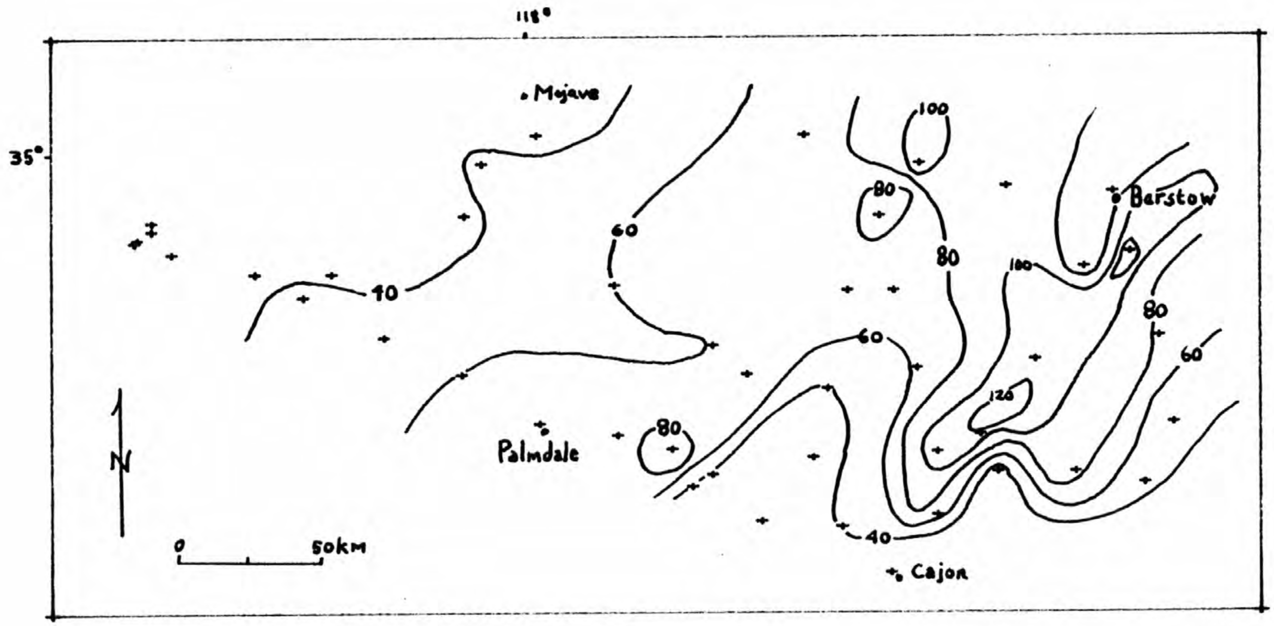


Figure 10.--Contour map of the helium concentrations for the Mojave Desert study. The contour interval is 20 ppb. The highest soil-gas helium concentrations occur between Barstow and Cajon. Helium concentrations are reported as parts per billion with respect to ambient air at 5,240 ppb.

sampled manually every few hours. The remaining stations had probes installed to a 1-meter depth and traced a 25-km traverse from San Juan Bautista through Hollister and ending at the Cienega Winery. For the most part, the traverse probes were sampled once daily.

Figures 11 through 44 show plots of the helium in soil-gas variations with time as well as the average helium (dashed line) and range in helium values for each station. Figure 45 presents the information on the barometric pressure, air temperature, relative humidity/precipitation, wind speed, and soil temperature. These parameters were measured at a base camp established near sample stations 9-11, 12-15, and 16-19. This base camp was adjacent to the continuous radon monitoring station established at the Mission Park Campground by Chi-yu King of the U.S. Geological Survey. Confirmation of the barometric pressure and relative humidity was provided by Paul Reasenberg (written commun., 1978), also of the U.S. Geological Survey, who had established a recording station nearby at St. Francis Retreat.

Discussion

The results of this initial investigation provide some insight into the causes of the observed daily variations of soil-gas helium concentrations. Variations in soil-gas radon concentrations have also been observed; barometric-pressure changes (Kraner and other, 1964) and precipitation (Gableman, 1972) have been reported as being the primary causes of the variation. In general, helium variations are much less than reported radon variations. The specific mechanisms involved in helium variations can be established from information gathered by this investigation, and an understanding of what constitutes a soil-gas sample can be established. The primary factors controlling the daily variation in soil-gas helium concentration are soil moisture and mixing with the atmosphere. Seasonal

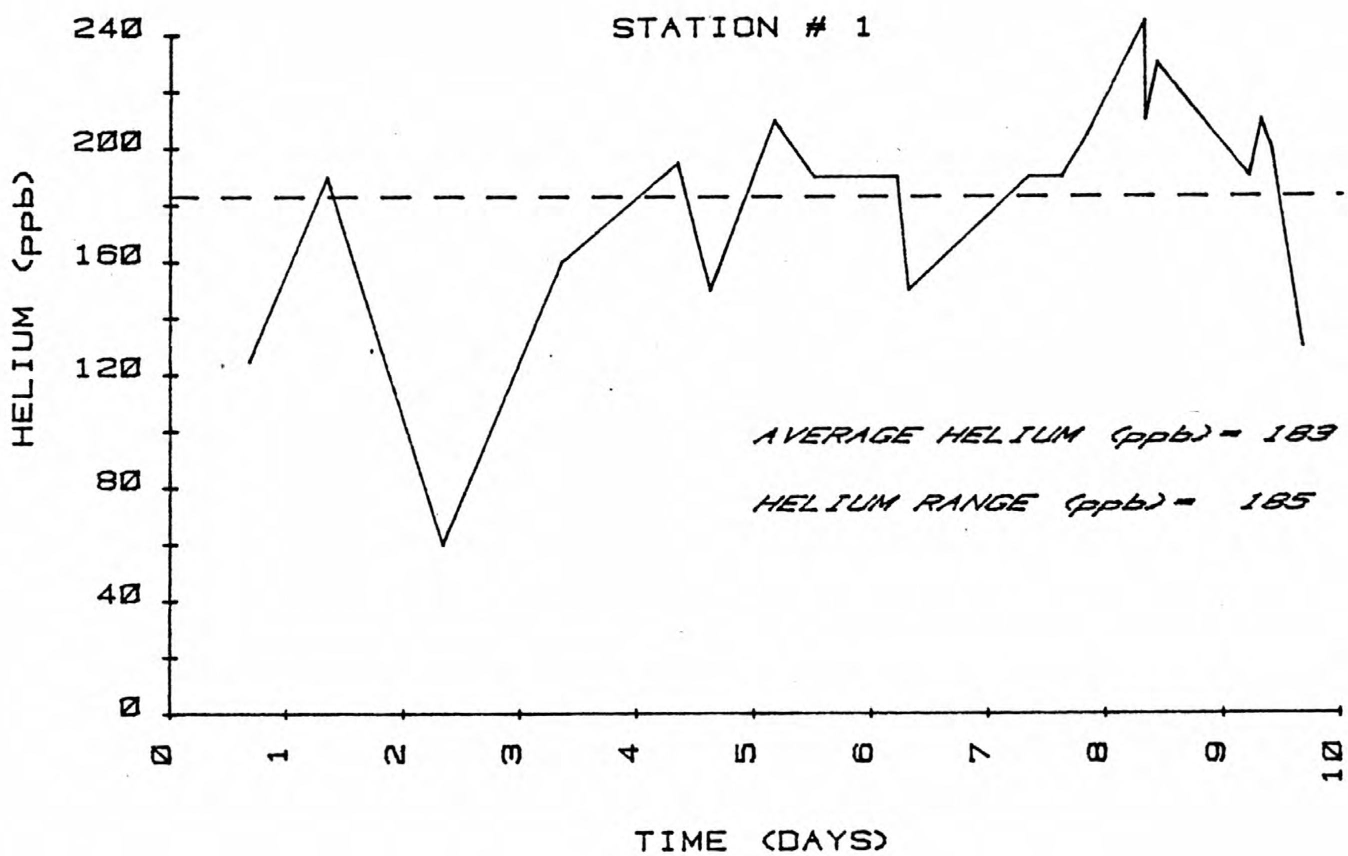


Figure 11: Graph of San Juan Bautista station 1 soil-gas helium variation.

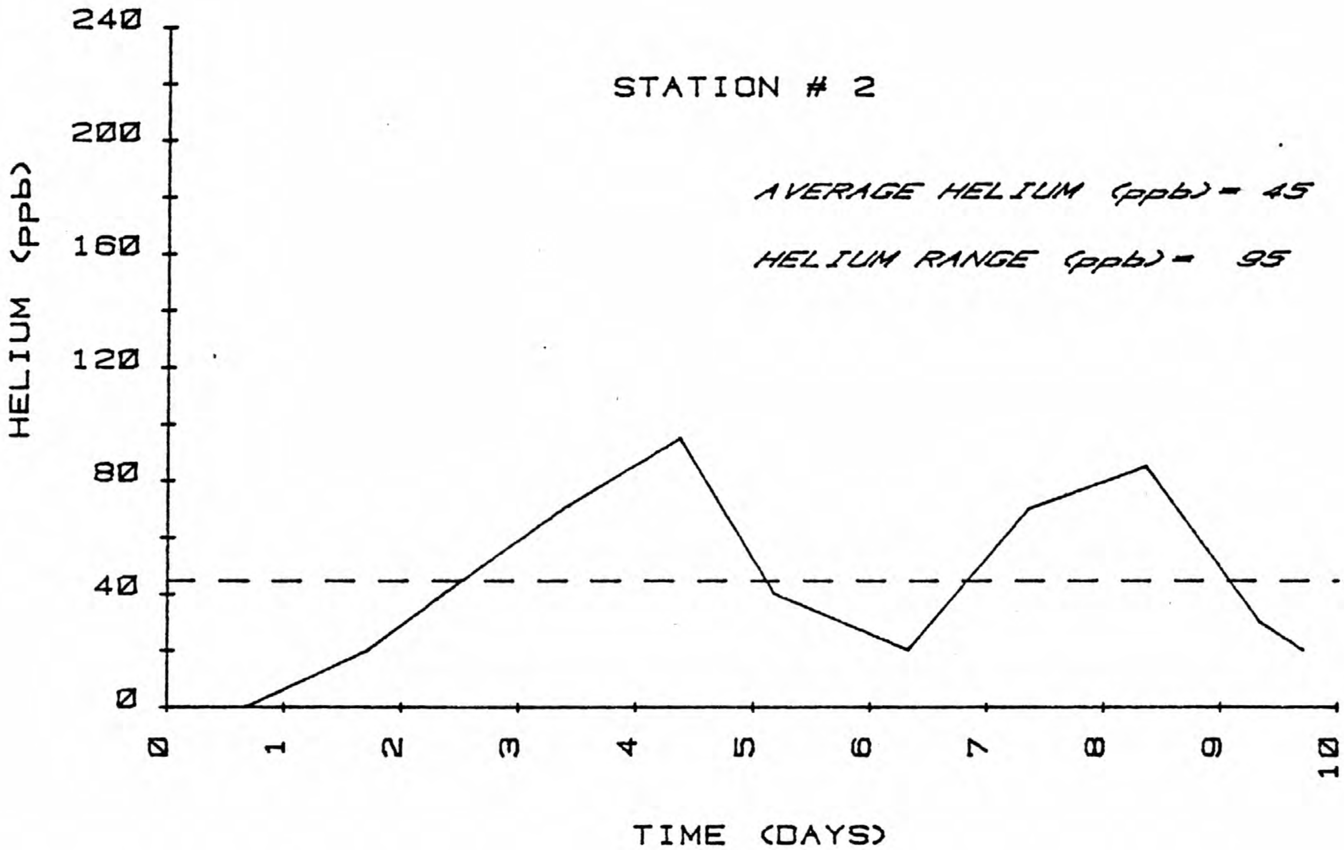


Figure 12: Graph of San Juan Bautista station 2 soil-gas helium variation.

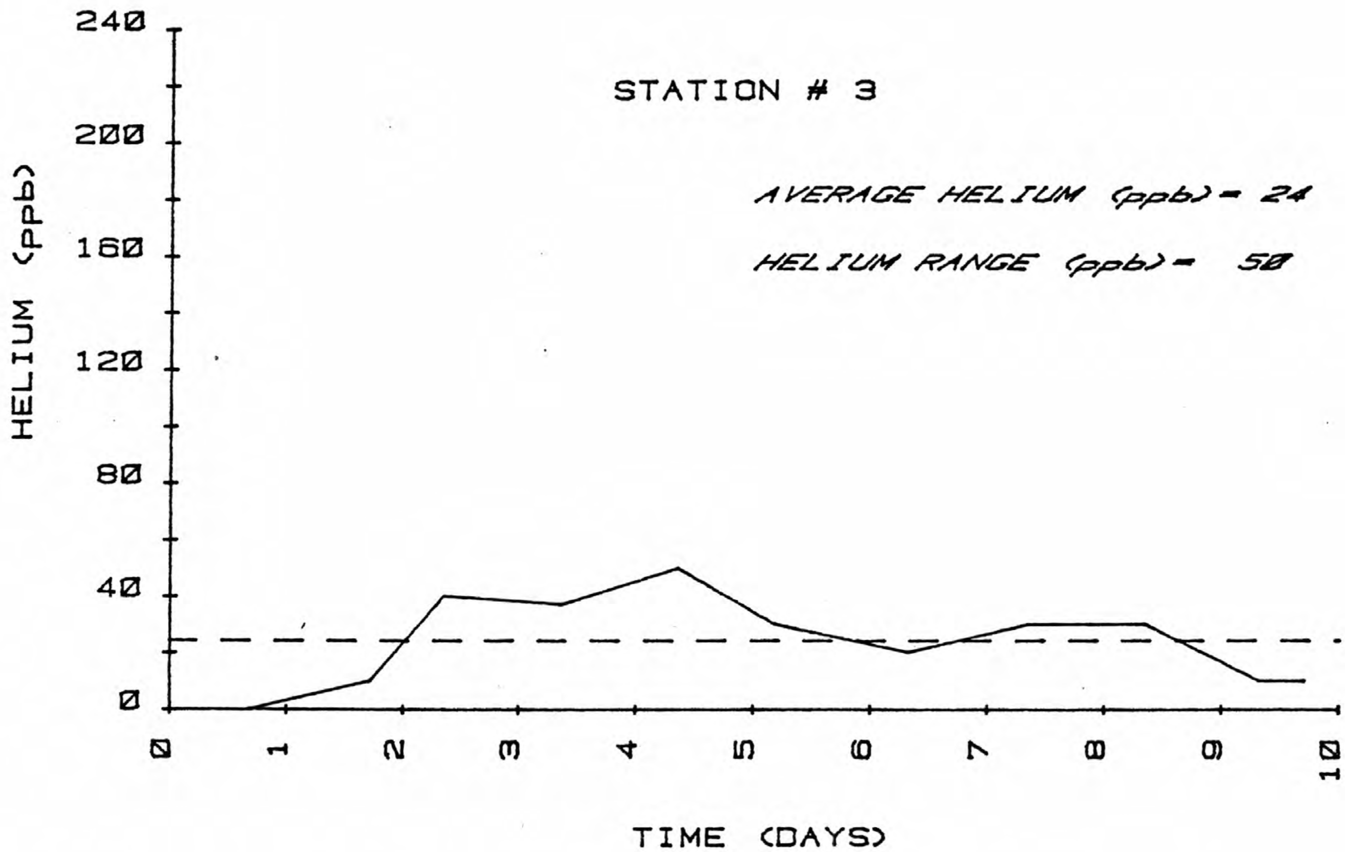


Figure 13: Graph of San Juan Bautista station 3 soil-gas helium variation.

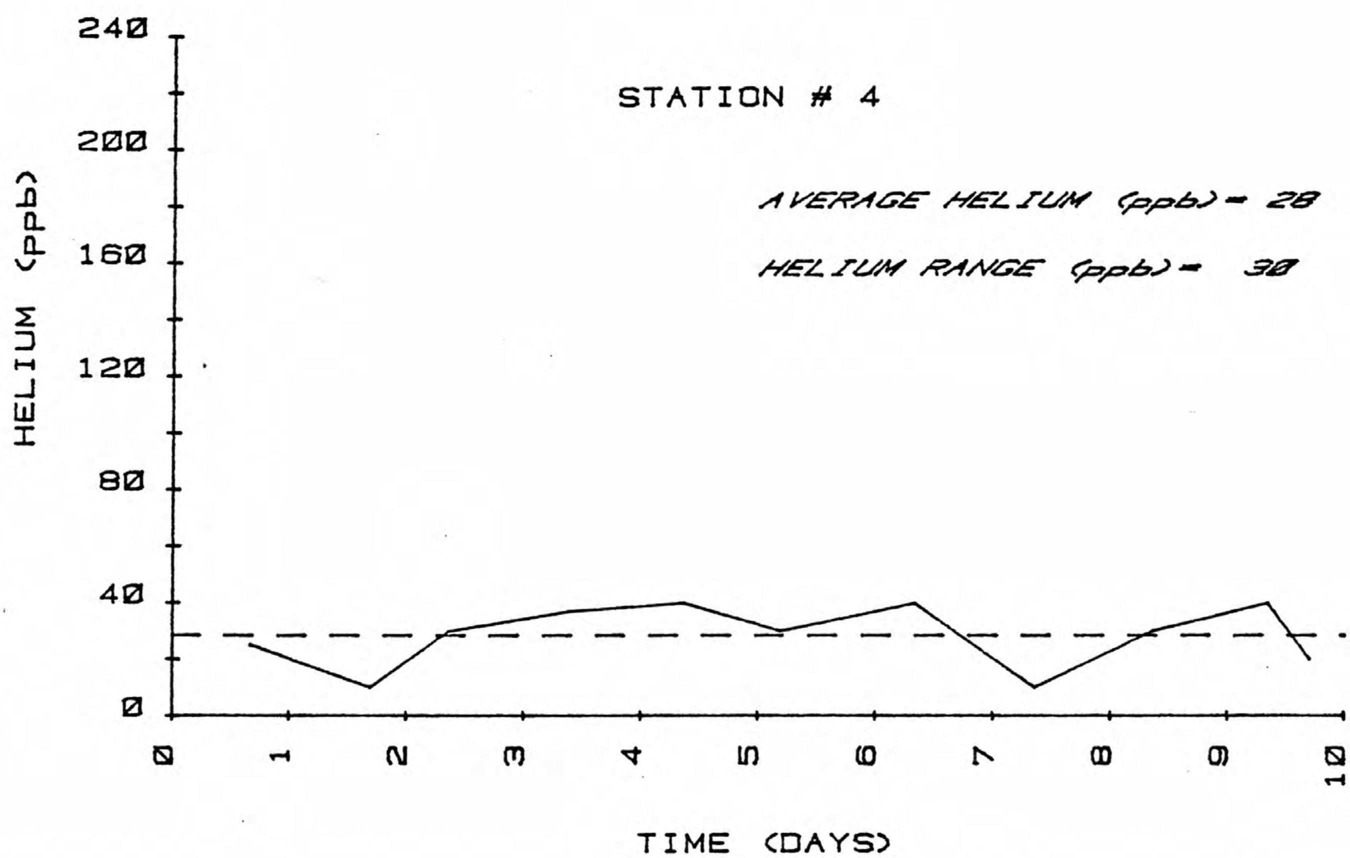


Figure 14: Graph of San Juan Bautista station 4 soil-gas helium variation.

