BibKey
46248

FINAL REPORT

TO MONTEZUMA CASTLE NATIONAL MONUMENT

OF INVESTIGATIONS OF MONTEZUMA WELL

Gerald A. Cole

Arizona State University

September 1965

ACKNOWLEDGEMENTS

I am very much indebted to the members of the National Park Service, and specifically to the personnel of Montezuma Castle National Monument, for their splendid cooperation. Although the personnel changed during our period at the Well, the attitude never did; we were given extreme courtesy and cheerful, friendly help at all times.

The National Science Foundation awarded the Arizona State University a grant (#13161) for me to initiate work on the Well. Without this aid we could not have started our studies. I am pleased to acknowledge the assistance of the Foundation in this respect.

The owner of the property which includes Soda Springs was kind enough to let me collect water there, and to observe the springs, which have a relationship, probably, to the artesian situation at Montezuma Well. I am indebted, therefore to Mr. Weber for his help.

Several specialists aided in the identification of organisms. Several have been mentioned in the text of this report. It would be only fitting to acknowledge here their specialized taxonomic aid. They include the following: Mildred S. Wilson, harpacticoid copepods; Harry C. Yeatman, cyclopoid copepods; Henery van der Schalie, molluscs; Eugene C. Ogden, pondweeds; Leonora K. Gloyd, odonatans; the late Percy Moore, hirudinelas; Clarence C. Goodnight; oligochaetes; David R. Lauck, hemipterans; Maurice T. James and

Max W. McFadden, Dipterans; Arland T. Hotchkiss, charophytes; Hugh B. Leech, coleopterans; and Rodger Mitchell, the arachnids.

Montezuma Well is a large limnocrene environment occupying a circular limestone depression in the Plio-pleistocene Verde formation in Yavapai County, Arizona (N lat. 34°, W long. 111° 45'). The rim of the steep-walled depression is 1,112 m above sea level and from 17 m to 24 m above the water level. Since 1947 it has been a detached portion of the Montezuma Castle National Monument administered by the National Park Service.

Limnological investigation of the Well was made possible through a grant from the National Science Foundation made to Arizona State University, Gerald A. Cole, Principal Investigator. The grant, NSF-13161, was made for the period of two years.

Investigation commenced in July 1960 when an inflatable raft became available; other limnological equipment had been ordered, but did not arrive until later. The raft and other gear were stored at an adobe storage shed one-half mile from the Well, near the campground. All equipment was transported from the shed, over the cliff and down to the water's edge and back up at each visit. Early work started with John G. Weise as assistant. His duties were taken over by William T. Barry later. Work went forward through the summer of 1962. There were sporadic visits after that with other personnel of ASU and of the University of Arizona involved. The latter were Richard Hevly, Paul S. Martin and Paul E. Damon. Dr. Louis A. Krumholz helped with mapping of the basin and preparation of the hydrographic map (Figure 1). We always

had more than courteous treatment and excellent dooperation from members of the National Monument staff.

The origin of the Well has been explained in various ways. Three misconceptions, which have no basis to support them are that the Well is an extinct geyser, a meteorite crater, or a volcanic crater. Several authors have attributed the Well to collapse of a cave which had been dissolved by ground water after the disappearance of pluvial Lake Verde (Blake 1906, Colton and Baxter 1932, Henderson 1933, McKee et al. 1947, Schroeder 1948). This is also the offical explanation presented by the Monument information bulletins. There is some question, however, that this is a typical limestone sink even though it lies in the calcareous Verde formation material. Lange (1957) presented a good case for a different origin...possibly a deep-lying salt lens similar to others known in the Verde Valley was involved. The expansion of hydration followed by dissolving of the salt brought about fracturing and collapse of overlying limestone and resulted in the depression now occupied by water. This hypothesis has some merit; the surrounding topography is not typical of karst regions, the Well being the only depression of this type in the Verde Valley.

Both Lange (1957) and Cole (1963) have compared Montezuma Well to certain cenotes of the Yucatán Peninsula which were studied by Pearse et al. (1936). Also in the wouthwest, Devil's Inkwell, one of the Bottomless Lakes of New Mexico, superficially

resembles the Well.

Water enters the Well from deep fissures at the bottom. At least three are involved and these have been sounded to some 40 m (Figure 1). Water entered at the rate of at least 4,159 m^3/ day during the period of the study. This estimate is based on the weir readings of water leaving the Well. The greatest weir readings we encountered implied the entrance and loss of 7,293m^3/ a day.

The outlet at the southeast margin of the Well is a subterranean one through which water plunges to emerge outside the cliffs which bound the Well. The inner outlet is termed the swallet by the Monument personnel. It is about five m above the outer outlet and some 60 m away. When the water leaves by way of the swallet, it reappears in a cave before emerging at the small outer outlet. On the basis of experiments with fluorescein dye, we can state that this journey takes seven minutes. The volume of the emerging water, measured at the first weir, is not equal to that leaving by way of the swallet. Once, when the swallet was blocked with sand bags, the level of the lake was raised several inches in a few hours, reducing the flow at the outer outled only about one-third. This implies subsurface outlets not yet located.

The outer outlet is at the head of a small irrigation ditch which runs parallel to Wet Beaver Creek, beginning about 3 m above the creek level. Some water is lost from the Well, which is not measured at the weir and does not go down the irrigation ditch.

At times this loss is conspicuous as seepage into Beaver Creek.

MORPHOMETRY

We prepared a bathymetric map of Montezuma Well (Figure 1) during the early summer of 1960. This was used to calculate the morphometric data shown in Table 1. A stadia-rod-and-transit survey was made first. From this the outline of the Well was plotted. Then more than 400 soundings were made at 2 m intervals along a calibrated line stretched between known points. From these soundings the contours were plotted. The deep, narrow fissures were not included in morphometric calculations, and contour lines were not plotted for them. Therefore, the maximum depth was considered to be 17 m, although roughly 28 m^2 lie below that depth. Even though the soundings were made at close intervals, we later found another small fissure northeast of the lake center. We sounded this to approximately 31 m. The approximate location of this hole is marked by an X in Figure 1.

The morphometric data presented in Table 1, show no unusual features. The shoreline development is not far from unity as would be expected in a solution-collapse basin. The volume development is 1.27, close to the mean index which Hayes (1957) calculated from the data of approximately 500 lakes. Because of the steep cliffs closely surrounding the Well, and because of the small wind-effective length, stratification and even meromixis might be expected. Neither feature applies, however, because of

the artesian nature of the Well and its well-defined outlet. Water on the order of one-tenth the total volume enters and leaves each twenty-four hour period.

Table 1

Some morphometric parameters of Montezuma Well, Yavapai Co. Arizona

Parameter	Value	
Area *	0.758 ha	1.87 acres
Maximum length	111.8 m	367 feet
Shoreline	321.7 m	1,056 feet
Shoreline development	1.04	
Volume	50,842 m^3	13,431,337 gallons
Volume development	1.18	
Maximum depth *	17 m	55.7 feet
Mean depth	6.7 m	22 feet
Mean depth/maximum depth	0.394	

* 28.36 m^2 are below the 17-m contour at the places where the water enters. Maximum soundings there were 42 m (138 feet).

TEMPERATURE and HEAT

Erroneous ideas persist that the water temperature of Montezuma Well is constant. Actually, the entire water mass warms and cools with the seasons. Highest temperatures occur during the months of July and August. At these times the Well water is in excess of 24° C. Lowest temperatures are encountered in December and January when the mean of the water column is slightly more than 19° C. In February the mean temperature is above 20° and may rise to 22°, but unseasonal cold snaps may cool the lake. For example, unusually cold weather on March 10 and 11, 1962, brought the mean temperature down to 19.46° C.

Waters of the deep inlets do approach constancy in temperature, however. Water in the west hole, which was encountered most often, had a mean temperature of 23.76° C and the annual range was only 0.73° C. Because they were difficult to find, the fissures were not sampled regulary, but the data we have suggest a slight seasonal undulating of the temperature of the entering water. The waves follow the changes in the mean temperature of the entire Well, although there may be a slight lag. (Temperature data are recorded graphically in Figure 2.)

The water in the east hole was slightly warmer, with a mean of 24.19°, and a maximum of 24.22° C. On October 7, 1961, the east hole water was 24.17°, while the west hole was 23.89° C. The small northeast hole (X on Figure 1) was sounded to 30.5 m on Feb. 11, 61 : it was 24.44° C, although the water of the west

fissure had been 23.38° the day before. In terms of Fahrenheit scale: the water which enters Montezuma Well is between 74° and 76° F.

Thermal stratification in the Well is limited to the surface waters and the abrupt change encountered upon entering the deep fissures. During summer days, the surface layer was often warmed to 28°---a high of 29.1° C was encountered once. During such days there may be a difference of more than 5° C within the Well, but conspicuous gradients are limited to the upper meter. Below this most changes involved only tenths of degrees and the lake was practically isothermal.

As the thermistor approached the deep fissures, usually there was no temperature change until it entered the hole. Then a vertical difference of only five or six cm would result often in a conspicuous change in temperature. The change was especially marked during winter, when warm water was entering the Well via the fissures. In summer, the entering water was sometimes slightly cooler than the main body of water. Only once did we find a broad cline; the mean temperature of the Well was 20.7°, and from 13 m to 17.8 m near the west hole the water warmed at the rate of 0.65°/m. On most occasions we could not detect the presence of a hole by lowering the thermistor vertically until we actually entered the hole. On rare occasions, however, we detected warm water on the bottom and we knew that we were in the vicinity of a fissure. From these observations it seems

that usually, entering water moved across the bottom of the Well. This might spin the water mass; some of our data on diel changes of temperature suggest this to be the case. For example, often the entire water mass cooled slightly at night and warmed during the day. Thus at 6:45 PM on October 7, 1960, the mean temperature of the Well was 23.01° C; the next day at 7:10 AM the mean was 22.85°, a decline of 0.16° C. By 11:30 AM it had gained a mean of 0.04°, and by 2:10 PM the lake's man temperature was 22.91° making, therefore, a total gain of 0.06° since morning at the rate of 0.01°/hour. These changes were not caused by temperatures at the surface only; in other words, the results were not achieved by summing those chantes in the warming and cooling of the surface waters alone. Instead, we detected slight gains and losses throughout the entire water column. The warming and cooling proceeded from the surface downward, allowing us to make some estimates of the magnitude of currents within the basin.

On some cold winter mornings clouds of vapor rose above the Well from the relatively warm water. At such times, skims of ice could be found at the margins of the lake in extremely shallow water.

In terms of heat, rather than temperature, the Well shows relatively little change throughout the year also. The warmest mean temperature, observed July 24, 1961, was 24.46° C; the coldest was December 27, 1961,...19.09° C. When these figures

are converted to total calories for the entire water mass, and divided by the surface area the following data are revealed:

Greatest heat	16,407 g cal/cm^2
Least heat	12,804 g cal/cm^2
difference	3,603 g cal/cm^2

The difference in the heat contents, referred to unit area, could be considered the annual heat budget of the Well. This is a very low figure, but this is a function of the daily input of calories via the warm entering water. Assuming 1.5 million gallons a day enter by way of the deep fissures at a mean temperature of about 24.1° C, the Well receives more than 1800 g cal/cm^2 per day, the internal energy content of the inlet waters referred to unit area of lake surface.

Besides the loss of calories in the internal energy content of the outlet, the evaporation rate is probably an inportant factor in cooling. We have some approximate rates of evaporation, based on losses from dishes placed at the Well's shores. During the winter months evaporation is some 0.433 dm/day; in the summer it may be at least one cm a day, our mean value being 0.89 cm/day. The corresponding heat losses based on employment of 585 cal/g latent heat, that which corresponds to 20° C, are winter, 253 g cal/cm^2/day; summer 521 g cal/cm^2/day. Some hot July days over 75 m^3 (19,800 gallons) may be lost via evaporation during the 24-hour period.

CURRENTS

In order to establish the presence of current patterns in the Well, fluorescein dye was introduced and watched. Furthermore, temperature changes in the water column over the deepest part of the lake were carefully observed. These changes involved vertical warming during the day, or cooling at night, and the tracing of isotherms moving downward. Figure 3 shows some results; in general there is a counter-clockwise pattern in the Well, with water moving downward at certain places.

Temperature changes over the deep west fissure implied vertical eddy diffusivity of 0.203 - 0.267 g cm/sec. These figures were derived from diurnal warming during November and December. Some October nocturnal cooling data implied rates on the order of 0.099 g cm/sec. The direct warming during the day by solar radiation certainly complicates the picture and these eddy-diffusivity data are open to much question.

Watching the downward movement of fluorescein near the east depression yeilded estimates of 1.6 - 1.8 g cm/sec as the dye angled downward. Other places in the lake do not pull the dye down; it simply hangs below the surface and spreads laterally.

In general, the counter-clockwise, spiral spinning of the lake, with certain spots showing sinking currents, is probably a function of the entering water.

SPECIFIC CONDUCTANCE

A Whitney conductivity meter, combined with an electrical underwater thermometer, was employed to determine specific conductance *in situ*. All results were converted later and referred to 25° C. Seasonal variations ranged from 1,122 to 1,394 micromhos/ cm, but vertical variations on any one date were negligible from surface to bottom.

An interesting artifact was encountered early in the study when extremely abrupt drops in conductivity meter occured as the electrodes were lowered into the deep fissures at the bottom of the Well. The apparent reductions in conductivity were on the order of 850 micromhos, giving the impression that water low in electrolytes was entering the basin. This problem was resolved in the laboratory using Montezuma Well water, sand collected from the deep fissures, and an electric stirrer. With the stirrer turned off and the electrodes in the water, readings were normal; with the stirrer in motion, sand swirled about the electrodes, blocking much of their surface and resulting in a rapid drop of the meter needle. Probably an identical situation was observed in Soda Springs, about 1.6 km from Montezuma Well. At Soda Springs water bubbles to the surface in pools of sand similar to those at the bottom of Montezuma Well...at the fissure inlets. The electrodes of the conductivity meter suspended in the shallow water (*ca.* 7 cm) gave a reading implying about 1,700 micromhos, but there was an immediate and precipitous drop of an apparent

800 micromhos when the electrodes were lowered into the turbulent sand.

As the deep fissures in Montezuma Well were encountered there was an immediate rise in temperature and the apparent drop in conductance. These meter readings held steady as the thermistor and accompanying electrodes were lowered. Toward the bottom of the fissures, however, conditions were different; then the needle of the conductivity dial swung back and forth in an erratic manner. Presumably at the bottom of each fissure, where water entered, there was relatively less sand and more electrode surface was exposed for short intervals.

LIGHT AND TRANSPARENCY

The turbidity of water at all depths in Montezuma Well was always zero when compared to a distilled-water blank. The B & L Spectronic "20" and the Hach DR Photometer were both used for this test.

Occasionally a submarine photometer, purchased from the Kahl Scientific Instrument Corp., was used for detecting light penetration in Montezuma Well. Other transparancy data were derived from a standard 20-cm Secchi disc. These instruments were used, usually between 1000 and 1400 hours.

There was a very nearly constant relationship between the lower limit of the euphotic zone and the Secchi disc value. The euphotic zone was defined as the region of the lake from the surfact to the depth where 99% of the surface radiation had been

absorbed. The mean value of the $\frac{\text{euphotic zone}}{\text{Secchi disc}}$ ratio was 3.03, euphotic zone applying to the Well depth where only 1.0% of incident solar radiation remained. Also the mean Secchi disc transparency was at the subsurface level where about 80% of surface radiation had been absorbed. Some data is shown on the following page in tabular form.

TABLE 2

Some optical properties of Montezuma Well, Yavapai County, Arizona

DATE	TIME	SECCHI DISC m	LOWER LIMIT EPHOTIC ZONE m
10 Aug. 60	1000	3.5	-
7 Sept. 60	1625	-	9.5
17 Sept. 60	1330	2.3	9.04
7 Oct. 60	1830	1.9	-
8 Oct. 60	1310	2.8	-
5 Nov. 60	1345	2.9	9.6
3 Dec. 60	1205	4.25	10.1
27 Dec. 60	1400	4.0	9.7
11 Feb. 61	1300	2.75	8.5
28 Mar. 61	1110	3.1	9.9
14 May 61	1020	2.75	9.1
21 June 61	1505	2.5	7.2
24 July 61	1155	3.5	10.0
16 Aug. 61	1220	3.6	11.5
30 Sept. 61	1200	2.75	9.73
28 Oct. 61	1447	3.0	9.1
10 Feb. 62	1400	2.75	8.8

CHEMICAL METHODS

Total hardness, expressed as mg/l of $CaCo_3$, was titrimetrically determined with EDTA, using the Hach Chemical Company's MonoVer liquid indicator-buffer-inhibitor solution. Calcium hardness was determined similarly after precipitating magnesium with 8N DOH. Calcium ion was calculated by multiplying the calcium hardness, expressed as $CaCO_3$, by 0.4. Magnesium hardness was considered the difference between total hardness and calcium hardness. An estimate of the magnesium ion was made by multiplying magnesium hardness by 0.243. This is the reciprocal of 4.115, the figure used to convert magnesium to magnesium hardness (see Ellis et al. 1948).

