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A MAGNETOTELLURIC TRAVERSE ACROSS THE YELLOWSTONE REGION

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Abstract. Five magnetotelluric stations were taken in the Yellowstone region. Sufficient coherent signal was obtained in the frequency band 10^{-4} to 10^{-1} hz to yield useful apparent resistivity (ρ_a) spectrums. At stations near Yellowstone the resistivity was linearly proportional to ω at long periods; this is due to the existence of a high conductivity substrate at some depth. The effective thickness of the low conductivity surface zone as inferred from the intercept of the response curve is consonant with the geological setting; it is thin (<5 km) in the Yellowstone thermal area, and thicker on the Snake River Plain (≈ 15 km). Stations well away from Yellowstone show $\rho_a \sim \omega^{0.7}$, suggesting a lower gradient of conductivity in the substrate. Precise inversion of the data is not practical: however, the comparison of ρ_a at neighboring stations shows distinct differences in electrical response of the crust which may be discussed in a geological context.

Knowledge of the crustal thermal regime in the Western United States is important for tectonic interpretations (Suppe et al., 1974; Blackwell, 1971). Magnetotellurics offers a possible tool for thermal measurements, due to the strong dependence of electrical conductivity on temperature. Some 20 MT stations have been taken by Princeton University workers over the past six years on and near the Yellowstone area in an effort to determine the magnetotelluric signature of a known thermal area, and to determine the extent of the difficulties associated by violation of the classical MT assumptions of a locally uniform source and a plane-parallel stratified earth (Cagniard, 1953).

Lewis (1970) obtained impedance spectra which showed the effect of the shallow zone of thermally controlled conductivity at Yellowstone. In this letter we report more recent measurements showing the way these results vary with geological setting. Part of the experiment was to follow the trace of the presumed hotspot, with stations in the Snake River Plain, the Madison area, and the Old Faithful area. Two further sites were chosen to represent different surface properties in nearby nonthermal crust: the exposed crystalline basement rock in the Big Horn Uplift, and the thick sedimentary setting of the Powder River Basin (Figure 1).

Apparent Resistivities

Apparent resistivity, ρ_a, spectra are given in Figure 2 (as solid lines; symbols refer to six-parameter fits). The spectra are selected according to a signal to noise criterion discussed below. In every case ρ_a grows rapidly with frequency, showing an inflection in the trend around 10^{-3} to 10^{-2} hz. Linear frequency dependence for ρ_a is unusual. We may gain an important perspective on the controlling resistivities if we consider first a model consisting of a uniform layer of thickness h and resistivity ρ underlain by a halfspace of infinite conductivity. The apparent resistivity is then:

$$\rho_a = \rho \left|\tan kh\right|^2 \qquad (1)$$

where

$$k = \sqrt{-i\mu\omega\rho^{-1}} \qquad (2)$$

The function (1) grows as $\rho_a = \mu\omega h^2$ at low frequencies, is constant at $\rho_a = \rho$ at high frequencies, with a transition around $\omega = 2\rho/\mu h^2$. The data from sites 1,2,3, and 5 are compatible with this kind of model and with the known geological setting, as regards the low frequency and transitional behavior. All show a linear frequency dependence, and scale on the resistivity axis as the squared effective thickness of the upper layer. The latter behavior is in reasonable accord with the thickness of the Powder River sediments, the virtual absence of a resistivity region over Yellowstone, and the intermediate nature of the plateau basalts elsewhere. The Big Horn uplift curve has a slope which cannot be fit by this kind of model. To obtain the observed ω^2 slope, the MT field at the Big Horn site must "feel" the conductive substrate more rapidly as frequency decreases than we find for the extreme one-dimensional model discussed above. This can occur plausibly by treating the Big Horn uplift as a resistive "island" in a 2 or 3 dimensional

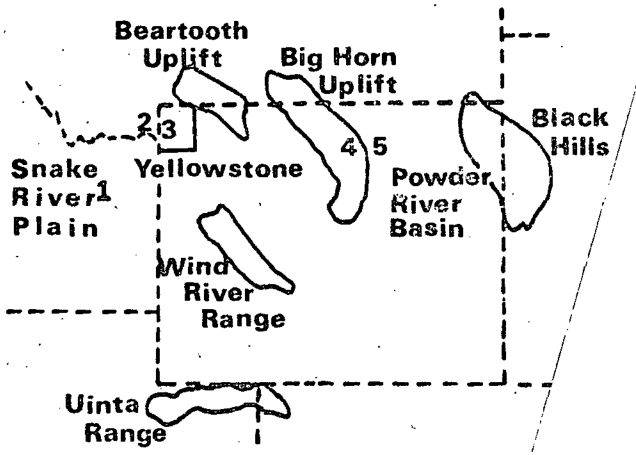

Fig. 1. Magnetotelluric site locations.
Camus River, Idaho; 2. West Yellowsto
tana; 3) Old Faithful, Yellowstone Pa
4. Hesse Mountain, Big Horn Mountain
ming.)

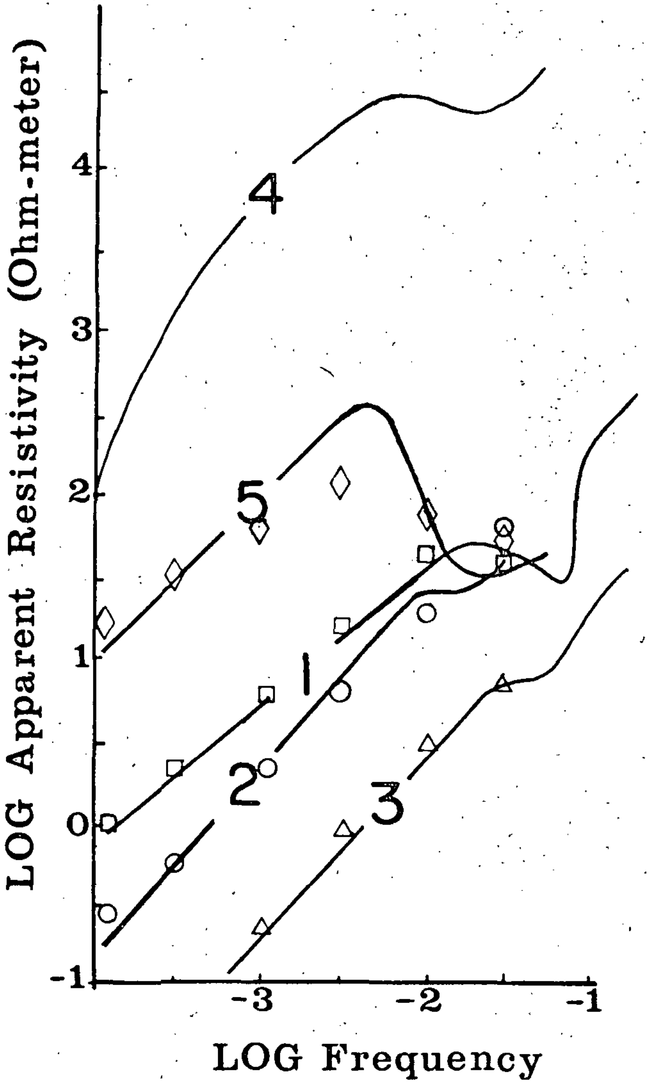

Fig. 2. Apparent resistivity spectrums observed for the 5 stations. Symbols are theoretical one-dimensional calculations, as described in text.

$$\rho_a = \frac{1}{\mu\omega}\left|\frac{E}{H}\right|^2 = \frac{1}{\mu\omega}\left|Z\right|^2$$

sense surrounded by conductive materials (Porath and Dziewonski, 1971). Near 10^{-2}hz, both edge effects from the surrounding sedimentary basins and penetration into the conductive substrate of the crust are unimportant, giving a valid resistivity around 3x10^4 ohm-meters for the crystalline rocks of the Big Horn basement.

Theoretical Models

The apparent resistivities have been fit by a more realistic one-dimensional continuous resistivity model of six parameters. The Cagniard equations (Cagniard, 1953; Vozoff, 1972) were integrated from a high conductivity halfspace at depth up to the earth's surface. The properties of this halfspace are set by Parker (1971) in his reconstruction of the gross-earth conductivity profile. In the vicinity of 200 km he infers resistivity to be in the range 2-10 ohm-meters, with little gradient below that depth.

Our modeling indicates the linear frequency dependence of ρ_a requires that resistivities approach the half-space with an exponential depth dependence. The exponential is most naturally associated with a thermal resistivity regime. The functional form for parameterization of thermally controlled conductivity is suggested by a combination of the Boltzmann function $e^{-E/kT}$, where E is an activation energy, and the temperature distribution with depth. We take the linear form $T = T_0 \cdot z/(z-z_0)$ (Hermance and Grillot, 1974; Blackwell, 1971). Combining these gives the form: conductivity $\propto$ exp (a - b/z), where a and b are determined by conditions at the end points of the function (Figure 3). In addition to the surface resistivity, which is fixed at 1 ohm-meter, six free parameters define the model: z_0 - z_3, ρ_r, and ρ_i. These have been varied until a least square fit to the data is obtained.

The model can be made to fit the data reasonably well for sites 1-3 and 5 (symbols in Figure 2). The resistivities inferred from the response curves (Figure 2) are shown in Figure 3 (curves labeled "a"; associated parameter values appear in Table 1, entries "a"). The resistivities show the obvious trend of a more conductive body closer to the surface as Yellowstone is approached

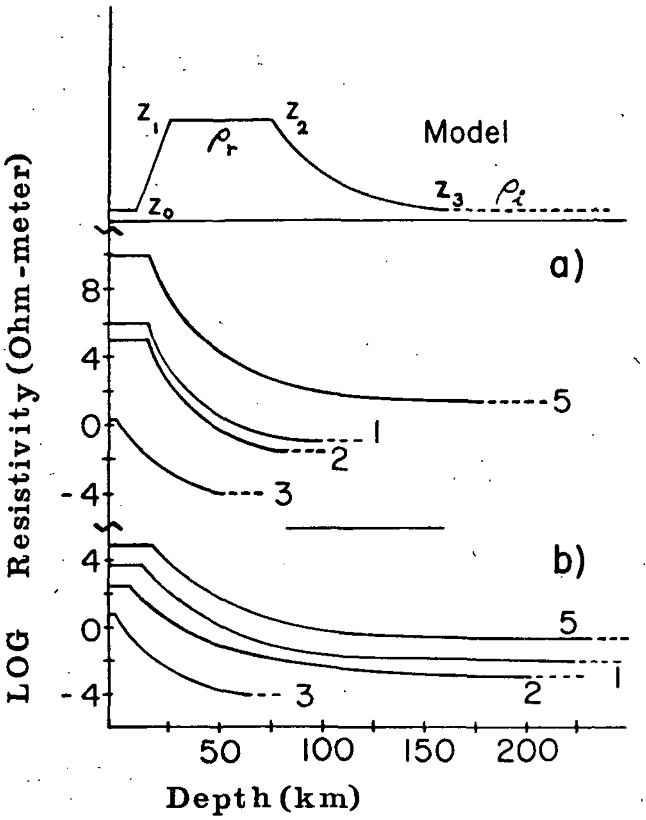

Fig. 3. Resistivity model and inferred resistivity structures. Model consists of a fixed surface resistivity (1 ohm - m) followed by a zone of increasing resistivity (Z_0 - Z_1) and a zone of fixed resistivity ρ_r, Z_1 - Z_2 ; from Z_2 - Z_3 , the resistivity decreases exponentially to a constant, infinite substrate layer of resistivity ρ_i. Inferred resistivity structures are given for sites 1-3 and 5. Curves "a" result from fits to the response curves of Fig. 2; Curves "b" to continued response curves, as discussed in text.

Table 1. Values of model parameters for fits shown in Fig. 2 (entries labeled "a") and fits to linearly extrapolated data (entries labeled "b"). Parameter identities keyed to a model shown in Fig. 3. Depth in km; resistivity in ohm-m.

	DATA	Z_o	Z_1		Z_2	Z_3	
Snake River Plain	a)	.036	.43	10^6	15	90	.10
	b)	.036	.43	10^4	10	250	.008
Madison Plateau	a)	.05	.08	10^5	15	75	.033
	b)	.05	.08	2×10^2	8	200	.003
Yellowstone	a)	.45	.5	2	3.3	45	5×10^{-4}
	b)	.45	.5	8	2.5	60	.0007
Big Horn Mntns.	a)	-	-	-	-	-	-
	b)	-	-	-	-	-	-
Powder River Basin	a)	.04	.64	10^{10}	15	175	20
	b)	.04	.64	10^5	10	300	.01

from either flank. However the combination of incompleteness of the frequency range, with inaccuracies in both slope and position of response curve lead to unrealistic parameter values. On the hypothesis that resistivities are thermally controlled, and further that there is approximate thermal equilibrium beneath the Yellowstone region, we may plausibly construct linear response curves for the frequency range 10^{-4} - 10^{-6} Hz. These continued response curves, when fit to the resistivity model, give a more realistic set of parameter values (Table 1, entries "b"; Figure 3, curves "b"). Further experimentation with fitting shows that potential for considerable parameter variation exists within the limits of slope and position within which we may choose our response curves. In short, at our present level of resolution, we are able to develop a plausible picture of a thermally controlled resistivity regime at crust and near mantle depths, but cannot provide good estimates of a detailed resistivity structure.

Method of Data Analysis

We now describe the method by which the apparent resistivity curves in Figure 2 were obtained from the raw data. Figure 4 shows a set of resistivity estimates from Big Horn, Powder River, and Yellowstone stations. Each estimate is a point pair giving "maximum" and "minimum" estimates for each sample window in which the coherence (E/H) is greater than 0.33. The two estimates differ according to the way the incoherent energy is treated. The height of the bar has a *maximum* of 3x, which is a forteriori determined by this minimum allowed coherence.

Four channels, E_x, E_y, H_x, and H_y, were digitally sampled after low pass filtering. The pairs (E_x, H_y) and E_y, $-H_x$) were treated separately in an analysis for the scalar impedance:

$$Z = |E/H| \tag{3}$$

Data series of 4096 points, with duration of 6 hours and sampling interval of 5.2 seconds were Fourier analyzed by an FFT algorithm. The overestimate of impedance Z_o and the underestimate Z_u were then formed from the following smoothed cross-spectral estimates obtained by the method of band averaging (Hermance, 1973; Hinich and Clay, 1968).

$$Z_u\ (\bar{\omega}) = \langle EH \rangle_{\bar{\omega}} / \langle HH \rangle_{\bar{\omega}} \tag{4}$$

$$Z_o\ (\bar{\omega}) = \langle EE \rangle_{\bar{\omega}} / \langle EH \rangle_{\bar{\omega}} \tag{5}$$

where: $$\langle XY \rangle_{\bar{\omega}} = \frac{1}{N} \sum_{i}^{N} X\ (\omega_i) Y^*(\omega_i) \tag{6}$$

and: $$\langle\ \rangle_{\bar{\omega}} = \text{geometrical mean } (\omega_1 \ldots \omega_N) \tag{7}$$

We interpret these expressions through the following model of signal and noise:

$$E = E_c + E_n \tag{8}$$

$$H = H_c + H_n$$

$$Z = \langle E_c H_c \rangle / \langle H_c H_c \rangle = \langle E_c E_c \rangle / \langle H_c E_c \rangle \tag{9}$$

$$\langle E_c H_n \rangle = \langle H_c E_n \rangle = \langle E_n H_n \rangle = \langle H_c H_n \rangle = \ldots = 0 \tag{10}$$

where the band averaging $\langle \ldots \rangle$ is by hypothesis equivalent to ensemble averaging. Then (4) becomes:

$$Z_u\ (\bar{\omega}) = Z / (1 + \langle H_n H_n \rangle / \langle H_c H_c \rangle\ ) \tag{11}$$

and (5) becomes:

$$Z_o\ (\bar{\omega}) = Z \cdot (1 + \langle E_n E_n \rangle / \langle E_c E_c \rangle) \tag{12}$$

Electrode and system noise, as well as certain characteristics of the natural MT fields, obey the averaging assumptions (10), giving Z_u and Z_o which bracket the assumed scalar Z. When geological structures give rise to current channeling, then $\langle H_c E_n \rangle$, $\langle E_c H_n \rangle \neq 0$, and an anisotropic impedance tensor $\underline{Z}$ must be assumed. We also obtain the relationship:

$$\text{coh}\ (E,H) = Z_u(\bar{\omega}) / Z_o(\bar{\omega}) \tag{13}$$

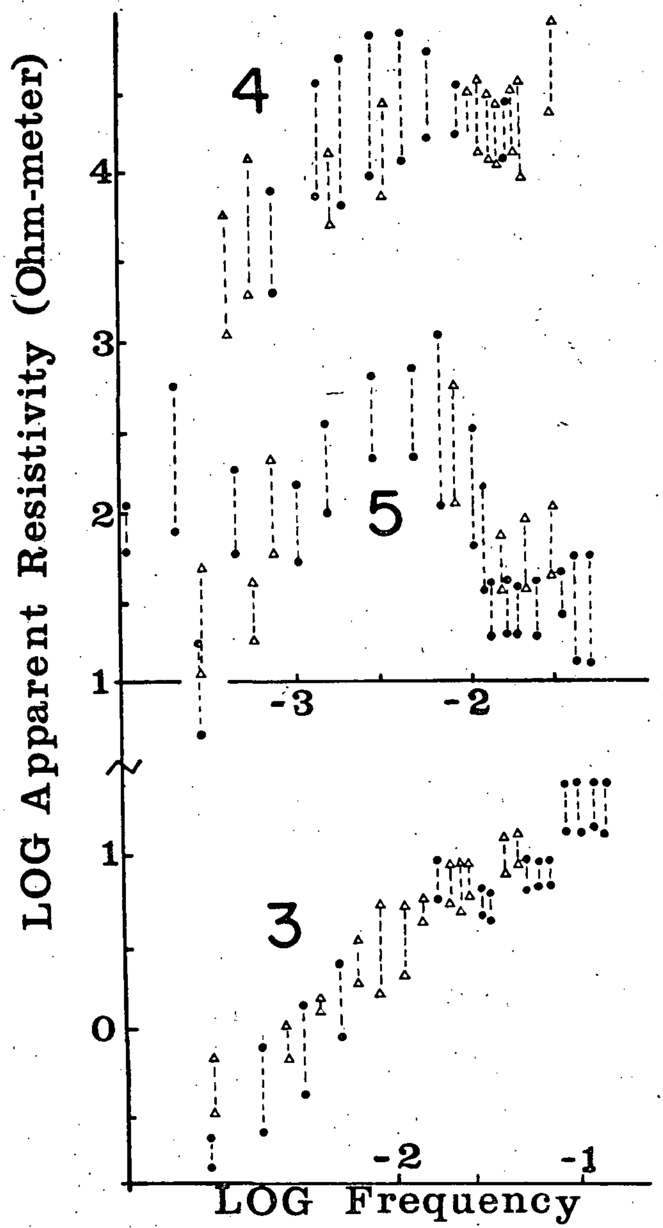

Fig. 4. Sample of magnetotelluric earth-response curves for three sites. Each frequency point at a site is represented by an upper and lower estimate of apparent resistivity, as discussed in the text. Circles and triangles denote separate data collections. Points are selected from frequency averaged, 4096 point, 6-hour long data samples.

By setting a selection criterion coh (E,H) $\geq$ a cut-off value, C, for the selection of data, we agree to deal only with signals whose coherence permits the estimates to be made only to an uncertainty of less than a given factor. Most reported MT data has C $\geq$ .9. Our relaxation of this criterion to C = .33 still permits the salient parameters of the apparent resistivity to be resolved to the degree needed for this kind of study. In the complex geological settings where we took this data, only fair luck was had in obtaining coherences as high as 0.9 for the band of 3-4 octaves. At a given station we would find, typically, that a data window giving high coherence on one (E,H) pair would show practically zero coherence on the other. On subsequent data windows low coherence on both pairs or a switching of the high coherence to the other channel would be equally likely. High coherence, then, is obtained when the polarization of the source field is fortuitously oriented with respect to the geological structure at the station. We found artificial rotation of the measuring axes (Word, et al., 1971; Vozoff, 1972) inadequate as a means of obtaining high coherence signals.

The battery-powered amplifiers and digital cassette recording system used in this study are sufficiently easy to handle that it would be practical for a crew of two to operate 3 stations simultaneously. For further work in western thermal regions this configuration would allow some separation of the effects of source inhomogeneity and geological structure. We note further that the field reconnaissance for geothermal anomalies may be based on the amplitudes of band limited signals seen at periods around 300 seconds in the field. This kind of immediate information can facilitate getting more useful stations occupied during a field program.

Acknowledgements. We acknowledge with gratitude substantial contributions to this work by R. Von Colln, for preparation of the computer system; S. Langendorf, for field assistance; Prof. J. Claerbout, Stanford University, for discussions on data handling; Prof. R. Smith, University of Utah, for laboratory space; S. Canter, Chief Naturalist, Yellowstone Park, for access to Yellowstone sites; and the Stony Brook-Millstone Watersheds Association, Inc., for cooperation in New Jersey.

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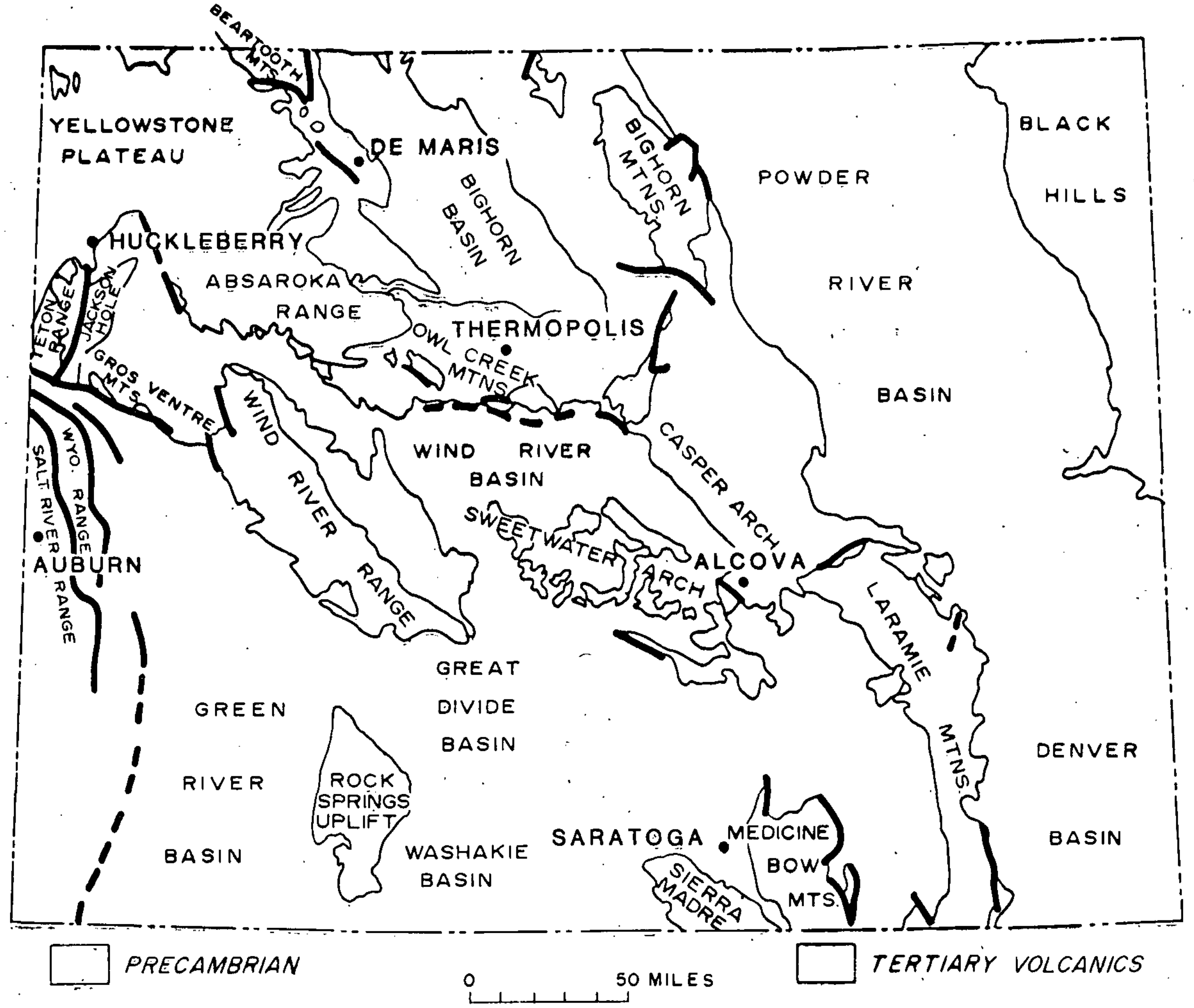

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The opponents of vaccination in England have of late been more active than ever; and, as a result of their activity, a royal commissioner has been appointed, whose duty it shall be to make a full investigation of the whole subject, and submit a report thereon. Friends of vaccination should welcome such an inquiry, as the method stands upon such a firm foundation of facts as to be able to stand the most searching examination. If it has not accomplished all that is claimed for it, the failure is due to insufficient or inefficient performance of the operation; and the sooner such abuse of it is made public, the better. It is a rather remarkable coincidence that just at this time events should transpire at Sheffield, England, which show the value of vaccination. Small-pox has recently been very prevalent in that city. In a population of about 320,000 there have been 6,088 cases of the disease, of which number 590 proved fatal. Dr. Barry, who has made a report to the Local Government Board, finds that the attack-rate of the vaccinated children under ten was 5 in a thousand; of the unvaccinated of the same age, 101 in a thousand. The death-rates for the same classes were respectively .09 and 44. In every hundred-thousand of those twice vaccinated, there were eight deaths; once vaccinated, 100 deaths; and unvaccinated, 5,100 deaths.

SOAPING GEYSERS.[1]

At the Buffalo meeting, October, 1888, Dr. Raymond presented a paper entitled "Soaping Geysers," in which he called attention to the use of soap by tourists to cause eruptions of several of the well-known geysers in the Yellowstone Park. Incorporated in this paper appears a communication received from me, written from camp in the park, in reply to some inquiries on the subject. The letter discussed somewhat briefly the means employed by visitors to the park to hasten the eruptions from hot-springs and reservoirs of hot water, which remain dormant for days, or even weeks or months, at a temperature near the boiling-point, without any display of geyser-action. As the paper has called forth considerable comment, I desire to elucidate one or two points in relation to the temperature of the springs, and to answer some inquiries about the composition of the thermal waters.

In the summer of 1885, a Chinaman, employed as a laundryman for the accommodation of the tourists at the Upper Geyser Basin, accidentally discovered, much to his amazement, that soap thrown into the spring from which he was accustomed to draw his supply of water produced an eruption in every way similar to the actual workings of a geyser. Tourists with limited time at their command, who had travelled thousands of miles to look upon the wonders of the Yellowstone, soon fell into the way of coaxing the laundryman's spring into action, to partly compensate them for their sore disappointment in witnessing the periodical eruptions of Old Faithful. Successful attempts upon this spring soon led to various endeavors to accelerate action in the dormant and more famous geysers. In a short time, so popular became the desire to stimulate geysers in this way, that the park authorities were compelled to enforce rigidly the rule against throwing objects of any kind into the springs.

In connection with a thorough investigation of the thermal waters of the Yellowstone Park and the phenomena of the geysers, I undertook a number of experiments to ascertain the action of soap upon the waters, and to determine, if possible, those physical conditions of various pools and reservoirs which permitted the hastening of an eruption by the employment of any artificial methods. This investigation, conducted from time to time, as opportunity offered, throughout the field-season of 1885, included experiments upon the geysers and hot-springs of the Upper, Lower, and Norris Geyser Basins. The results proved, beyond all question, that geyser-action could be forced in a number of ways, but most conveniently by the application of soap. The greater part of the more powerful geysers undergo no perceptible change with a moderate use of soap, although several of them may, under favorable physical conditions, be thrown at times into violent agitation. In most of the experiments, Lewis's concentrated lye, put up in half-pound cans for laundry purposes, was employed. Each package furnished a strong alkali, equivalent to several bars of soap. In this form, alkali is more easily handled than in bars of soap, more especially where it is required to produce a viscous fluid in the larger reservoirs; and, in conducting a series of experiments for comparative purposes, it seemed best, in most instances, to employ the same agent to bring about the desired results.

Old Faithful, the model geyser of the park, exhibits such marked regularity in its workings, that attempts to hasten its action appear futile. The interval between eruptions is about 65 minutes, and rarely exceeds the extreme limits of 57 and 72 minutes. After an eruption of Old Faithful, the reservoir fills up gradually; the water steadily increases in temperature; and conditions favorable to another eruption are produced under circumstances precisely similar to those which have brought about the displays for the past eighteen years, or as far back as we have authentic records. The few experiments which have been made upon Old Faithful are insufficient to afford any results bearing on the question; but it seems probable that soon after the water attains the necessary temperature an eruption takes place.

Of all the powerful geysers in the park, the Bee-Hive offers the most favorable conditions for producing an eruption by artificial means, all the more striking because the natural displays are so fitful that they cannot be predicted with any degree of certainty.

---

[1] Abstract of a paper read before the American Institute of Mining Engineers, New York meeting, February, 1889, by Arnold Hague.

Observations extending over a period of several years have failed to determine any established law of periodicity for the Bee-Hive, even for three or four consecutive months; although they indicate that some relationship may exist between its display and those of the famous Giantess. Frequently the Bee-Hive will play several times a day, and then become dormant, showing no signs of activity for weeks and months, although the water may stand above the boiling-point the greater part of the time. The name "Bee-Hive" was suggested by the symmetry of the cone built around the vent. It rises about 4 feet above the sloping mound of geyserite, and in cross-section measures about 3 feet at the top, while at the bottom of the cone the vent is less than 10 inches in width. From the top of this narrow vent it is possible to sink a weight only 17 feet before striking a projecting ledge, which interferes with all examination of the ground below. The constant boiling and bubbling of the water, the irregularity of its action, and the convenient location of the geyser, within an easy walk from the hotel, make attempts to accelerate the eruptions of the Bee-Hive most attractive to tourists.

In most instances such efforts are futile: yet success does so frequently reward the astonished traveller, that, unless the geyser were carefully watched by the authorities, attempts would be made daily throughout the season. If the conditions are favorable to an eruption, it usually takes place in from 10 to 25 minutes after the addition of laundry-soap or lye. It is doubtful if more than two eruptions of the Bee-Hive have ever been produced on the same day by artificial means, although I know of no reason, based upon the structure of the geyser, why more displays might not be obtained; for the reservoir and vent fill up with boiling water very rapidly after each eruption.

Although the Giantess is situated only 400 feet from the Bee-Hive, these two differ in surface and underground structure, and mode of action, as widely as any two of the more prominent geysers of the park. Around the Giantess no cone or mound has formed. The broad basin is only partially rimmed in by a narrow fringe of silicious sinter, rising above and extending out over the deep blue water. At the surface, this basin measures about 15 to 20 feet in width by 20 to 30 feet in length. It has a funnel-shaped caldron, 30 feet in depth, ending in a vertical vent or neck 12 feet deep, through which a sounding-lead may be dropped into a second reservoir, meeting a projecting ledge or obstruction of some kind 61 feet below the surface. After an outburst of the Giantess, the basin, which has been completely emptied of its water, gradually fills again to the top; and for days before another eruption a steady stream of hot water overflows the brim. The intervals between the eruptions of the Giantess vary from twelve to twenty days, and the displays last several hours, being unsurpassed for violence and grandeur by any geyser in the Upper Basin. Artificial means have never been successful in bringing this geyser into action, although for days before an eruption it is an easy matter to cause an agitation of the water by throwing into the basin small pieces of sinter, or to produce a boiling on the surface, lasting several minutes, by simply stirring the water with a stick.

The Giant, one of the most violent of the geysers in the Upper Basin, more closely resembles the Bee-Hive than any other of those along the Firehole River. It has built up a cone 10 feet in height, one side of which has been partly broken down by some eruption more violent than any witnessed at the present day. Through this notched side, steam and broken jets of water are constantly emitted; and on this account but little examination has been made of the underground reservoirs and vents. The Giant is fitful in its action, at times playing with considerable regularity every fourteen days, and at other times lying dormant for nearly a year. I have no positive knowledge that an eruption of the Giant has ever been produced by any other than natural causes. At the time of my experiments, no eruption of the Giant had taken place for several months, although the water was constantly agitated; so much so, that it was quite impossible to examine the vent with any satisfactory results. The only effect produced by the application of lye was additional height to the column of water thrown out, and a decided increase in the thumping and violence of the boiling.

In the Lower Basin, the Fountain has been more carefully studied than the other geysers; and, its action and periodicity of eruptions having been fairly well ascertained, it afforded the most favorable conditions for observing the action of soap and lye upon the waters. In its general structure, the Fountain belongs to the type of the Giantess, having a funnel-shaped caldron, which, long before an eruption, overflows into an adjoining basin. At the time of my experiments upon the Fountain, the intervals between eruptions lasted about four hours. This interval allowed sufficient time to note any changes which might take place. My own experiments with lye yielded no positive results; although it seemed highly probable that action might be hastened by the application of soap or lye just before the time for an eruption, or when, for some cause, the eruption was overdue. I preferred to make the attempt to bring about an explosion before the usual time, only waiting until the water in the pool had nearly reached the boiling-point. All experiments failed. The previous year, when wishing to produce action for the purpose of photography, I was enabled to accomplish the desired result by vigorously stirring with a slender pole the water near the top of the vent connecting with the lower reservoir. In this instance, it should be said, the usual interval of time between eruptions had long since passed: the geyser was, so far as time was concerned, a half-hour overdue. My opinion now is that the experiments with lye failed because the temperature had scarcely reached the boiling-point.

The Monarch, in the Norris Basin, is quite unlike those already described, and affords evidence of being a much newer geyser. It is formed by two convergent fissures, on the line of a narrow seam in the rhyolite, probably coming together below the surface. The main vent measures about 20 feet in length, and at the surface 3 feet in width. But slight incrustation is found around the vent, the conditions not being very favorable to deposition. In this narrow fissure, the water, which ordinarily stands about 15 feet below the surface, constantly surges and boils, except immediately after an eruption. The intervals between eruptions vary somewhat from year to year; but at the time of these experiments the action was fairly regular, the geyser playing every four hours. I was successful in obtaining an eruption quite equal to the natural displays, which throw a column of water 50 feet into the air. Here at the Monarch there is no surface reservoir; and the narrow fissure, filled with loose blocks of rocks around which the water is in constant agitation, prevents all measurements of depth.

The results of the many experiments, not only upon active geysers, but upon a large number of hot-springs, determine fairly well the essential conditions which render it possible to bring about geyser-action by artificial means. Negative results are frequently as valuable for this inquiry as experiments yielding imposing displays.

Outside of a few exceptional instances, which could not be repeated, and in which action was probably only anticipated by a few minutes in time, geyser eruptions produced by soap or alkali appear to demand two essential requirements, — first, the surface-caldron or reservoir should hold but a small amount of water, exposing only a limited area to the atmosphere; second, the water should stand at or above the boiling-point of water for the altitude of the geyser-basin above sea-level. The principal factor which makes it possible to cause an eruption artificially is, I think, the superheated and unstable condition of the surface-waters. Many of the geysers and hot-springs present the singular phenomena of pools of water heated above the theoretical boiling-point, and, unless disturbed, frequently remain so for many days without exhibiting any signs of ebullition. It may not be easy to describe accurately these superheated waters; but any one who has studied the hot springs and pools in the park, and carefully noted the temperatures, quickly learns to recognize the peculiar appearance of these basins when heated above the boiling-point. They look as if they were "ready to boil," except that the surface remains placid, only interrupted by numerous steam-bubbles, rising through the water from below, and bursting quietly upon reaching the surface.

Marcet, the French physicist, has specially investigated the phenomena of superheated waters, and has succeeded in attaining a temperature of 105° C. before ebullition. Superheated waters in nature, however, appear to have been scarcely recognized, except during the progress of the work in the Yellowstone Park, in connection with a study of the geysers. The altitudes of the geyser basins above sea-level have been ascertained by long series of barometric readings, continued through several seasons. In conducting a series of observations upon the boiling-points of the thermal waters in the park, Dr. William Hallock, who had charge of this special investigation, determined the theoretical boiling-point by noting the mean daily readings of the mercurial column. The exact boiling-point of a pure surface-water, obtained from a neighboring mountain-stream, and the boiling-point of the thermal waters from the springs, were determined from actual experiments by heating over a fire, employing every possible precaution to avoid sources of error. Surface-waters and deep-seated mineral waters gave the same results, and coincided with the calculated boiling-point at this altitude. Hundreds of observations have been carefully taken where the waters in the active and running springs boiled at temperatures between 198° and 199° F.

As will be shown later in this paper, the thermal waters are solutions of mineral matter too dilute to be affected to any appreciable extent as regards their boiling-point by their dissolved contents. The theoretical boiling-point for the springs and pools in the Upper Geyser Basin may be taken at 92.5° C. (198.5° F.). In many of the large caldrons, where the water remains quiet, a temperature has been recorded of 94° C. (201.2° F.) without the usual phenomena of boiling. This gives a body of superheated water, with a temperature at the surface of 1.5° C. (2.7° F.) above the point necessary to produce explosive action. Thermometers plunged into the basins show slightly varying temperatures, dependent upon their position in the basin. They indicate the existence of numerous currents, and a very unstable equilibrium of the heated waters, which are liable, under slight changes, to burst forth with more or less violence. It is under these conditions that geyser-action can be accelerated by artificial means. If into one of these superheated basins a handful of sinter pebbles be thrown, or the surface of the water be agitated by the rapid motion of a stick or cane, or even by lashing with a rope, a liberation of steam ensues. This is liable to be followed by a long boiling of the water in the pool, which in turn may lead to geyser-action. There is some reason to believe that, at least in one instance, an eruption has been brought about by a violent but temporary gust of wind, which either ruffled the water or disturbed the equilibrium of the pool, and changed momentarily the atmospheric pressure.

In Iceland, travellers have long been accustomed to throw into the geysers turf and soft earth from the bogs and meadows which abound in the neighborhood, the effect produced being much the same as that of sinter pebbles and gravel upon the geysers in the National Park. So well was this understood, that at one time a peasant living near the Iceland locality kept a shovel solely for the accommodation of those visiting the geysers.

In my letter to Dr. Raymond, I mention the curious fact that the laundryman's spring, now known as the Chinaman, in which geyser-action may most easily be produced by artificial means, has never been regarded by the Geological Survey as any thing but a hot-spring; and no one has ever seen it in action without the application of soap, except in one instance, when it was made to play to a height of twenty feet after stirring it vigorously with a pine bough for nearly ten minutes. In our records it is simply known as a spring.

If soap or lye is thrown into most of the small pools, a viscous fluid is formed; and viscosity is, I think, the principal cause in hastening geyser-action. Viscosity must tend to the retention of steam within the basin, and, as in the case of the superheated waters, where the temperature stands at or above the boiling-point, explosive liberation must follow. All alkaline solutions, whether in the laboratory or in nature, exhibit, by reason of this viscosity, a tendency to bump and boil irregularly. Viscosity in these hot-springs must also tend to the formation of bubbles and foam when the steam rises to the surface; and this, in turn, aids to bring about the explosive action, followed by a relief of pressure, and thus to hasten the final and more powerful display. Of course, relief of pressure of the superincumbent waters upon the column of water below the surface basin is essential to all eruptive action. These conditions, it seems to me, are purely physical. Undoubtedly the fatty substances contained in soap aid the alkali in rendering the water viscous. On the other hand, when concentrated lye is used, it acts with greater energy, and furnishes a viscous fluid where soap would yield only surface suds, insufficient to accomplish any phenomenal display.

It is well known that saturated solutions of mineral substances raise the boiling-point very considerably, the temperature having been determined for many of the alkaline salts. In general, I believe the boiling-point increases in proportion to the amount of salt held in solution. Actual tests have shown that the normal boiling-point of silicious waters in the park does not differ appreciably from the ordinary surface-waters; mainly, I suppose, because they are extremely dilute solutions.

The amount of lye required to produce a sufficiently viscous condition of the waters increases but slightly the percentage of mineral matter held in solution.

All the waters of the principal geyser-basins present the closest resemblance in chemical composition, and, for the purposes of this paper, may be considered as identical in their constituents. They have a common origin, being, for the most part, surface-waters which have percolated downward for a sufficient distance to come in contact with large volumes of steam ascending from still greater depths. The mineral contents of the hot-springs are mainly derived from the acid lavas of the park plateau, as the result of the action of the ascending steam and superheated waters upon the rocks below. These thermal waters are essentially silicious alkaline waters, carrying the same constituents in somewhat varying quantities, but always dilute solutions, never exceeding two grams of mineral matter per kilogram of water. When cold, they are potable waters, for the most part slightly alkaline to the taste, and probably wholesome enough, unless taken daily for a long period of time.

Dr. Raymond has made the suggestion that the addition of caustic alkali would possibly precipitate some of the mineral ingredients found in these waters, thereby changing their chemical composition sufficiently to affect the point of ebullition. At the same time he remarks that the geyser-waters are probably too dilute solutions to be much influenced by such additions. Any one who glances at the analyses of the waters of the Bee-Hive, Fountain, and Fearless must see, I think, that they are not only too dilute to undergo any marked change of temperature, but that the mineral constituents consist mainly of the carbonates and chlorides of the alkalies, associated with a relatively large amount of free silica, which would remain unacted upon by caustic alkali. There is nothing in the waters to be thrown down by the addition of alkali, or to permit any chemical combinations to be formed by the addition of a small amount of soap. The desire of tourists to "soap a geyser" during their trip through the park grows annually with the increase of travel; so much so, that there is a steady demand for the toilet-soap of the hotels. If visitors could have their way, the beautiful blue springs and basins of the geysers would be "in the suds" constantly throughout the season. Throwing any thing into the hot-springs is now prohibited by the government authorities. It is certainly detrimental to the preservation of the geysers, and the practice cannot be too strongly condemned by all interested in the National Reservation.

THE EAST GREENLANDERS.

Capt. Holm's expedition to East Greenland was as remarkable on account of its geographical results as in regard to the ethnological observations made among the isolated tribes of the northern parts of the east coast of Greenland. The results of his journey have been published, and form the tenth volume of the "Meddelelser om Grönland." In a recent number we referred to the linguistic and folk-loristic papers. Of no less importance are the general anthropometric and ethnographical results of the expedition.

Dr. Søren Nansen has submitted the craniological material and the measurements of Capt. Holm to an elaborate discussion, from which we glean the following facts. The whole population consisted of 548 heads, 245 of whom were males, while 303 were females. The size of the people is below the average, being 1,647 millimetres; while in the southern parts of the coast the average

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GENETIC IMPLICATIONS OF SOME ELEMENTS ASSOCIATED WITH URANIUM DEPOSITS, SHIRLEY BASIN, WYOMING

By E. N. HARSHMAN, Denver, Colo.

Abstract.—A systematic distribution of uranium, selenium, ferrous and ferric iron, carbon, beryllium, and sulfate sulfur is shown by analytical data on samples of unaltered sandstone, ore, and altered sandstone from a roll-type uranium deposit in the lower Eocene Wind River Formation of the Shirley basin. Transportation of uranium and other elements in a neutral to slightly alkaline, oxidizing solution and deposition by changes in the Eh and pH of that solution are suggested by the geochemistry of these elements at low temperatures and pressures.

Field and laboratory investigations of unoxidized uranium deposits in sandstone have resulted in considerable data on the possible sources of uranium and the geochemistry of its solution, transportation, and deposition. In spite of these data, and perhaps because uranium is a widely distributed element, easily dissolved and transported by solutions of diverse character, there is little agreement on the genesis of the deposits.

It is improbable that any one genetic concept can be applied to all uranium deposits in sandstone, for each has its own peculiarities of detail. On the other hand, most deposits have similarities that suggest that certain broad geochemical proceses may have been responsible for their origin.

C. F. Davidson (1964) suggests that "in geological theorizing it is wise to extrapolate from the known to the unknown, from the young to the old, from the simple to the complex." The Shirley basin uranium deposits are young, simple in form, and since their formation, apparently unaffected by significant redistribution of uranium or by weathering. In this paper certain physical and chemical data, and genetic concepts interpreted from these data, are presented. Extrapolation of the concepts to older and more complex deposits is not attempted.

GEOLOGY AND ORE DEPOSITS

The major uranium deposits in the Shirley basin (fig. 1) are in a well-defined belt coincident with the lowest part of a basin filled with clastic and tuffaceous rocks of fluviatile and lacustrine origin. The basin was eroded in rocks of Cretaceous and older age, and was filled with rocks ranging in age from Eocene to Miocene that aggregated at least 1,500 feet in thickness. The ore deposits are in sandy beds of the Wind River Formation of early Eocene age which rests unconformably on the Cretaceous and older rocks.

Near the deposits, the Wind River Formation ranges from 300 to 500 feet in thickness. It is composed of clayey siltstone, arkosic sandstone, and conglomerate, all interbedded and poorly cemented. The sediments for the most part were derived from granitic rocks to the west. Regional dips are about 1° northward. Plant and vertebrate fossils indicate that the early Eocene environment was subtropical. Carbonaceous trash is abundant in the fine-grained rocks in the lower part of the basin and common in the sandstones interbedded with them.

The present ground-water table is at depths of a few feet to more than 300 feet below the ground surface. Ground water is tributary to the present surface drainage system and flows southward at gradients of 10 to 30 feet per mile.

The principal anions in the Shirley basin ground water are bicarbonate (210 parts per million) and sulfate (110 ppm) as shown by analyses of 25 water samples collected by the writer from the Wind River Formation. Radioelements include uranium (20 parts per billion), radium (10 picocuries per liter), and radon (as much as 200,000 pc/liter). The pH of the ground water ranges from 6.6 to 8.3; the median pH is about 7.8.

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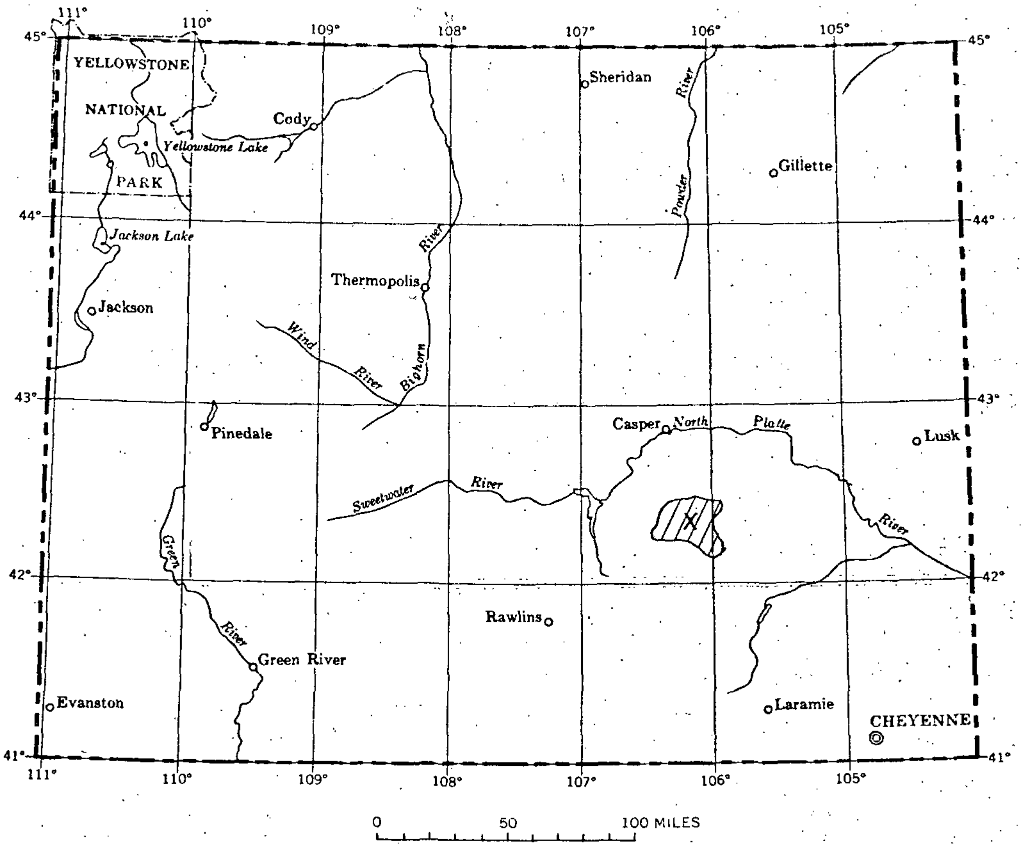

FIGURE 1.—Index map of Wyoming, showing location of Shirley basin (diagonal lines) and the Petrotomics Co. pit (X). The Utah Construction and Mining Co. mine is 2½ miles north of the Petrotomics Co. pit.