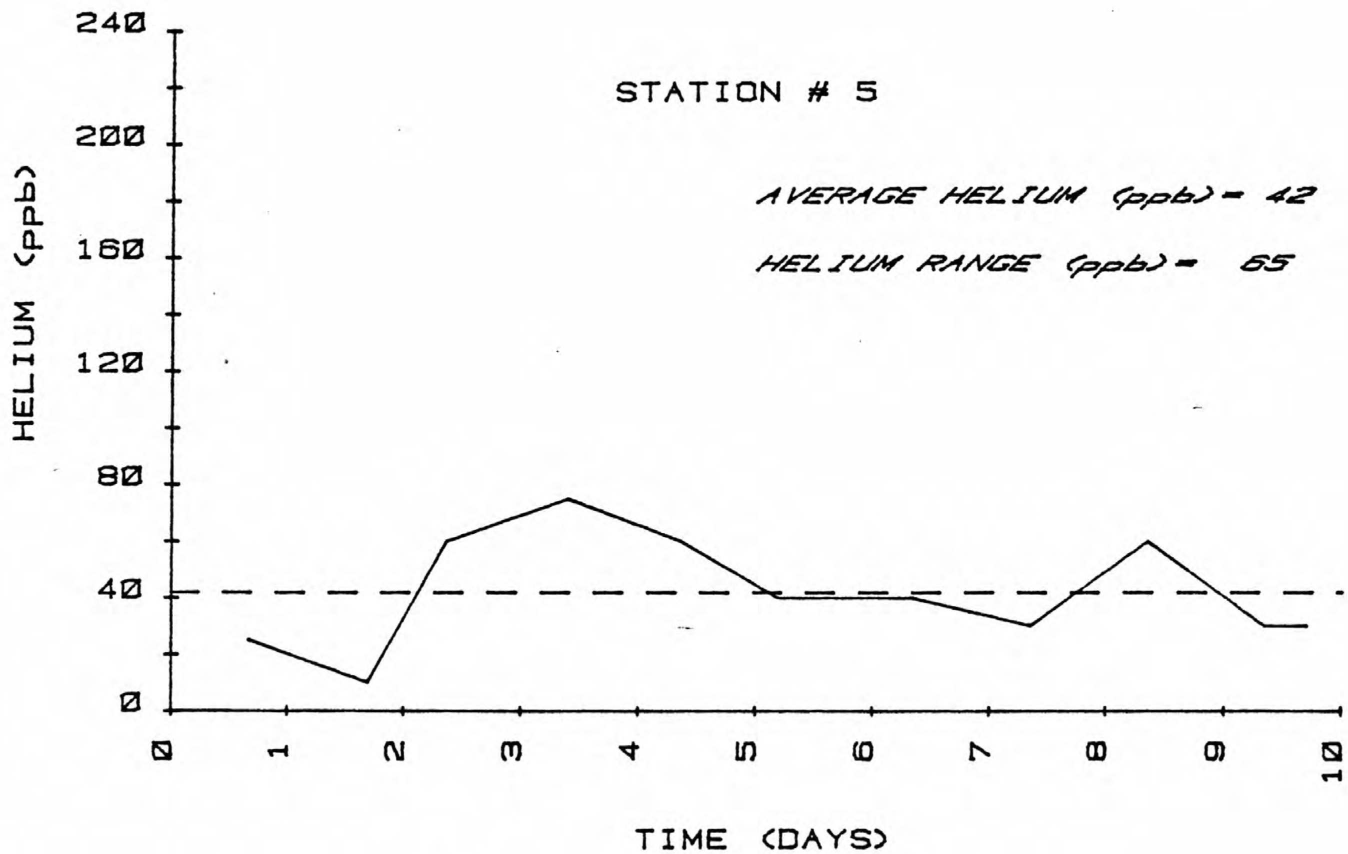


Figure 15: Graph of San Juan Bautista station 5 soil-gas helium variation.

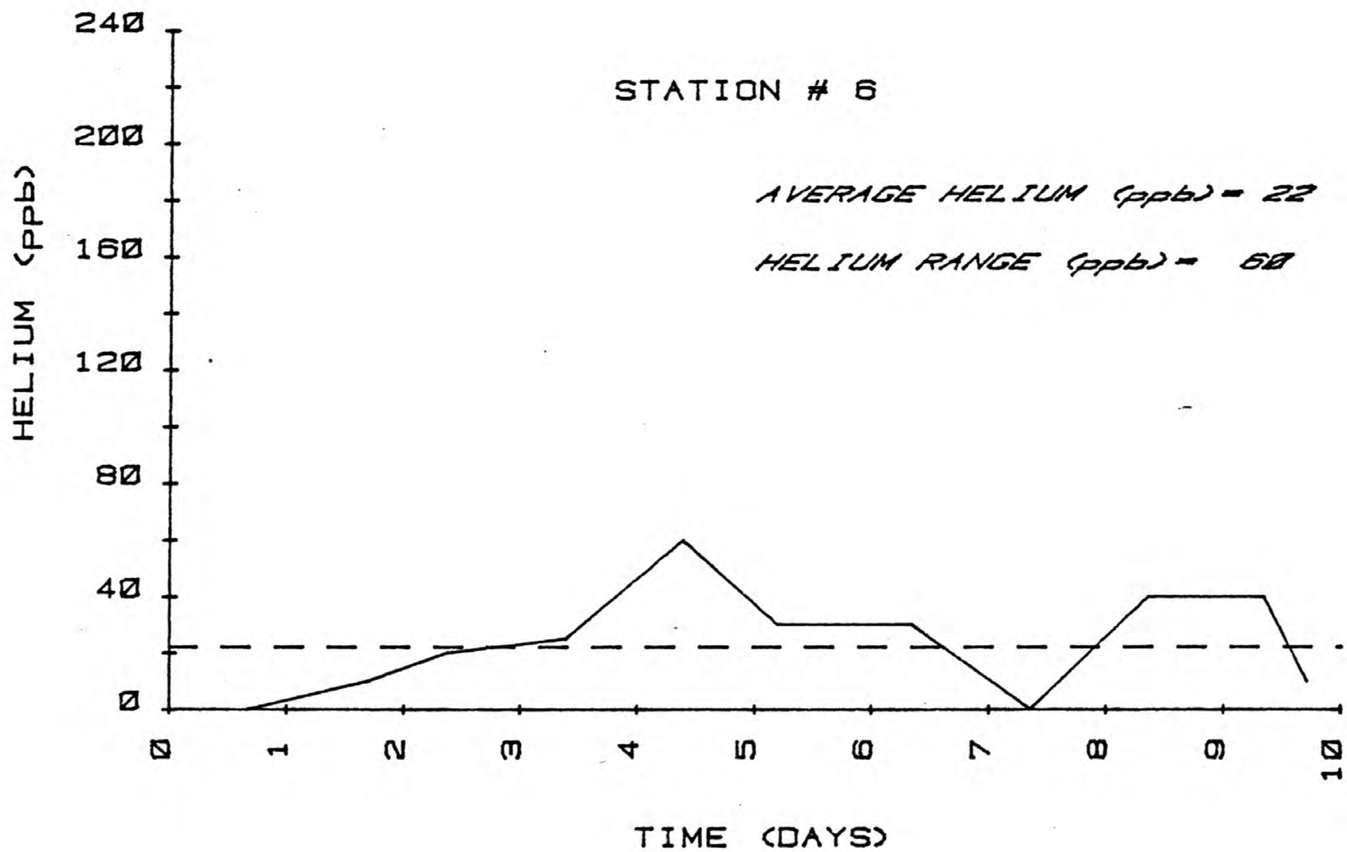


Figure 16: Graph of San Juan Bautista station 6 soil-gas helium variation.

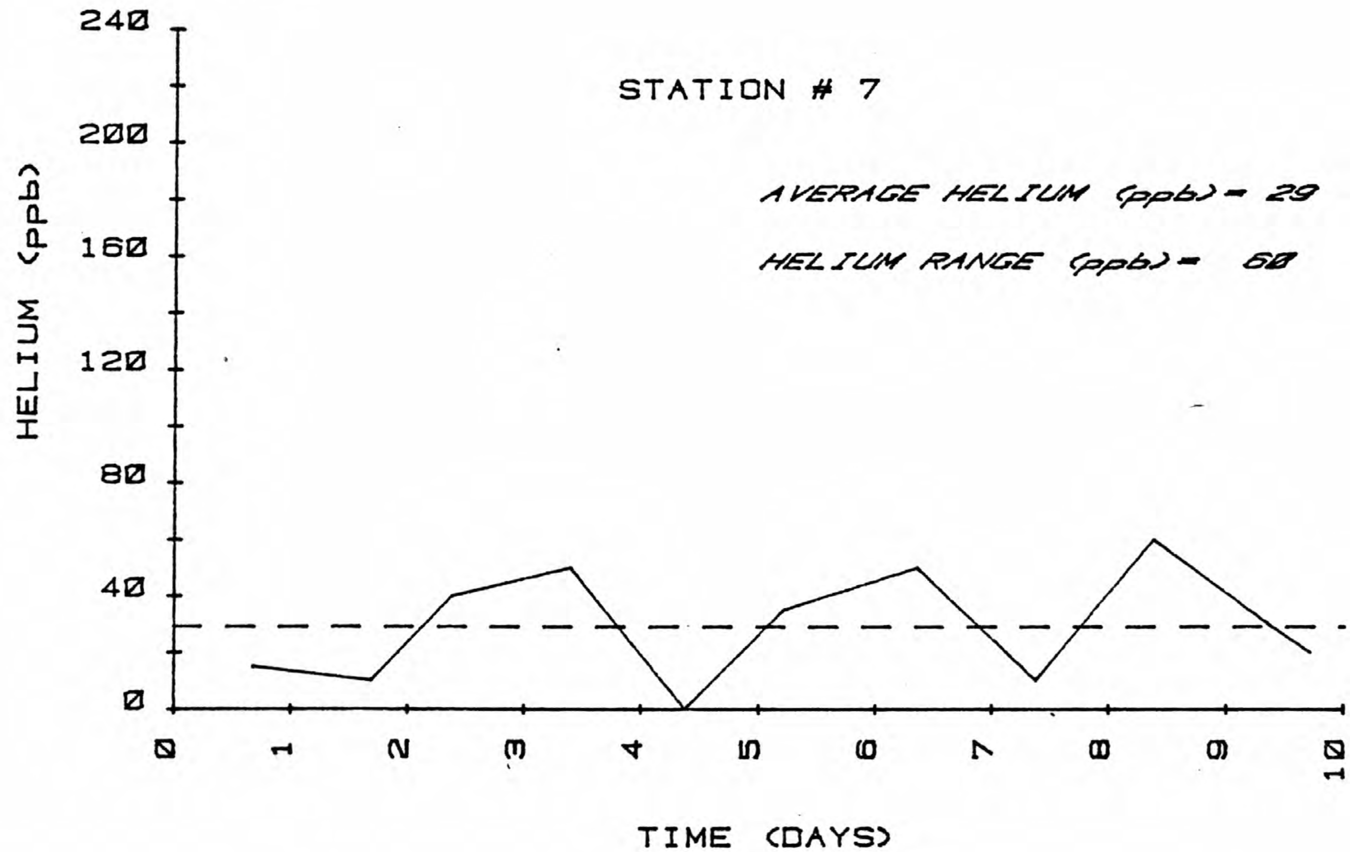


Figure 17: Graph of San Juan Bautista station 7 soil-gas helium variation.

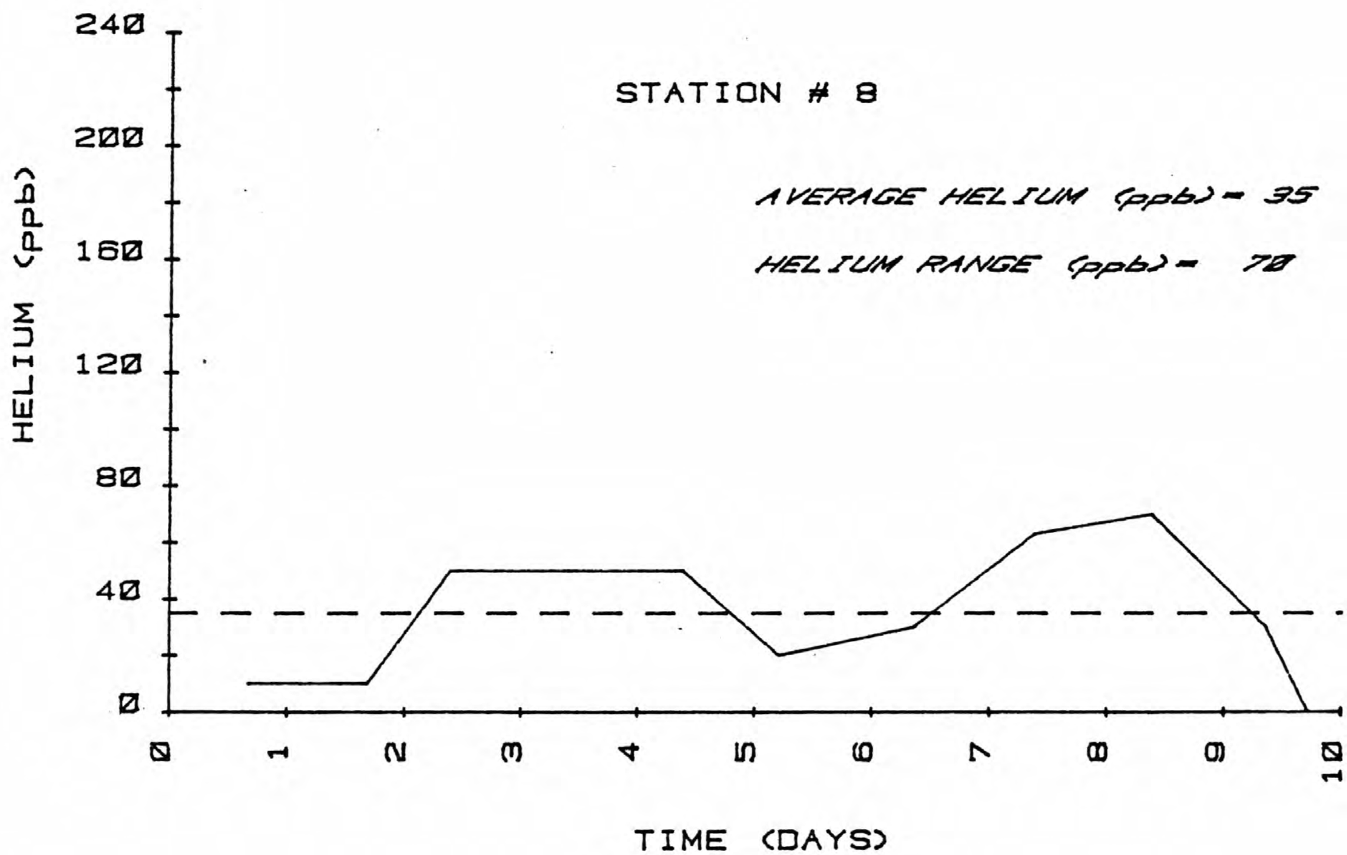


Figure 18: Graph of San Juan Bautista station 8 soil-gas helium variation.

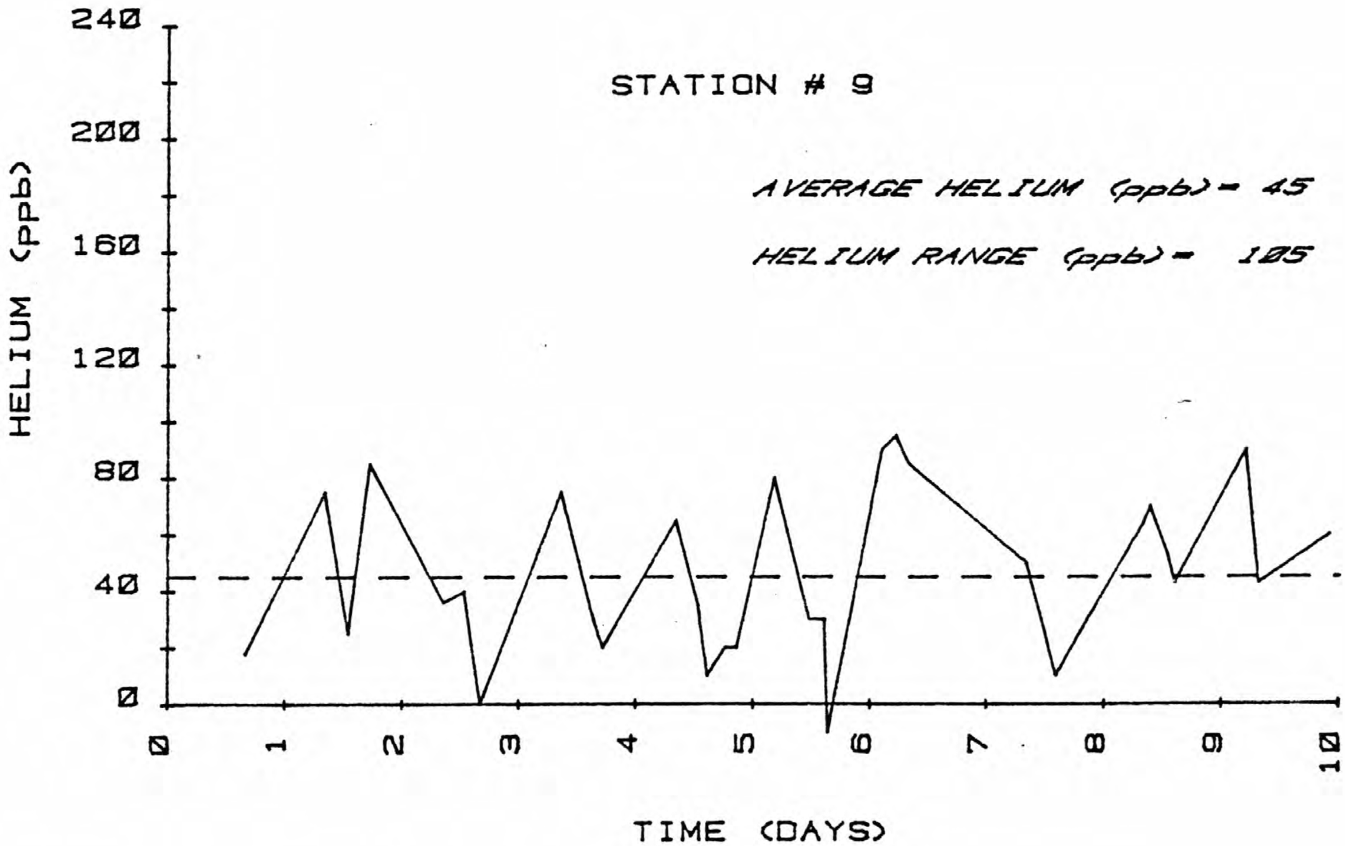


Figure 19: Graph of San Juan Bautista station 9 soil-gas helium variation.

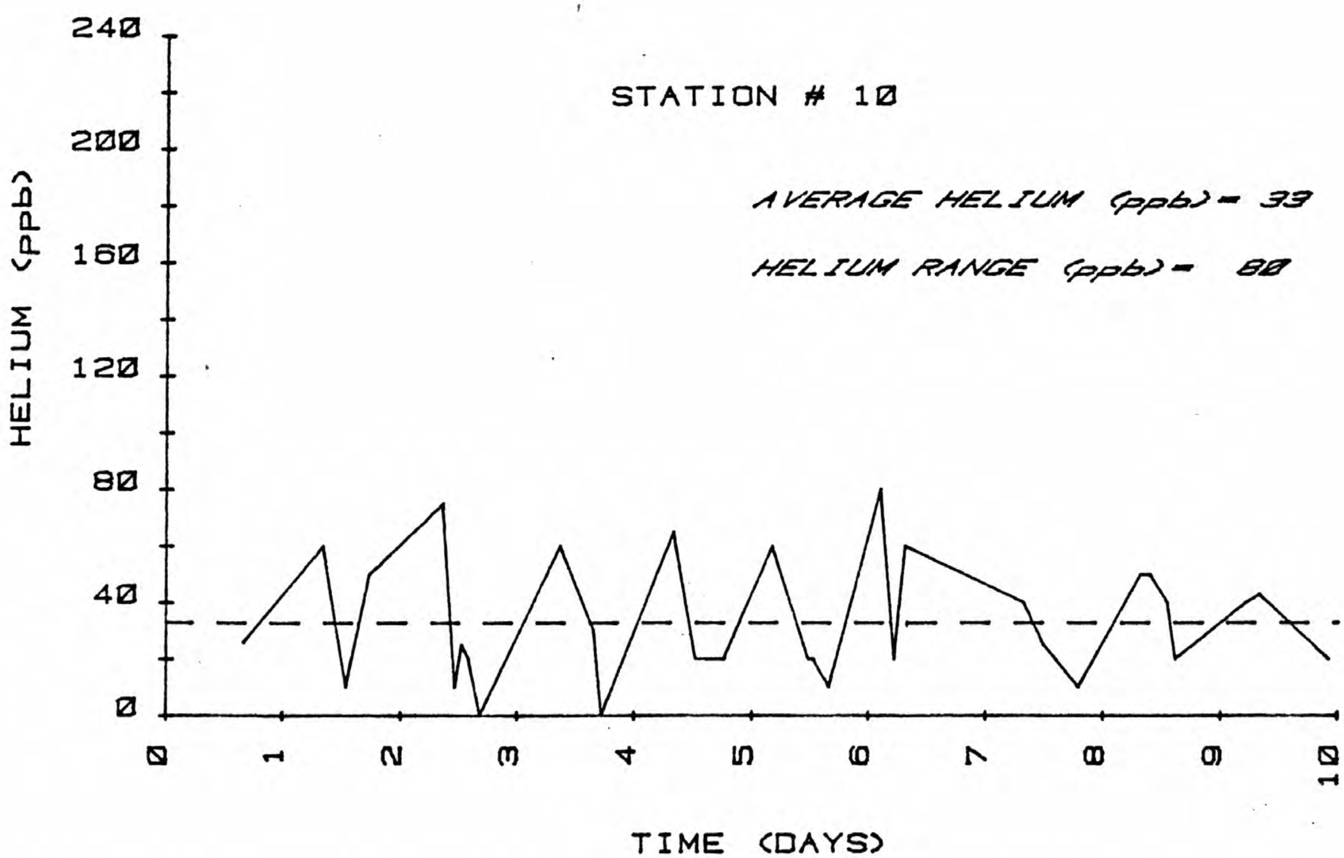


Figure 20: Graph of San Juan Bautista station 10 soil-gas helium variation.