Sodium and potassium were determined by flame photometry using a Coleman Model 2 Flame Photometer, and making comparisons with standard curves we had prepared.

Total alkalinity was established by titration with 0.02 N H_2SO_4, using bron crecel green or Hach's AlkaVer as the indicator. Fifty ml of sample were used and some difficulties were experienced which will be discussed later.

Chloride was titrated using a modification of the Clarke mercuric nitrate method. This proved far more satisfactory than the Mohr silver nitrate method which we employed early in the investigation.

Sulfate was turbimetrically established, using the Hach DR colorimeter or a B & L Spectronic "20", and comparing the results

with a standard curve. Both instruments were calibrated by us for all ions and compounds to be determined photometrically. Sulfate was precipitated as a fine suspension of barium sulfate, after addition of the Hach Chemical Co.'s SulfaVer powder.

Iron was assayed colorimetrically by the 1,10-phenanthroline method after reducing all iron to the ferrous state. Standard curves were prepared and utilized. Silica was colorimetrically determined by the heteropoly-blue method. Phosphate was determined by the ammonium-molybdate-stannous chloride method with six minutes allowed for color development; no appreciable fading or change in intensity occured within 10 minutes. Total phosphate was determined from samples which had been boiled in acid; metaphosphate was calculated as the difference between total and orthophosphate; the last was the phosphate in unhydrolyzed samples. The phosphate determinations were made within 48 hours of collection and all samples were preserved in the usual method with chloroform.

Ammonium nitrogen was measured by direct Nesslerization and spectrophotometry. The high calcium values in Montezuma Well water render the ammonium-N figures less than valid. Nitrate nitrogen was assayed photometrically by a modification of the diazotization method. Nitrate nitrogen was determined by the Brucine method which yeilds the sum of nitrate-N and nitrite-N; the nitrite value was subtracted from the Brucine-N to establish nitrate-N.

Fluoride was determined on some occasions, using the Megregian-Maier method.

Hydrogen-ion concentrations were determined immediately after collecting the water samples, utilizing an analytical pocket pH meter made by Analytical Measurements, Inc., Chatham, New Jersey. This instrument is calibrated in units of 0.2_pH.

Free CO_2 was determined early in the study by nomographs on p. 74 of Standard Methods..., 11th ed. (Amer. Publ. Health Assoc. 1960). In the range of CO_2 with which we were dealing the nomograph calibrations are very crowded; it was decided, therefore, that the same degree of accuracy could be attained by calculation. Therefore, we turned to using Table 8, p. 36 in the 9th edition (1947) of Standard Methods..., a table based on the relation between pH and fractional activities of alkalinity and acidity constituents (Moore 1939). Direct titration with NaOH gave too low values, because the CO_2 rapidly leaves the Well water upon aeration.

Dissolved oxygen was determined titrimetrically by the by the Alsterberg modification of the Winkler method. Usually a 0.0125 N solution of sodium thiosulfate was used in titration.

WATER CHEMISTRY

Principal inorganic ions

Total alkalinity determinations showed bicarbonate to be the main ion in the waters of Montezuma Well. On a weight basis, bicarbonate amounted to 682 mg/liter. This was derived from the

mean total alkalinity value divided by 0.8202. A discussion of total alkalinity and $-HCO_3^-$ is better postponed until hydrogen ion and free CO_2 are treated, however.

Chloride was the second most abundant of the anions; our titrations revealed a mean of 37.4 mg/l. Sulfate amounted to only 12 mg/l. The water, on the basis of the classification presented by Clarke (1924) is clearly the carbonate type. The diagram presented by Cole (1963; 428, Fig. 14.7) shows there are many Arizona waters with the same relative anionic composition, but few are so mineralized.

Calcium is the principal cation, and the mean value is 111.3 mg/l. The second most abundant of the metallic cations is Sodium; a mean value of 51.6 mg/l was determined with flame photometry. Magnesium was second to calcium on the basis of milliequivalents, but was the third most abundant on a weight basis, averaging 38.1 mg/liter. The average potassium value was only 5.4 mg/l.

Total alkalinity, pH and CO_2

Total alkalinity in Montezuma Well is due to bicarbonate alone, although water samples after short storage periods contain carbonate. The mean of all total alkalinities we determined from the Well was 559.9 mg/l (n = 50), which is equivalent to about 682 mg/l $-HCO_3^-$. The highest total alkalinity encountered was 599 mg/l. This, as was true of all our alkalinity figures, is expressed as $CaCO_3$ and is equivalent to 730 mg/l of bicarbonate ion.

During the 1940's and 1950's the USGS, Bureau of Grounwater, analyzed samples from Montezuma Well (see Table 3). They reported "bicarbonates" from 595 to 629 mg/l, the mean being 603.8 mg/l. This would be equivalent to 495 mg/l total alkalinity expressed as $CaCo_3$. Then, if the old USGS reports really express $-HCO_3^-$ concentrations from conversions of total alkalinity titrations, there has been a recent incre ase in total alkalinity. If their data, however, really refer to total alkalinity (not bicarbonate), our 1960-62 data reflect a decrease. A balancing of the anion and cation milliequivalents suggests that the USGS figures do apply to bicarbonate; the balancing would not be so good, if total alkalinity values were recorded. In our mean data there is a six per cent error in the milliequivalents...the anions are too numerous. These data are all shown in a comparative manner in Table 3.

In this hard carbonate water and storing of samples and subsequent titrations presented some problems. We titrated for alkalinity in preserved samples in the Tempe laboratory, where we soon learned that this titration and those for total hardness and calcium hardness had to be done immediately; areation resulted in the rapid precipitation of carbonate. Also, because of the volume of standard 0.02 N acid necessary in the titrimetric procedure, we used only 50 ml of sample and employed a factor of 20 in calculating the results, thereby increasing the

chance for error. Whatever the reason, in many vertical series the bicarbonates were distributed irregulary, and variations in total alkalinity on the order of 20 mg/liter existed at times... a difference of about 3.0%. Sometimes the softest water was at the surface, at other times in the deepest part of the Well. There was no discernible pattern, and there were no corresponding fluctuations in relative conductance.

Whenever the water level of the Well lowered, some carbonate was precipitated by evaporation at the margins. However, when the water rose again this material was dissolved, and no marl deposits exist in the basin. Emergent Chara parts are encrusted with lime, but they have not created, over the years, any bed of calcareous material.

Hydrogen-ion, expressed conventionally as pH, ranged from 6.15 at night or on dull, overcast days to 6.9 on bright sunny days. There was no pronounced vertical stratification...only temporal changes were involved, and these were largely diel, rather than seasonal. The acidity of Montezuma Well is caused by carbonic acid alone; aeration of samples resulted in a rise of pH and the ensuing precipitation of carbonate. One such sample, to which phenolphtalein was added after aeration, was titrated to the colorless end point with H_2SO_4. The CO_2 deficit thus determined was about 10.4 mg/l.

Calculations show tremendous quantities of CO_2 were involved in bringing such hard water down to the acid pH ranges we en-

countered. For example, at an alkalinity of 560 (the mean during 1960-62) and a pH of 6.2, the free carbon dioxide is about 687 mg/l; at pH 6.9 it is 137 mg/liter. This may be the reason that no fish are present in the Well in spite of the adequate supply of dissolved oxygen. The effects of free CO_2 in strong concentrations upon the respiration of fishes is discussed by Doudoroff (1957), ...concentrations between 100-200 ppm rapidly fatal to moderately susceptible freshwater fishes in well-oxygenated waters...concentrations between 50 and 100 ppm can cause immediate distress--may be lethal after prolonged exposure.

Nutrients and minor ions

Phosphate was determined on unfiltered samples only. Occasional vertical series from the Well yeilded a mean of 0.546 total phosphate, and 0.229 mg/l of ortho-PO_4 (Table 3). Several samples from the swallet gave a mean of about 0.500 mg/l total-PO_4 and 0.3 mg/l ortho-PO_4 leaving the Well. Less appeared at the outlet below and beyond the cave...0.402 mg/l total and 0.275 mg/l ortho-phosphate. Phosphate is lost, therefore, at the approximate rate of 2.3 kg/day.

Assays of nitrogen were made sporadically and no trends can be inferred from our data. The means, HN_4-N 0.38, NO_2-N 0.001, and NO_3-N 0.06 mg/l, are shown in Table 3. As stated earlier, direct Nesslerization is probably unsatisfactory as a method and the validity of the ammonium nitrogen datum is questionable.

The nitrogen/phosphorus ratio of about 2.5 in Montezuma Well

waters is rather low. This is because of the relative abundance of phosphorous compounds, which are unusually abundant in the Well.

At the end of 1961 our mean determination for silica was 22mg/l (see Cole 1963: 427, Table 14.4) Since that time some values as high as 28 mg/l were encountered. Montezuma Well waters are moderately high in silica; we are considering 25 mg/l as a typical value. This figure may fluctuate seasonally as diatoms utilize SiO_2, but we can say nothing about the trends.

No special study was made of iron in Montezuma Well waters. Our figure of 0.038 mg/l was based on total iron in unfiltered samples.

The few determinations of fluoride showed no unusual amounts. Table 3 shows that the USGS figures during the 40's and 50's were about twice our mean of 0.25 mg/liter.

Several times the "cuprethol" method was attempted for copper analysis. This did not work because of interfering substances, of which calcium must have been most important. A cloudy, white precipitate formed, but no yellow color could be developed in the Montezuma Well water, although the reagents gave satisfactory results with other waters, including Tempe tap water.

Manganese could never be demonstrated in Montezuma Well. Our reagents oxidized manganese in other waters to the intensely colored permanganateion, but no color could be developed from the Well samples.

Dissolved oxygen

As far as we were able to determine, dissolved oxygen enters Montezuma Well through the deep fissures at the bottom of the depression. This is quite different from the situation in many springs, where subsurface water is anaerobic as it emerges. There was great difficulty in getting adequate samples from the fissures because sand interfered with the closing of the Kemmerer water sampler. With a crude bottle train, however, some samples were obtained, and the oxygen was found to be 6.25 mg/l. This would represent about 75% of saturation at the prevailing temperatures.

Oxygen values in the Well did not differ much from top to bottom at any one time. There were some exceptions to this: at the end of quiet, sunny days there was more oxygen in the surface layer than below: and sometimes an oxygen minimum was found from 3-8 m below the surface. This minimum may have been associated with a concentration of planktonic crustaceans which were at these levels on bright days.

The diel changes which occurred in the dissolved oxygen will be discussed under the heading of primary productivity and photosynthesis. There were diel changes, but in spite of this, daily means including samples from various depths are probably worth discussing. No oxygen saturation values in excess of 85% were ever encountered in limnetic samples, although saturations approaching 100% occurred in the surface of the weed beds during summer days. In general, mean oxygen values ranged from lows of about 5.9 mg/l (ca. 70% of saturation) in mid-September to highs of 8.29 mg/l in February (ca. 85% saturated).

Comparative aspects of the water chemistry

Some general aspects of the water quality of Montezuma Well have been presented. Some comparisons are worthy of discussion.

First, the waters of Wet Beaver Creek should be discussed because there are rumors that the Well water is in some way related to the Beaver Creek flow. A very few data exist; these show there is little similarity between the two adjacent bodies of water. On November 4, 1960, water was collected from the creek a few meters above the outer outlet of the Well, where we assumed there would be little contamination by seepage from the Well. The residues following filtration and evaporation were 638 mg/l and 323 mg/l for the outlet waters and the creek respectively. Total hardness, expressed

Ca Co_3, was 424 and 222 mg/l for the two, and total alkalinity was 582 mg/l and 300 mg/l, the lower figure in each instance applying to Beaver Creek. The creek's pH was 7.9 at the time, a value far in excess of any pH readings ever taken from the outlet of the Well.

Second because various people suggested that Soda Springs was comparable in some ways to Montezuma Well, the springs were visited on 6 July 1962. The temperature of incoming waters was 24.3° C, very close to summer temperatures in the inlet fissures of the Well. The conductance was greater however, about 1,700 micromhos as compared to perhaps 1,200 micromhos/cm in the Well. This may have been an artifact based on malfunctioning of the conductivity meter; the total milliequivalents of Soda Springs weter were lower than the mean of Well waters. The pH of the incoming water was 6.4 and the total alkalinity was 448 mg/l (expressed as $CaCo_3$) and due to bicarbonate along. From these data a free CO_2 content of about 347 mg/l can be computed. The large bubbles emerging from the soupy, sand slurry are probably mostly CO_2. Presumably the sand slurry in the bottom of Montezuma Well would resemble the surface springs at Soda Springs.

Table 3 shows the data for my analyses of 6 July 1962, my analyses of Montezuma Well waters, and some USGS data on file in the Phoenix office. The data of 1962 show the Soda

Springs waters are somewhat like those of Montezuma Well but more dilute. Exceptions are the potassium and sulfate values which are almost identical. The Ca/Mg ratio is 2.77 in Soda Springs and about 2.9 in the Well. Turning to the USGS values, we find Soda Springs is more concentrated than those of Montezuma Well. Exceptions are the similar silica, sulfate and potassium values. The milliequivalent values of cations and anions balance reasonably well for my determinations and excellently for the USGS data. The total milliequivalents of the major ions were about 19.7 in 1962, however, and 28.5 in the analyses of the USGS a few years before. It must be remembered that there are several issues making up Soda Springs. Perhaps they differ from one another, or show marked seasonal differences. Perhaps the USGS sample, which was so much more concentrated than mine, was taken from a different spring. Whatever the case may be, the name Soda did not apply in 1962 ....and earlier, also, the USGS analyses show calcium bicarbonate water rather than sodium bicarbonate water.

TABLE 3

Comparative chemistry of the water of Montezuma Well and Soda Springs, Yavapai County, Arizona.

	Montezuma Well		Soda Springs	
	USGS means	Present means	USGS	6 July 62
Ca^{++}	114.4	111.2	145	96.9
Mg^{++}	38	38.1	47	34.5
Na^{+}	53.4	51.6	70	38
K^{+}	2	5.4	5	5.1
HCO_3^{-}	603.8	682	775	560
Cl^{-}	36.8	37.4	46	28.9
SO_4^{--}	12.6	12	14	12
PO_4^{---} total		0.546		0.80
PO_4^{---} ortho		0.229		0.15
PO_4^{---} meta		0.315		0.65
NH_4-N		0.38		1.74
NO_2-N		0.001		0
NO_3-N	0.216	0.06		0.21
SiO_2	27.3	ca 25	18	18.5
Iron		0.038		0.02
F^{-}	0.5	0.25		
Boron	2.0			
TDS (evap.)		616		

All units in mg per liter

ENVIRONMENTAL CHANGES IN THE IRRIGATION DITCH

An interesting study which we scarcely touched is that of the changes taking place in the water leaving the Well as it passes down the irrigation ditch. We sampled several sequential stations several times; the means of some chemical data at these stations are instructive.

Station I was the swallet, surface water of the Well which flows through tangled vegetation, branches, pondweeds and algae. Station II was the outer outlet some 66 m away; this water consists of the swallet contribution plus water from other subsurface outlets, all of which flows through subterranean caverns. The water of the second station is much like the mean of waters from various strata in Montezuma Well. Station II is seven minutes away, as the water flows, from the swallet. Station III was a section of the ditch about 781 m away from the outlet. It was directly north of the two houses shown on the Map, Drawing No. NM-MC 7107-A, October 1960, and entitled "Irrigation Ditch and Irrigated Lands, Montezuma Well Area". Station IV was 272 m farther down the ditch at the adobe storage sheds just beyond the campground. Station V, which we called the second weir, was 518 m and about 30 minutes flow time away from the sheds. This is the Parshall Flume #6 shown on the map. Station Va was 1 m beyond, a pooled area just below the flume or "second weir". The total distance was 1.632 km (1.014 mile), and the flow time probably was roughly 1 hr and 30 minutes from the swallet.

William T. Barry presented the accumulated information about the ditch at the Arizona Academy of Science meetings in the spring of 1962. This included data through March 10-11, 1962. Barry's data included information obtained by John Weise, Barry and me. The data are shown in Figures 4-8 and in Table 4.