Large tongues of altered[1] sandstone, formed in the most transmissive parts of thick sandstone beds, were the loci for ore deposition. Two such tongues at different stratigraphic levels have been delineated by exploration and development drilling, and the upper tongue has been partly exposed by mining operations in the Petrotomics Co. open pit and in the Utah Construction and Mining Co. mine 2½ miles to the north. A third tongue, possibly a split from the upper tongue, may be present locally. Data on it are meager, and it is not discussed in this report. The upper tongue is 5 miles long in a northwesterly direction and has a maximum width of 3 miles. It is at depths of 100 to 450 feet below the ground surface and is as much as 200 feet above the base of the Wind River Formation. The upper tongue ranges in thickness from a few feet near its edge to about 70 feet, several thousand feet back from the edge.

The lower tongue is separated from the upper one by 50 to 70 feet of silty claystone. It has not been exposed by mining operations, but drilling data suggest that it is similar to the upper tongue. In part, the two tongues are superimposed, although the upper tongue extends farther to the north and west than does the lower one.

The major ore bodies in the Shirley basin are at the margins of tongues of altered sandstone in a curved zone between altered and unaltered sandstone. An ore body in its most simple form is crescent shaped in cross section, has a sharp contact with altered sandstone on the concave side, and grades into unaltered sandstone on the convex side. Ore bodies are elongate parallel to the margins of the altered sandstone tongues. Ore bodies of this configuration are commonly known as rolls.

Epigenetic minerals in the ore are uraninite, pyrite, marcasite, calcite, hematite, native(?) selenium, and an unidentified sulfate mineral; in altered sandstone they are goethite, limonite, and ferroselite.

The geology and ore deposits of the Shirley basin are discussed in more detail in papers by Harshman (1961, 1962), Melin (1964), and Rosholt and others (1964). Similar deposits in Russia have been described, most recently by Kashirtseva (1964).

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[1] In this report the term "altered" is used in a restricted sense to refer to those physical and chemical changes, excluding mineralization, effected by the ore-bearing solution on the medium through which it passed. "Unaltered" denotes a lack of such changes.

SAMPLES AND ANALYSES

A portion of the western edge of the upper altered sandstone tongue was well exposed by mining operations in the northwestern part of the Petrotomics Co. open pit. The exposure was sampled in vertical channels spaced horizontally 5, 10, and 50 feet apart. The samples in the channels were broken at each observed change in mineral composition; they ranged from 2 inches to 10 feet in length. Fifty-six samples were collected, consisting, from west to east, of (1) unaltered and unmineralized sandstone, (2) ore, and (3) altered sandstone. All samples were analyzed for U, eU, mineral carbon, organic carbon, sulfide sulfur, sulfate sulfur, total iron, ferrous iron (corrected for iron in FeS_2), ferric iron (by difference), selenium, and arsenic. Semiquantitative spectrographic analyses for 51 elements were made on all samples, and mercury determinations, by the atomic absorption method sensitive to 5 ppb, were made on a suite of 24 samples.

Figure 2*A* is a scale drawing of the exposure in the Petrotomics pit. It is a vertical section, normal to the trend of the edge of the altered sandstone tongue, and it shows the relation of ore to altered and unaltered sandstone, the configuration of the edge of the tongue at this location, and the position and length of 20 samples discussed in this report. The 20 samples shown on figure 2*A* constitute a suite extending horizontally across altered sandstone, ore, and unaltered sandstone. Data from analyses on the 20 selected samples shown on figure 2*A* are compatible with similar data from the 36 samples not shown on the figure.

ANALYTICAL DATA

A systematic distribution of uranium, selenium, ferrous and ferric iron, carbon, beryllium, and sulfate sulfur, with respect to the contact between altered sandstone and ore, is shown by analyses of the 20 selected samples (fig. 2*A*) as well as by analyses of several hundred other samples from the Petrotomics Co. open pit and the Utah Construction and Mining Co. underground mine.

Figure 2*B* shows graphically the selenium content of the sample suite. Of particular interest are the low selenium content of unaltered sandstone, less than 0.5 ppm, the moderate selenium content of most of the ore, 2 to 15 ppm, and the moderate selenium content of most of the altered sandstone, 10 to 60 ppm. The presence of a high concentration of selenium in altered sandstone near the contact with ore is shown also by the analyses plotted on figure 2*B*, but not shown, because of sample locations, is the large amount of selenium known to be present in ore near the contact. Analyses of close spaced samples from ore bodies in the Petrotomics pit and the Utah mine show that selenium in amounts of as much as 1,200 ppm occurs in a zone about 1 foot wide parallel to, and extending about 6 inches each way from, the contact between altered sandstone and ore.

The distribution of ferrous and ferric iron as well as the amounts of ferrous iron in pyrite are shown on figures 2*C* and *D*. Of interest are: (1) a ferrous/ferric ratio of about 2 to 1 in the samples of unaltered sandstone most distant from ore and therefore least affected by ore deposition, in contrast to a ferrous/ferric ratio of about 1 to 1 in the samples of altered sandstone most distant from ore; (2) the nearly equal amounts of total iron in both altered and unaltered sandstone samples distant from ore; (3) the decrease in the ferric iron content of altered sandstone samples with increasing proximity to ore; (4) the high ferrous iron, high total iron, and low ferric iron contents of ore; and (5) the absence of pyritic ferrous iron (pyrite) in altered sandstone except for minor amounts near the contact with ore. Similar iron distributions are shown by analyses of sample suites from the Utah mine.

Analyses for carbon are shown on figure 2*E*. They confirm observations made in the open pit that: (1) moderate but erratic amounts of carbonized fossil plant debris are contained in ore and unaltered sandstone, (2) very minor amounts of such debris are present in the outer few feet of the altered sandstone tongues, and (3) no carbonized debris is present in the altered sandstone from the interior of the tongues.

Minor amounts of beryllium are associated with uranium in the Shirley basin deposits. Of the 20 samples shown on figure 2*A*, ore samples 312 and 319 contain 0.00015 percent Be, all other samples contain less than 0.0001 percent, the lower limit of detectability. The following Be distribution is shown when the analyses of these 20 samples are combined with the analyses of 145 samples from the Utah mine and the Petrotomics open pit:

	Number of samples		
Material	*Total*	**Be** *detectable*	**Be** *not detectable*
Ore	77	30	47
Altered sandstone	46	2[1]	44
Unaltered sandstone	42	0	42

[1] Samples adjacent to ore.

Statistically there is no doubt that the uranium ore is enriched in beryllium, although the amounts of Be present in the highest grade ore are generally 0.0003 percent or less.

The high sulfate content shown in figure 2*B* is characteristic of some but not all of the Shirley basin uranium ore bodies. Sulfate-bearing ore placed in

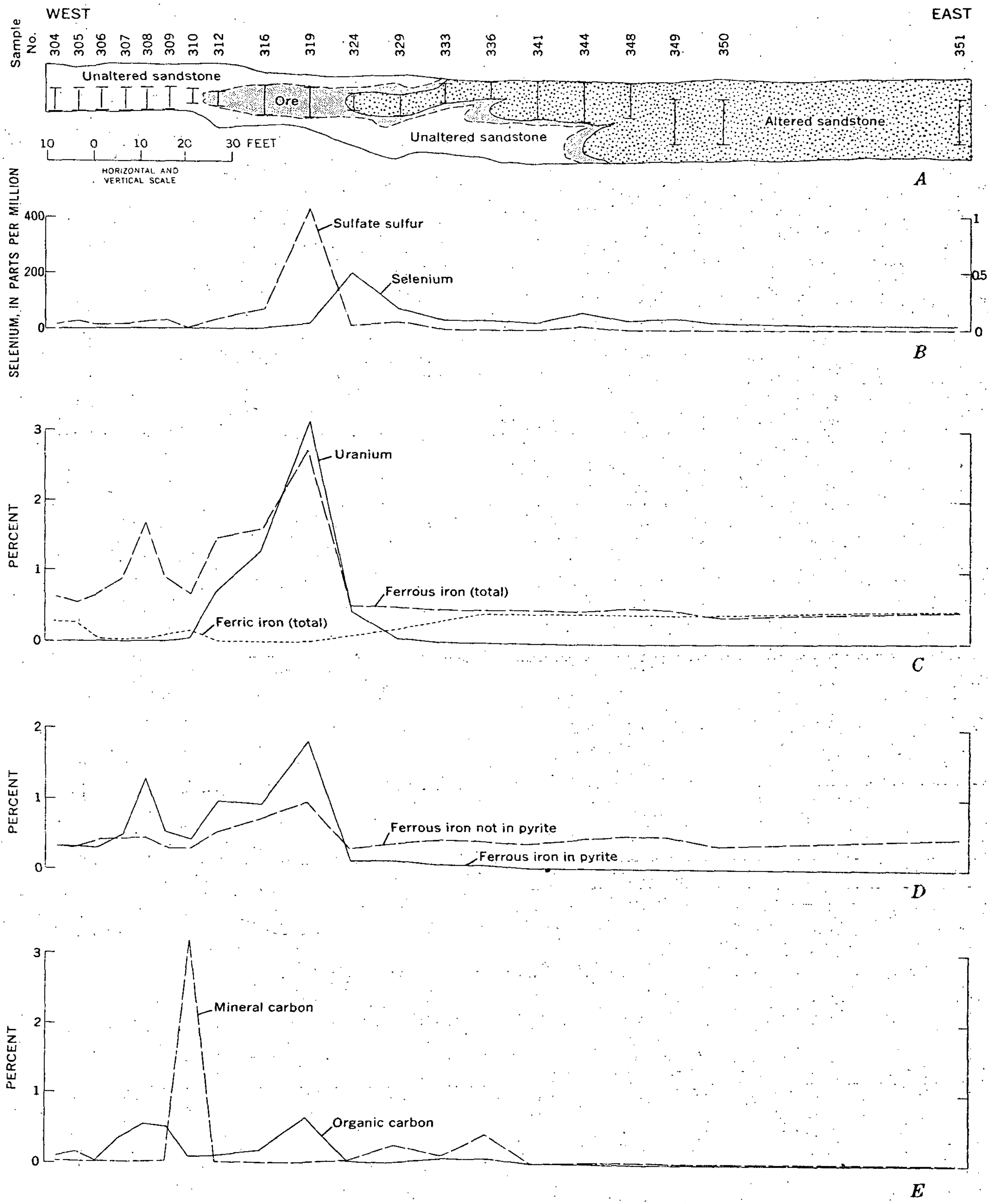

FIGURE 2.—Vertical section (*A*) through uranium ore body, showing sample locations and analytical data (*B–E*) from Petrotomics Co. pit, Shirley basin, Wyoming.

distilled water and heated on a steam bath for 10 hours yielded a solution saturated in calcium sulfate and enriched in iron. Analytical data on the high-sulfate-bearing samples are inconclusive regarding elements possibly combined with the sulfate, and no sulfate-bearing mineral has been recognized in polished sections of the ore.

GENETIC IMPLICATIONS OF ANALYTICAL DATA

Certain genetic implications regarding the character of the solutions that transported uranium and other elements to the site of deposition may be drawn from the distribution of some of the elements in the deposits and their geochemistry at low temperatures and pressures.

Selenium, one of the more diagnostic elements with respect to the character of the transporting medium, is intimately associated with ore and altered sandstone, and undoubtedly was transported with uranium in the ore-bearing solutions. According to Lakin (1961), the selenite ion $((\mathrm{Se_2O_3})^{-2})$ is readily formed at moderate oxidation potentials in mildly acid or alkaline solutions. However, the selenite is almost immediately immobilized by reacting with ferric ions present in most ground water to form an insoluble precipitate, probably a basic ferric selenite.

Selenate ion $((\mathrm{SeO_4})^{-2})$ is soluble in most natural waters, but it is formed only under restricted Eh and pH conditions. In acid solutions, oxidation potentials far higher than can be reasonably expected in the most rigorous natural environments are required to oxidize selenium to selenate. However, in solutions of about pH 7 and greater the moderate oxidation potentials common in near-surface ground waters will oxidize selenium as selenate and it is probable that solutions of this character dissolved and transported selenium in the Shirley basin.

The geochemistry of beryllium, particularly in a low-temperature–low-pressure environment, is poorly known. Beus (1962) refers to transportation of beryllium as a complex with chlorine, fluorine, or carbonate in alkaline solutions. Govorov and Stunzhas (1963) have demonstrated that alkalic carbonatoberyllate complexes are stable in the pH range 6.8 to 11.8 at temperatures of about 80° to 210°C and that the complexes are decomposed with the precipitation of beryllium compounds as a result of a decrease in alkalinity. Available data therefore suggest that beryllium, intimately associated with uranium in the Shirley basin deposits, was transported in low-temperature alkaline solutions, but the data do not preclude transportation in solutions of other character.

Pyrite and carbonized plant debris, not present in altered sandstone except in small amounts near the margins of the altered tongues, are ubiquitous components of unaltered sandstone throughout the Shirley basin. The dispersed pyrite bears no relation to ore deposition, and its absence in altered sandstone implies destruction by the ore-bearing solutions. Similarly, the absence of carbonized plant debris in the altered sandstone tongues implies its destruction by chemical reactions, for the presence or absence of such debris is related spacially to the altered-unaltered sandstone contact and not to primary sedimentary features. The destruction of pyrite and of carbonized plant debris by the ore-bearing solution clearly implies that the solution was oxidizing.

The ferrous/ferric iron ratios of 2/1 in unaltered sandstone and 1/1 in altered sandstone reflect the destruction of pyrite in the latter by the ore-bearing solution and a redistribution of the iron so released, in part as ferric iron in geothite and (or) limonite and in part as ferrous iron in the clay minerals. This redistribution and conversion of at least a part of the iron from the ferrous to the ferric state implies an oxidizing ore-bearing solution.

Deposition of uranium and the elements associated with it in the Shirley basin deposits appears to have resulted principally from a decrease in the Eh of the ore-bearing solution, although a moderate drop in its pH may have been a contributing factor. Strongly reducing conditions in the zone of deposition are indicated by: (1) the decrease in ferric iron content of samples of altered sandstone taken progressively closer to ore, (2) the low ferric and high ferrous iron content of ore, (3) the high pyrite content of ore, and (4) the high selenium content of a narrow zone near the contact of ore and altered sandstone. Although the exact nature of the reducing agent for the Shirley basin deposits is not known, it may have been $\mathrm{H_2S}$ of biogenic origin as suggested by Lindgren and others (1910) for the agent that reduced copper in "red-bed" deposits of New Mexico, and as suggested by Jensen (1958) as a possible reducing agent for uranium deposits in the Gas Hills area of Wyoming and the Colorado Plateau area of Colorado, Utah, and New Mexico.

There is some evidence to support the conjecture that the Shirley basin uranium deposits, as we now see them, are the final stage of a continuing process of solution and redeposition, "frozen" by a disruptive change in the conditions under which the ore elements were being dissolved and transported or by a change in the reducing environment responsible for ore deposition. Minor amounts of pyrite, carbonized plant debris, uranium, and selenium found in altered sandstone near the contact with ore are believed to represent the leached remnants of former ore bodies. Particularly indicative of leaching are the corroded pyrite grains seen in heavy-mineral separates from altered sandstone in the Petrotomics pit, and described by Melin (1964) from altered sandstone in the Utah mine. These corroded grains contrast with the euhedral pyrite grains characteristic of ore and unaltered sandstone.

CONCLUSIONS

The geochemistry of certain elements associated with uranium in the Shirley basin ore deposits suggests that the ore-bearing solution was neutral to weakly alkaline and oxidizing ground water. It probably dissolved uranium and other elements from tuffaceous and arkosic sedimentary rocks that once filled the basin. The solution migrated through the porous sandy members of the Wind River Formation and moved from the flank of the basin down the hydraulic gradient toward the lower part of the basin. As the solution moved basinward its oxidation potential was lowered by reaction with the minerals in the sandstone, particularly pyrite, and by intermixing with reducing solutions buffered by H_2S of biogenic origin. Ore deposition is known to have occurred at depths of as much as 500 feet below the ground surface, a depth at which deposits are now found, and it may have occurred at depths of as much as 1,500 feet, the estimated thickness of Tertiary rocks that once filled the basin. Deposits formed in a narrow zone where the oxidation potential of the solution was reduced below that required for continued transportation of uranium and the associated elements. The spent ore-bearing solution, considerably changed chemically, passed beyond the zone of the ore deposition and eventually was discharged from the basin.

The zone of deposition is considered to have been a dynamic feature migrating basinward by oxidation and solution of ore on the updip side of the zone and by reduction and redeposition on the downdip side. Oxidation of pyrite on the updip side probably resulted in a sharp drop in the pH of the ore-bearing solution, but as these solutions passed through and beyond the zone of deposition, normal alkalinity would be restored by reaction with arkoses in the Wind River formation. Approximations of Eh and pH values believed to have been controlling factors in the solution, transportation, and deposition of uranium and associated elements in the Shirley basin deposits are shown on figure 3.

The processes described in this report as responsible for the genesis of the Shirley basin uranium deposits are similar to genetic processes by which secondary sulfide deposits are formed. In the formation of both types of deposits there are: (1) oxidation and solution of selected elements on the updip side of a mineralized zone, (2) a rather sharp drop in the pH of the water due to oxidation of pyrite, (3) downward migration of the water and its dissolved elements, and (4) reduction and redeposition of the dissolved elements. In addition, the gossans characteristic of many secondary sulfide deposits and the altered sandstone characteristic of the Shirley basin uranium deposits are similar chemically and in their position relative to ore. The concept of deep secondary enrichment may have application, along with other ore guides, in exploration for uranium deposits.

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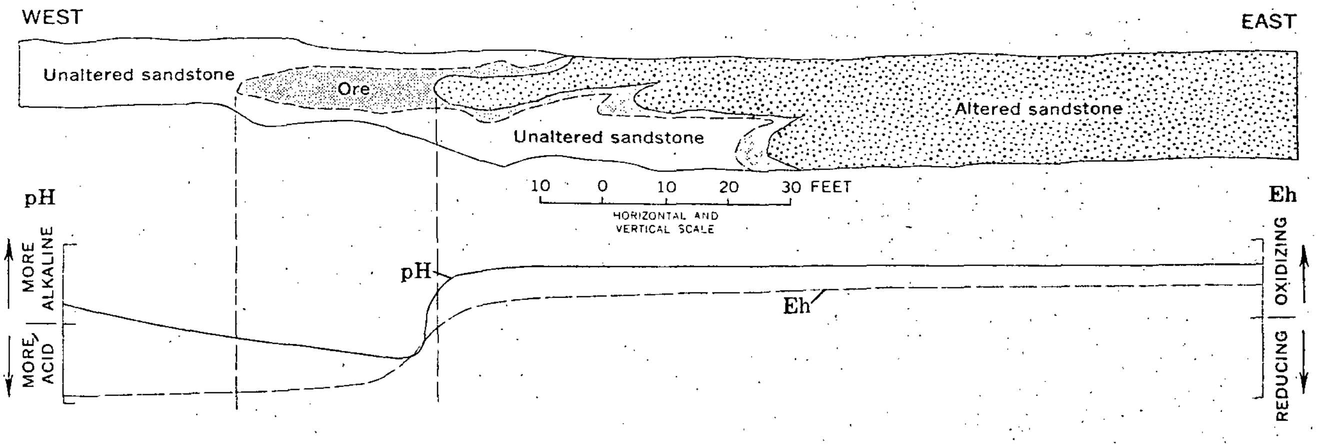

FIGURE 3.—Postulated Eh and pH conditions during transportation and deposition of uranium and other elements, Shirley basin, Wyoming.

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PRELIMINARY DATA FROM SIX TEMPERATURE GRADIENT HOLES NEAR CODY, WYOMING

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PRELIMINARY DATA FROM SIX TEMPERATURE GRADIENT HOLES NEAR CODY, WYOMING

INTRODUCTION

Six holes were drilled near Cody in northwest Wyoming in an effort to define a low- to moderate temperature hydrothermal resource. The holes were drilled during January, February, and March of 1980. The total depths of the holes ranged from 116.0 meters (380.5 ft.) to 56.4 meters (185.0 ft.). The project was financially supported by Cooperative Agreement DE-FC07-791-D12026 between the U.S. Department of Energy and the University of Wyoming. This report briefly summarizes the mechanical details of the drilling and casing, and presents preliminary geothermal data for the holes.

EVIDENCE FOR HYDROTHERMAL SYSTEM

The DeMaris Hot Springs, a group of at least seven vents ranging in temperature from 24° to 37° C are one mile west of Cody in northwest Wyoming (see Figure 1). The springs occur on the southeastern flank of a large anticline, the Rattlesnake anticline, where the impermeable Chugwater Formation has been eroded through by the Shoshone River. Within 1000 feet of the hot springs a well that passed through the Chugwater Formation yeilds 208 gallons per minute of water at 34°C. This well and the hot springs appear to define the northern boundary of the hydrothermal system.

A series of travertine and sulfur deposits crop out along the eastern flank of the Rattlesnake anticline. The deposits are near the contact of the Chugwater Formation and the underlying rock units. The travertine deposits extend approximately two miles south of the DeMaris Hot Springs. In this area the Rattlesnake anticline merges into a smaller structure known as the Horse Center anticline.

The thermal data for the Horse Center anticline suggest that the regional hydrothermal system extends as much as seven miles south of Cody. The most

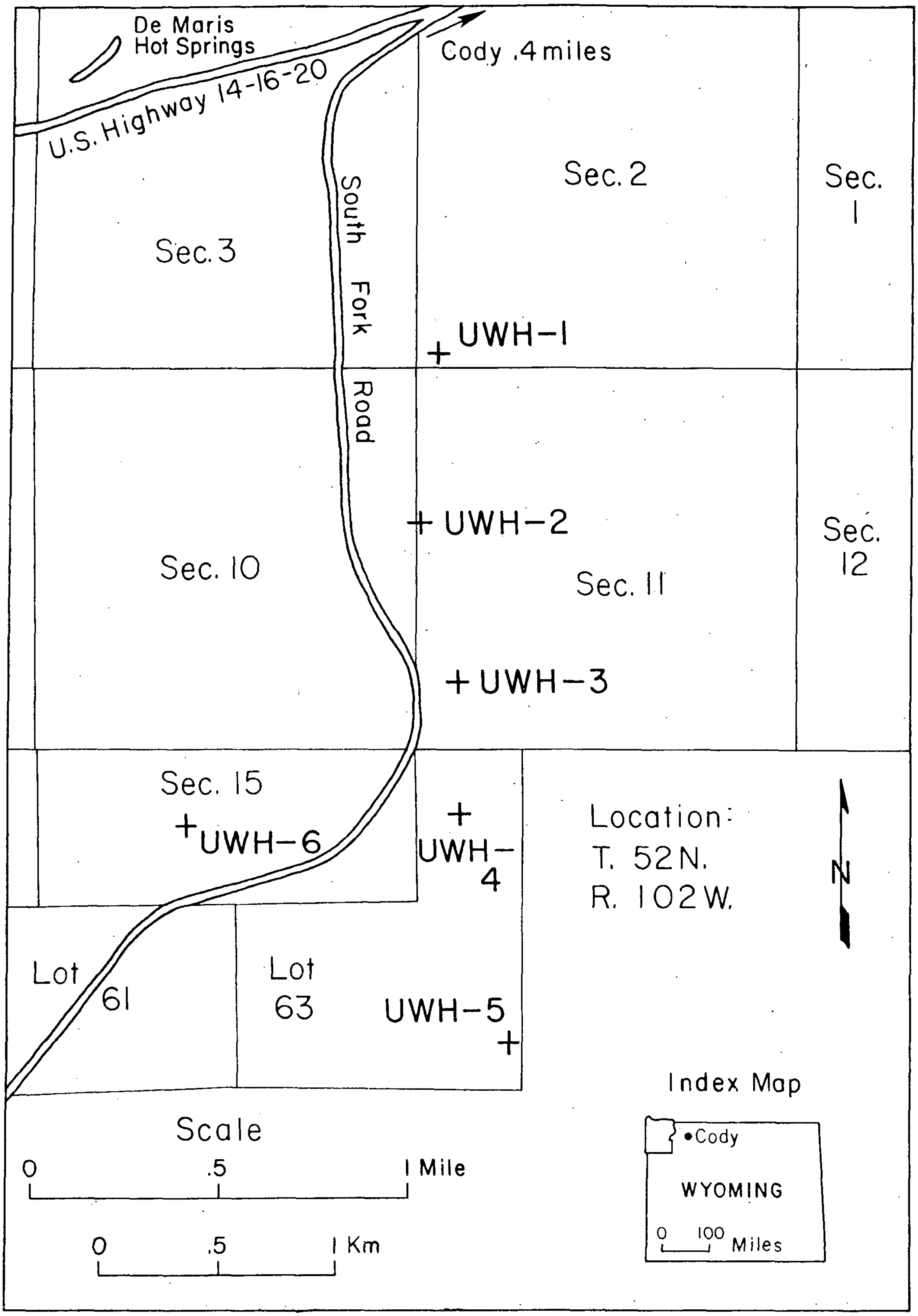

Figure 1. Locations of drill holes (UWH-1 through UWH-6).

convincing data are the thermal gradients of 49 to 205 °C/km in the anticline, based on bottom hole temperatures in eleven oil wells. (Twenty-three "dry" oil wells have been drilled in the structure. Of these, eleven wells yield gradients of 49 to 205 °C/km, five wells yield normal to slightly high gradients of 24 to 37 °C/km, while seven wells had no reported bottom hole temperature).

Our agreement with the U.S. Department of Energy has made it possible for us to log temperatures in three of the five unplugged wells in the Horse Center anticline. The resulting temperature-depth profiles for the wells are plotted in Figure 2. Figure 3 shows the locations of the holes in the area.

Well Letha C-4 may be on the southern edge of the thermal high because the bottom hole temperature of 38.4 °C at 320 meters yields the lowest gradient of 96 °C/km (see Fig. 2). A maximum temperature of 47.5 °C was measured at 500 meters in hole Rose Government 1 (Fig. 2). In contrast, the bottom hole temperature is 45.1 °C at 185 meters in Gains Government C-2 (Fig. 2) and the calculated gradient is 190 °C/km.

Referring to drill hole geology, the three remeasured wells were collared in the Chugwater Formation. Two of the holes ended in the Tensleep Sandstone, with the depth to the Tensleep ranging from 138 to 290 meters.

GEOLOGIC AND DRILLING STRATEGY

The Horse Center - Rattlesnake anticlines geothermal system may be explained by the combined effects of local geology, local hydrology and the regional geothermal gradients. Briefly, we believe that waters in deep porous units are warmed by the thermal gradients outside the middle portions of the anticlines. These waters then quickly gain access to shallower depths by moving upward along the steep limbs of the anticlines. The Chugwater Formation

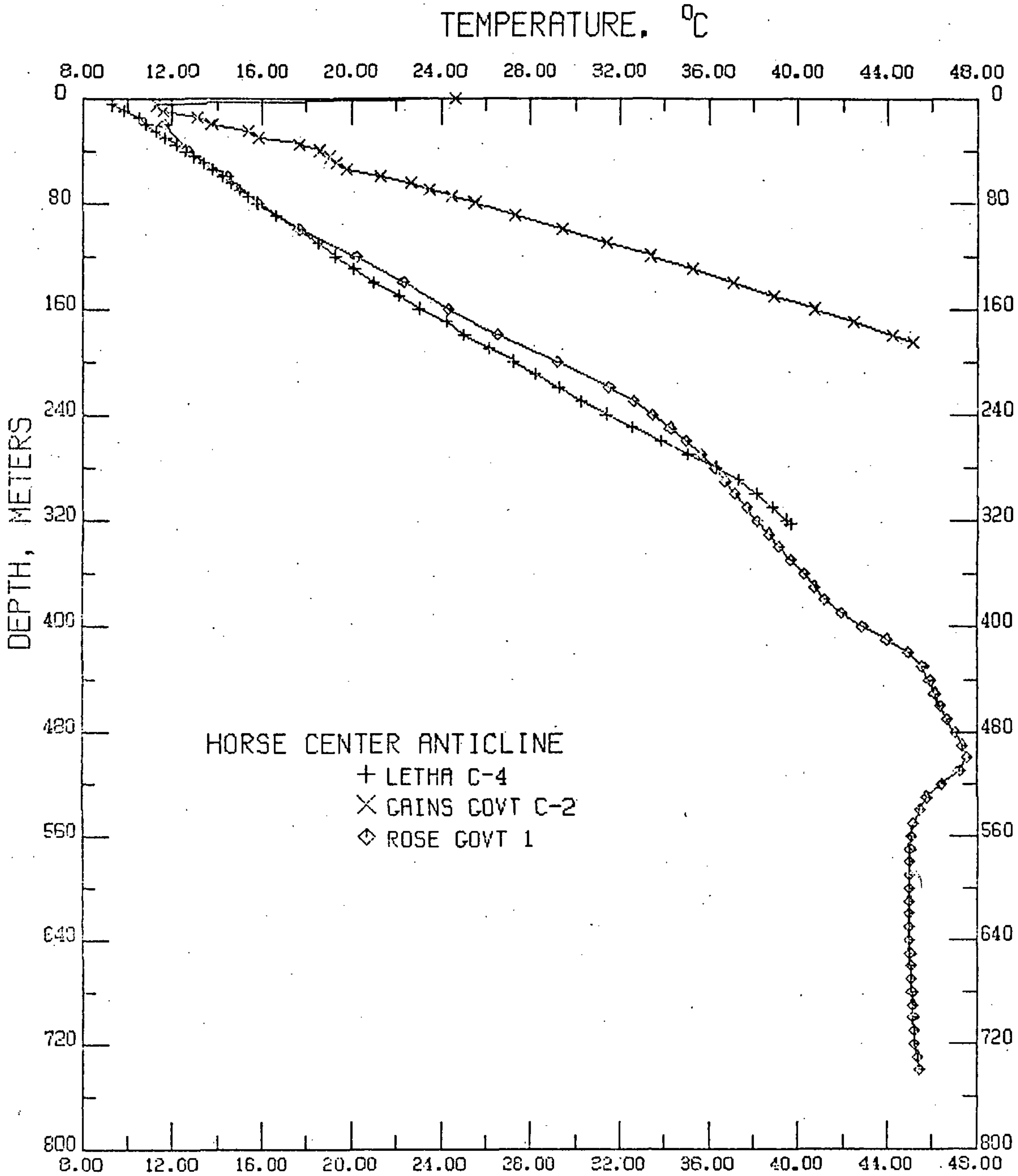

Figure 2. Temperature plots for three oil wells on the Horse Center anticline.

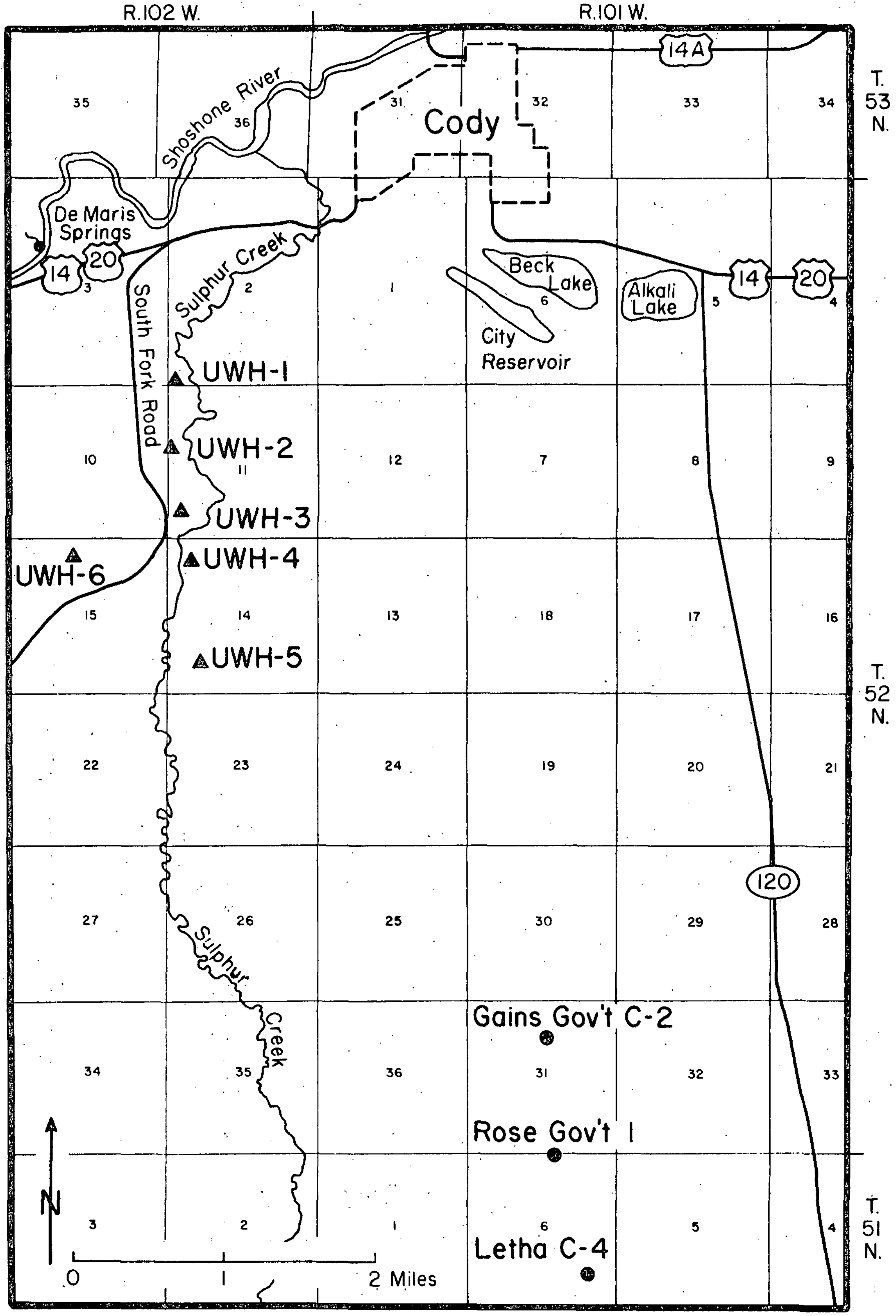

Figure 3. Map showing locations of drilled holes (triangles) and the three thermally logged oil wells (circles).

appears to be an impermeable cap rock above the water bearing units in the central parts of both structures.

The above described model is shown in a general way in Figure 4. The six holes in the Cody-Horse Center region were drilled in the vicinity of a "potential site area" on the southeastern flank of the Rattlesnake anticline.

DRILLING METHODS

The holes were drilled with air or foam using a Frank's Model FJ4HP truck mounted drill rig. The rig was capable of drilling to a depth of 610 meters (2,000 feet). A 5 1/8" tri-cone rotary bit was used to drill the softer units. This bit could not be used for all of holes UWH-3, UWH-4, and UWH-6 because extremely hard units were encountered; therefore a 5 1/8" down hole hammer was used to drill portions of these holes.

The air and foam drilling mediums worked successfully when "dry" fractures etc., were encountered. At some sites, however, water flows or aquifers were encountered and fine sand flowed into the holes as rapidly as drilling proceeded. These "running" sands greatly impeded or prevented further drilling and so cementing was tried to hold the walls of the holes or "stabilize" the sands. The Dowell Company was employed for this grouting, and a special cement was used because the warm subsurface waters had high sulphate contents. This cement gelled in as little as three minutes, and interested readers are referred to the Dowell Company for details on components of the mixture.

The Dowell company was able to cement zones in the upper part of hole UWH-2. When drilling continued downward in this hole, however, other zones of "bad" ground were encountered. These deeper zones could not be cemented because they were either in large caverns or in aquifers with very large volumes of water or high flow rate. A similar problem was encountered at the bottom

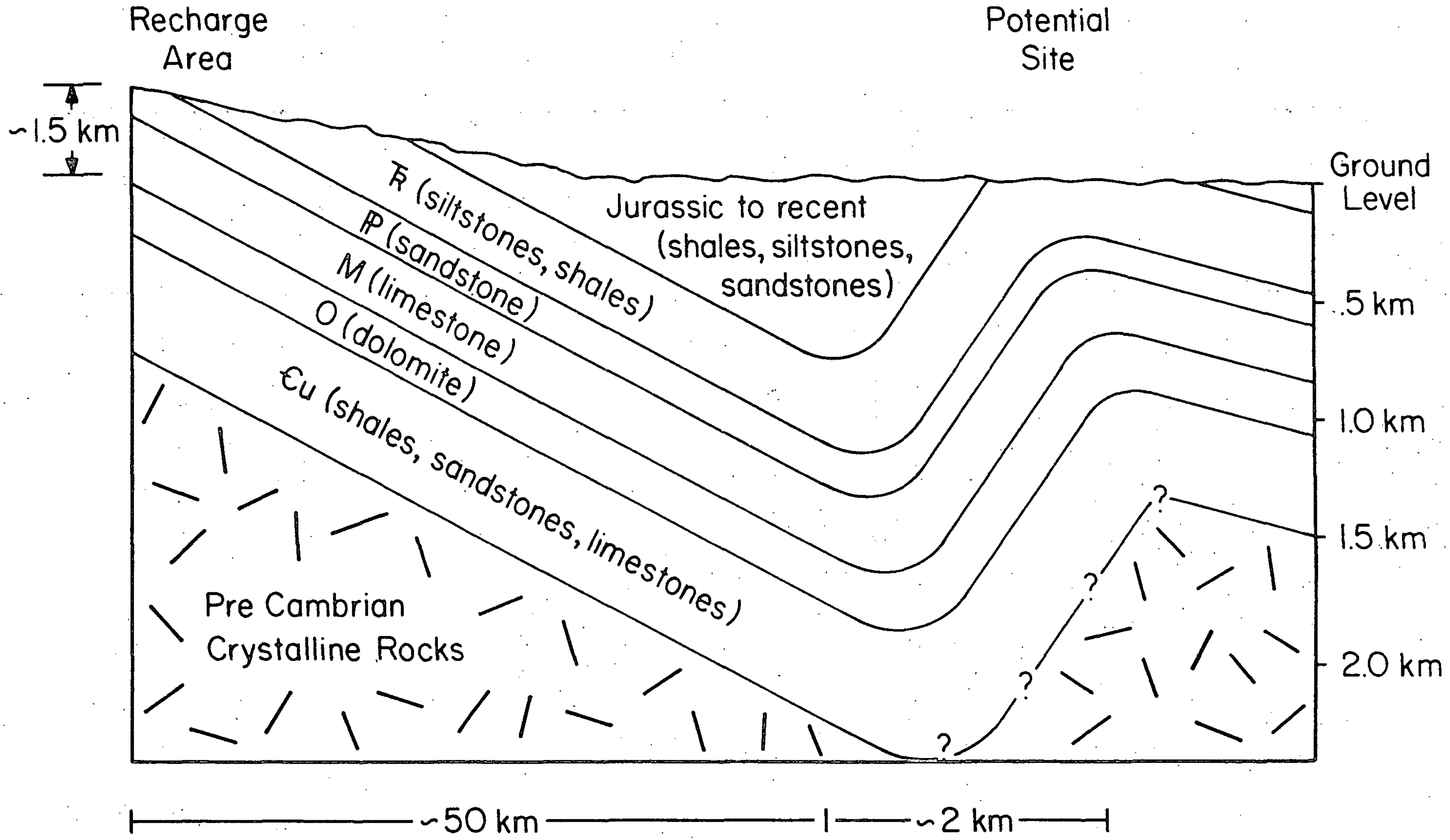

Figure 4. Generalized model of reservoir source and recharge area.

of hole UWH-4. For example only 1.7 meters (5 feet) of "fill up" occurred in UWH-2 when 2.3 meters^3 (80 ft^3) were pumped into the bottom of the hole. Consequently, drilling of UWH-2 and UWH-4 was terminated at 123 and 101 meters, respectively, because further drilling was not possible without very costly casing of the troublesome zones.

COMPLETION METHODS

Each well was completed so that temperature gradients could be monitored for an indefinite period of time. This was accomplished by setting an access pipe as deep as possible in each hole. The access pipe is 1¼ inch inside diameter schedule 40 black iron pipe.

The pipe in holes UWH-1, UWH-3, UWH-5 and UWH-6 is grouted with neat cement. The grouting procedure directly followed the methods outlined in Moses and Sass (1979). Grouting was done in an effort to stop vertical flows of water in the annuli between the pipe and the walls of the boreholes. This technique was not used at sites UWH-2 and UWH-2 because both holes bottomed in large cavities and/or very bad ground; therefore, cement would have flowed laterally rather than vertically up around the pipe. Another reason for not cementing pipe in UWH-2 is that it is desirable to deepen this hole in the future, if funding can be obtained.

A latching plug was "chased" to the bottom of the 1¼" pipe in all of the holes. The plug cleaned the pipe and created a tight seal at the end of each string of casing. Each string of pipe was then filled with water, the collars were capped, and each drill site was restored according to the requirements of the State of Wyoming and our agreement with the Department of Energy.

PRELIMINARY RESULTS

Figures 5-10 are plots of the preliminary temperature - depth data for the six holes. A combined plot of these data is in Figure 11. Other measurements in holes UWH-1 - UWH-5 are plotted in Figures 12-17; these measurements were made at times before those shown in Figures 5-9. Tables 1-6 list locations, land owner data, information on drilling, casing and cementing, and generalized lithology for the holes.

Bottom hole temperatures, cased depth, least squares estimates for the gradients in the holes and depth ranges for the gradient calculations are listed below.

Hole	Bottom Hole Temperature °C	Cased Depth meters	Gradient °C/km	Depth Range meters
UWH-1	26.6	98.5	156.7	10- 98.5
UWH-2	35.4	116.0	161.4	10- 45
UWH-3	25.3	72.0	181.7	5- 72
UWH-4	13.2	96.7	14.6	5- 96.7
UWH-5	18.3	108.7	78.2	10-108.7
UWH-6	20.4	85.1	108.1	18- 85.1

Rotary chip samples were collected at 3 meter (10 feet) spacings for each hole. The chips were used to determine stratigraphy as drilling progressed. Related geothermal research involves thermal conductivity measurements of the samples. A final report on the resulting heat flow values and regional thermal interpretations for the holes should be fowarded in the next 4-6 months.

PRELIMINARY INTERPRETATION

The Cody-Horse Center hydrothermal system is believed to extend on a line south-southeast from the DeMaris Hot Springs to well Letha C-4 (see Figure 3). The width of this zone varies from one to about two miles.

The area of greatest potential use is in T. 52 N., R 102 W., S½ of section 2, and W½ of section 11 (see Figures 1 and 3). In this area warm waters (34 °C (93 °F)) can be reached at shallow depths (51 to 300 meters (168 to 1,000 feet)). The maximum temperature of this system may approach 55 to 65 °C (131 to 149 °F) at depths of 260 to 500 meters (853 to 1640 feet). Warm waters will be found at the shallower depths in the more western portions of this potential use area.

The main aquifers for the Cody-Horse Center hydrothermal system are the Tensleep Sandstone, Madison Limestone, and Bighorn Dolomite. These formations are reported to have good porositites and permeabilities with flows in the Madison Limestone and the Bighorn Dolomite sometimes exceeding 1,000 gallons per minute (Lowry, 1976). However, the water flow of wells drilled into these aquifers may vary greatly between wells due to secondary fracture permeability, secondary silica cementation of the Tensleep Sandstone, and the cavernous nature of the Madison Limestone and Bighorn Dolomite.

TABLE 1. Drilling and other data for the hole UWH-1

Well Name:	UWH-1
Area:	Cody, Wyoming
Location:	SW¼ SW¼ Sec. 2, T. 52 N., R. 102 W.
Elevation:	5120 ft.
Landowner:	Coy Gail; Cody, Wyoming
Commenced Drilling:	January 2, 1980
Completed Drilling:	January 3, 1980
Total Drilling Depth:	327 ft.
Casing Set:	January 4, 1980
Depth of Casing:	321 ft.
Casing Cemented:	January 4, 1980
Sacks of Cement Used:	60 sacks neat cement with 6 gallons water per sack used to cement casing
Lithology:	0 to 2 feet; surface gravels 2 to 327 feet: Triassic Chugwater Formation; red siltstones, red shales, and fine red sandstone
Notes:	Drilling on this hole progressed smoothly. The formation became moist at 40 feet but never flowed any quantity of water into the drill hole.

TABLE 2. Drilling and other data for hole UWH-2

Well Name:	UWH-2
Area:	Cody, Wyoming
Location:	SW¼, NW¼, Sec. 11, T. 52 N., R. 102 W.
Elevation:	5160 feet
Landowner:	Coy Gail
Commenced Drilling:	January 11, 1980
Completed Drilling:	March 19, 1980
Total Drilled Depth:	403 feet
Casing Set:	18 joints (378 ft.)
Depth of Casing:	378 feet
Casing Cemented:	No. (see notes)
Sacks of Cement Used:	45 sacks neat cement, 80 sacks Dowell 12-3 R.F.C. cement (see notes).

Lithology:	0 to 20 feet:	Travertine; white, powdery
	20 to 130 feet:	Triassic Chugwater Formation; red siltstones, red shales and fine red sandstone.
	140 to 180 feet:	Triassic Dinwoody Formation; tan and gray siltstone and dolomite. Started making over 5 gallons per minute water at 140 feet.
	180 to 200 feet:	No sample return.
	200 to 403 feet:	Pennsylvannian Tensleep Sandstone; light gray to tan, sometimes siliceous sandstone. At 220 feet small cubes (1/16 inch) of pyrite were present.

Notes:

The hole was making up to 200 gallons per minute of H_2S smelling water starting at 280 feet. The temperature of the water measured at the surface was 18° C.

Starting at this depth of high water flow, zones of loose, well washed sand were encountered. The hole

Table 2 continued

Notes continued:	would not stay open through these zones. Consequently various cement jobs (a total of 4) were tried. These were successful to a depth of 403 feet where it was decided that further cementing would be too costly. The $1\frac{1}{4}$ inch casing was put in the hole but not grouted in place. It was felt that due to the large, warm water flows in the bottom of the hole the grout would have been washed away.

TABLE 3. Drilling and other data for hole UWH-3

Well Name:	UWH-3	
Area:	Cody, Wyoming	
Location:	SW¼ SW¼ Sec. 11, T. 52 N., R. 102 W.	
Elevation:	5180 ft.	
Landowner:	Jerry and John Housel	
Commenced Drilling:	January 3, 1980	
Completed Drilling:	February 5, 1980	
Total Drilled Depth:	333 ft.	
Casing Set:	February 5, 1980	
Depth of Casing:	13 joints (273 ft.)	
Casing Cemented:	February 5, 1980	
Sacks of Cement Used:	55 sacks, 6 gals. H_2O/sack	
Lithology:	0 to 95 feet:	Permian Park City Formation; gray to tan siliceous limestone. At 50 feet there was a strong sulfur odor.
	100 to 333 feet:	Lost circulation
Notes:	At 180 feet the rock becomes very hard. A hammer is used from this depth on to complete the hole. The 1¼ inch casing was set to 273 feet because of a zone at 275 feet that kept closing off.	

TABLE 4. Drilling and other data for hole UWH-4

Well Name:	UWH-4
Area:	Cody, Wyoming
Location:	NW¼, NW¼, Sec. 14, T. 52 N., R. 102 W.
Elevation:	5160 feet
Landowner:	Dale and Roberta Pike
Commenced Drilling:	March 7, 1980
Completed Drilling:	March 18, 1980
Total Drilled Depth:	333 ft.
Casing Set:	March 18, 1980
Depth of Casing:	314 ft.
Casing Cemented:	No. (see notes)
Sacks of Cement Used:	50 sacks Dowell 12-3 RFC cement (see notes)

Lithology:	0 to 90 feet:	Permian Park City Formation; grey to tan siliceous limestone.
	90 to 106 feet:	Poor sample recovery
	106 to 218 feet:	Pennsylvanian Tensleep Sandstone (?); light gray to tan siliceous sandstone with sometimes as much as 20% white silica chips. Small (1/16 inch) quartz spar present at 126 feet
	218 to 333 feet:	Lost circulation.

Notes:

At 218 feet a well washed sand was encountered before circulation was lost.

A cement job was done by Dowell at 333 feet but was unsuccessful. Consequently, the 1¼ inch casing was not cemented in place due to the large water flow and/or cavern that was present.

