UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Near-surface Helium Anomalies Associated With Faults and Gas Accumulations in Western Pennsylvania

by

Alan A. Roberts[1] and John B. Roen[2]

Open-File Report 85-546

[1]Denver, CO

[2]Reston, VA

1985

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INTRODUCTION

Abnormally high concentrations of helium in soil-gas have been observed in connection with petroleum and natural gas reservoirs (Debnam, 1969; Ball and Snowdon, 1973; Dyck, 1976; Roberts, 1981), uranium and thorium deposits (Clarke and Kugler, 1973, Dyck, 1976; Clarke and others, 1977; Dyck and Tan, 1978; Reimer and others, 1979; Pogorski and Quirt, 1980; Reimer, 1985), geothermal waters (Mazor, 1974; Roberts and others, 1975; Hinkle, 1980), and fault and fracture systems (Pierce and others, 1964; Eremeev and others, 1973; Ovchinnikov and others, 1973; Jones and Drozd, 1983). Helium in soil-gas has its ultimate origin from mainly two sources: (1) primordial helium, trapped within the earth during its early formation, and which has subsequently been degassed from the mantle and migrated to the surface, and (2) alpha decay of radioactive elements such as uranium and thorium and their daughter products in which alpha particles pick up a pair of electrons to form the stable helium atom. As a result of these two processes there is a continual flux of helium through the Earth's crust to near-surface soils, with subsequent loss to the atmosphere and eventually to outer space. Over geologic time a steady state equilibrium has been achieved within the atmosphere in which the loss to outer space precisely counterbalances the input from the Earth with a resultant steady state concentration of helium in the atmosphere of 5.24 parts per million by volume (ppm) (Gluekhauf, 1946; Oliver and others, 1984). Most soil-gases shallower than 1 meter are in constant communication with the atmosphere and, as a result, soil-gas helium concentration is fairly close to that observed in the air itself. However, if there is a significant subsurface source of helium, such as a helium-containing natural gas reservoir or a fault or fracture system, contributing abnormally large amounts of helium locally to the continued flux then soil-gas helium concentrations are observed on the order of tens or hundreds of parts per billion by volume (ppb) above the normal atmospheric background.

This paper presents the results of two helium surveys run in Pennsylvania and discusses the relationship of the abnormally high helium to known or suspected faults and to petroleum or natural gas reservoirs.

EXPERIMENTAL METHODS

Soil-gas samples were obtained by pounding a thick-walled, stainless steel probe 0.75 m (2.5 ft) into the ground. The probe was capped on the bottom end and communication with the soil-gases was accomplished through eight holes drilled through the sidewall near the bottom of the probe. The top of the probe was fitted with a septum holder containing a rubber septum through which a side-hole hypodermic needle was inserted. One 10 cubic centimeter (cc) sample of gas was withdrawn from the probe and discarded in order to purge the dead volume of the probe and septum holder (total volume less than 2 cc). A second 10 cc sample is withdrawn into a plastic syringe, the syringe needle hole capped with soft, silicone tubing, and the sample stored for analysis later the same day on the U.S. Geological Survey (USGS) developed, field-portable helium analyzer (Friedman and Denton, 1975; Roberts and others, 1975; Reimer, 1976; Reimer and Denton, 1978). Each sample analysis was bracketed by ambient air analyses and all concentrations are reported as excess helium relative to ambient air. The instrument was calibrated periodically by analysis of known helium-in-air standards to account for electronic drift and change in instrument sensitivity from a variety of environmental influences. The instrument had a precision of 20 ppb under field conditions. Leakage rates from plastic syringes have been measured and are insignificant for samples within the range of expected helium concentrations for periods of up to 8 hours.

Two different sampling techniques were employed for the two surveys reported in this paper. For the survey in southwestern Pennsylvania (near Masontown), samples were collected along several traverses with sample spacings ranging from 1.5 to 6 m (5 to 20 ft). Samples were collected simultaneously by each of 4 field crew members, with an average time for collection at each sample station of about 4 minutes. For the survey in northwestern Pennsylvania (near Titusville) samples were collected by two crews of two members each. Sampling sites were located at 1/3 km (1/4 mi) intervals along roads and two samples were taken at each site, on opposite sides of the road where possible.

Previous surveys conducted by the author and coworkers have demonstrated that potentially significant variation in helium concentrations in soil-gas may be observed during the course of a day and from day to day. In order to estimate the magnitude of these variations and to effect a first order correction, a reference probe was established at a location central to a given survey area. This probe was sampled several times each day and the helium concentrations were plotted as a function of time on a given day. As has been previously observed, there existed a regular decrease of about 3 to 10 ppb/hour in helium concentrations during the course of a day in which no significant rain has occurred. Day to day variations also were observed resulting from a complicated interaction of environmental variables. These variations could become fairly large if significant amounts of rain fell on the survey area during the survey. For both of these surveys, the variation of helium concentrations for these reference-probe samples was small compared to the levels of anomalous helium concentrations observed in the survey. Therefore, no alteration of the interpretation of survey results was necessary after correction for temporal variation. However, if one were to attempt interpretion of subtle differences between sample values (on th order of 50 to 80 ppb), then these corrections would be on the same order of magnitude as the sample differences and any such interpretation would be much more tentative.

One set of four samples, taken at one sample site in the northwestern survey, was observed to be very high in helium content (about 10,000 ppb). Four additional 20 cc aliquots of these samples were stored in previously evacuated stainless steel cylinders subsequent to field anaylsis. These samples were analyzed in a laboratory on a scanning, quadrapole, mass spectrometer (McCarthy, 1985) for major gas constituents. This procedure was followed for two reasons: (1) If the large amount of helium observed were a result of a leaking pipeline or other culturally related source of natural gas, then the methane concentration would be correspondingly high. Pipeline gas from this location was analyzed at 0.1 percent helium. Thus, if the source of the 10,000 ppb of helium in these samples was gas from leaky pipeline containing 0.1 percent helium, the soil-gas would contain about 1 percent methane. (2) Alternatively, if major quantities of other normal soil-gas constituents such as oxygen or nitrogen had been consumed, then the analysis of the remaining gas would yield correspondingly high helium values. For a normal background sample (5 ppm helium) prior to gas consumption, loss of another gas would result in an apparent increase in the helium concentration of about 50 ppb per percent gas consumed. If, for example, all the oxygen had been consumed, the resultant gas would contain about 6 ppm helium (1,000 ppb in excess of air). Analysis of the sample with 10,000 ppb helium on the mass spectrometer yielded normal concentrations of nitrogen and oxygen and a methane content of only 0.05 percent. Thus, the high helium content of this soil-gas must be related to a natural, subsurface source of helium.

DESCRIPTION OF SOUTHWESTERN PENNSYLVANIA SURVEY AREA

Kemp and Ross (1907), Smith (1912), and Hickok and Moyer (1940) described a peridotite dike system in Fayette and Greene Counties, Pennsylvania intruding into a northwest-trending, vertical to near vertical, joint or fracture system in Pennsylvanian and Permian rocks. Roen (1968) described this fracture system as a series of parallel, vertical or nearly vertical, fractures and small, left lateral strike-slip faults cutting surface and near-surface, nearly flat-lying beds of sandstone, shale, limestone, and coal of the Late Pennsylvanian Pittsburgh and Uniontown Formations and the Late Pennsylvanian and Early Permian Waynesburg Formation. The trend of the peridotite intrusion zone is N 51° W, almost normal to an axial trend of low-amplitude folds in these strata. From examination of the few outcrops in this area, along with study of the near-subsurface rocks in coal mines, Roen (1968) was able to map about 11 km of this zone, the central 4.3 km of which were intruded by the peridotite (fig. 1). The fault was mapped to the northwest to Muddy Creek, beyond which extensive soil cover and vegetation precluded further mapping. Continuation of the fault to the northwest as far as Rices Landing (fig. 1) was hypothesized on the basis of lineaments formed by stream valleys and observation of a vertical fracture set in a shale highwall near Lewis Crossing (fig. 1).

RESULTS AND DISCUSSION OF SOUTHWESTERN PENNSYLVANIA SURVEY

The first helium traverse was performed along the road about 45 m (150 ft) southeast of Roen's (1968) Middle Run locality (fig. 1), at which Roen (1968) reported the total width of the intrusion zone to be about 25 m (80 ft) with individual dikes between 0.1 and 1 m (.3 to 3 ft) wide. Sample spacing along this traverse was 1.52 m (5 ft) with the traverse extending for 30 m (100 ft) on either side of the extrapolated location of the main dike in the creek cut. Figure 2 displays the results of the analysis of these samples for helium content. There exists obvious noise in helium values that is inherent in sampling any given location. This noise is due to a variety of differences in the soil micro-environment, such as local variation in the soil permeability just below the probe tip due to variable soil composition or moisture. Therefore, the collection of a large number of samples on any traverse or survey is necessary in order to have confidence in trends observed in the data. It is often helpful to display the data utilizing some sort of