Figures 4-8 show clearly the mean changes which occur in the ditch, but comment is warranted. Specific conductance, (Figure 4), which reflects total electrolytes, drops from station to station down stream. Temperatures are more or less uniform, varying only slightly on any particular day. The drop in conductance, therefore, is not a function of temperature but reflects a loss of ionized substances as the water progresses.

Several common ions which contribute to conductance do not change appreciably down the ditch; these are sodium, chloride, sulfrate and potassium (Figure 5). By contrast, free CO_2 shows almost a ten-fold decrease downstream, accompanied by a rise in pH (Figure 6). There is, therefore, a decrease in hydrogen-ion concentration. There is no residual acidity in Montezuma Well water...all acdity is caused by carbonic acid.

Dissolved oxygen increased somewhat down the ditch but there may be little significance attached to this; the atmospheric exchange of water moving at a velocity of about 0.2 m/sec must be great. The mean increase in oxygen (about 1.1 mg/l), assuming the ditch to have a mean width of one m, from the outer outlet to Station V would imply the net production of photosynthetic oxygen at the rate of 162 mg/m^2/hour. Even though we can place little faith in this as a measure of productivity, it seems worth mentioning that this is in no way balanced by the tremendous loss in CO_2. Obviously most of the latter is not taken up via photosynthesis. The mean loss of CO_2 down the ditch would amount to 34.5 g/m^2/hr. On a Molar basis that is more than 150 X too much to balance the O_2 production!

On the 15th of September 1962, fluorescain dye traveled from the outlet to the adobe-shed station (IV) in one hour; the water temperature was 25° C; the weir reading implied $5{,}966 \times 10^3$ liters/day. In that stretch of the ditch the oxygen changed from 6.2 to 6.5 mg/l during the period 1600 - 1700 hours. The apparent net photosynthesis was 71 mg O_2/m^2/ hour. The CO_2 loss was, at the same time, 278 mg/l, amounting to 65.6 g/m^2/hour.

The water passed from the outer outlet to station V in 1.25 hours on 15 May 64. The increase in oxygen amounted to 154.6 mg/m^2 for the entire run, at the rate of 123.7 mg/m^2/ hour. The run started at 1415 hours. From the outlet to Station IV the increase in oxygen was 205 mg/m^2/hour. From Station IV to Station V the change amounted to 52 mg O_2/m^2 in 0.25 hours...a rate of 208.5 mg O_2/m^2/hour.

The extreme loss in free CO_2 leads to a consideration of the bound CO_2 which leaves the Well and it is here that the important loss in electrolytes occurs. Total alkalinity due to bicarbonate decreases as water flows down the ditch (Fig. &). It precipitates as insoluble carbonate when agressive CO_2 is lost to the atmosphere and the carbonic acid content lowers. The seemingly anomalous increase of bicarbonate at Station V reflects data which were taken when the wier was plugged. Pooling of the ditch on those days promoted decomposition, and acidic conditions with some conversion of carbonate to bicarbonate.

Calcium and magnesium ions follow the pattern of total alkalinity. Calcium and magnesium are precipitated as carbonate compounds but go into solution at Station V when the weir is impounded. The change in the Ca/Mg ratio reflects the greater solubility of the magnesium compounds. On Aug. 16, 1961, we sampled the outlet, Station V, and a section of the ditch at the southwest edge of the Rimrock line. This was some 15 minutes' walking time below Station V. The Ca/Mg

ratio was different at each station ... 2.97, 2.15 and 1.18 respectively. Total hardness, expressed as mg/l of $CaCO_3$, decreased down stream from 426 to 420 to 390. Total alkalinity, similarly expressed was 561, 536 and 508 at the three collecting sites. The loss in calcium alone amounted to 27.8 mg/liter. From the weir reading of that day we calculate the following loss during the 24-hr period: 142.732 kg of calcium was lost; 786.7 lbs of calcium carbonate left the water as a precipitate; 563.743 kg of calcium left the Well in solution; expressed as calcium carbonate, this amounts to a loss of 3,106 lbs via the outlet that day and one fourth left the water by the time it had reached the Rimrock station outside the Monument.

Other substances, perhaps best described as nutrient compounds and contributing little to total conductance, also change as the water flows down the ditch. The compilation o f silica analyses through March 61, show slight decrease from station to station except when pooling occurred at station V. Normally silica was lower at station V than at Station IV. Phosphate also decreases downstream, except for the abnormal increase due to plugging of the weir at Station V. Accompanying the decreases in silica and phosphate is a decrease in chlorophyll, a correllation which seems unusual (Fig. 8). This is because there is a loss of Well phytoplankton from the fast-flowing ditch waters. A new community of chlorophyllous

organisms along the edges and bottom of the ditch is responsible for the utilization of silica and phosphate but these encrusting diatoms and algae are not readily collected in simple water samples.

Usually when the "second weir" was not blocked the chlorophyll there was lower than in the little pool (Station Va) beyond it. This is not reflected in figure 8. There may be an accumulation of material including the algae derived from the Well's plankton, or there is a little ecosystem, with its own floating algae and green flagellates, in the tiny pool below the weir.

Table 4

Chemical and physical changes occurring in the irrigation water leaving Montesuma Well, Yavapai Co., Ariz. Means of analyses through 10 March 1982 included; data at Sta V include those from time when weir was impounded.

	Sta I	Sta II	Sta III	Sta IV	Sta V	Sta Va
Conductance	1025	1114	995	970	951	907
Temp. C°	20.37	21.25	19.00	19.25	20.5	18.5
Sodium	49	51.8	52.5	53.5	58	52.5
Chloride	36.25	36.5	36.5	37.0	36.0	35.0
Sulfate	11.58	11.45	13.5	12.7	10.04	14.5
Potassium	5.0	5.5	5.5	5.5	5.5	5.7
Free CO_2	262	265	192	61	45	29
pH	6.6	6.68	6.7	7.2	7.36	7.52
Dissolved O_2	7.57	7.43	8.48	8.08	8.52	9.19
Total alk. as CaCO3	541	567	497	497	511	468
Calcium	111.0	111.5	95.29	96.8	94.5	87.6
Magnesium	40.9	37.4	37.9	35.7	35.06	-
Silica	27.9	27.4	26.1	24.4	28.6	22.1
Total PO_4	0.55	0.402	0.375	0.287	0.660	0.487
Chlorophyll	12.2 mg/m^3	16.8	8.0	5.42	8.50	5.42

SEDIMENTS OF MONTEZUMA WELL

Cores of sediment were collected from the deep areas of Montezuma Well by John Tait of Tempe, an accomplished skin diver. Plastic tubes and corks were taken to the bottom for sampling. The tubes were pushed into the substrate as far as possible and were corked before being returned to the surface. One core included 57.5 cm, the other only 44 cm.

The longer core, especially, showed several alternating bands of organic ooze and fine sand. This suggests that entering water holes have shifted position from time to time, depositing sand always near their vicinities, or perhaps at times, higher velocities of entering water spread sand over greater areas of the bottom. (This sand is the material described by some divers as "boiling oatmeal" at the deep fissures; this material interfers with the operation of water samplers of the Kemmerer type. Also there is a tremendous suction developed in these fissures and presumably by the fine sand; as dredges, for example, are lowered to the fissures there is at first a slight feeling of buoyancy experienced but going deeper there is a reversal of this and a strong suction pulls the dredge down. Tying the dredge line to the rubber raft reveals something of the strength for the line becomes very taut and a decided list in the raft occurs, although we were never in danger of tipping over. Pulling up a dredge that is down 10 or 15 m in the fissures is extremely difficult

and can be done inch by inch using the oars as levers.) Sand from the west hole was examined by Mr. Floyd Twenter, USGS Phoenix, who stated that in his opinion it is derived from the Supai formation. The reddish color has been leached away and the sand appears to have undergone severe erosion. It appears that the sand has been cascading and tumbling in the fissures for some appreciable length of time.

Figure 9 shows core diagrams. The bottom 19 cm of the longer core was of compact, somewhat dry mud with fibrous material in it ... probably sedge and grass roots. There were at least six faint sand bands in this organic material. The organic matter and the rootlets suggest a time when the Well was shallow, perhaps a wet meadow with water streaming across it to an outlet near the bottom of the present basin. Subsequent plugging of the outlet would have raised the level. Perhaps, the roots are derived from Potamogeton and would represent a stage when the lake was shallower but not necessarily a marshy meadow. There is much to be learned about the history of Montezuma Well from a study of subsurface cores as well as sediments up the basin slopes above the present water level.

Several representative samples from different levels in the long core were sent to Paul S. Martin at the Geochronology Lab in Tucson. Dr. Martin and Richard H. Hevly examined these sediments for pollen remains. The results were nearly ideal; within the short column the pollen relics changed from the

modern composition to predominatly Pinus pollen, which suggests a Pleistocene pollen rain and that the forest surrounding the Well during the Pleistocene was much like that on the Mogollon Rim at Flagstaff today. Hevly (in litt.) stated, " At a depth of 26 cm. significant change occurs in the composition of the pollen rain, suggesting that at the time of deposition of those sediments pine, oak, and juniper were the dominant elements of the vegetation surrounding the well." In addition, the core showed pollen of Myriophyllum and Sarcobatus. The former is an aquatic plant, which does not occur in the Well today. Sarcobatus is not listed in MacDougall's account of the seed plants of the Monument. In 1962 a small relict stand of live oak was found in a shallow depression just north of the Well. This grove might be of great interest in light of the evidence of a widespread oak stand in the past.

Martin planned to use the Montezuma Well pollen profile in a review paper on Quaternary ecology but withdrew it when a section of the core was radiocarbon dated. Sediments from above the pine-oak maximum were prepared for dating at the Geochronology Lab by Paul E. Damon. Roots were picked from the material so that modern remains would not contaminate the older sediments. Assuming the decline in pine pollen represented the end of the Pleistocene ... some 10,000 years ago... the sample should have revealed a carbon 14 date of about 5,000

years. Instead it showed the incredible age of more than 20,000 years before the present. Although this anomaly is based on the age of the CO_2 which bubbles in with the deep fissures, it shook Dr. Martin's faith in the pollen profiles from the core. As non-palynologists we can only regreat this turn of events and stand firm in our belief that the pollen profiles constructed at the Geochronology Lab are worthwhile in spite of the impossibility of putting accurate dates on the various levels.

A later trip to the Well yielded cores of more than two-m length. These longer cores were taken with a modified and somewhat improvised piston core sampler. John Tait, Richard Neal and Marc Neal were with us serving as divers again. This was in March 1963. Martin and Hevly were present. The cores were carried to Tucson for analysis but proved worthless; the samples were more than one-half sand ... material which has no pollen content at the Well. The complete failure of a Shapiro-freezing core sampler which exploded each time its mixture of dry ice and acetone was submerged in the warm waters of the Well was the high light of the trip. The bullet-like frozen cork shot across the lake several times, but no one was hurt. Had absolute alcohol been substituted for acetone, success might have been realized.

The deeper sediments, not associated with the fissures, were fine-grained and organic. It was light tan in color, an ooze which was not retained by a No. 40 sieve (interstices 0.4 mm). This material made up about 90% of the sediment. Another 5% was sand which passed through the sieve meshes, and about 5% was fibrous plant material which was retained. At 7.5 m near the weed margin, fibrous and leafy plant remains were common. Some samples of the ooze were somewhat gelatinous. Once we dredged what appeared to be water-soaked wood fragments from the deep water toward the north side of the lake.

There is a peat deposit (Fig. 1) at the north edge of the lake. This is fibrous, polleniferous material, containing gastropod remains, and composed primarily of Scirpus. The bed is usually somewhat exposed, but may be covered by four or five cm of water. It extends into the deeps but we have not been able to trace its extent carefully and accurately. Skin divers have described a ledge ... a steep cliff of crumbly plant material toward the north side of the lake. The unusual configuation of the contours, 3 m - 11 m, shown opposite the peat bed in Figure 1 are real; we think that they represent the edge of a submerged peat mass. Cole (1963: 403,404) discusses this peat deposit briefly, pointing out the relative scarcity of such deposits in the southwest, and suggesting that the currents are at a minimum, and stagnant conditions prevail at

the end of the pond opposite the outlet. Thus, even though the volume of the Well is only about one-tenth the daily inflow, and the Well does not seem to be the type of a place where peat could form, conditions opposite the outlet may have been conducive to peat formation in the past.

THE RADIO-CARBON ANOMALY IN MONTEZUMA WELL

Dr. Paul E. Damon, of the Geochronology Laboratories, Univ. of Arizona, dated a small segment of a core sample which had been collected from a depth of some 15 m in Montezuma Well. The organic matter in the core, dated by the Carbon 14 method, showed an age entirely inconsistant with the pollen relics in the same level. The pollen suggested the campled part of the core was post-Pleistocene; the radiocarbon age was much greater. This led to a series of tests on the material in the Well (Damon et al. 1964).

The CO_2 evolved from the water of Montezuma Well contains about 5% modern CO_2, and an apparent age of some 25,000 years. Stems and other parts of the submerged Potamogeton illinoansis were also dated at approximately the same age as the CO_2 in the water. Some Chara from the south shore was also collected and dated later at the Geochronology Labs. These plants were partially emergent because of fluctuating water levels in the shallows, and used atmospheric as well as dissolved CO_2 in photosynthesis. The Chara material had an apparent age of about 17,000 years, implying 12% moder carbon. This is probably one of the greatest anomalies known in carbon 14 dating, but it is probably not unique. There must be many cases in Arizona where photosnthetic organisms utilize "fossil" CO_2 from artesian water which would be very low in carbon 14 content. Fossil

Springs, Soda Springs and other outlets under the Mogollon Rim must be similar.

In early September 1963 Damon and I went to the Well to attempt another dating experiment. Grass was collected from the Well's shore, near the large cottonwood tree, and at intervals clear to the rim on the south side. This was one species of grass that had sprung up since the August rains. It was hoped that a gradient in apparent age would be revealed ... the grass at the water's edge being of apparently greater age than that grass up the basin slope. The rationale was that CO_2 lost from the water surface would be utilized much more by the plants at the shore level than those farther up the slope, and that the former would appear, therefore, much older. It did not work!! The shoreline grass dated modern in age.

CHLOROPHYLL

Chlorophyll was determined by filtering measured amounts of water, using membrane filter, pore size 0.8 m. Filtration was accomplished at the storage sheds near the campground using an electric, portable pump.

Our methods were those of McConnell (mimeographed, personal communication). The membrane filter was trimmed, rolled and placed in a small vial. To this 20 ml of 95% alkalized acetone was added and the vial was stoppered with an acetone-leached cork. The filter was dissolved and the vial kept on ice until further work at Tempe. The contents of the vials were paper filtered and the filtrate made up to 25 ml. The green extract was compared with a blank consisting of a trimmed filter dissolved in identical acetone. The B & L Spectronic "20", with a wave setting of 663 mu and a red filter was then used to determine optical density. Further calculations were as follow:

$$25\ (O.D. \times 7.5)\ \left(\frac{1{,}000}{\text{filtered volume ml}}\right) = \text{mg chlorophyll/m}^3$$

The procedure was not entirely satisfactory. The phytoplankton of Montezuma Well consists of cells which do not dissolve completely in the acetone, and a green debris was left behind on the paper filter. We attempted to correct this by grinding the membrane filter in clean sand while adding acetone. The sand and cellular debris were placed in the vial and refrigerated prior to paper filtration. This still did not correct the

situation completely ... there was some chlorophyll which did not go into solution, apparently remaining within the cells. Therefore, all of our optical densities and computed chlorophyll values were too low, and we abandoned chlorophyll determinations after November 1962.

The average chlorophyll in the Well was computed from the amounts in samples at different levels, multiplied by the appropriate lake volumes. Also, simultaneous samples from the swallet and the outer outlet were compared. The mean of mean from the lake levels was 17.6 mg/m^3, while the outer outlet's mean was 16.8 mg/m^3. The swallet water, which was essentially a 0-m sample which had flowed through weed beds, was 12.2 mg/m^3. The surface water mean from near the center of the Well was 20 mg/m^3. From these data it appears that the outer-outlet water might be adequate for sampling chlorophyll in Montezuma Well. Perhaps studies of, for example, diel chlorophyll changes could be simplified by collecting at the outlet at the head of the irrigation ditch. Parenthetically. the loss of chlorophyll at the Well outlet amounted to about 125 grams per day.

The vertical distribution of the chlorophyll in the Well was not uniform; usually there were lowest values midway down and the deepest water was more like the surface than the middle strata. Thus at 15-15.5 some 6 m below the mean photic zone's

lower boundary, there was usually particulate chlorophyll much like that of the surface waters. Possibly the intermediate low point was brought about by the grazing of zooplankters. On at least two occasions the low point in the chlorophyll curve corresponded to a low point in the oxygen curve; these two may have been related, or perhaps they both reflect a dense concentration of planktonic animals.