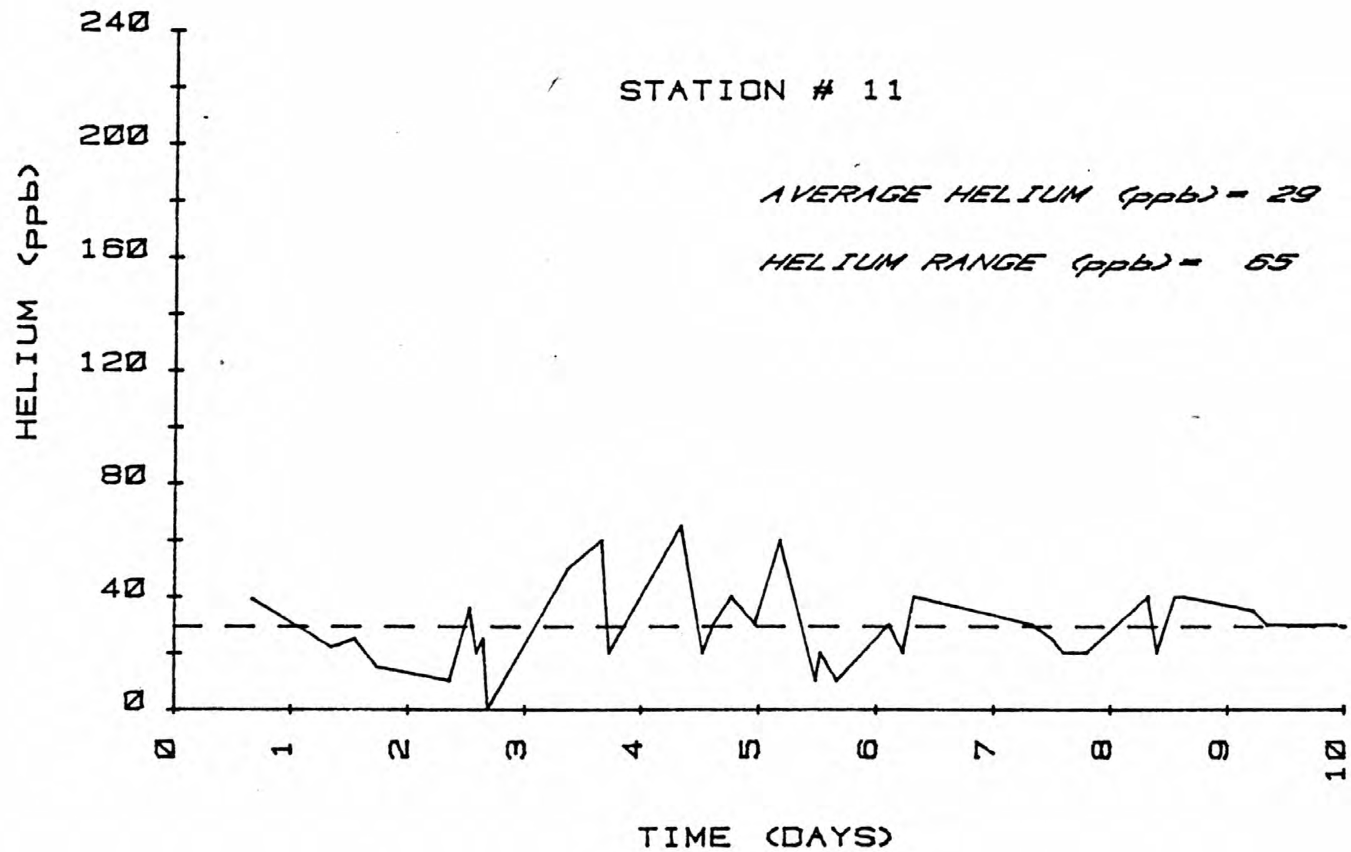


Figure 21: Graph of San Juan Bautista station 11 soil-gas helium variation.

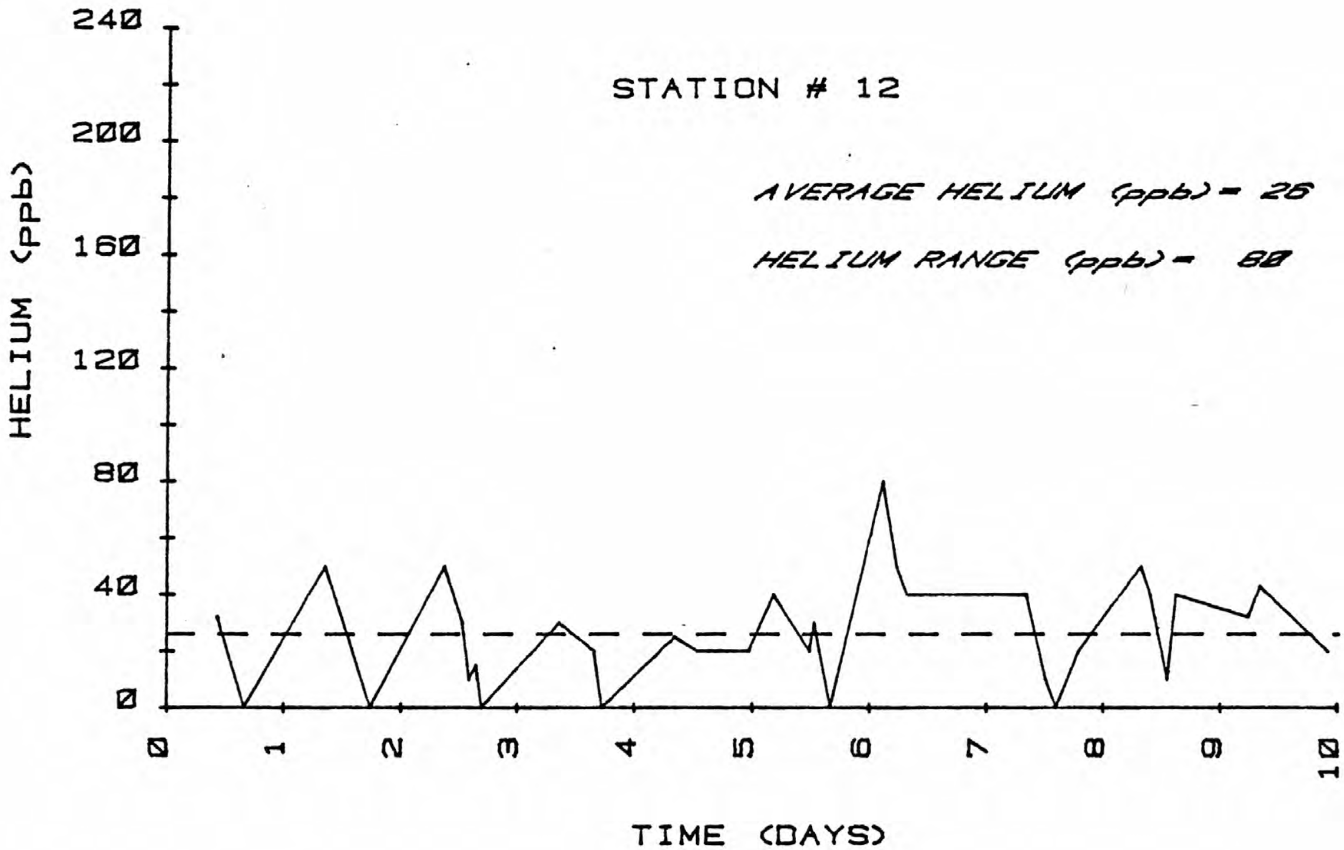


Figure 22: Graph of San Juan Bautista station 12 soil-gas helium variation.

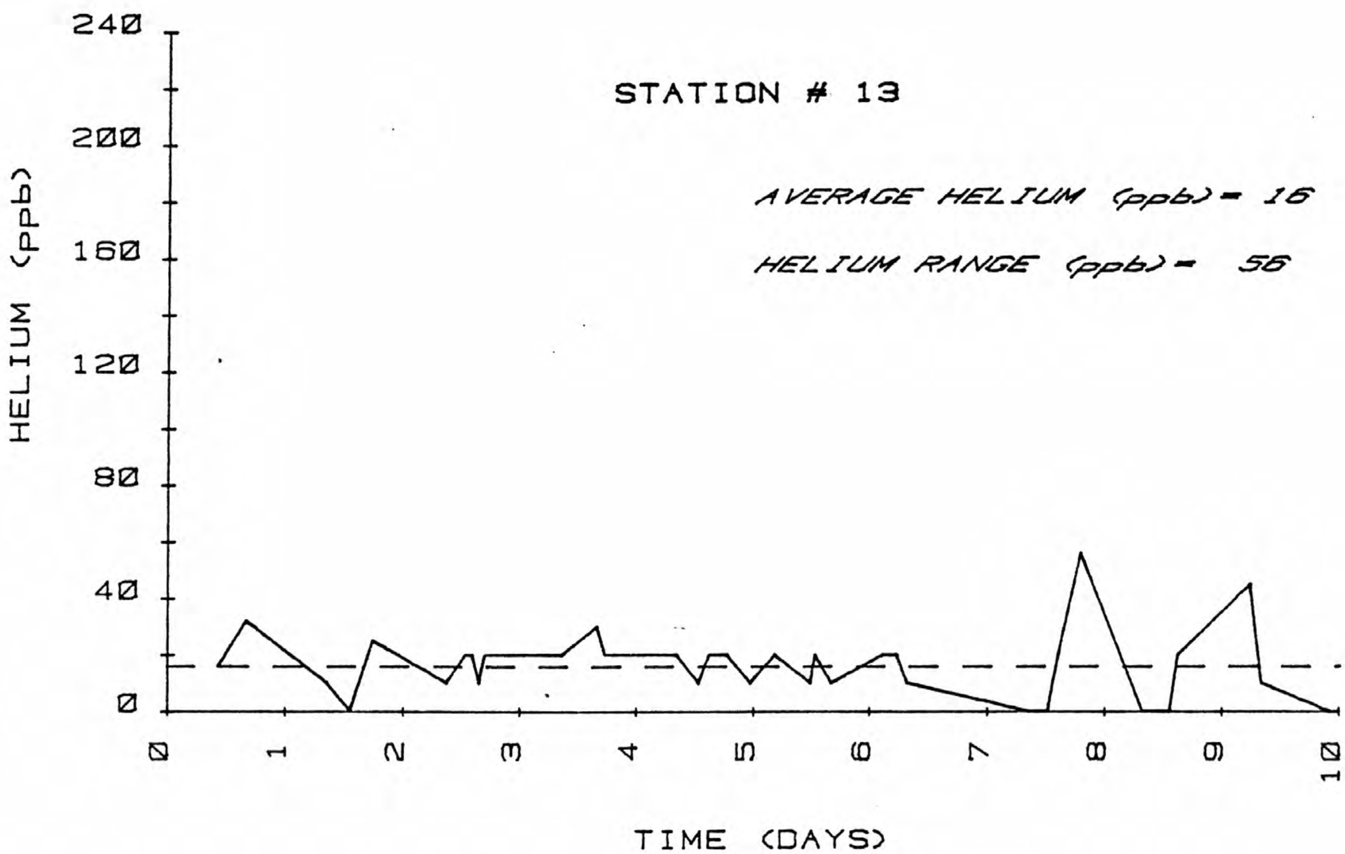


Figure 23: Graph of San Juan Bautista station 13 soil-gas helium variation.

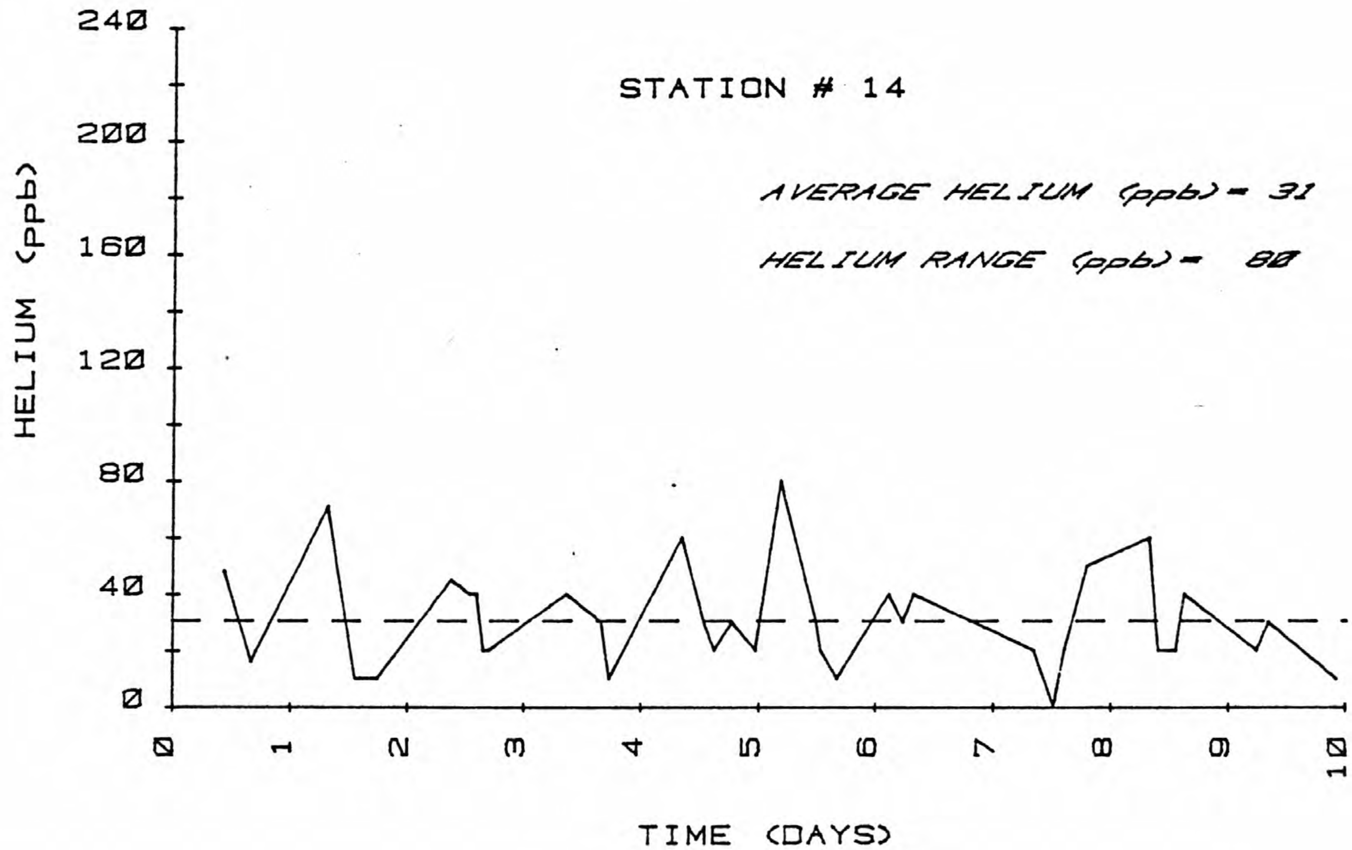


Figure 24: Graph of San Juan Bautista station 14 soil-gas helium variation.

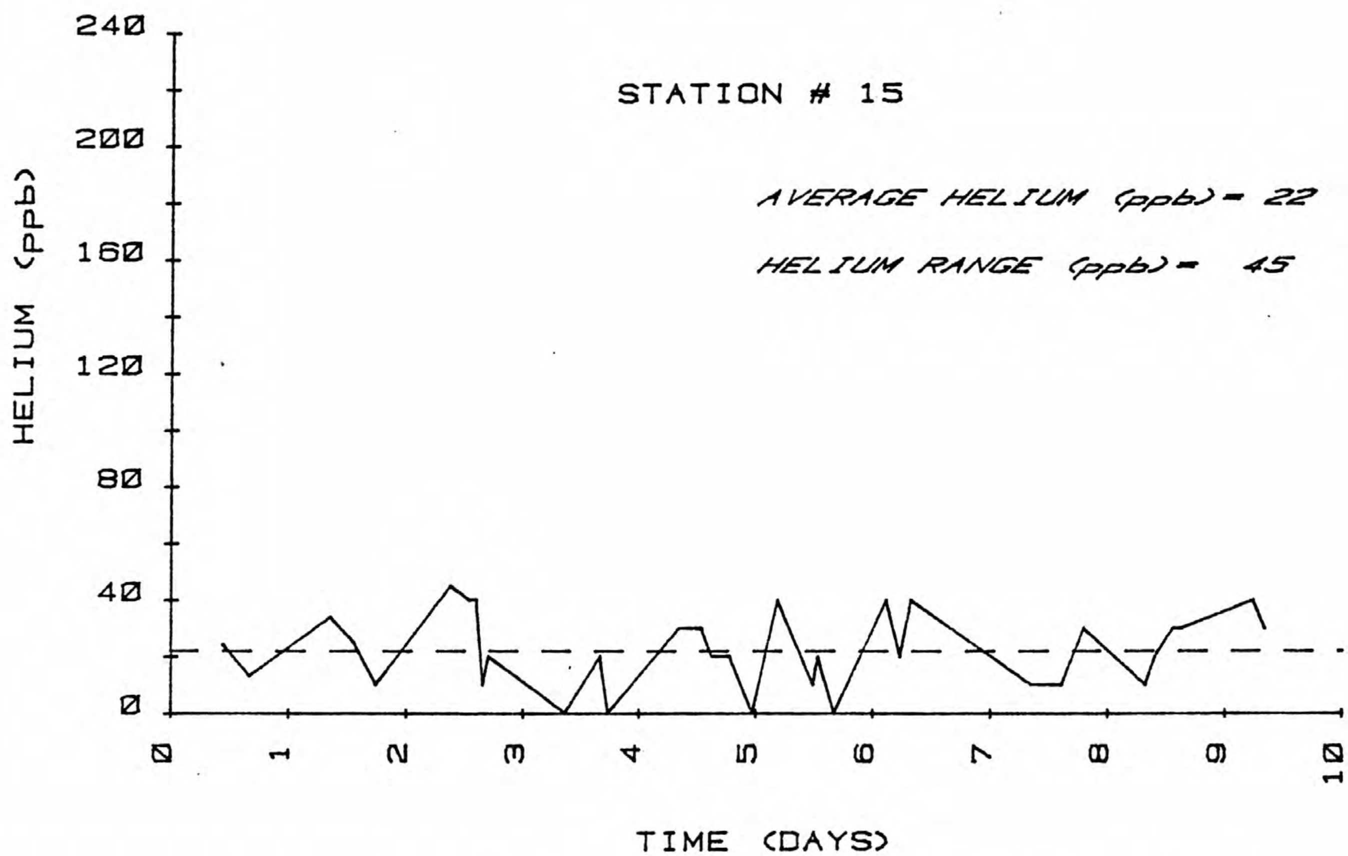


Figure 25: Graph of San Juan Bautista station 15 soil-gas helium variation.