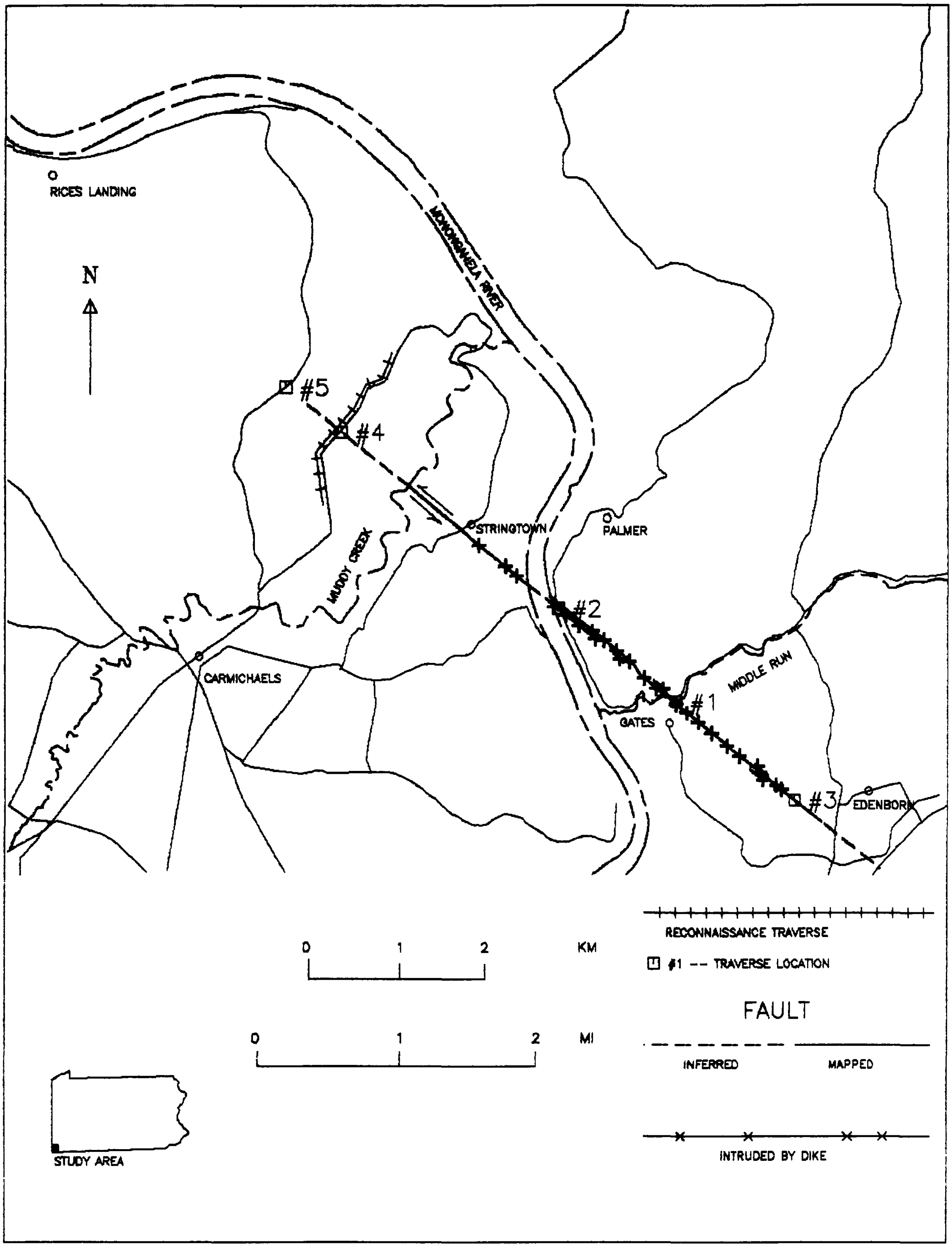

Figure 1.--Map of the fault zone and traverse locations (modified after Roen, 1968).

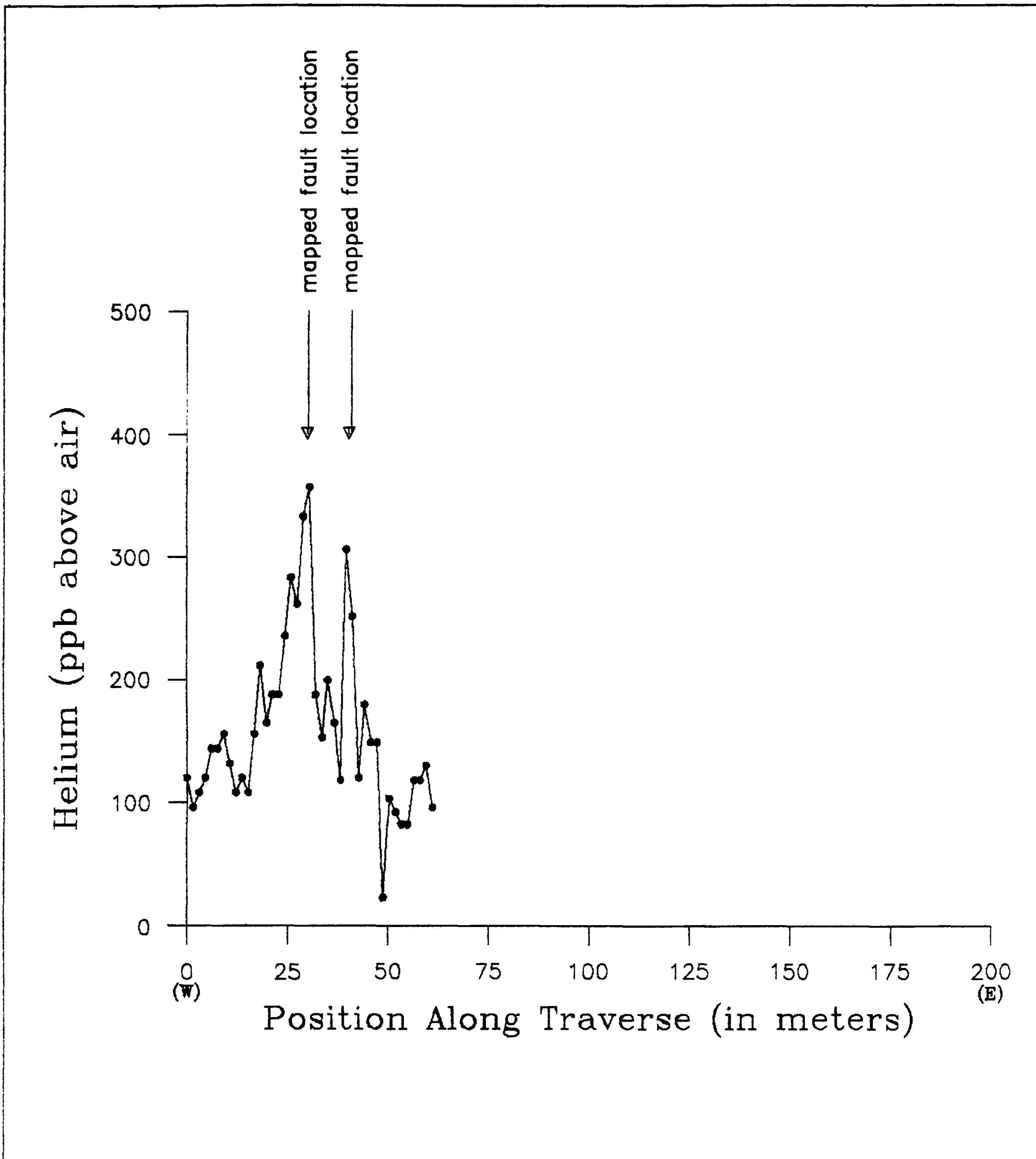

Figure 2.--Unfiltered helium concentrations along traverse #1.

averaging algorithm to filter out some of this noise. Figure 3 displays these data after treatment with a three point running average filter.

Most of the samples along the traverse had helium contents in excess of 100 ppb above atmospheric concentrations in contrast to three samples taken several hundred feet to the east (not shown in fig. 3), which had helium contents within 40 ppb of atmosphere. These elevated values indicate that helium is migrating up along the whole fault and fracture zone and that the surface expression of this helium migration is a zone of enhanced helium in soil-gas at least 60 m (200 ft) wide centered on the main dike. In addition, within this zone of generally enhanced helium the concentrations peak above 300 ppb directly over the main dike and fall off in a somewhat regular manner away from this point (figs. 2 and 3). A second, lower, maximum in helium concentrations is observed 12 m (40 ft) east of the highest peak, probably an indication that another significant fracture cuts the near-surface rocks at this location. The results from this first traverse suggest that helium is migrating up along this fault system and that a relatively precise location of the surface traces of faults can be obtained from the data.

A second traverse crossing the mapped fault location was conducted along the road beside the Monongahela River (fig. 1) at sample intervals of 1.52 m (5 ft). Figure 4 displays the results from this traverse after treatment with the three-point, running average filter. The most significant feature of figure 3 is the peak located just north-northwest of the center of the traverse with helium values in excess of 150 ppb. Helium concentrations on either side of this peak drop off to 10 to 50 ppb, concentrations almost indistinguishable from normal background values. This peak coincides with the fault location as mapped by Roen (1968). Elevated helium values were also observed at both ends of this traverse, but interpretation of these values was not possible due to the fact that the position and shape of these anomalies was not determined by extension of the traverse.

A third traverse was conducted over the postulated extrapolation of the fault to the southeast near Edenborn (fig. 1). Figure 5 displays a three point running average for helium concentrations from this traverse. These data are difficult to compare directly to the values from the previous two traverses as there was an intervening rainstorm.

Previous studies have shown that soil-gas generally tends to increase in helium concentration immediately following a rain. Thus, a reference probe located some distance from the survey location is of minimal value in correcting these values for the rain as the amount of rain falling on the two areas may be significantly different. This post-rain increase in helium concentrations values is possibly because the top few centimeter of the soil becomes significantly less permeable when wet and thus may act as a barrier or cap to the continual outgassing of helium from the earth. Thus, after a rain, helium concentrations build up under this cap. As the soil dries out, this relatively impermeable barrier is lost and helium concentrations drop back to pre-rain observations. However, the relative values along this traverse should be reliable and peaks within the traverse should still indicate subsurface sources of helium.