An exception to the statements in the paragraph above was the tremendous concentration of chlorophyll at 5 m on 4 May 62. There was no replicate sample for this level that day, so the concentration of 177.4 mg/m^3 may have been in error.

AQUATIC MACROPHYTES

Potamogeton illinoansis Morong is the conspicuous pondweed in the Well. Several years ago E. C. Ogden called the material from the Well a hybrid population, P. illinoansis X P. gramineus. The stem anatomy of the plant is like P. graminius in the lower part, but in the upper part it resembles P. illinoensis (E. C. Ogden, in litt.). This is the plant obvious to spectators from the rim of the Well. It grows to about 7-8 m long and, thus, marks about the 7.5 m contour in the Well. Slightly deeper than this, the same species can be found but does not reach the surface; there is a puzzling, abrupt line between the pondweeds which reach the surface and produce emergent spikes and those which do not attain the surface, approaching no closer than 2.5 - 3.0 m below.

Potamogeton pectinatus L. also grows in the Well. This is a widely distributed species, but typical of hard waters. Its most luxuriant growth is in the shallows near the peat bed. A third pondweed, P. natans L., occurs in the irrigation ditch near the camp ground and the adobe sheds, but is not in the Well. We have never seen flowering or fruiting spikes in this species.

Zannichellia palustris L, the horned pondweed, is represented by a few plants in the shallows north of the large cottonwood tree, from which we launched our raft.

Near the swallet, Nasturtium and pennywort are common. They are mixed with algal colonies, which form macroscopic masses.

The bulrush Scirpus validua occurs in two stands at the Well. At the north shore, associated with the peat deposit, there is a sparse stand. The rather extensive peat ledge is primarily composed of Scirpus remains. Directly opposite on the south shore, between the large cottonwood tree and the emergent rock (shown on our bathymetric map as a tiny island), are some more Scirpus plants. No peat deposit is associated with this stand. Some Typha angustifolia, the narrow-leaved cattail, is associated with the Scirpus; they occur nowhere else in the Well.

In the shallows of Montezuma Well there are at least two species of Chara. A small species has 14 chromosomes and apparently is C. vulgaris; a larger form has 28 chromosomes and appears to be C. contraria. The occurrence of these two species in the same habitat is rare (A. T. Hotchkiss, in litt.). The differences, if they exist, in localities and microhabitats of these two species in Montezuma Well is a problem which is unsolved at present. On the basis of rather superficial

observations, C. contraria is especially common just to the east of the peat bed at the north shore. The other species may be more abundant at the south margin.

Some of the Chara plants have become encrusted with marl; this occurs when plant parts protrude above the surface. There are no marly beds associated with the Chara, however.

ALGAE

We have not made a thorough study of the algae of Montezuma Well. A point of reference, however, is the paper of Kidd and Wade (1963); these authors collected in the Well and in adjacent Beaver Creek. Unfortunately, they did not examine the planktonic algae. Their study is interesting, because it shows the effects of water chemistry (and perhaps current) on algal populations. Nineteen species are reported by these workers from the Well; another 19 were collected from the creek. No species were common to both the Well and Beaver Creek. There is a least one exception to this ... they reported the red alga Batrachospermum from the creek. We have found this to be also abundant in the irrigation ditch near the outer outlet of Montezuma Well. The restriction of red alga to the outlet is probably a function of free CO_2 there. Minckley and Tindall (1963) discuss this and cite Buttner (1960), who demonstrated that Batrachospermum can not utilize half-bound CO_2 ... $-HCO_3^-$ ... in photosynthesis, but require the presence of free CO_2. It's occurrence in Beaver Creek is not easily explained on this basis unless water charged with CO_2 from the Well, or Soda Spring water is present. Kidd and Wade do not identify their collection sites carefully. However, seepage from the Well could create a spring-outlet habitat in Beaver Creek near the head of the irrigation ditch.

On page 70 Kidd and Wade (l.c.) mention Oscillatoria limosa, but do not designate a locality. This species does occur in the Well and in the irrigation ditch near the Well outlet.

In general, the planktonic aleae of the Well are minute; probably the greatest number of the phytoplankters are diatoms. The algae which have been reported by Kidd and Wade are largely benthic forms, or those species which form masses in the Potamogeton during the summer, contributing much to the primary productivity of this weed bed.

MOLLUSCA

The snails of Montezuma Well include two amnicolide and a pulmonate species. The first two are *Amnicola integra* (Say) and a *Somatogyrus*, similar to *S. subglosus* (Say), but which may be an undescribed species (Van der Schalie*in litt.*). The pulmonate is *Physa ampullaceae* Gould, but Dr. Van der Schalie points out *in litt.* that it is a most depauperate type and unusually small for *Physa*. There is a good chance that the gastropods of the Well include endemic forms, not referable to any named species.

We dredged upthe valves of the sphaeriid clam *Pisidium*, but we never collected a live specimen. Its valves and those of snails are common and well-preserved in the peat bed at the north shore. A study of these subfossils would be an excellent opportunity; the peat would be cored quite easily, and would also be a source of pollen relicts.

ANNELIDA

Oligochaeta

In the bottom sediments of Montezuma Well, and especially in the deeps, are two species of oligochaete worms. They are present in numbers up to 10,000/m^2. One of them is clearly a tubificid worm. The more common of the two species may be an aberrant tubificid (C. J. Goodnight, pers. communication), but that is all we can say about it at present. It bears a pair of stout, curved setae on the ventral surface of most segments. We are sending material to Dr. Brinkhurst in Great Britain, who may be able to identify the worm; no Americans have been willing to designate a genus or species for this worm.

Hirudinea

The leeches of Montezuma Well have attracted some attention. They are common on the bottom, but belong to the plankton community also. At night they swim in the surface waters where they can be collected with net and flashlight. During the bright daylight hours they remain below the surface and apparently avoid nets with a marked measure of success. Our attempts to sample them quantitatively resulted in, what we are sure were, underestimates of the populations present.

The species is Erpobdella punctaea Leidy in having one pair of labial and two pairs of buccal eyes, and the genital pores separated by two annuli. It differs in having the dorsal surface cross-barred instead of longitudinally striped. In this last respect it resembles E. p. annulata, described by Percy Moore from the northwest. Dr. Moore examined our specimens, but we were unable to send him, with success, live sexually unspent individuals.

CRUSTACEA

There are two common cyclopoid copepods in the Montezuma Well plankton. These are Tropocyclops prasinus mexicanus Kiefer and the larger, less abundant Macrocyclops albidus (Jurine). For some reason, there are no calancid copepods in the plankton, although they occur in the plankton of nearby stock tanks and ponds.

In the shallows, among the Charra plants, there is an harpacticoid copepod. This may be identical to a species of Elaphoidella first found in Alaska and Saskatchewan by Mildred S. Wilson (in litt.).

The Chara beds also support numbers of the Ostracoda. These are Darwinula stevensoni (B.&R.) and Herpetocypris reptans (Baird).

The most ubiquitous crustacean is the amphipod Hyalella azteca (Saussure); it is found in all communities of the Well and may be the most important source of nutrition for predators in the Well. Its occurrence as a plankter is worthy of note, but probably reflects the absence of fish. Furthermore, a great number of the Montezuma Well amphipods are a golden-orange color (about the hue of a goldfish). Early, erroneous reports of a golden fairyshrimp in the Well were based on this high frequency of gold color among the Hyalella, which are, of course, not fairyshrimp.

Some Hyalella get swept out of the Well and end up in the irrigation ditch. These individuals may be found by lifting stones near the outlet: the displaced amphipods take refuge there. We found none past the first weir in the ditch.

In addition to the absence of calanoid copepods in the Well plankton, the absence of planktonic cladocerans is noteworthy. There are some cladocerans referable to Alona Baird in the weed beds at the margin of the lake. Because of the taxonomic difficulties involved in identifying species of this group we will go no further than this in our determination of this group of littoral chydorids.

INSECTA

Odonatans

Telebasis salva (Hagen) and Enallagma civile (Hagen) are two damselflies which reporduce in the Well. Other odonatans fly across the water and oviposit there, but with little success. These species probably fly up from Beaver Creek. We found only one dragonfly naiad and one cast skin (5 May 62) in spite of a great deal of dredging and netting. These were found on the peat bed at the north side of the Well.

Summer collections included mostly naiads of Emallagma; in early spring Telebasis naiads were commoner, and this is the more abundant of the two species in the Well.

The adults of the two damselfly species are easily distinguished. Telebasis is the dainty red damselfly seen perching on desert vegetation up the slopes of the basin almost to the rim. Enallagma adults are blue and less conspicuous.

The soft-bodied naiads of these species are predaceous, but also serve as prey for other predators in the Well. Water scorpions (Ranatra) and dytiscid beetles were often observed feeding upon them. Interestingly, the adult Telebasis fall prey to lizards which climb terrestrial plants to capture them.

We do not know much about the life cycles of these damselflies. Late winter and mid-summer emergences of Telebasis occur.

Hemiptera--the bugs

The most abundant hemipteran in Montezuma Well is a small veliid water strider, referable to Microvelia Westwood. These tiny bugs are common at the surface and especially on the weed beds.

Abedus breviceps Stål is the only belostomatid bug which we found. It is fairly common swimming among the marginal weeds. Dr. David R. Lauck (in litt.) has a series of the similar Belostoma bakeri Montandon that was collected some years ago from Montezuma Well, but Abedus was the only member of the family which we collected. Abedus males (Belastoma also) carry the eggs attached dorsally. During the third week in June we captured egg-carrying individuals. Empty egg cases persist during the summer as debris among the pond weeds, and nymphs are common through August at least.

Ranatra quadridentata Stål, the waterscorpion, maintains a remarkable population in the Well. During the summer they are all over the weed beds and even swim freely in the open water. During the winter they are not so common. Tiny nymphs appear in late March, and empty egg cases are common debris items through July. Ranatra is a vigorous predator. Although

both Abedus and the water scorpion feed on the damselfly naiads, Ranatra also attacks and sucks the juices of the belostomatid. Both Ranatra and Abedus are often covered with the colonial peritrich ciliate Epistylis.

One corixid bug was seen in the Well's open water in mid-February 1961, but this was the only occurrence noted. We never observed notonetid bugs, which is surprising; these predaceous forms are very common in stock tanks throughout the region.

Coleopteran insects

- The beetles of Montezuma Well are represented by the tiny Hydroscapha natans LeConte, the spectacular larvae of Cybister sp. and Hydrophilus sp. The last two are predaceous and capture Abedus and the odonatan naiads.

Hydroscapha has been recorded previously only from southern portions of California, Nevada and Arizona. It has been reported from hot springs with temperatures of 40° -45° C; it is, however, remarkably tolerant to low temperatures also, and its occurrence in the Well may not be due to the warm water there.

Dipteran insects

The flies of Montezuma Well are the most diversified taxonomic group of the insects, but still there are relatively few species. The absence of chironomid larvae in the soft

organic sediments is one of the major faunistic puzzles, because it seems that this would be an ideal habitat for some species, Although there are several species of midges probably present in the marginal weed masses, the most conspicuous one is referable to the genus Pentaneura Phillippi.

Heleid larvae referable to Dashelea sp. and Culicoides variipennis (?) are extremely abundant wiggling in the surface waters among the Potamogaton tips. Also, mosquito larvae, tentatively identified as Anopheles freeborni Aitken, occur in small numbers.

Stratiomyid flies may be extremely important as a food source for the predaceous insects of Montezuma Well. Judging by the cast pupal skins appearing in early June, there is a fairly large population in the shallows and especially in the Chara beds and among algal mats. Only the larvae have been studied. The most abundant is Odontomyia Meigen (+=Eulalia) which may belong to the communis-arcuata complex (M. T. James, in litt.). Other larvae belong to Euparyphus Gerstaecker (M. W. McFadden in litt.).

ARACHNIDA

There are several spiders about the Well and running across the water surface, but we can say no more about those. In the shallows at the south end and especially near the Chara beds there, are a few water-soaked logs. These harbor many small oribatid mites. We never saw any typical swimming water mites at the Well. Scorpions (Vejovis) are not rare in the desert about the Well, but they, as is true for all the arachnidas, are pretty much ; we did not pay much attention to the entire group.

AMPHIBIA

During every month of the year frogs referable to Rena pipiens Schreber can be found at the Well. In the dead of winter, about 1 Jan. we have found them to be more abundant at the irrigation ditch near the outer outlet than around the Well margin. Larvae were never conspicuous in the Well.

The canyon tree-toad, Hyla arenicolor Cope, hides in crevices of the boulder piles at the southwest margin of the Well, and among the large stones west of the peat bed on the north side.

Perhaps both these amphibia are preyed upon by the garter snakes which are occasionally seen about the Well margins.

MISCELLANEOUS

Around the margins of the Well are three terrestrial isopods. They are all indroduced crustaceans, originally derived from outside this continent...perhaps Europe. The species are Armadillidium vulgare (Latreille), Porcellio laevis Latreille and Porcellionides pruinosus (Brandt). Of these three, Porcellio is the most abundant in Arizona, occurring abundantly in residential areas of Phoenix and Tucson. The other two are relatively scarce. Montezuma Well represents the greatest concentration of these that I have seen in Arizona.

Outside the Well, in the irrigation ditch near the outlet and sometimes in the shallows of the Well, there occurs a protogoan which can be seen easily with the unaided eye. This is Carchesium, a colonial peritrich ciliate. Its attached colonies resemble a white monid such as Saprolegnia.

Flatworms have been found beneath the rocks and in shore pools at the outlet and the Well, respectively. Also, small shore pools around tree roots occasionally contain aquatic insects we never saw in the Well...trichopterans, for example. These are very rare.

REPTILES

Kinosternon sonoriense Le Conte, the Sonoran Mud Turtle is common in the Well and in the irrigation ditch which leaves it. We observed turtles every month of the year; at times a dozen or more could be observed from the lookout at the west side of the Well's rim. They are especially abundant in the weeds at the southwest margin of the lake. We did not examine the gut contents of any turtles, because we had no permission to do so, but it appears from their method of foraging that they capture insects and amphipods in the pond weeds.

Eggs are laid during the last week of March, or perhaps somewhat earlier. By the middle of September small turtles about 3.2 cm long (carapace length) can be found. The two largest turtles we found were 14.1 cm long; one of these weighed 430 g. Many of the larger individuals were covered with the unusual alga, Basicladia.

We attempted to estimate the populations by marking and releasing individuals, but we never caught the same individual twice.

Kinosternon has an elongate shall but the young individuals, below 7 cm long, are practically round with a length/width ratio of 1.0. When the animals attain 7 cm in Montezuma Well, the ratio approaches 1.5, the mean being 1.47 for

turtles greater than 5-cm carapace length (Fig. 10).

The gain in weight is marked until the turtles reach about 13 cm; then there seems to be no marked gain with increase in length (Fig. 11). Mature turtles from 12-3 cm long have a mean weight of 349 g.

The female turtles climb high up the basin slope to lay their eggs. In some instances they seem to have climbed about as far as possible ... vertical rock cliffs have stopped them. The eggs are deposited in shallow nests in dry soil on all sides of the Well, but especially at the north and east. The rather long journey from the water for oviposition explains why mummified Kinosternon occasionally can be found in the desert south of the Well. These females probably moved out of the irrigation ditch to lay their eggs.

The predation on the turtle eggs is extreme, and the basin slope is pitted with diggings and egg shells. There is evidence that raccoons, striped skunks and spotted skunks are involved in the destruction of many nests. Of course muskrats, Ondatra zibethicus (L.) are present in the Well and are especially common at the north and east sides. We cannot say, however, that they destroy turtle nests.

Packrat nests contain egg shells and turtle bones , but these rodents may only collect them rather than actually destroy.

The rock squirrel, Citellus variegatus (Erxleben) is common and may be destructive. Also, we have seen Eutamias dorsalis (?), a chipmunk, in the basin, and found the remains of a grey fox (Urocyon). Perhaps all these mammals destroy turtle eggs.

BIRDS

The birds of the Well are represented by several aquatic species and such insect catchers as the Black Phoebe (Sayornis nigricans). Also, there are about 28 old nests of the cliff swallow, Petrochelidon pryrhonota, on the steep rocky cliff at the south side of the Well; but this colony was abandoned some time before 1960 and we saw no activity there.

- Coots and ducks (Baldpates especially), Pied-billed grebes and Sora Rails were present during fall and winter months. In November 1960 and December 1961, a Canada Goose was on the lake, and on 21 June 1961 two Canvasback ducks were present. This represents, at most, a very sketchy account of the birds of Montezuma Well.