TABLE 5. Drilling and other data for hole UWH-5

Well Name:	UWH-5
Area:	Cody, Wyoming
Location:	NW¼, SW¼, Sec. 14, T. 52 N., R. 102 W.
Elevation:	5210 feet
Landowner:	Glenn Nielson
Commenced Drilling:	February 27, 1980
Completed Drilling:	February 28, 1980
Total Drilled Depth:	360 ft.
Casing Set:	(17 joints) 357 ft.
Depth of Casing:	354 ft.
Casing Cemented:	February 28, 1980
Sacks of Cement Used:	35 sacks neat cement, 7 gals. H_2O/sack
Lithology:	0 to 360 feet: Jurassic Sundance Formation; green to gray shale, thin brownish limestone and sandstone layers. From 235 feet to 329 feet a red shaley zone was encountered.
Notes:	Drilling on this hole progressed smoothly. The formation became moist at about 100 feet but never flowed water into the drillhole.

TABLE 6. Drilling and other data for hole UWH-6

Well Name: UWH-6

Area: Cody, Wyoming

Location: NE¼, NW¼, Sec. 15, T. 52 N., R. 102 W.

Elevation: 5280 feet

Landowner: Carrol Koster

Commenced Drilling: February 6, 1980

Completed Drilling: February 26, 1980

Total Drilled Depth: 311 feet

Casing Set: 9 joints (189') (see notes)

Depth of Casing: 185 feet

Casing Cemented: February 26, 1980

Sacks of Cement Used: 30 sacks neat cement with 6 gallons H_2O/sack

Lithology:

0 to 10 feet: Rounded stream gravel, ½ to 2 inches in diameter.
11 to 19 feet: Light tan mud out of hole.
20 to 269 feet: Pennsylvanian Tensleep Sandstone; hard silicified sandstone chips dark gray to tan colored. Sporadic, small (less tan 1/8 inch) sulfur veinlets in upper 90 feet.
270 to 310 feet: Lost circulation.
311 feet: Became stuck in hole.

Notes: Stuck in hole from Feb. 7 until Feb. 25. During that time the bit was pulled free from 289 ft. up to 186 ft. by injecting 10 gallons diesel fuel in the compressed air. At 186 ft. the bit became plugged. Five gallons 33% HCl acid was put in the drill pipe. Circulation returned 4 hours later when the drill pipe broke free at the downhole hammer. The last 8 joints (164 feet) of drill pipe to come out of hole were covered with a black tarry substance. The substance was extremely black and had a musky to burnt odor.

Table 6 continued.

Notes continued:

The hammer was stuck in the hole at 186 feet. Consequently the 1¼ black iron pipe was set to that depth and cemented in place with 30 sacks neat cement.

A thermal log of the well was attempted only to find an obstruction in the 1¼ inch casing at a depth of 21 feet. Consequently the only downhole temperature-depth data was that taken during breaks in drilling.

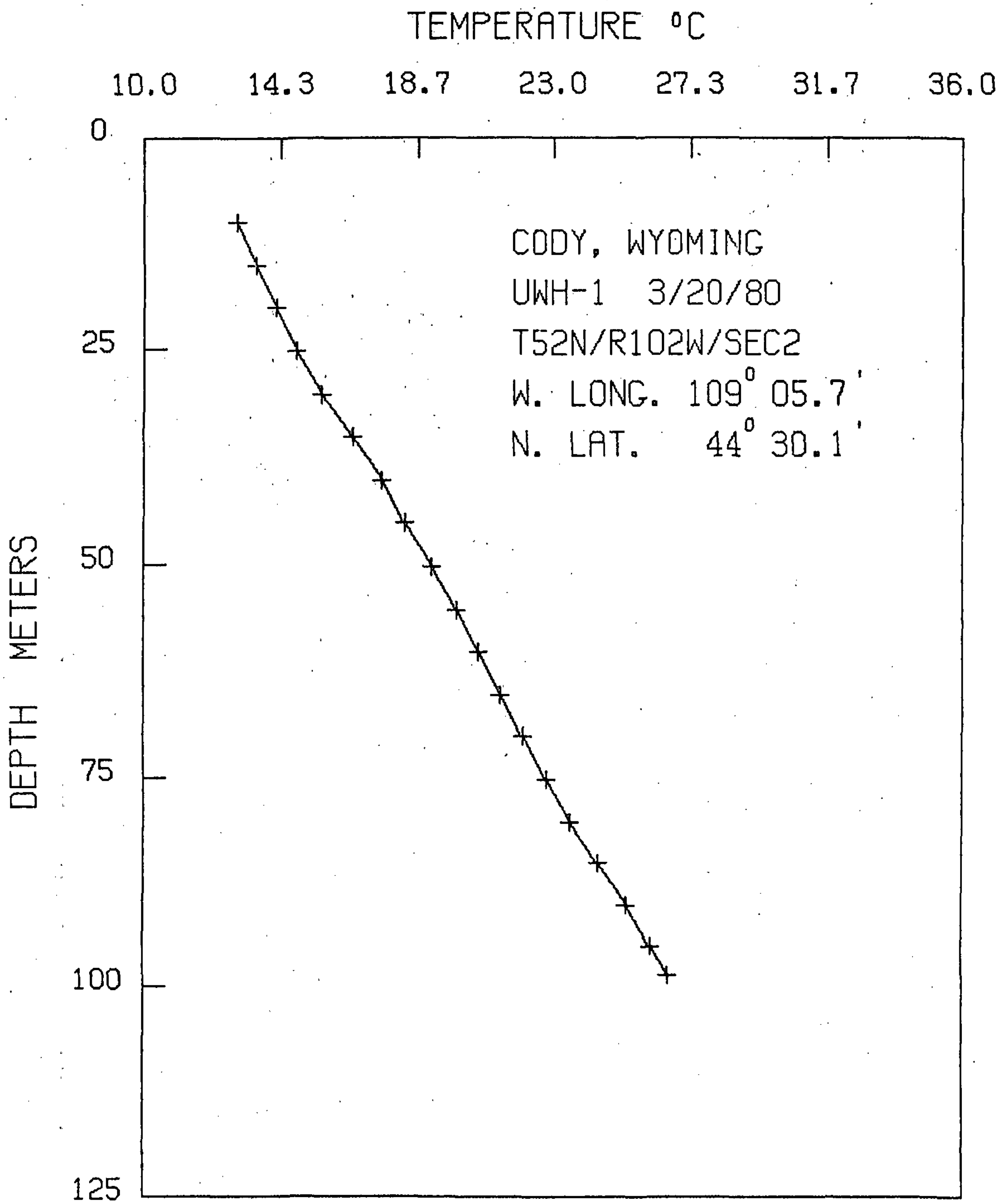

Figure 5. Temperatures as functions of depth in hole UWH-1 (3/20/80).

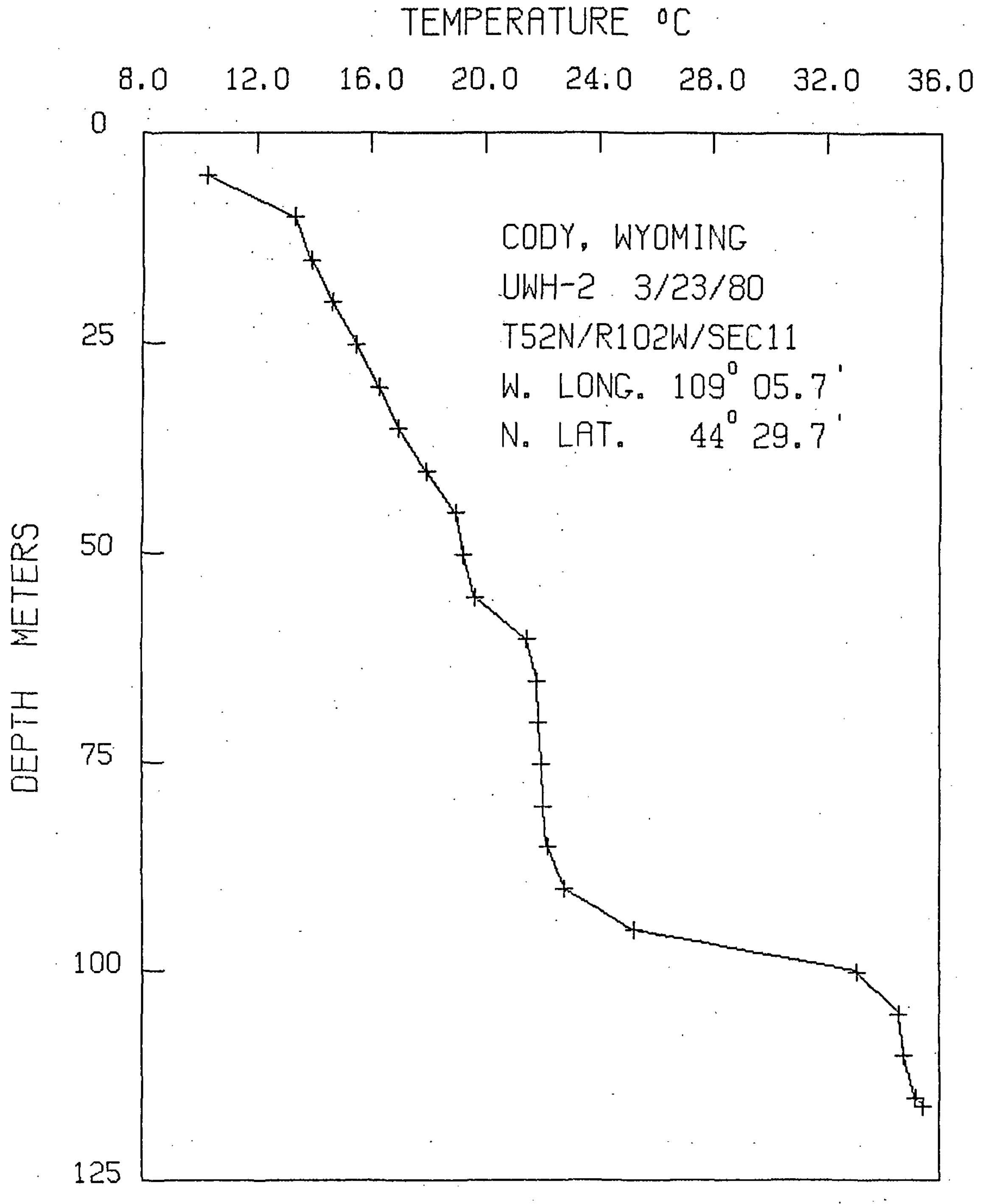

Figure 6. Temperatures as functions of depth in hole UWH-2 (3/23/80).

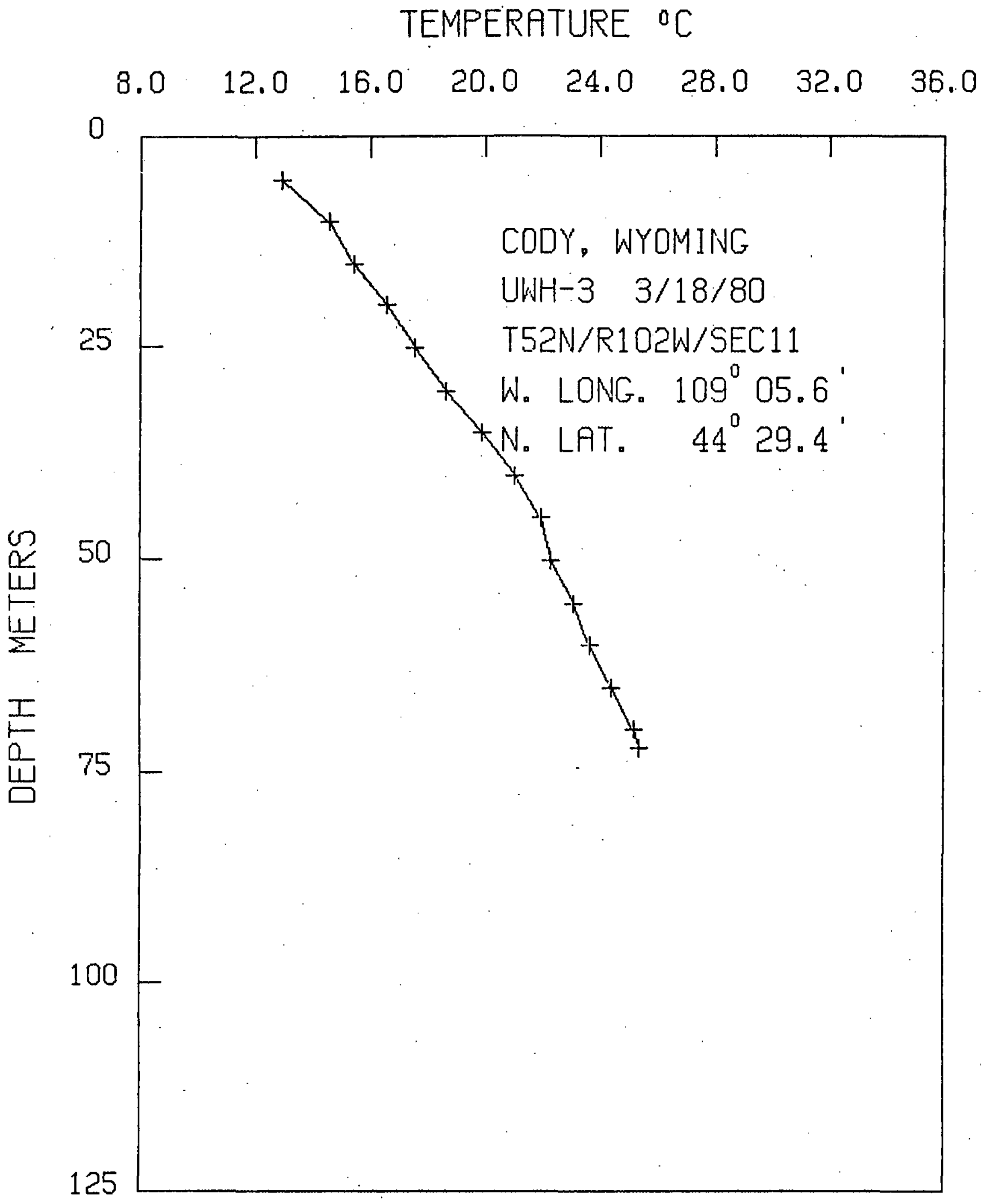

Figure 7. Temperatures as functions of depth in hole UWH-3 (3/18/80).

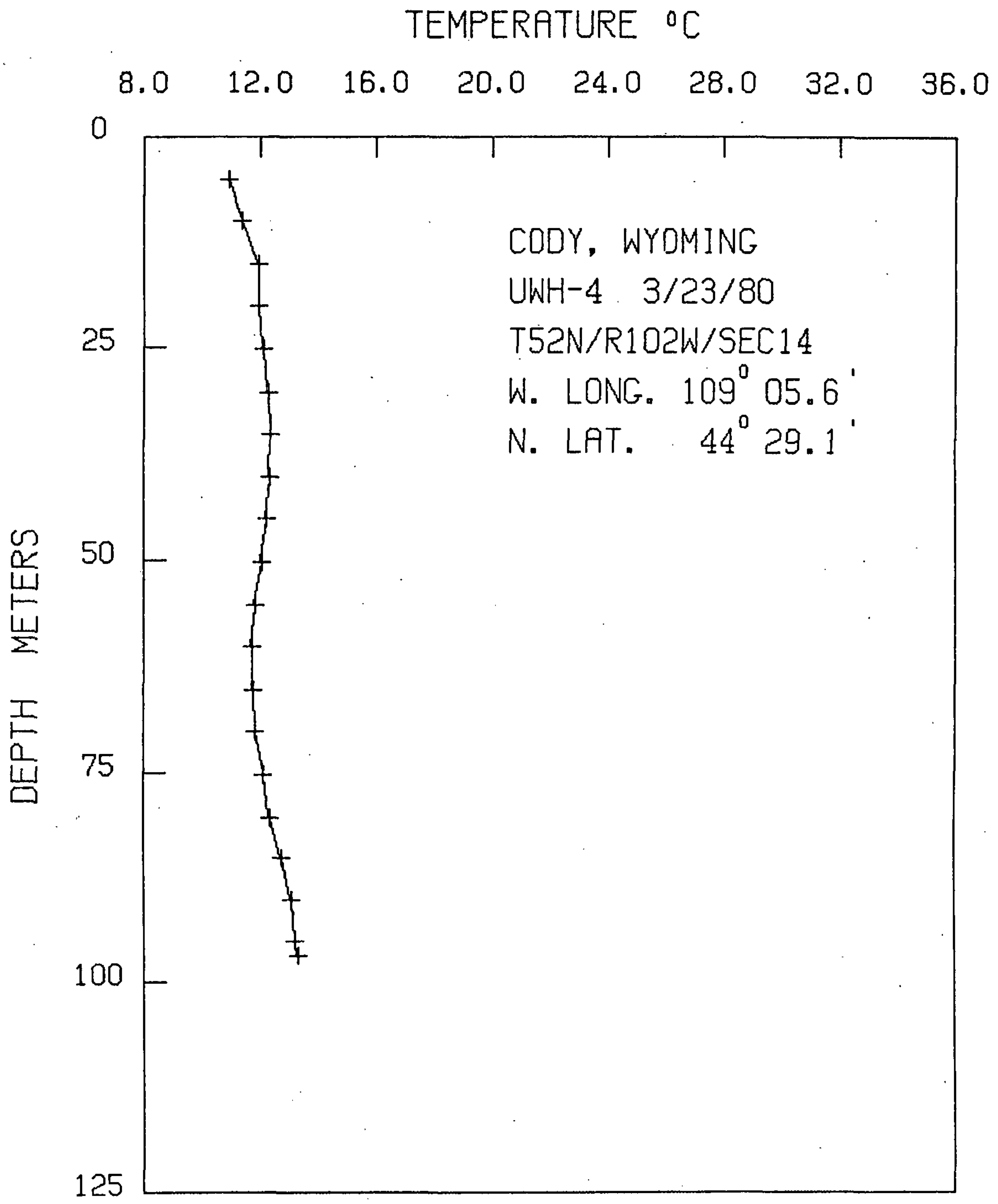

Figure 8. Temperatures as functions of depth in hole UWH-4 (3/23/80).

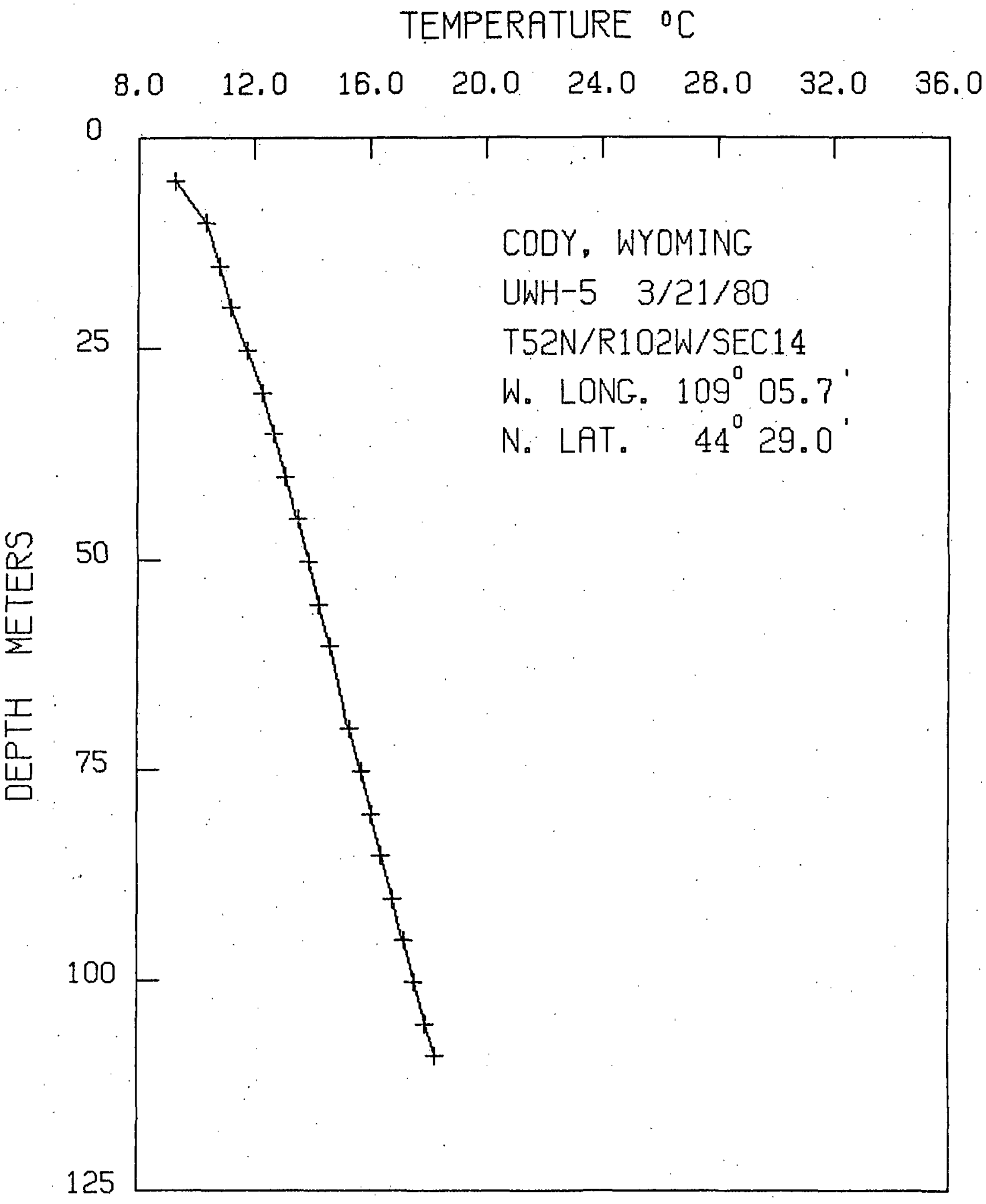

Figure 9. Temperatures as functions of depth in hole UWH-5 (3/21/80).

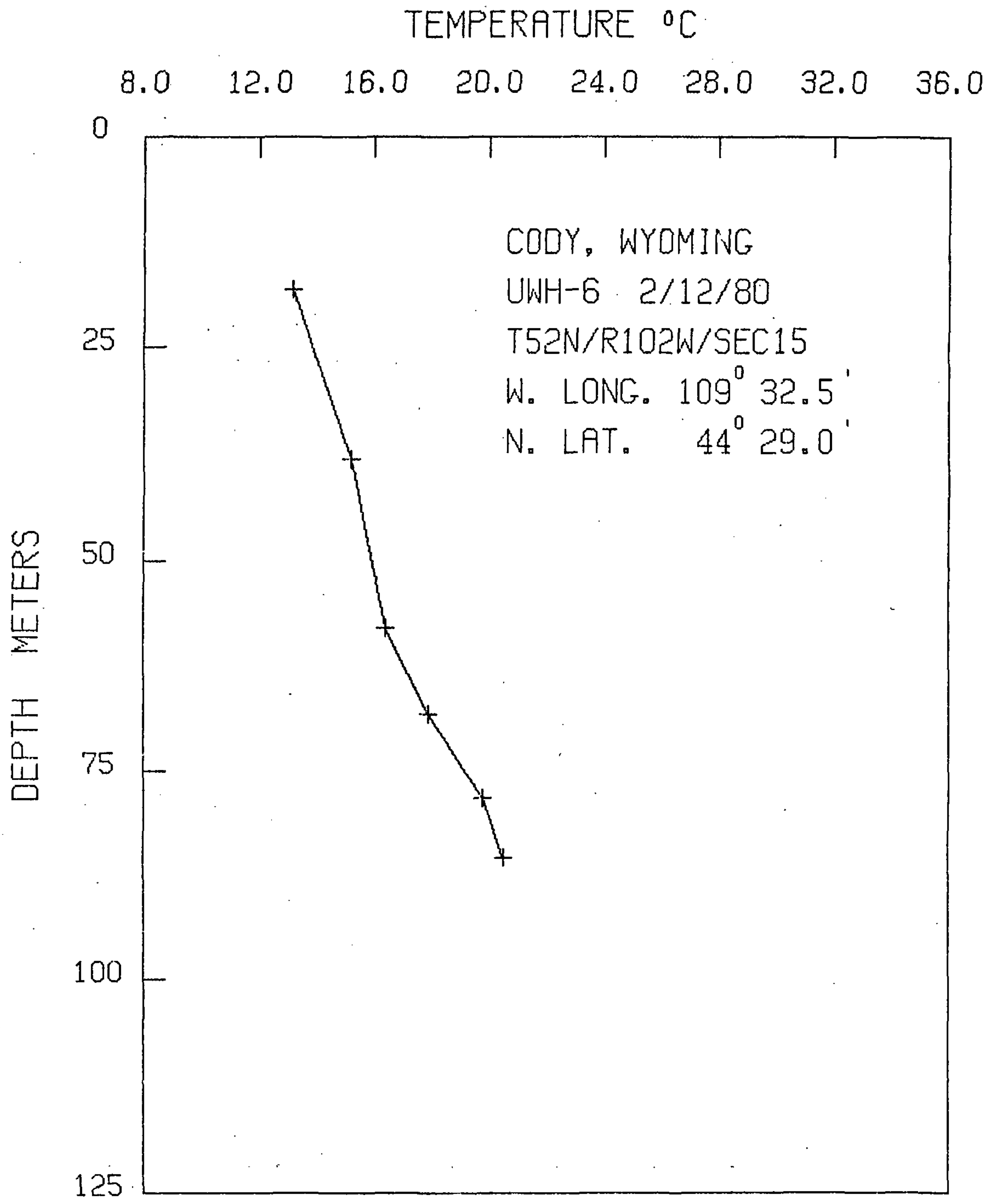

Figure 10. Temperatures as functions of depth in hole UWH-6 (2/12/80).

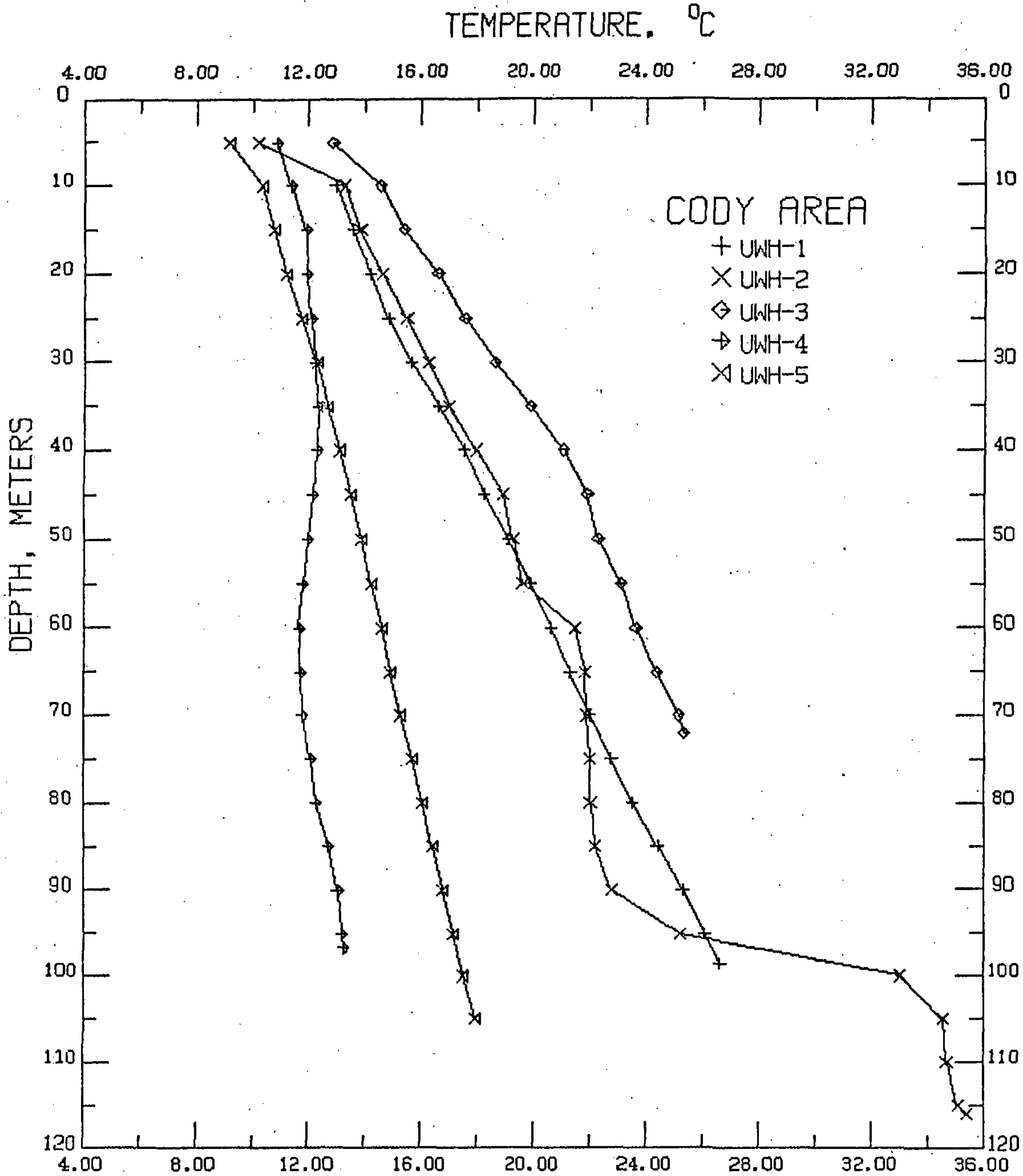

Figure 11. Temperatures as functions of depth in UWH drill holes.

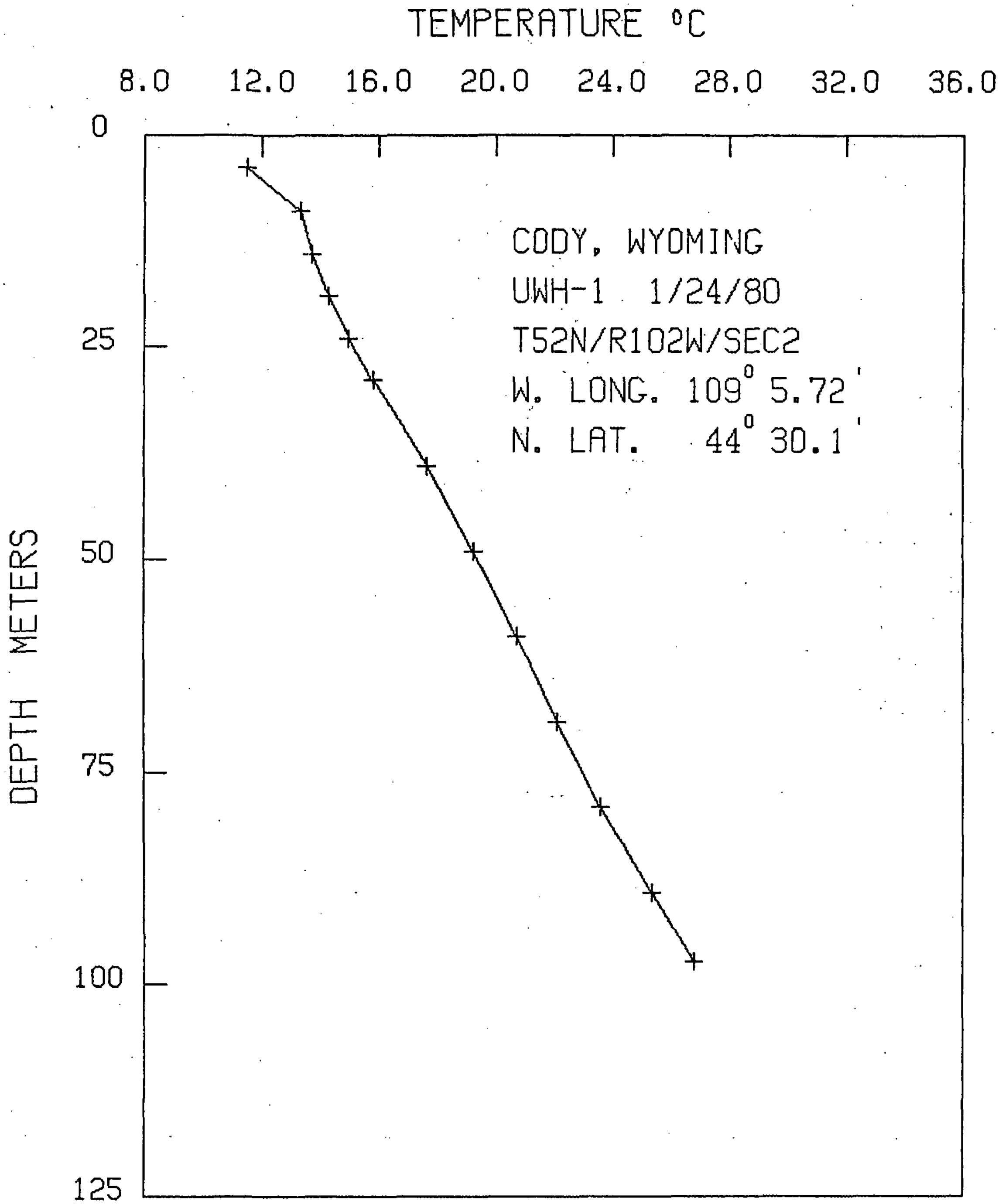

Figure 12. Temperatures as functions of depth in hole UWH-1 (1/24/80).

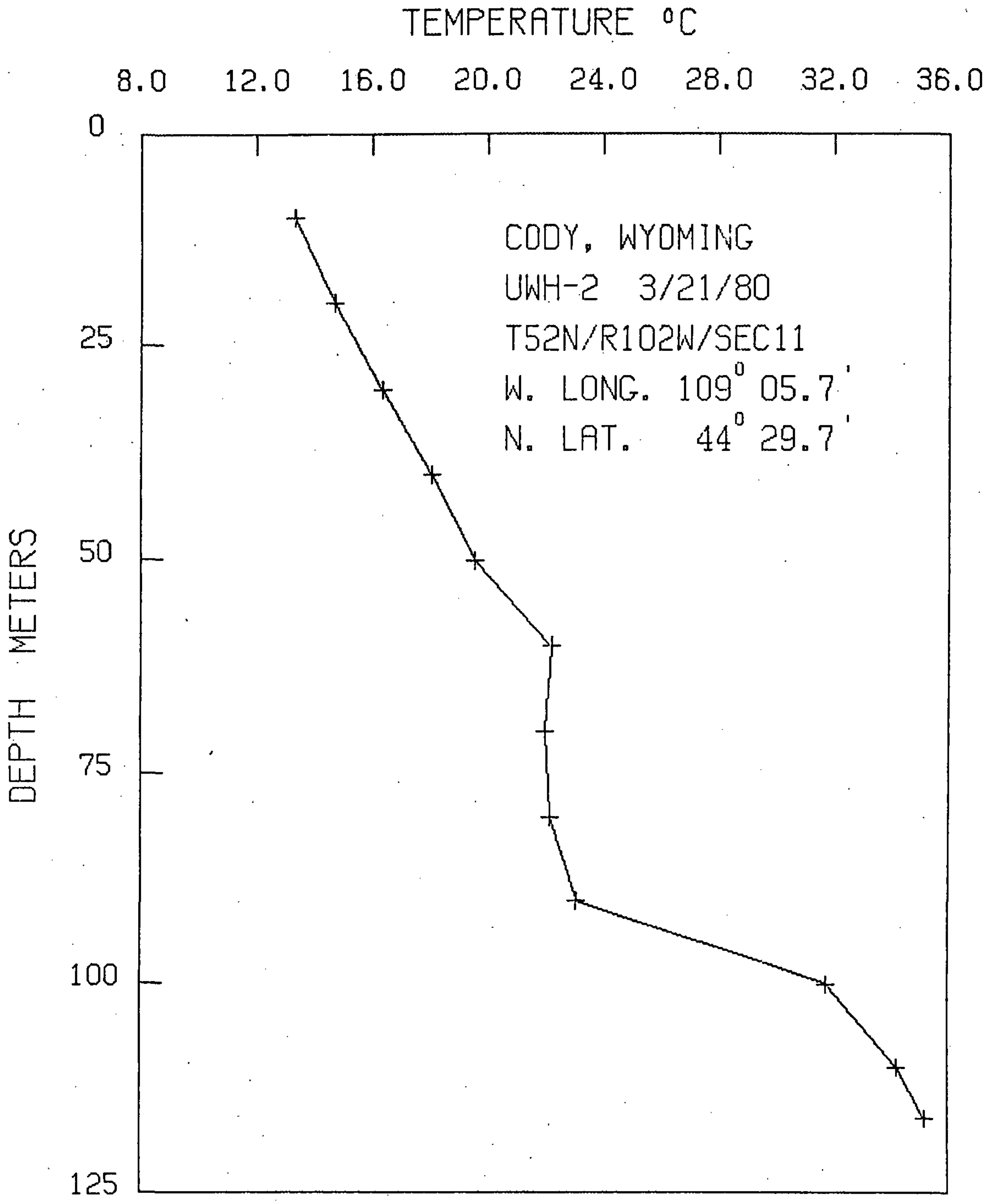

Figure 13. Temperatures as functions of depth in hole UWH-2 (3/21/80).

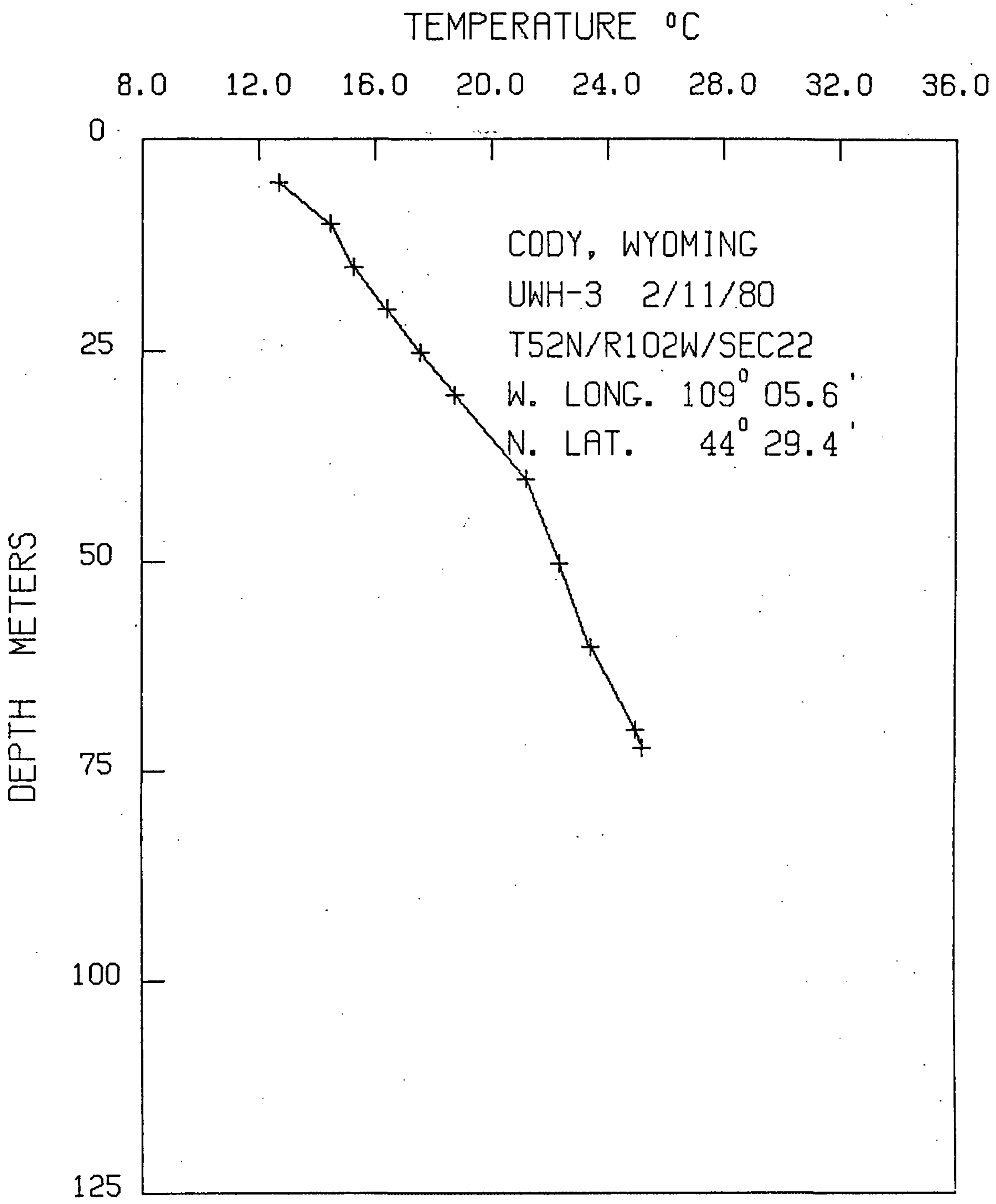

Figure 14. Temperatures as functions of depth in hole UWH-3 (2/11/80).

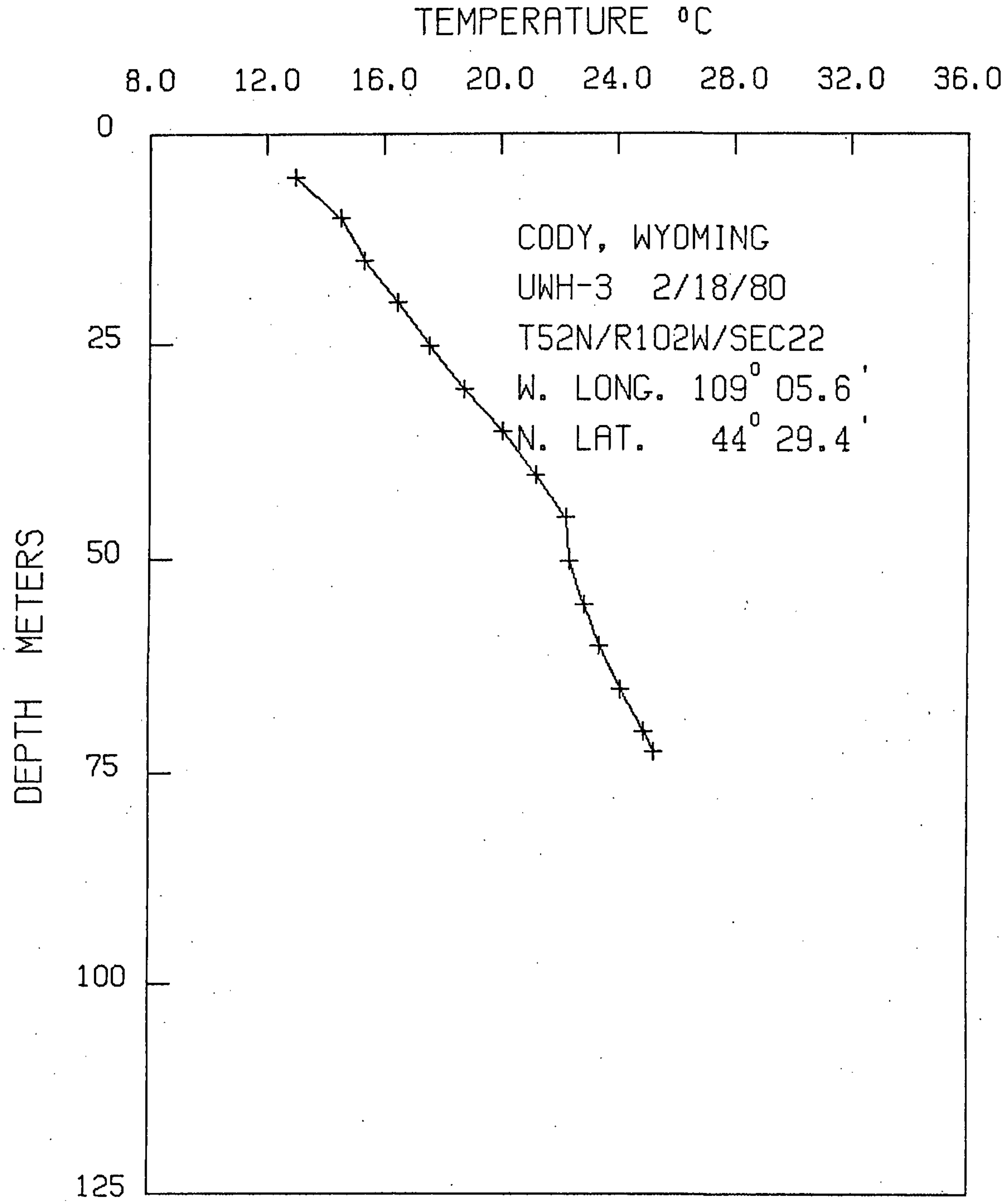

Figure 15. Temperatures as functions of depth in hole UWH-3 (2/18/80).

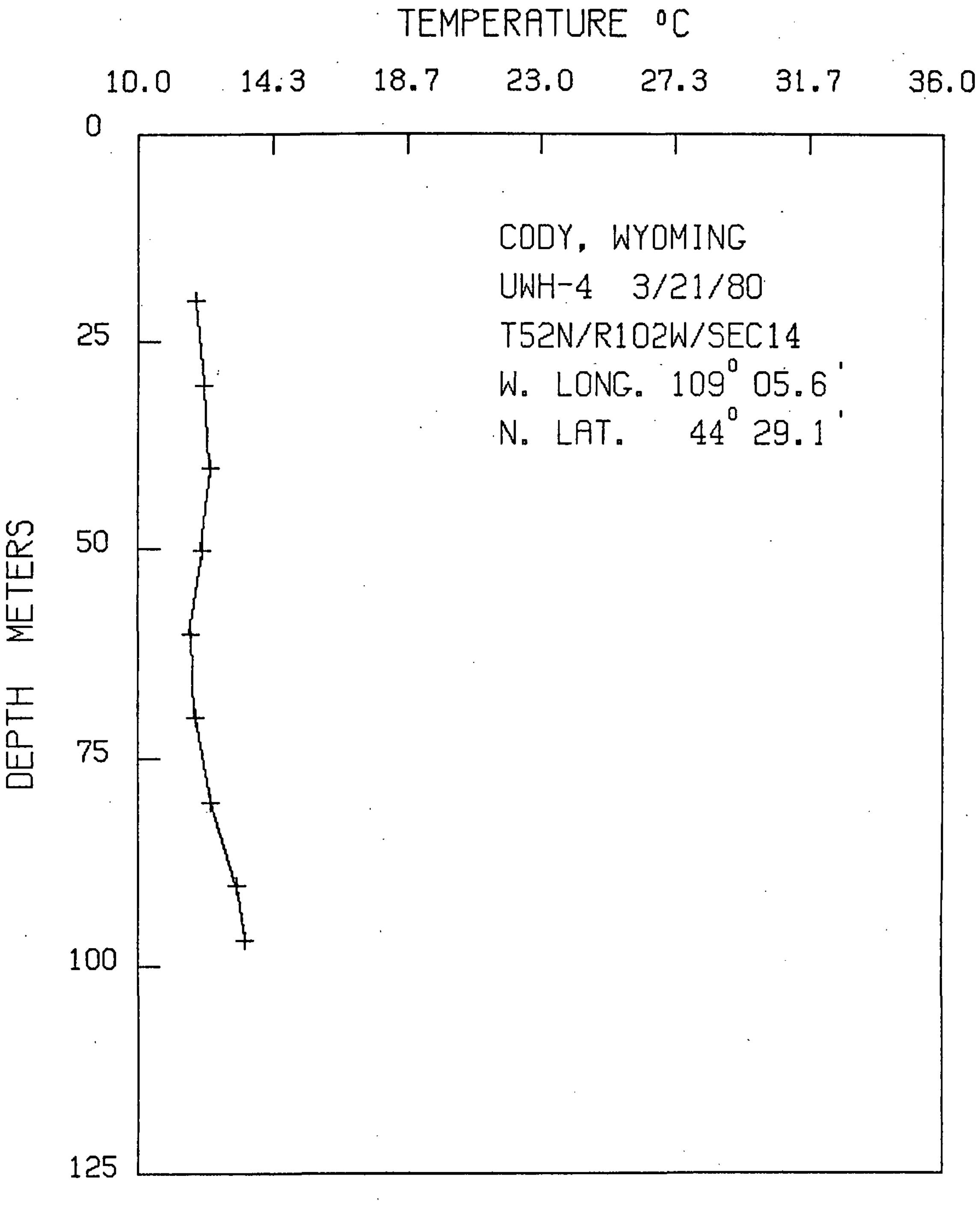

Figure 16. Temperatures as functions of depth in hole UWH-4 (3/21/80).