Two major peaks are observed in figure 5, at 115 m (380 ft) and at 140 m (450 ft) along the traverse. The southwestern end (from 107 to 183 m (350 to

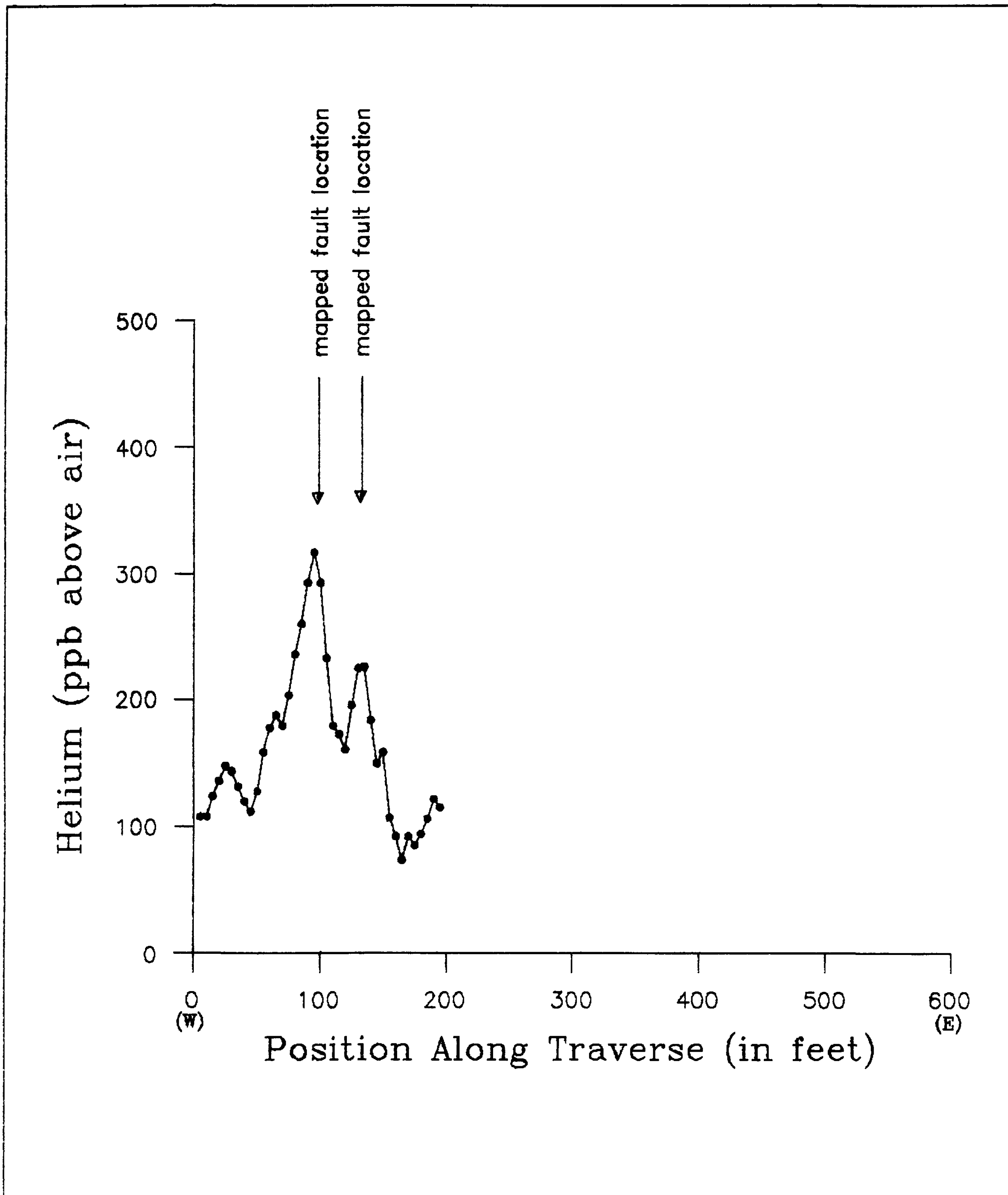

Figure 3.--Helium concentrations along traverse #1 after three-point running average filtering.

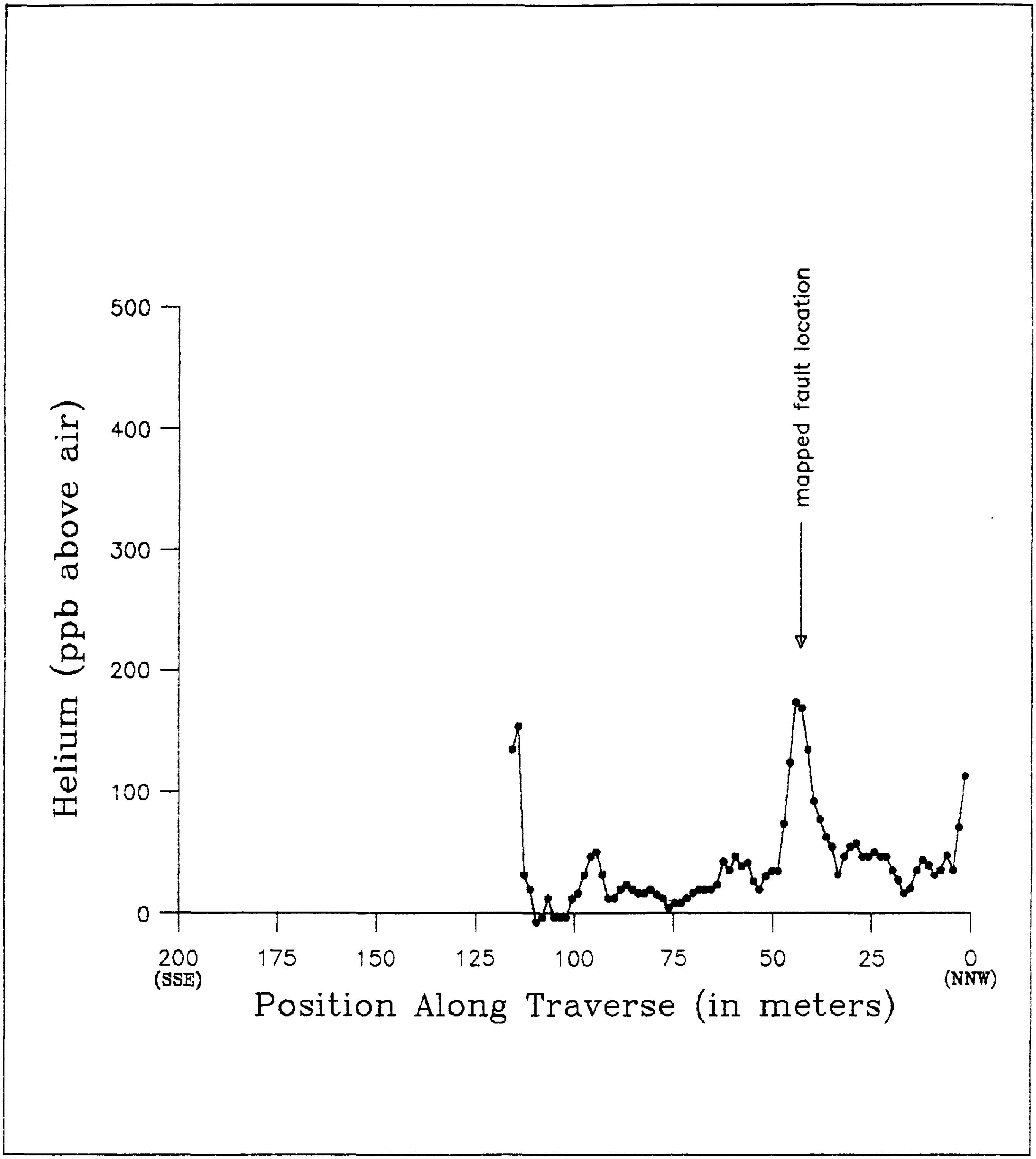

Figure 4.--Filtered helium concentrations along traverse #2.

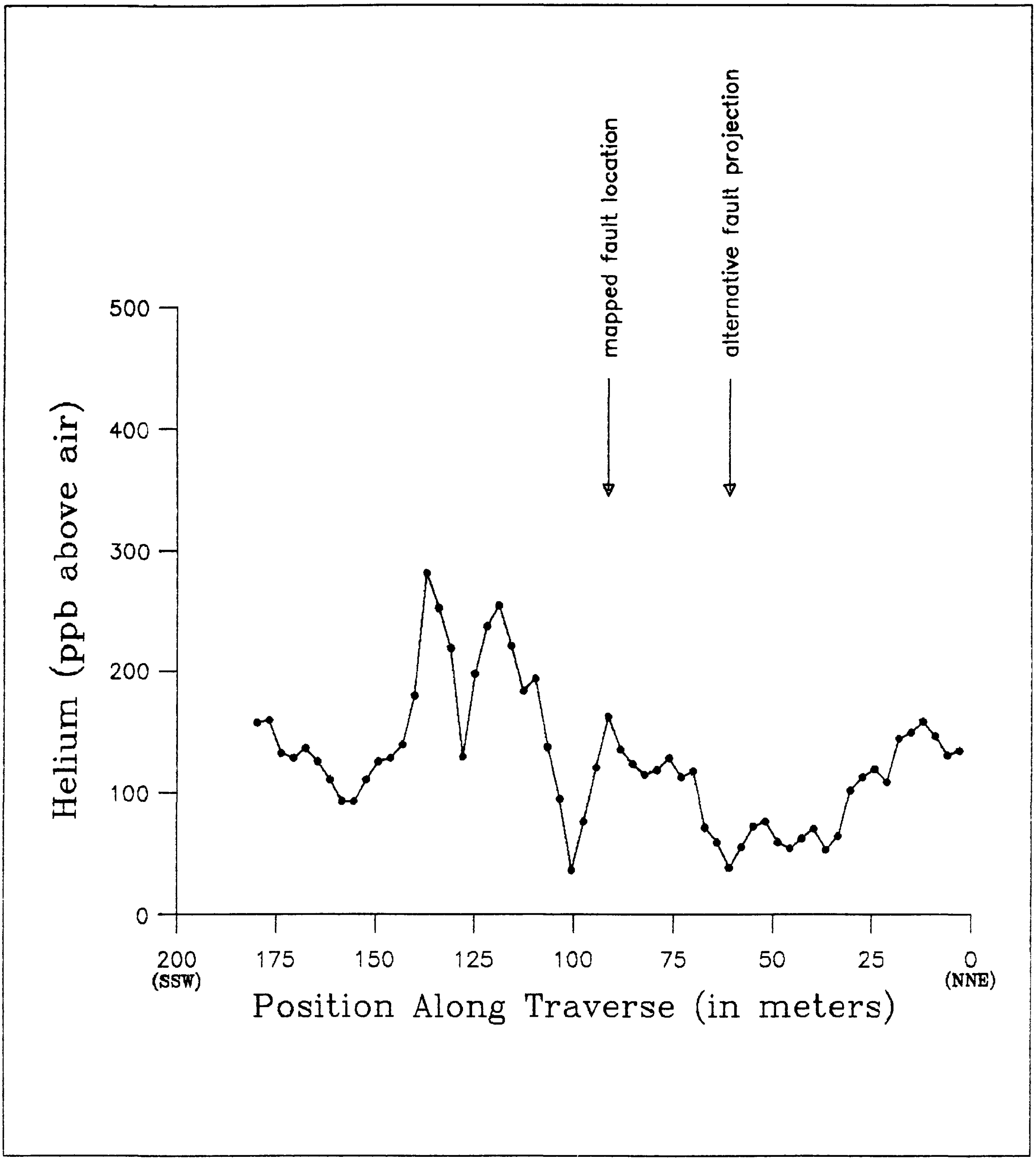

Figure 5.--Filtered helium concentrations along traverse #3.