PRIMARY PRODUCTIVITY

Primary productivity in the Well is due, in large measure, to the marginal pond weeds (Potamogeton illinoensis Morong) which grow to a depth of roughly seven meters. Their annual production is difficult to assay because they do not die each winter; the emergent fruiting spikes do not protrude above the surface during the colder months, but most of the plant survives in the "perpetual summer" of the warm Well water. Other complications occur; for example, on 13 Feb. 61 the pond weeds did not protrude above the surface but were overlain by a tangled mass of floating plant parts which had drifted from other regions of the weed bed. Because growth was continuous, it was not possible to harvest a sample of the weed crop just before it died as can be done with terrestrial crops or the macrophytes of lakes with extreme seasonal fluctuations in temperature.

In the summer of 1961 we made several collections of the large Potamogeton in an attempt to establish methods of sampling this important plant population. On 25 July the mean fruiting spike per plant was 3.8 and the upper meter of each plant weighed 6.35 g wet weight, or about 15% of this dry weight, 0.95 g. The stem, lacking leafy branches, below the upper meter weighed about 1.9 g wet weight for each meter of length. There was a mean of 386 plants/m^2 which implied a

wet weight of 2,451 g/m^2 in the uppermost meter of water. Thus plants in 7 m of water weighed about 17.75 g with stems included, and the standing crop, therefore, was 6,851.5 g/m^2 or 1,028 g/m^2 dry weight. Twenty-three days later, 14 Aug. 61, the pondweeds were sampled again at approximately the same place. The mean was then 5.6 spikes per plant, and the upper meter of each plant weighed 16.7 g, representing a growth of 0.45 g wet weight/day (0.0375 dry weight/day). The upper meter ofpondweed material had a mass of 6,446 g/m^2, representing a gain of 3,995 g/m^2 at the rate of 174 g/m^2/ day. On a dry weight basis this is 26 g/m^2/day.

The emergent flowering and fruiting spikes probably represent new growth each year; we found 2,162 spikes/m^2 in mid-August. Fifty spikes had a wet weight of 11.4 g, which implies 492.9 g/m^2 ... 73.9 g dry weight/m^2. This, of course is at least 4,929 kg/ha of new growth each year on a wet weight basis. For the area involved (about 0.422 ha occupied by the pond weeds), this is 2,080 kg/annum, or 312 kg/annum dry weight in the Well.

Westlake (1963) has summarized the scattered data on plant productivity in various habitats. His discussion of freshwater macrophytes includes useful comparative information. The most productive lakes produce from 400-700 g/m^2, dry weight. Perhaps the warm flowing waters of Silver Springs,

Florida (Odum 1957) are more similar to Montezuma Well than are temperate lakes. The dry weight of the continuously growing Sagittaria community, including algal epiphytes, is 809 g dry weight/ m^2. The August samples from Montezuma Well show over 1620 g dry weight/ m^2 at a depth of seven meters. Arbitrarily accepting half this amount as an estimate of the standing crop, because 7 m represents the region where the tallest plants occur, we find the plant crop in Montezuma Well is comparable to the highest production known in aquatic macrophytes.

Estimates of the Potamogeton photosynthetic rate were made by suspending funnels and inverted jars over the weed beds and allowing oxygen bubbles to displace water in the jars. This is scarcely an accurate method of measuring all the oxygen produced, because the water in the collecting vessels must become at least saturated before the gas begins to displace the water. Also, bubbles accumulate in the funnel, and in the tubes leading to the jars or collecting vials; they were not always dislodged with success. Several of these pieces of apparatus were set up at different places in the weed beds on 24-25 July 1961. The mean value of gas collected was 0.1 ml per cm^2 for each daylight hour.* This equals about 0.014 mg

*A month earlier, 22 June, we allowed a drifting funnel-tube-vial to gather bubbles along the weeds at the south margin of the lake. Bubbles were collected from the submerged Potamogeton beds, therefore, and at the rate of 0.1026 ml/cm^2 hour.

$O_2/cm^2/hour$. There were twelve hours of sunlight on the lake surface each day, permitting us to calculate a net photosynthetic rate of 0.168 mg $O_2/cm^2/day$. From another viewpoint, about 7 grams of glucose (net) were produced per m^2 each day in late July. There are several reasons why photosynthesis rate is underestimated by the trapped-bubble-volume method, but still the increase in dry weight of pondweed, mentioned two pages before, seems far too high for the productivity implied by the experiments discussed above. The gain is on the order of 4-times too great ... our estimates of gross photosynthesis in July, however, is in line with the estimates of plant growth. This is about 0.691 mg $O_2/cm^2/day$, and is discussed below.

Assays of photosynthesis and respiration of the planktonic community were attempted at first by light-dark bottle experiments. This proved tedious, and occasionally anomalous results were obtained by this method. Therefore, after noting that the wind's effect on the surface of the Well was usually negligible, we turned to following diel oxygen changes in the lake. We treated the night hours as the dark bottle, and daylight hours as the clear bottle. Many of our data came from water samples taken simultaneously from several depths. In such instances the products of exygen in mg/liter and the lake volumes at the levels in question were plotted

against depth on graph paper. From the areas enclosed by the resultant curves, oxygen for the entire water mass was established planimetrically. The changes, whether caused by net increase of O_2 by photosynthesis during the day, or caused by night-time respiration along, were divided by total lake area and by the hours involved in the change. These steps gave rates of change referred to unit area of the Well surface.

Although the vertical oxygen curve was not exactly uniform, it was necessary on some occasions to determine oxygen from one level only, sacrificing accuracy in the interest of time. In such instances oxygen values at a depth of 8 m were observed at sunset, sunrise and some time during the next afternoon ... preferably at sunset again. The changes were multiplied by the entire lake volume and divided by area and divided by area and hours involved to derive rates. The data secured in this manner were treated according to the procedure described by McConnell (1962-1963) although we did not use his graph-paper technique. Sunset to sunrise decreases in oxygen were assumed to be caused by respiration and the hourly rate was calculated and assumed to apply throughout the sunrise-sunset hours of the following light period. The sum of this calculated respiration and the observed increase in oxygen during daylight hours was treated as gross

photosynthesis (oxygen consumed in respiration plus excess oxygen produced by photosynthesis and not respired).

There are several things to be considered in this discussion. First, atmospheric diffusion was ignored in all instances. Second, probably the marginal weed-bed photosynthesis contributed to the oxygen of the nearby water, but, conversely, much oxygen produced by Potamogeton was lost by bubbling to the surface. Our data from 24-25 July 61 show that in the upper 5 m of water, far less than the mean photic zone depth, 0.05 mg/l of oxygen was lost to the atmosphere each daylight hour. Third, the weed region was included in the areal computations of photosynthetic rates even though the oxygen was sampled rom the open water. Fourth, the diel oxygen changes occurrred throughout the water column and were considered in the computations even though photosynthesis may have been limited to the euphotic zone.

Daily gross photosynthesis data from 1960, 1961 and 1962 were weighted and summed for the derivation of monthly means. From these an annual production of 255.17 mg O_2/cm^2 (2.55 kg/m^2) was calculated. This figure is probably conservative because data from rainy and cloudy days were included. Other data to report are: a mean of 21.25 mg O_2/cm^2/month; a mean of 0.699 mg O_2/cm^2/day: and a mean net photosynthetic rate of 0.431 mg O_2/cm^2/day.

The net photosynthesis mean was balanced by a night-time respiration of 0.419 mgO_2/cm^2. Thus we are led to conclude that the Well represents a steady-state system with community productivity and respiration balancing. A quote from Patten (1959) is in order, "When an exact balance between negentropy gains and losses is achieved, the ecosystem has reached a stable equilibrium with respect to order-disorder. Such a condition, sustained, marks climax." In Montezuma Well, if the discrepancy between respiration and net photosynthesis is significant, the excess (0.012 mg $O_2/cm^2/day$) may be balanced by the loss via the outlet, and the net output is zero. Montezuma Well, like Silver Springs, Florida, is a theoretical climax ecosystem. The accumulated peat mass at the north shore may represent an earlier and successional stage in the history of the Well, when the excess information of Patten's model was accumulated as biomass, and the net output was positive.

Comparative data from southwestern waters are scarce, but McConnell (1963) and Kemmerer (1965) have presented production figures for Arizona fishing impoundments. In Pena Blanca Lake a three-year mean of 1.6 kg O_2/m^2 gross productivity and a daily mean of 0.4 mgO_2/cm^2 was shown by McConnell. Kemmerer expressed his results on a volume basis, but showed increased productivity in Pena Blanca since

McConnell's 1959-61 data. He converted McConnell's pelagial productivity to 249 g O_2/m^3 and compared it to his own estimates of 291.55 g O_2/m^3 for 1964. A similar conversion could be made for the Montezuma Well annual production. This would make it about 382 g O_2/m^3.

McConnell (1963) based most of his results on an assimilation number, the ratio O_2 produced chlorophyll on an hourly basis. Empirically determined, the mean number 2.04 was used. In Montezuma Well the ratio $\frac{\text{mg } O_2 \text{cm}^2/\text{hour}}{\text{mg chlorphyll/liter}}$ was 2.63. This was based on pelagial chlorophyll only, the contribution from the pond weeds being neglected.

A plot of total respiration against gross photosynthesis (daily), as shown in Figure 12, reveals they approach a 1:1 ratio. Thus the measurement of night-time respiration could be utilized alone for calculating the gross photosynthesis with some degree of accuracy in Montezuma Well.

Photosynthesis rates can be calculated from diel fluctuations in CO_2 in most bodies of water. In Montezuma Well, however, there is little relationship between moles of CO_2 disappearing and moles of O_2 appearing during daylight hours ... or the reverse, when respiration alone occurred. In all cases more CO_2 was gained during the night and lost during daylight hours than could be accounted for on the basis of oxygen changes alone. In some instances the unexplained

daytime decreases were almost identical to the unexplained, excessive night-time gains. Some of these excesses were, for example: 13.4 and 13.9 mg of CO_2/cm^2/hour for the night and day of 29-30 Sept. 61; 2-3 Dec. 61 they were 5.5 and 5.8 mg $CO_2/cm^2/hr$; and 11 Feb. 61, 10.2 and 11.8 mg $CO_2/cm^2/hr$. Such figures would imply unreasonable photosynthetic rates.. . a mean of about 2.8 of carbon fixed per cm^2 per hour of daylight.

The excess loss of CO_2 during daylight hours may be partly a function of the warming of surface waters. Also, the bubbling of photosynthetically produced oxygen from submerged vegetation may remove great quantities of CO_2. The bubbles passing through supersaturated waters may reach the surface containing relatively large amounts of CO_2, although they started up as oxygen. The tremendous gains at night are not easily explained. If we assume the water entering the Well is equal to that leaving and measured at the first weir, some guesses can be made about the CO_2 input. Assuming 6.2 as the entering pH and the mean total alkalinity 560 mg/l, the CO_2 should be about 686 mg/liter. If 1.5 million gallons of water enters each day, we can calculate some $3,895.2 \times 10^6$ mg of free CO_2 accompanying the water.

On an areal basis this would amount to 51.3 mg per cm^2 and only 2.13 mg CO_2/cm^2/hour. The physical-chemical limnology of the CO_2-pH-carbonate equilibria is one of the most fascinating problems awaiting study in Montezuma Well.

COMMUNITIES

Plankton

The plankton contains four conspicuous animals. These are : Hyalella azteca; E po della punctata annulata; Tropocyclops prasinus mexicanus; Macrocyclops al idus. The first two of these are found in all communities of the Well. Hyalella, in open water, occasionally can be seen at the surface where it is a ne ton feeder.

On dark overcast days and at night the plankton rises to the surface, and crystal clear waters of the Well become turbid with them. During the day when the sun is bright the community is below the surface. Skin-divers report a layer of a hipods below which is a stratum of swimming leeches. The leeches can not be sampled adequately ... they are remarkably adept at avoiding nets and probably dredges. We can say some things about the vertical distribution of the other plankters, however.

On a bright day at about noon (10 Aug. 60) we made vertical hauls from different depths to the surface, using a plankton net of No. 20 Bolting silk, and with an open-end area of 144.6 cm^2. All animals were counted from each haul and by subtracting the counts of short hauls from longer hauls, we arrived at some figures for depth distribution. The Secchi disc transparency was 3.5 m, from which we can estimate

a photic depth of approximately 10.5 m. The animal distribution is shown in Table 5. Below 8 m there were almost no amphipods; 98% of them were concentrated between 3-8 m, the greatest density at the 4-5 m level. Among the copepods there was a similar distribution, the maximum concentration at 3 m for the adults and at 4 m for the immature nauplius stages. Only one leech was captured.

The number of planktonic crustaceans in the lake at the time of the Aug. 10 sampling can be calcualted in the following manner. Assume open water is bounded by the 7-m contour, the area is ca. 4220 m^2, and the volume of each one-m contour is 4220 M^3. The results of the computation are as shown below.....

Nauplii.....715.3 x 10^6 or 169 x $10^3/m^2$

Adults & copepodid

cyclopoids.....5523.7 x 10^6 or 1637 x $10^3/m^2$

Amphipoda.....236.8 x 10^6 or 56.1 x $10^3/m^2$

TOTALS.....6475.8 x 10^6 or 1862 x $10^3/m^2$

Some other quantitative data are: 14 May 61, 796 Hyalella per m^2; cyclopoids, 2,170/m^2; on 22 June 61, with a coarse #2 net, 198 amphipods/m^2, and 50 cyclopoids/m^2. There are other data for the upper three or four meters, only.

Strands of Mougeotia and Spirogyra appeared in many collections, but these plants were relatively scarce and were

probably derived from the pond weeds. Some Arcella occasionally appeared, but these amoeboid protozoans were rare in plankton samples. Centropyxis, another shelled sarcodinid also occurred rarely.

The Chara beds

In the shallows are beds of Chara which harbored community organization not seen elsewhere. Hyalella and the leech were there, but, as stated earlier, they are ubiquitous in the Well. Elaphoidella sp. and the two ostracods, Darwinula and Herpetocypris seemed to be restricted to the charophyte masses. Oribatid mites and the stratiomyid flies were also much more common there. The study of the chara-beds and perhaps the peat deposit alone would be very interesting. These are microhabi ts within the larger environment.

Table 5. Vertical Distribution of Zooplankters in Montezuma Well, Yavapai County, Arizona, 10 August 1960

Secchi disc 3.5 m 1000 hours; collections at 1200 hrs.

Strata	Copepods/liter adults & copepodids	nauplii per liter	Hyalella per liter
0-1 m	5.5	4.1	0
1-2 m	0	0	0
2-3 m	102.7	0.4	0.4
3-4 m	386.0	35.6	4.3
4-5 m	-	129.4	14.2
5-8 m	271.3	-	6.5
8-14 m	minus	minus	minus

Minus values obtained when longer columns had fewer animals than shorter columns sampled.

Marginal Weed Beds

Ranatra, Abedus, Telebasis, Enallagma, Culicoides, Dasyhelea, Microvelia and the three gastropod species were the most conspicuous members of the upper portions of the weeds, if we discount Hyalella. We attempted to sample the weeds quantitatively by drawing a metal sieve vertically up through them. The mesh was about 0.4 mm and there was swirling of water within the sieve and loss of insects over the rim because the mesh was too fine to let water pass through rapidly. The smaller insects, especially were washed out and our sampling was very selective. Generally, we captured 300-400 animals by drawing the sieve of 9-inch diamter up from about 4 m below the surface. Hyalella was always the most abundant, from 33 to 93% of the total catch. In February and March we always caught many arachnids but at other time of year they were not common. The damsel flies were about 5% of the catch and dytiscids and Ranatra were only a small part of the haul, even though they were obvious from the raft.

Bottom Communities

We dredged some species from depths of 0-8 m beneath the pond weeds. These included several of the forms also present in the weeds themselves. However, the forms that we got in benthis samples of the littoral zone were: the two damsel flies, Hydrophilus, Cyoister, Hydroscapha, Physa, Amnicola,

and Somatogyrus. Possibly Pisidium occurs there, but we captured no live individuals.

Our dredge hauls from the 10-16 m contour-bounded depths contained the two oligochaetes mentioned on page 37. These species were not found at shallower depths, but it is important to realize that they were not alone in the deeper sediments. The hirudinean, Erpobdella, and Hyalella were also there. Surprisingly, when we were near sandy places even at depths as great as 15.5 m, the operculate snails were very abundant.