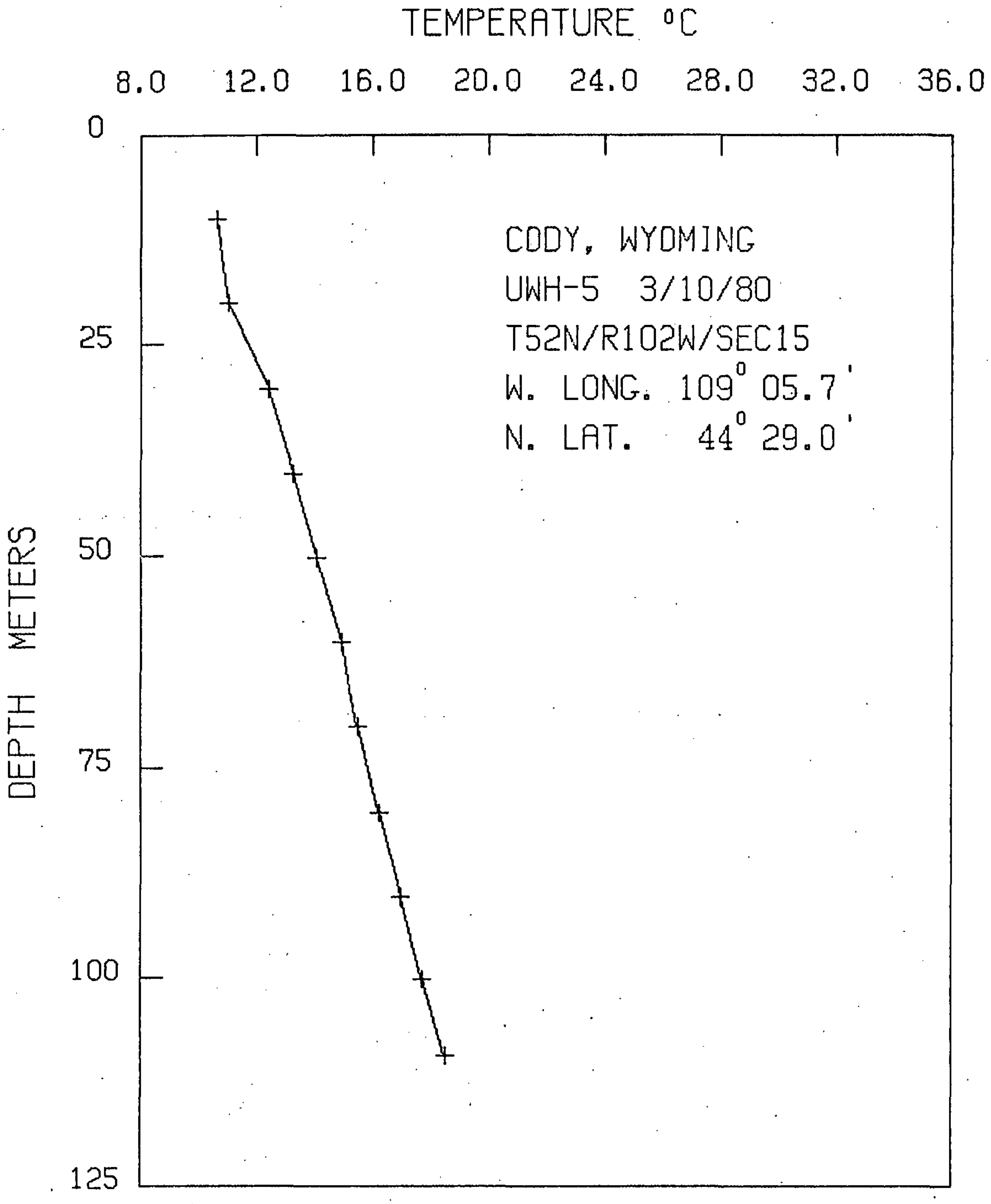

Figure 17. Temperatures as functions of depth in hole UWH-5 (3/10/80).

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Distribution of Soil Mercury and the Development of Soil Mercury Anomalies in the Yellowstone Geothermal Area, Wyoming

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Abstract

Soil mercury concentrations from Yellowstone National Park were determined using a thin gold film mercury detector. Reconnaissance sampling along roads and trails using a 1.6-km-sample interval revealed narrow soil Hg anomalies that are restricted to thermal regions and are surrounded by large areas with lower levels of soil mercury. Background levels of mercury in Yellowstone soils are 20 ppb with an anomaly threshold of 40 to 50 ppb. Detailed sampling on a 50-m grid was carried out in one vapor-dominated and three water-dominated areas. Although two of the water-dominated areas contain anomalous concentrations of soil Hg, there is no direct correlation between the Hg anomalies and the presence of hot springs. The third hot water area, the Mammoth Hot Springs, contains no significant soil Hg anomaly. In the vapor-dominated system there is a strong correlation between soil Hg anomalies and intense vent activity. Partitioning of mercury into the vapor phase during subsurface boiling and subsequent separation of the vapor phase from the thermal waters are believed to be the major controls on the formation of soil Hg anomalies at Yellowstone. Geothermal exploration using soil Hg concentrations could be carried out on a local scale in Yellowstone but because of the narrow Hg anomalies would not be feasible on a regional scale.

Introduction

THE association of mercury mineralization with past and present geothermal activity is well documented (White, 1967; Dickson and Tunell, 1968). More recently, several studies have revealed anomalous quantities of mercury in a number of geothermal areas both with and without Hg mineralization. Studies by Fang (1978), Landa (1978), and McNeal and Rose (1974) have shown that most soils readily adsorb Hg vapor and retain the adsorbed Hg to temperatures of at least 100°C. Low-level Hg anomalies in soils in geothermal areas demonstrate that soils in geothermal areas accumulate mercury. Detection of the resulting soil Hg anomalies in geothermal areas has been proposed by Matlick and Buseck (1976), Klusman and Landress (1978), and Phelps and Buseck (1978, 1979) as a potential exploration technique for geothermal activity.

Although the general relationship of excess mercury and geothermal activity has been demonstrated, no detailed investigations aimed at relating the type of geothermal activity occurring in a particular area to the characteristics of the associated Hg anomaly have been carried out. In order for the Hg technique to be successful as an exploration tool, it is imperative that these correlations be determined and understood. In this paper, we present the results of a detailed study of the distribution of mercury in soils in the geothermal systems of Yellowstone National Park, Wyoming. We have shown that the soil Hg anomalies developed in a geothermal area can be extremely complex, and the way in which the anomalies are interpreted is strongly dependent upon the type of geothermal system present.

Geology and Geothermal Activity of Yellowstone National Park

Yellowstone and surrounding areas have been the site of repeated Quaternary volcanic activity. Three major phases of caldera collapse and eruption of rhyolitic tuffs have occurred in the past two to three million years (Christiansen and Blank, 1972). The most recent activity, terminating approximately 70,000 years ago, resulted in the formation of the Yellowstone caldera and in associated eruptions of rhyolitic tuffs and lava flows which blanket most of the park (Christiansen and Blank, 1972). Although there has been no volcanic activity in historic times at Yellowstone, Eaton et al. (1975) have proposed the existence of a magma chamber at a depth of six km

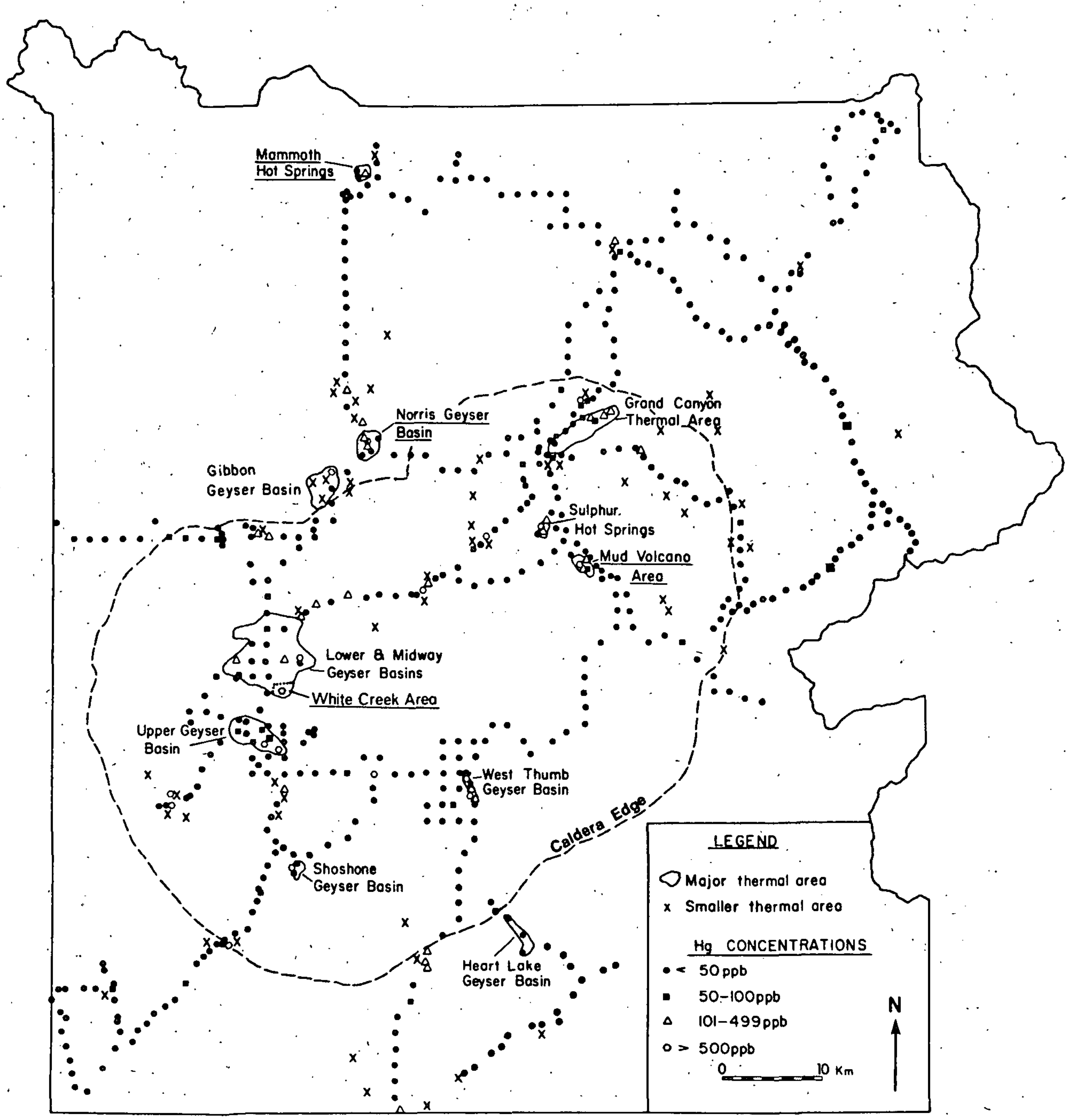


FIG. 1. Map of Yellowstone National Park showing the major thermal areas, outline of the Yellowstone caldera, and the results of reconnaissance soil sampling for mercury. Underlined names are the thermal areas that were sampled in detail.

or more beneath Yellowstone. Cooling of this magma body is believed to be the source of heat for the geothermal activity at Yellowstone.

A variety of types of geothermal activity are found within Yellowstone National Park. Water-dominated systems discharging high chloride thermal waters and actively depositing sinter occur in the Upper, Lower, Midway, Heart Lake, West Thumb, Shoshone, Norris, and Gibbon Geyser Basins (Truesdell and Fournier, 1976). Areas characterized by fumarolic activity and acid hot springs are found locally in the elevated portions and around the edges of some of the water-dominated systems. Vapor-dominated thermal areas occur in the regions along and east of the Yellowstone River (Truesdell and Fournier, 1976). Hot springs depositing travertine are found in the extreme northern part of the park at Mammoth and at a few other isolated locations throughout the park.

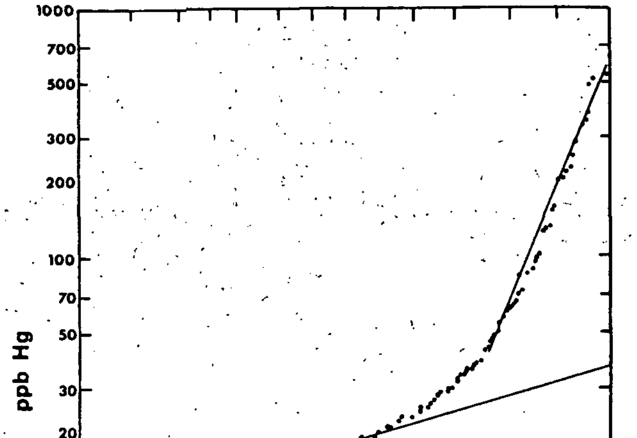


FIG. 2. Cumulative frequency plot on normal probability paper of log Hg contents of all soil samples collected at a 1.6-km interval along the roads and major foot trails in Yellowstone National Park.

Sample Collection and Analytical Technique

Sampling was carried out in two stages. In the first stage, samples were collected at approximately 1.6-km intervals along the roads and major foot trails throughout the park. This reconnaissance phase of sampling was performed in order to determine the overall distribution of mercury in Yellowstone National Park, to outline areas of interest for detailed sampling, and to determine a background level of mercury in the soils. Areas selected for detailed study were sampled on a 50-m grid.

Work by Klusman and Landress (1978) and Capuano and Bamford (1978) has shown that Hg anomalies resulting from geothermal activity overwhelm any differences in soil Hg concentrations that result from variations in soil type. Therefore, soil samples were collected from a depth of 5 to 10 cm and no attempt was made to stay within a particular soil horizon. The unsieved samples were placed in plastic "zip-lock" bags and sealed. Upon returning to the base camp, the samples were air dried in a cool, shaded location, sieved using an 80-mesh, stainless-steel sieve, and the minus-80 fraction was stored in a tightly sealed glass vial for analysis.

Mercury analyses were performed using a Jerome Instrument Corporation Model 301 thin gold film detector. Details of the analytical procedure have been presented by McNerney et al., (1972) and Matlick and Buseck (1976). The thin gold film detector is portable in the field and has an absolute sensitivity of 0.5 ppb Hg. Under field conditions, the relative precision is ±20 percent (2σ) at the 50-ppb level. Sample sizes used for analysis ranged from <0.01 to 0.3 g, depending upon the mercury content of the soil. Mercury is removed from the sample by heating in a quartz bulb to 800°C for one minute. The liberated mercury is collected on a gold-plated wire while the other gases are vented to the atmosphere. The gold-plated wire is subsequently heated, thereby releasing the Hg which is then collected on a thin gold film. The resulting change in electrical resistivity of the gold film is proportional to the amount of mercury collected.

Results of Reconnaissance Sampling

The results of the reconnaissance phase of sampling have been reported previously (Phelps and Buseck, 1978, 1979) and will only be summarized here. Figure 1 shows the major geologic and geothermal features of Yellowstone National Park together with the results of the reconnaissance sampling. In general, Figure 1 shows that most of the soils in Yellowstone have low levels of mercury. However, elevated concentrations of mercury occur in soils near thermal areas and extend outward for no more than one kilometer from the edge of the thermal activity.

Previously, we reported background levels of mercury in soils from Yellowstone of 20 ppb Hg with a threshold value (2σ variation of calculated value) of 50 ppb (Phelps and Buseck, 1979). To calculate the background the mean Hg content of all samples collected farther than one kilometer from a known thermal feature was determined. As an alternative method for background determination, all the results of the reconnaissance sampling were put on a lognormal cumulative frequency plot. The results (Fig. 2) show at least two populations of mercury (two straight line segments of the curve) in the Yellowstone soils. By following methods similar to those of Sinclair (1974), the maximum background level of mercury (intersection of background line with the 50th percentile) in Yellowstone soils can be estimated to be 20 ppb Hg. The threshold value (98th percentile of background line extension) is approximately 40 ppb Hg. These values agree well with those reported by us earlier.

Background levels of 20 ppb Hg with a threshold of 40 to 50 ppb are comparable to values reported by Davies (1976) for western Britain and by Klusman and Landress (1978) for Long Valley, California;

TABLE 1. Summary of the Physical and Chemical Characteristics of the Four Thermal Areas Studied in Detail

Data (exclusive of the soil Hg values) are from Truesdell and Fournier (1976), White et al. (1971, 1975), and Fournier et al. (1976).

Area	Type of activity	Estimated reservoir T (°C)	Dominant H_2O type	Dominant surficial deposit	Soil Hg characteristics (in ppb)			
					Min.	Max.	Geometric mean	No. of samples
Norris	Water-dominated	>250	high Cl, neutral to slightly acid	sinter	13	> 92,000	800	400
Lower Geyser Basin	Water-dominated	>200	high Cl, alkaline	sinter	<5	>100,000	27	160
Mammoth	Water-dominated	73	bicarbonate	travertine	<1	144	9	110
Mud Volcano-Sulphur Caldron	Vapor-dominated	>235	low Cl, acid	none	15	> 38,000	200	335

they are essentially identical to those reported from the Roosevelt, Utah, thermal area by Capuano and Bamford (1978). The background values obtained for Yellowstone soils are somewhat lower than those determined by using the same methods and analytical techniques for soil from the Coso geothermal field, California (D. Phelps, unpub. data, 1978).

In order to determine whether there is any geologic control on the background concentration of mercury in soils, background values were computed for areas underlain by different rock types and for areas inside and outside the Yellowstone caldera (Phelps and Buseck, 1979). No significant variation in the computed background values for these different geologic environments was detected. Most notably, there is no significant difference in the computed background levels of soil Hg for areas inside and outside the Yellowstone caldera.

Results of Detailed Sampling

In order to obtain a thorough understanding of the distribution of mercury in the Yellowstone geothermal systems, four sites were selected for detailed soil sampling on a 50-m grid. These areas are the Norris Geyser Basin, the White Creek area of the Lower Geyser Basin, the Mammoth Hot Springs, and the Mud Volcano-Sulphur Caldron area (Fig. 1). They represent the entire range of types of geothermal activity found at Yellowstone. Their physical and chemical characteristics are summarized in Table 1.

The White Creek area, Lower Geyser Basin

Results of Hg analyses of soil samples collected from the White Creek area are shown in Figure 3. There is an erratic distribution of mercury in the soils, at least at the 50-m scale. Although values up to 100,000 ppb Hg were detected in some soils, there is no smooth transition from background level samples to peak values. Even though most anomalously high values occur within the main cluster of thermal features, there is no apparent correlation between the occurrence of extremely high soil Hg and the presence of an individual thermal feature. Indeed, background levels of mercury occasionally occur in soils collected more than 50 m from a hot spring.

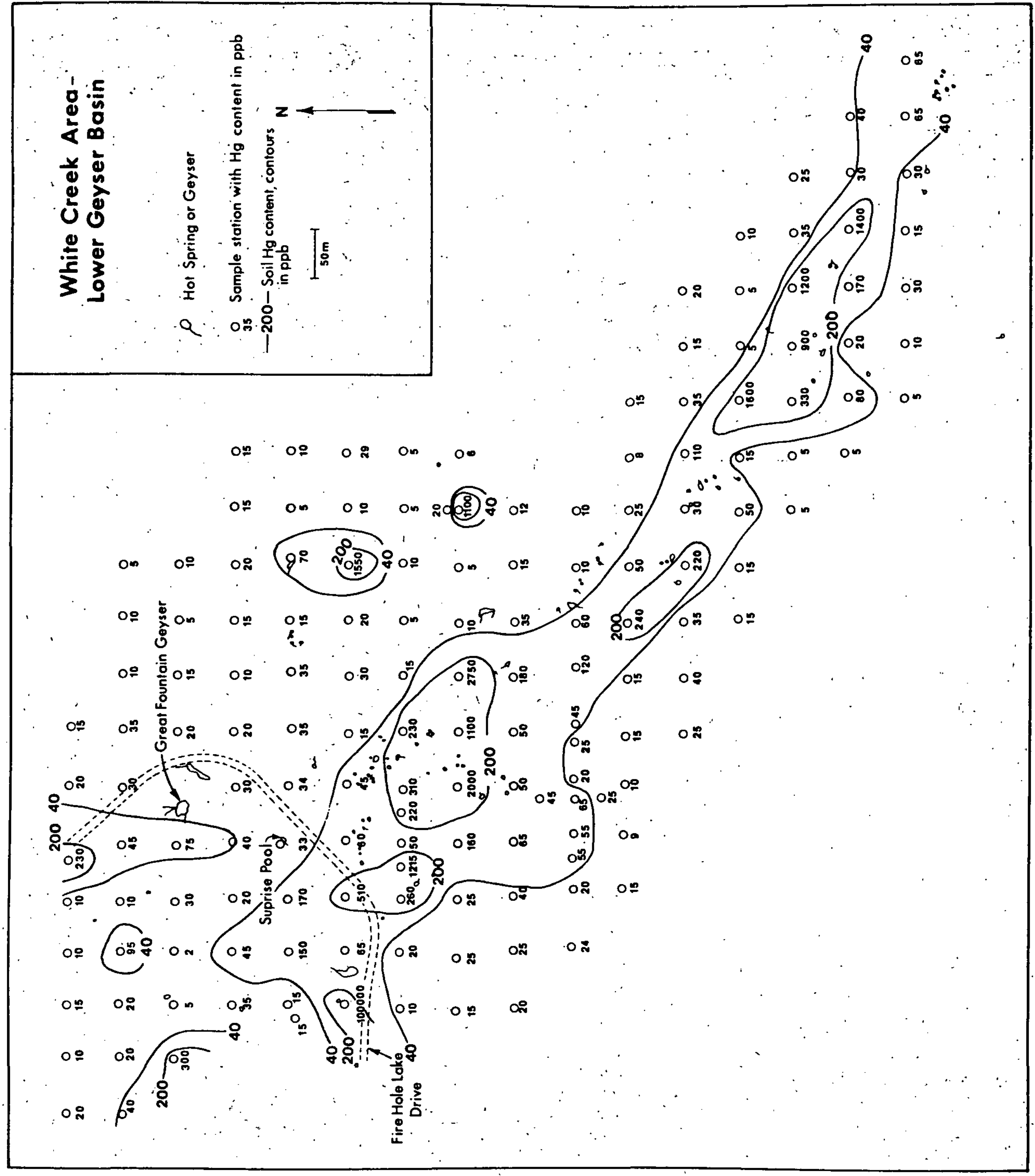
Norris Geyser Basin

Figure 4 shows the results from soil samples collected from the Norris Geyser Basin. There are several areas within the Norris Geyser Basin that are characterized by extremely high contents of soil Hg (>10,000 ppb). These regions are usually defined by at least four or five samples and are surrounded by areas of lower, but still anomalous, levels of soil Hg. Most of the soils sampled in the Norris Geyser Basin contain > 100 ppb Hg, although some areas (again usually defined by several samples) well within the limits of thermal activity contain essentially background levels of soil Hg. Whereas the zones of extremely high soil Hg (>10,000 ppb) are defined by several samples, there is often an abrupt transition to areas with 1,000 ppb soil Hg or less. The transition may occur over distances as short as 50 or 100 m. In addition, there is no direct correlation between the presence of thermal features and the level of soil Hg.

The above observations suggest an overall correlation between the presence of near-surface thermal waters at Norris and the occurrence of anomalously high values of soil Hg, but the observations point to complex controls on the fine scale distribution of mercury within the geyser basin. The nature of these controls will be discussed in a later section of this paper.

Mud Volcano-Sulphur Caldron area

Results of soil sampling from the Mud Volcano-Sulphur Caldron area (Fig. 5) reveal two major, well-defined soil Hg anomalies and several smaller


White Creek Area-
Lower Geyser Basin
Hot Spring or Geyser
Sample station with Hg content in ppb
—200— Soil Hg content, contours in ppb
N
50m
Great Fountain Geyser
Suprise Pool
Fire Hole Lake Drive

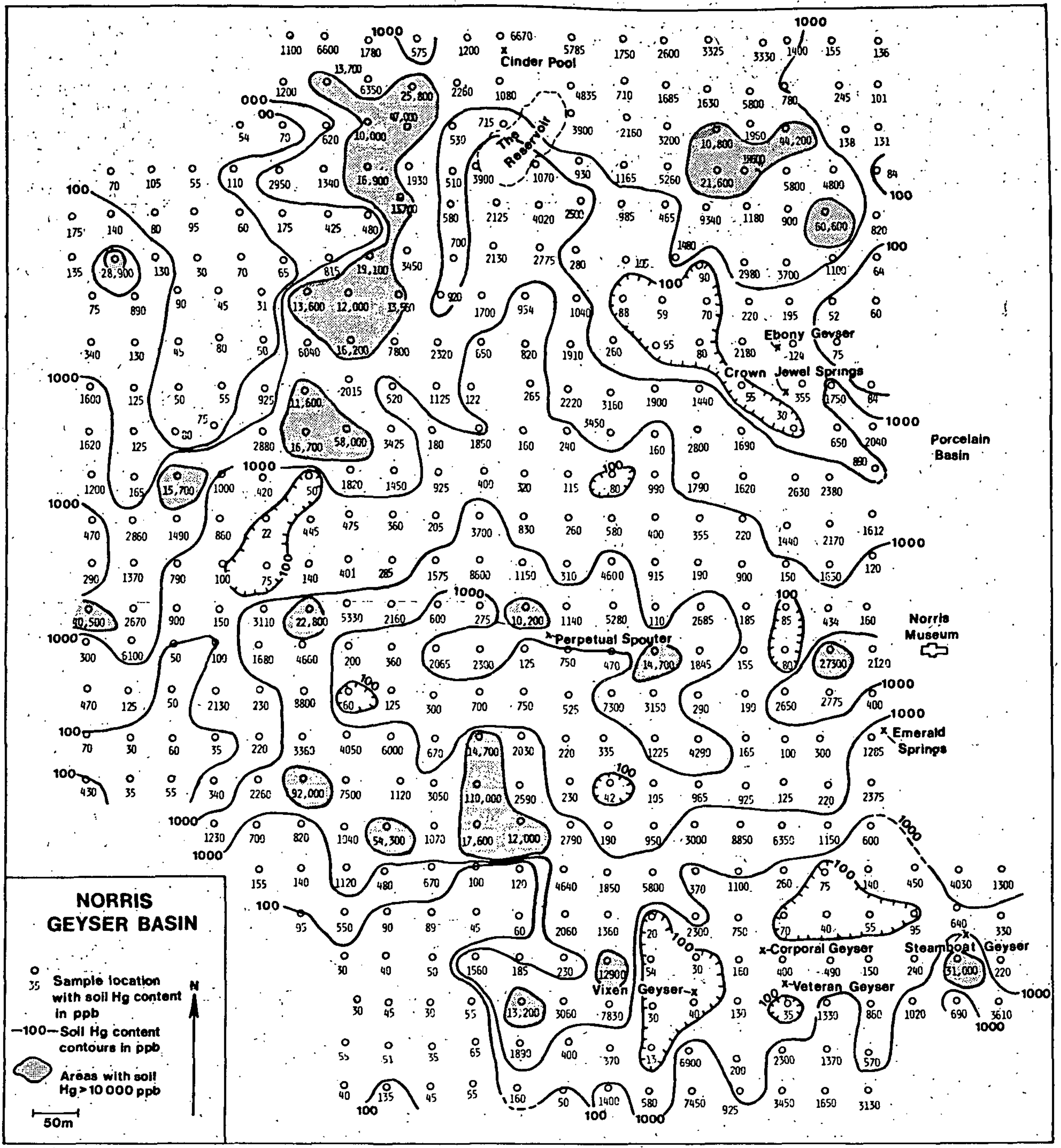


FIG. 4. Sample location map of the Norris Geyser Basin showing the Hg content of soil collected at each sample station and soil Hg contours.

anomalies. The two large anomalies are approximately centered over the Mud Volcano-Dragon's Mouth and Sulphur Caldron vent areas, respectively. The smaller anomalies correspond to areas of less intense activity or to individual vents. The two major anomalies are elongate in a northwest-southeast direction and are parallel to the trend of a fault (Christiansen and Blank, 1972) along which several mud pots and furmaroles are located. It is somewhat surprising that there is no soil Hg anomaly associated

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FIG. 3. Sample location map of the White Creek area of the Lower Geyser Basin showing the Hg content of soil collected at each sample station.

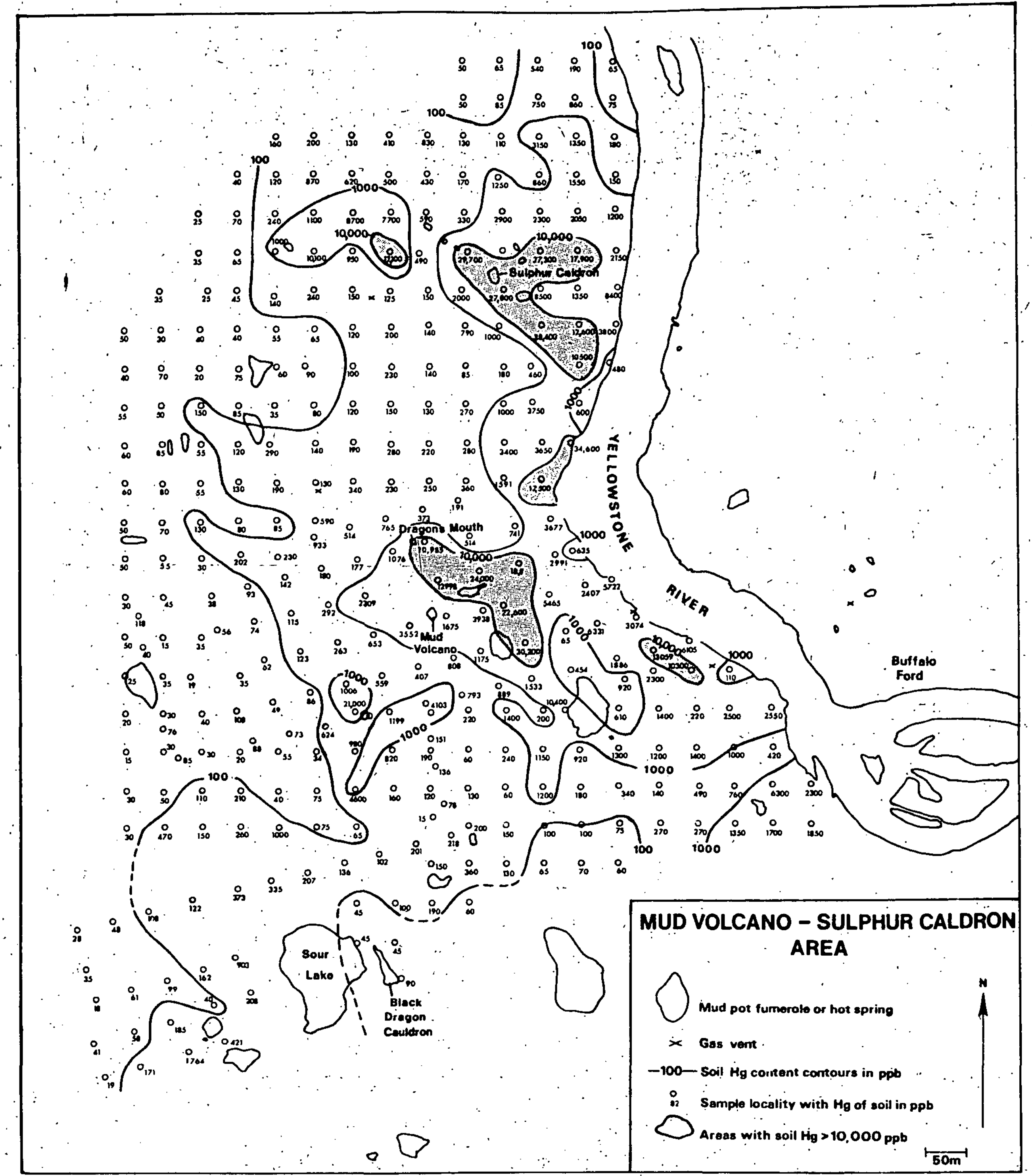

FIG. 5. Sample location map of the Mud Volcano-Sulphur Caldron area showing the Hg content of soil collected at each sample station and soil Hg contours.

with the Black Dragon's Caldron-Sour Lake vents, nor is there a soil Hg anomaly associated with the area of steaming ground west of Sulphur Caldron and north of Dragon's Mouth.

In most cases, the soil Hg concentrations in the Mud Volcano-Sulphur Caldron area show gradational increases from background levels to peak values, form smooth contours, and are considerably less

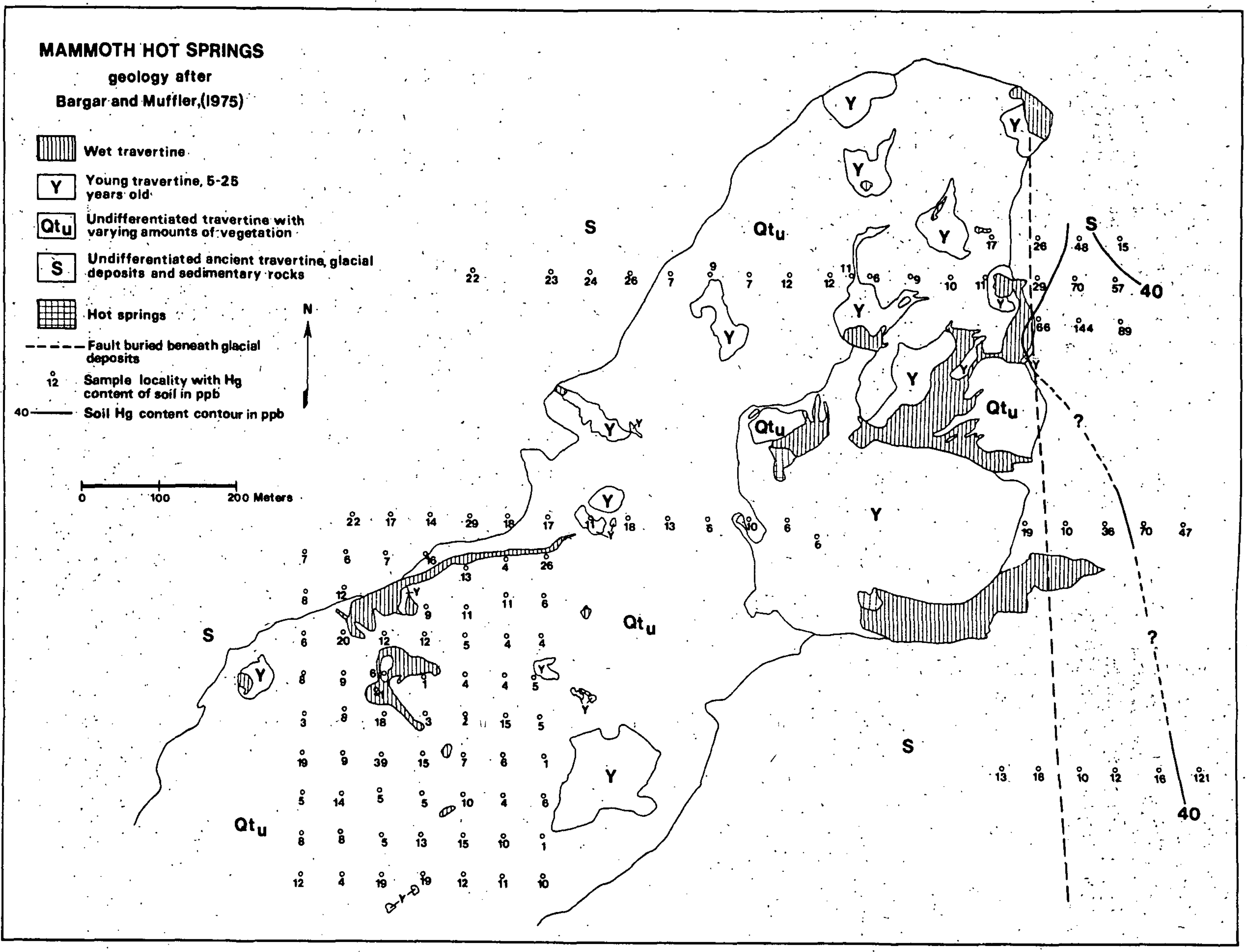

FIG. 6. Sample location map of the Mammoth Hot Springs area showing the Hg content of soil collected at each sample station. Dashed line is the trace of the fault that lies beneath the glacial deposits (Christiansen and Blank, 1972).

erratic than those detected at Norris. The close correlation of soil Hg anomalies with areas of intense vent activity in the Mud Volcano-Sulphur Caldron area suggests an overall relationship between the occurrence of the Hg anomalies and the presence of thermal activity. However, as with the Norris and Lower Geyser Basins, the data from the Mud Volcano-Sulphur Caldron area indicate that the relationship is complex.

Mammoth Hot Springs

The results from the Mammoth Hot Springs area are presented in Figure 6. The most striking observation is that within the hot springs area no soil Hg anomaly was detected. In fact, many of the values obtained from soils rich in travertine debris were considerably below the overall Yellowstone background level of 20 ppb Hg. The only soil Hg anomaly detected in the Mammoth area occurs in glacial debris just to the east of the main hot springs area (Fig. 6). The anomaly is elongate in a north-south direction and parallels the trace of a fault that is buried beneath the glacial deposits (Christiansen and Blank, 1972).

Interpretation of Soil Hg Anomalies in Yellowstone

Water-dominated systems

It is clear that there exists a strong correlation between the presence of near-surface thermal activity and the occurrence of anomalous quantities of soil Hg. However, the complexity of the Hg anomalies detected in the Yellowstone water-dominated geothermal systems indicates that several factors are involved in the distribution of mercury in the thermal areas.

Robertson et al. (1978) have shown that in a high-temperature geothermal system where there is an abundant separation of a vapor phase, the majority of the mercury present in the system will be transported in the vapor phase rather than in the thermal waters. The actual concentrations of mercury in coexisting thermal waters and vapor phase depend upon a number of variables, such as, approach to equilibrium, types and abundance of dissolved constituents in the thermal waters, and pH of the thermal waters. However, the strong partitioning of mercury into the vapor phase detected by Robertson et al. (1978) suggests that the major control is the amount of vapor phase separation from the thermal waters. Such partitioning has a significant effect on the development of soil Hg anomalies in water-dominated geothermal systems.

In the high-temperature, water-dominated geothermal systems of Yellowstone there is abundant evidence of extensive subsurface boiling (White et al., 1975; Truesdell and Fournier, 1976; Truesdell, 1976). Truesdell (1976) suggests that in the Shoshone Geyser Basin subsurface boiling occurs 600 m below ground level where dissolved gases in the thermal waters are partitioned into the vapor phases. These gases then rise to the surface independently of the thermal waters and give rise to a series of fumaroles, gas vents, and acid hot springs near the fringes of the Shoshone Geyser basin. The thermal waters continue their migration to the surface where they form the abundant high SiO_2, alkaline hot springs and geysers of the Shoshone Geyser Basin.

The data of Robertson et al. (1978) indicate that mercury as well as dissolved gases are partitioned into the vapor phase during subsurface boiling, thereby depleting the residual water in both dissolved gases and mercury. Continued boiling as the water migrates upward further depletes the thermal waters in mercury, so that by the time the waters reach the surface to be discharged as hot springs, they are severely depleted in mercury. Therefore, even if there is extensive near-surface boiling, we would not expect to find significant Hg anomalies associated with these hot springs. However, soil Hg anomalies *would develop in the area where the Hg-laden vapor,* segregated during the subsurface boiling event, intersects the surface to form fumaroles and acid hot springs. Depending upon the relative paths followed by the gases separated during subsurface boiling and the thermal waters remaining after vapor phase separation, the resultant soil Hg anomaly could occur in either of two positions relative to the area of discharge of the thermal waters. If both the mercury-bearing vapor and the residual thermal waters follow the same path after subsurface boiling, then the resultant soil Hg anomaly will coincide with the area where the thermal waters are discharged as hot springs. Alternatively, if either the thermal waters or the vapor phase undergo significant lateral flow after vapor phase separation, then the Hg anomaly formed by the escaping Hg-bearing vapors could be separated from the area of discharge of the thermal waters by a considerable distance. Of course, all gradations between these two "end-member" possibilities might be encountered.

The highly irregular patterns of the soil Hg anomalies in the water-dominated systems of Yellowstone reflect the complex interplay of several factors. The interaction of multiple stages of steam separation from thermal waters rising to the surface through the intricate plumbing system inherent to geyser basins could generate the complex soil Hg patterns characteristic of the Yellowstone geyser basins. In addition, differences in the clay mineralogy and the types of organic matter in the soils affect the ability of a soil to take up and retain mercury (Fang, 1978;

Landa, 1978). Although these effects of soil mineralogy and composition are small compared to the size of the Hg anomalies found in thermal areas, combined with other variables they can intensify local complexities.

In the present study, we investigated the distribution of mercury in the high-temperature, water-dominated Norris Geyser Basin and the White Creek area of the Lower Geyser Basin. As would be expected in water-dominated systems that have undergone subsurface boiling, there is little local correlation between the presence of hot springs or geysers and soil Hg anomalies in either area (Figs. 3 and 4). The extremely erratic distribution of soil Hg and the lack of continuous soil Hg anomalies in the White Creek area suggest appreciable lateral movement of either the thermal waters or the Hg-bearing vapor after subsurface boiling. There are, however, coherent soil Hg anomalies within the Norris Geyser Basin. Many of the Hg anomalies at Norris occur near the edges of the geyser basin where fumarolic activity and acid hot springs predominate. The largest continuous soil Hg anomaly in the Norris Geyser basin has a definite north-south trend and suggests control of Hg migration by a north-south fracture. The fact that the soil Hg anomalies at Norris occur close to and in some cases coincident with the major hot springs and geysers indicates that, subsequent to subsurface boiling, the separated gases (containing Hg) and thermal waters migrated to the surface along approximately parallel paths. Truesdell and Fournier (1976) and Fournier (pers. commun., 1979) propose rapid, near-vertical rise of thermal waters in the Norris system, consistent with the near superposition of the soil Hg anomalies and the hot springs and geysers.

The Mammoth Hot Springs are an example of a water-dominated system in which there has been extensive lateral movement of the thermal waters following major phases of steam separation. The Mammoth Hot Springs lie at the northern end of a fault zone that extends northward from the Norris Geyser Basin. Truesdell and Fournier (1976) propose that the Mammoth thermal waters originate in the Norris thermal area and travel northward along the fault zone to Mammoth. Along the way the thermal waters undergo extensive steam loss and dilution with cold meteoric waters, thus strongly depleting the thermal waters in mercury as well as dissolved gases. The lack of a soil Hg anomaly in the Mammoth Hot Springs is consistent with massive steam loss by the Mammoth thermal waters prior to entering the Mammoth area. The weak, north-south-trending Hg anomaly a few hundred meters east of the Mammoth Hot Springs (Fig. 6) is problematic but probably can be attributed to the presence of a north-south fault that is buried beneath glacial deposits (Christiansen and Blank, 1972).

Vapor-dominated systems

In terms of interpretation of soil Hg anomalies, vapor-dominated systems lack many of the complexities of water-dominated systems. In vapor-dominated systems the pressure-controlling medium is vapor, whereas water is present only locally as a minor phase in cracks and pore spaces (White et al., 1971). The abundant vapor is presumably derived from boiling occurring at a deep water table (White et al., 1971) where dissolved gases and mercury are partitioned into the vapor phase. The complications in a water-dominated system, such as subsurface boiling and separation of the vapor phase from the thermal waters, are absent in a vapor-dominated system. In such a system, mercury is transported in the vapor phase; thus the location of soil Hg anomalies is directly related to areas of major discharge (i.e., areas of abundant upwelling of vapor).

The Mud Volcano-Sulphur Caldron area in Yellowstone National Park is a vapor-dominated geothermal system (White et al., 1971, 1975). Geophysical studies (resistivity, self-potential, and induced-polarization surveys) led Zohdy et al. (1973) to propose major steam upwelling in a zone approximately 1.6 km wide extending from just north of Sulphur Caldron to the vicinity of Buffalo Ford. White et al. (1975), on the basis of drill hole data, suggested that Sulphur Caldron represents a major vent area of a vapor-dominated system.

Almost the entire area suggested by Zohdy et al. (1973) to be underlain by a vapor-dominated system contains anomalous quantities of soil Hg (Fig. 5). However, within this broad area of anomalous soil Hg occur several well-defined, narrow Hg anomalies. The two largest coincide with the Mud Volcano-Dragon's Mouth and Sulphur Caldron hot springs, respectively. We interpret the soil Hg data to indicate that the Sulphur Caldron vents and the Mud Volcano-Dragon's Mouth vents are two separate areas of intense upwelling of vapor and probably represent the main vents of the Mud Volcano-Sulphur Caldron vapor-dominated system. Our interpretation is consistent with that of White et al. (1975), who concluded that their drill hole, which was located 100 m north of Sulphur Caldron, only penetrated the margins of the Sulphur Caldron system. The geophysical data of Zohdy et al. (1973) do not have sufficient resolution to differentiate two systems so close together. The lack of significant soil Hg anomalies in places of vigorous vent activity, such as the Black Dragon's Caldron vicinity, is surprising. One possible interpretation is that the Black Dragon's Caldron area lies on the fringes of the vapor-dominated system outside the region of major vapor upwelling. Likewise, the area of steaming ground west of Sulphur Caldron and north of Dragon's Mouth may also lie on the fringe of the system.

Christiansen and Blank (1972) mapped a northwest-striking fault in the Mud Volcano-Sulphur Caldron area. The strong northwest-southeast elongation of the two largest anomalies suggests control by this fault and associated fractures. The smaller anomalies located northwest of Sulphur Caldron and southwest of Mud Volcano are probably extensions of the major anomalies. The strong anomaly located on the west bank of the Yellowstone River may represent another major vent area on one of the northwest-striking fractures; however, most of the anomaly appears to be covered by the Yellowstone River and is thus inaccessible to soil sampling.

Geothermal Exploration

Matlick and Buseck (1976), Klusman and Landress (1978), Phelps and Buseck (1978, 1979), and Capuano and Bamford (1978) have proposed using soil Hg concentrations as an exploration tool for geothermal activity. The procedure, which has the advantage of being fast and relatively inexpensive, is to survey an area for soil Hg concentrations and determine the location of soil Hg anomalies. Capuano and Bamford (1978) reported a good correlation between producing geothermal wells and soil Hg anomalies in the Roosevelt geothermal area, Utah.

Using soil Hg as an exploration technique requires that there be a direct relationship between the presence of thermal activity and excess mercury. Although in a general sense this relationship has been shown to be valid, our study has revealed that the relationship is not a simple one. This is especially true in water-dominated systems where the soil Hg anomalies may be widely separated from the main area of geothermal activity. In such cases use of soil Hg anomalies for drill site selection could be misleading unless used in conjunction with other techniques. On the other hand, our data show that in vapor-dominated systems soil Hg anomalies accurately locate areas of major upwelling and provide valuable information for drill site selection studies.

Matlick and Buseck (1976) suggested that the Hg method could be useful as a reconnaissance technique in determining areas of potential geothermal activity. They reported soil Hg anomalies in Long Valley, California, that are several kilometers in length and breadth, extending well beyond regions of surface thermal activity. These anomalies were easily detected using a 1.6-km sampling grid. In contrast, the Yellowstone soil Hg anomalies are narrow and do not extend for more than one kilometer beyond the fringes of the thermal areas. Thus, in Yellowstone, a 1.6-km sampling grid would be much too large to define the soil Hg anomalies, and the soil Hg technique would not be effective as a regional exploration tool.

It is not clear whether the majority of thermal areas exhibit narrow soil Hg anomalies like those detected at Yellowstone, or broad Hg anomalies like those reported by Matlick and Buseck (1976) from Long Valley, California. Narrow soil Hg anomalies with high peak to background ratios similar to those at Yellowstone were reported from the Roosevelt geothermal area (Capuano and Bamford, 1978). Preliminary data from the Coso Hot Springs area in California (Phelps and Buseck, 1978; D. Phelps, unpub. data, 1978) reveal a broad area, several kilometers wide, containing anomalously high concentrations of soil Hg. However, the limited data from Coso do not form smooth contours, and the apparent broad Hg anomaly may actually represent several smaller, coalescing anomalies. Both the Long Valley and Coso soil Hg anomalies are based on reconnaissance soil sampling using a 1.6-km grid. On the other hand, Klusman and Landress (1978) sampled a 1.6-km^2 area using a 100-m grid in Long Valley, California, within the region sampled by Matlick and Buseck (1976). Klusman and Landress detected several soil Hg anomalies similar in size and magnitude to those detected by us in Yellowstone. These results suggest that the broad Hg anomalies reported by Matlick and Buseck (1976) may also consist of multiple smaller Hg anomalies. Studies are currently in progress in several thermal areas in order to clear up this apparent discrepancy.

