PAGEOPH, Vol. 122 (1984/85)

0033-4553/85/040369-07$1.50 + 0.20/0

Prediction of Central California Earthquakes from Soil-Gas Helium Fluctuations

By G. M. REIMER[1]

Abstract – The observations of short-term decreases in helium soil-gas concentrations along the San Andreas Fault in central California have been correlated with subsequent earthquake activity. The area of study is elliptical in shape with radii approximately 160 × 80 km, centered near San Benito, and with the major axis parallel to the Fault. For 83 percent of the $M > 4$ earthquakes in this area a helium decrease preceded seismic activity by 1.5 to 6.5 weeks. There were several earthquakes without a decrease and several decreases without a corresponding earthquake. Owing to complex and unresolved interaction of many geophysical and geochemical parameters, no suitable model is yet developed to explain the observations.

Key words: Helium; Earthquake prediction; Soil gas.

1. Introduction

On many occasions the concentrations or fluxes of earth volatiles have been observed to vary before or after seismic activity (ULOMOV and MAVASHEV, 1971; WAKITA *et al.*, 1980). These changes were commonly seen in groundwater (SULTANKHODZHAYEV *et al.*, 1976), springs (MENDENHALL *et al.*, 1981), or soil gas (REIMER, 1981). Hypotheses that a change in the physical condition of the earth in a seismic zone causes variations in the volatile concentration are common; dilation, compression, rock strain, and hydrologic mixing could all contribute to the observations (CHEN *et al.*, 1973; SCHOLZ *et al.*, 1973; JIANG and LI, 1981). If it could be demonstrated by field measurements that the concentration of a volatile species changes before rock failure, perhaps induced by changes in the geophysical regime, then a predictive precursory phenomenon will have been identified.

Helium is one volatile element that has only recently been examined to determine if it may be a precursory indicator. Helium, which is a noble gas, has unique characteristics for measurement and interpretation. It is chemically inert, radioactively stable, nonbiogenic, and highly mobile. Both isotopic (CRAIG *et al.*, 1981) and bulk measurements (REIMER, 1981) have been reported for earthquake-related investigations.

[1] U.S. Geological Survey, Denver Federal Center, Denver, Colorado 80225, USA.

The longest research and monitoring program for soil-gas helium has been conducted by the U.S. Geological Survey. Initially this effort was a spin-off from a project dedicated to developing equipment for helium measurements in energy-exploration applications and to accumulate a data base to aid in interpretation. One objective was to determine if there was a significant seasonal variation of soil-gas helium and, if so, how great an effect it would have on data comparisons. There were few practical restrictions on where a study area could be established to measure seasonal variations. By the selection of a location along the San Andreas Fault it was thought possible to observe not only the seasonal variations but also any unique concentration variations that might be related to seismic activity in the area. This study would provide only qualitative observations; definitions of what constituted an anomaly or coincidence with an earthquake would be empirical.

2. *Sample location and analytical technique*

A section of the San Andreas Fault between Tres Pinos and San Benito, in California, was selected as the study area. This area was ideal logistically, because there were other earthquake-monitoring activities near by, and personnel were available for sample-collecting on a weekly basis. Initially ten sample stations were established (Figure 1) along a 15 km segment of the fault. Some stations were established later on a

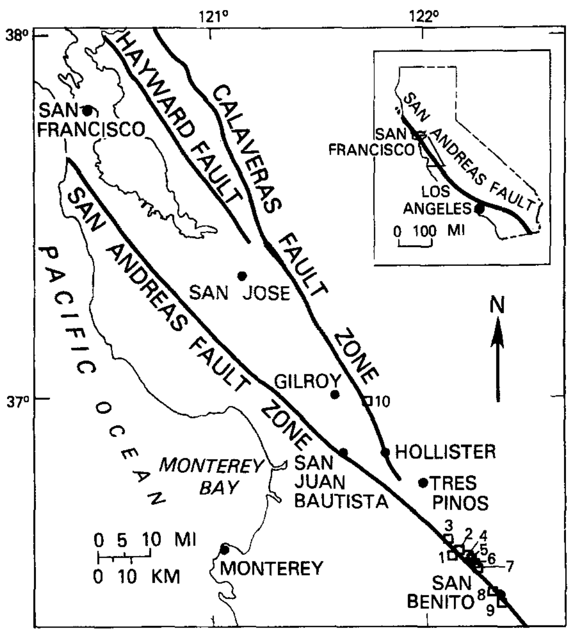

Figure 1
Map showing location of helium soil-gas sample-collecting stations near San Benito, California.