The largest populations were in organic sediments with plant remains making up a big part of the material. At 13.3 m (5 Nov. 60) in such sediments there were 41,600 animals/m^2; 15,800 and 24,710 of this total was composed of the oligochaete worms and operculate snails respectively. The same day at 16 m in a region near the west fissure, where there was much sand, the count was 4,000/m^2 with oligochaetes and snails making up the greatest numbers, 34% and 51%, respectively. At 17 m near the east fissure with more organic material in the sediments the total number of animals was similar ... 3832/m^2 ... but 63% of these were oligochaetes and only 7% snails.

The total mass and volume of bottom fauna is/are low, but the deeps are rather varied. The presence of oxygen at

all depths in the Well plays a role here. Nematode worms, ostracods, occasionally, and insects of different types were dredged from the deepest part of the basin at times. However, the sediments are difficult to screen, the biomass is not great in spite of the large numbers, and we have many samples which were never worked up further. We did ascertain that the bottom fauna contains no chironomaid larvae. This is one of the mysteries of the Well. The absence of planktonic rotifers, Cladocera and calanoids is another puzzling feature of the Well.

LITERATURE CITED

Blake, W. P. 1906 Origin of the depression known as Montezuma's Well, Arizona. Science, new series 24: 568

Clarke, F. W. 1924. The data of geochemistry. 5th ed., U.S. Geol. Surv. Bull. 770: 1-841.

Cole, G. A. 1963. The American Southwest and Middle America. In Limnology in North America. (D.G. Frey, Ed.). Univ. Wisconsin Press: Madison. 393-434.

Colton, H. S. and F. C. Baxter. 1932. Days in the Painted Desertland and the San Francisco Mountains. 2d ed. Museum North. Ariz.: Flagstaff. 113 p.

Demon, P. E., C. V. Haynes, and G. A. Cole. 1964. Carbon 14 content of aquatic plants, Montezuma Well, Arizona. Trens. Amer. Geophys. Union 45 (1): 117. abstr.

Doudoroff, P. 1957. Water quality requirements of fishes and effects of toxic substances. In The Physiology of Fishes Vol. 2. (M. E. Brown, Ed.) Academic Press Inc.: New York. 403-430.

Ellis, M. M., B. A. Westfall, and M. D. Ellis. 1946. Determination of water quality. U. S. Fish and Wildl. Serv., Res. Rept. 9: 1-122.

Hayes, F. R. 1957. On the variation in bottom fauna and fish yield in relation to trophic level and lake dimensions. Jour. Fish. Res. Board Canada 14: 1-32.

Henderson, J. 1933. Caverns, ice caves, sinkholes, and natural bridges. Part II. Univ. Colorado Studies 20 (3-4): 130.

Kemmerer, A. J. 1965. Relation of the chemistry of inflow waters to organic productivity in small fishing impoundments. M. S. Thesis, Univ. Ariz.: Tucson. 1-85. (mimeo'd copy)

Kidd, D. E., and W. E. Wade. 1963. Algae of Montezuma Well, Arizona and vicinity. Plateau 36: 63-70.

Lange, A. 1957. Studies on the origin of Montezuma Well and cave, Arizona. Cave Studies 1 (9): 31-45. 1 pl.

McConnell, W. J. 1962. Productivity relations in carboy microcosms. Limnol. & Oceanogr. 7: 335-343.

_____. 1963. Primary productivity and fish harvest in a small desert impoundment. Trans. Am. Fish. Soc. 92: 1-12.

McKee, E. D., H. Hastings, and H. S. Colton. 1947. Montezuma Well, result of preliminary soundings, July 18, 1947. Ms. in files Mus. North. Ariz., Flagstaff.

Minckley, W. L. and D. R. Tindall. 1963. Ecology of Batrachospermum sp. (Rhodophyta) in Doe Run, Mead County, Kentucky. Bull. Torrey Bot. Club 90: 391-400.

Moore, W. W. 1939. Graphic determination of carbon dioxide and the three forms of alkalinity. Jour. Am. Water Works Assn. 31: 51.

Odum, H. T. 1957. Trophic structure and productivity of Silver Springs, Florida. Ecol. Monogr. 27: 55-112.

Patten, B. C. 1959. An introduction to the cybernetics of the ecosystem: the trophic-dynamic aspect. Ecology 40: 221-231.

Pearse, A. S. (editor). 1936. The cenotes of Yucata. A zoological and hydrographic survey. Carnegie Inst. Washington, Publ. 457.

Ruttner, F. 1960. Uber die Kohlenstoffaufnahme bei Algen aus Rhodophycean-Gatung Batrachospermum. Hydrol. 22: 280-291.

Schroeder, A. H. 1948. Montezuma Well. Plateau 20: 37-40.

Westlake, D. F. 1963. Comparisons of plant productivity. Biol. Rev. 38: 385-425.

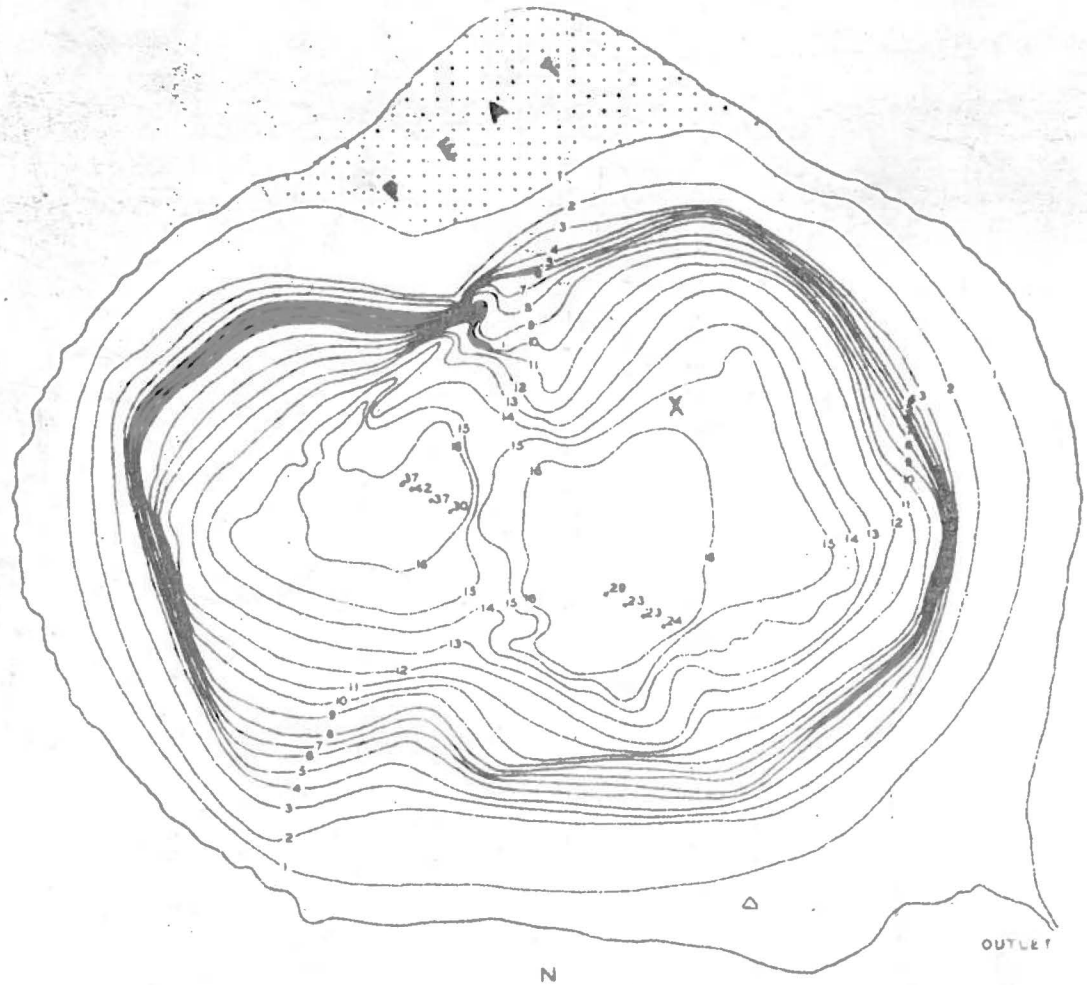


FIGURE 1

N

MONTEZUMA WELL

MONTEZUMA CASTLE NATIONAL MONUMENT

YAVAPAI COUNTY, ARIZONA

AUGUST 1000

FEET

0 20 40 60 80 100

0 8 16 24 32

METERS

DEPTHS IN METERS

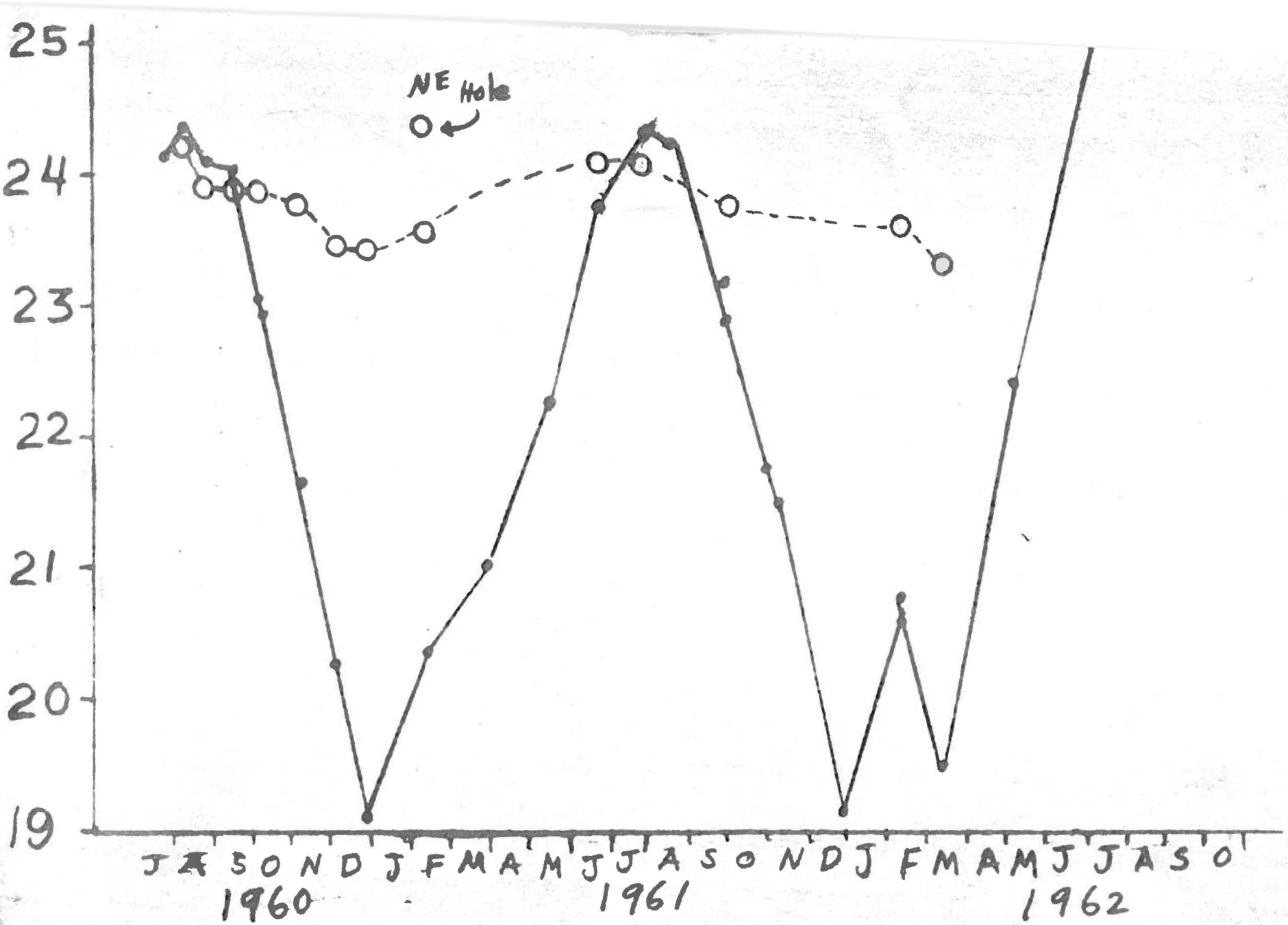
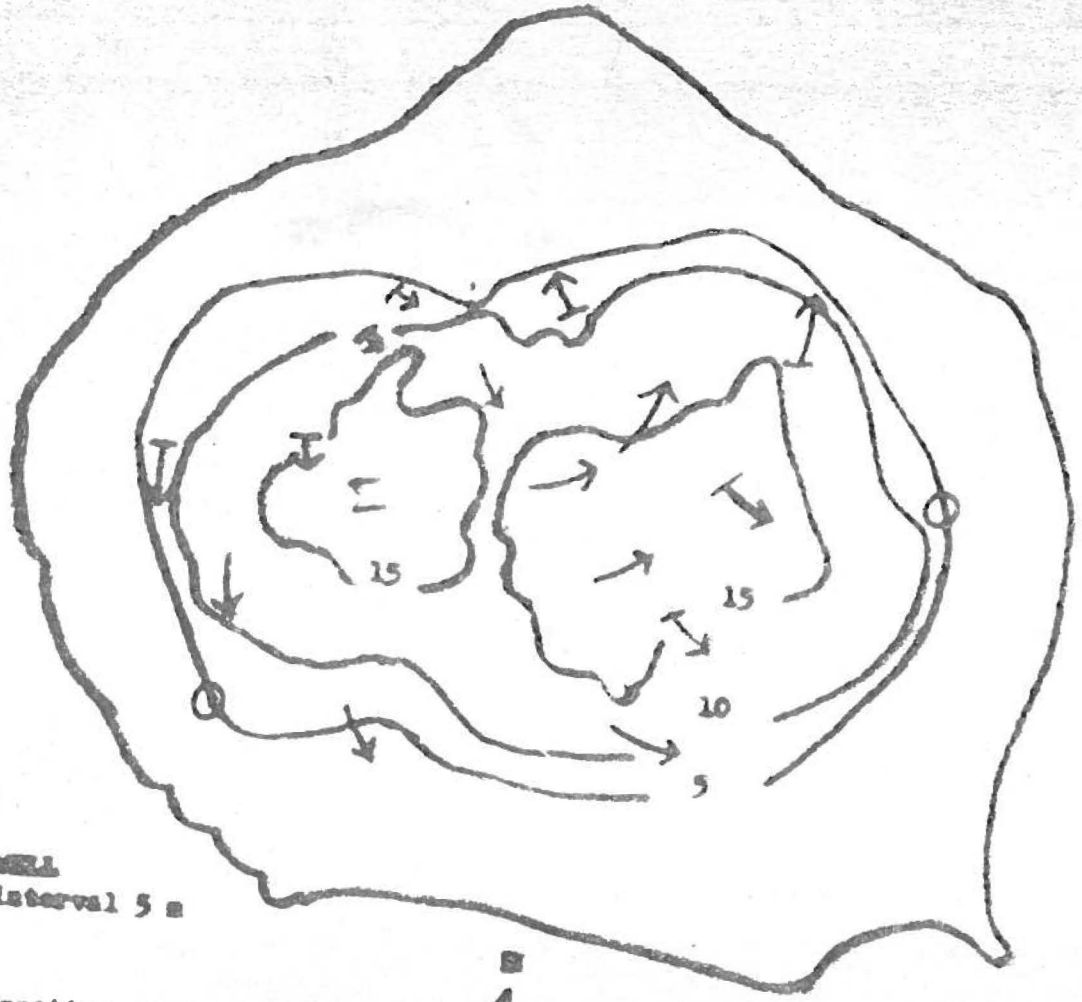


FIGURE 2 Mean Temperatures in Montezuma Well. Dashed line & open circles = temperature of inlet waters