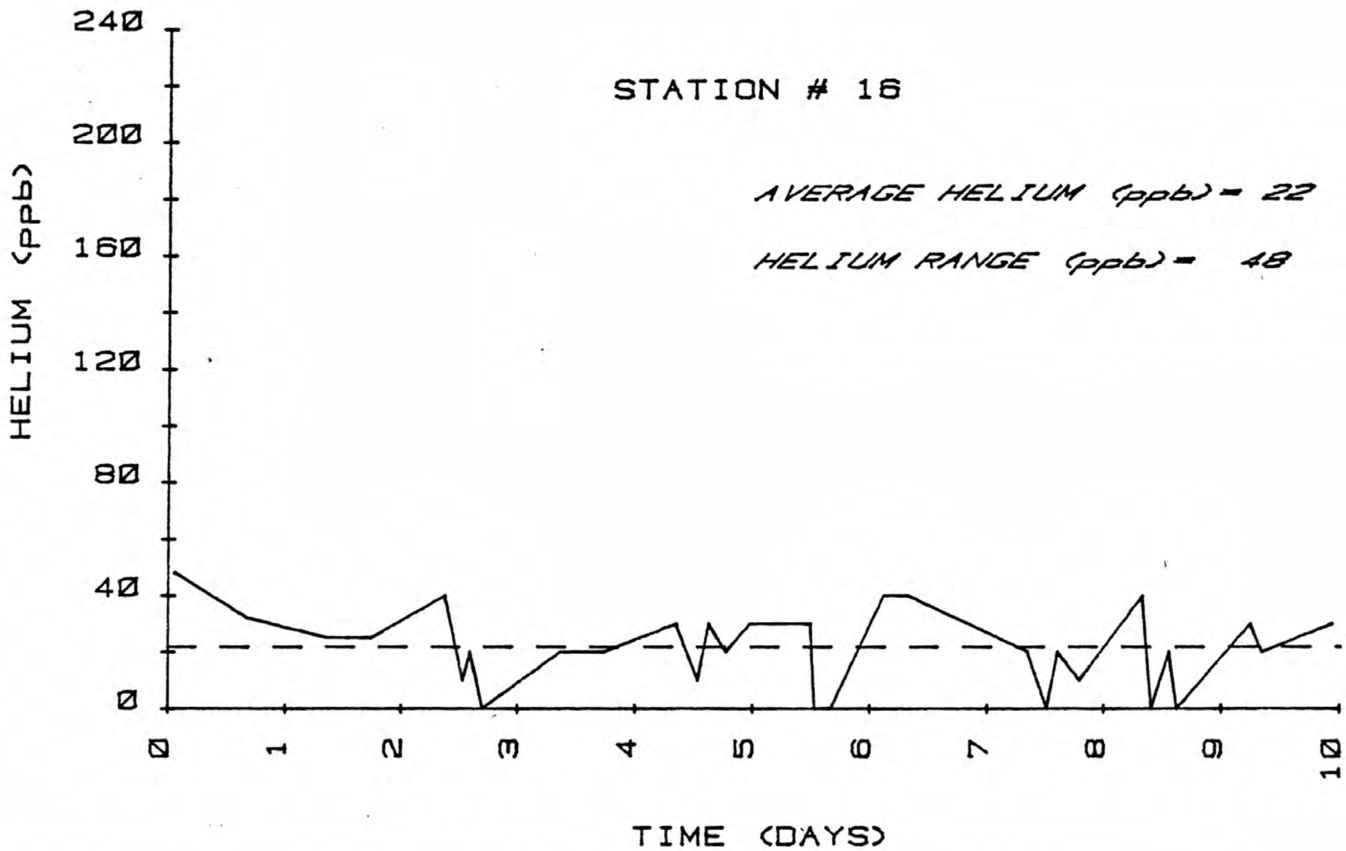


Figure 26: Graph of San Juan Bautista station 16 soil-gas helium variation.

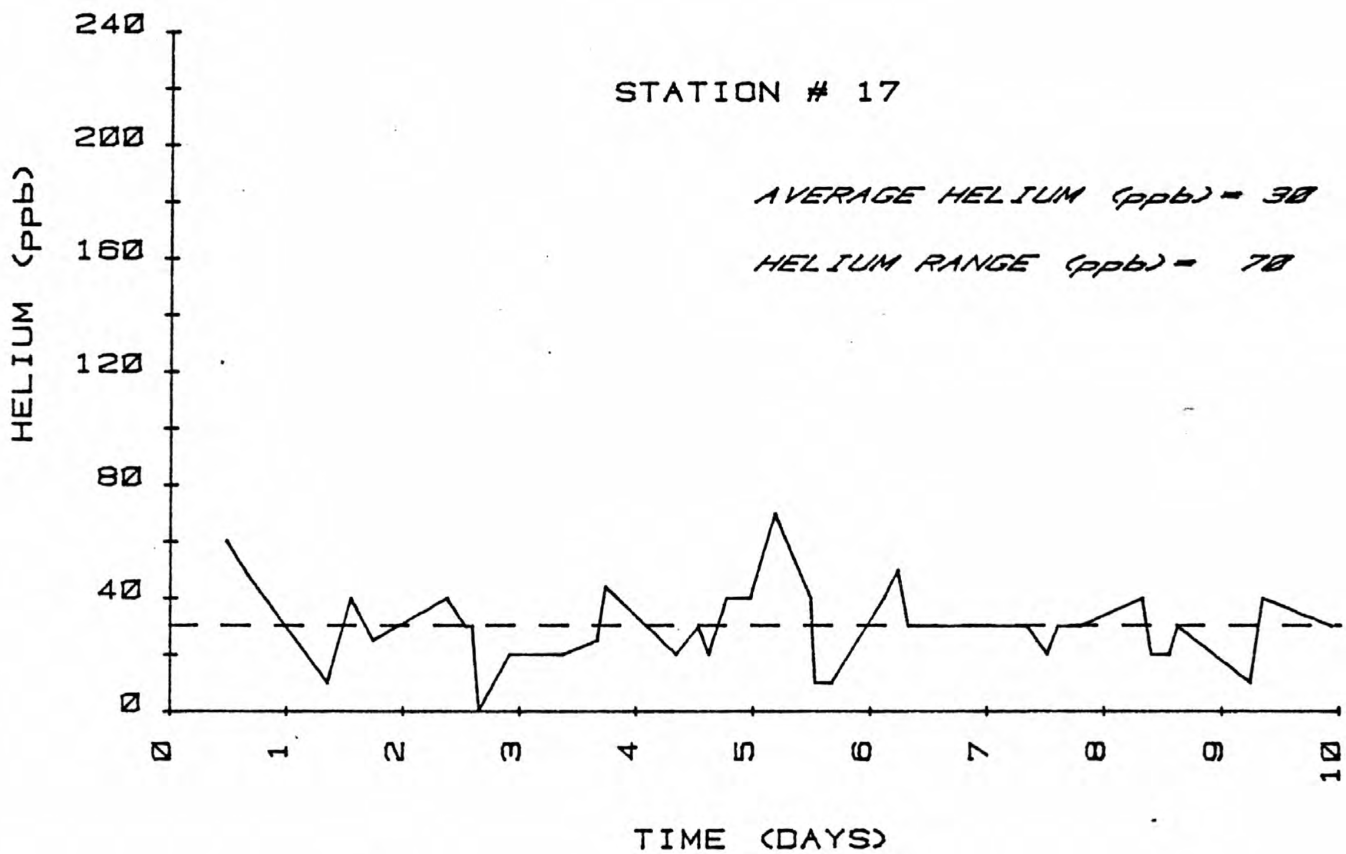


Figure 27: Graph of San Juan Bautista station 17 soil-gas helium variation.

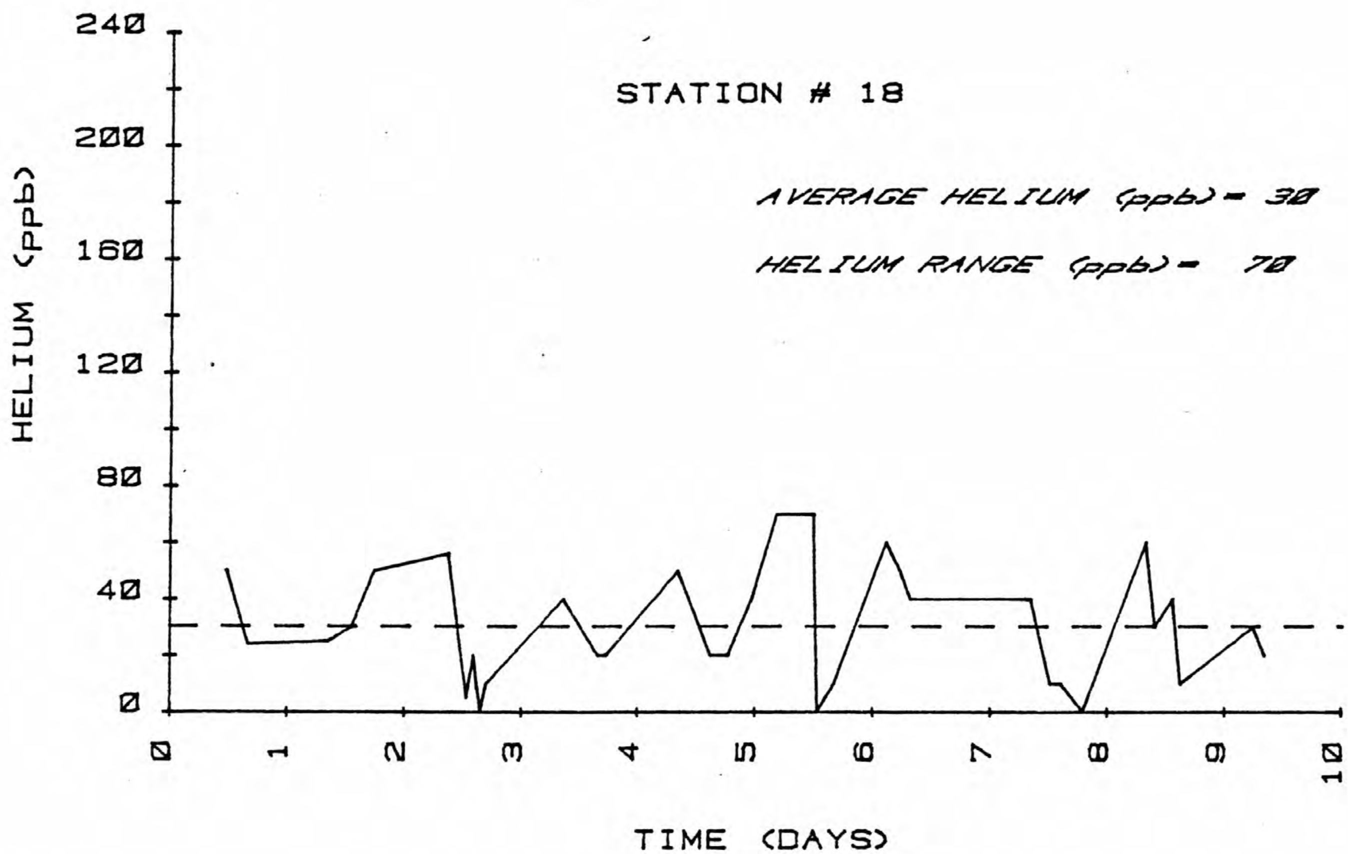


Figure 28: Graph of San Juan Bautista station 18 soil-gas helium variation.

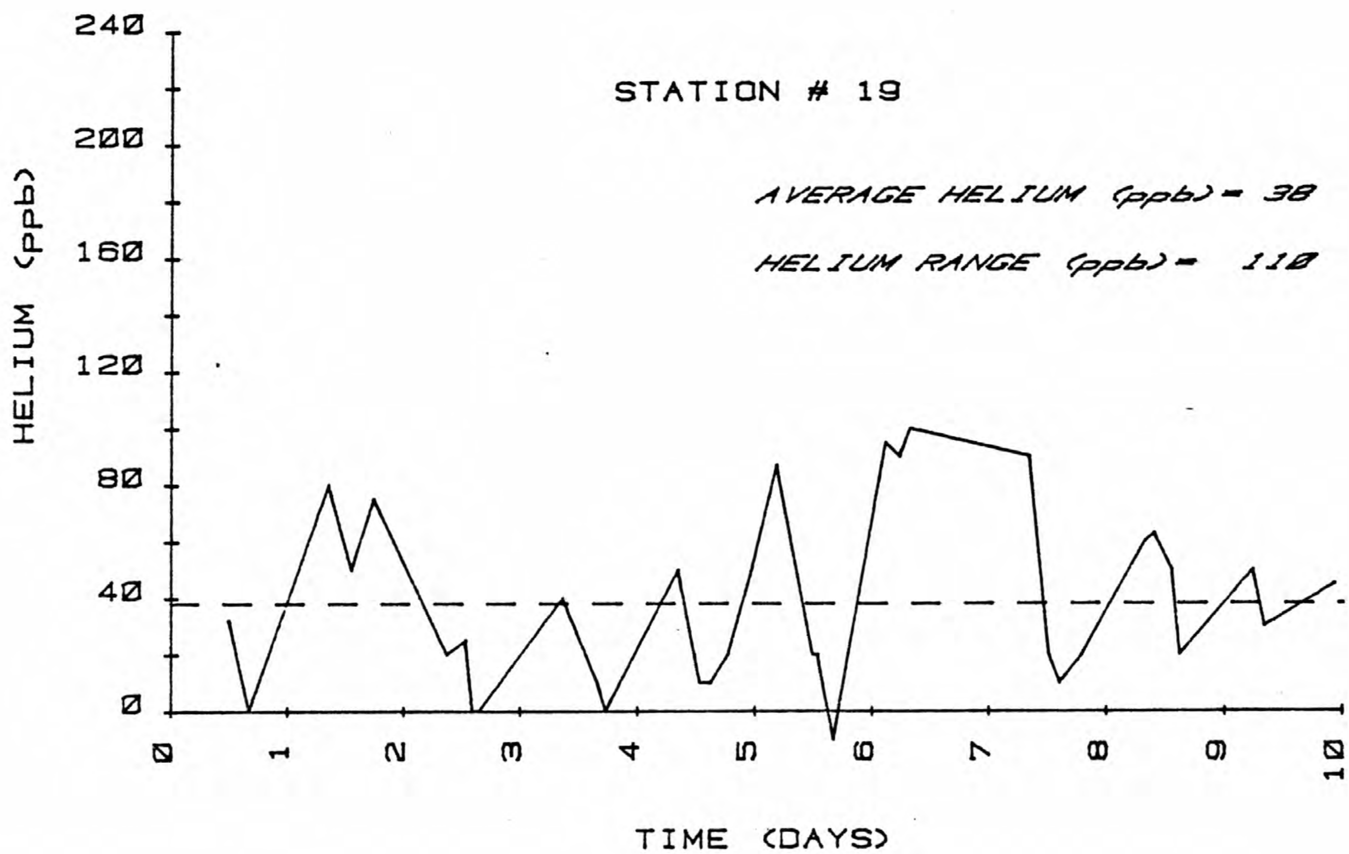


Figure 29: Graph of San Juan Bautista station 19 soil-gas helium variation.

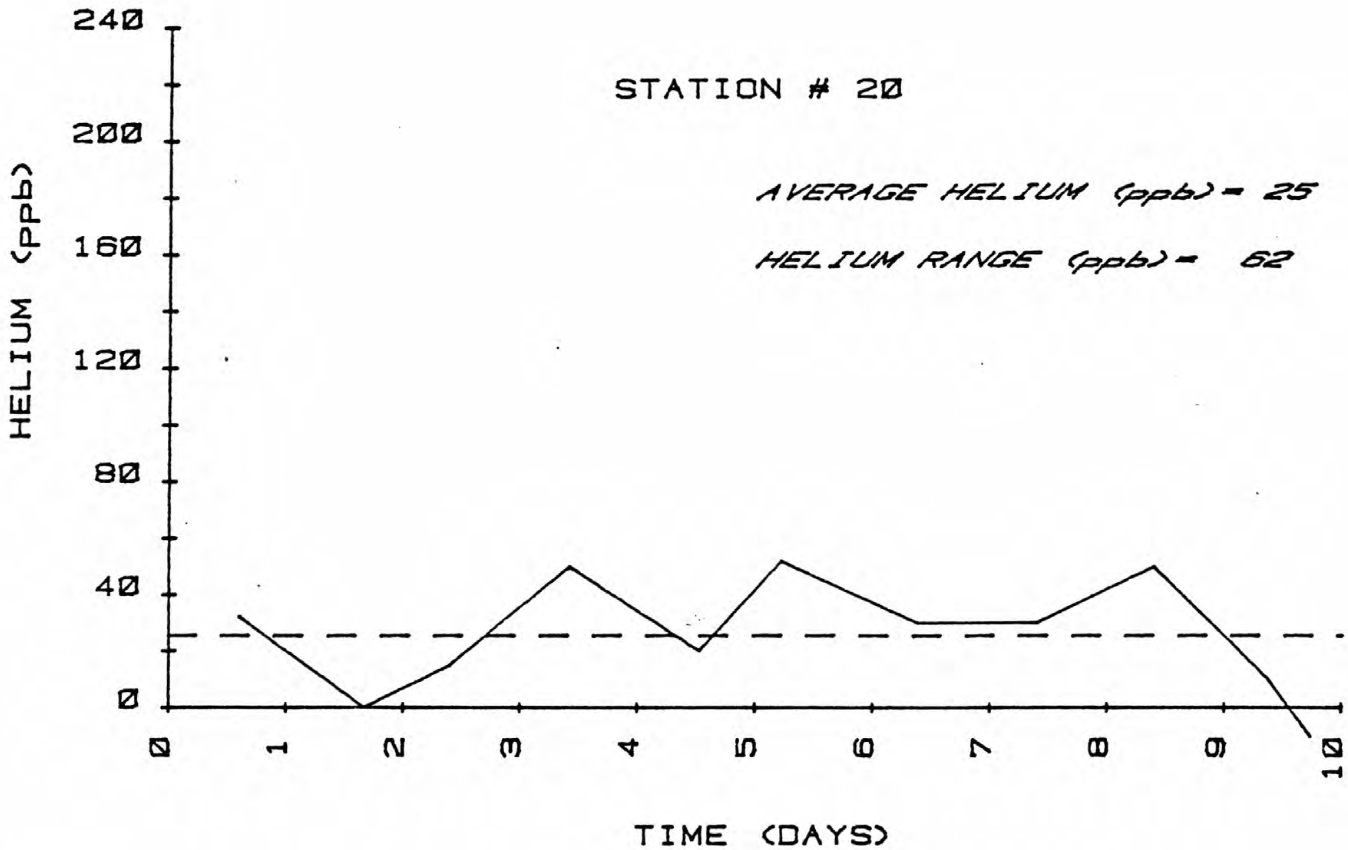


Figure 30: Graph of San Juan Bautista station 20 soil-gas helium variation.