Conclusions

Soils in Yellowstone National Park exhibit pronounced Hg anomalies in most thermal areas. Peak to background ratios may be as high as 5,000:1, with background values of 20 ppb Hg. All the soil Hg anomalies detected in Yellowstone are restricted to the immediate vicinity of the thermal areas, even though the peak to background ratios are extremely high. In the water-dominated systems the soil Hg anomalies are complex and do not correlate directly with the occurrence of hot springs or geysers. These characteristics are interpreted to be the result of extensive subsurface boiling, partitioning of the mercury into the vapor phase, and subsequent separation of the vapors from the Hg-depleted thermal waters. In vapor-dominated systems these complexities are absent and the soil Hg anomalies accurately locate areas of steam upwelling.

The correlation of near-surface thermal activity and excess mercury is confirmed in our study. In a general way this relationship is useful for locating geothermal activity. However, because of the complexities of the distribution of mercury, use of soil Hg anomalies for detailed exploration in water-dominated areas must be carried out with caution. In geothermal areas where the Hg anomalies and hot springs do not coincide, it can be concluded that subsurface boiling and separation of the thermal waters and Hg-bearing vapor has occurred. On the other hand, in vapor-dominated systems soil Hg anomalies can be used to delineate accurately the areas of major steam upwelling and thus can provide valuable information for drill site exploration. The narrowness of the soil Hg anomalies in the Yellowstone system limits the effectiveness of the Hg technique as a regional exploration tool in Yellowstone. Data from other geothermal areas are inconclusive and do not provide an unequivocal answer as to whether soil Hg content will be generally useful as a regional exploration tool. However, it is clear from this and other studies that soil Hg is useful on a local scale for geothermal exploration.

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SEDIMENTATION OF ROCKS OF LEONARD (PERMIAN) AGE IN WYOMING AND ADJACENT STATES[1]

R. P. SHELDON[2], E. K. MAUGHAN[3], AND E. R. CRESSMAN[4]

INTRODUCTION

This report is largely based on the regional studies of the north-western United States phosphate deposits initiated by the U. S. Geological Survey, just after World War II, under the direction of V. E. McKelvey. Studies into the genesis of these phosphorites have allowed the formulation of an hypothesis of exploration (McKelvey, 1963; Sheldon, 1964) that has been very useful in discovering new deposits in other places. For example, since 1956 the concept has been used successfully in locating possibly commercial deposits in Peru, Turkey, Saudi Arabia, Australia, India, and Colombia. The hypothesis is far from being exhausted through use, and continued application of it should result in additional discoveries of phosphorgenic provinces.

This report is not an attempt to fully present the exploration hypothesis, but only to present a part of the geologic analysis that went into the hypothesis. Also, this report is not premised on the supposition that all problems of phosphate geology of the Permian rocks of the Rocky Mountains are solved. Much is not understood about the sedimentation of phosphorite and related rocks, and in fact not all geologists specializing in the geology of phosphorite would agree to any or all of these concepts of sedimentation. However, the Kazakov-McKelvey concepts are developed to the fullest in this paper and other concepts are given short shrift, in part because of lack of space and in part because no other concept explains so well so many of the worldwide features of phosphorite and related rock, or for that matter has been so successful in locating new deposits.

Richard P. Sheldon, a native of Tulsa Oklahoma, is currently Chief, Branch of Organic Fuels, U. S. Geological Survey. He received his early training at Yale University where he received a B.S. degree in Geology in 1950. He later enrolled in Stanford University where he was awarded a Ph.D. in 1956. Dr. Sheldon is well known for his detailed investigations of the Phosphoria Formation in western Wyoming and adjacent areas. He has authored or co-authored some 24 papers that deal mainly with the geology and mineral resources of the Phosphoria. He currently resides in Denver, Colorado.

Biographies for E. K. Maughan[3] and E. R. Cressman[4] omitted because of space and time limitations.

STRATIGRAPHIC DATUM

Three maps (figs. 1, 2, and 3) have been prepared for a selected horizon within rocks of Leonard age in the middle Rocky Mountain and northern Great Plains regions, and thus are an attempt to present the sedimentation at a relatively instantaneous point of time during the Leonard Epoch of the Permian Period. The first (fig. 1) is a lithofacies map. The second (fig. 2) is a paleogeographic map showing areas of nondeposition, location of the shore zone, and the distribution of certain submarine features on the shelf and in the geosyncline; also, it shows the direction and type of water currents, and the prevailing wind direction. The third map (fig. 3) shows sedimentation in terms of direction of transport, physical-chemical environments, and grain size and composition of the sediment.

TIME HORIZON.—The approximate time horizon selected is determined wholly on the basis of physical stratigraphy. Paleontologic dating has helped in defining and correlating rocks of Leonard age. However, available faunal data are not sufficient for the resolution of a single time horizon.

The basis for selecting the horizon in the west differs from that in the east. The western half of the area comprises the Cordilleran geosyncline, where transgressions and regressions of facies are believed to have been caused by tectonic movements, and where contacts between lithic units cut across time horizons. In the east, on the other hand, change in type of sedimentation probably was caused largely by epeirogenic move-

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[4] U.S. Geological Survey, Lexington, Kentucky

ments or by eustatic sea-level changes; and here, contacts between the thin lithic units are believed to approximate time horizons.

TIME HORIZON IN WEST.—In Leonard time facies of various types were deposited in the Cordilleran geosyncline (Cressman, 1955; Sheldon, 1957; Cheney, 1957). These facies apparently were determined largely by depth of water; therefore, a real distribution of facies is systematic. From west to east or from deepest to shallowest water, the sequence of principal facies is black mudstone, dark dolomite and phosphorite, chert, limestone, dolomite, and sandstone.

Eastward advance of the sea in Leonard time caused a transgressive overlap of these facies. After the maximum advance, regression produced offlap of the same facies. At any one locality, the time of maximum transgression is represented by the beds deposited in deepest water (Sears and others, 1941, p. 105; Israelsky, 1949, p. 97), and this time is represented on the maps.

The selected horizon lies within various stratigraphic units. In southeastern Idaho, southwestern Montana, part of western Wyoming and northern Utah it is within the Meade Peak Phosphatic Shale Member of the Phosphoria Formation. In northwestern Wyoming it is within the lower member of the Shedhorn Sandstone. In part of central Wyoming and northeastern Utah it is near the middle of the Franson Member of the Park City Formation.

TIME HORIZON IN EAST.—A relatively simple suite of facies was deposited on the shelf in the eastern part of this region during Leonard time. The sediments deposited in the mildly negative eastern area were mainly red mudstone and gypsum, but locally, the rocks include sandstone, dolomite, anhydrite, or halite.

Transgressions and regressions similar to those in the geosynclinal region occurred on the shelf, but the effects were modified by the relative flatness and tectonic stability. Small epeirogenic movements or eustatic sea-level changes probably affected very large areas. Consequently, sedimentary units in this region are thin and widespread and are probably almost time-stratigraphic. Transgressions and regressions in the mildly negative area were not necessarily contemporaneous with transgressions and regressions within the geosyncline.

The stratigraphic horizon in central Wyoming that is correlated with the time of maximum transgression in western Wyoming has been projected into eastern Wyoming and adjacent areas where it is in the lower part of the Opeche Shale. In south-central Wyoming and adjacent parts of Colorado this horizon is believed to be near the top of the Lyons Sandstone to the east of the Rocky Mountains and within the Schoolhouse Sandstone to the west.

FACIES MAP

The facies map (fig. 1) is used to interpret paleogeography and types of sedimentation. Plotting of different rock types or rock suites generally produced a distinctive pattern on the map, except in a few localities where rock types were anomalous; these anomalies were ignored. Several of the facies shown represent rock suites rather than individual rock types. The facies in western Wyoming and adjacent parts of Idaho, Montana, and Utah is a suite of dark pelletal phosphate, mudstone, and dolomite. In the eastern part of the region, rock suites of (1) red mudstone, carbonate rock, anhydrite, and gypsum and (2) red mudstone, halite, and minor amounts of anhydrite, gypsum, and dolomite, are mapped as single facies. Other facies represent widespread, single rock types that are easily classified and delineated.

Localities shown on the facies map are plotted according to their present positions without regard for foreshortening from folding and overthrusting. The environmental maps derived from the facies map may be misleading in the western or geosynclinal part of the region, where much foreshortening has occurred along thrust faults. Any differences from original position, however, probably affect only the distances between boundaries and not the horizontal sequence of facies or of environments interpreted from them.

Four areas of no deposits occur within the region. One is in Montana, extending southward into northern Wyoming; another is in South Dakota; a third corresponds to the ancestral Front Range in north-central Colorado and extends a short distance into Wyoming; and a fourth corresponds to the ancestral Uncompahgre highland in eastern Utah and western Colorado.

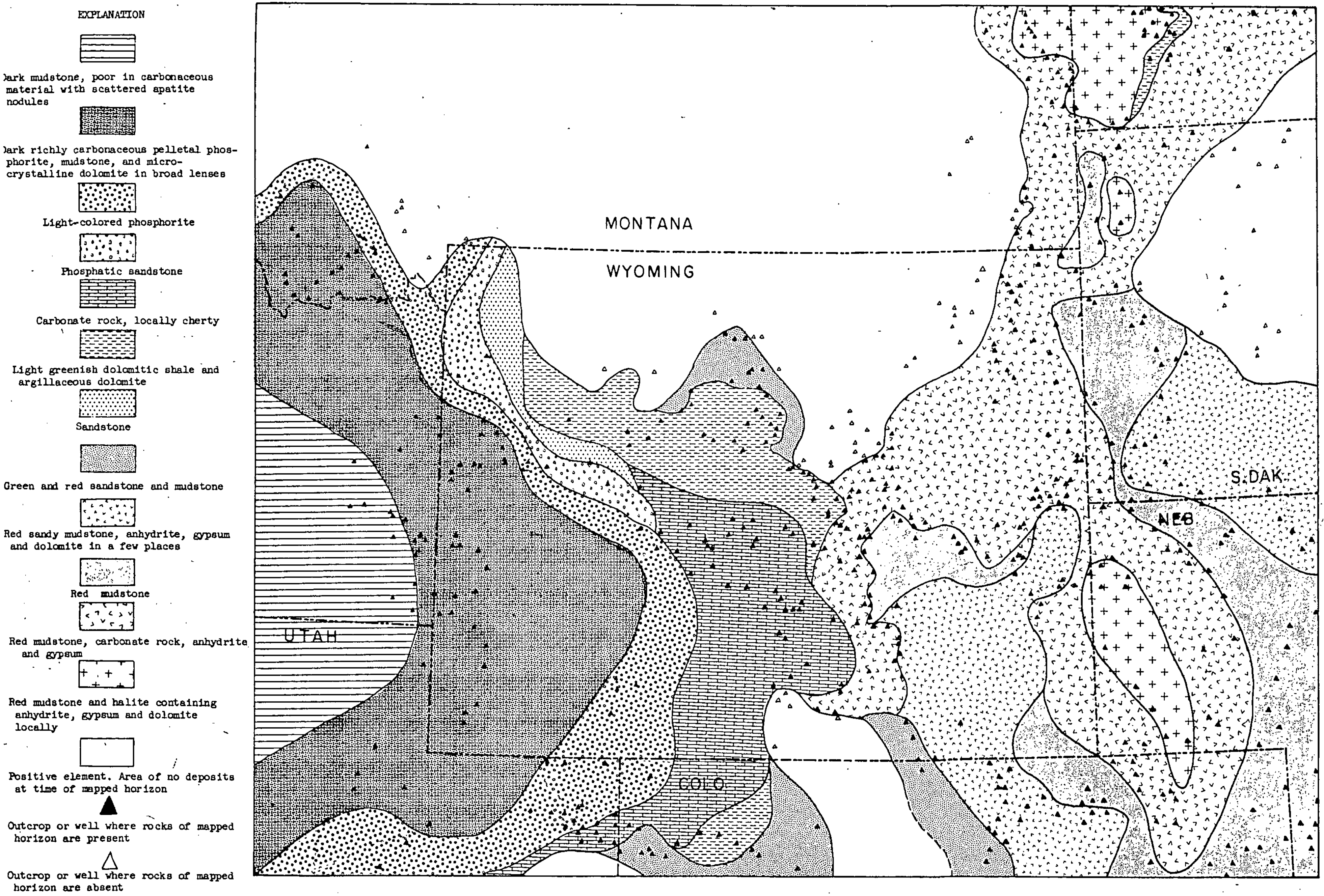


FIGURE 1.—Lithofacies of an horizon of Leonard age.

Areas of no deposits were positive elements throughout Permian time, as strata of interval B thin toward and terminate against them. In most places these positive elements were never covered by Permian sediments, as indicated by the presence of gravel and coarse sand in interval B rocks flanking them. A possible exception is in the northwestern part of the region (Wyoming) where sediments may have been deposited and subsequently removed; here no coarse material was laid down adjacent to the positive element (Sheldon, 1957).

Quartz sandstone occurs at margins of the areas of nondeposition. In northwestern Wyoming the sandstone belongs to the Shedhorn Sandstone. On the west side of the ancestral Front Range highland, in northwestern Colorado, one of these units is a part of the Schoolhouse Sandstone; east of the highland, another is part of the Lyons Sandstone. In other areas the sandstone belongs to heterogeneous units that also contain red mudstone, anhydrite, gypsum, and dolomite.

Clay and quartz mudstone dominate the rock away from areas of no deposits. In the western part of the area the mudstone is dark colored; in the central part, light gray to light greenish gray; and in the eastern part, red.

Red sandy mudstone, part of the Owl Canyon Formation, is distributed widely in southeastern Wyoming and adjacent parts of South Dakota, Nebraska, and Colorado. It intertongues with the Lyons Sandstone westward toward the ancestral Front Range highland.

Chemical sediments are about equal in amount to detrital sediments. Dark phosphorite and dolomite are assgciated with dark mudstone in western Wyoming and adjacent parts of Montana, Idaho, and Utah. The facies composed of these rock types is bounded on the north, east, and south by light-colored phosphorite, in part sandy. The light-colored phosphorite grades eastward into quartz sandstone in northwestern Wyoming, but into light-colored cherty clastic limestone in central Wyoming. Farther east the chemical rocks are anhydrite, gypsum, light-colored dolomite, and halite and are interbedded with red and light-greenish gray mudstone and siltstone. Some minor constituents that are useful in making environmental interpretations are organic matter, pyrite, glauconite, and ferric oxide.

Although chert is abundant in other Permian strata in the region, it is absent at the selected horizon; however, the clastic limestone in south-central Wyoming is cherty. Chert beds at other horizons are mainly in the area where dark mud, dolomite, and phosphate represent the time of maximum Leonard transgression.

Dark dolomite occurs in the western part of the area, and light-colored dolomite occurs in the eastern part. The dolomite facies are finely crystalline and interbedded with mudstone, and they are separated by a northerly trending belt of rock composed of sand-size particles of quartz, on the north, and of calcite, on the south.

PALEOGEOGRAPHIC ENVIRONMENTS

The paleogeography of the area, as interpreted from the facies map, includes (1) the relief and drainage pattern of land areas, (2) the topographic forms of the shore zone, (3) the configuration of marine areas and direction of water currents, and (4) dominant wind direction.

LAND AREAS.—Land areas roughly coincide with areas of no deposits on the facies map. Sandstone surrounding the land areas generally supports this interpretation, but locally sediments may have been deposited on the areas shown as land at this selected time and later stripped off. Also, sandstone fringing the areas of erosion locally is terrestrial.

The land probably was low. Detrital sedimentation in the adjoining basins was bout the same in amount as chemical sedimentation, which would not have occurred if much detritus were supplied by high land. Later in Permian and in Triassic time few features of relief were encountered as the sea widely transgressed across these land areas.

Direct evidence of drainage basins on the land is absent, but areas of detritus in southeastern Wyoming, southwestern South Dakota, and north-central Colorado may indicate the positions of stream mouths. The stream channels probably were small, relatively closely spaced, and formed many coalescing deltas.

Shore-zones are inferred in several places. In north-central Colorado and southeastern Wy-

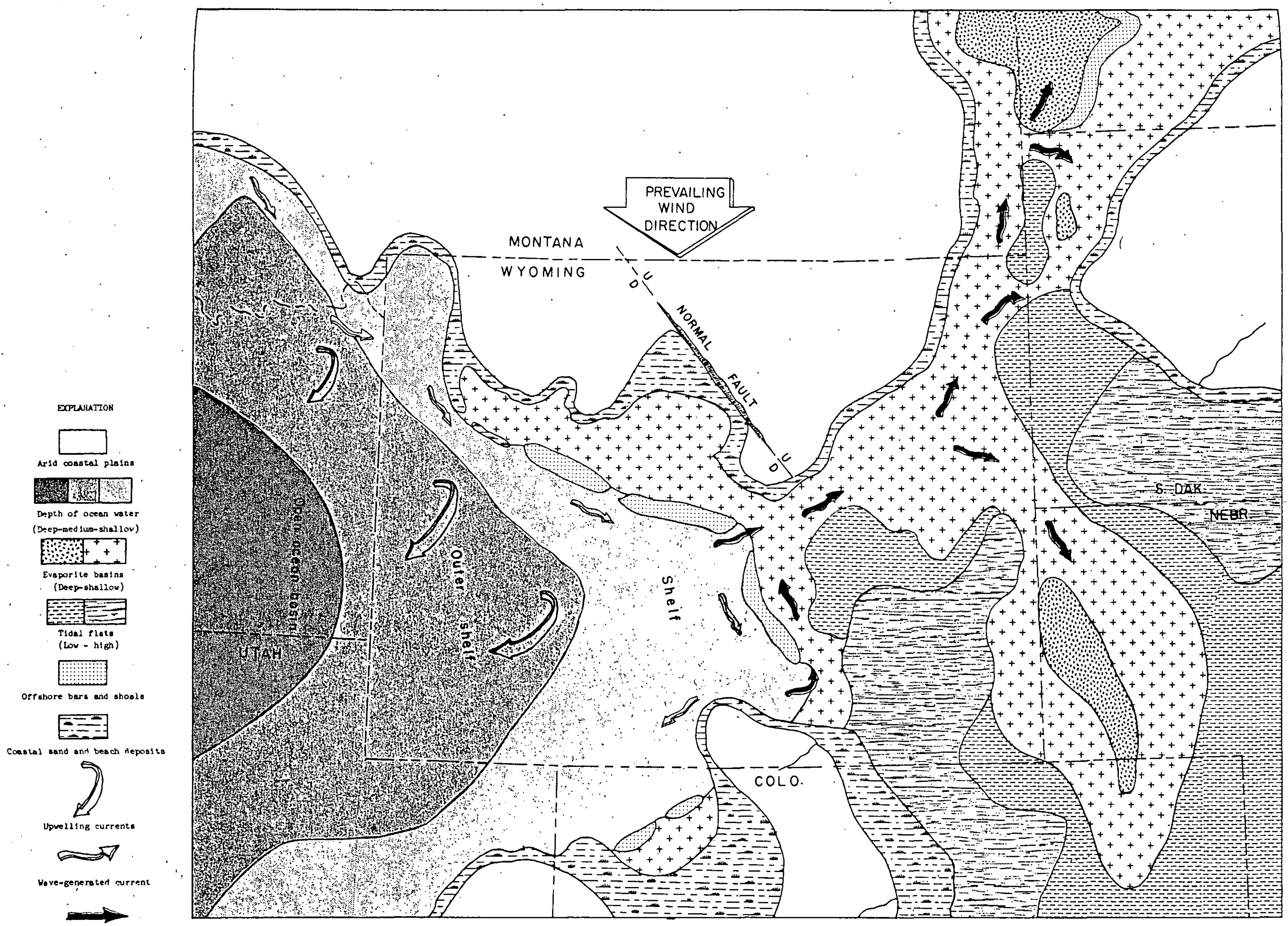


FIGURE 2.—Paleogeography of an horizon of Leonard age.

oming, crossbedded sandstone considered eolian lies adjacent to water-laid rocks. In northwestern Wyoming, elongate bodies of sandstone extend southward from the land areas. These sandstone bodies, and similar units at other horizons in the Permian, grade eastward into mudstone and westward into phosphorite or chert, and extend as much as 100 miles southward. They are probably remnants of barrier islands and offshore bars trending southward from the land areas, although sedimentary structure in these sandstone units has not been studied adequately to furnish conclusive evidence.

In north-central Wyoming a Permian(?) fault scarp is inferred, approximately coincident with the present Big Horn Mountains. The fault possibly was active about the time of the maximum eastward transgression of Leonard time. Rocks of Leonard age thin and terminate northward along the Big Horn Mountains, but extend 50 miles farther north on the west side than on the east. Thicknesses and facies of these rocks are similar on both sides of the mountains, except locally where strata in the lower half are thicker and coarser-grained adjacent to the west flank. These data suggest that the eastern block was higher than the western.

WATER AREAS.—The Phosphoria sea, an eastward extension of the ocean that occupied the Cordilleran geosyncline in Permian time, formed an open bay in western Wyoming. A large but restricted sea covered most of the region in eastern Wyoming. These two bodies of water were connected by a strait in central Wyoming, which separated the Montana and Colorado land areas.

The embayment in western Wyoming was bounded by land in Montana and by the ancestral Uncompahgre and Front Range highlands to the south. The western limit of the ocean is unknown, but may have been bordered by a volcanic island arc in western Idaho, Oregon, and Nevada.

A positive area or platform may possibly have lain not far west of the area mapped. In southwestern Montana a western source of sand (Cressman, 1955), inferred for other horizons in the Permian section, may also have been effective during Leonard time. Furthermore, in Montana, the facies boundaries of the mapped horizon (fig. 1) swing southward. In northeastern Nevada and northwestern Utah, facies boundaries of rocks of Leonard age swing northward, suggesting a western submarine high or sill.

Relative depths of the ocean can be inferred from the sediments. The deepest part, within the open-ocean basin, was in southeastern Idaho and adjacent Utah and Nevada, and was clearly below normal open-ocean wave base. Rocks in that area consist of thinly laminated, dark mudstone and rare nodules of apatite.

Flanking the deep basin to the east and south was an area of somewhat shallower water overlying the outer shelf. The rocks believed to have formed in the shallower water are thin, richly carbonaceous, pelletal phosphorite; microcrystalline dolomite; and mudstone. Some of the strata are laminated and others are thin- to thick-bedded. Sediments consisting of apatite pellets had the finest fraction of clay and quartz winnowed off. The ocean floor in this area probably was fairly deep but somewhat above wave base.

East and south of the outer shelf was a shallow marine area of the inner shelf. The rocks formed there include quartz sandstone, oolitic and skeletal phosphorite, and bioclastic limestone. All of these rocks were formed from well washed sand-size sediments and were deposited well above normal wave base. East of the inner shelf, a red and light greenish gray mudstone facies occurs and is interpreted as having formed in very shallow water. The boundary between sand-size sediments and muds is not established. The boundary between similar sediments, at a horizon near the top of the Permian, has been interpreted by Campbell (1956) and H. F. Murray (oral commun., 1958) as a Bahama-bank type of offshore, carbonate sand bar, behind which lay a lagoon partly filled with mud. This interpretation is adopted here. Thus, the eastern edge of the Phosphoria sea is shown as a string of barrier islands and offshore bars crossing the strait between the two land areas. Features of the eastern boundary of the open ocean in both the northern and southern parts of the area seem to indicate normal shore zones of the edge of land.

A large body of water partially cut off from the open sea extended eastward from central Wyoming into the Williston basin to the northeast and into the Julesburg basin to the southeast. This water body connected westward with the Phosphoria sea and was bordered on the east by the Siouxia land area, on the northwest by the land area in Montana, and on the southwest by the ancestral Front Range highland. Its northeastern limit probably extended northward from Siouxia and eastward from the land area in central Montana. Presence of this land connection is inferred as no Permian rocks are preserved in the northern part of the Williston basin. The southeastern limit was a positive element extending northeastward along the Las Animas arch.

Sediments deposited in this restricted body of water indicate that depth was relatively uniform and shallow. Detrital components are thinly stratified, widely distributed, and relatively homogeneous; this suggests deposition within the zone of wave-current and tidal action. The shallow depths varied slightly from place to place and areas of shoals, lagoons, deltas, and evaporite basins are evident or suggested by the rocks.

Detritus within the eastern part of the region probably was distributed by waves and currents, and deposited in extensive tidal flats adjacent to the ancestral Front Range highland on the west and Siouxia on the east. These tidal flats consist chiefly of sandstone and mudstone in the west, but only of mudstone in the east. The two facies probably formed in the littoral zone and in an adjacent neritic or shoal zone, respectively, and are differentiated herein as high and low tidal flats. Periodically the high tidal flats were slightly submerged. Mud, winnowed from the detritus, was carried farther into the basin and deposited in low tidal flats that were generally slightly submerged, but periodically may have been emergent.

Mud, interstratified with evaporite, was deposited in continuously submerged lagoons at the margins of the Phosphoria sea and of the restricted waters to the east. Water probably was relatively shallow in most places, but the evaporite basins may have been slightly deeper.

Within the eastern area were three evaporite basins. The most northerly and largest was approximately coincident with the Williston basin in western North Dakota. Another smaller basin was in northwestern South Dakota, and the most southerly basin was in western Nebraska. Halite and anhydrite are interstratified with the mudstone. Elsewhere in this area, mudstone is interstratified chiefly with gypsum and dolomite.

WATER CURRENTS.—Water currents in marine areas probably included upwelling ocean currents on the outer shelf, wave-generated currents on the inner shelf, channel currents in the restricted waters, and a net flow of water into the evaporite basins.

Evidence of upwelling ocean currents over the outer shelf is indirect. The necessity for invoking upwelling currents is shown by McKelvey (McKelvey, Swanson, and Sheldon, 1953) who has applied results of studies by Kazakov (1937, p. 111; 1938) and Brongersma-Sanders (1948) to Permian phosphorites. The main argument is that the amount of phosphate in the Phosphoria Formation is more than five times greater than that in the sea today, so that the Phosphoria sea must have drawn on the resources of a major part of the ocean by circulation over a long time. Furthermore, oceanographic conditions for apatite deposition, in terms of phosphate supply and physical-chemical environment, are met in areas of upwelling where recent phosphorites occur almost exclusively. The area of inferred upwelling is shown on figure 2 by curved arrows.

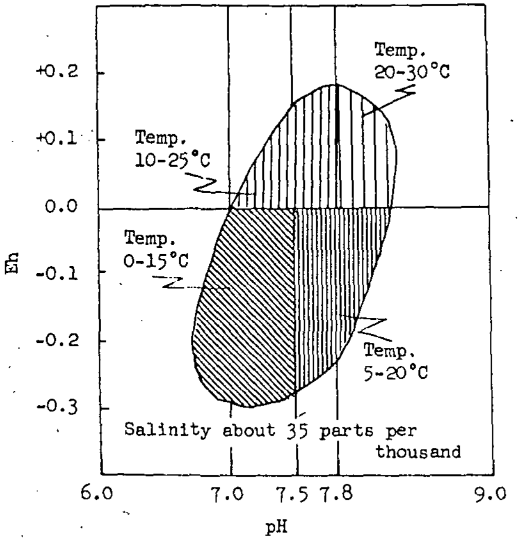
Wave-generated currents with southerly movement are shown along the inner shelf on figure 2. Evidence for these currents are the elongate sandstone bodies extending southward from the west side of the land area in Montana. One of these sandstone bodies is shown on figure 1. Further evidence for south-flowing currents is the fact that no sand was carried northward along the inner shelf from the land in the southern part of the area even though sand was being shed from this area.

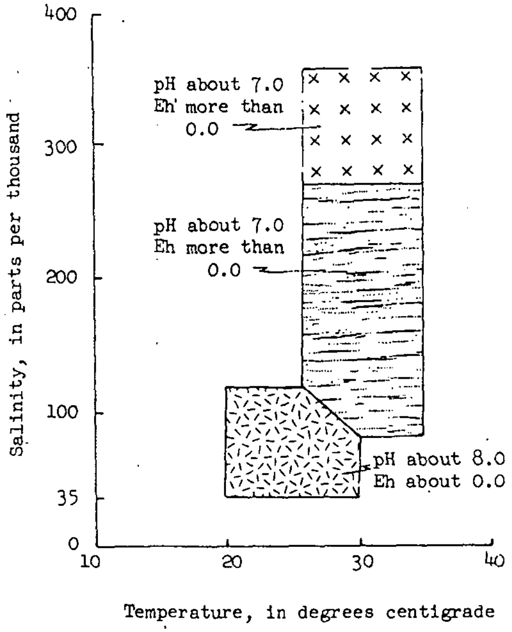
Tides probably gave rise to channel currents in the area of restricted water to the east. Such currents would have had a profound effect on the sediments within this eastern area, and they seem necessary to account for the widespread laminated and homogeneous sandstone and mudstone strata deposited here.

Evaporation of water, indicated by precipitation of salts in the lagoons and evaporite basins, resulted in greater inflowing than outflowing currents. The net current resulting from this disparity is indicated by arrows on figure 2. Detrital

EXPLANATION FOR FIGURE 3

Physical-chemical relations in depositional environment





Bottom sediment composition

1 Carbonaceous quartz and clay mud; minor apatite
2 Carbonaceous dolomite, quartz, and clay mud, and pelletal apatite sand; minor pyrite.
3 Pelletal, oolitic and skeletal apatite sand, quartz sand, and modern glauconite sand; locally conglomeratic; little carbonaceous matter
4 Skeletal-calcite and skeletal-silica sand; minor glauconite sand
5 Dolomite, quartz, and clay mud; minor ferrous silicate mud
6 Quartz sand and clay, quartz, and dolomite mud; minor ferric oxide and ferrous silicate mud
7 Quartz and clay mud and quartz mud; minor calcium sulfate, dolomite, and ferric oxide mud
8 Clay, quartz, and calcium sulfate mud; minor quartz sand and ferric oxide mud
9 Clay, quartz, calcium sulfate, and dolomite mud; minor ferric oxide mud and quartz sand
10 Clay, quartz, halite, and calcite sulfate mud; minor dolomite and ferric oxide mud
11 Dolomite and calcium sulfate and some quartz and clay mud; minor ferric oxide mud
12 Quartz sand

Direction of sediment transport

⇒ Sand-size particles
→ Mud particles
- - -→ Organically generated debris

▭ Approximate boundary between bottom sediments of different composition
▭ Shore and near-shore deposits; mostly quartz sand; some quartz and clay mud
▭ Land

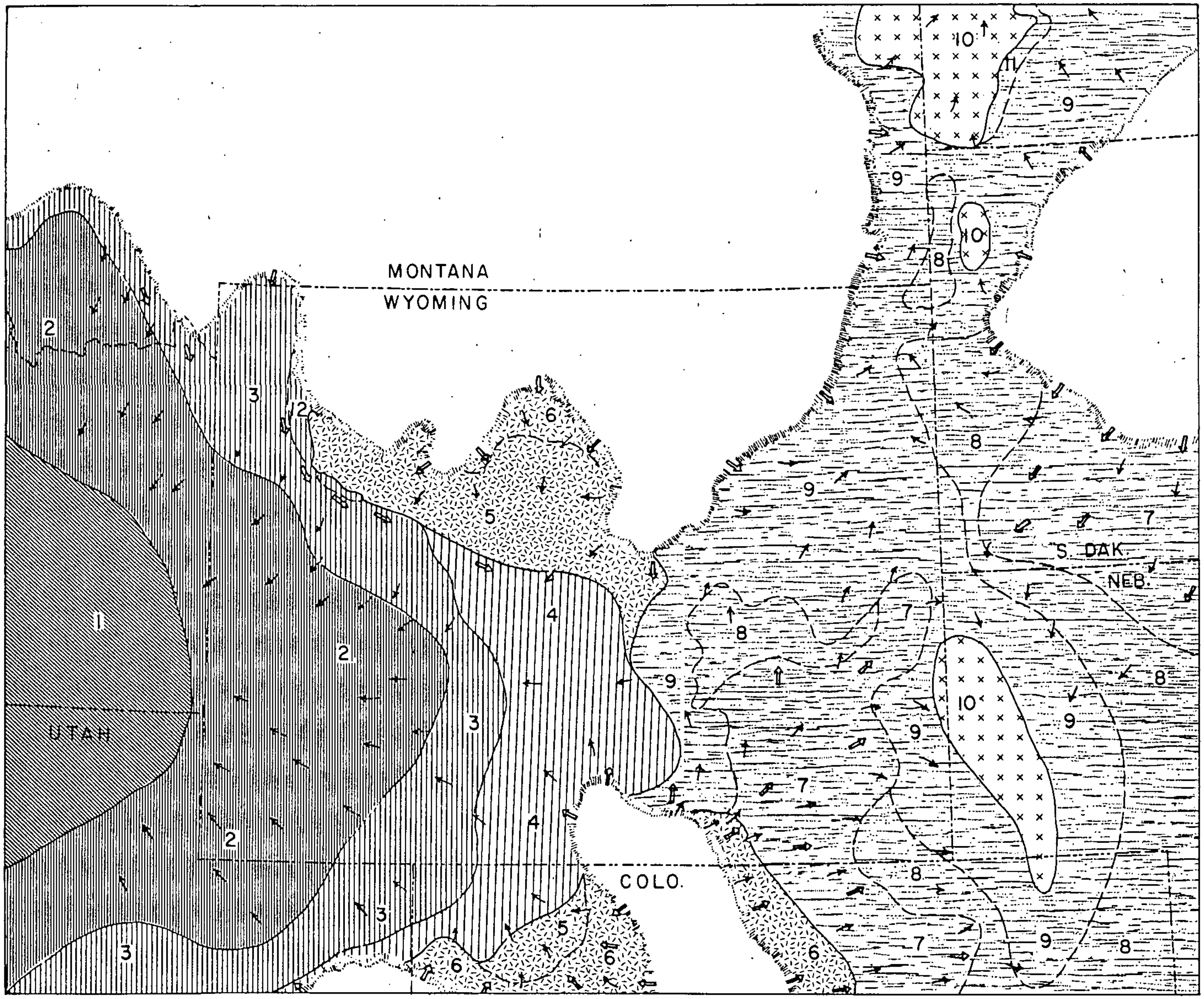


FIGURE 3.—Sedimentation of an horizon of Leonard age.

particles would have a net drift in the direction of the arrows because of this current.

Wind direction.—The prevailing wind direction at the time of maximum Leonard transgression is considered to have been approximately south.

The strongest evidence of eolian deposition is the large-scale, wedge-type crossbedding in the Lyons Sandstone in southeastern Wyoming and northeastern Colorado. Statistical studies of crossbeds in this formation at several places in the northern Front Range indicate that prevailing wind directions were from nearly due north (R. F. Wilson, oral commun.; E. K. Maughan, unpublished). A similar prevailing wind direction is indicated by studies of the Schoolhouse Sandstone in northwestern Colorado (F. G. Poole, oral commun.). Also, studies of crossbedded rocks, believed to be wind-deposited in the nearby Colorado Plateau, indicate that prevailing winds there persistently came from the north in late Paleozoic and early Mesozoic time (Poole, 1957, p. 1870).

Additional evidence of wind direction comes from the probable water current direction. One of the conditions of upwelling in the northern hemisphere on the west side of land areas is that the surface-water currents have a southerly component; otherwise, the Coriolis force would work against the upwelling. Thus, the concept of upwelling is consistent with southward wind direction. South-flowing, wave-generated currents are also consistent with this wind direction. Finally volcanic ash from the western volcanic terrane is only locally preserved within Permian sediments in this area, indicating that west winds were rare.

Climate.—Climate of the region during Leonard time probably was arid. Evaporation exceeded supply in the eastern restricted waters, resulting in deposition of anhydrite or gypsum, and halite. In modern coastal areas adjacent to areas of upwelling, aridity is characteristic (Brongersma-Sanders, 1948, p. 23).

PHYSICAL AND CHEMICAL ENVIRONMENTS

Aspects of various environments during sedimentation are interpreted on figure 3. Grain size and composition of the sediment are shown by numbers. Direction of sediment transport is shown by arrows for the mud, sand, and organic debris fractions. Inferred physical-chemical environments of deposition are shown in terms of pH, Eh, temperature, and salinity.

Detrital sediments.—The detrital sediments are composed mainly of quartz and clay, and are classified on the map into sand- and mud-size grains. Quartz sand entering the Phosphoria sea was not transported far from shore, except south of the land area in Montana where spits and barrier islands were built by longshore wave-generated currents. Sand from land areas in Colorado and South Dakota was transported, probably by currents, and deposited on tidal flats in the restricted water body in the east. Additional sand was deposited along the shore and, at least in southern Wyoming and northern Colorado, formed dunes.

Mud also was carried into the restricted water body and deposited over most of the sea floor in relatively quiet water; some was carried westward through the shoal area in central Wyoming. This mud, mixing with other mud coming directly from the adjacent land areas, apparently bypassed the inner shelf, which was above wave base, and was deposited in thin beds, partly on the outer shelf but mostly in the western ocean basin.

Chemical sediments.—All of the chemical sediments were normal products from sea water. In the open ocean in the western part, apatite, silica, calcite, and organic matter were deposited. Dark richly carbonaceous dolomite may not have been deposited directly from the ocean but may have replaced calcium carbonate penecontemporaneously. The silica probably formed from accumulations of sponge spicules. In the restricted eastern waters dolomite, calcite, anhydrite or gypsum, and halite were deposited. Ferric oxides of unknown origin are also present.

Deposition of this wide suite of chemical sediments requires that the water pass through a number of chemical changes. Physical-chemical parameters controlling apatite stability have been studied by Kazakov (1937). Parameters controlling the stability of many of the other minerals have been summarized by Krumbein and

Garrels (1952). McKelvey and others (1953) and Sheldon (1957) have applied these concepts to the Permian rocks of the Middle Rocky Mountains. The spatial relations of inferred chemical environments for the time plane represented on figures 1 and 2, are shown on figure 3.

In the normal marine environments in the western part, the stability of the chemical sediments was controlled mainly by pH and Eh; the inferred pH and Eh fields are shown by pattern on figure 3. On the other hand, in the restricted eastern waters temperature and salinity were more significant and these also are shown by pattern. In the following discussion, the physical-chemical environment of deposition in each area is discussed, from the open-ocean basin on the west to the evaporite basins on the east.

Rock from what was the open-ocean basin in the west contains pyrite, organic matter, and rare nodules of apatite. The pyrite and organic matter indicate that the depositional and early diagenetic environment was reducing ($Eh<O$). In addition, the environment probably was mildly acid to mildly alkaline (pH near 7.0). This is indicated by the paucity of carbonate minerals, which are unstable below pH about 7.8 (Krumbein and Garrles, 1952). The scarcity of apatite also indicates relatively low pH (Kazakov, 1937). In places pH less than 7.0 is indicated by uraniferous black shale within the Meade Peak (Sheldon, 1959, p. 109-111). Chemical sedimentation was very slow in the open basin, and was mainly organic matter. It is likely that abundant phytoplankton resulting from upwelling ocean currents were the chief source of the organic matter in the sediments (McKelvey and others, 1953, p. 59-60). Temperature of the depositional environment in the open-ocean basin was probably close to the temperatures of 0-15° C found today in deeper ocean waters (Sverdrup and others, 1942, fig. 209, p. 741). Salinity probably was normal.

On the outer shelf, east of the open-ocean basin, the water was somewhat shallower and different sediments were deposited. Dark organic mudstone, pelletal phosphorite, and dolomite are interbedded and probably intertongue laterally. Chemical environments probably were gradational between the open-ocean basin and the outer shelf, as dark mudstone is in both areas. However, the abundance of dark phosphorite and dolomite indicate that on the outer shelf the pH was higher than in the basin. It is presumed that alkalinity fluctuated near pH 7.8, because phosphorite indicates pH smaller and dolomite indicates pH greater than 7.8. Negative Eh is indicated by the abundant organic matter and by pyrite.

The deposition of phosphorite may have been due to warming of upwelling phosphate-rich water near the surface to between 5° and 20° C, and a consequent rise of pH (Kazakov, 1937; McKelvey and others, 1953). As in the open ocean, deposition of organic matter was also a result of the upwelling. The deposition of carbonate sediment, now dolomite, is an enigma. The resulting rock is microcrystalline with a mosaic texture; petrography gives no clue to its origin. Some foraminifera replaced by apatite have been reported from dark pelletal phosphorite (Emigh, 1958; E. L. Yochelson, personal commun., 1960), and it is possible that penecontemporaneous dolomitization of foraminiferal deposits accounts for the dark dolomite. In any case, the pH apparently was fairly high so that the carbonate sediment was stable. Salinity of the waters on the outer shelf probably was normal.

The inner shelf lies east of the outer shelf. Apatite and quartz sand accumulated over most of the inner shelf, but in the southeast siliceous calcite sand was deposited. The apatite is composed of oolites, light-colored pellets, and bioclastic grains, including fragments of brachiopods, fish scales and bone, sharks' teeth, and internal molds of gastropods. Glauconite as internal molds of fossils are common accessory grains. The depositional environment seems to have been oxidizing ($Eh>O$), as shown by the absence of organic matter and the presence of remains of benthonic oxygen-consuming animals. The pH was only mildly alkaline, as shown by the scarcity of carbonate rock and the abundance of apatite.

Across the southeastern part of the shelf calcium carbonate was deposited, mostly as fragments of benthonic invertebrate fossils. Thus, the depositional environment was oxidizing and moderately alkaline, or Eh greater than O and pH greater than about 7.8. Some of the limestone is cherty, and most likely the silica originated from siliceous sponge spicules similar to those at a higher horizon in the northern Wind River Mountains (Finks and others, 1961). Temperatures were higher than to the west, probably within the range of 20-30° C. Salinity was probably normal.

The lagoons were adjacent to the positive elements and probably separated from the inner shelf by islands and bars. Rock formed in them is mostly mudstone. Red and green mudstone are interstratified. Near the shore, the mudstone is colored predominantly red by ferric oxide. Away from the shore, it is predominantly green from ferrous compounds. Lack of organic matter indicates that the environment was unfavorable for its development or preservation in the lagoon.

The carbonate rocks in this area indicate pH greater than 7.8± and on figure 3, alkalinity is arbitrarily indicated as $pH > 8.0$. Eh is believed to have been about 0 on the basis of interfingering of strata containing ferric and ferrous compounds, and the lack of organic matter. Ferrous iron is precipitated in an environment of Eh less than -0.1 volt where pH exceeds 7.8± (Krumbein and Garrels, 1952, fig. 8). On the other hand, salinity, discussed below, seemingly was not high enough to limit organic development and it is assumed that a small amount of organic matter was produced but was oxidized and not preserved. The Eh, therefore, would seem to have been greater than 0. These apparently contradictory values of Eh probably are the result of fluctuating conditions between an oxidizing and reducing environment and, without further study and information, permits only an approximation that Eh 0. Temperature of 20° to 30° C, and salinity of 35 to 125 parts per thousand are suggested by the evaporite rocks.

Sediments believed to be those of tidal flats formed within the depositional basin east of the strait in central Wyoming. One of these flats extended northward and eastward from the northern part of the ancestral Rocky Mountain uplift. Another extended westward from the Siouxia positive element. The rocks are mostly red sandstone and mudstone. The rare chemical sedimentary rocks are primarily dolomite and gypsum or anhydrite.

The carbonate and sulfate rocks indicate a relatively warm, super-saline environment. Temperature is assumed to have ranged from 25° to 35° C, and salinity necessary for precipitation of these rocks is believed to have ranged from 75 to 275 parts per thousand.

The lack of organic material indicates Eh greater than 0. No data are available for minerals which might define the pH in which these sediments were deposited. The explanation for figure 3, indicates pH 7.0, but the natural range of evaporite rocks extends from as low as $pH = 2.6$ to as high as $pH = 10.48$ (Baas-Becking and others, 1960, p. 260-261).

The evaporite basin covered most of the eastern part of this region, except for the sand and mud flats. The evaporite basin is divided into a central part and an outer part, according to the minerals formed in each. Halite and related evaporite rocks formed in the central part; gypsum or anhydrite and related evaporite rocks formed in the outer part; red mudstone is common in both parts. The evaporite basin had three centers, indicated on figure 3, in which halite was formed.

The rocks formed in the outer part of the evaporite basin are similar to those formed in the inferred tidal flats. Evaporite rocks, however, predominate over detrital rocks in the basin. The physical-chemical parameters in the outer part of the evaporite basin are believed to have been similar to those on the flat: temperature 25° to 35° C, salinity 125 to 275 parts per thousand, $Eh > 0$, and pH 7.0.

The central part of the evaporite basin differed significantly only in salinity. Halite, which precipitates from sea water concentrated to about one-tenth of its original volume (J. Usiglio, quoted in Clarke, 1924, p. 221), is believed to have precipitated in this area from water with salinity ranging from about 275 to 350 parts per thousand. Temperature is believed to have been warm and a range of 25° to 35° C is inferred. Lack of organic matter indicates Eh greater than 0, and pH is not indicated by any sediments for the reasons discussed above.

CONCLUSIONS

The maps and data presented here seem to indicate that the relations between Permian sediments formed in western Wyoming and those formed in markedly different environments in eastern Wyoming were similar to present day relations along several continental margins where cold, upwelling waters, rich in nutrients and organic matter, are areas of phosphate deposition west of arid continental regions (Brongersma-Sanders, 1948). The great similarity between areas of Permian and modern phosphate deposits and related arid environments adds evidence and seems to justify the interpretations presented here. These interpretations, however, are subject to correction and refinement as the rocks are studied further, as knowledge of geochemistry advances understanding of depositional environments, and as further knowledge enables distinction between primary and diagenetic origin of the rocks.

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RESTORATION OF GROUNDWATER QUALITY FOLLOWING PILOT-SCALE ACIDIC IN SITU URANIUM LEACHING AT NINE-MILE LAKE SITE NEAR CASPER, WYOMING

by William H. Engelmann, P. E. Phillips, Daryl R. Tweeton,
Kent W. Loest, and Michael T. Nigbor

* * * * * * * * * * * * * * * * * * * outside presentation

To be presented before the Environmental Uranium Symposium at the Annual Meeting of the Geological Society of America, November 5-8, 1979, San Diego, Calif., and published in the Proceedings

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RESTORATION OF GROUNDWATER QUALITY FOLLOWING PILOT-SCALE ACIDIC IN SITU URANIUM LEACHING AT NINE-MILE LAKE SITE NEAR CASPER, WYOMING

by

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ABSTRACT

The results of a pilot-scale leach and restoration test, which is the subject of a cooperative agreement between the Bureau of Mines and a joint venture consisting of the following companies: Rocky Mountain Energy, Mono Power, and Halliburton, is described. The leaching phase is briefly described, since this aspect of the test was the subject of a previous Bureau paper. Leaching was done with H_2SO_4 (pH range of 1.6-3.9) and H_2O_2 (250-3000 ppm of 35% H_2O_2) over an 11-month period.

The restoration phase began November 1978 and was completed in about 8 months. Water samples were taken from observation wells located between injection and production wells as the leach solution was decreased in strength. Groundwater quality in the leached ore zone was restored by injecting clean groundwater. This was supplemented by clean water produced from recovered solution, by a combination of chemical precipitation and reverse osmosis. In situ measurements of pH, Eh, dissolved oxygen,

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conductivity, and temperature were made by a downhole probe in one of the wells. Water samples were taken and analyzed for U, V, Na, K, Ca, Mg, SO_4, Cl, F, Fe, Mn, Al, Si, Ti, Zr, Cr, Co, Ni, Cu, Zn, As, Se.

INTRODUCTION

The In Situ Mining Division of the Bureau of Mines, Twin Cities Mining Research Center and a Joint Venture consisting of Rocky Mountain Energy, Halliburton, and Mono Power Company entered into a cooperative agreement aimed at modeling in situ leaching of uranium with sulfuric acid at the Venture's Nine Mile Lake test site near Casper, Wyoming (Figure 1). The results of an 11-month leaching phase conducted on a five spot (Pattern No. 2) were previously reported by the Bureau (1).

Geology

The uranium mineralization occurs in the Teapot Sandstone Members of the Upper Cretaceous Mesaverde Formation. Unlike many sandstone uranium deposits, this deposit occurs in a fairly well sorted beach sand, rather than a stream channel. The sand contains quartz, feldspar, and minor amounts of mica, black minerals, glauconite, carbonaceous fragments, blue to earthy clay inclusions, and disseminated argillaceous materials. The carbonate content is quite low.