CURRENTS IN

MONTEREBAY AREA
Contour interval 5 m

Symbols
- direction
- direction & down
- down alone
- nothing

N

1

FIGURE 3

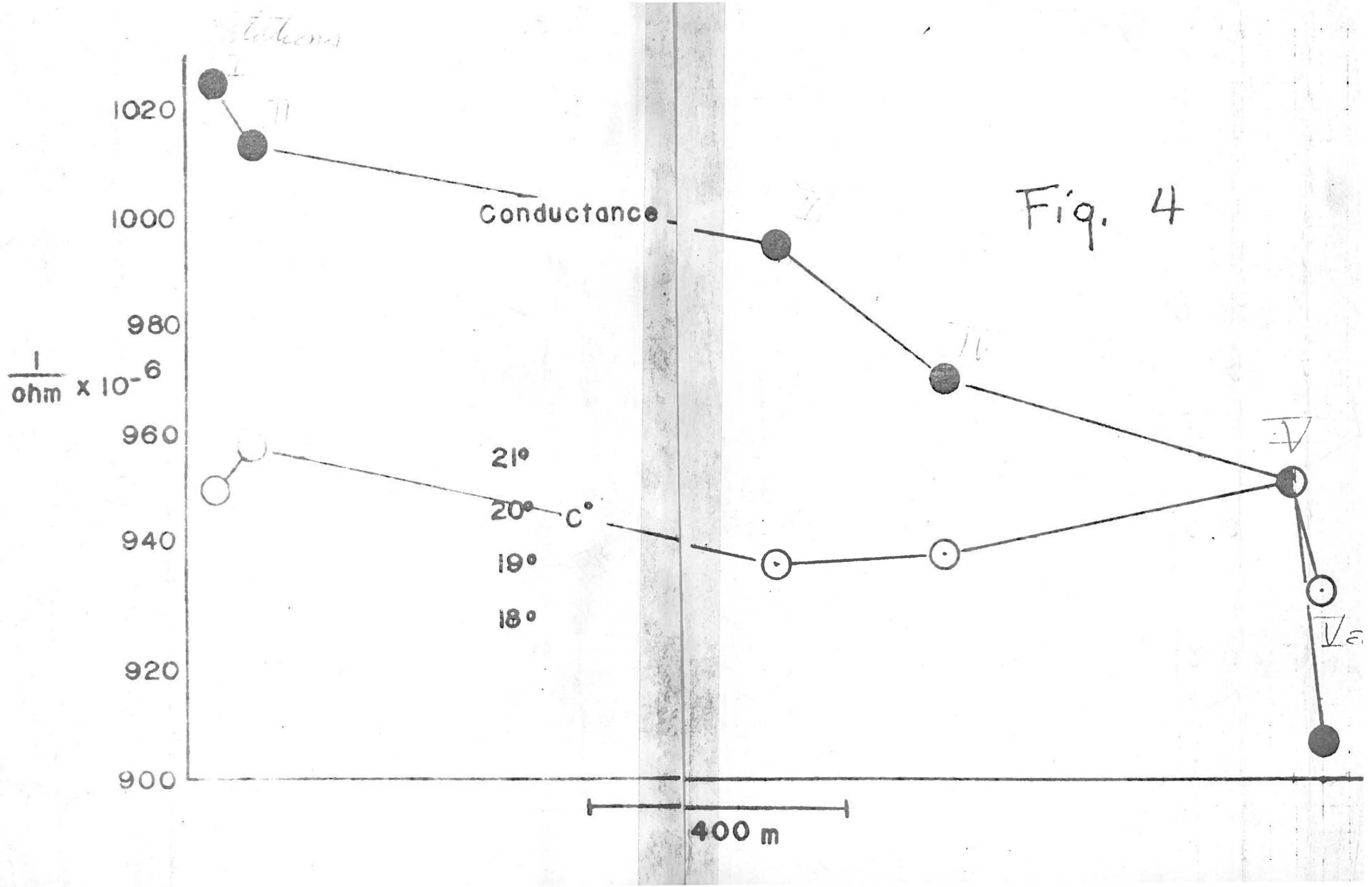

1020
1000
980
960
940
920
900
1/ohm x 10-6
Conductance
21°
20° C°
19°
18°
400 m

Fig. 4

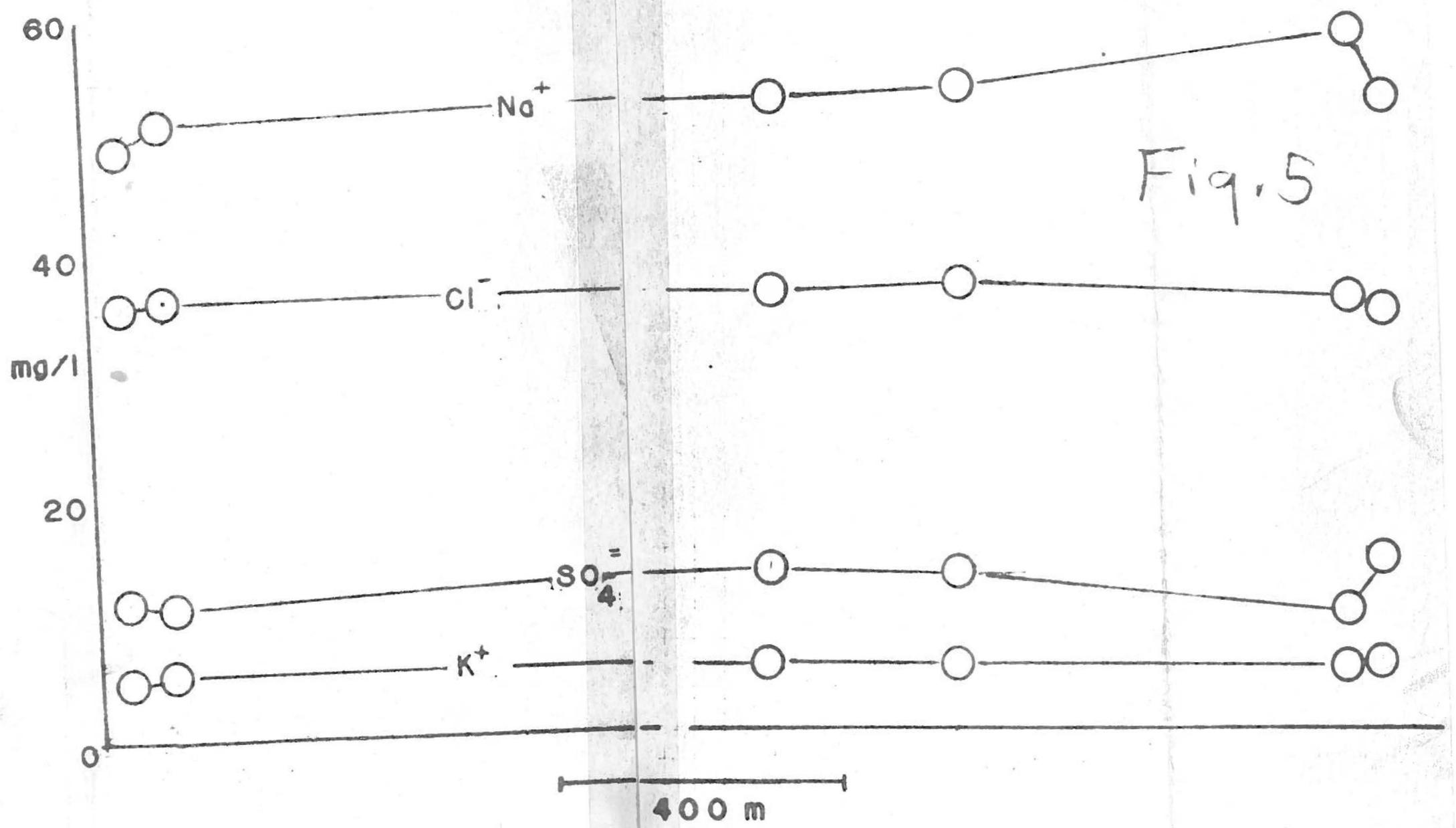


Fig. 5

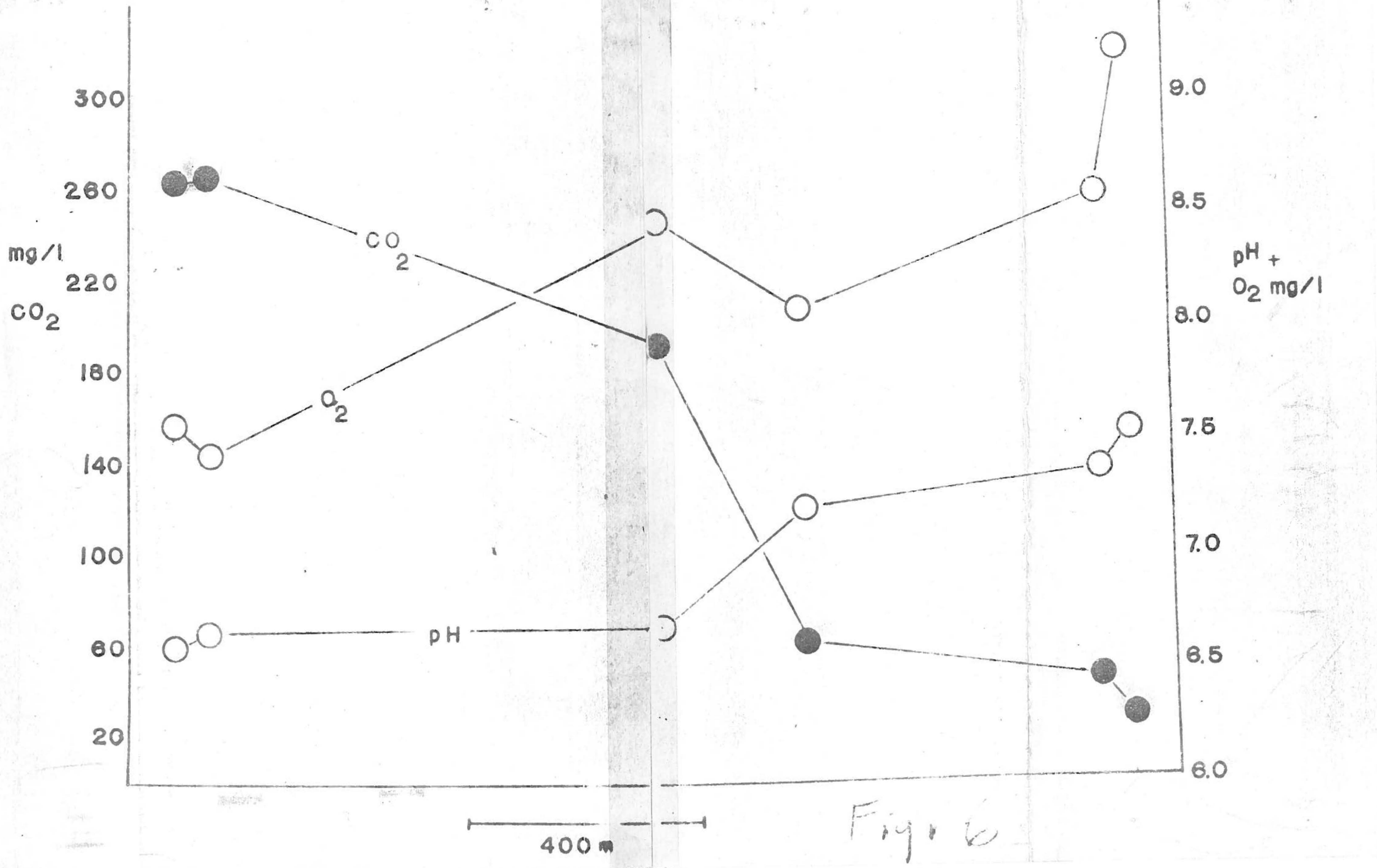

300
260
220
180
140
100
60
20
mg/l
CO_2
CO_2
O_2
pH
9.0
8.5
8.0
7.5
7.0
6.5
6.0
pH +
O_2 mg/l
400 m

Figure 6

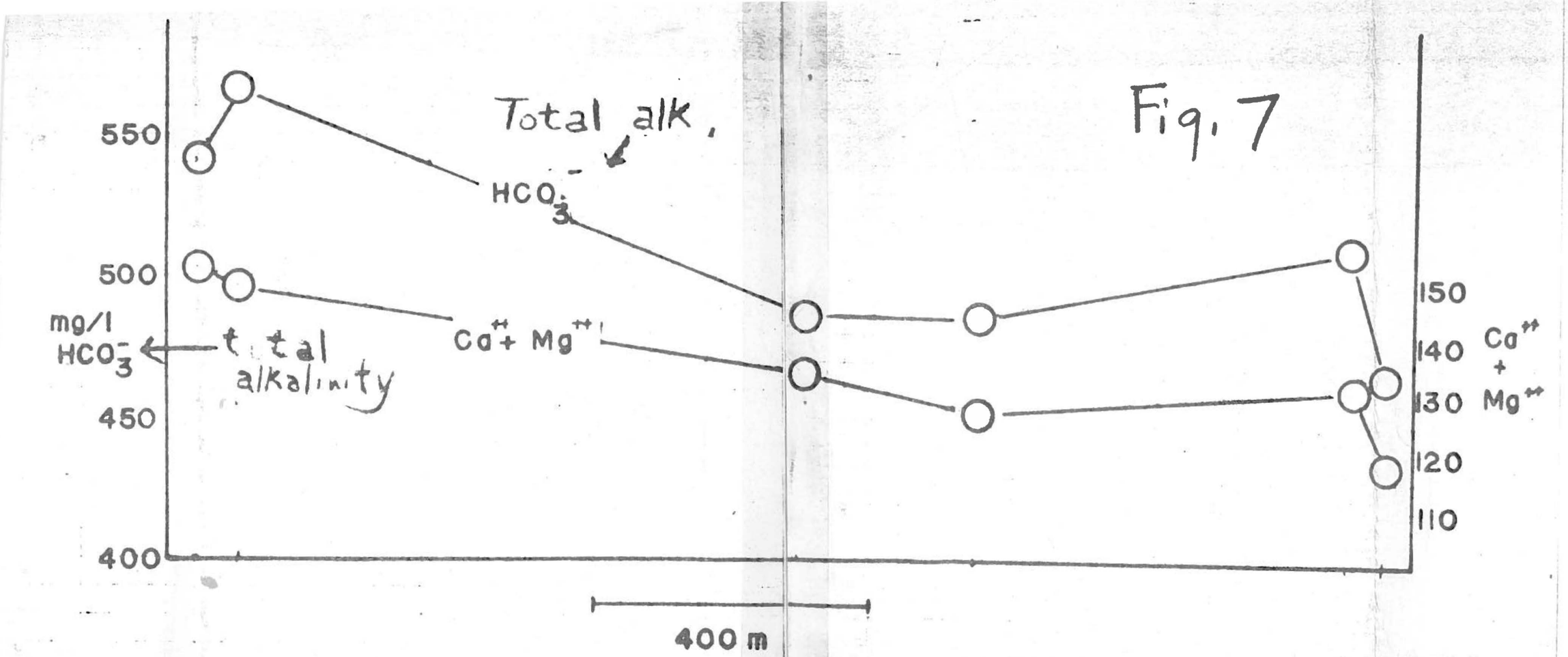

Total alk.
HCO_3^-
$Ca^{++} + Mg^{++}$
mg/l HCO_3^-
total alkalinity
550
500
450
400
150
140
130
120
110
Ca^{++} + Mg^{++}
400 m

Fig. 7

Fig. 7

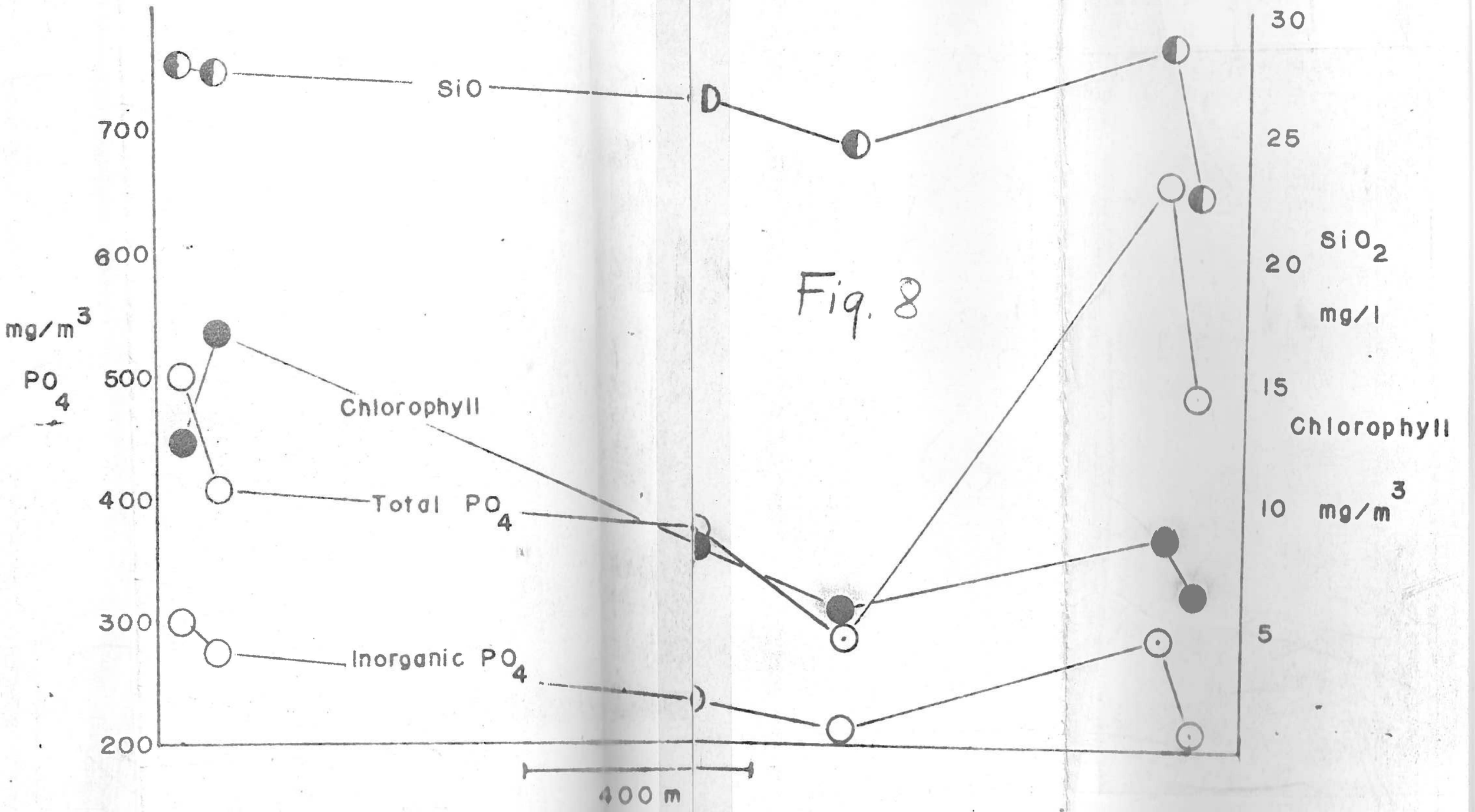

SiO
700
600
mg/m3
PO4
500
Chlorophyll
400
Total PO4
300
Inorganic PO4
200
400 m
30
25
SiO2
20
mg/l
15
Chlorophyll
10
mg/m3
5