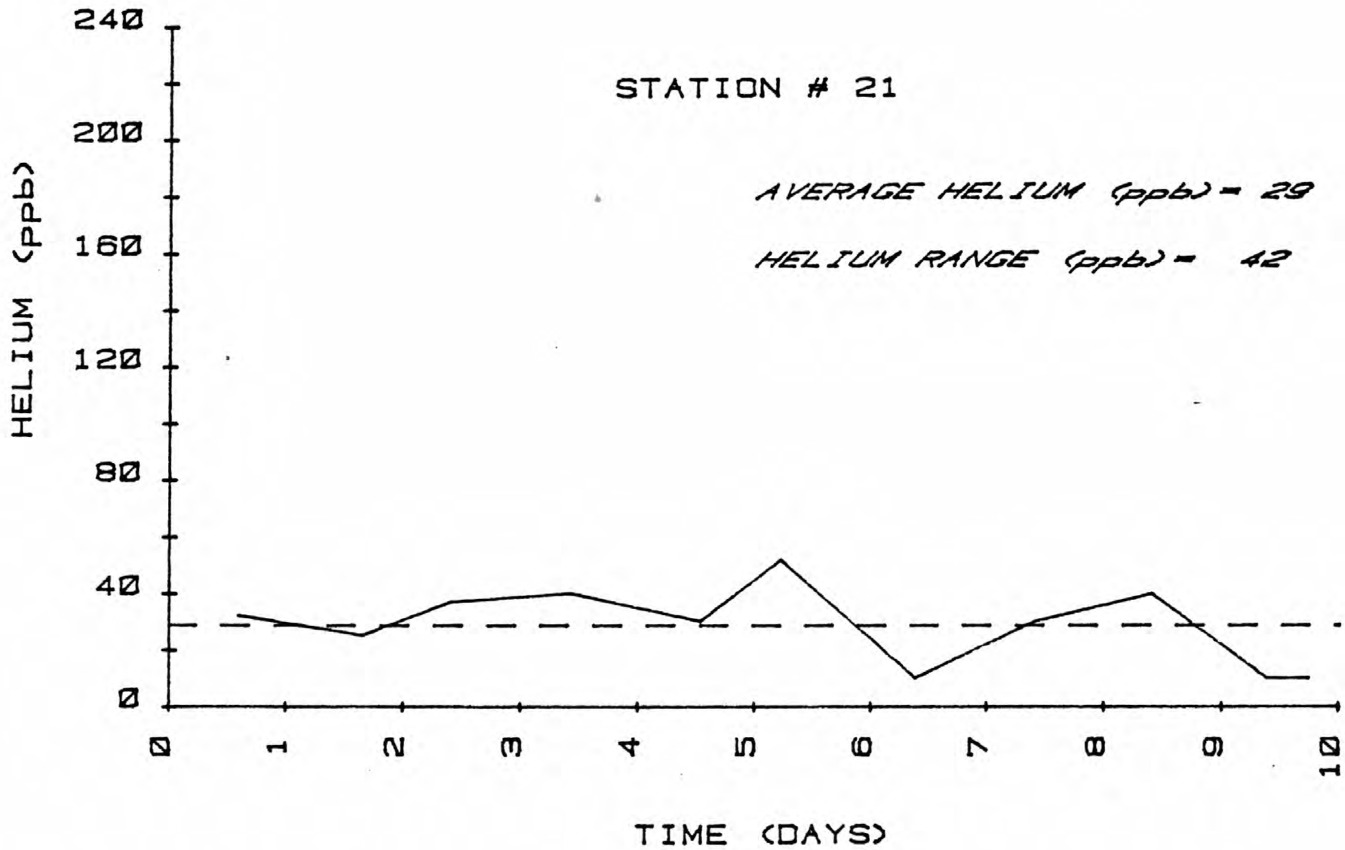


Figure 31: Graph of San Juan Bautista station 21 soil-gas helium variation.

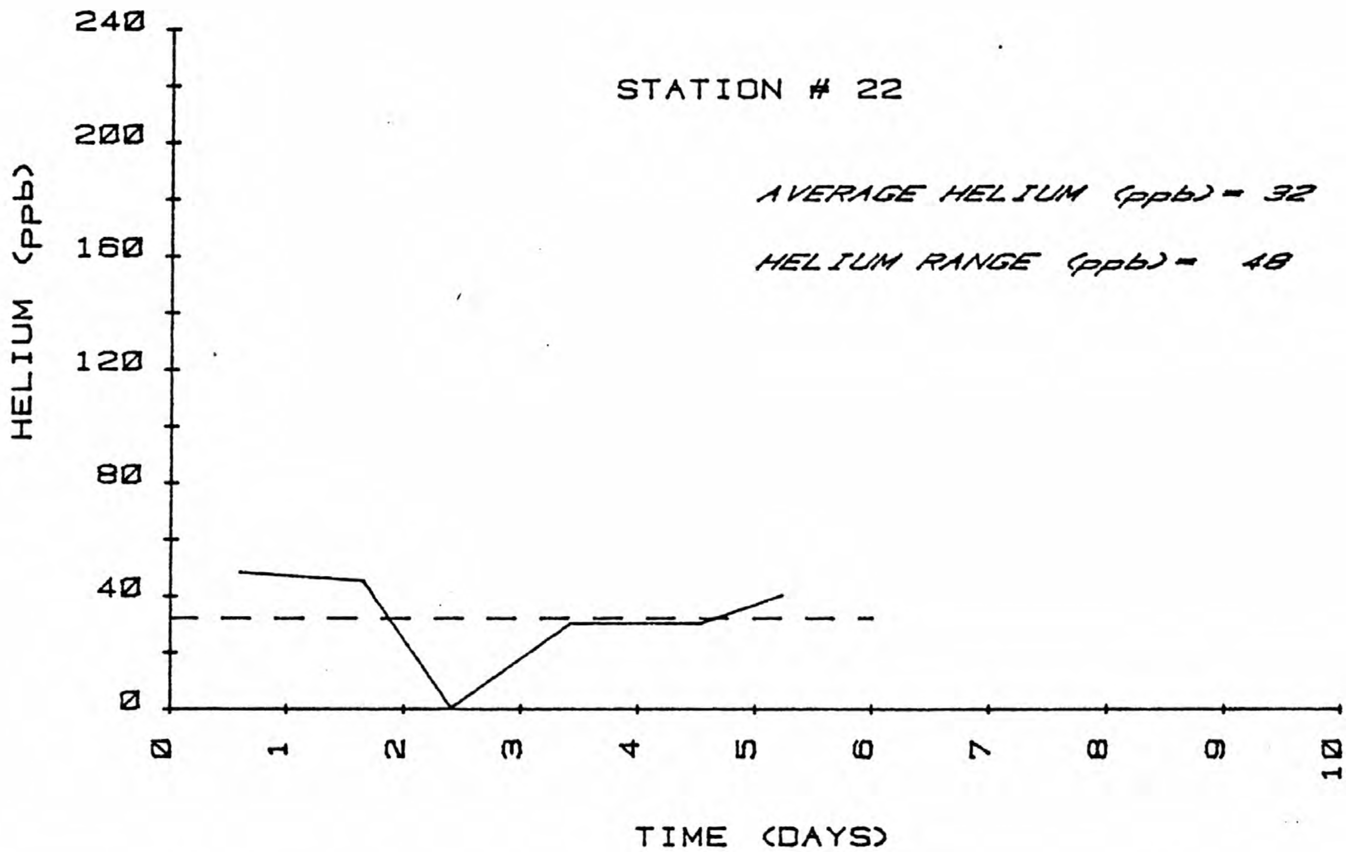


Figure 32: Graph of San Juan Bautista station 22 soil-gas helium variation.

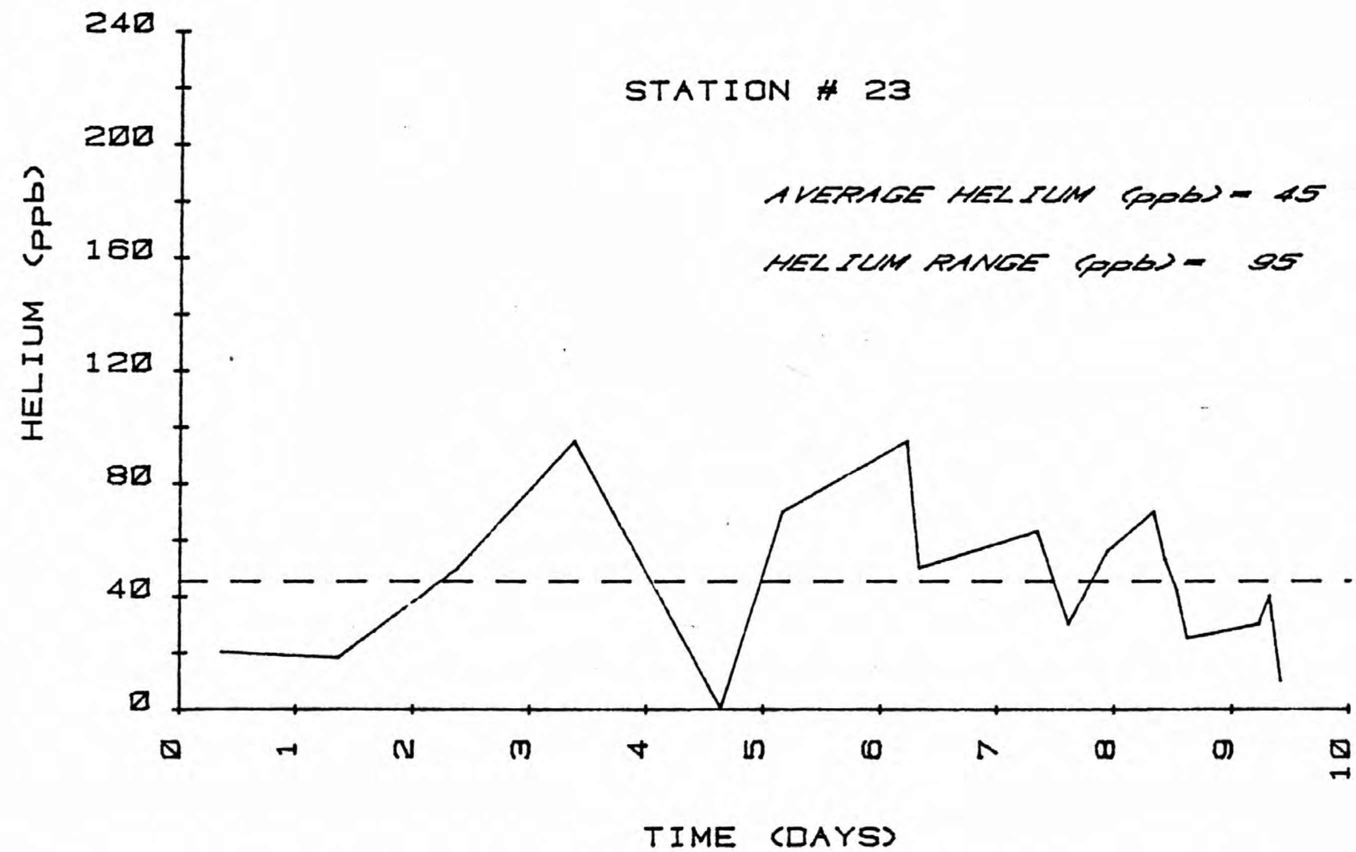


Figure 33: Graph of San Juan Bautista station 23 soil-gas helium variation.

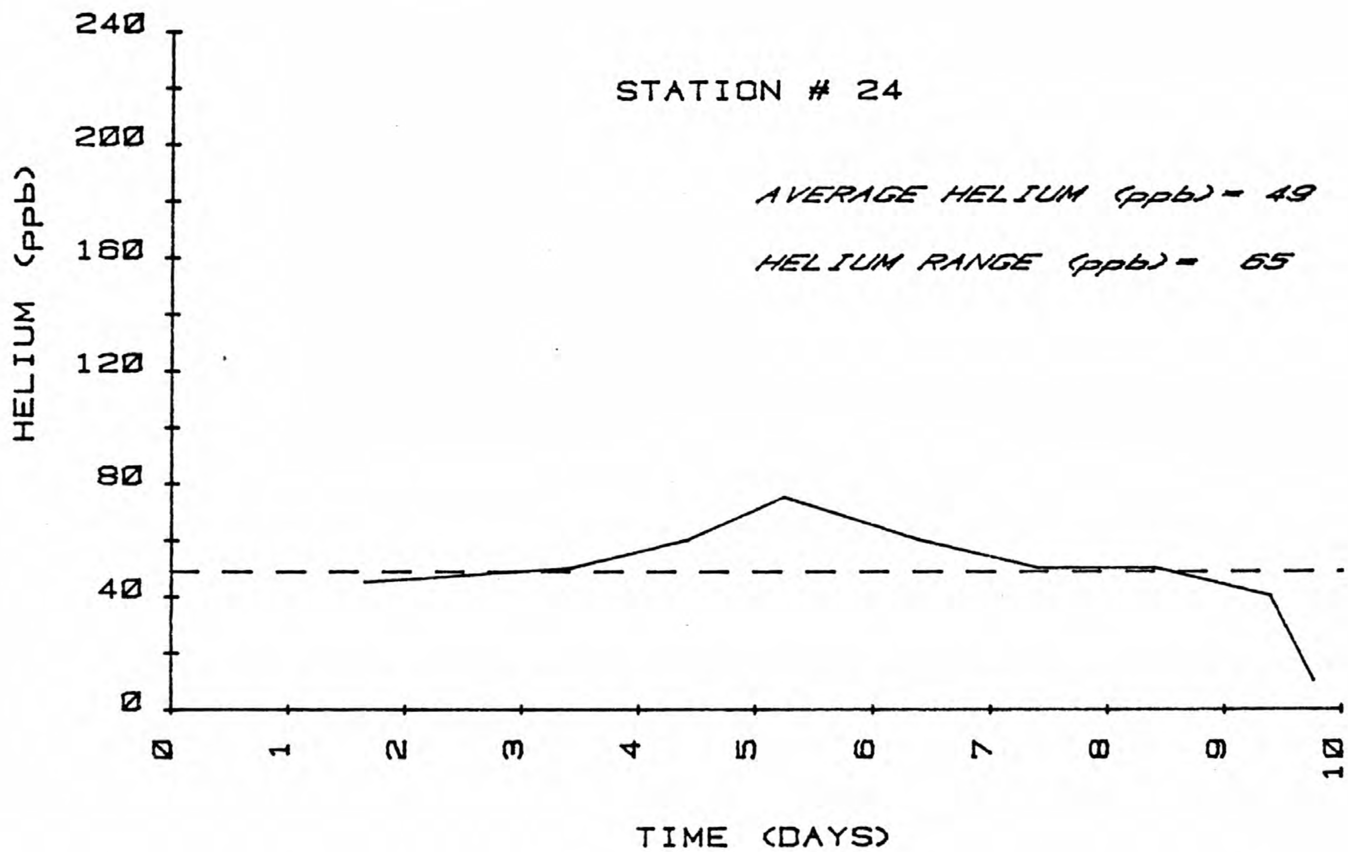


Figure 34: Graph of San Juan Bautista station 24 soil-gas helium variation.

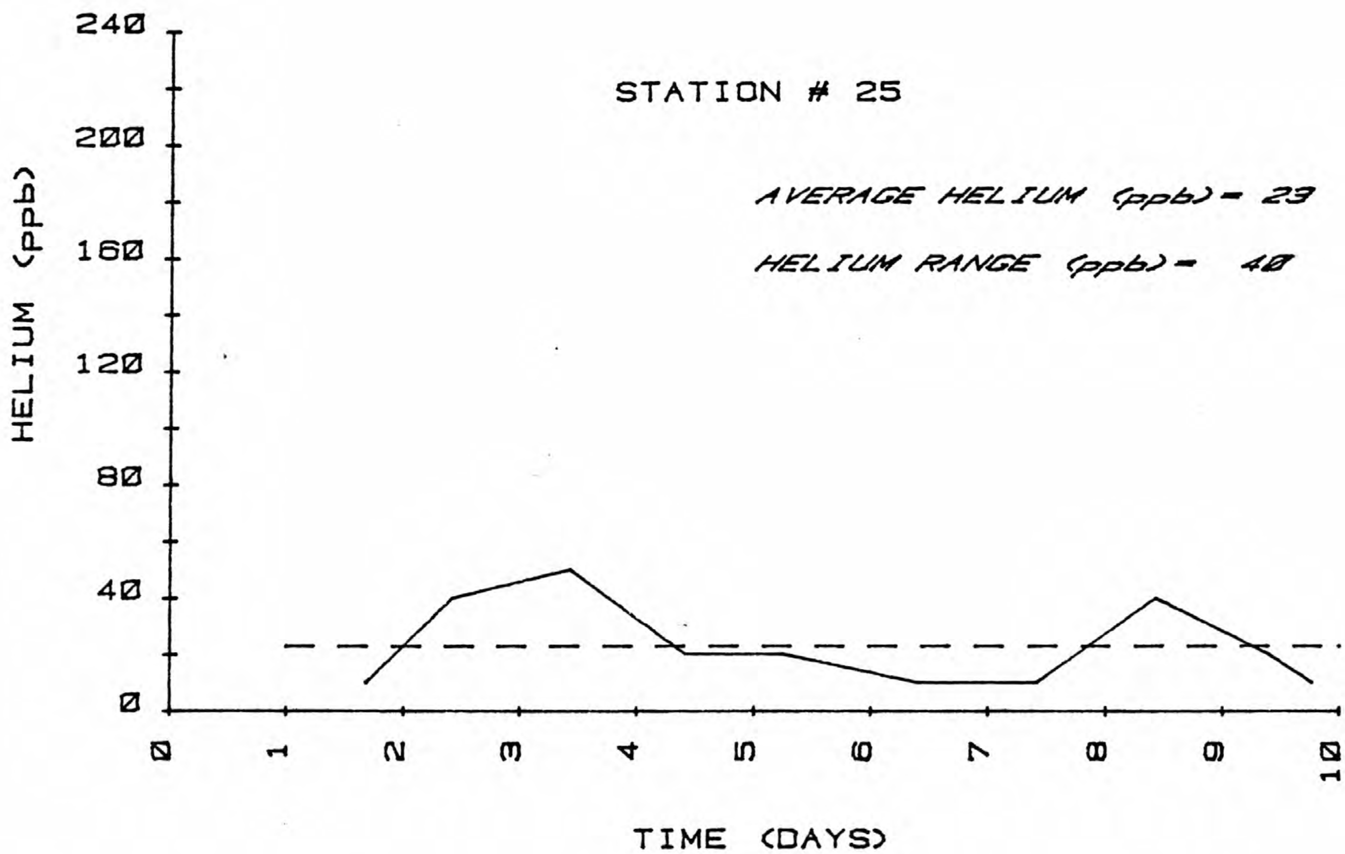


Figure 35: Graph of San Juan Bautista station 25 soil-gas helium variation.

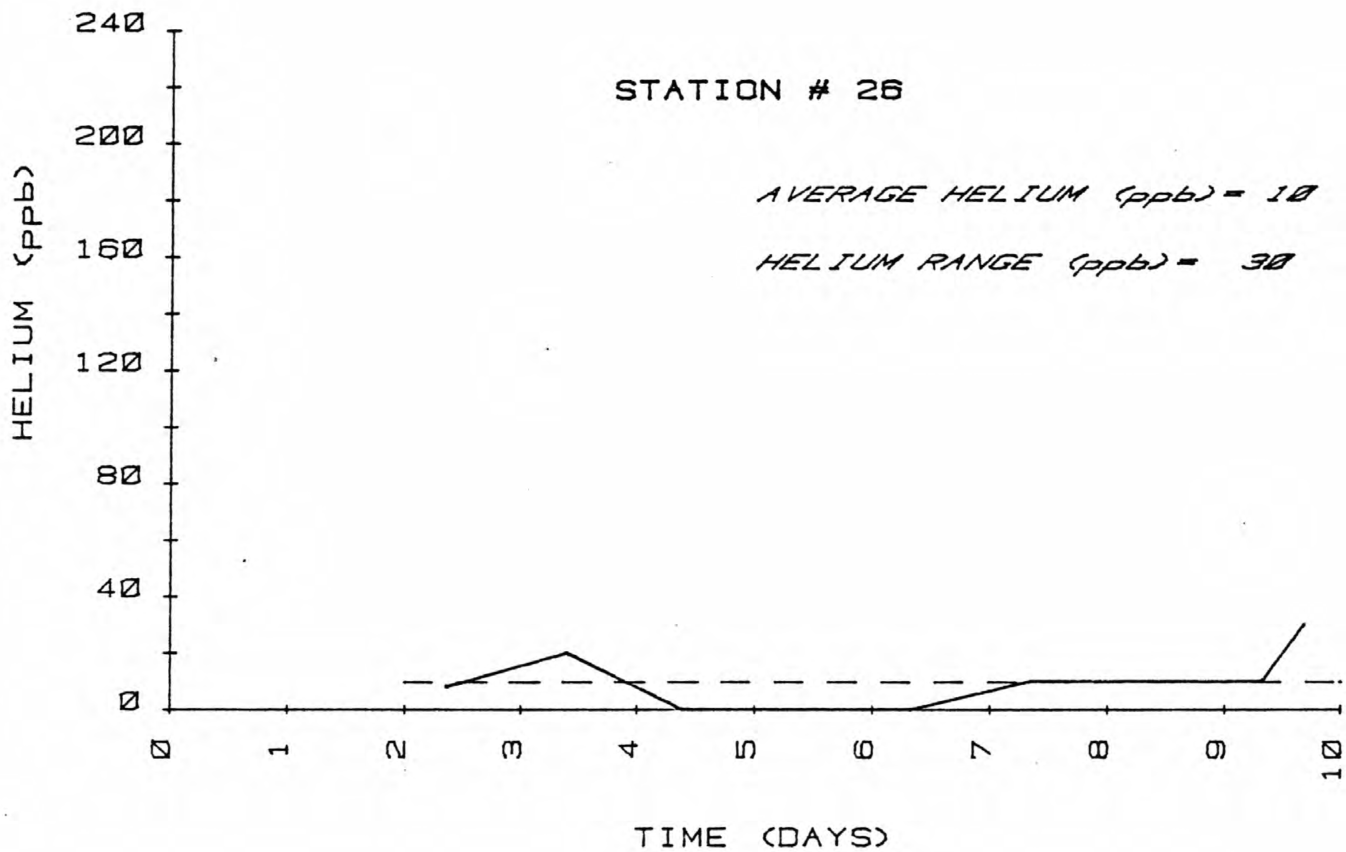


Figure 36: Graph of San Juan Bautista station 26 soil-gas helium variation.