The mineralization is of the roll front type. The principal uranium mineral is uraninite (UO_2) with minor coffinite $U(S_1 O_4)_{1-X}(OH)_{4X}$. Uranium is sometimes associated with vanadium as Montroseite VO(OH).

Hydrology

The Teapot sandstone is an artesian aquifer in the project area, being confined by the overlying Lewis shale and the underlying Pumpkin Buttes shale. The formation dips to the E-NE at about 7 degrees with groundwater movement in that direction at about 3m/yr. (10 ft./yr). The aquifer is reached at the outcrop approximately 3 km (2 miles) west of the test area. Groundwater in the project area is generally used for livestock. Because of the generally low yields and high mineral content, irrigation, industrial and residential use are limited. The groundwater is a sodium sulfate type with TDS quite variable over the project area. TDS seems to be a function of the distance from the outcrop and the quantity of recharge.

Leaching with sulfuric acid obviously changes a number of these parameters very significantly, especially the pH, Eh, SO_4, Ca, V, Ti, and Fe. In situ leach operations are required by the Wyoming Department of Environmental Quality (DEQ) to restore the groundwater to its original condition. In the past, this has been interpreted to mean that it must be returned to its original use and all significant parameters must be returned to its original range. Thus the study of groundwater restoration is an integral part of designing a successful in situ leach process.

LEACHING PHASE

Wellfield Description

The pilot-scale leaching operation used a wellfield (Pattern No, 2) positioned in a 15 m (50ft)-radius five-spot pattern. Sulfuric acid solution and oxidizer was injected into the four corner wells of the pattern. (See figure 2). The Center well served as a production well. Within this pattern, the Bureau drilled three observation (sampling) wells (labeled OB1, OB2, and OB3). A plan view of all the wells at the depth of the ore zone are shown in figure 3. Note in figure 3 that the deviation of the drill-string has produced a rhomboidal configuration of the four injection wellbore locations at the depth of the ore zone.

All wells were cased with 13 cm (5 in) polyvinylchloride (PVC) plastic pipe. The injection and production wells were cemented through the entire sand formation and were then perforated in situ with the Bureau of Mines' water-jet perforator (2). Horizontal slots of 0.5 mm (0102 in) diameter were cut over 2.8-4.9m (9-16 ft) intervels, at approximately the 160 m (525 ft) depth. OB1, OB2, and OB3 each had 10 m (33ft) horizontal slots, at the 160 m (525 ft) midpoint depth. More detail is given in a previous paper by Tweeton et al (1).

The primary sampling wells were OB1 and OB3. OB2 was not used since water samples from this well were radically different from the rest of the pattern well. Seepage from another aquifer is suspected. These sampling wells were located to allow sample-taking at intermediate points between the injection and production wells for the following two reasons: (1) If a downhole data-gathering probe (described in a later section) were placed in a production well below the pump, then the probe could not be pulled up for periodic calibration without interfering with production, and (2) taking samples only from production and injection wells would not provide all the information needed for geochemical modeling, e.g., a condition wherein uranium was dissolving but reprecipitating before reaching a production well would be indistinguishable from one where uranium was not dissolving, unless there was an intermediate sampling point.

The pattern was generally operated at about 158 ℓ/min (42 gpm) production from the center with 38 ℓ/min (10 gpm) input per injection well, resulting in an overproduction of about 7/min (2 gpm) to maintain hydrologic control. Water sampling from OB1 and OB3 was done with 34 ℓ/min (9 gpm) pumps hung just above the slotted sections.

Lixiviant Circulation

Content vs. Time

While many Texas and Wyoming in situ leach operators heretofore have used an ammonium bicarbonate/carbonate leach, this is the only site currently using H_2SO_4 solution. Injection began December 1, 1977 with dilute H_2SO_4 (0.15 g/l) added. The H_2SO_4 strength was increased to about 1.5 g/l on December 30, 3 g/l on January 10, 1978, and 5 g/l on April 3. If strong acid were added initially, uranium and other elements could be mobilized at high concentration near the injection well only to be reprecipitated near the production well as groundwater diluted the H_2SO_4 further. Additional problems, ~~and~~ such as CO_2 liberation which could cause loss in permeability, could also be a problem. The rate at which acid strength was increased was intended to be conservative.

Hydrogen peroxide (H_2O_2) was added starting January 21 at 250 mg/l and the concentration was slowly raised to 3000 mg/l within 1 month. During the remainder of the leaching phase, the H_2O_2 concentration was in the range of 1000-3000 mg/l.

Flowrates and Volumes

The circulating solution was stripped of uranium values by ion exchange, and additional H_2SO_4 and H_2O_2 added to the raffinate to fortfy the lixiviant for reinjection. The total circulating solution has been estimated at 4.57×10^6 liters (1.21×10^6 gal) for this pilot-scale leaching operation. This recirculation and extraction of uranium values continued in a consistatn manner until September 5, 1978. At that time, no additional H_2SO_4 was added to fortify the reinjected solution.

On September 16, 1978, a partial flow of the raffinate was directed to the evaporation pond as clean water produced from treated raffinate and native groundwater were being injected into the ore zone to start restoration. By November 11, 1978, all barren liquor (raffinate) was routed to the evaporation pond and only native groundwater (from a well about 400 m away) was injected into the ore zone. Thereby the active leaching phase made the transition to the restoration phase. Leaching was curtailed by a need to investigate restoration, not become uranium was exploited. Uranium content of the recovered solution was about 50 ppm when acid addition ceased.

Surface Recovery Process

During the leaching phase of pattern No. 2, uranium pregnant liquor concentration was in the range of 60 to over 300 mg/l U_3O_8. Average values were near 100 mg/l.

The recovery of uranium from the production wells (pregnant solution) was accomplished by a series of hydrometallurgical unit processes. The pregnant solution was pumped through an ion exchange (IX) system, which selectively adsorbed the anionic uranyl-sulfate complex.

The uranium-depleted solution (raffinate) was refortified with H_2SO_4 to raise concentration to the 3-5 g/l level. More H_2O_2 was added to maintain an oxidation-reduction potential (Eh) of +450-600 mv.[1] This refortified lixiviant was then returned to the injection wells.

Uranium adsorbed on the 1X resin was stripped off with a very strong H_2SO_4 solution (over 100 g/l). U_3O_8 was precipitated with ammonia and thickened until Percol 351.[2] Thickened yellow cake was filtered on a

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[1] Oxidation-reduction (Eh) measurements mentioned in this paper use the convention of + oxidation and - reduction.

[2] References to specific products is made to facilitate understanding and does not imply endorsement by the Bureau of Mines.

90 cm X 30 cm (3ft X 1ft) drum filter and dissolved in HNO_3 for shipment. This method of concentrate handling is used for pilot plant purposes only.

Excursion Monitoring

During the pilot-scale leaching of pattern No. 2, monitor wells located outside of the radius of the five-spot pattern were sampled on a regular basis. These wells were approximately 49 m (160 ft) from the production well. Monitor wells were sampled routinely before and during pattern operation to provide a continuing record of baseline water condition. Sampling did not indicate any excursion during leaching or restoration. Both monitor and leaching wells will be sampled periodically after restoration to determine if water conditions have stabilized.

Waste Management

Since production of solution exceeded injection by about 5% to maintain a hydraulic gradient toward the production well, an equivalent portion of the barren solution was sent to the evaporation pond. This bleed-stream was drawn from the raffinate tank.

Other wastes routed to the evaporation pond include brine and precipitates (as slurry) from the water treatment plant during the restoration phase (described under Restoration section).

RESTORATION PHASE

Groundwater Quality Data Gathering

In Situ Measurements With Downhole Probe

In observation well OB3, six water quality parameters were measured in situ. Oxidation-reduction potential (Eh), hydrogen ion concentration (pH), dissolved oxygen (D.O.), conductivity (cond.) temperature and depth were measured using a special downhole probe.

The probe used was a Hydrolab system 8000. It consisted of two parts; the downhole sending unit with sensors and the surface data control unit. The transmitter or sending unit is about 7.6 cm (3 in.) in diameter and 46 cm (18 in.) long.

The probe measures the following parameters:

1. Temperature, using a linear thermistor. Range: -5 to +45°C (23° to 113° F).
2. Depth, using a strain gage transducer. Range: 0-200m (0-656 ft).
3. Dissolved oxygen, using a semipermeable Teflon membrane. Range: 0-14 ppm
4. Conductivity, using a platinum four-electrode cell. Range: 0-200 millimhose/em.
5. pH, using a glass electrode and silver/silver chloride reference. Range: 0-14 pH.
6. Oxidation-Reduction Potential, using a platinum electrode and silver/silver chloride reference. Range: -2000 to +2000 mV.

Laboratory and field experience indicated that the probe required recalibration approximately every 30 days in this environment. The depth sensor was quite sensitive to barometric pressure changes and would have required calibration several times per day had it been used in this project. The pH showed some tendency to drift upward after approximately two weeks in the well. For this reason, surface measurements of pH were taken as the most accurate. All other parameters showed little tendency to drift and required only small corrections after one month.

The downhole probe was placed 45 m (476 ft) from the surface. This is approximately 3 m (10 ft) above the screen and 10 m (36 ft) below the pump.

It was found in previous work that these parameters, especially Eh and D.O., needed to be measured as near to the screened intervals in the well as possible. A comparison was made in OB3, where both in situ and surface measurements were taken, large discrepancies between the measurements can be noted (see Appendix).

Effect of Hydrology on Sampling

Figure 4 shows a streamline pattern for the leaching side using average restoration injection and production flowrates. Injection rates of 20 ℓ/min (4.95 gpm) for each injection well and production rates of 20 ℓ/min (22 gpm) were used. Injection of restoration water took place at the four corner wells and production was from the center wells.

The pattern was generated by a computer program, ISL-50, developed at the Bureau by Schmidt (3). The shape of the pattern is determined by a number of factors including injection and production rates, directional permeability, aquifer thickness and screen placement. The shape of the pattern has an important effect on the interpretation of water samples taken from the observation wells.

OB3 is located almost directly between the injection and production well. Because of this, all of the streamlines flowing in the vicinity of OB3 are traveling at nearly the same velocity. This makes changes in OB3 sharp and well defined. Geochemical changes between the injection well and OB3 are easier to identify. When the average restoration flow rates are used in the program, it takes 7 to 10 days for water to travel from the injection well to)B3.

OB1 lies near a wide range of streamlines. Travel times for water leaving the injection well and arriving at OB1 vary from 4 to 19 days.

Average restoration flow rates were again used in this calculation. The effect of this is to spread changes out and reduce their definition. If the composition of the injection solution changes, the water in OB1 begins to change after four days and continues to change for approximately two weeks. Geochemical changes between the injection well and OB1 are more difficult to describe.

Water Sampling Procedure

The quality and reliability of geochemical analyses depend heavily on the sampling technique. Samples from OB1 and OB3 were taken at the well head. Samples of the injection solution were taken from the plant. Samples were collected at approximate weekly intervals. The following sampling procedure has evolved from earlier similar projects and seems to give the most consistant results:

1. Each well is pumped for a minimum of 45 min to fill the well bore with fresh formation water.
2. Downhole readings are taken in OB3 with the probe.
3. Four liter (1 gal) samples are taken for analysis.
4. The samples are filtered with 0.45 micrometers (μm) filters to remove sediment.
5. Half of each sample is acidified with HCl to keep all cations in solution.
6. Labortory measurements of pH, Eh, conductivity, and temperature are taken on an unacidified portion.
7. Samples are stored in clean polyethylene bottles and shipped to the Bureau's Center in Minneapolis for further analysis.

Cation and Anion Analysis

In addition to the above chemical parameters, cation and anion analyses were performed on the weekly samples. Specific elements and the analytical method are listed in Table 1. The time lag from sampling to analysis ranged from one to six weeks but averaged about two to three weeks.

Computer Data Storage

All the chemical analyses taken for the project has been stored on a computer file. It is available in printout or plotted format and is also included in the Appendix of this paper.

Analysis of Groundwater Data

Water Quality vs. Time Plots

From weekly chemical analysis the water quality parameters that had the largest change in value starting from baseline through the leaching phase, and return toward original value as restoration progressed (150 day restoration study period) were the following: U, V, Ca, SO_4, pH, Fe, As, Se, Eh, Conductivity, and dissolved oxygen (figure 5-15). Other parameters that were regularly analyzed, but not graphed here because at relatively small concentration changes were the following: Na, K, Al, Zn, Si, P, Mn, Mo, and groundwater temperature. These values throughout the study period, along with data used for the above noted figures are shown in the Appendix.

Note in the graphs the baseline concentration region, derived from an averaging of three to six independent water analyses (depending on element) run prior to the leaching operation.

Examination of the figures show that most groundwater quality parameters are at baseline or very near, over the 220-day study period.

Geochemical Trends Toward Restoration

At the start of restoration, uranium values remaining in the ore zone were uneconomical to extract by ion exchange techniques. However, as restoration proceeded, the acidity levels moved toward the neutral zone (pH 7) and the uranium levels in solution dropped even further because at decreased solubility at the higher pH levels.

It is worthwhile to view several geochemical occurances that were found in the restoration of the groundwater within the ore body. The following water quality changes are not unexpected from geochemical principles but are given here since this is the first restoration of an acid-leached uranium-bearing orebody in the United States. Even though this is a pilot scale operation, its successful completion opens the way for commercial acidic in situ leaching ventures for deposits with relatively low calcium and clay content.

Co-occurance of Some Elements and Parallel Changes of Concentraction Levels

As the groundwater concentration levels of various elements are reduced toward baseline levels certain pairs of elements exhibit similar concentration changes. A best example was found with uranium and vanadium. Rising and falling uranium levels in solution was mirrored by the vanadium levels. Figures 5 and 6 show this closely parallel tracking behavior.

Similarly, iron and aluminum ions, some of which were solubilized from roughly parallel decreases (not graphed, see Appendix), as pH levels rose toward neutrality as restoration progresses.

Sodium and potassium ion levels in groundwater are commonly inversely linked. The data (Appendix) showed that sodium levles moved slightly upward from 300 to 400 ppm in the first 100 days at restoration, while potassium trended downward from about 10 to 6 ppm in the same time period. Calcium from the native groundwater and from the treated water pumped into the ore zone is believed to exchange sodium ions from the clay in the ore zone, thereby increasing the sodium levels slightly.

Environmentally Sensitive Elements

Arsenic and selenium levels (figures 11 and 12) are of environmental importance because of their high toxicity are easy mobilization in acidic media. These elements were analyzed on a regular monthly basis. During 150 days of restoration, arsenic values ranged from 14-75 ppb, while selenium ranged from 20-82 ppb. Arsenic concentration values were close to National Primary Drinking Water Standard (50 ppb). Selenmium was above the primary standard at 10 ppb. However, the aquifer within the ore zone was not intended to supply drinking water for human consumption. No public water supply wells are recorded within 5 km (3 mi) of the test site.

Relationships of Restored Ore Zone Groundwater Quality to Other Baseline Criteria

The restoration of Pattern No. 2, which began in November 1978, appears to be almost complete. Table 2 compares the groundwater of Pattern No. 2 after leaching and restoration operations with Pattern No. 2 preleach groundwater and with native groundwater outside the ore zone. The native groundwater outside the ore zone shows significant variation in quality. In general, none of the values shown in Table 2 are within the EPA drinking water standard of 500 ppm total TDS; however, water of this quality is satisfactory for livestock (4).

A comparison of water quality before and after leaching and restoration operations indicates that the restored groundwater is close to preleach quality and is within the water quality range outside the ore zone. Graphs showing the change in water quality during restoration are shown in Figure 16. This Figure highlights the gradual rise in pH which has occurred. The pH appears to be only a function of the total gallons of solution recovered during restoration and should return to preleach value.

Comparison of Pilot-Scale Restoration to Laboratory Experiments

Laboratory studies of restoration were conducted by the University of Texas at Austin as part of Bureau of Mines Contract No. HO282016. The Principal Investigators were Dr. Michael Breland and Prof. Robert S. Schechtor. Experiments simulating both leaching and restoration were performed, but only restoration will be discussed in this report.

Experimental Procedure

The laboratory studies were performed with a blended core material from the Nine-Mile Lake Site. The core material had been stored unfrozen in plastic bags for several months, so it was probably partially oxidized in storage.

Four different types of restoration experiments were performed on columns, which had been previously leached with H_2SO_4 solutions. The first experiment used a 120x7.6 cm column, and the restoration solution was 3 pore volumes of 25 pct groundwater and 75 pct distilled water followed by completing the restoration with 100 pct groundwater.

The second experiment used a smaller (60x2.5 cm) column of ore. This was also restored, using the same method.

The third experiment was another smaller column with restoration using only 25 pct ground water - 75 pct distilled water for the complete restoration.

The fourth experiment used two of the smaller-sized columns were restored using a saturated $Ca(OH)_2$ solution.

The term "restoration" as used in describing the laboratory studies means that time at which the H^+ ion effluent concentration closely matched the feed concentration.

The flow rate in all of these experiments was about 3 m (loft)/day. This rate was about five times the field flow rate near OB3 during restoration. The laboratory restoration experiments were conducted before the field restoration, so the laboratory flow rate had to be chosen before the field flow rate was established.

All of the experiments except the ones using $Ca(OH)_2$, were with ore that had been leached with sulfuric acid for studies of the leaching phase. The studies of the leaching phase were done with H_2SO_4 increased in several steps, as had been used in the field. The final step involved 4.0 g/l H_2SO_4 plus 1.3 g/l H_2O_2. After the final step of each series of leach studies, the feed solution was changed to the restoration solution (25 pct ground water plus 75 pct distilled water or 100 pct ground water). The effluent was collected at least once per pore volume.

The 25 pct ground water - 75 pct distilled water combination was used because Rocky Mountain Energy was considering recirculating a combination of 25 pct ground water and 75 pct water that had been purified by reverse osmosis. It was recognized that water from a reverse osmosis unit contains more dissolved solids than distilled water, but for standardization, comparison, and interpretation, distilled water was preferred over osmosis product water. The ground water was from the Nine-Mile Lake Site.

In the $Ca(OH)_2$ restoration experiments, the ore was first saturated with H^+ ions by running a 3 g/l solution of H_2SO_4 through the column until the effluent pH was less than 0.3 pH units different from the feed pH. Then the influent was switched to the $Ca(OH)_2$ solution.

Comparison of Results

Restoring the ore in the larger column required a pore volume of ground water after the 3 pore volumes of 25 pct ground water - 75 pct distilled water. The pH of the effluent rose from 2 to 3 in about 2 pore volumes near the end of restoration, the pH rose from 3.5 to 7.5, as shown in figure 17.

Most of the ions were reduced to baseline levels within 3 to 5 pore volumes. The restoration required the excess pore volumes because of the tenacity with which H^+ ions are held by clays. Hydrogen ions have a greater affinity for montmorillonite clay than even triply charged Al cations do. This tenacity may be caused by hydrogen-bonding to the O atoms of the clays.

One approach to comparing field and laboratory results is on the basis of relative volumes required for leaching and restoration. In the laboratory, restoration required about 50 pct of the solution volume for leaching. The field data agreed quite closely. The restoration of pH was close to complete after 40 pct as much solution had been pumped out during restoration as had been injected during leaching.

Another approach to comparing is on the basis of pore volumes. A factor for connecting days of field operation to pore volumes was calculated with the Bureau's hydrologic computer program termed ISL-50 (3). The calculations indicated that 10.5 days of field operation corresponded to 1 pore volume for solution moving to OB3 from the vicinity of the nearest injection well. The site had been well characterized, so such factors as the differences in down-hole well spacings and transmissionities could be taken into account. Nevertheless, the result should be considered an estimate, subject to considerable error.

As indicated in a previous section, the streamline flowing near OB1 correspond to widely varying flow rates, so assigning a specific correspondence between days of field operation and a pore volume of solution moving to OB1 from the nearest injection well could not be made. Therefore, the field results compared with laboratory results do not include OB1.

Using the pore volume basis for comparison, restoration of pH levels in the field was more gradual than in the laboratory. As shown in figure 9, the pH in OB3 had risen to 4.5 by the 46th day of restoration, corresponding to 4.4 pore volumes. Thus the pH made this rise earlier in the field than in the laboratory. The pH in OB3 rose only gradually after that, going to 5.8 by the 69th day and remaining approximately 5.8 until at least the 109th day of restoration, corresponding to over 10 pore volumes. The pH was 5.9 on the 146th day and 6.7 on the 151st day.

The more gradual change in field pH may have been caused by the high clay content in the confining layers immediately above and below the uranium-bearing zone. The laboratory core material was from the uranium bearing zone only. In the field, part of the leach solution would contact the clayey confining layers and the release of H ions from that clayey material could be quite slow.

The behavior of Eh in the laboratory was governed only partly by the change in pH. At 12-13 pore volumes, the pH increased by 3.7 units. A corresponding theoretical change in Eh would be (3.7)(60mV) = 220 mV. As shown in figure 18, the observed decrease was only 100 mV, indicating that the solution become oxidizing. This, together with the fact that during leaching studies the Eh increased more than could be attributed to decreases in pH, suggests that the solution was transporting O_2 from the air.

The behavior of Eh in the field was quite different. As shown in figure 13, the Eh in OB3 dropped from 380mV at the 29th day of restoration to 60 mV at the 39th day. At 10.5 days per pore volume, 39 days corresponds to 3.7 pore volumes. In situ field conditions became more reducing before the pH rose, judging from the fact that the Eh dropped significantly by the 39th day whereas the pH did not rise significantly before 46 days.

Conductivity dropped quickly in both the field and laboratory, as shown in fiqures 14 and 19, respectively. In the field, the conductivity became lower than the preleach value due to the injection of process water (ground water from another location) of lower conductivity than the leach field baseline. In the laboratory, it dropped to about the same value as before leaching.

Sodium in the laboratory reached a fairly constant value after only a few pore volumes (see figure 20). Similarly, the data (Appendix) shows that the field Na concentration was below 350 ppm, about half of the preleach value by the 29th day of restoration. The concentration slowly rose after that. Sodium concentrations were fairly constant during leaching in both the field and laboratory.

Calcium concentrations showed more interesting behavior. In the laboratory, the Ca concentration increased as restoration progressed, indicating that Ca was being desorbed (see figure 21). In OB3, the Ca concentration was 70 ppm, about half the preleach value, by the 29th day of restoration. It showed a small tendency to rise, going to 100 ppm by the 46th day (Figure 7).

Uranium, V, Fe, and SO_4 in the laboratory were reduced to fairly low levels in several pore volumes (see figures 22, 23, 24, and 25). A sharp peak occured after the 100 pct ground water flush was started. This peak is due partly to the ground water containing more of these ions than the distilled water did. As expected, SO_4 (see figure 25) and conductivity also took a sharp jump at that point.

In the field, SO_4 was below preleach concentrations by the 29th day of restoration (see Figure 8) as a result of the injected clean process water. Uranium was very low in OB3 by the 29th day, and only a few ppm persisted in OB1 for about 100 days (see figure 5). Vanadium concentrations stayed high for about 69 days (see figure 6), and iron stayed high for about 146 days (see figure 10). The concentrations of vanadium and iron are sensitive to pH, so the slow decline in these values is explained by the slow rise in pH.

Laboratory restoration studies with the smaller (60x2.5 cm) column gave results similar to those with the larger column, indicating that the smaller column can be used to conserve core material and to reduce the cost of test work.

In a second restoration with the smaller column, 25 pct ground water and 75 pct distilled water was used for the entire restoration, instead of changing to 100 pct ground water after 3 pore volumes. The restoration required 28 pore volumes, much more than when using 100 pct ground water. Since reducing the H ion concentration involves cation exchange, the greater effectiveness of 100 pct ground water is not surprising since it has four times the ionic strength of the 25 pct solution.

A laboratory restoration experiment was also performed using a saturated $Ca(OH)_2$ solution. About 11 pore volumes were required to attain pH restoration (see figure 26). This is not very different from the amount of flushing required with ground water. Approximately 14 pore volumes were required with ground water, but 3 of those pore volumes were with 25 pct ground water and would be only as effective as about 1 pore volume of 100 pct ground water. Thus, about 12 pore volumes of 100 pct ground water would be required versus 11 pore volumes of saturated $Ca(OH)_2$. The $Ca(OH)_2$ solution was not tested in the field.

It is possible that keeping the Ca concentration more carefully controlled near the theoretical maximum of 450 ppm could increase the effectiveness. The observed concentration varied from 250 to 450 ppm. Most of the variation was probably due to CO_2 in the atmosphere dissolving in the solution and reacting with the $Ca(OH)_2$ to form insoluble $CaCO_3$. Theoretically, the saturated $Ca(OH)_2$ solution could be very effective for pH restoration since the Ca would displace H ions from clay and the H would be neutralized by the OH.

Groundwater Monitoring and Site Abandonment

In order to monitor the confinement of the leach solutions, four monitor wells were placed around the pattern at a spacing of about 160 feet from the production well. Each of these was screened over the entire lower part of the sand.

The monitor wells were sampled routinely before and during pattern operation to provide a continuing record of baseline water conditions. Monitoring did not indicate any excursions during leaching or restoration. Both monitor and leaching wells will be sampled periodically after restoration to determine if water conditions have stabilized. Those wells not to be utilized during commercial leaching operations will be plugged prior to start up of the commercial field.

The evaporation pond contains the bleed stream of barren leach solution produced during the leaching phase, as well as the waste product streams from the restoration phase. After evaporation is complete, the remaining solids from the pilot operation will be placed in an approved tailings disposal site. Assuming a commercial plant is constructed at Nine Mile Lake, this material will be placed in the evaporation pond construction for the larger plant. Ultimately the evaporation pond site will be reclaimed either by placing all solids in another exisiting tailings disposal site, or by burying the material in a clay-lined pit with sufficient liner and capping material to contain all potential pollutants.

CONCLUSION

Restoration of the Nine Mile Lake pilot scale acidic uranium leaching site can be regarded as a very informative and successful attempt at restoration.

In summary, pH appears to be the parameter that returns slowest to the preleach baseline region. Nearly all of the other parameters returned to the baseline region within 150 days. Laboratory experiments conducted by the University of Texas through Bureau contract show that restoration of pH may be accelerated by the use of a calcium hydroxide injection solution.

Accurate establishment of baseline water quality and baseline variability is very important to the definition of restoration. Accurate measurements of some parameters like Eh and dissolved oxygen should be made in situ using one of the commercially available down-hole probes. Field water sampling procedure has a dramatic effect on the accuracy of laboratory chemical analysis. Standardized techniques such as those outlined by Wood for the USGS should be followed (5).

The use of acid as a leadout sidesteps many of the environmental problems associated with amonium carbonate/bicarbonate leachants. The successful restoration of this site adds to the viability of sulfuric acid as an alternative leachant.

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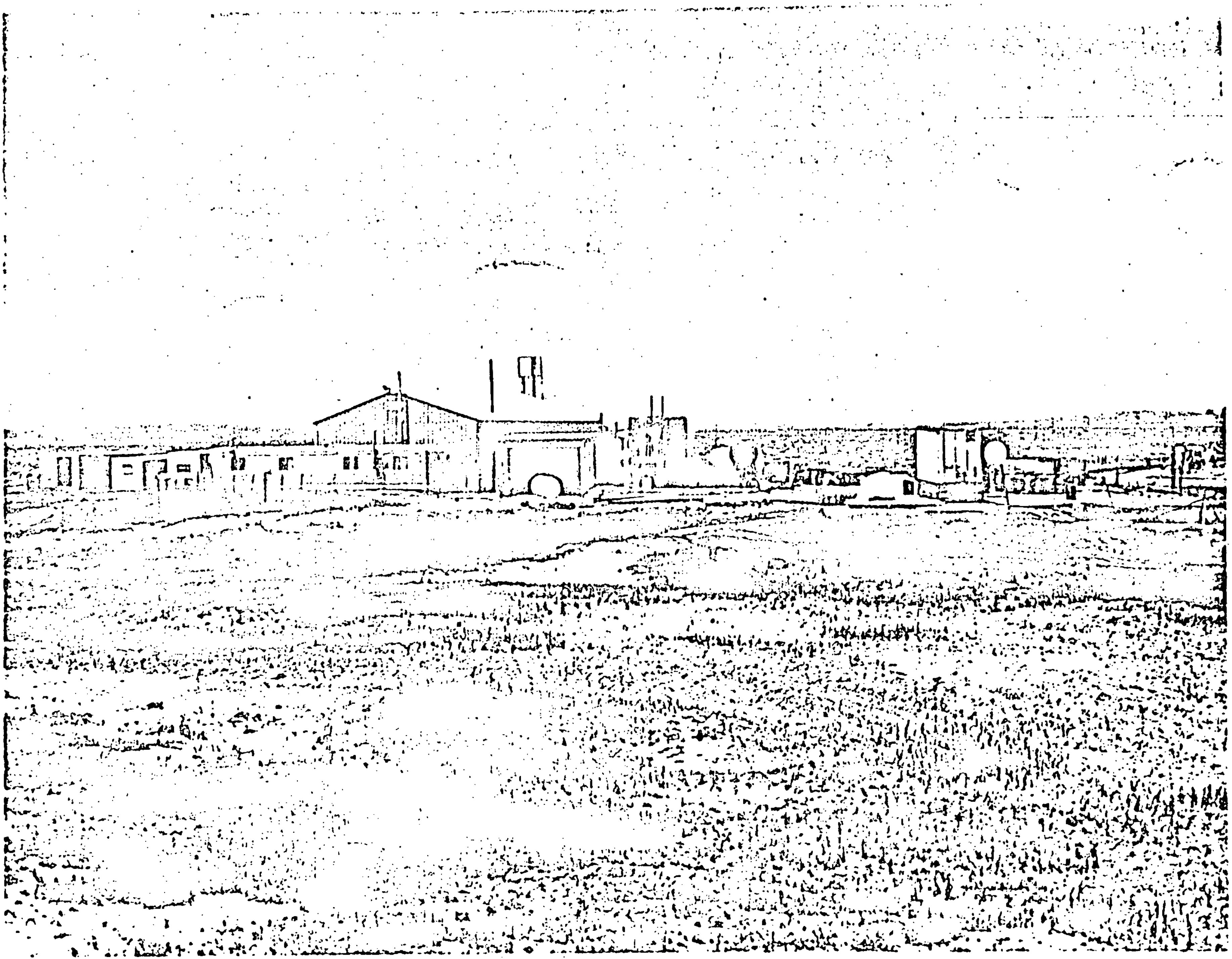


Figure 1. View of joint venture in situ pilot leaching facility of Nine Mile Lake

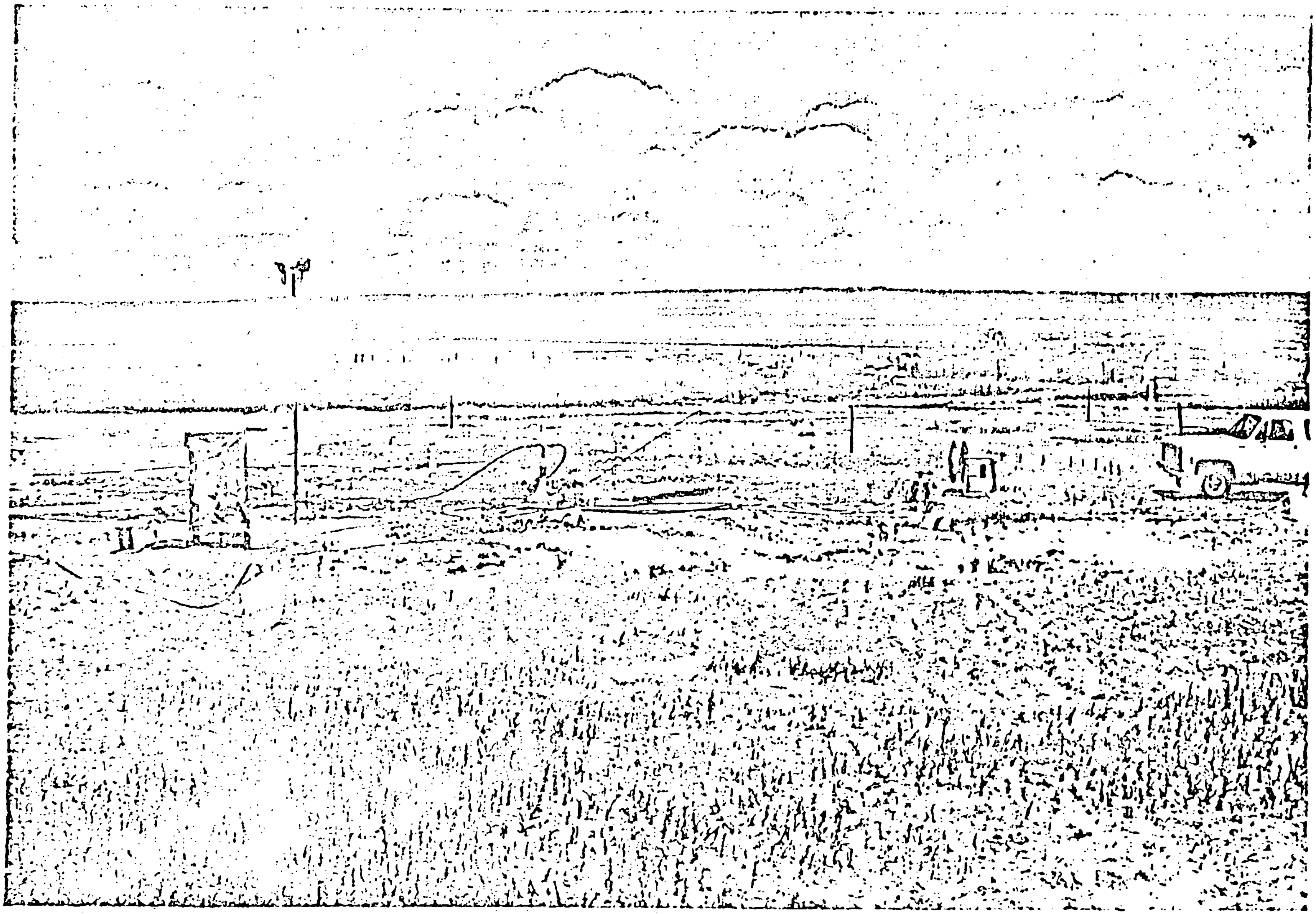


Figure 2. View of five-spot pilot test area (pattern no. 2)

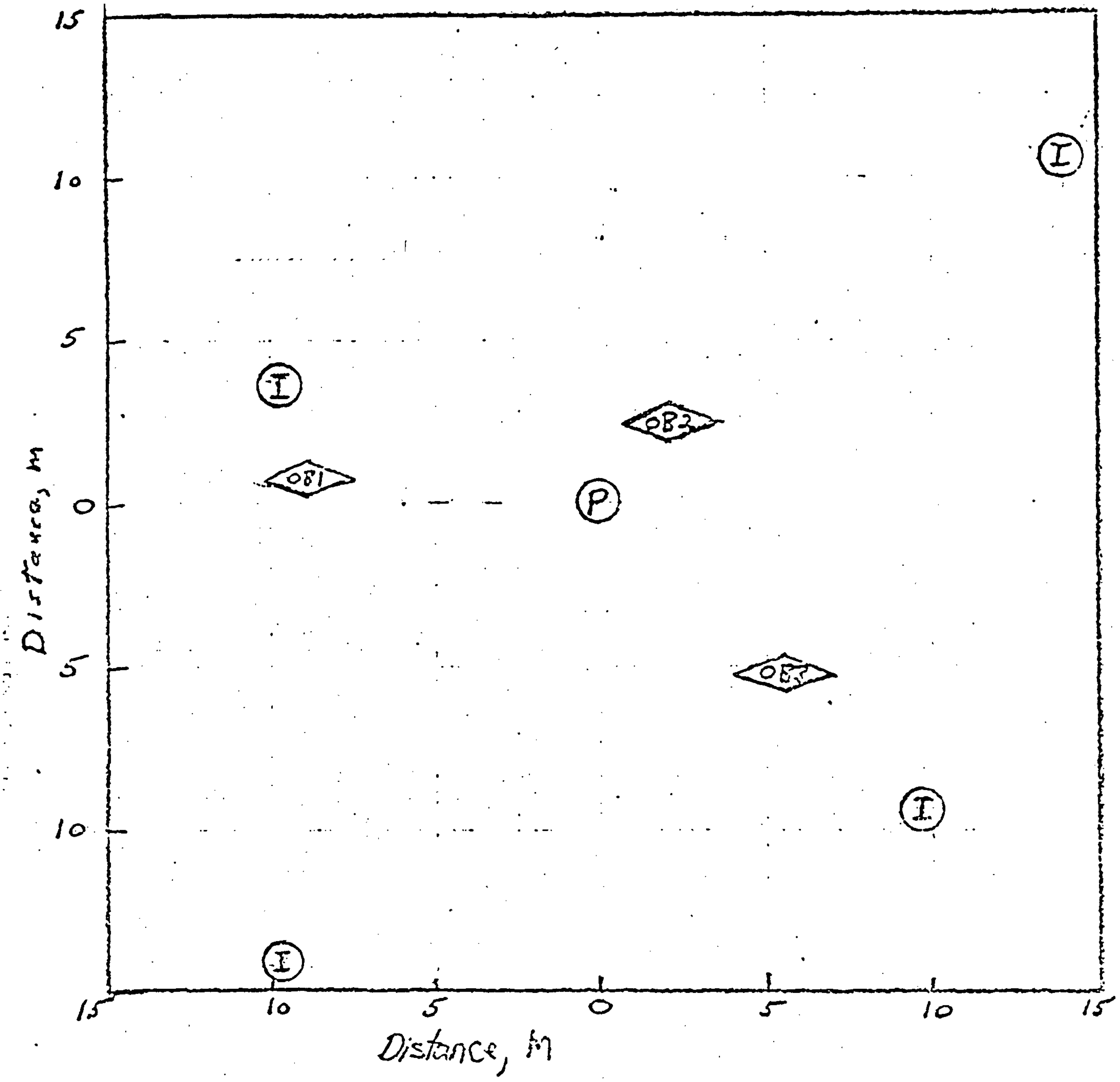
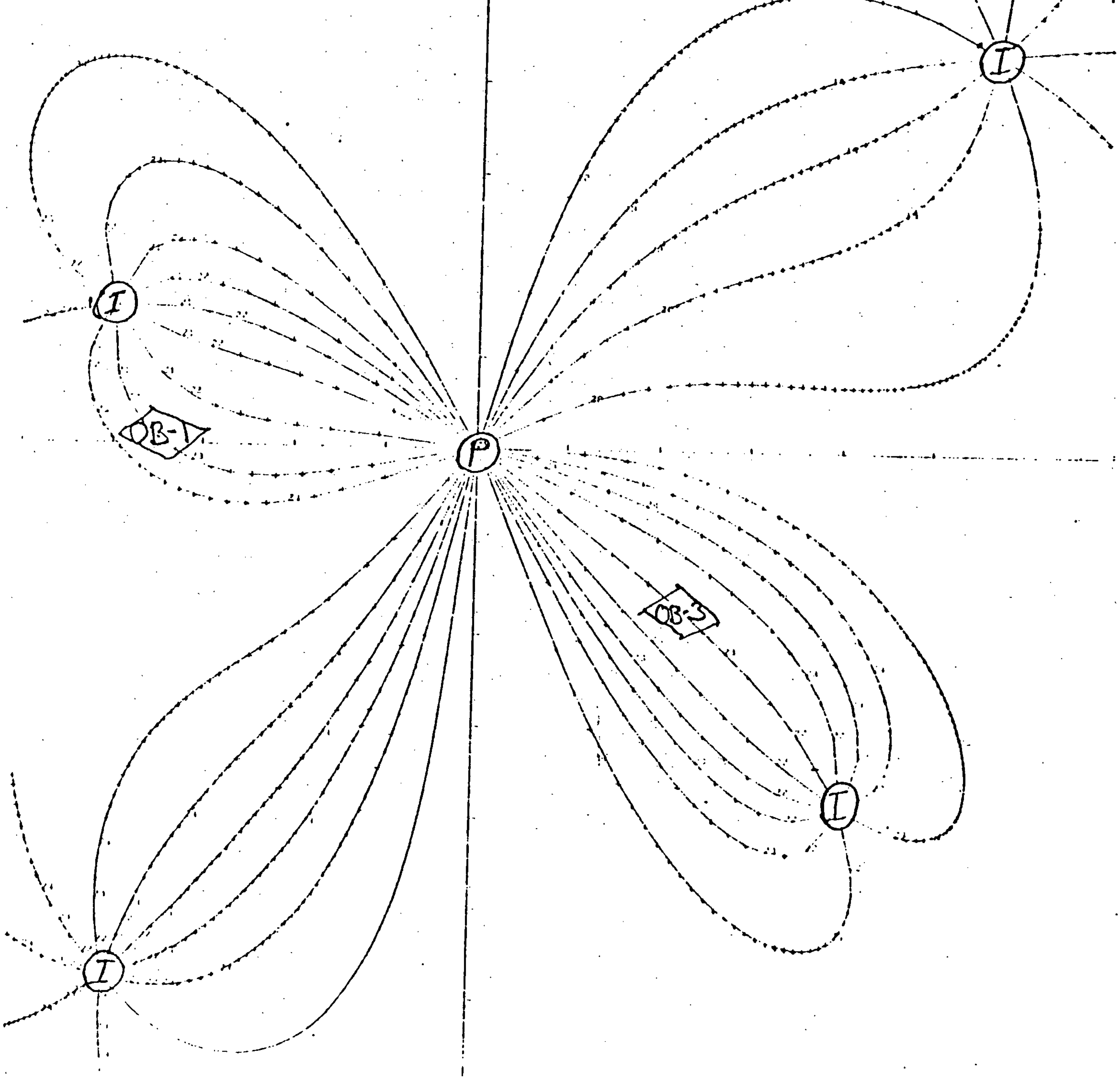


Figure 3. Plan view of five-spot pattern and observation wells

Figure 4. — NINE MILE LAKE RESTORATION PATTERN (12 MONTHS)



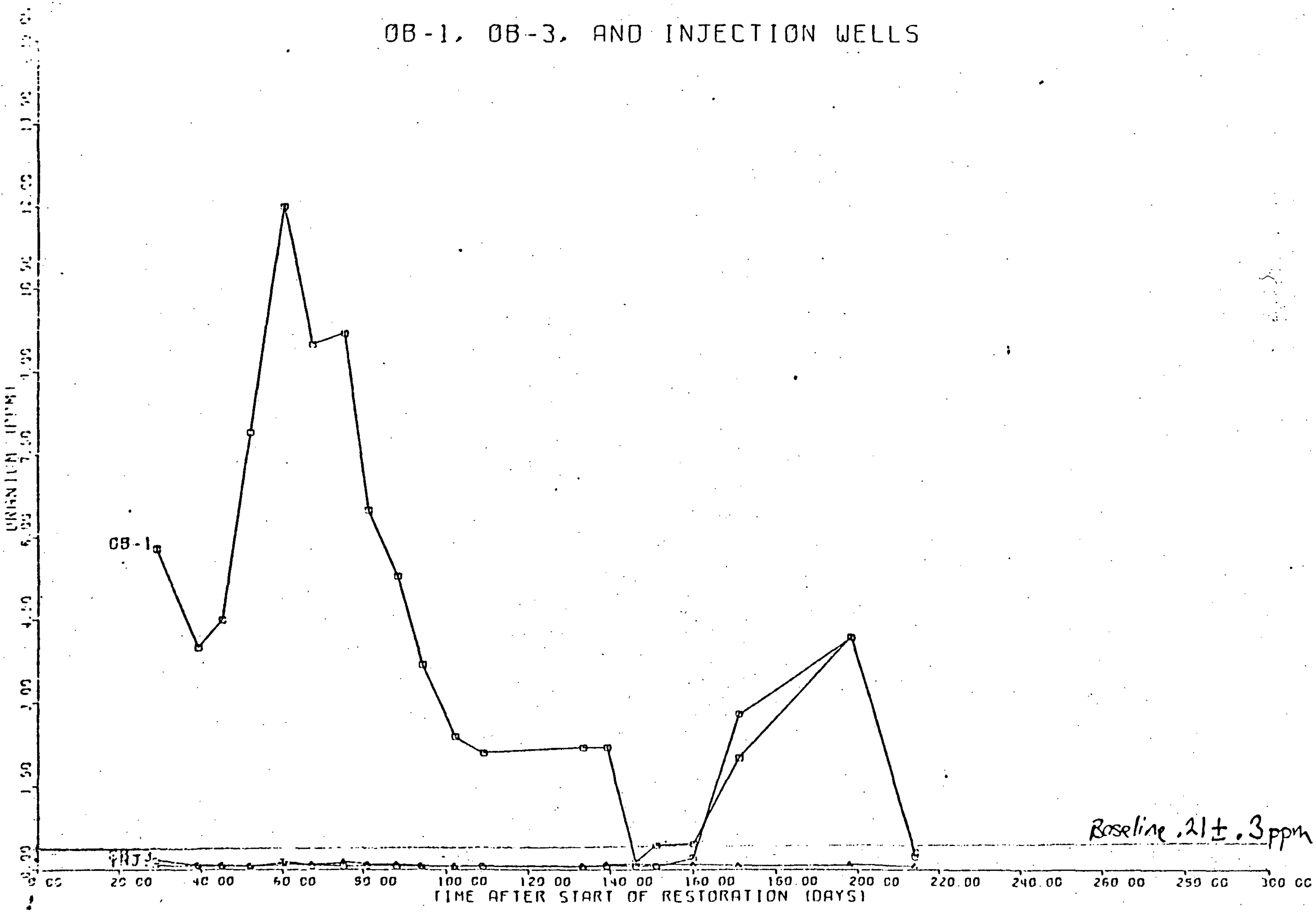
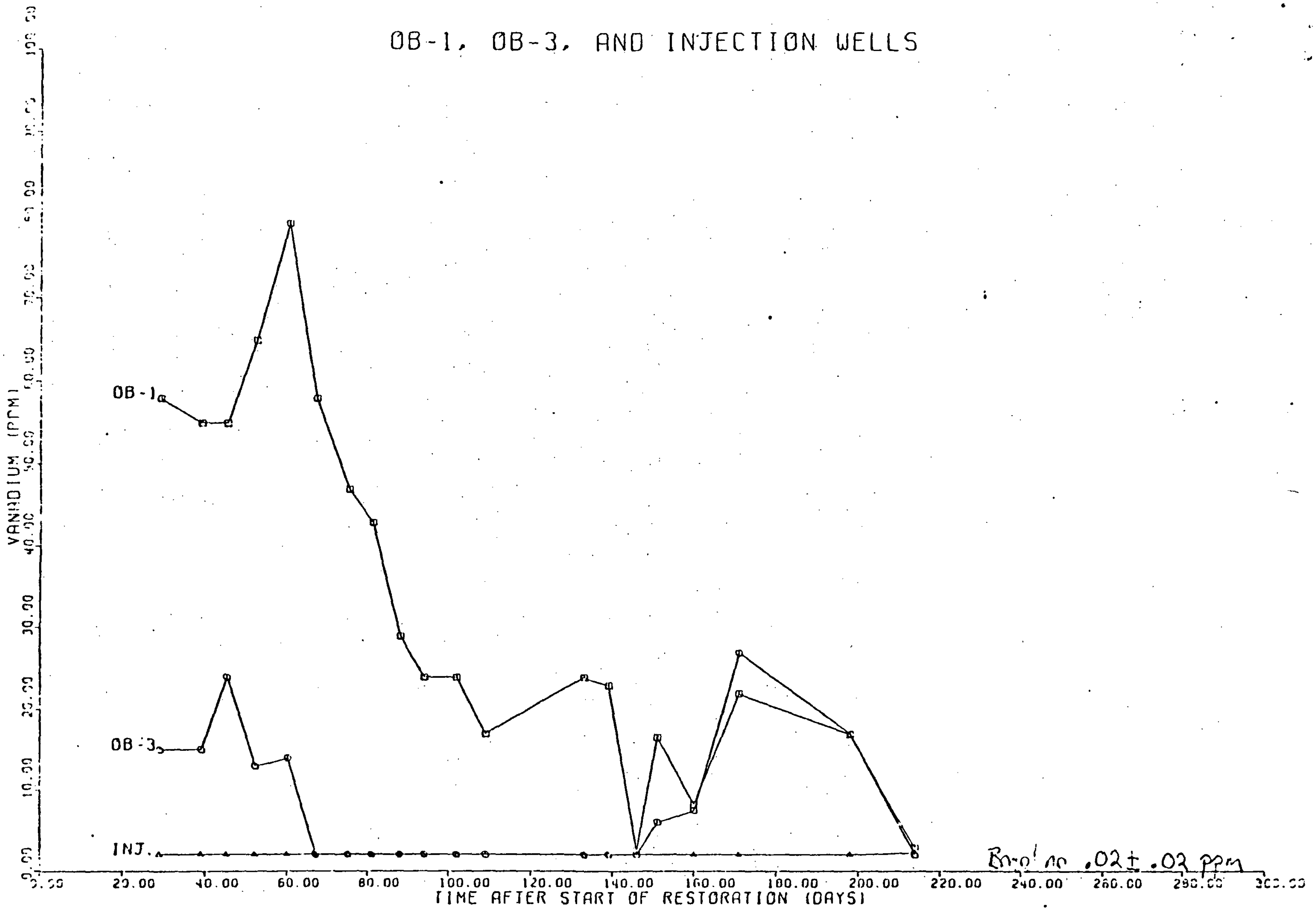
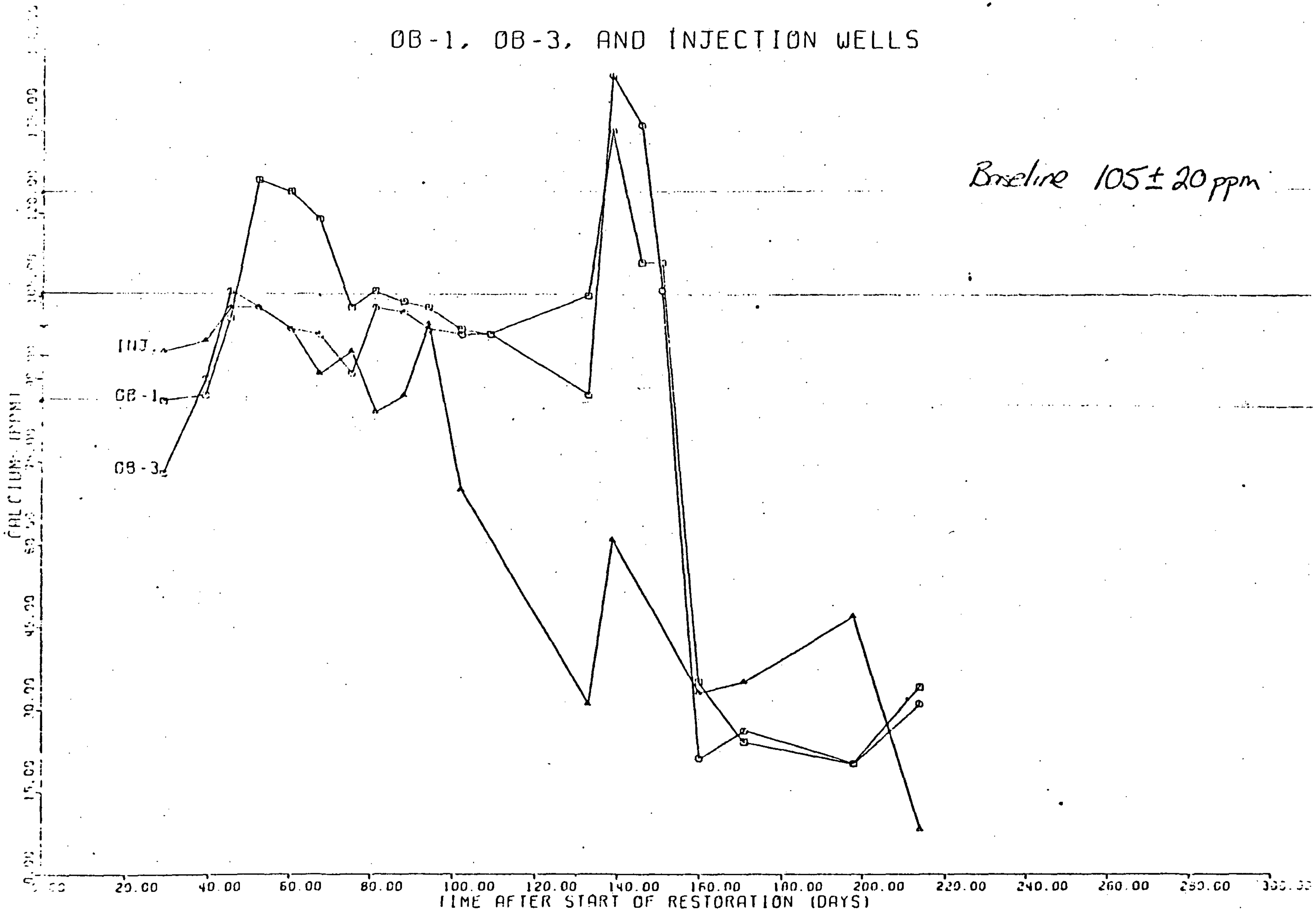