Fig. 8

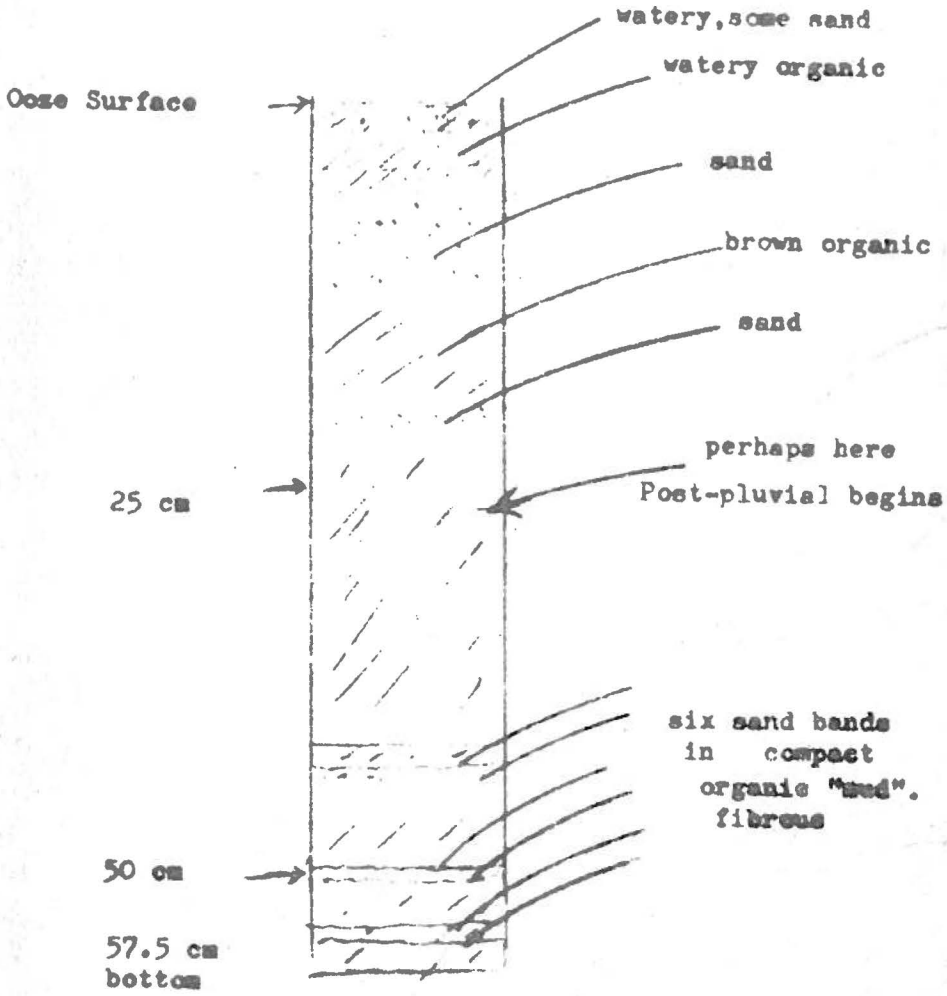


FIGURE 9 Diagram of a cores sample from Montezuma Well

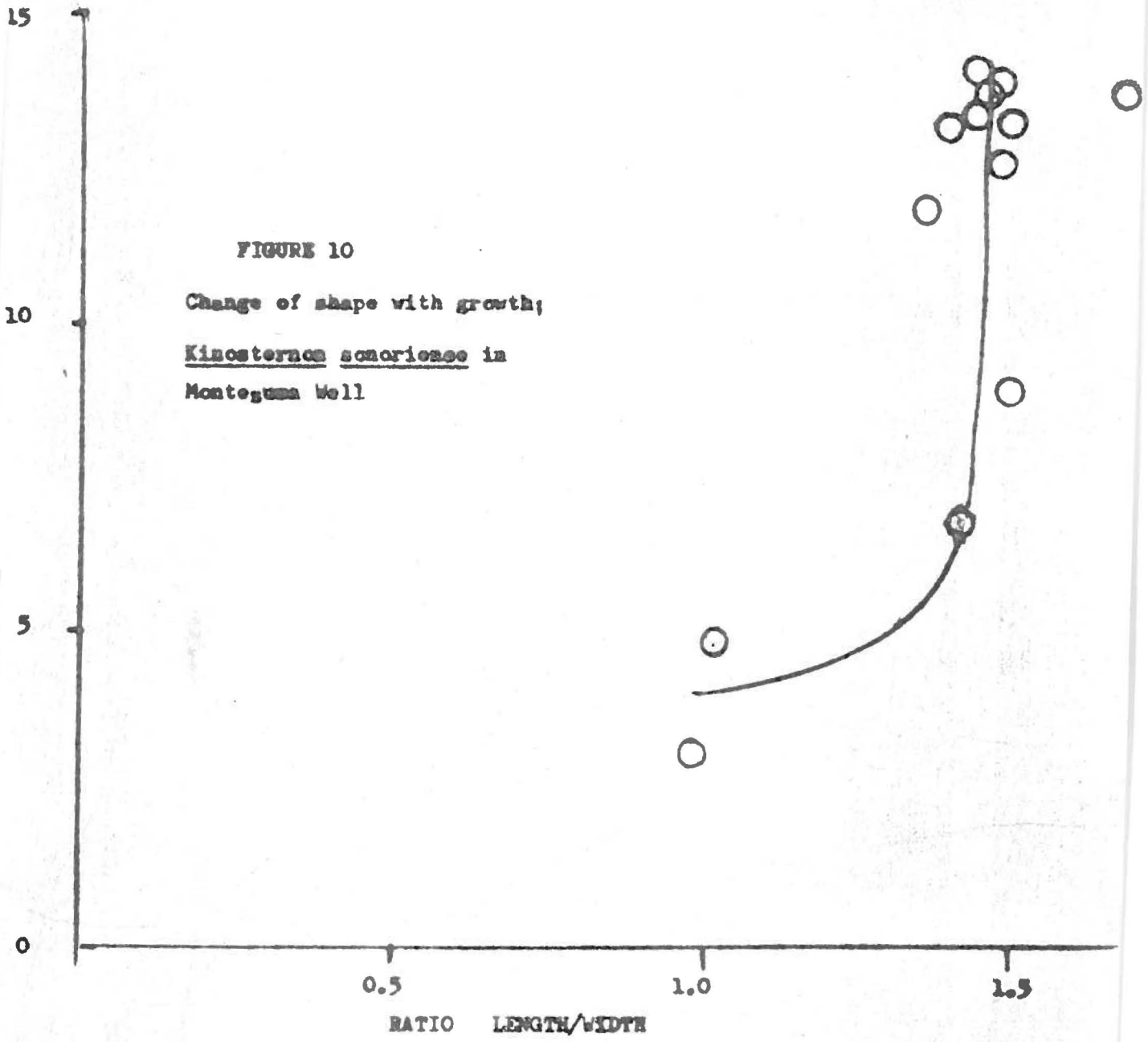


FIGURE 10

Change of shape with growth;

Kincosternon scorpioides in

Montezuma Well

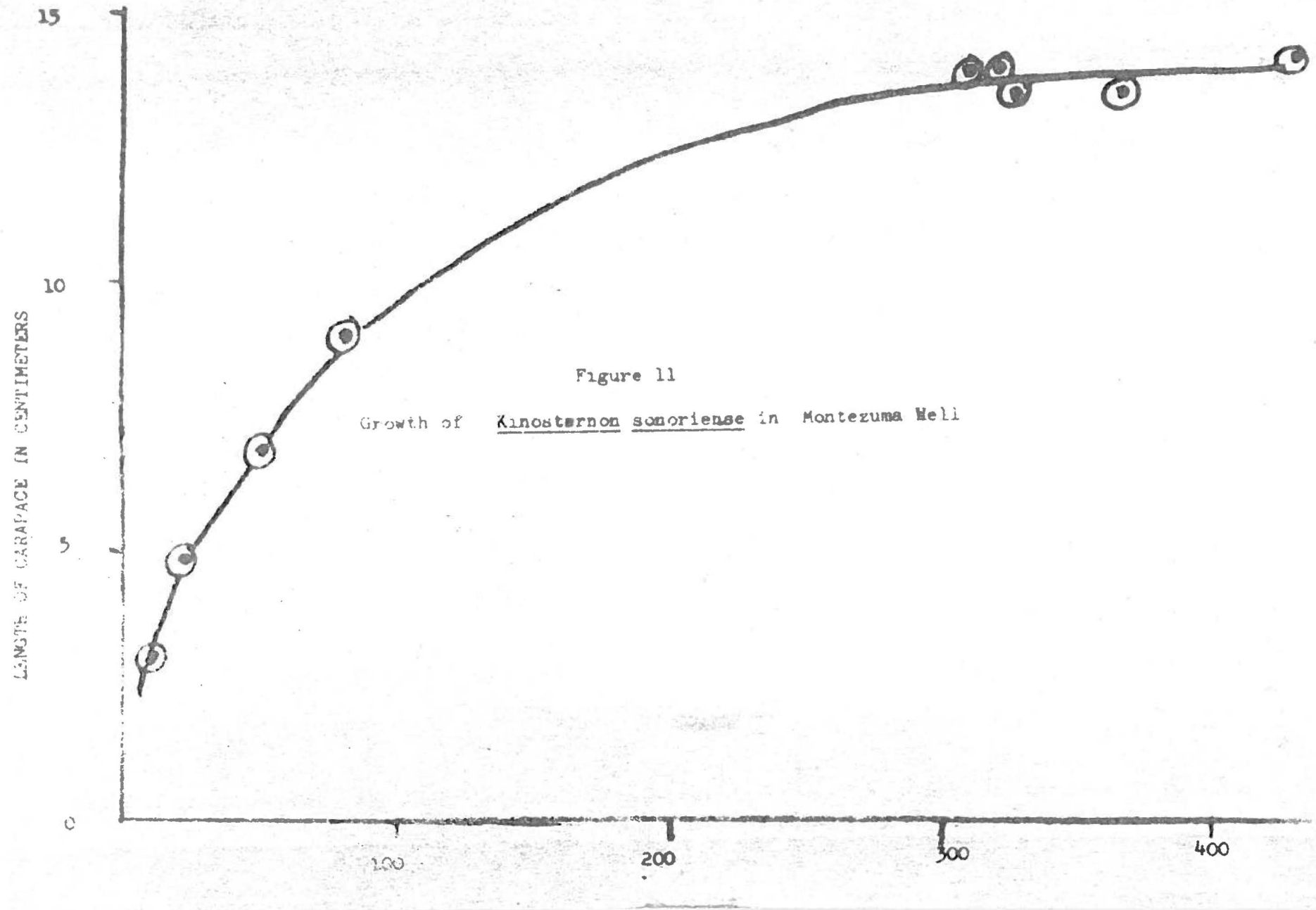


Figure 11

Growth of Kinosternon sonoriense in Montezuma Well

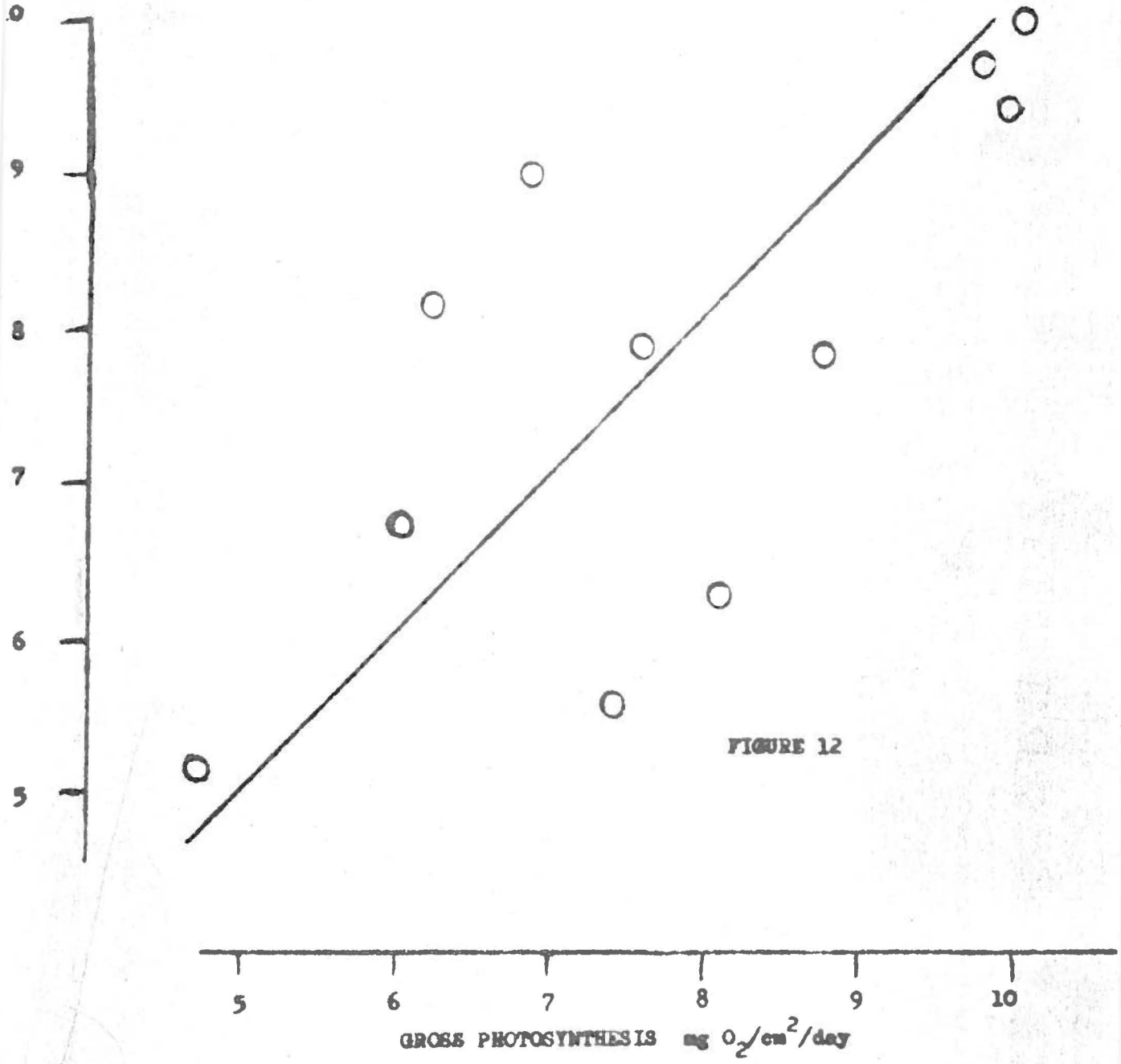


FIGURE 12