600 ft)) of the survey was done one day later than the rest of the traverse. To ensure direct comparability between concentrations measured on the two days, sites between 110 and 122 m (360 and 400 ft) inclusive were resampled. The peak observed within this part of the traverse was reproduced, both in position and magnitude. Thus, we are sure that neither of these peaks resulted from differing meteorological conditions between the two days. However, the higher level of helium concentrations along the entire traverse, compared to the values from the previous two traverses, is likely due to the rain storm, although the possibility that this general elevation of helium concentrations is real cannot presently be ruled out. The two peaks in helium concentration are found approximately 45 m (150 ft) southwest of the previously mapped position of the fault. We believe that these high values are associated with the fault and that the location of these peaks represents a more precise location for the fault than the extrapolated location.

Two additional traverses were conducted across the northwesterly extrapolation of the fault towards Rices Landing. One, (traverse #4), was run at 6.1 m (20 ft) spacing along a road about 1 km (0.6 mi) northwest of Roen's (1968) most northwesterly direct observation of evidence of the fault at Muddy Creek. Traverse #5, also at 6.1 m (20 ft) spacing, was run along a road 0.9 km (0.5 mi) northwest of traverse #4. Figures 6 and 7 depict the results of three-point, running averages of the helium values for these traverses. Only one significant peak was observed along each of the traverses, with helium concentrations 100 to 150 ppb higher than those found off of these peaks. These peaks fall within the range of possible extrapolated locations of the fault from mapping. The existence of these areas of elevated helium concentrations supports a hypothesis that the fault extends at least this far to the northwest, the locations of the helium anomalies being the surface location of the fault where it crosses the traverses.

The observed helium anomalies associated with the fault in this survey are all in the range of 15 to 45 m (50 to 150 ft) wide. Due to the noise involved with helium surveying, single value anomalies should be verified by replicate sampling. Traverses run at a sampling interval of 6 to 8 m (20 to 25 ft) may have produced at least two-point anomalies. Traverses run at a spacing of 15 to 45 m (50 to 150 ft) could easily have yielded only single-point anomalies, and greater spacings could easily have missed the anomaly completely. Figure 8 displays the results of a traverse run at 0.33 km (0.2 mi) spacing along the road used for traverse #4 superimposed on the results from this more closely spaced traverse. The helium anomaly clearly stands out from the rest of the samples. However, the anomaly width is much less than the spacing between samples along the rest of the traverse. At this wide spacing there would have been less than a 1 in 10 chance that a sampling site would have fallen on the anomaly.

From the traverses in southwestern Pennsylvania we conclude that helium surveying can be of significant utility in helping to map faults in areas where conventional mapping techniques are severely hindered by soil or vegetation cover. Helium surveying could also be of use in providing precise surface locations of faults which have only approximately been mapped by geophysical or remote sensing techniques or topographic expression. However, helium surveys might require a very large number of samples to be used for reconnaissance mapping of faults.

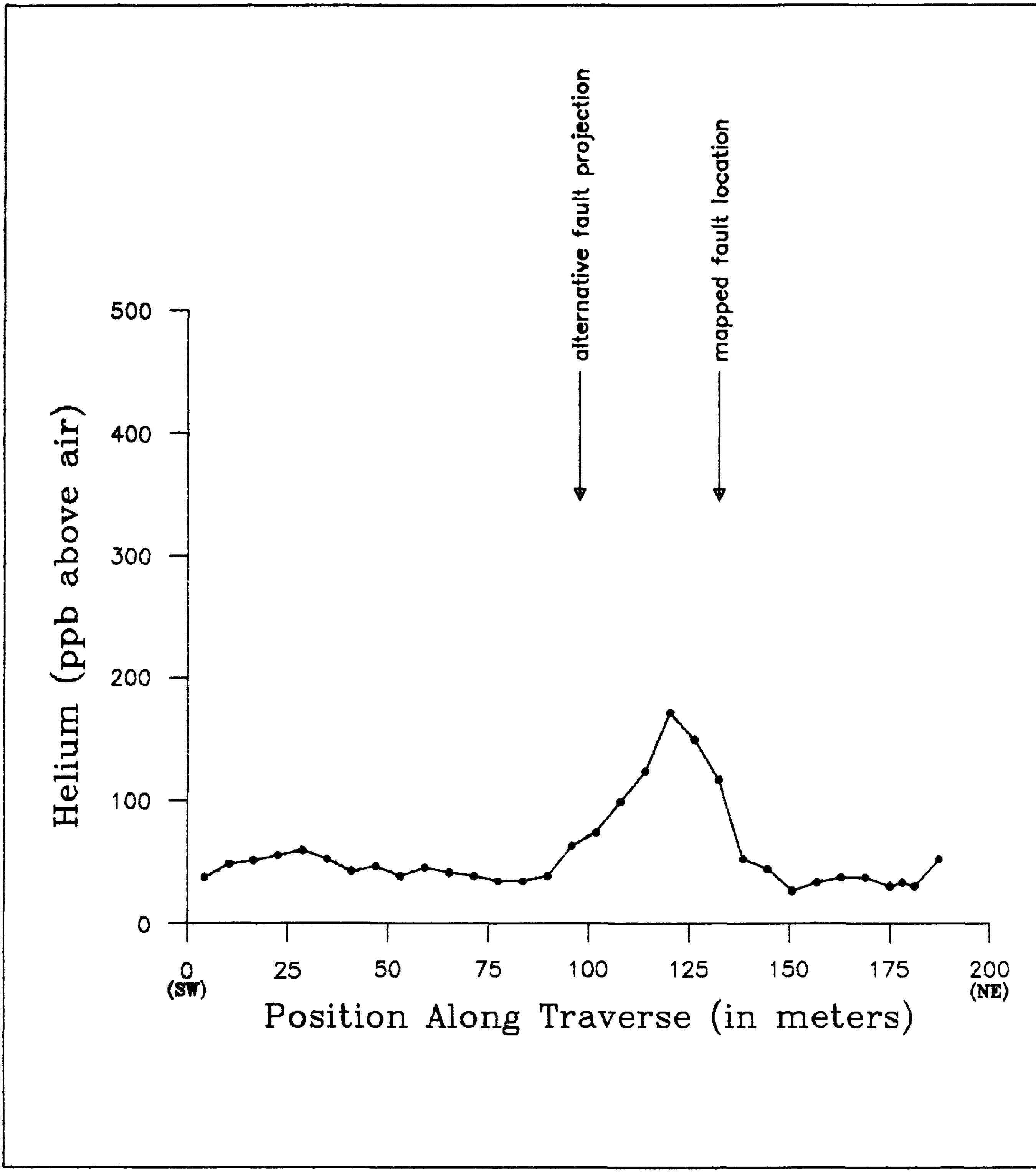

Figure 6.--Filtered helium concentrations along traverse #4.

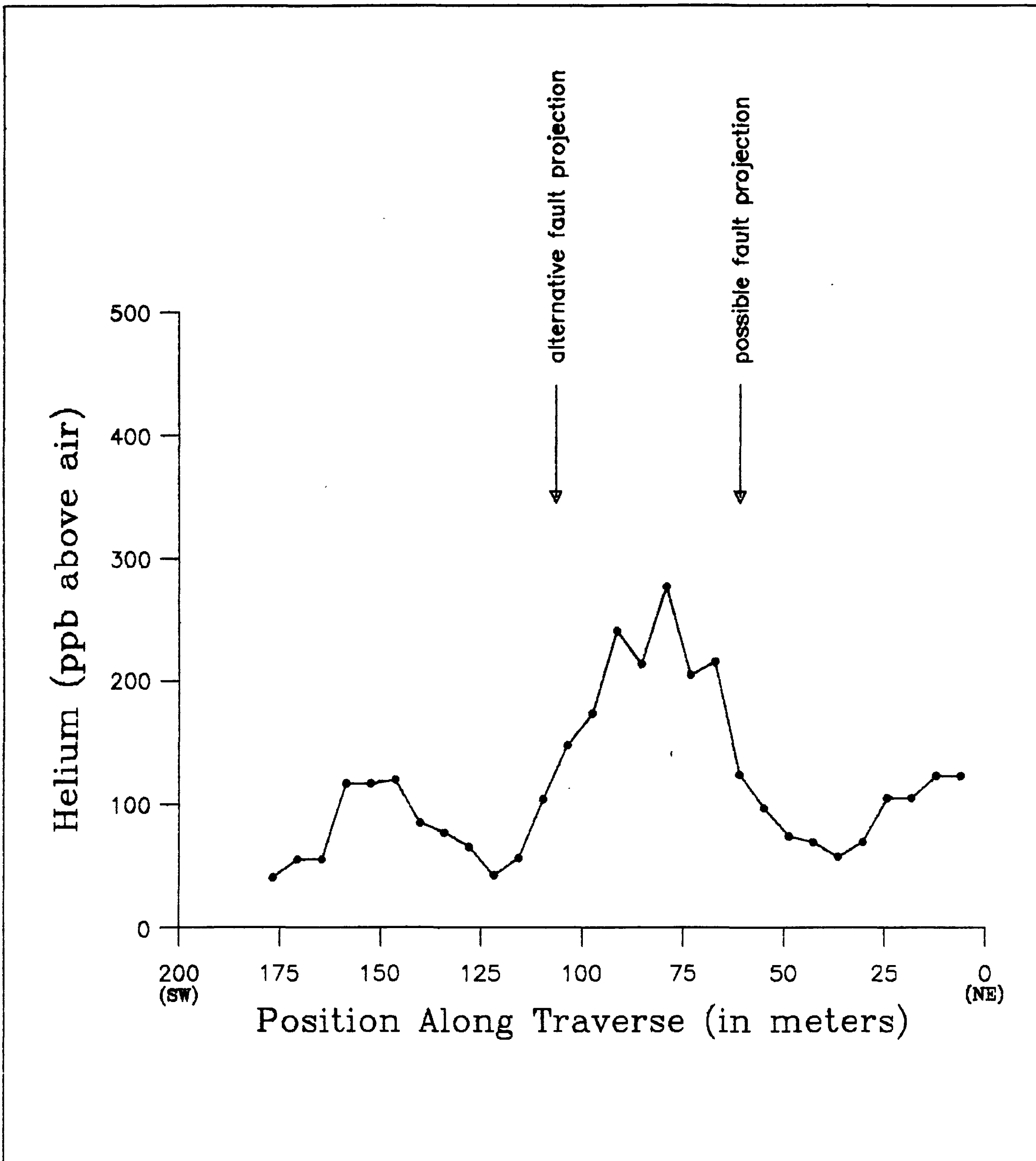

Figure 7.--Filtered helium concentrations along traverse #5.