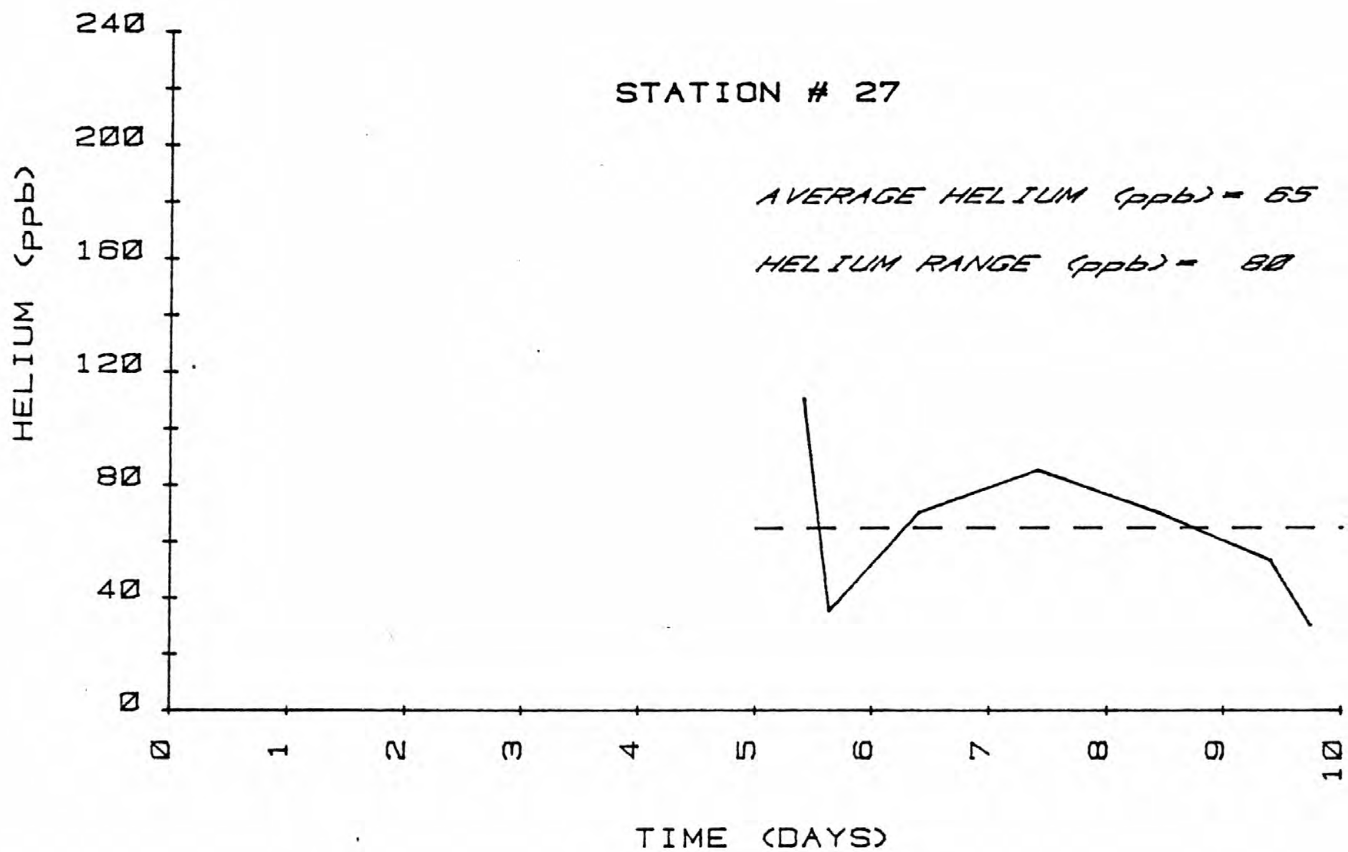


Figure 37: Graph of San Juan Bautista station 27 soil-gas helium variation.

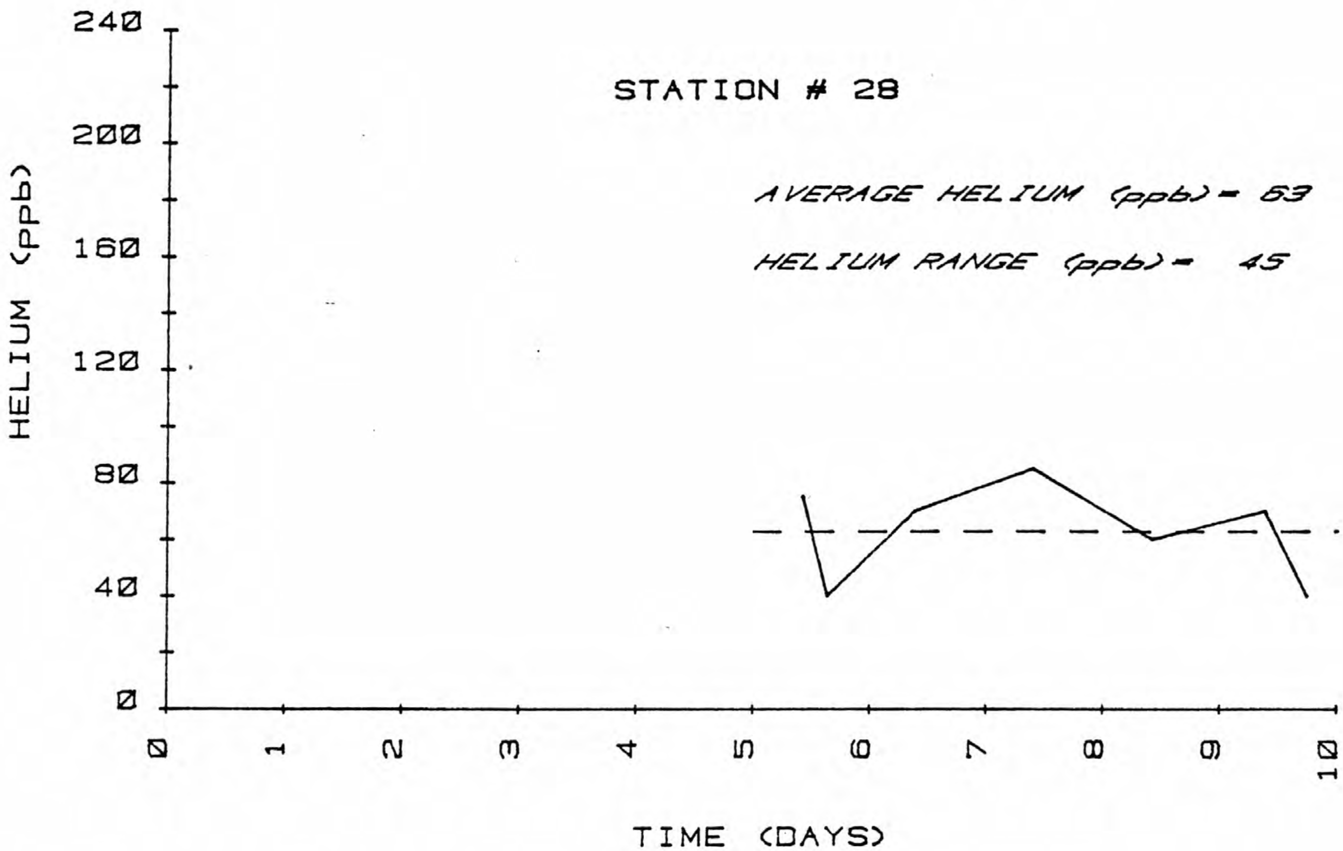


Figure 38: Graph of San Juan Bautista station 28 soil-gas helium variation.

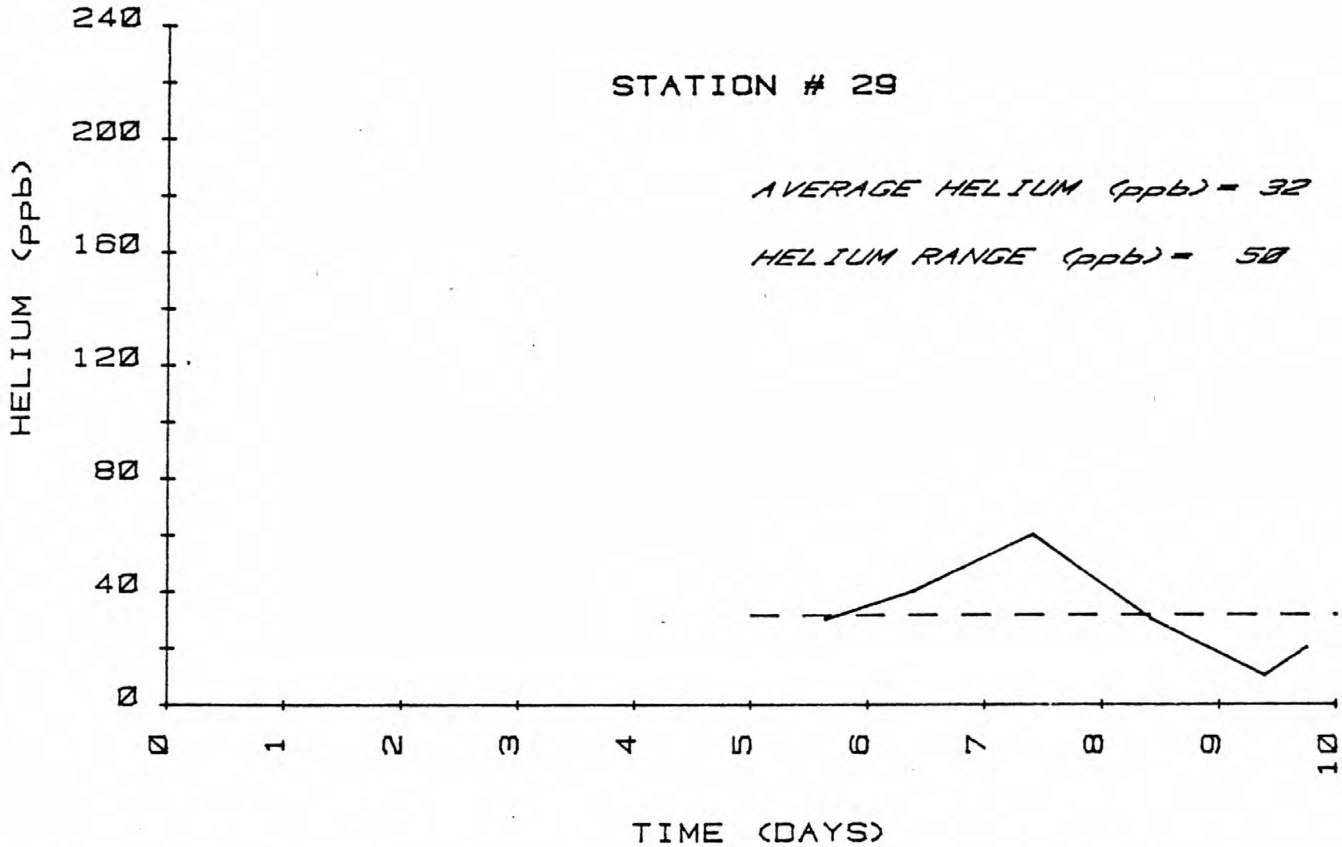


Figure 39: Graph of San Juan Bautista station 29 soil-gas helium variation.

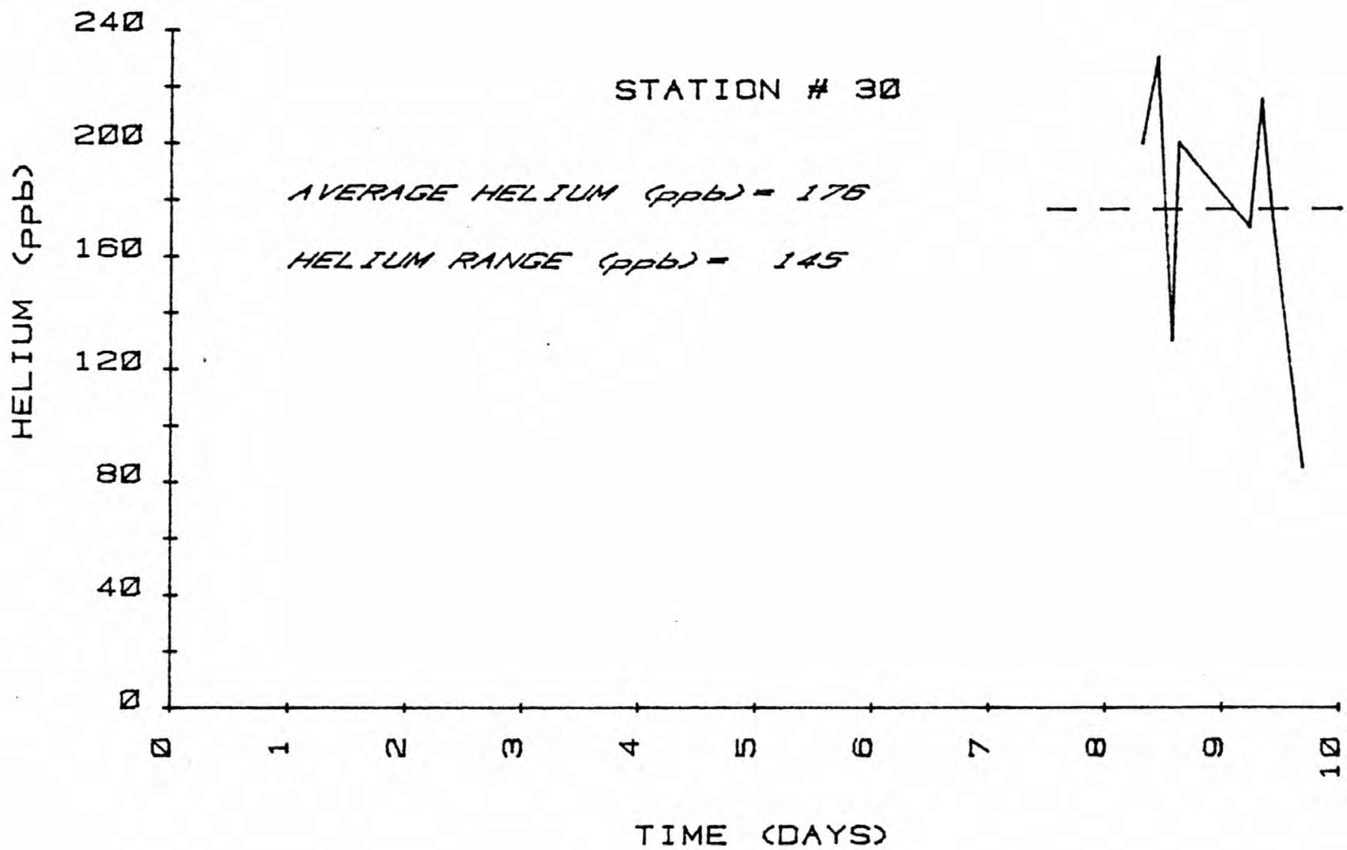


Figure 4Ø: Graph of San Juan Bautista station 3Ø soil-gas helium variation.

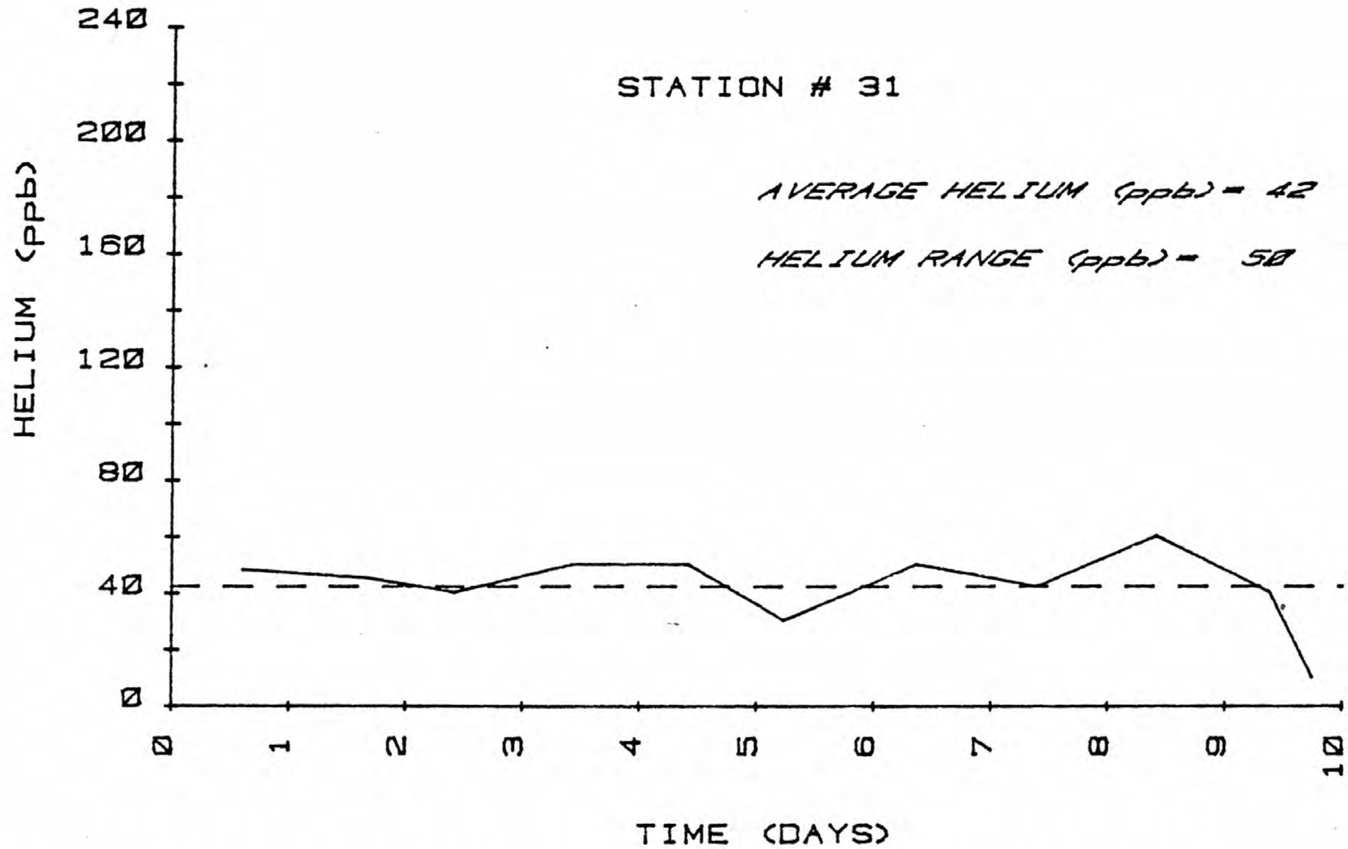


Figure 41: Graph of San Juan Bautista station 31 soil-gas helium variation.