temporary basis, for evaluation of the consistency of data obtained from the original stations. Samples are collected in a 20 cm^3 hypodermic syringe through a hollow stainless-steel probe that has been set permanently to a depth of 2 m. The 2 m depth was selected as being relatively free from the diurnal influences noted in an earlier study (REIMER, 1980). The samples are transferred to evacuated stainless-steel valved cylinders and sent to the U.S. Geological Survey's Denver facility. The cylinders have been overpressurized so that the samples may be recovered in a hypodermic syringe. The amount of gas recovered, measured by the rebound of a syringe plunger, is an indication of whether there has been gross leakage from the cylinders. Samples are analyzed on a mass-spectrometer leak detector on which a specially designed constant-pressure inlet system accepts the samples injected from a syringe (REIMER, 1976).

The instrument is calibrated by means of a series of helium reference standards prepared by the U.S. Bureau of Mines in Amarillo, Texas. Each analysis is bracketed by a reference gas, to compensate for any instrument drift or sensitivity changes during the analytical run. Sensitivity of the instrument is 10 ppb (10 parts in 10^9) with equal precision.

3. *Data processing*

In this effort to develop empirically a successful earthquake-prediction technique from the helium soil-gas data, various limits were assumed and statistical manipulations were utilized. As long as these conditions are reasonable and within the framework of observations gathered in other studies, a fairly successful prediction model may be developed. Initially the following simple conditions were selected.

1. Average the soil-gas helium data from all stations.
2. Use a three-week moving average for the stations.
3. Select a cutoff limit of $M = 4(-0.2)$ for helium and earthquake comparisons.
4. Select a 160 km radius for the geographic extent of related earthquake events.
5. Define a helium decrease as at least two successive weeks of a 4 ppb or more concentration decrease, averaged from all stations.
6. Select a time frame, days or weeks, in which a helium variation may be regarded as an event precursory to subsequent seismic activity.

Conditions 1 and 2 were selected from the experience gained in research on surveys related to energy resource, and to be within the practical limitations of our analytical capability. There is sufficient variability in sample-collecting, both in technique and short-term environmental or meteorological factors, that the preferred way to process the data is to have a statistically significant number of samples with which to work (REIMER and ROBERTS, 1984). The averaging moderates the extremes caused by singular variations. For example, in the data processing for this study one sample station (number 10) was excluded because its location in a low-lying area made it extremely susceptible to precipitation-induced helium variations.

Conditions 3 and 4 were arbitrarily selected but give some practical limits for data processing. For this study the original 'circle' of earthquake events has already been changed to an ellipse with major axis parallel to the San Andreas Fault. This change excluded the Coalinga earthquakes that began in 1982. Conditions 5 and 6 were developed from observations made during the first few months of the study and have remained unchanged from that time. Helium decreases seemed to be aberrant from the evolving baseline and correlated to later seismic activity with a lead-time window of 1.5 to 6.5 weeks, beginning with the first decrease. The precursory window, expressed in weeks, is consistent with the frequency of sample collection. Earthquake locations and magnitudes were obtained from a listing provided by the National Oceanic and Atmospheric Administration in Boulder, Colorado.

4. Data and discussion

Figure 2 is the plot of the averaged soil-gas helium concentrations for data collected between May, 1979, and December, 1983. The seasonal cycle is clearly defined, with reversals occurring about February and July. The shaded areas on the figure indicate the periods of helium decrease as defined by our conditions, and the dots by the cyclical trace of helium concentrations represent the time of the earthquakes within our defined area of influence. As mentioned earlier, this area of influence was changed during the