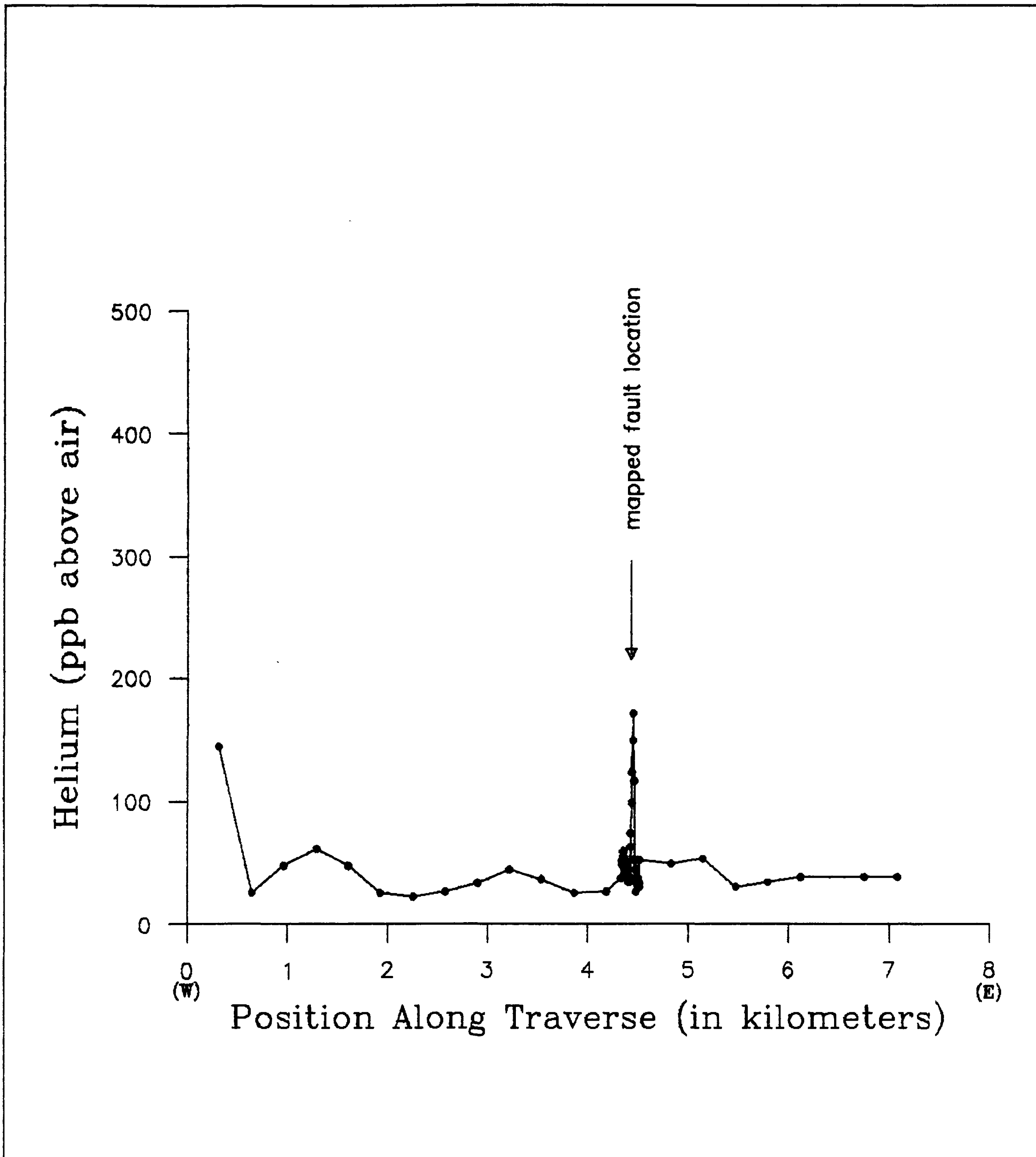

Figure 8.--Filtered helium concentrations along regional extension of traverse #4.

Traverse #4 was conducted over a known gas accumulation, the Carmichaels field, which might be expected to result in elevated concentrations of soil-gas helium from microseepage of gas from the deposit. However, with the exception of the narrow band of high values associated with the fault, helium concentrations along this traverse were at or near background levels. The Carmichaels field is very old (discovered in 1861 (Socolow, 1982)) and is likely to be near depletion. Thus, microseepage of gases from the reservoir might not presently be significant and no helium anomaly would be associated with this field.

DESCRIPTION OF NORTHWESTERN PENNSYLVANIA SURVEY AREA

Rodgers and Anderson (1984) have recently projected the Tyrone-Mt. Union Lineament into the Plateau province in the vicinity of Titusville, Pennsylvania. Their studies suggested that this lineament represents a zone of above normal fracture permeability and enhanced fluid movement. The Athens gas field, just west of Centerville, intersects the lineament at the extreme southwest portion of the field (fig. 9) and produces gas from the Silurian Medina Sandstone. Seven wells in the field located within 1 km (0.6 mi) of the lineament also encountered significant gas shows in a Devonian Shale 300 m (1000 ft) below the surface (Rodgers and Anderson, 1984). In addition, these wells "had background concentrations of methane (at least 10 times larger than wells farther from the lineament) in the drilling mud all through the section--from the glacial outwash-bedrock contact at 30 m (100 ft) below the surface to those organic-rich shale zones at 300 m (1,000 ft)" (Rodgers and Anderson, 1984, p. 95). This suggests that gas from the Devonian Shale may have migrated via the fractures associated with the lineament to the Earth's surface. Rodgers and Anderson (1984) also reported that analysis of near-surface soils revealed anomalously high methane concentrations directly over the lineament. Medina reservoir-gas composition studies led Rodgers and Anderson (1984, p. 96) to the tentative conclusion that "If reservoir geochemical variations noted here are related to the fracture zone, it would imply that fracturing extends from the surface to at least 1,370 m (4,500 ft), which is the approximate depth to the Medina sand reservoir."

RESULTS AND DISCUSSION OF NORTHWESTERN PENNSYLVANIA STUDY

The Medina Gas, in the Athens field, contains more than 0.1 percent (1,000 ppm) helium. If the anomalous methane concentrations in the near-surface soils is from the Medina Sandstone, then the soil-gas should contain abnormally high helium concentrations. The mean-methane concentration that Rodgers and Anderson (1984) measured within the lineament zone was 255 ppm compared to 60 ppm outside the lineament zone. If most of this methane were from the Medina Sandstone, then the helium content of these soil-gases should be on the order of 300 ppb above background. Their highest methane content (2,841 ppm) would correspond to more than 3,000 ppb helium.

A helium sampling traverse was run, therefore, across this lineament near the Athens field. Sample spacing was 0.33 km (0.25 mi), identical to that used by Rodgers and Anderson (1984), with two samples collected at each site, generally on opposite sides of the road. Figure 10 is a plot of the average helium concentrations for the two samples at each site. Figure 11 displays the same data after treatment with the three-point, running average filter. It is clear from both figures 10 and 11 that anomalously high helium