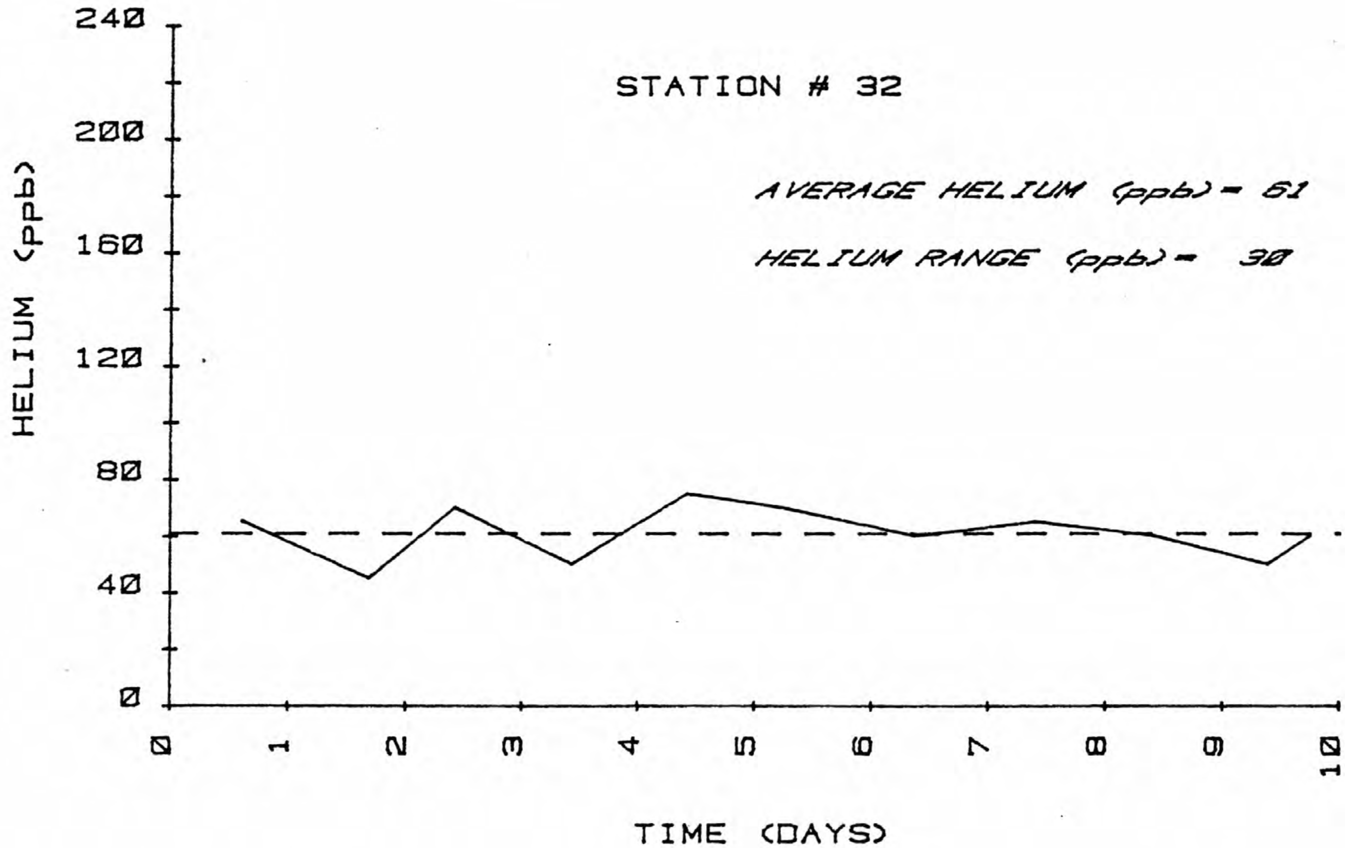


Figure 42: Graph of San Juan Bautista station 32 soil-gas helium variation.

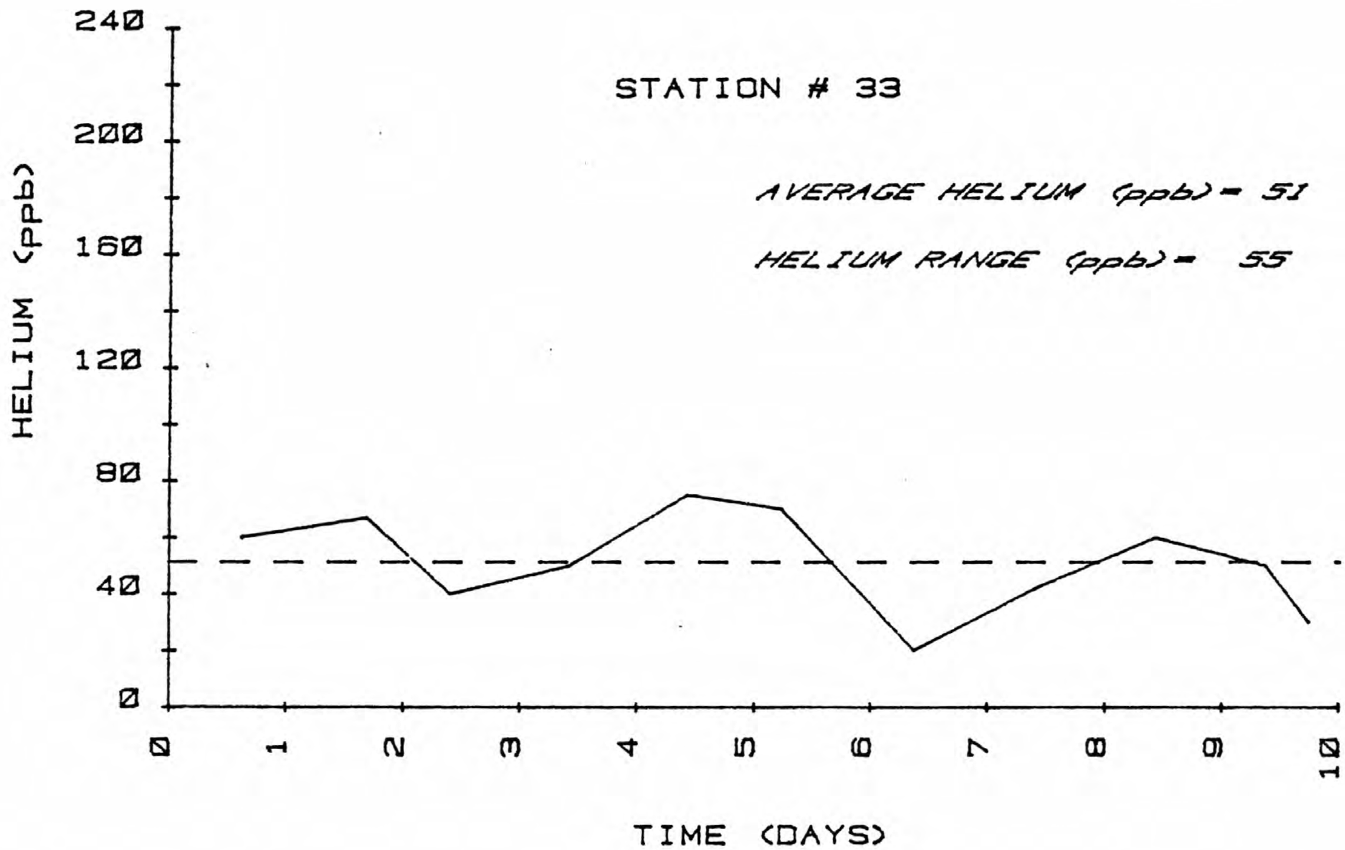


Figure 43: Graph of San Juan Bautista station 33 soil-gas helium variation.

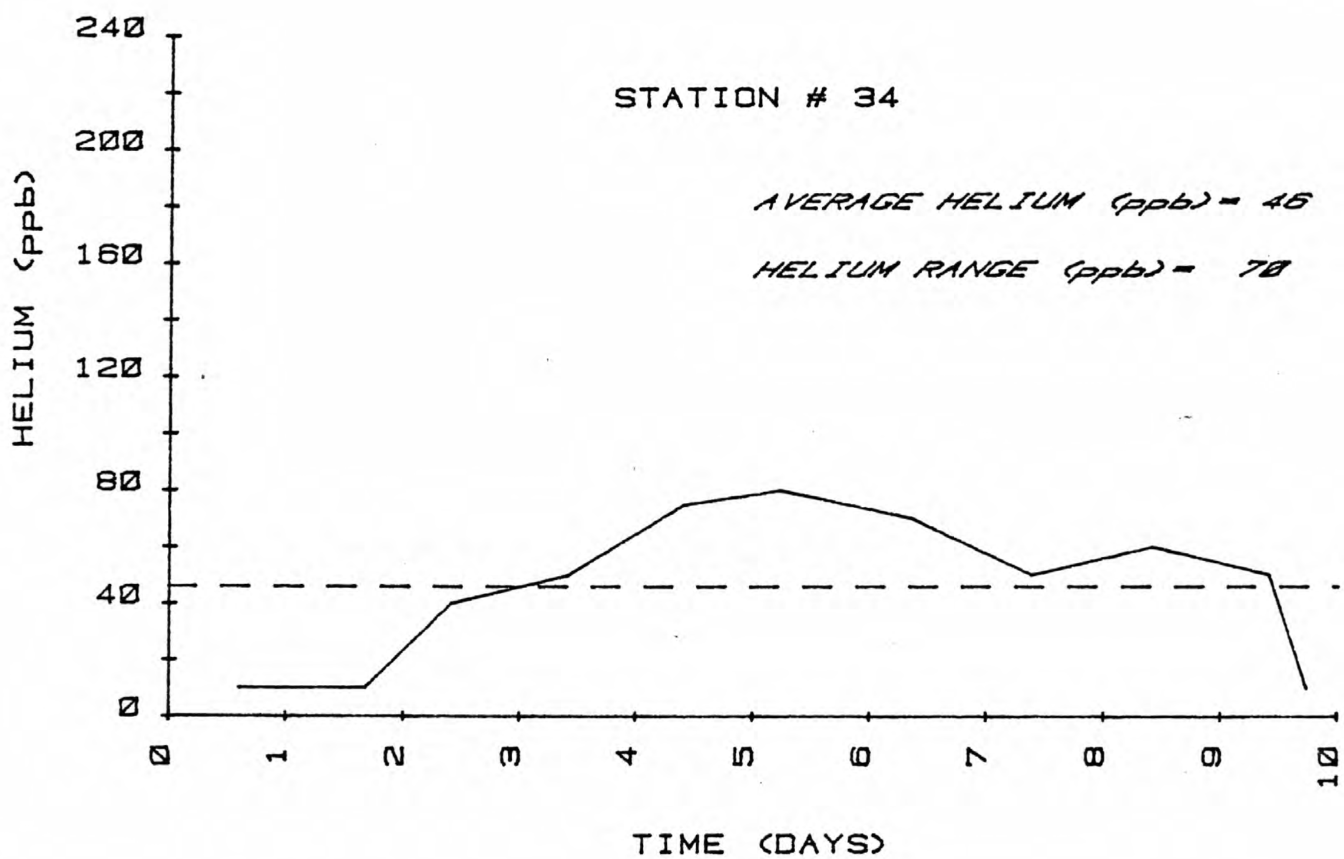


Figure 44: Graph of San Juan Bautista station 34 soil-gas helium variation.

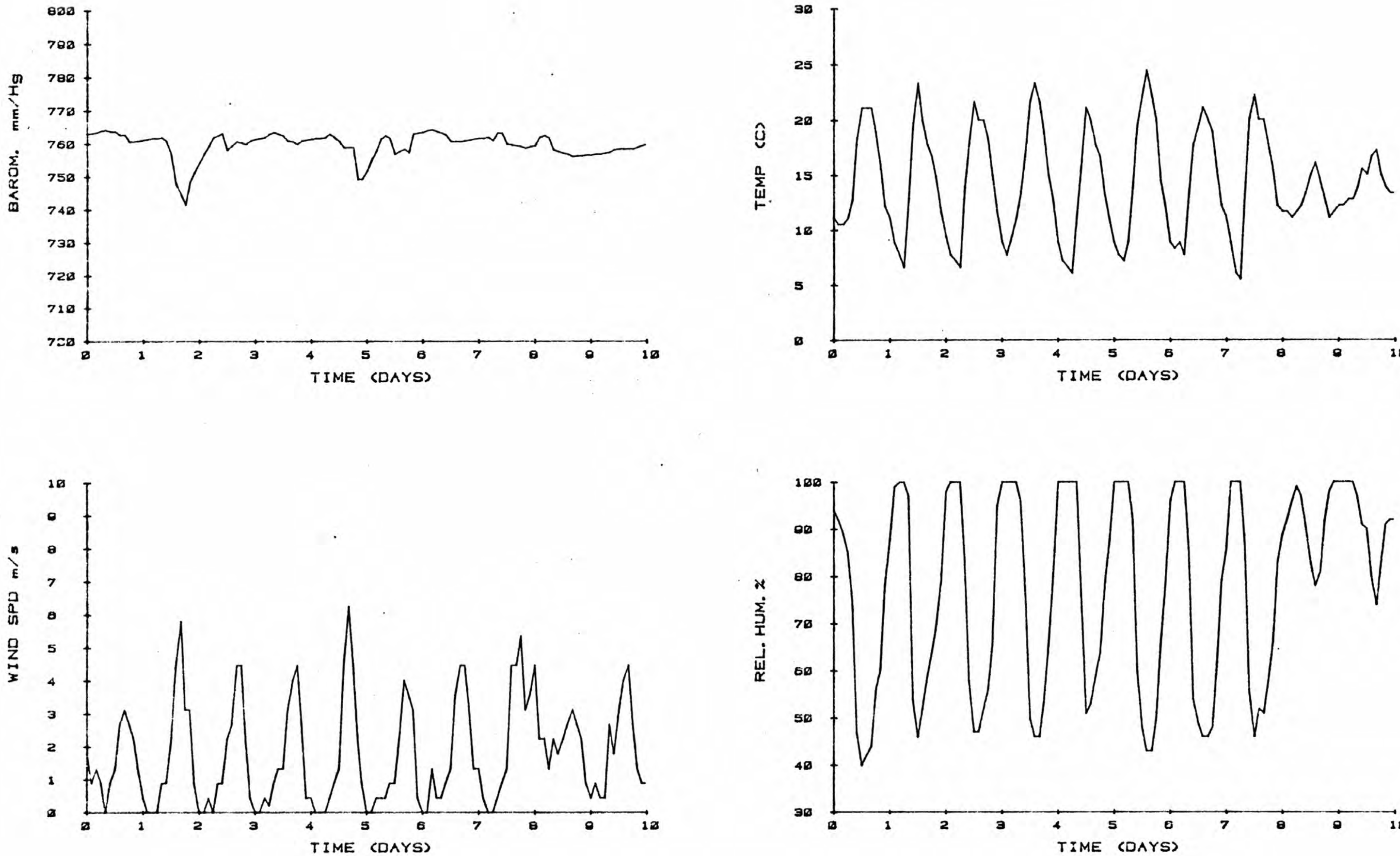


Figure 45.--Graph of some meteorological parameters for the San Juan Bautista study.

variations are not considered in this report, but can be controlled by the same sample parameters as daily variations, with an additional effect caused by annual vegetation and bacteria life cycles. A discussion of the data from the individual field studies illustrates the effects of the various parameters affecting the soil-gas helium concentration.

The Idaho Springs study was conducted during late April 1978, typically a period of rapidly moving spring storms in the Rocky Mountain region. The particular sampling location was chosen because of the known high helium concentrations in the soil gas (Roberts and others, 1975). It was hoped that even minor meteorologic variations would have an easily detectable effect on the helium concentration. The study was conducted for 8 days. Samples were collected from the three probes every few hours the first 4 days and samples were only collected three or four times during daylight for the next 4 days. Except for slight fluctuations caused by wind the first day, the barometric pressure was relatively constant, fluctuating only ±1.5 mm of Hg over the first 4-day period. A slow increase began the next day, with a decrease the sixth day, which was the last record of the barometric pressure. Precipitation in the form of rain and snow began on the second day of sampling. The precipitation was light but continuous for the remainder of the study. As the soil moisture increased, the soil gas helium concentration began to increase. During the first 4 days, a daily cycle of the helium concentration is evident from all stations. The daily high is in the morning hours, and the low is in the afternoon and evening hours. The shallower probes (fig. 5) from stations two and three show greater daily variations than the deeper probe at station four. The response to the increasing soil moisture content is rapid in the 0.5-m probe at station two, intermediate for the 0.75-m probe at station three, and slowest at the 1.0-m probe at station four. This study shows a direct positive correlation of the helium soil-gas concentration with soil moisture (derived from precipitation). Also, daily cycles of the helium concentration were observed, even though the barometer was relatively steady. Previous studies (Reimer and others, 1976b; Platt, 1978) also indicated daily helium variations of a similar intensity with a fluctuating barometer. Change in barometric pressure seems to have little effect on the soil-gas helium concentration. Also, the magnitude of the daily variation was observed to decrease with increasing probe depth.

The Red Desert study was conducted in December 1977, and July 1978. The location is directly over an 80-m-deep, low-grade uranium deposit; it was chosen because it presented a local source for helium in a region of known periodic strong winds. Sample collecting took 1 day on each occasion, and 1-m probes were used. Winds were observed to range from 80 to 100 km/h, with gusts to 120 km/h during the December 1977 study. Winds did not exceed 30 km/hr for the July 1978 study. The average helium for the 47 stations of the first study was 1±10 ppb and the average for the second study involving 54 samples was 15±9 ppb helium. Although these averages do not differ greatly, the range of values for the separate studies varies, -21 to +24 ppb for the December study and 0 to +48 for the July study. No particular contour pattern is present in the December study, but a noticeable pattern is revealed by the second study. Some seasonal effects may also be present, but they are not considered here. It appears from this Red Desert study that increased winds reduce the soil-gas helium concentration and have a pronounced effect on the local distribution of helium in soil gas (figs. 8 and 9). Undoubtedly, the soil type and porosity would be major factors controlling the magnitude of influence by the wind.

The Mojave Desert study was conducted during late June 1978. The intent of this study was to obtain a regional average and distribution of the helium soil-gas concentration in the vicinity of the Palmdale Bulge. Forty-five samples were collected at a 1-m depth. Sample collecting took 2 days to complete. Wind speeds were less than 30 km/hr and no precipitation occurred during this study. The average helium concentration was 51.5 ppb, and the range was from -10 to 150 ppb.

Even though the sample density was on the order of one sample every 250 km^2, a regional pattern is revealed (fig. 10). The area of the highest helium concentrations occurs in the eastern part of the area sampled, generally in a linear region from Barstow, Calif., to north of Cajon, Calif. There is no immediate explanation for the location of this regional soil-gas helium anomaly. Considering the geologic description of the area (Dibblee, 1967; Byers, 1960), higher helium may possibly be associated with the greater thickness of sedimentary fill. The fact that this helium high occurs approximately in the center of the defined region of the southern California uplift is interesting (Castle, 1978).

The San Juan Bautista study was conducted during early June, 1978. The intent of this study was to observe the diurnal variations of the helium concentration in soil gas at a location near the San Andreas Fault and to compare those variations to changes in several meteorological parameters. A total of 34 permanent sampling stations were established. The stations consisted of five groups of three to four probes each, and the remaining probes were placed on a traverse from San Juan Bautista east to Hollister then south to the Cienega Winery. The probes in the groups were pounded into the ground to different depths ranging from 0.5 to 2 m. The traverse probes were all at a 1 m depth. Three groups were established near the Mission Farm campground at San Juan Bautista. Samples from these probes were collected every few hours. Samples from the remaining groups and the traverse probes were collected once a day. A recording weather station was installed at a temporary base camp at the campground. Comparison to the meteorological conditions (fig. 4 and 5) were made only for the three nearby groups of probes. The helium variations for these groups are shown in figures 19-29.

Several trends are observed for analyses of those groups. The helium concentrations follow a diurnal cycle. As sampling depth increases, the average helium decreases and the range of helium variability also decreases (table 3). There is greater stability of the helium concentration at greater sampling depths. Another trend is shown in figures 46-48. Higher helium concentrations occur in the samples collected from midnight to noon than from noon to midnight. This trend is real for samples collected down to 1 m but becomes obscured by the analytical precision for samples collected deeper.

A comparison was made of the helium variations of these three probe groups to the following parameters: barometric pressure, air temperature, relative humidity, precipitation, wind speed, and soil temperature. All those measured parameters, except precipitation, also follow a diurnal cycle.