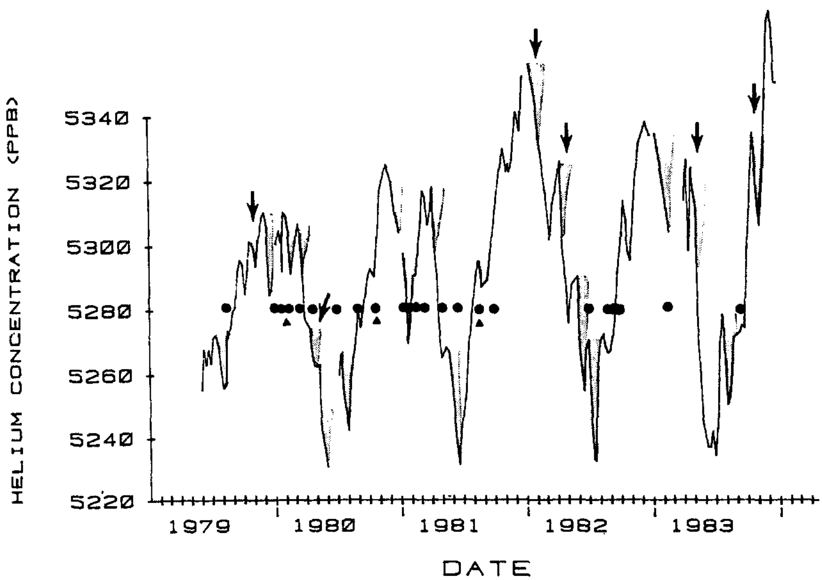

Figure 2
Helium soil-gas concentrations near San Benito, California, from May 1979 to December 1983. Shaded areas are helium decreases, dots are earthquakes of $M = 4$ or greater, arrows represent decreases without an earthquake following in 1.5 to 6.5 weeks, triangles indicate earthquakes without preceding decreases. Date divisions are in months. Breaks in the helium data line are periods when samples were not collected.

course of our observations. By changing it to an elliptical rather than a circular shape we have excluded the Coalinga region and seek our correlations with the San Andreas, Hayward, and Calaveras fault systems that project to an intersection near our sample-collecting region. There have been 25 earthquakes (excluding obvious aftershocks) that meet our $M = 4(-0.2)$ criterion. Some of these earthquakes, such as the January, 1981, and August, 1982, series have been described as clusters: earthquakes of similar magnitude spatially or temporally related but not necessarily preshocks or aftershocks of any singular event (RALEIGH, oral communication, 1981). It is unclear how to treat those groups at this time. Table 1 is a listing of the dates of the helium decreases and

Table 1

Date of the beginning of the helium decrease and corresponding earthquake data. The first two digits of the date are the year of the twentieth century, and the last three digits represent the cumulative calendar day of that year. Similar letters clusters.

Helium decrease date	Earthquake date	Location		
		Lat. (N)	Long. (W)	Mag.
79192	79218	37.102	121.503	5.9
79297				
79332	79358	36.975	122.272	4.0
	80024a	37.852	121.815	5.5
	80027a	37.737	121.740	5.8
80030	80066	36.669	121.373	4.0
80065	80104	36.762	121.548	4.8
80100				
80128	80170	36.898	121.683	4.1
80191	80236	37.569	121.672	4.1
	80287	36.595	121.085	4.1
80337	81007b	36.866	121.630	4.5
	81015b	37.383	121.737	4.8
80365	81027c	36.843	121.633	4.1
	81062c	37.548	121.945	4.4
81091	81115	37.090	121.885	4.1
81141	81160	36.747	121.362	4.2
	81226	36.773	121.293	4.2
81224	81271	36.792	121.587	3.9
82007				
82096				
82148	82170	36.530	121.073	4.0
82180	82221d	36.597	121.242	4.5
	82230d	37.025	121.745	4.5
	82236d	37.468	121.815	4.0
	82240d	37.845	121.782	3.8
	82243d	36.648	121.325	4.0
82361	83036	36.680	120.855	4.1
83108				
83199	83241	35.803	121.353	5.4
83283				

the earthquake events during the period of evaluation. As defined by our criteria, there have been 15 helium decreases that match the 25 subsequent earthquakes. If the several earthquakes in each cluster are considered one event, there are 15 helium decreases matched with 18 earthquakes; this is an 83 percent correlation, truly a remarkable success rate. Included in this period were 6 'false alarms' and 3 earthquake events without a preceding decrease. It is easier to explain the unmatched decreases than the unmatched earthquakes; stress changes may occur in the geophysical regime, creating the observed helium variation without necessarily leading to rock failure.