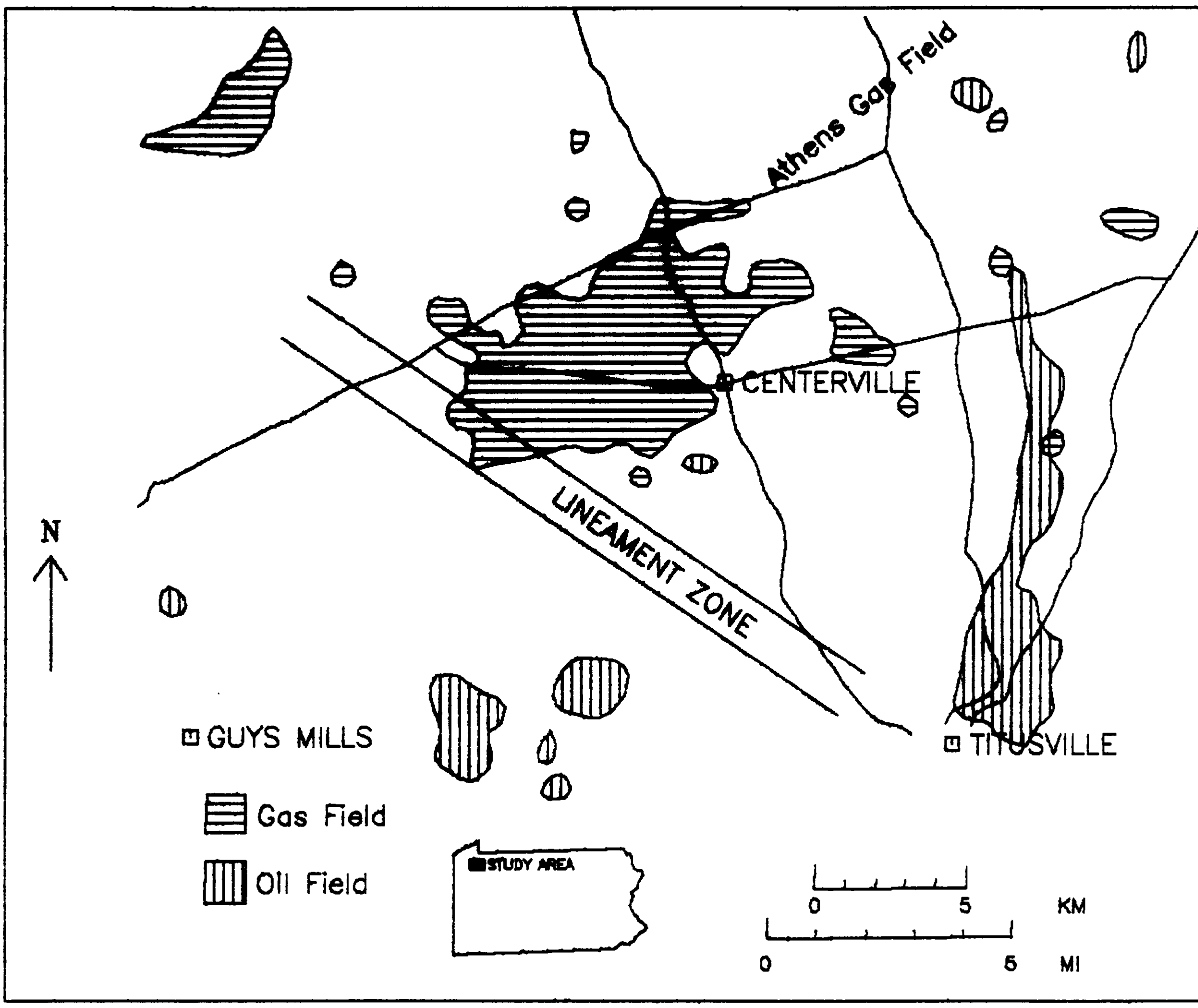

Figure 9.--Location map for Athens gas field and projection of lineament zone.

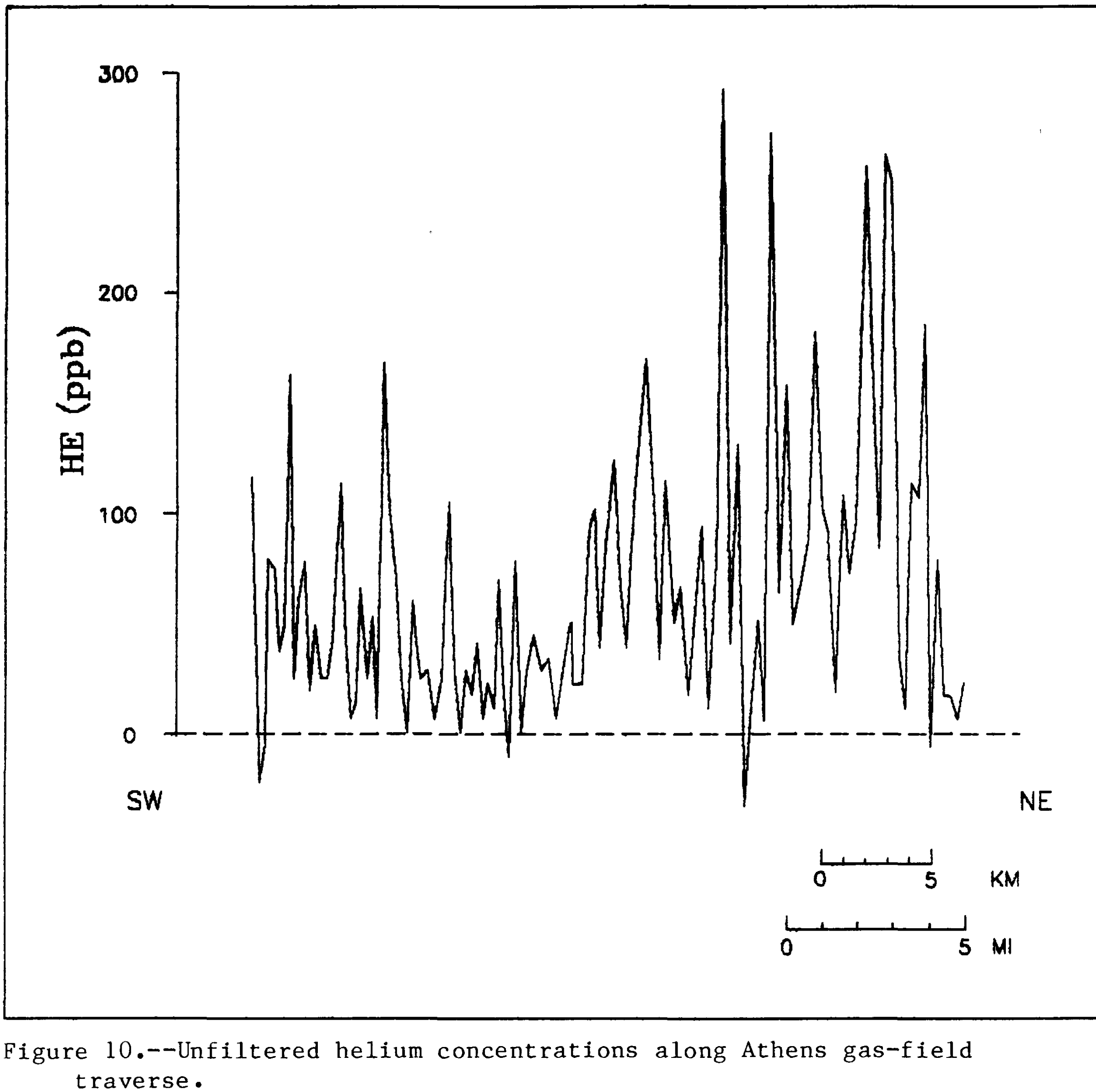

Figure 10.--Unfiltered helium concentrations along Athens gas-field traverse.

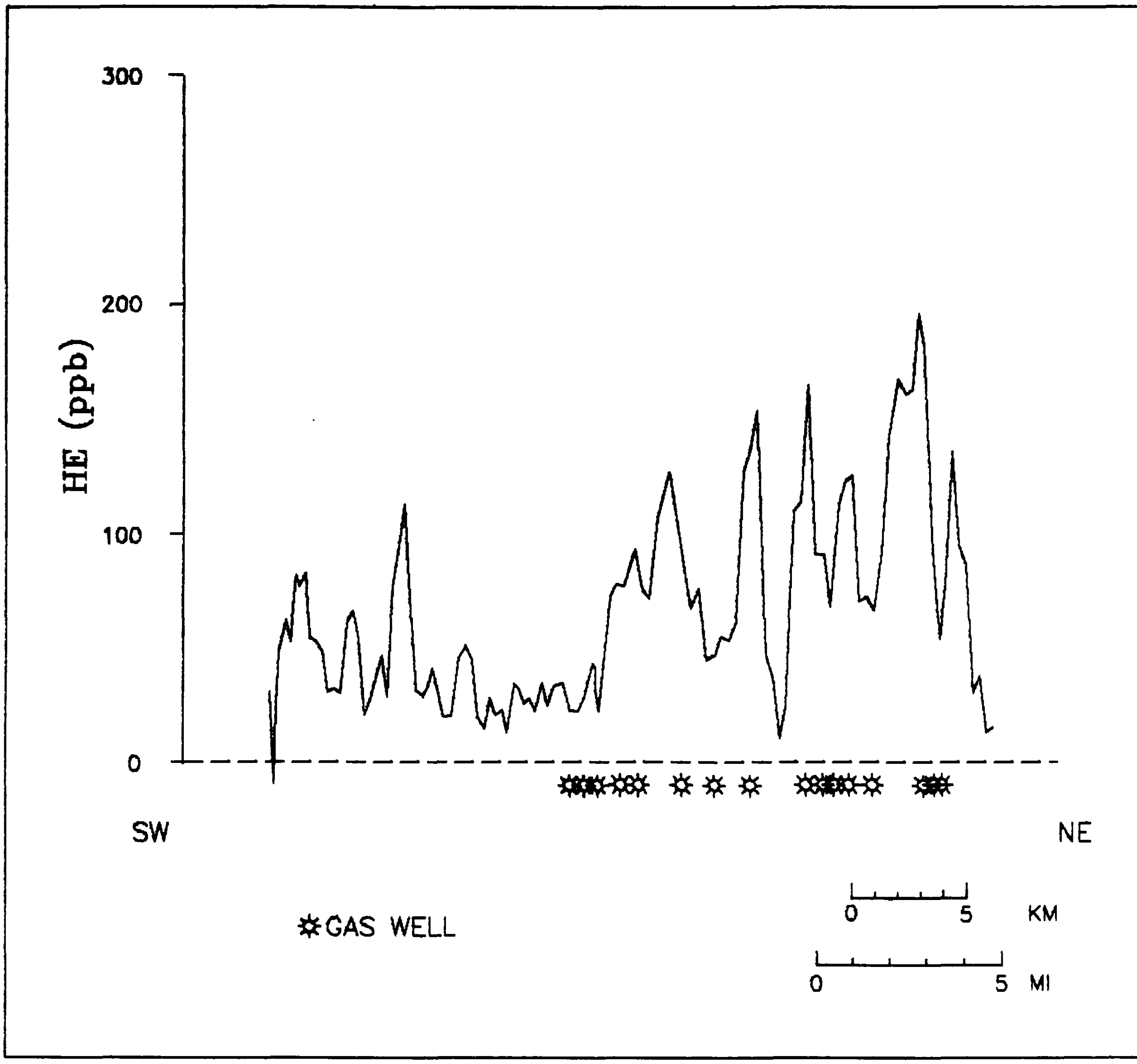

Figure 11.--Filtered helium concentrations along Athens gas-field traverse and position, along traverse of gas wells within 1/2 km of the line.

concentrations are found on the northeastern half of the traverse with a wide section of low concentrations just to the southwest of the center of the traverse. The profile from figure 11 has been overlaid on figure 9 to give figure 12 in order to show helium concentrations in relation to the oil and gas production in the area (Socolow, 1982) and the lineament (Rodgers and Anderson, 1984). Clearly, no helium anomaly is associated with the lineament in this survey. The helium concentrations associated with the lineament averaged less than 25 ppb above atmospheric background and are among the lowest of the entire traverse. Figure 13 displays the more recent well locations in the area (from the Petroleum Information Corporation Well History Control System Data Base) superimposed on the oil and gas fields from Socolow's (1982) map. A combination of these two sources was used because the Petroleum Information data include few wells drilled prior to 1970, whereas the oil and gas map does not include the most recent wells. The gas wells plotted along the bottom of the profile in figure 11 represent relative locations of gas wells located within 0.5 km of the traverse. A relatively good correspondence is observed between the areas of known gas production and the highest helium concentrations. In figure 12 a marked pattern of high values starts within the Athens gas field and continues to the northeast almost to the end of the traverse which is typical of the pattern expected from microseepage of gas from a reservoir at depth to the surface. Figure 14 is an overlay of the helium traverse on figure 13 to demonstrate the relationship between anomalously high helium concentrations with the gas production in the area.