Figure 5. Uranium concentration vs. time



Bkg'nd .02 ± .02 ppm

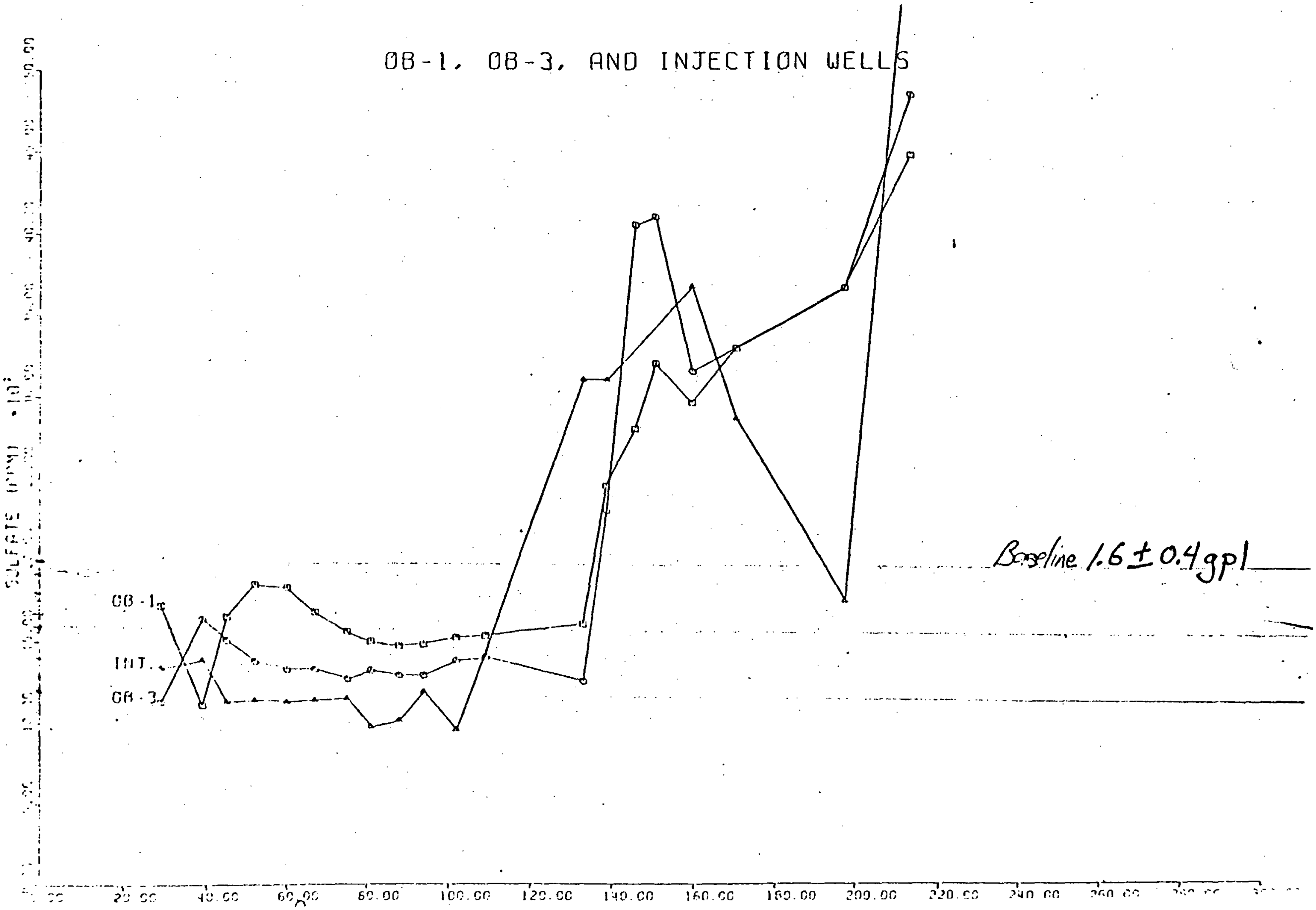
Figure 6. Vanadium concentration vs. time



Baseline 105 ± 20 ppm

Figure 7. Calcium concnetration vs. time

Figure 8. Sulfate concnetration vs. time



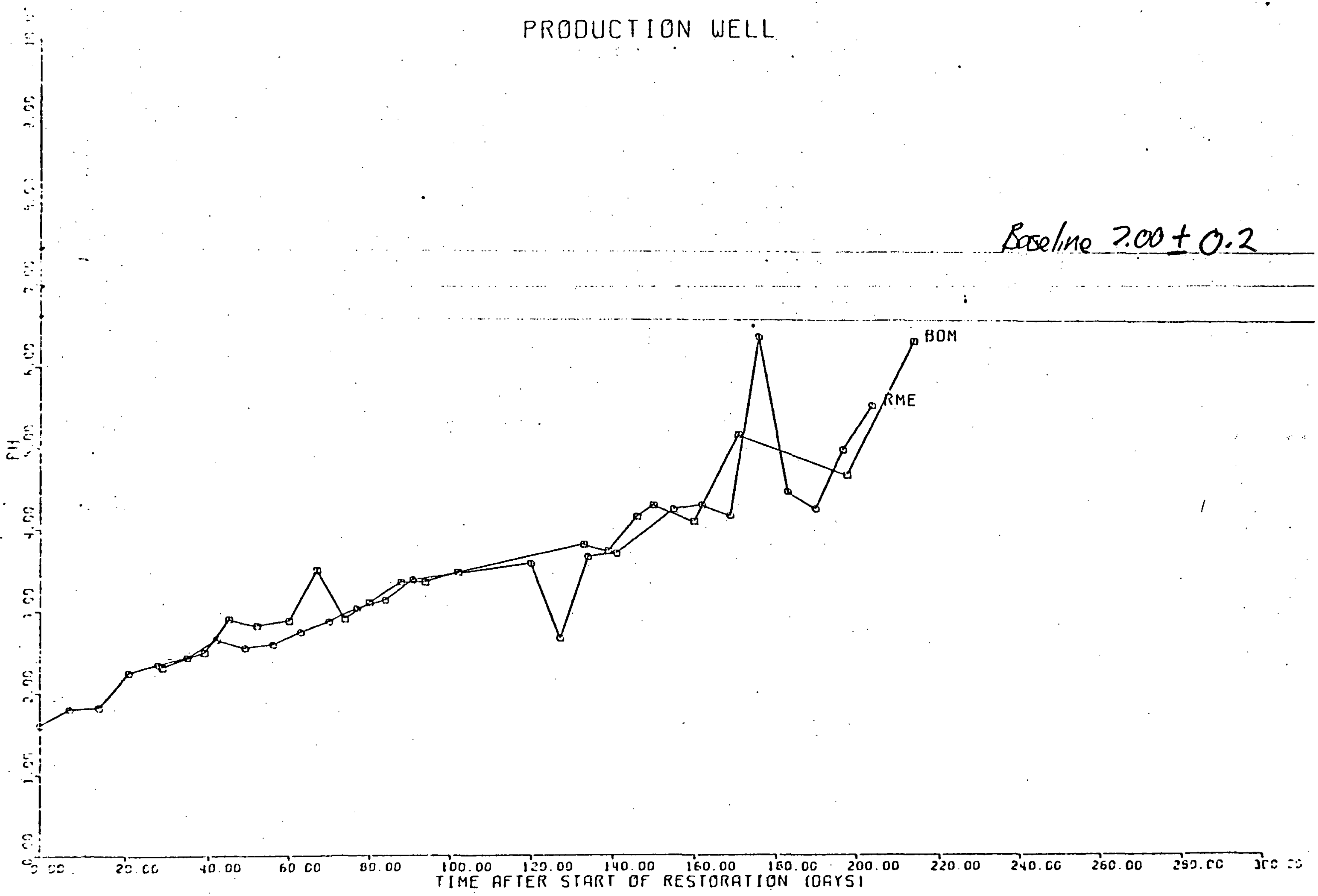
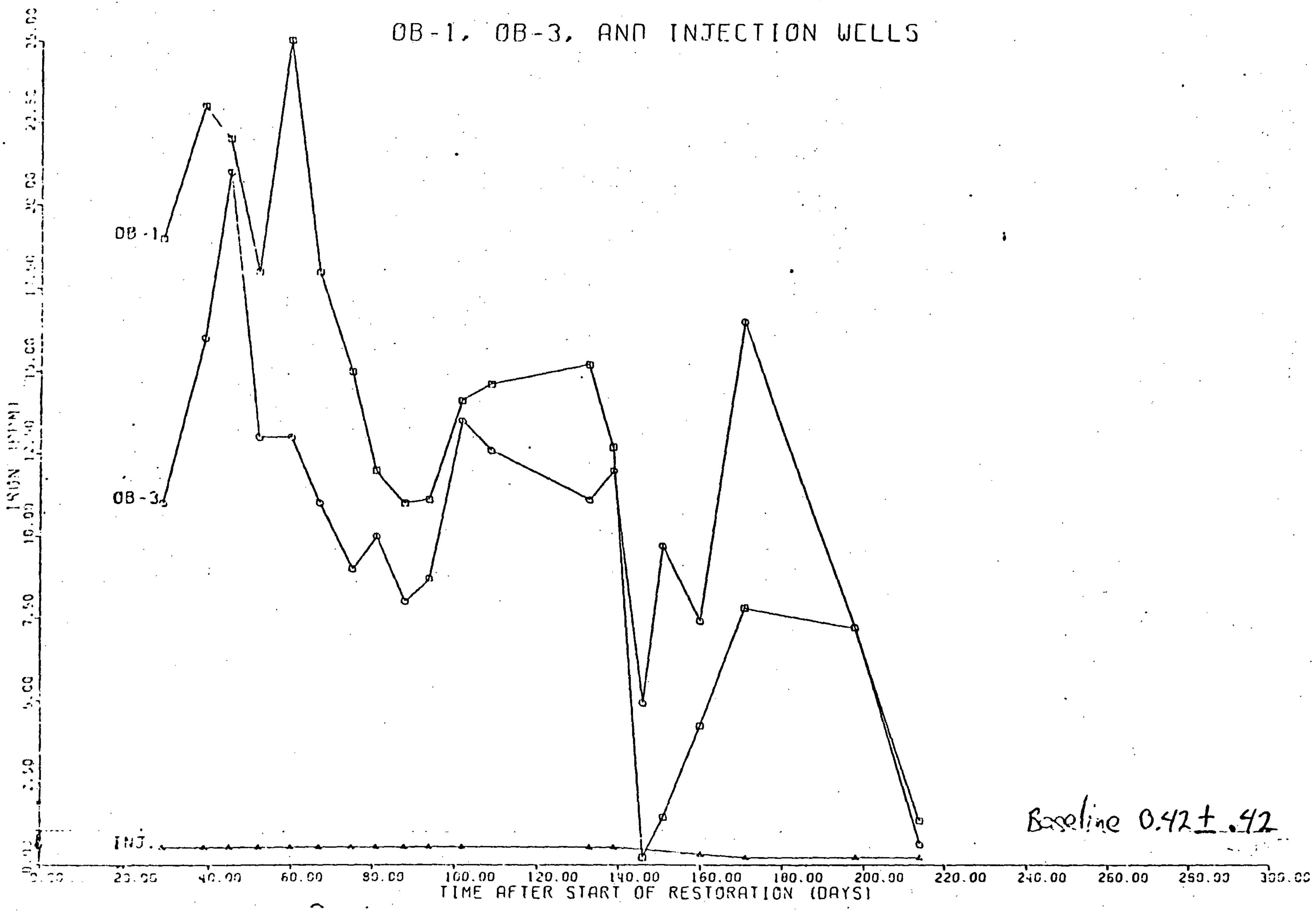


Figure 9. pH vs. time

Figure 10. Iron concentration vs. time



Baseline 0.42 ± .42

Form No. 6-175

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF MINES

CALCULATION SHEET

SIGNATURE ______________ DATE ______________

TITLE ______________ JOB No. ______________

SUBJECT ______________ SHEET No. ______________

U.S. GOVERNMENT PRINTING OFFICE:1963-O-681087 (831-229)

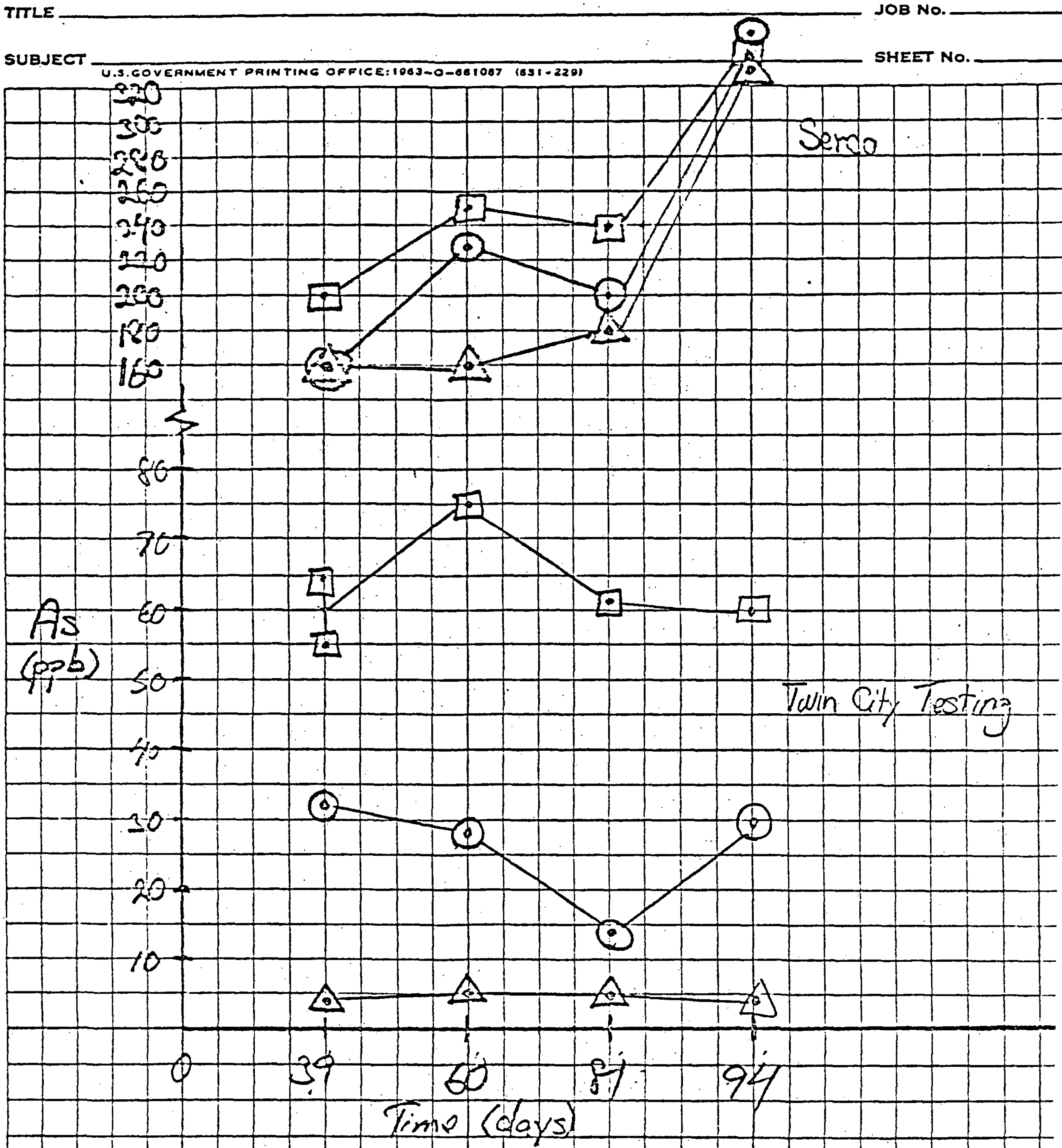


Figure 11. Arsenic concentration vs. time

DEPARTMENT OF THE INTERIOR
BUREAU OF MINES

CALCULATION SHEET

SIGNATURE ____________ DATE ____________

TITLE ____________ JOB No. ____________

SUBJECT ____________ SHEET No. ____________

U.S. GOVERNMENT PRINTING OFFICE: 1963-O-681087 (831-229)

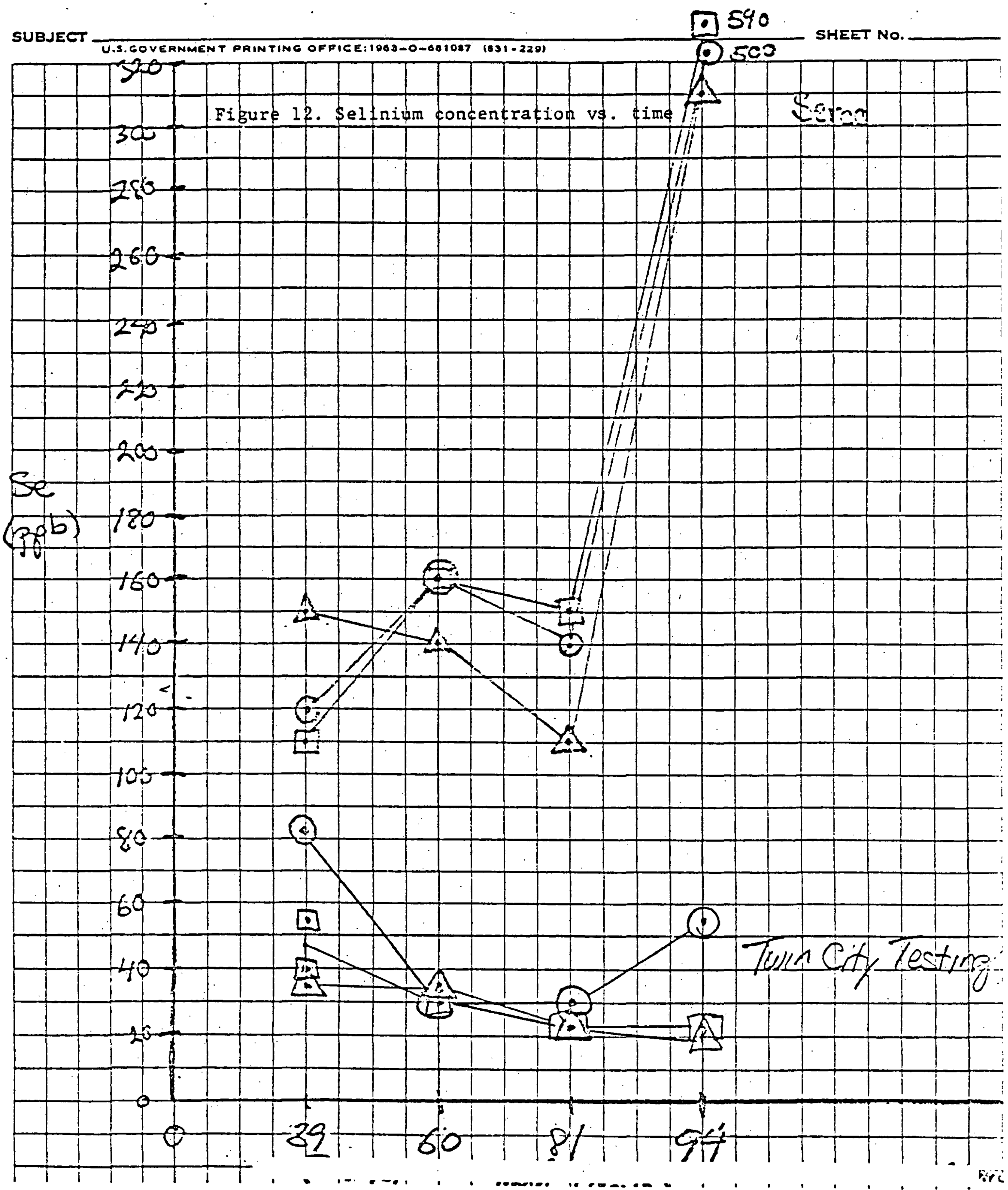
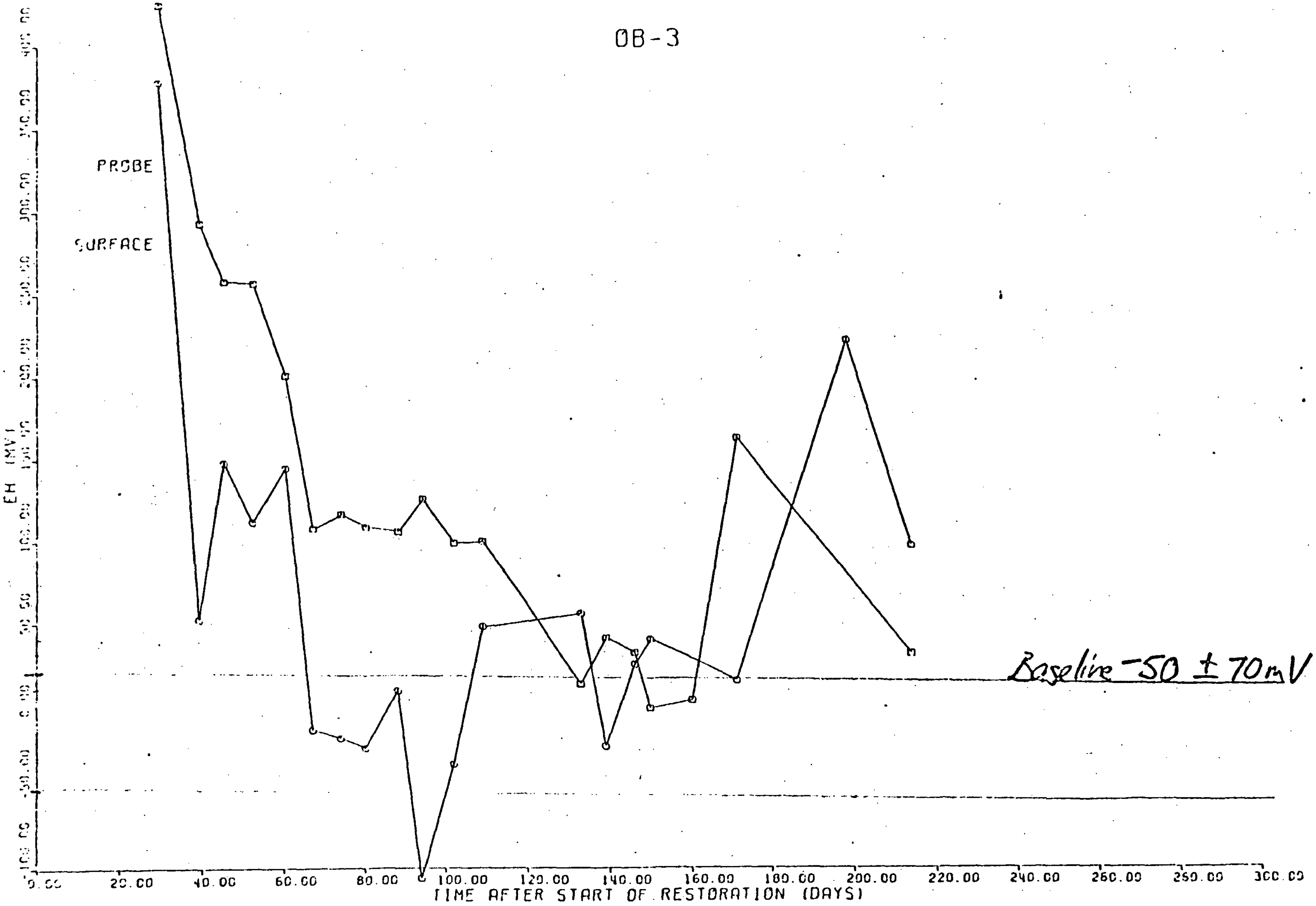
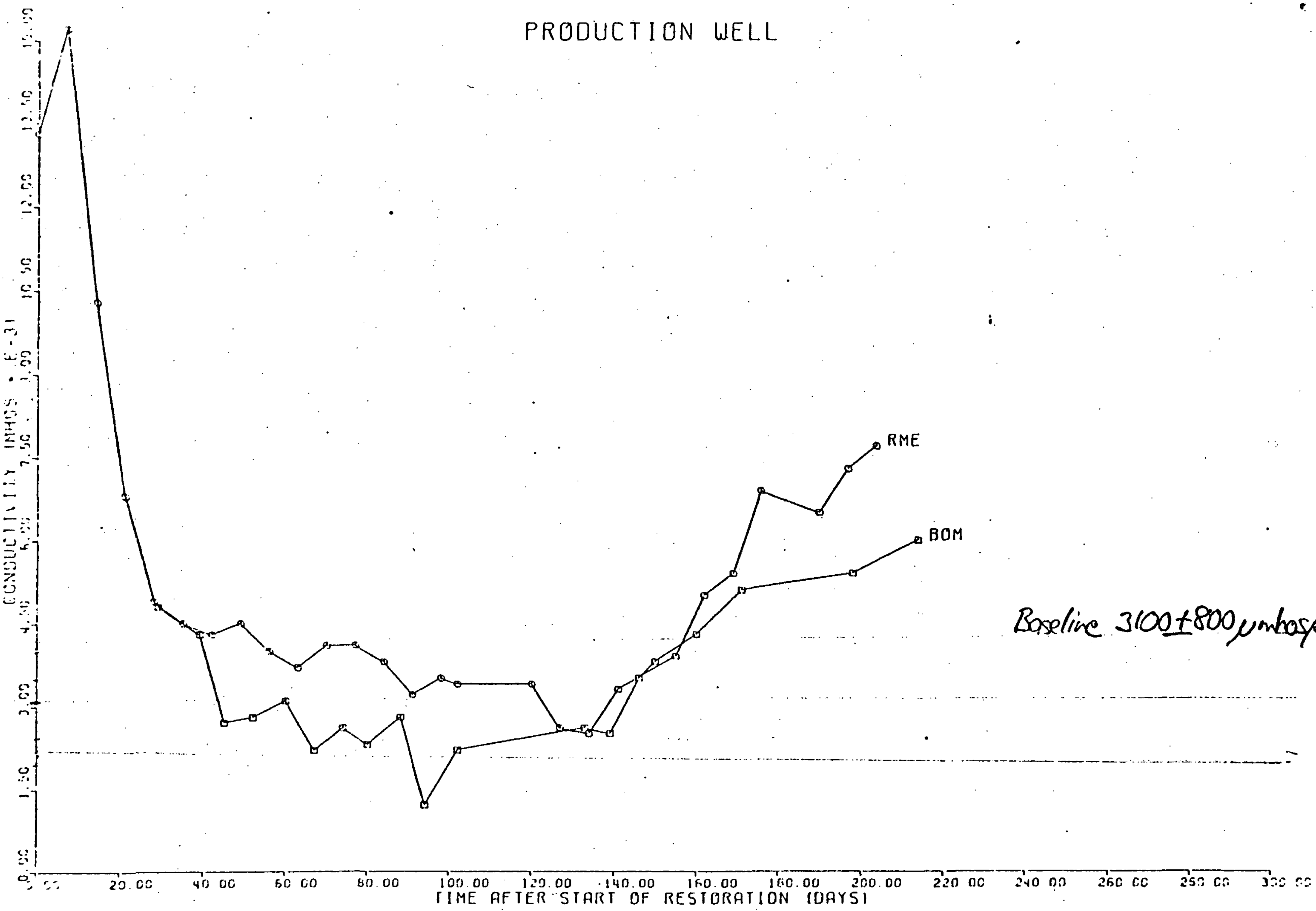


Figure 12. Selinium concentration vs. time



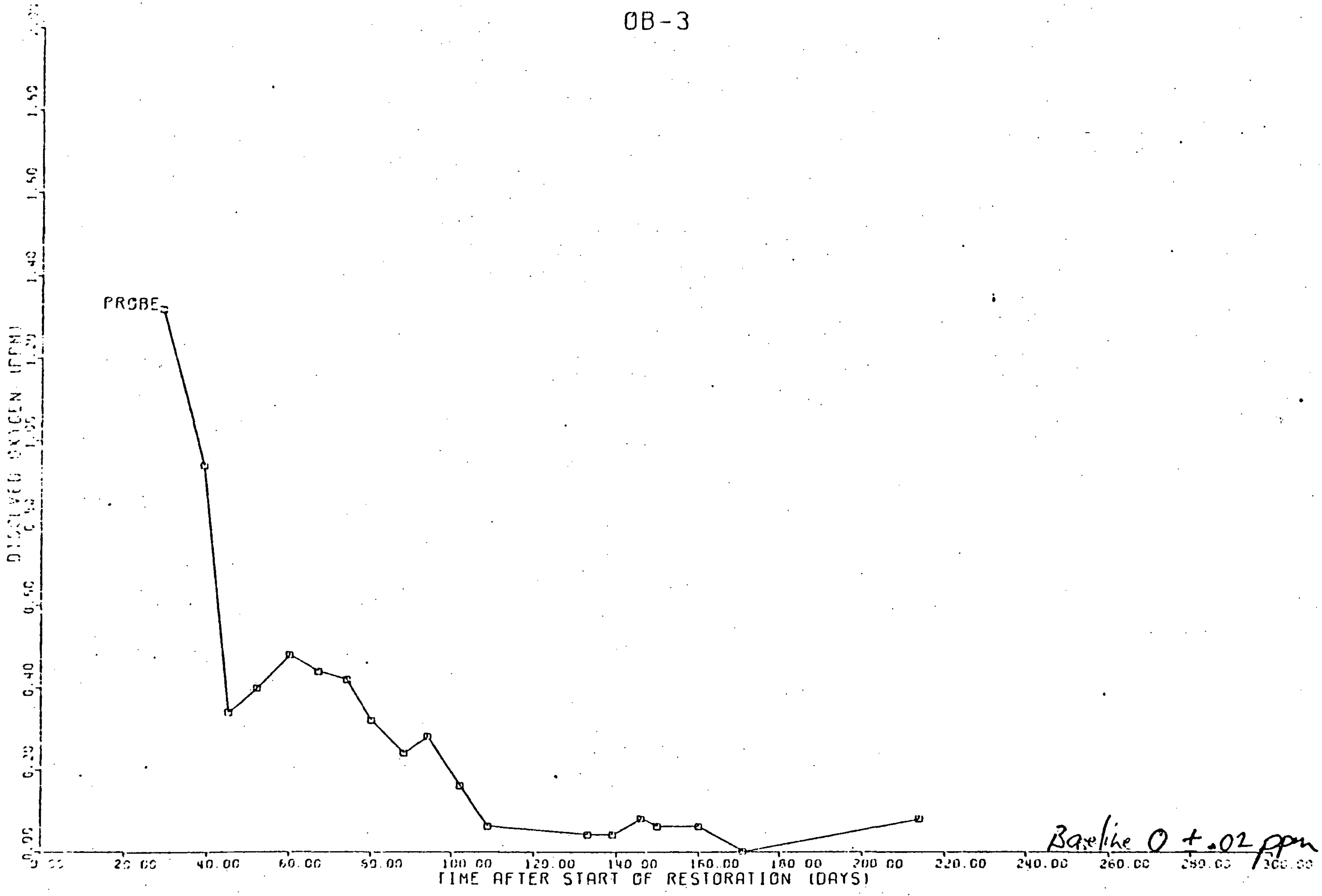
Baseline -50 ± 70mV

Figure 13. Oxidation-reduction potential (Eh) vs. time



Baseline 3100±800 μmhos/cm

Figure 14. Conductivity vs. time



Baseline 0 + .02 ppm

Figure 15. Dissolved oxygen vs. time .

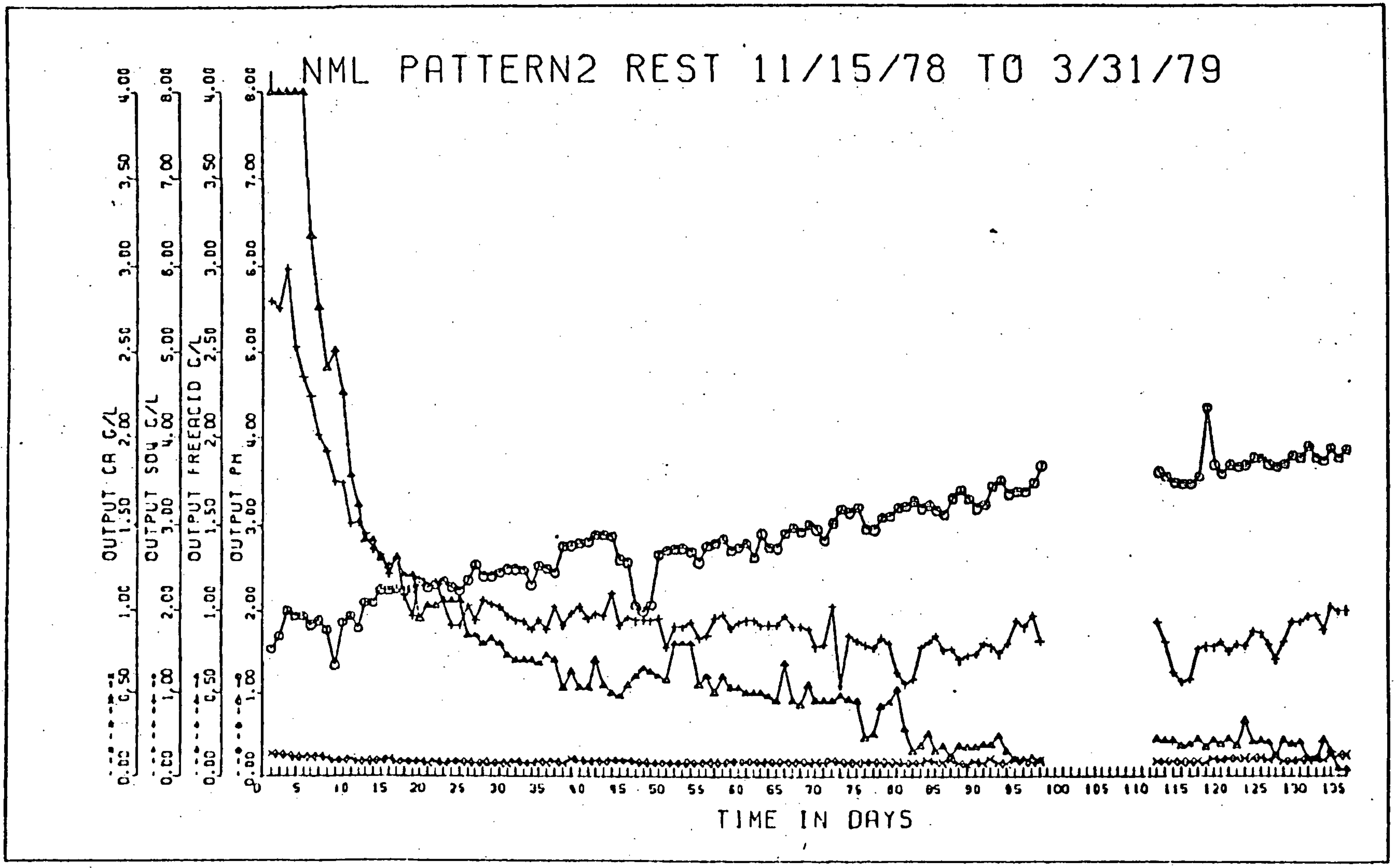


Figure 16. Changes in production well water quality with time

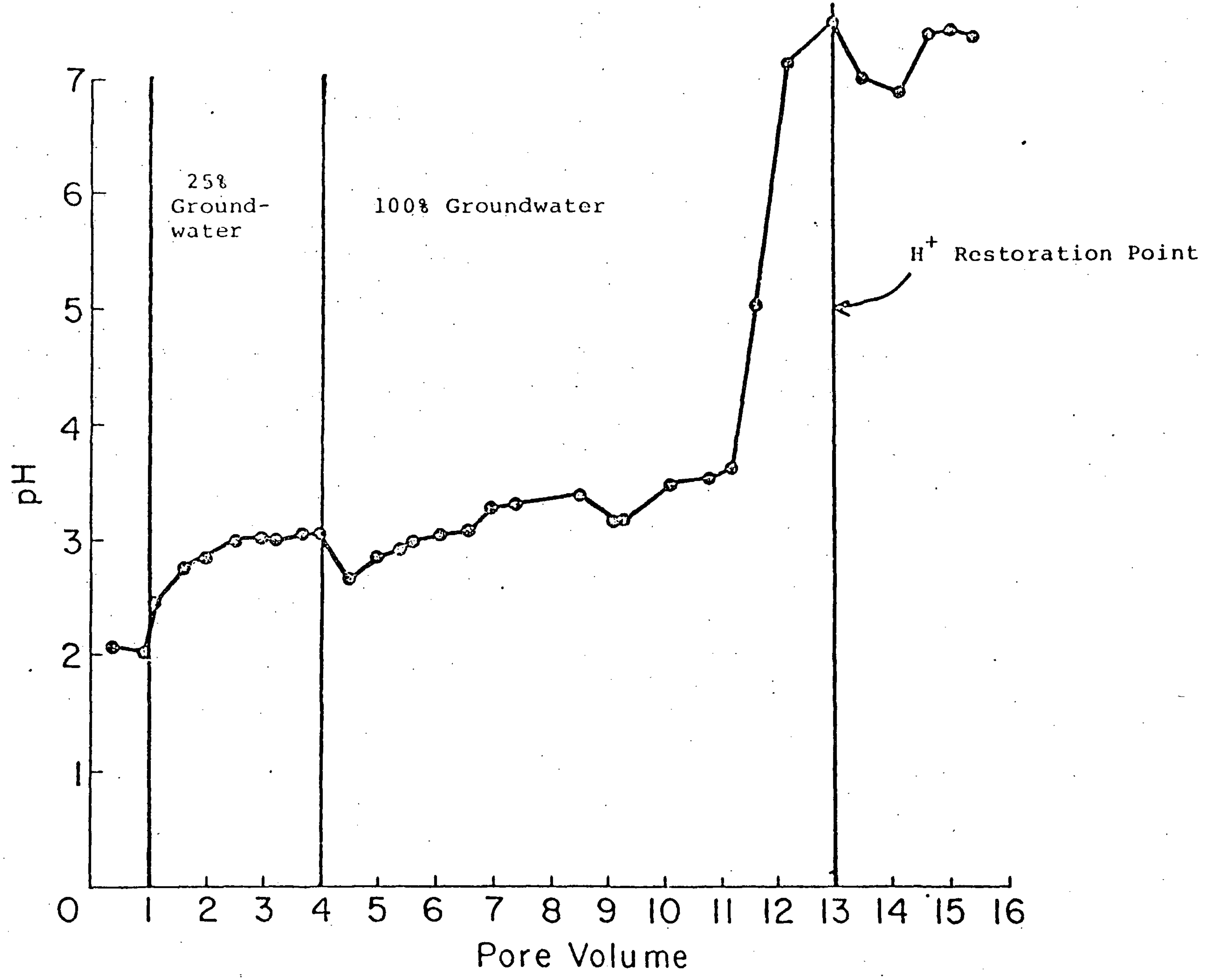


Figure 17. pH vs. pore volume during sample restoration, in a 120 cm column

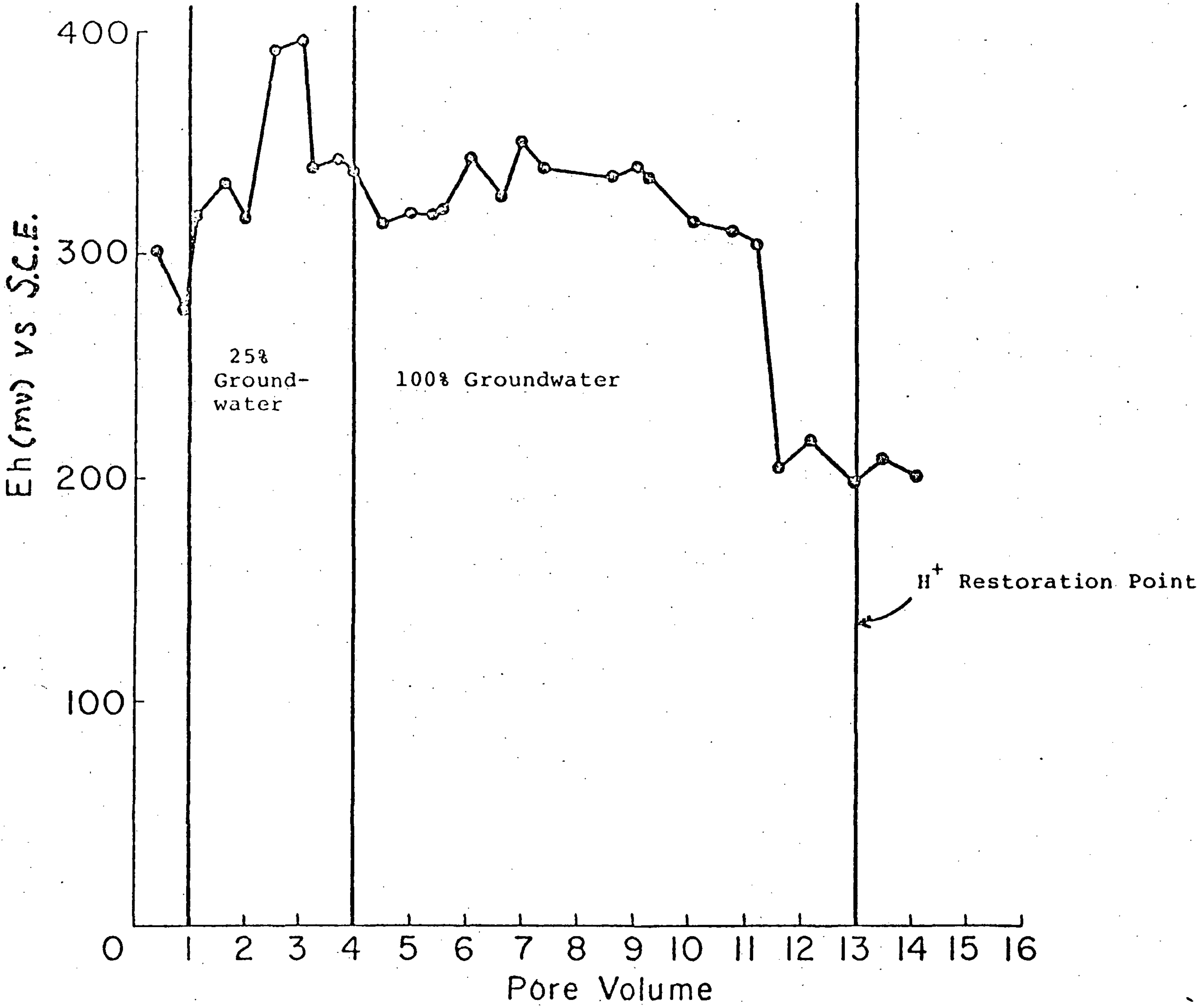


Figure 18. Eh vs. pore volume during smaple restoration in a 120 cm column

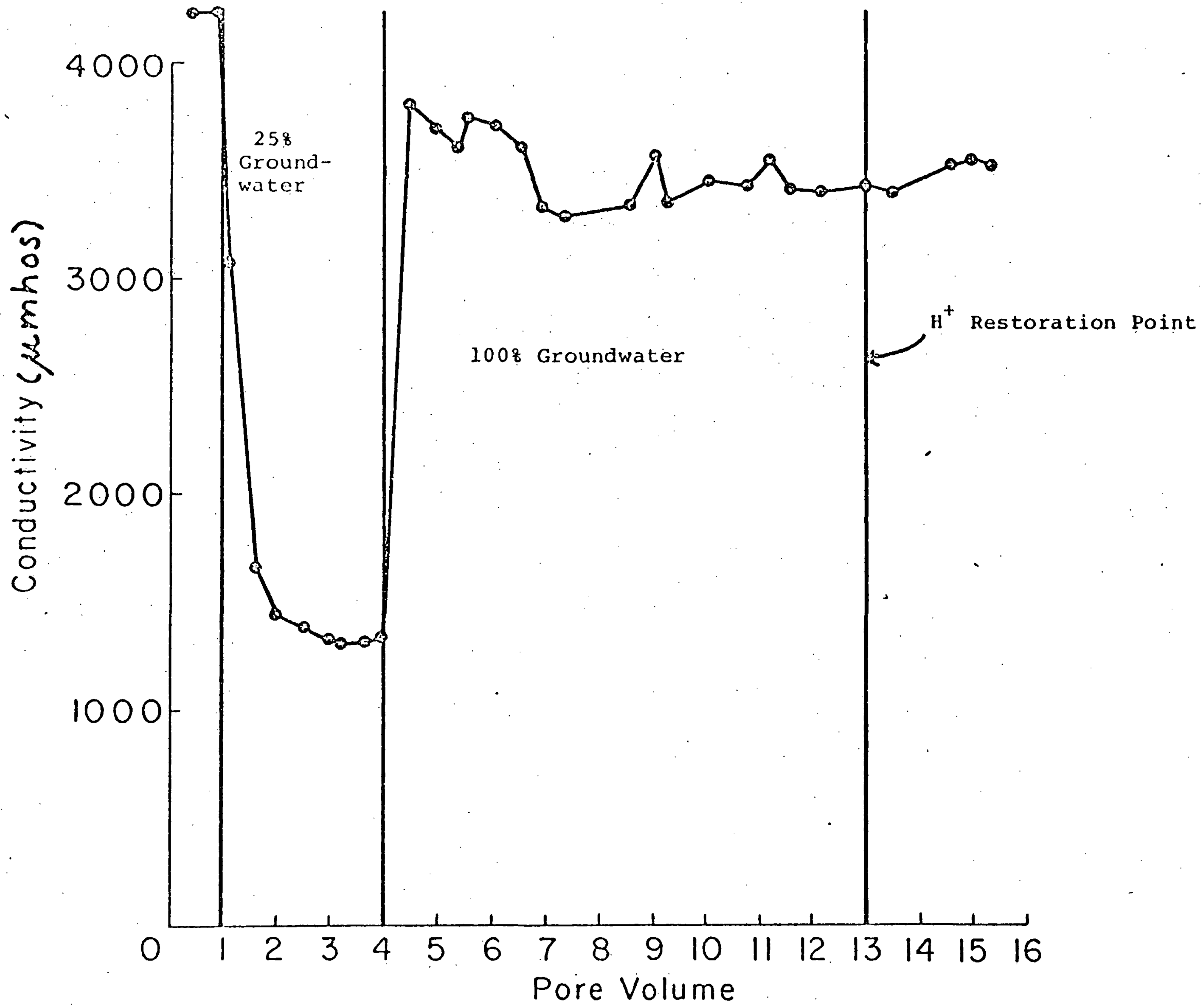


Figure 19. Conductivity vs. pore volume during sample restoration, in a 120 cm column