To date there is no satisfactory model to explain the observed helium soil-gas decreases. Compression, causing a decrease in permeability, dilation, causing a release of water and subsequent impedance to gas flow, involvement of different aquifers in response to changes in stress, or even the release of other gases, effectively diluting the helium, may all be plausible explanations. Because this is an empirical data fit, several other observations are pertinent in that, at present, they add an uncertainty factor to the correlation. The total time window of the decreases is 105 weeks out of 240 weeks of the study period. This means that 45 percent of the time is covered by a period of higher earthquake probability. Although the 83 percent helium–earthquake correlation is better than chance, the number of events is still few. There is no pronounced increase in correlation if only those earthquake events closest to our sample-collecting stations are considered. Questions about proximity, magnitude, lead time, and epicentral depth are unanswered. Clearly, additional studies are warranted for an understanding of the mechanisms of helium-gas changes responding to geophysical changes, but if the correlation level remains high over the next several years, then helium measurements may be a successful earthquake-prediction technique for this area in California.

5. *Conclusion*

Helium soil-gas decreases and earthquake activity in central California have shown a remarkable positive correlation. If the reasons for this relationship can be understood, or if further studies continue to demonstrate a significant correlation, an effective precursory phenomenon may have been identified. Although current evidence indicates the technique is not completely and unequivocally successful, it gives promise that, when helium data are considered with other information, an even greater success in earthquake prediction may be achieved.

Acknowledgements

This program was supported by the Earthquake Prediction Research Program of the U.S. Geological Survey. I thank Calvin Walkingstick for collecting the soil-gas samples and Terry Offield for unfailing encouragement and interest in this project.

Carl von Hake of the National Oceanic and Atmospheric Administration kindly provided the earthquake listing.

REFERENCES

CHEN, Y., PENG, G., and GAO, Z. (1973), *A Preliminary Survey of the Conditions of Genesis of Radon on the Groundwater in Peking and Adjacent Regions* (in Chinese), Sci. Geol. Sinica *2*, 167–174.

CRAIG, H., CHUNG, Y., LUPTON, J. E., DAMASCENO, S., and POREDA, R. (1981), *Investigation of Radon and Helium as Possible Fluid-Phase Precursors to Earthquakes*, U.S. Geol. Survey, Open-file Report 81-278, 36 pp.

JIANG, F., and LI, G. (1981), *The Application of Geochemical Methods in Earthquake Prediction in China*, Geophys. Res. Letts. *8*, 469–472.

MENDENHALL, M. H., SHAPIRO, M. H., MELVIN, J. D., and TOMBRELLO, T. A. (1981), *Preliminary Spectral Analysis of Near-Real-Time Radon Data*, Geophys. Res. Letts. *8*, 469–472.

RALEIGH, C. B. (1981), oral communication.

REIMER, G. M. (1976), *Design and Assembly of a Portable Helium Detector for Evaluation as a Uranium Exploration Instrument*, U.S. Geol. Survey, Open-file Report 76-398, 16 pp.

REIMER, G. M. (1980), *Use of Soil-Gas Helium Concentrations for Earthquake Prediction: Limitations Imposed by Diurnal Variation*, J. Geophys. Res. *85*, 3107–3114.

REIMER, G. M. (1981), *Helium Soil-Gas Variations Associated with Recent Central California Earthquakes: Precursor or Coincidence?*, Geophys. Res. Letts. *8*, 433–435.

REIMER, G. M., and ROBERTS, A. A. (1984), Correcting Soil-Gas Helium Concentrations for Diurnal Variations, in preparation.

SCHOLZ, C. H., SYKES, L. R., and AGGARWAL, Y. P. (1973), *Earthquake Prediction: A Physical Basis*, Science *181*, 803–810.

SULTANKHODZHAYEV, A. N., CHERNOV, I. G., and ZAKIROV, T. (1976), *Hydrogeoseismological Premonitors of the Gazli Earthquake* (in Russian), Dokl. Akad. Nauk. Uzb. SSSR *7*, 51–53.

ULOMOV, V. I., and MAVASHEV, B. Z. (1971), *Forewarning of the Tashkent Earthquake*, in *The Tashkent Earthquake of 26 April 1976*, Tashkent, Izdatel'stvo "FAN" Uzbekskoi SSR, pp. 188–192.

WAKITA, H., NAKAMURA, Y., NOTSU, K., NOGUCHI, M., and ASADA, T. (1980), *Radon Anomaly: A Possible Precursor of the 1978 Izu-Oshima-Kinkai Earthquake*, Science *207*, 882–883.

(Received 19th March 1984, revised 25th May 1984, accepted 4th June 1984)