We conclude that the anomalously high helium concentrations in this survey are probably due to microseepage of gas from the Medina Sandstone and are unrelated to the lineament zone. There are several possible explanations as to why we observed no anomalous helium concentrations associated with the lineament zone. In the traverses over the precisely mapped portions of the known fault reported on in the first part of this paper, we observed high helium concentrations in only a narrow band directly over the fracture with the values dropping to background within tens of meters. Thus, as discussed above, the Athens field traverse with 0.33 km (0.6 mi) spacing would have a small probability of encountering a sample within the zone of high helium concentrations expected to be associated with a given fracture. In contrast, microseepage of gas from a helium containing reservoir vertically through a microfracture system would be expected to give a much more dispersed area of high helium concentrations as was observed. A second possible explanation is that this helium traverse did not intersect that portion of the lineament within which fractures extend into gas-containing reservoir rocks. Unfortunately, the traverse did not coincide with the area of the seven southwestern-most wells in the Athens field in which Rodgers and Anderson (1984) reported methane gas throughout the top 100 meters of section. Instead, the traverse was located 1.5 to 3 km (0.9 to 1.8 mi) to the south. We did not perform methane analyses on our samples, so we do not know if these samples had anomalously high methane concentrations. Therefore, our results do not answer the question raised by Rodgers and Anderson (1984) as to whether or not the methane in the Devonian Shale was the result of migration from the Medina reservoirs downsection. Our data do, however, strongly suggest that sufficient permeability exists in the rocks above the gas reservoirs to allow migration of measureable quantities of helium to the surface, and support the hypothesis that helium surveys can be of use in locating the surface outline of subsurface gas deposits.

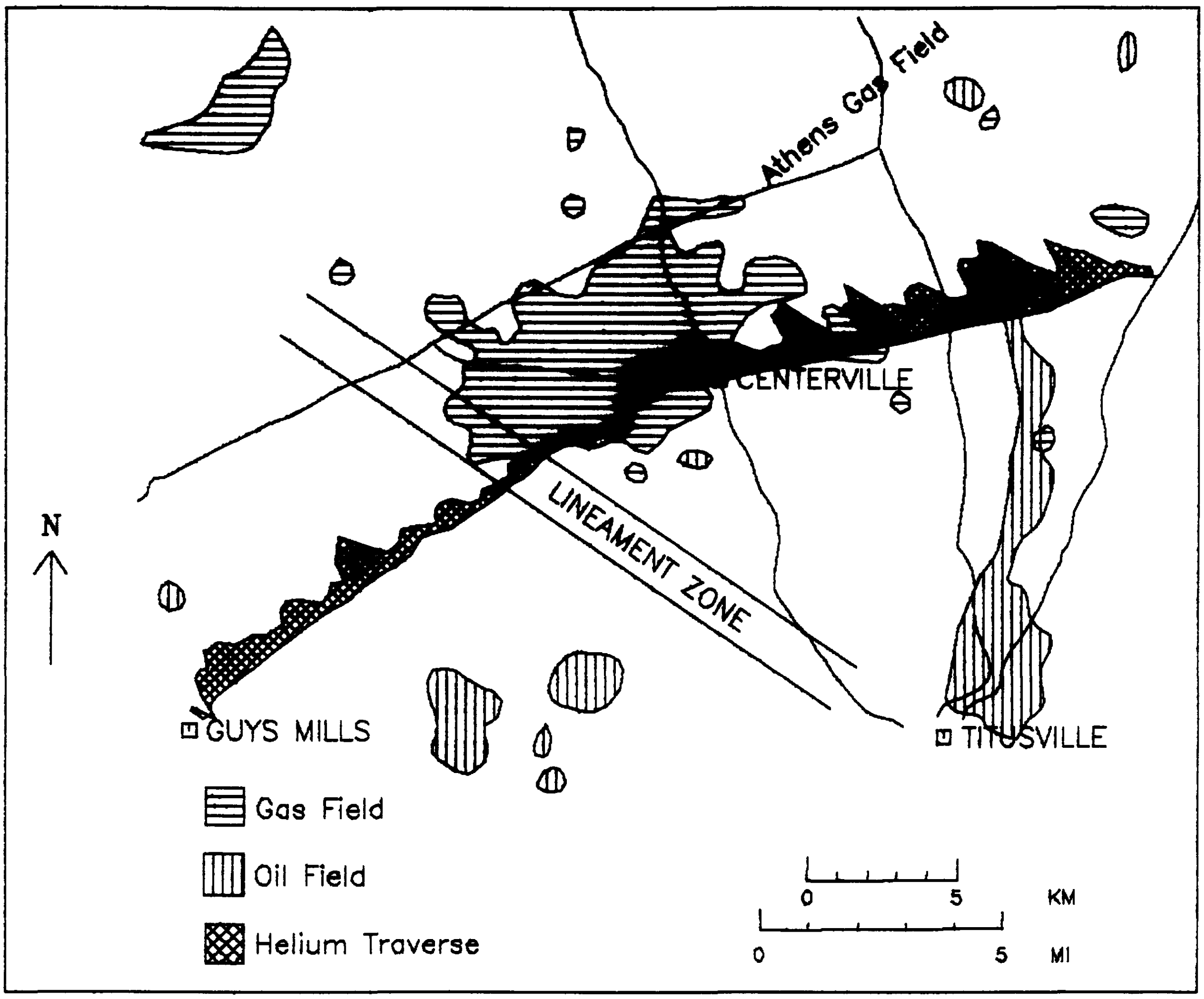

Figure 12.--Filtered helium concentrations along Athens gas-field traverse showing relationship to lineament zone and known oil and gas fields.

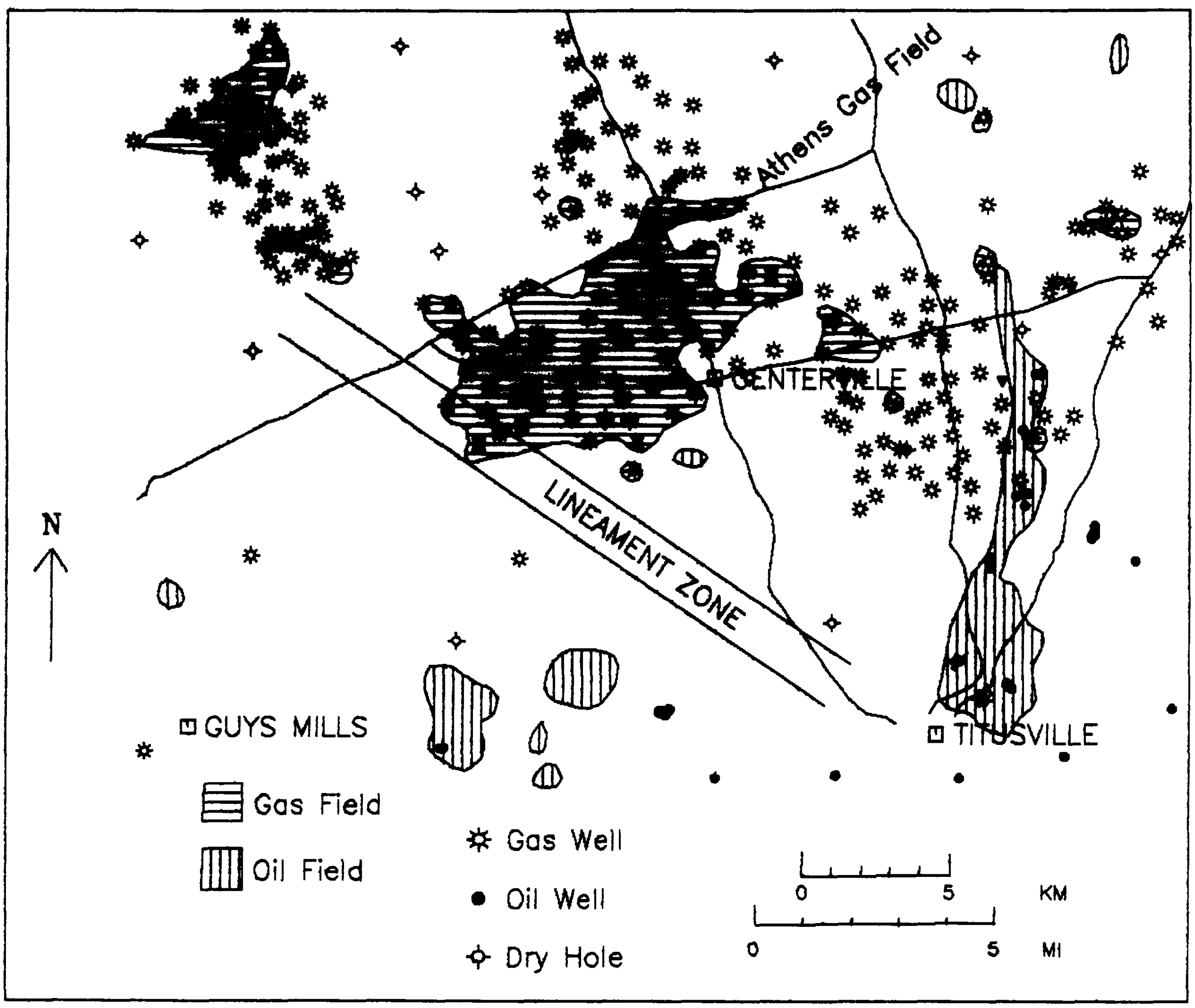

Figure 13.--Oil and gas field map of Athens field area overlain by recent drilling results.