Caution should be exercised when comparing parameters that are cyclic. The correlation may be merely coincidental or a remote reflection of some other effect. This seems to be the case with the correlations that can be made in this study. Table 4 lists the correlation coefficients for the three probe groups and barometric pressure, air temperature, wind speed, and relative humidity. The coefficients from samples taken from 1.5 and 2.0 meters can be generally disregarded; in those samples the confidence of analytical accuracy is low because the helium concentration differences from sample to sample are small. Again mentioning the possible danger of direct

Table 3.--Comparison of probe depth and soil-gas helium variability in the San Juan Bautista study area

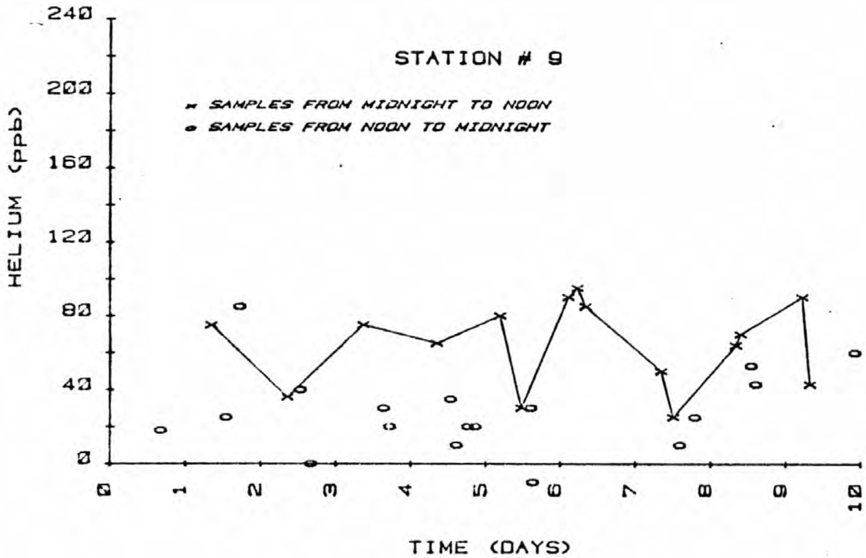
[Groups are stations adjacent to each other]

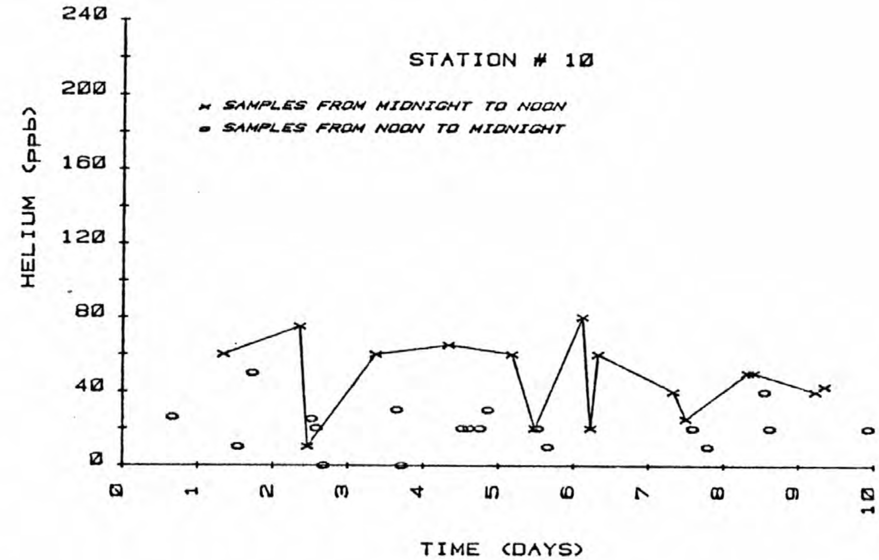
Probe depth (m)	Station No.	Average He (ppb)	Range of He (ppb)
0.5	9	45	105
1.0	10	33	80
1.5	11	29	65
.5	12	26	80
1.0	14	31	80
1.5	15	22	45
2.0	13	16	56
.5	19	38	110
1.0	18	30	70
1.5	17	30	70
2.0	16	22	48

Table 4.--Correlation coefficients for three probe groups and four meteorological parameters in the San Juan Bautista study area

[S, significant correltions at the 98 percent confidence level. Samples takenatprobedepthof1.5and2.0mmayhavemisleadingcorrelation coefficients because the limit of analytical sensitivity had been reached]

Station No.	Probe depth (m)	Barometric pressure	Air temperature	Wind speed	Relative humidity
9	0.5	0.119	-0.717s	-0.667s	0.740s
10	1.0	.197	-.598s	-.572s	.635s
11	1.5	.156	-.343	-.286	.384
12	.5	.361	-.627s	-.656s	.641s
14	1.0	.364	-.433s	-.413s	.374
15	1.5	.213	.299	-.271	.274
13	2.0	-.015	.033	.238	-.108
19	.5	.038	-.757s	-.618s	.722s
18	1.0	.111	-.567s	-.634s	.520s
17	1.5	.102	-.324	-.201	.170
16	2.0	.237	-.482s	-.468s	.386s





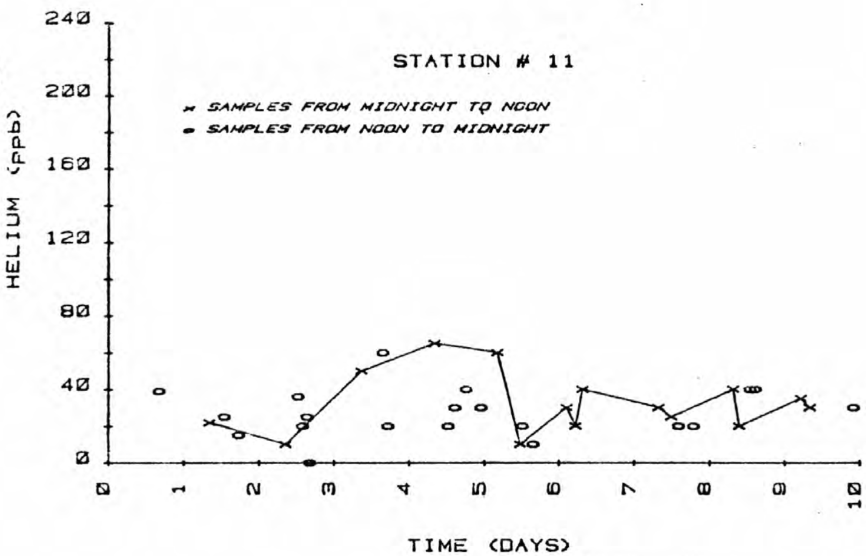


Figure 46.--Graph of sample group 9-11 of the San Juan Bautista study. The probe depth for stations 9, 10, and 11 was 0.5, 1.0, and 1.5 m, respectively. The daily variation decreased with increased probe depth, and samples collected during the morning hours generally had higher helium concentrations than samples collected during the afternoon hours.

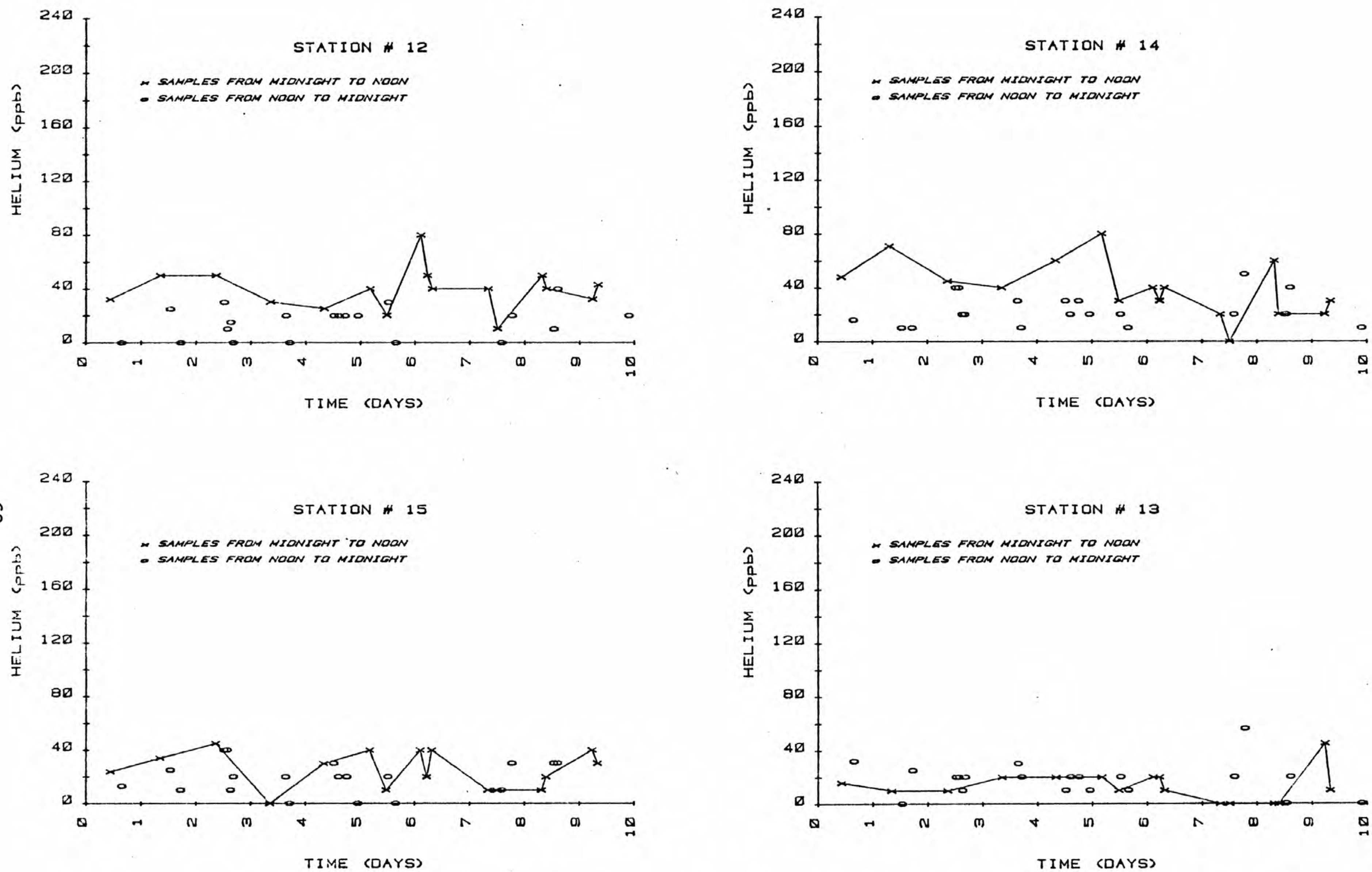


Figure 47.--Graph of sample group 12-15, San Juan Bautista. The probe depth for stations 12, 14, 15, and 13 was 0.5, 1.0, 1.5 and 2.0 m, respectively. The daily variation decreased with increased probe depth, and samples collected during the morning hours generally had higher helium concentrations than samples collected during the afternoon hours.

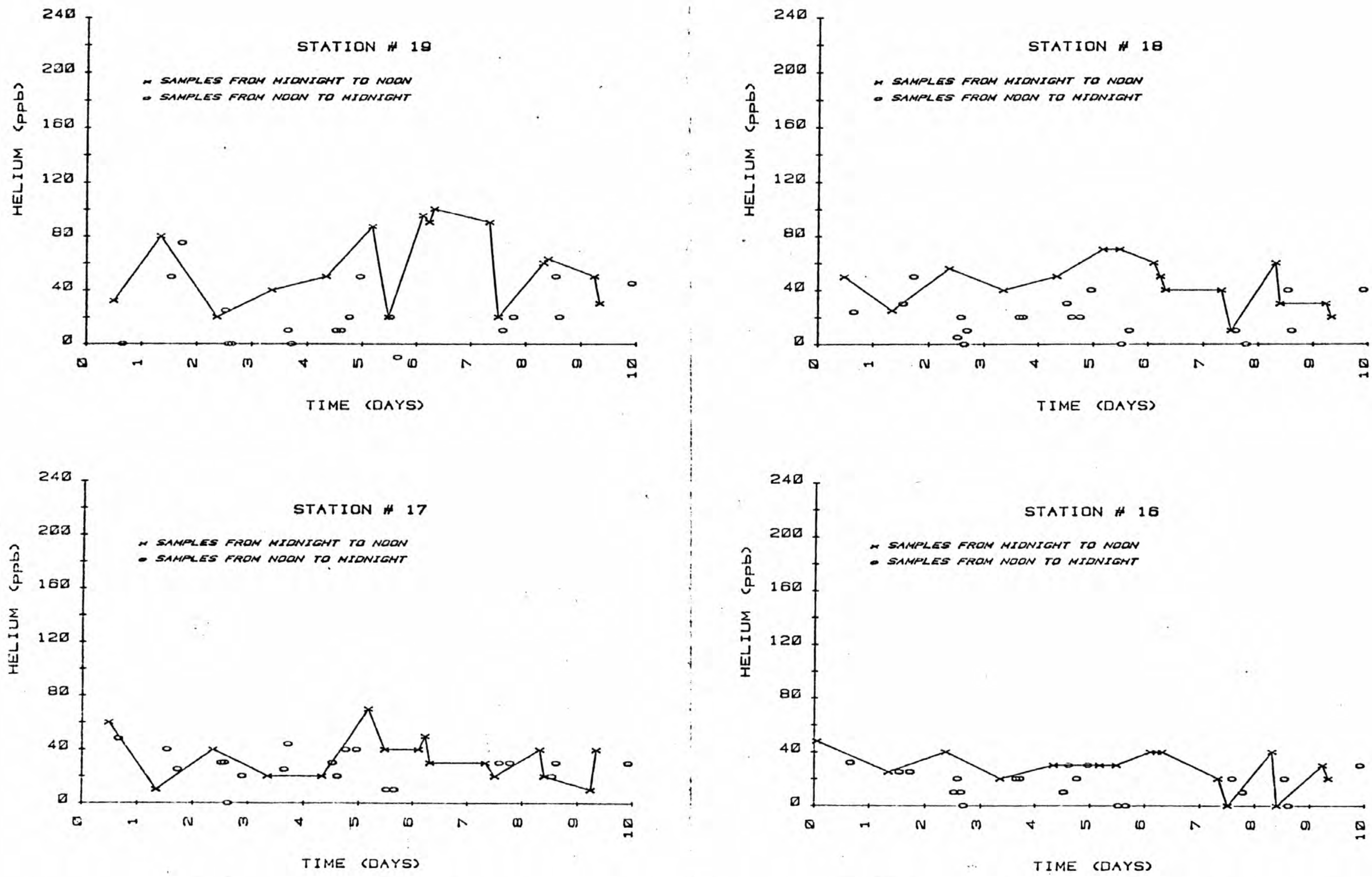


Figure 48.--Graph of sample group 16-19, San Juan Bautista. The probe depth for stations 19, 18, 17 and 16 was 0.5, 1.0, 1.5 and 2.0 m, respectively. The daily variation decreased with increased probe depth, and samples collected during the morning hours generally had higher helium concentrations than samples collected during the afternoon hours.

conclusions, some correlations are noted. High helium correlates with low air temperature and low wind speed, and low helium with low relative humidity. There is no correlation with barometric pressure.

Soil temperature, measured at a depth of 15 cm, ranged from 18^{o}-21^{o}C. It also followed a diurnal cycle similar to that of to air temperature, but with a lag time of 3-4 hours. A trace of precipitation occurred on the ninth day of the study, but it did not appear to have any pronounced effect on the soil-gas helium concentrations.

Samples from the remaining probe groups and traverse probes were collected about once a day. They all showed a similar trend of rising and falling helium concentrations. Figures 11 and 18 are representative of this "bimodal" trend, which has significance when using helium surveys for exploration purposes. The trend shows that the helium soil-gas variability is consistent with time over a fairly large area. By establishing several permanent stations and sampling them several times during the day, it should be possible to correct the helium concentrations taken from any other station to a single data base. Station 1 and station 30 (figs. 11 and 40), with averages of about 180 ppb He, have the highest soil-gas helium concentrations recorded in the study area. Those stations were established very near fault scarps, and the high concentrations may be reflecting a more open channel to greater depths than at the other stations.

Soil-gas Sampling Model

These studies provide some information necessary to develop a model of the soil-gas sampling technique and the causes of the soil-gas helium variations. Other soil gases very probably respond differently to the various natural and environmental parameters evaluated in this report for possible helium correlations. Therefore, the application of this model to other gases should be considered only qualitatively.

The analysis of helium in these studies is reported as a volumetric measurement--ppb He in soil gas in excess of ppb He in the reference gas. The reference used is the atmosphere, which contains a constant 5,240 ppb helium (Glueckauf, 1946). The concentration of helium in the soil gas depends on the supply by the generating source (radioactive decay), the modes of transport and retention, and the presence of diluting gases, principally the atmosphere or generation of CO_2 or CH_4 by plants or bacteria. Therefore, when the soil-gas helium concentration is reported as a negative value (with respect to atmosphere), it means the presence of diluting gases.

The helium contained in the soil gas near the soil-air interface is in a fragile state of equilibrium. From experimental measurements, the helium experiences diurnal variation, the intensity of which decreases with sampling depth. The sampling procedure used in this study was designed to present a minimal disturbance to the environment being sampled.

A total of 20 cm^3 of gas, including a purge of the probe, is removed from a probe. For most soils, this represents drawing the gas from a volume with a radius not exceeding 10 cm and rarely exceeding 5 cm.

The soil gas is contained in the soil pore spaces, trapped on grain surfaces, and trapped or dissolved in the water which may also be contained in pore spaces or trapped on grain boundaries. When a gas sample is taken from a probe, not only is the pore-space gas collected, but also the gases contained in the soil moisture. The amount of soil moisture present can have a great influence on the concentration of any measured gas.

When a great deal of moisture is available, such as was the case with the Idaho Springs study, two mechanisms to increase the soil-gas helium concentration become prominent. The first is the decrease in exchange of soil gas with the atmosphere caused by a barrier formed by the moisture. The water fills the pore spaces, swells the clays, and thus reduces the pathways for both helium escape and atmospheric dilution. This effect was also noted for radon (Gableman, 1972). A second mechanism is that the water becomes a medium into which the helium can dissolve and be subsequently degassed by later sampling. A different mechanism controlling the soil-gas helium concentration is the degree of atmospheric pumping. Wind and air temperature are perhaps the primary causes of the pumping mechanisms. Wind can directly force the atmosphere into the upper portion of the soil and can withdraw the gas from the soil by a bernoulli effect. Increasing the air temperature and thus heating the extreme upper portions of the soil can also have a pumping effect on the soil gas. The soil-moisture content in the near surface also decreases with the increased heating. As the temperature decreases, the soil moisture can increase. This last effect seemed dominant in the San Juan Bautista study. in which helium values were greatest in the cool and moist early morning hours when dew formed; as the day warmed, the helium concentrations decreased. The highest helium values were obtained from the shallowest probes, suggesting a major influence by the surface soil-moisture abundance. The temperature and related moisture pumping mechanism has an influence only on samples collected at shallow depths; the effect is lost in the limits of the analytical sensitivity by a depth of 2 m.

Pumping caused by changes in barometric pressure is not observed to have any influence on the variations in helium concentration within the limits of the analytical sensitivity of this study.

Conclusions

The helium concentration in the near-surface soil gas fluctuates on a diurnal cycle. The predominant controls of this fluctuation are soil moisture, wind speed, and temperature-induced atmospheric pumping. At a 2-m sampling depth, for the moderately compact soils investigated in this study, no detectable changes in helium concentration (within ±10 ppb) were observed as an influence of wind speed or temperature variations.

The range of the fluctuations, based on a background of the 5,240 ppb He in air, was within 4 percent (200 ppb) and more typically about 1 percent (50 ppb). In soil-gas surveys conducted for exploration, anomalies have been described that are within the 1-4 percent variation (Reimer and Otton, 1976). The confidence in these anomalies is increased if several stations are established for continued monitoring during the course of the survey and if the limits of the diurnal variation for that area are established and any appropriate corrections are made. The diurnal fluctuations for helium seem to be regular and predictable.

The regularity of helium soil-gas variations is important for the purpose of establishing monitoring stations to predict earthquakes. The ideal locations for those stations would be in fault zones, preferably at active fault scarps, where the possibility exists for signal transfer from greater depths. At a sufficient sampling depth, the diurnal variation of the soil-gas helium concentration is not significant enough to impose any limitations on the use of soil-gas helium concentrations for further earthquake-prediction investigations.

Plans for Future Studies

The necessary background information has been gathered for discerning true changes in the soil-gas helium concentration. The next phase of investigation will involve establishing several permanent stations to a 2-m depth along the San Andreas Fault near San Juan Bautista, California. It is proposed to sample these stations on a routine basis, perhaps twice weekly, to observe the long-term helium variations and to attempt to establish a relationship to actual earthquake activity.

Additional information will be sought to discern to what extent a relationship exists between ground water and soil-gas helium concentrations and also if it is feasible to collect gas samples from deep drill holes penetrating a fault.

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