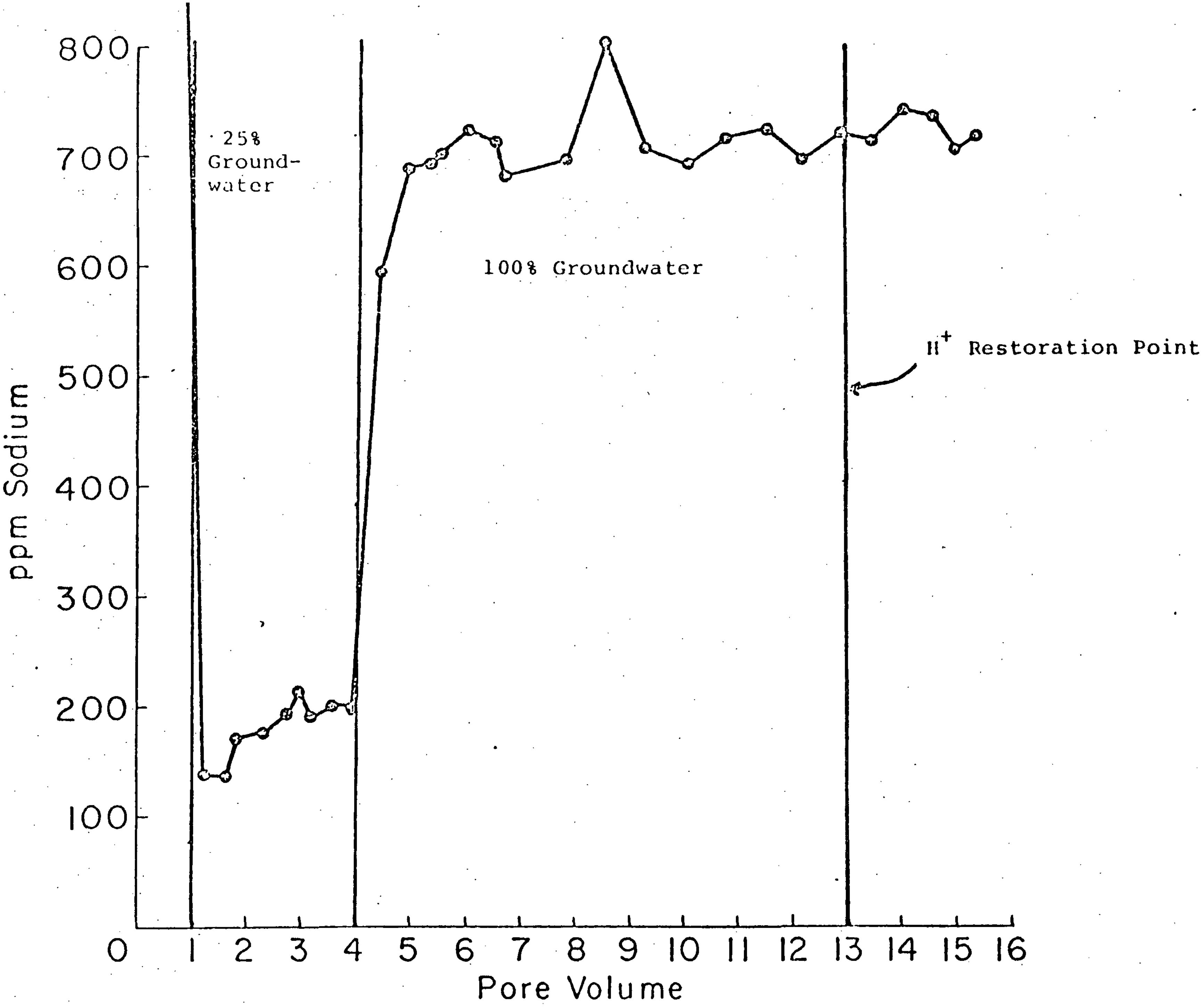


Figure 20. Sodium vs. pore volume during sample restoration, in a 120 cm column

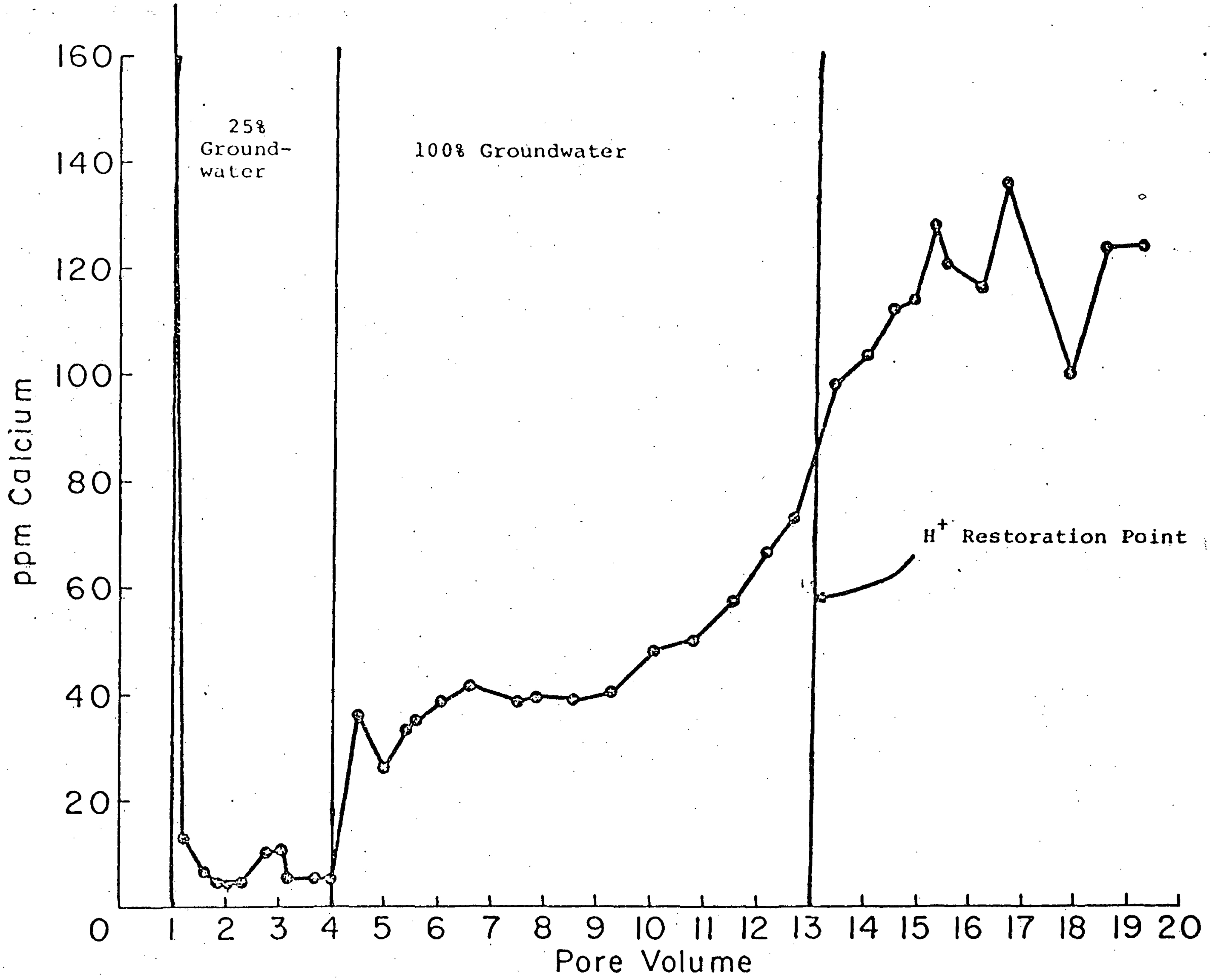


Figure 21. Calcium vs. pore volume during sample restoration, in a 120 cm column

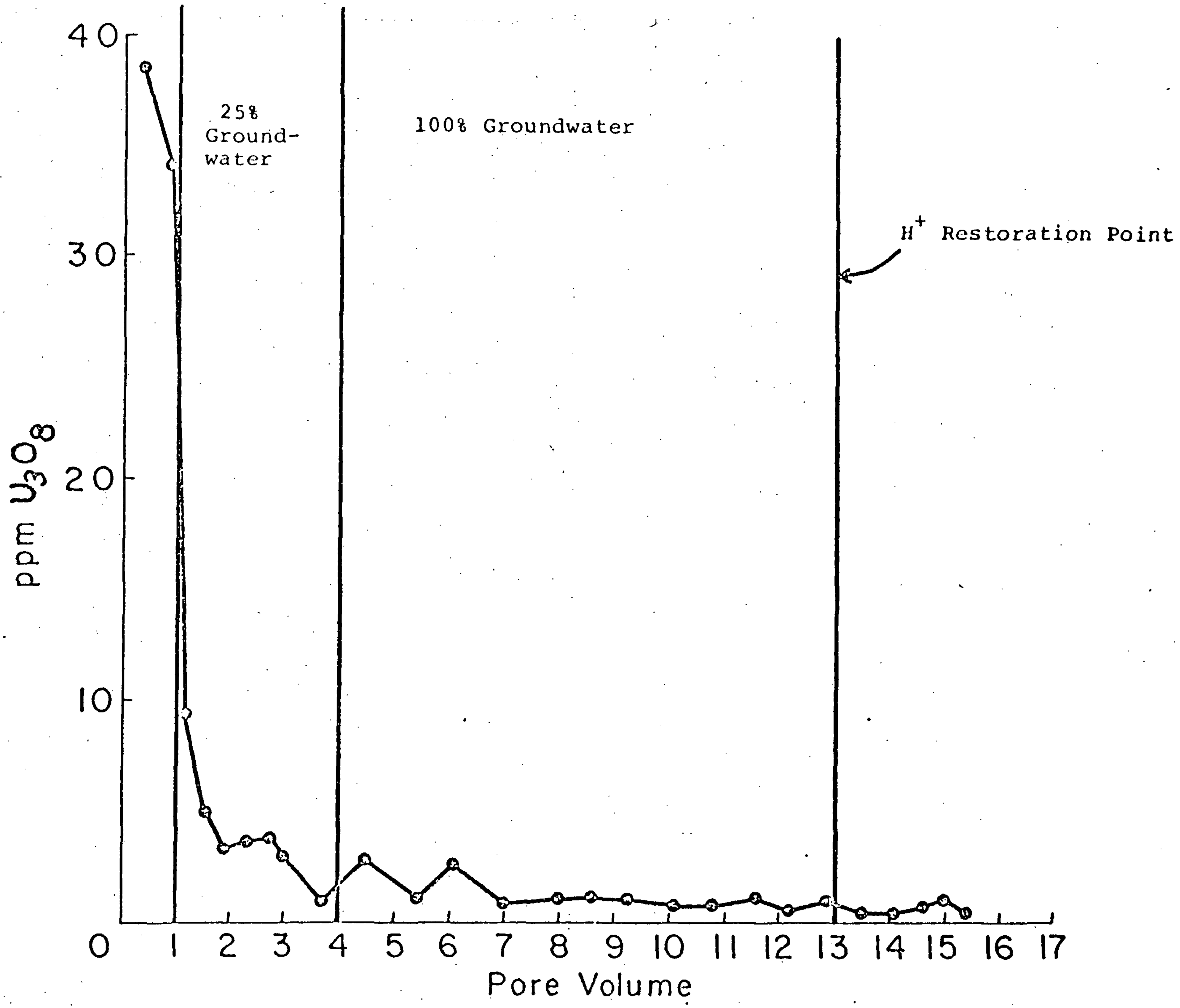


Figure 22. Uranium vs. pore volumn during sample restoration in a 120 cm column

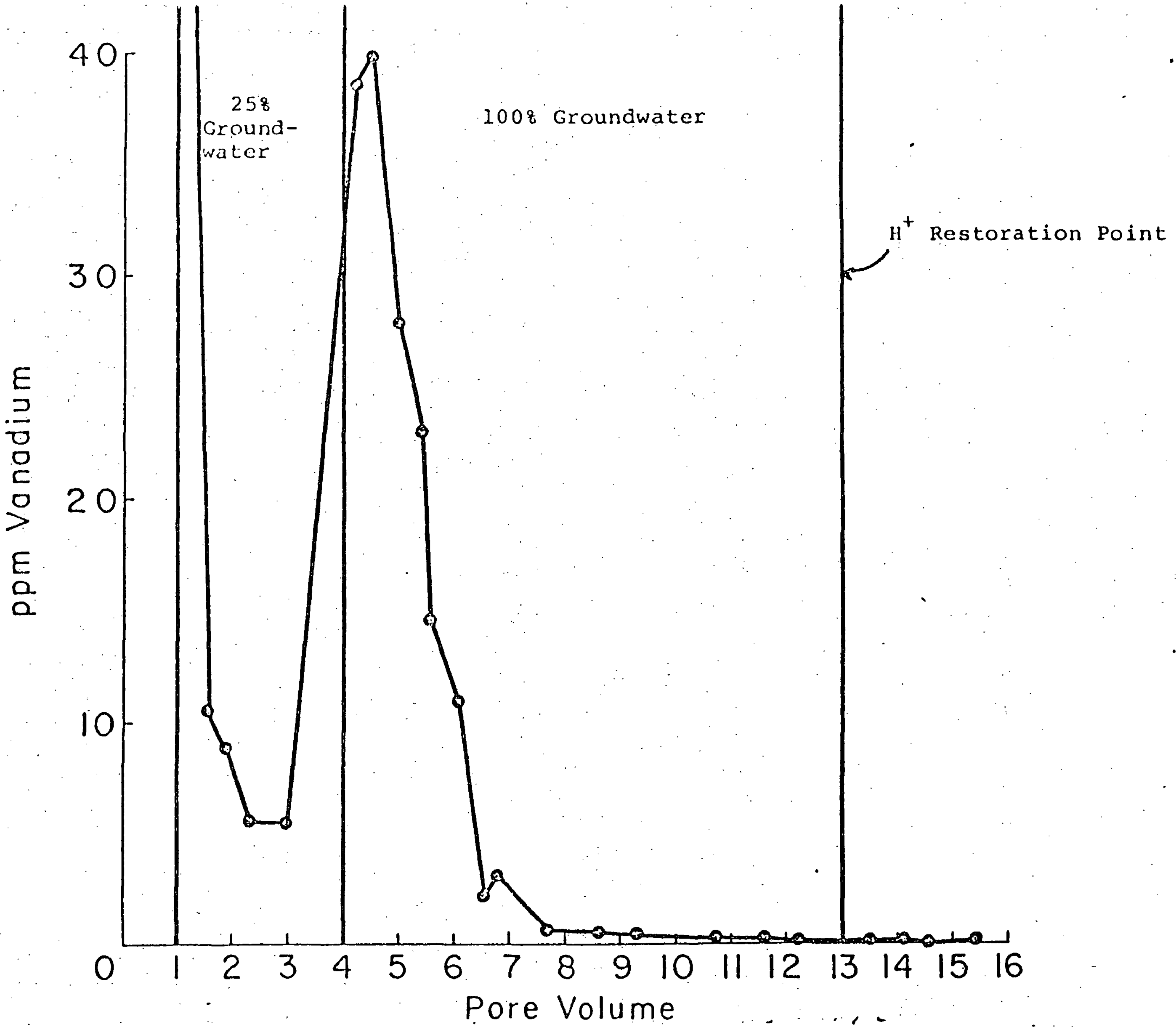


Figure 23. Vanadium vs. pore volume during sample restoration in a 120 cm column

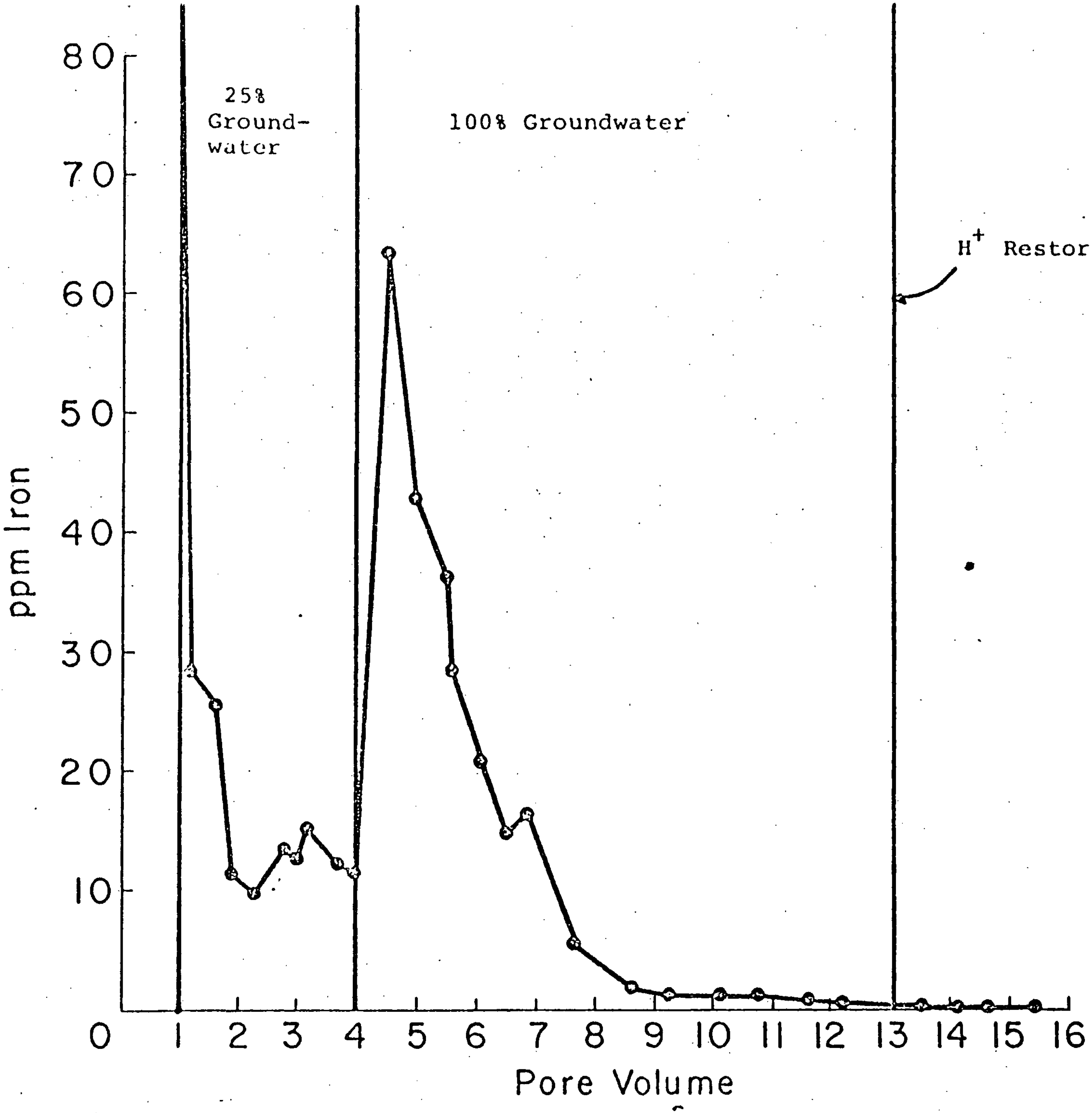


Figure 24. Iron vs. pore volume during smaple restoration in a 120 cm column

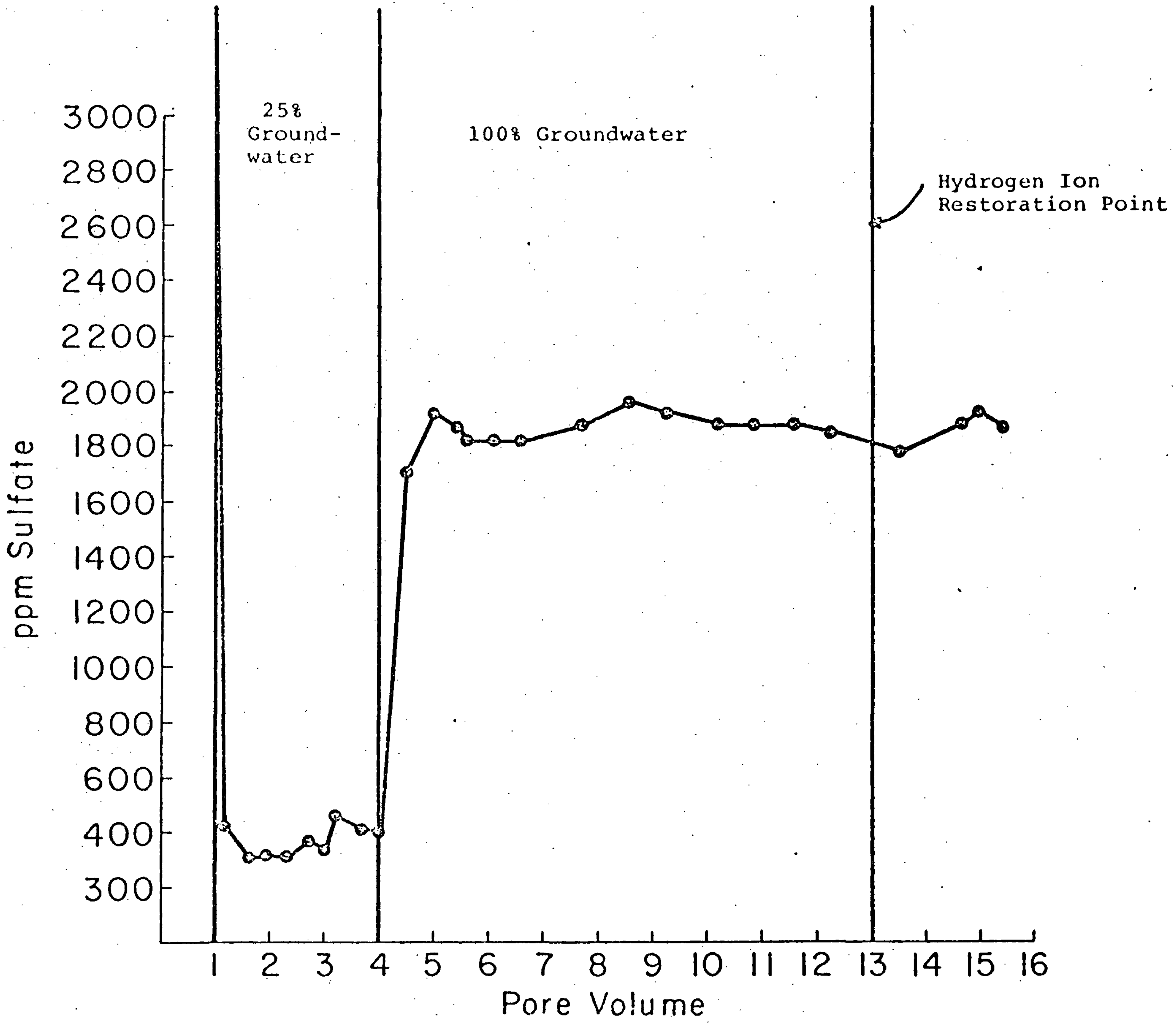


Figure 25. Sulfate vs. pore volume during sample restoration in a 120 cm column

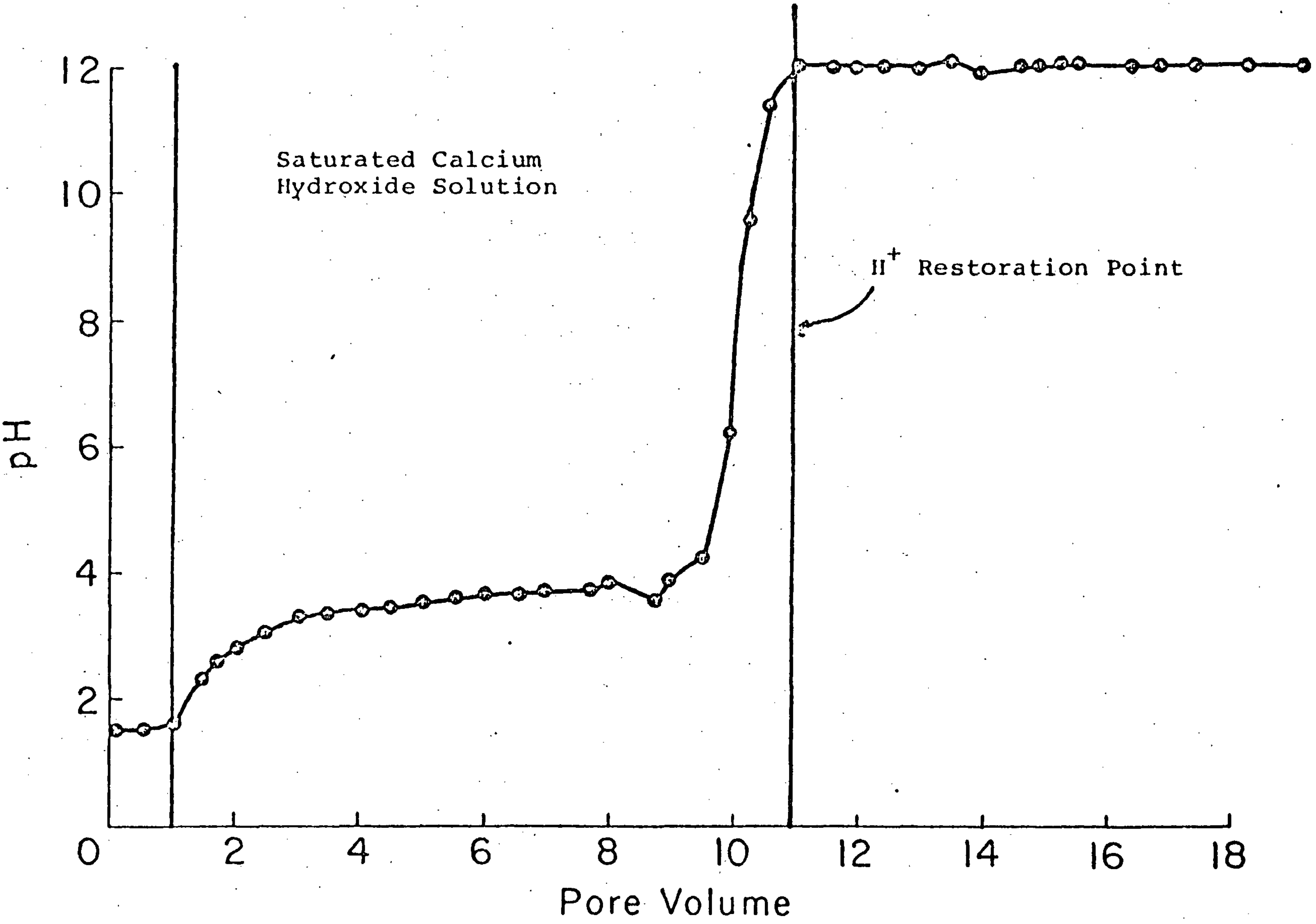


Figure 26. pH vs. pore volume for calcium hydroxide restoration solution in a 60 cm column

TABLE 1. - List of cations and anions and methods of determination

Ion	Method	Ion	Method
Sodium	1	Silicon	1
Potassium	1	Uranium	2
Calcium	1	Arsenic	3
Magnesium	1	Selenium	3
Zinc	1	Aluminum	1
Iron	1	Sulfate	4
Manganese	1	Chloride	5
Zirconium	1	Fluoride	5
Titanium	1	Phosphorus	6
Vanadium	1	Sulfide	5

1. Atomic adsorption - direct aspiration
2. X-ray fluorescence
3. Atomic adsorption - graphite furnace
4. Gravimetric
5. Ion-selective electrode
6. Colormetric

TABLE 2. - Groundwater parameter; comparing preleach and restored groundwater[1]

	Native groundwater outside ore zone	Preleach pattern groundwater	Restored groundwater
pH	6.8	5.8-7.9	6.0
free acid	10	10	20
Calcium	110	20-360	65
Sulfate	1620	300-3600	2,200
Total dissolved solids	2660	680-5450	3,000

[1] All values in parts per million (except pH).

APPENDIX: BUREAU OF MINES CHEMICAL ANALYSES

DATE	NO.OF DAYS	WELL	U	V	SE	AS	SI	ZN	MN	FE	MG	CA	K	NA	P	F	CL	SO4
12/06/78	29	OB-1	5.8	58.			49.	4.4	.29	19.	47.	86.	11.	333.	.52	1.0	38.	1.72
12/16/78	39	OB-1	4.0	55.	.11	.20	47.	4.2	.31	23.	50.	87.	12.	337.	.24	1.2	44.	1.11
12/22/78	45	OB-1	4.5	55.			46.	4.0	.38	22.	53.	101.	11.	349.	.34	1.7	35.	1.65
12/29/78	52	OB-1	7.9	65.			39.	6.0	.40	18.	63.	126.	12.	354.	.33	.73	39.	1.85
1/06/79	60	OB-1	12.0	79.	.16	.25	39.	6.0	.50	25.	67.	124.	13.	391.	.18	.83	36.	1.83
1/13/79	67	OB-1	9.5	58.			34.	5.0	.39	18.	63.	119.	12.	370.	.14	.83	37.	1.68
1/20/79	75	OB-1	9.7	47.			32.	4.0	.28	15.	60.	103.	12.	375.	.11	.79	39.	1.56
1/26/79	81	OB-1	6.5	43.	.15	.24	30.	3.4	.23	12.	58.	106.	8.0	419.	< .05	1.1	36.	1.50
2/03/79	88	OB-1	5.3	29.			28.	3.3	.22	11.	57.	104.	7.8	409.	< .05	.90	47.	1.47
2/09/79	94	OB-1	3.7	24.			29.8	3.1	.20	11.1	57.	103.	8.4	400.	< .05	1.1	40.	1.48
2/17/79	102	OB-1	2.4	24.			30.5	2.9	.20	14.1	54.	99.	8.2	690.	< .05	.81	36.	1.52
2/24/79	109	OB-1	2.1	17.			32.0	2.7	.30	14.6	53.	98.	8.3	420.	< .05	.82	35.	1.53
3/20/79	133	OB-1	2.2	24.			30.4	2.7	.35	15.2	55.	105.	8.0	470.	.05	.68	25.	1.60
3/26/79	139	OB-1	2.2	23.			24.6	2.6	.39	12.7	66.	135.	9.0	790.	< .05	.53	29.	2.45
4/02/79	146	OB-1	.12	2.5			27.3	1.5	.30	.2	51.	111.	9.3	1130.	< .05	1.1	34.	2.80
4/07/79	151	OB-1	.43	16.6			29.5	1.4	.27	1.4	59.	111.	10.3	1310.	.05	1.7	37.	3.20
4/16/79	160	OB-1	.45	8.2			29.	.8	< .20	4.2	49.	35.	11.9	1020.	< .05	1.2	35.6	2.96
4/27/79	171	OB-1	2.0	22.0			35.	4.6	.21	7.8	50.	24.	12.7	1090.	.074	.8	36.4	3.29
5/24/79	198	OB-1	4.2	17.0			29.	5.1	.20	7.2	42.	20.	12.3	1200.	.086	.77	41.5	3.66
6/09/79	214	OB-1	.31	2.9			11.	.15	< .20	1.3	35.	34.	12.9	1630.	.11	.61	47.2	4.47
12/06/78	29	OB-3	.16	15.			32.	1.4	.22	11.	46.	73.	9.	286.	.07	.66	41.	1.13
12/16/78	39	OB-3	.07	15.	.12	.16	31.	1.6	.18	16.	51.	90.	11.	324.	.05	.68	44.	1.64
12/22/78	45	OB-3	.06	24.			29.	2.1	.35	21.	53.	106.	10.	338.	.12	.62	36.	1.51
12/29/78	52	OB-3	.06	13.			30.	1.4	.25	13.	52.	103.	10.	324.	< .05	.58	37.	1.38
1/06/79	60	OB-3	.13	14.	.16	.23	25.	1.0	.24	13.	53.	99.	10.	356.	< .05	.33	37.	1.33
1/13/79	67	OB-3	.07	< 2.			21.	1.0	.23	11.	52.	98.	10.	359.	< .05	.33	38.	1.33
1/20/79	75	OB-3	< .05	< 2.			19.	1.0	.19	9.	53.	91.	10.	355.	< .05	.38	39.	1.27
1/26/79	81	OB-3	.07	< 2.	.14	.20	18.	1.2	.23	10.	54.	103.	7.2	399.	< .05	.51	39.	1.32
2/03/79	88	OB-3	.05	< 2.			15.	0.9	.21	8.	55.	102.	7.0	397.	< .05	.50	43.	1.29
2/09/79	94	OB-3	< .05	< 2.			15.	0.8	.20	8.7	52.	99.	7.4	370.	< .05	.78	36.	1.29
2/17/79	102	OB-3	< .05	< 2.			18.6	1.2	.30	13.5	50.	98.	7.5	380.	< .05	.75	35.	1.38
2/24/79	109	OB-3	< .05	< 2.			20.7	1.0	.20	12.6	51.	98.	7.7	410.	< .05	.76	35.	1.40
3/20/79	133	OB-3	< .05	< 2.			16.4	.7	.31	11.1	42.	87.	6.6	420.	< .05	.56	25.	1.25
3/26/79	139	OB-3	.06	< 2.			12.7	.4	.45	12.0	70.	145.	8.5	790.	< .05	.38	30.	2.30
4/02/79	146	OB-3	< .05	< 2.			15.1	.5	.46	4.9	60.	136.	10.6	1630.	< .05	.40	31.	4.05
4/07/79	151	OB-3	.06	6.1			17.0	.5	.35	9.7	44.5	106.	10.9	1850.	.20	2.7	32.	4.10
4/16/79	160	OB-3	.21	7.5			18.	.3	< .20	7.4	26.	21.	10.6	1160.	.17	2.2	34.2	3.15
4/27/79	171	OB-3	2.8	27.			38.	8.1	.35	16.5	5.7	26.	13.8	1000.			37.2	
5/24/79	198	OB-3	4.2	17.0			29.	5.1	.20	7.2	42.	20.	12.3	1200.	.086	.77	41.5	3.66
6/09/79	214	OB-3	.22	< 2.			10.	< .1	< .20	0.6	28.	31.	13.0	1830.	.19	1.3	36.1	4.84
12/06/78	29	INJ.	.07	< 2.			< 5.	< .1	.22	< .5	53.	95.	10.	311.	< .05	1.4	39.	1.34
12/16/78	39	INJ.	.05	< 2.	.15	.16	< 5.	< .1	.19	< .5	53.	97.	10.	316.	< .05	1.2	44.	1.39
12/22/78	45	INJ.	.06	< 2.			< 5.	< .1	.26	< .5	53.	103.	9.	306.	< .05	1.4	41.	1.13
12/29/78	52	INJ.	.06	< 2.			< 5.	< .1	.25	< .5	53.	103.	10.	296.	< .05	1.3	38.	1.14
1/06/79	60	INJ.	.08	< 2.	.14	.16	< 5.	< .1	.21	< .5	54.	99.	10.	334.	< .05	.81	36.	1.13
1/13/79	67	INJ.	.09	< 2.			< 5.	< .1	.19	< .5	53.	91.	10.	345.	< .05	.80	36.	1.14
1/20/79	75	INJ.	.13	< 2.			5.	< .1	.18	< .5	53.	95.	10.	347.	< .05	.78	46.	1.15
1/26/79	81	INJ.	.08	< 2.	.11	.18	< 5.	< .1	.15	< .5	46.	84.	5.5	334.	< .05	.93	36.	0.97
2/03/79	88	INJ.	.08	< 2.			< 5.	< .1	.16	< .5	48.	87.	5.8	359.	< .05	.80	39.	1.01
2/09/79	94	INJ.	< .05	< 2.			< 5.	< .1	.20	< .5	55.	100.	7.1	370.	< .05	1.1	40.	1.19
2/17/79	102	INJ.	< .05	< 2.			6.0	< .1	.10	< .5	39.	70.	5.2	320.	< .05	1.2	32.	.95
3/20/79	133	INJ.	.062	< 2.			6.2	< .1	.10	< .5	13.5	31.	15.5	1540.	< .05	.83	40.	3.10
3/26/79	139	INJ.	.087	< 2.			< 5.	< .1	.14	< .5	26.9	61.	8.8	1490.	< .05	1.0	29.	3.10
4/16/79	160	INJ.	.080	< 2.			< 5.	< .1	< .20	.3	30.	33.	12.8	1310.	.05	.76	34.2	3.67
4/27/79	171	INJ.	.060	< 2.			< 5.	< .1	.20	< .2	35.	35.	12.4	1050.	< .05	.63	37.2	2.86
5/24/79	198	INJ.	.080	< 2.			< 5.	< .1	.21	< .2	50.	47.	10.9	640.	< .05	.59	43.3	1.74
6/09/79	214	INJ.	.050	2.3			< 5.	< .1	< .20	< .2	17.	8.	13.0	2330.	< .05	.60	36.1	6.02

APPENDIX: FIELD LABORATORY MEASUREMENTS

	NO.OF			OB-3			OB-1			INJECTION			PRODUCTION		
DATE	DAYS	WELL	TEMP	PH	EH	COND	PH	EH	COND	PH	EH	COND	PH	EH	COND
12/06/78	29			3.30	378	2000	2.70	396	2600	6.68	178	1750	2.31	335	4800
12/16/78	39			3.30	52	2000	3.30	123	2600	6.85	92	1800	2.49	323	4300
12/22/78	45			4.50	148	1800	3.24	49	2100	6.62	154	1800	2.90	273	2700
12/29/78	52			4.95	112	1750	2.95	235	2400	6.48	200	1750	2.82	241	2800
1/06/79	60			5.22	145	2200	4.50	52	3200	6.75	-23	1900	2.88	297	3100
1/13/79	67			5.75	-15	2000	4.70	-4	2300	6.55	150	1800	3.50	181	2200
1/20/79	74			5.65	-20	1800	4.70	42	2200	6.50	-52	2000	2.90	255	2600
1/26/79	80			5.80	-26	1800	4.95	-9	2000	6.65	-40	1900	3.10	81	2300
2/03/79	88			6.10	9	2000	5.15	2	2000	6.50	98	1800	3.35	180	2800
2/09/79	94		14.0	5.95	-107	1600	5.05	-57	1900	6.75	52	1750	3.35	188	1200
2/17/79	102		14.8	5.82	-36	2000	5.98	-30	2000	6.42	72	1750	3.47	192	2200
2/24/79	109		13.4	5.82	48	2000	5.13	53	2000						
3/20/79	133		15.7	5.97	56	2200	5.05	41	2500	6.46	15	4700	3.81	160	2600
3/26/79	139		13.5	5.89	-25	3500	5.15	45	3800	6.87	42	4500	3.73	43	2500
4/02/79	146		13.5	5.93	25	5400	5.91	65	4400	7.26	10	5800	4.15	150	3500
4/06/79	150		16.4	6.69	40	6400	6.23	10	5200	6.90	0	7000	4.29	110	3800
4/16/79	160		17.0				5.98	15	4800	6.57	-60	5800	4.09	-80	4300
4/27/79	171		16.5	5.10	15	4900	4.35	0	5000	6.75	195	5400	5.15	30	5100
5/24/79	198		21.0	4.65	222	5400	4.65	222	5400	1.80	222	17500	4.65	420	5400
6/09/79	214		17.3	7.23	97	7800	6.95	157	7000	8.22	262	8000	6.29	187	6000

APPENDIX: DOWNHOLE PROBE MEASUREMENTS FOR OH-3

DATE	NO.OF DAYS	WELL	TEMP	PH	EH	COND	D.O.
12/06/78	29	PROB	13.1	4.70	425	2030	1.32
12/16/78	39	PROB	12.7	6.50	293	2690	.94
12/22/78	45	PROB	12.5	6.50	258	2710	.34
12/29/78	52	PROB	12.6	6.63	257	2660	.40
1/06/79	60	PROB	12.3	7.27	201	2660	.48
1/13/79	67	PROB	12.3	7.30	108	2630	.44
1/20/79	74	PROB	12.1	7.79	117	2630	.42
1/26/79	80	PROB	12.0	7.24	109	2670	.32
2/03/79	88	PROB	12.3	7.20	106	2650	.24
2/09/79	94	PROB	12.7	7.61	126	2630	.28
2/17/79	102	PROB	12.7	7.32	99	2730	.16
2/24/79	109	PROB	12.7	7.24	100	2790	.06
3/20/79	133	PROB	12.9	7.26	13	2640	.04
3/26/79	139	PROB	13.2	7.00	41	4500	.04
4/02/79	146	PROB	13.3	7.10	32	7400	.08
4/06/79	150	PROB	13.0	7.54	-2	7980	.06
4/16/79	160	PROB	13.6	7.22	3	6260	.06
4/27/79	171	PROB	14.2	5.58	163	5890	.00
6/09/79	214	PROB	16.1	9.92	31	9100	.08

APPENDIX: ROCKY MOUNTAIN ENERGY CHEMICAL ANALYSES

DATE	NO.OF DAYS	WELL	PH	EH	COND	U308	V205	FE	CA	SO4
11/07/78	0	INJ.	1.56	430.	12700	.002	.146	.044	.109	4.47
11/14/78	7	INJ.	1.99	350.	7100	.001	.002	.011	.086	1.47
11/21/78	14	INJ.	6.76	60.	2800	.001	.001	.001	.082	1.13
11/28/78	21	INJ.	6.75	100.	2750	.001	.001	.001	.082	0.81
12/05/78	28	INJ.	6.93	80.	2400	.001	.001	.001	.087	0.87
12/12/78	35	INJ.	6.90	90.	2500	.001	.001	.001	.085	1.84
12/19/78	42	INJ.	7.26	90.	2700	.001	.001	.001	.089	1.05
12/25/78	49	INJ.	6.74	125.	2800	.001	.001	.001	.089	1.22
1/02/79	56	INJ.	7.09	105.	2100	.001	.001	.001	.085	1.00
1/09/79	63	INJ.	7.81	150.	2500	.001	.001	.001	.086	0.87
1/16/79	70	INJ.	6.88	150.	2700	.001	.001	.001	.086	1.19
1/23/79	77	INJ.	6.73	50.	2800	.001	.001	.001	.083	0.96
1/30/79	84	INJ.	7.79	15.	2700	.001	.001	.001	.085	1.04
2/06/79	91	INJ.	6.66	45.	1470	.001	.001	.001	.079	1.16
2/13/79	98	INJ.	6.67	-30.	2969	.001	.001	.001	.069	1.26
2/17/79	102	INJ.	7.38	15.	5280	.001	.001	.001	.096	1.75
3/07/79	120	INJ.	7.00		2700	.001	.001	.001	.088	1.22
3/14/79	127	INJ.	5.65		2300	.001	.001	.001	.023	1.28
3/21/79	134	INJ.	5.79		4300	.001	.001	.001	.030	2.34
3/28/79	141	INJ.	6.99		4300	.001	.001	.001	.011	1.95
4/11/79	155	INJ.	7.69		4800	.001	.001	.001	.066	3.29
4/18/79	162	INJ.	6.69		7200	.001	.001	.001	.054	3.65
4/25/79	169	INJ.	6.95		8400	.001	.001	.001	.041	3.94
5/02/79	176	INJ.	7.46		5100	.001	.001	.001	.067	2.47
5/09/79	183	INJ.	7.07		10400	.001	.001	.001	.032	5.44
5/16/79	190	INJ.	9.71		8300	.001	.001	.001	.034	4.24
5/23/79	197	INJ.	9.99		9500	.001	.001	.001	.017	5.03
5/30/79	204	INJ.	9.88		7700	.001	.001	.001	.036	4.01
11/07/78	0	PROD	1.59	415.	13300	.051	.413	.121	.177	6.60
11/14/78	7	PROD	1.79	410.	15200	.042	.329	.102	.154	5.95
11/21/78	14	PROD	1.81	390.	10300	.042	.191	.066	.118	4.03
11/28/78	21	PROD	2.24	340.	6800	.029	.119	.044	.089	2.72
12/05/78	28	PROD	2.34	340.	4900	.022	.112	.032	.080	2.30
12/12/78	35	PROD	2.43	350.	4500	.018	.093	.028	.081	2.13
12/19/78	42	PROD	2.65	330.	4300	.015	.077	.024	.086	1.88
12/25/78	49	PROD	2.55	350.	4500	.012	.064	.027	.091	1.96
1/02/79	56	PROD	2.59	330.	4000	.012	.074	.022	.081	1.89
1/09/79	63	PROD	2.74	330.	3700	.013	.068	.021	.082	1.69
1/16/79	70	PROD	2.87	320.	4100	.011	.061	.018	.081	1.82
1/23/79	77	PROD	3.03	350.	4100	.009	.059	.018	.085	1.56
1/30/79	84	PROD	3.13	300.	3800	.007	.052	.015	.084	1.55
2/06/79	91	PROD	3.38	300.	3200	.008	.046	.013	.094	1.62
2/13/79	98	PROD		280.	3500	.007	.046	.013	.078	1.60
2/17/79	102	PROD		270.	3400	.007	.046	.015	.089	1.63
3/07/79	120	PROD	3.58		3400	.0068	.046	.014	.086	1.86
3/14/79	127	PROD	2.66		2600	.0062	.040	.013	.102	1.56
3/21/79	134	PROD	3.66		2500	.0063	.038	.012	.095	1.59
3/28/79	141	PROD	3.70		3300	.0061	.038	.013	.093	1.76
4/11/79	155	PROD	4.24		3900	.0051	.043	.013	.157	2.96
4/18/79	162	PROD	4.29		5000	.0061	.047	.014	.128	2.98
4/25/79	169	PROD	4.16		5400	.0033	.032	.015	.116	2.84
5/02/79	176	PROD	6.35		6900	.0003	.004	.001	.034	3.48
5/09/79	183	PROD	4.45			.0060	.029	.011	.089	3.46
5/16/79	190	PROD	4.24		6500	.0042	.033	.008	.075	3.58
5/23/79	197	PROD	4.96		7300	.0039	.023	.007	.065	3.78
5/30/79	204	PROD	5.50		7700	.0038	.026	.007	.066	3.92