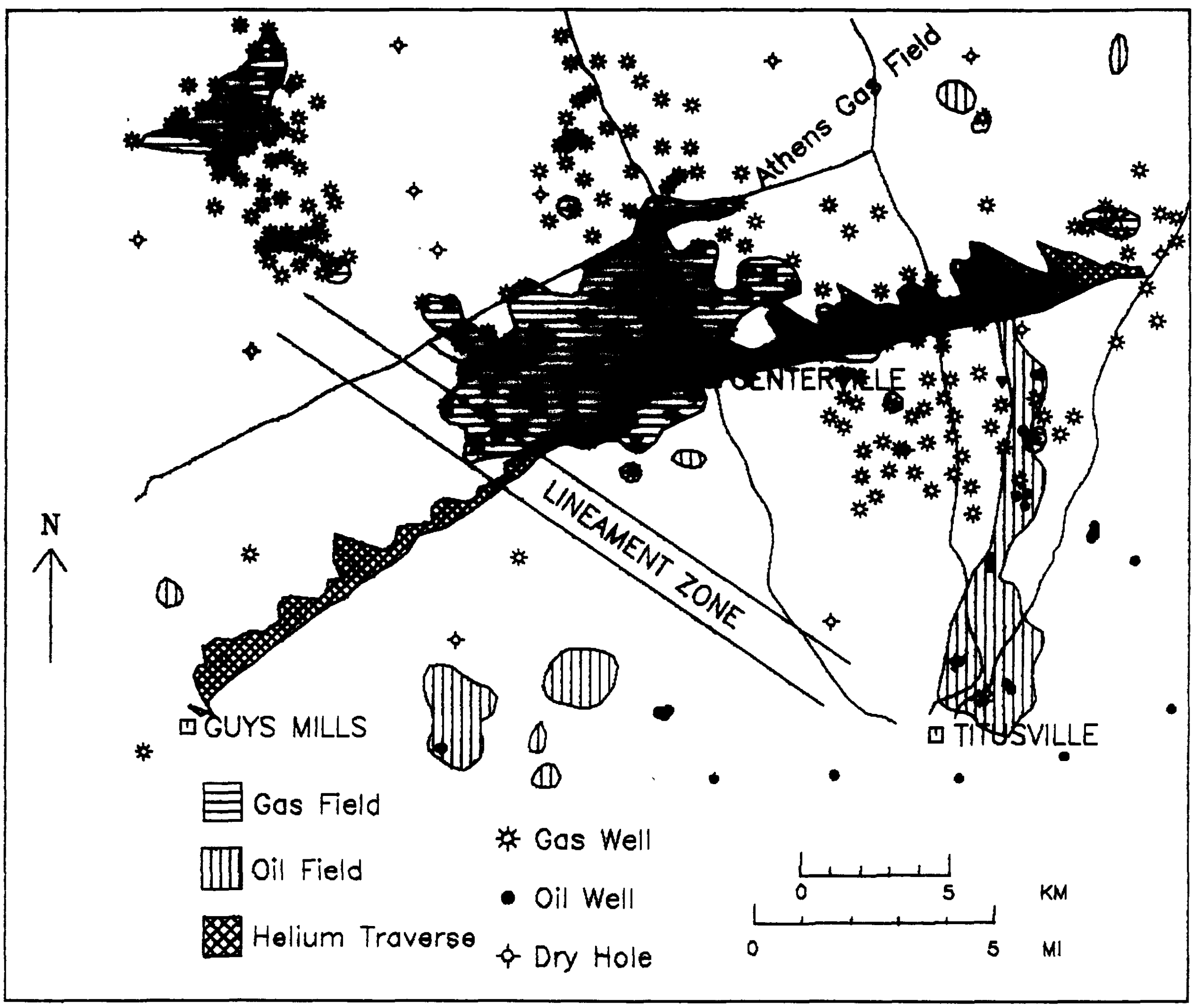

Figure 14.--Filtered helium concentrations along Athens gas-field traverse overlain by oil and gas production map.

ACKNOWLEDGMENTS

This work was performed in partial cooperation with the Morgantown Energy Technology Center (METC) of the Department of Energy (DOE) under Interagency Account No. DEAI21-83MC20422

REFERENCES CITED

Ball, N. L. and Snowdon, L. R., 1973, A preliminary evaluation of the applicability of the helium survey technique to prospecting for petroleum: Geological Survey of Canada, Paper 73-1B, p. 199-202.

Clarke, W. B., and Kugler, G., 1973, Dissolved helium in groundwater--A possible method for uranium and thorium prospecting: Economic Geology, v. 68, p. 243-251.

Clarke, W. B., Top, Z., Beavan, A. P., and Gandhi, S. S., 1977, Dissolved helium in lakes--uranium prospecting in the Precambrian terrain of Central Labrador: Economic Geology, v. 72, p. 233-242.

Debnam, A. H., 1969, Geochemical prospecting for petroleum and natural gas in Canada: Geological Survey of Canada Bulletin, v. 177, p. 1-26.

Dyck, W., 1976, The use of helium in mineral exploration: Journal of Geochemical Exploration, v. 5, p. 3-20.

Dyck, W. and Tan, B., 1978, Seasonal variations of helium, radon, and uranium in lake waters near the Key Lake uranium deposit, Saskatchewan: Journal of Geochemical Exploration, v. 10, p. 153-167.

Eremeev, A. N., Sokolov, V. A., Solovov, A. P., and Yanitskii, I. N., 1973, Application of helium surveying to structural mapping and ore deposit forecasting, <u>in</u> Jones, M. J., ed., Geochemical exploration 1972: London, Inst. Min. Metall., p. 183-192.

Friedman, Irving, and Denton, E. H., 1975, A portable helium sniffer: U. S. Geological Survey Open-File Report 75-532, 6 p.

Glueckhauf, E., 1946, A micro-analysis of the helium and neon contents of air: Proceedings of the Royal Society (London), v. 185, p. 98-119.

Hickock, W. O., IV, and Moyer, F. T., 1940, Geology and mineral resources of Fayette County, Pennsylvania: Pennsylvania Geological Survey 4th Series Bulletin C26, 530 p.

Hinkle, M. E., 1980, Survey of helium in soils and soil gases and mercury in soils at Roosevelt Hot Springs KGRA, Utah: U. S. Geological Survey Open-File Report 80-613, 31 p.

Jones, V. T. and Drozd, R. J., 1983, Predictions of oil or gas potential by near-surface geochemistry: American Association of Petroleum Geologists, Bulletin, v. 67, p. 932-952.

Kemp, J. F., and Ross, C. G., 1907, A peridotite dike in coal measures of southwestern Pennsylvania: New York Academy of Science Annals, v. 17, p. 509-518.

Mazor, E., 1974, Atmospheric and radiogenic noble gases in thermal waters--Their potential application to prospecting and steam production studies: United Nations Symposium on the Development and Use of Geothermal Resources, Proceedings, p. 793-802.

McCarthy, J. H., Jr., Lambe, R. N., and Dietrich, J. A., 1985, A case study of soil gases as an exploration guide in glaciated terrain--Crandon massive sulfide deposit, Wisconsin: Economic Geology, [in press].

Oliver, B. M., Bradley, J. G., and Farrar, Harry IV, 1984, Helium concentration in the Earth's lower atmosphere: Geochim et Cosmochim Acta, v. 48, p. 1759-1767.

Ovchinnokov, L. M., Sokolov, V. A., Fridman, A. I., and Yanitskii, I. N., 1973, Gaseous geochemical methods in structural mapping and prospecting for ore deposits, in Jones, M. J., ed., Geochemical Exploration 1972: London, Inst. Min. Metall., p. 177-182.

Pierce, A. P., Gott, G. B., and Mytton, F. W., 1964, Uranium and helium in the Panhandle gas field, Texas and adjacent areas: U. S. Geological Survey Professional Paper 454-G, 47 p.

Pogorski, L. A. and Quirt, G. S., 1980, Helium surveying for deeply buried uranium deposits: American Association of Petroleum Geologists, Bulletin, v. 65, p. 766-767.

Reimer, G. M., 1976, Design and assembly of a portable helium detector for evaluation as a uranium exploration instrument: U. S. Geological Survey Open-File Report 76-398, 18 p.

_____1985, Gaseous emanations associated with sandstone-type uranium deposits, in Finch, W. I. and Davis, J. E., eds., Geological environments of sandstone-type uranium deposits: Vienna, International Atomic Energy Agency, p. 335-347.

Reimer, G. M., and Denton, E. H., 1978, Improved inlet system for the U. S. Geological Survey helium sniffer: U. S. Geological Survey Open-File Report 78-588, 4 p.

Reimer, G. M., Denton, E. H., Friedman, I., and Otton, J. K., 1979, Recent developments in uranium exploration using the U. S. Geological Survey's mobile helium detector: Journal of Geochemical Exploration, v. 11, p. 1-12.

Roberts, A. A., 1981, Helium emanometry in exploring for hydrocarbons, part II, in B. M. Gottlieb, ed., Unconventional Methods in Exploration for Petroleum and natural gas II: Dallas, Southern Methodist University Press, p. 136-149.

Roberts, A. A., Friedman, Irving, Donovan, T. J., and Denton, E. H., 1975, Helium survey, a possible technique for locating geothermal reservoirs: Geophysical Research Letters, v. 2, p. 209-210.

Rodgers, M. R., and Anderson, T. H., 1984, Tyrone-Mt. Union cross-strike lineament of Pennsylvania--A major Paleozoic basement fracture and uplift boundary: American Association of Petroleum Geologists Bulletin, v. 68, p 92-105.

Roen, J. B., 1968, A transcurrent structure in Fayette and Green counties, Pennsylvania: U. S. Geological Survey Professional Paper 600-C, p. C149-C152.

Smith, L. B., 1912, A peridotite dike in Fayette and Greene Counties, Pennsylvania: Pennsylvania Topographic and Geological Survey Commission Biennial Report 1910-12, p. 150-155.

Socolow, A. A., 1982, Oil and Gas Fields of Pennsylvania: Commonwealth of Pennsylvania Department of Environmental Resources, Office of Resources Management, Bureau of Topographic and Geologic Survey, Map 3.