of the volcanic material following the spring breakdown of the Antarctic circumpolar circulation.

Daily values of the normal-incidence radiation at the South Pole indicate that the initial influx of the material occurred in several bursts in late November and early December, 1963. Analysis of the stratospheric circulation over Antarctica for these months shows that the dates of arrival at the South Pole coincide with a change in the circulation from circumpolar to meridional. The late arrival of the material in Antarctica is due to the stability of the stratospheric circumpolar circulation during the fall and winter seasons, which effectively restrained the influx until the breakdown of the circulation in the spring (*10*).

As a working hypothesis for the investigation of the radiation decrease, we are assuming that the observed effects were due to the eruption of Mt. Agung in March 1963. Other explanations, including an increase of extraterrestrial material (*11*), have been carefully examined and rejected as unlikely.

EDWIN C. FLOWERS
HERBERT J. VIEBROCK
Office of Meteorological Research, U.S. Weather Bureau, Washington, D.C.

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Radiocarbon Determinations for Estimating Groundwater Flow Velocities in Central Florida

Abstract. *Carbon-14 activity was determined from HCO_3^- in samples of groundwater obtained from the principal artesian aquifer in Florida. From these data the "age" of water obtained from a series of wells, each progressively farther down gradient on the piezometric surface, was established. Relative carbon-14 ages indicated a velocity of groundwater movement of 23 feet (7 meters) per year for about 85 miles (137 kilometers) of travel. A velocity of 23 feet per year was calculated independently from Darcy's law.*

For several years we have been working toward the use of naturally occurring C^{14} in the dissolved carbonate species in groundwater to obtain meaningful ages of groundwater. By age we mean the amount of time since the water was last in contact with the atmospheric reservoir of C^{14}. Several studies of C^{14} concentrations in groundwater have been made (*1*); however, determinations were usually made on spot samples and no systematic investigation of C^{14} concentrations in groundwater has been published.

We have collected water samples from the principal artesian limestone aquifer of central Florida and studied the aqueous chemistry and isotopic composition of the aquifer system. The isotopes being investigated include those of hydrogen, carbon, oxygen, and sulfur. This report concerns only results of the C^{14} determinations; results of the complete study will be published elsewhere.

In the area under study (Fig. 1) the hydrologic system is controlled by the large, high piezometric surface (*2*). The wells sampled (Fig. 1) were completed within the Ocala Limestone and other formations of Eocene age; they range in depth from about 150 to 300 m. Water flows from high portions of the piezometric surface, and at right angles to the equipotential contours, to lower points on the surface. The wells sampled were chosen so as to be as nearly as possible directly below one another in a gradient.

Many problems are associated with the use of C^{14} in dating groundwater. Among these are the initial C^{14} activity of the atmosphere and of rain; C^{14} activity of organic carbon in the soil zone; solution of C^{14}-depleted calcite; saturation of the aqueous phase with respect to calcite (*3*); and exchange between carbonate ions in the water and the CO_3 group in the calcite structure (*4*).

Large (approximately 114 lit.) samples of water were obtained from each of the locations shown on Fig. 1. Samples of this size were required in order to obtain the 3 g of carbon needed for the C^{14} dating process. The carbon was obtained from the total dissolved carbonate species by means of equipment and techniques similar to those described by Feltz and Hanshaw (*5*).

Table 1. Summary of C^{14} measurements and hydrologic data used to determine velocities, v, of ground water flow in the principal artesian aquifer of central Florida. We computed the C^{14} ages using 95 percent of the National Bureau of Standards oxalic acid standard as the initial C^{14} activity and 5570 ± 30 years as the half-life of C^{14}. A velocity of 33 feet per year for $v_{\text{hydrologic}}$ is equivalent to 10 meters per year.

No. of well and location	Information, between wells	Distance (mi)	Difference in piezometric surface (ft)	Hydraulic gradient (ft/ft $\times 10^4$)	$v_{\text{hydrologic}}$ (ft/yr)	U.S. Geol. Surv. Lab. No.	δC^{14} ±20‰	Apparent age (yr)	Difference in age (yr)	$v_{C^{14}}$ (ft/yr)
1. Polk City						W-1442	−657	8,600		
	1 and 2	28	40	2.7	33				5,500	27
2. Ft. Meade						W-1439	−827	14,100		
	2 and 3	14	14	1.9	23				11,070	7
3. Wauchula						W-1444	−956	25,170		
	3 and 4	23	16	1.3	16				3,130	39
4. Arcadia						W-1438	−970	28,300		
	4 and 5	18	14	1.5	18					
5. Cleveland						W-1443	−967	27,460		
	1 and 3	42	54	2.4	29				16,570	13
	1 and 4	65	70	2.0	24				19,700	17
	1 and 5	83	84	1.9	23				18,860	23

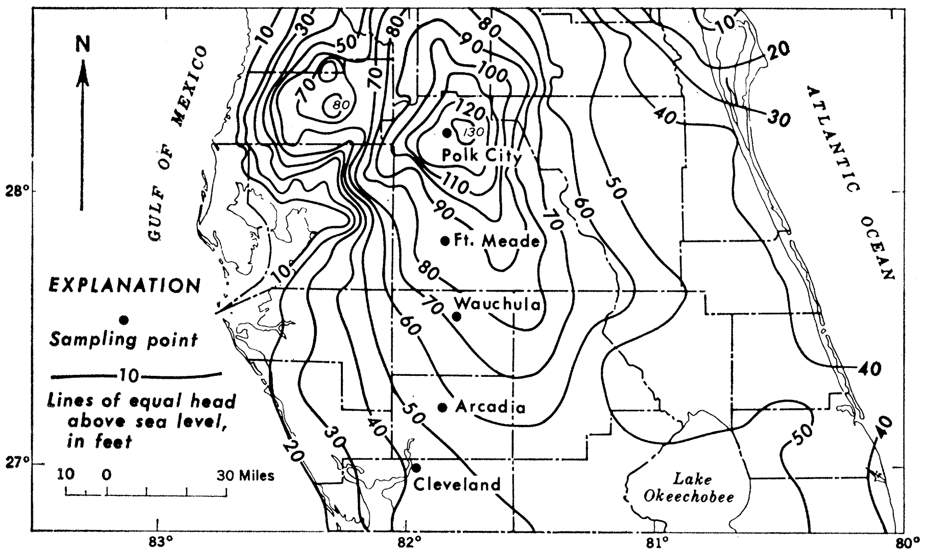

Fig. 1. Piezometric map of the principal artesian aquifer of central Florida showing sampling points (10 miles are equivalent to 16 km).

The C^{14} data presented in this report (Table 1) are uncorrected for possible fractionation. We emphasize that these are uncorrected ages and should not be construed to be absolute ages. In all likelihood the true ages are several thousand years younger than those shown here (*4*). Nevertheless, we believe the relative or increment age between sample points is nearly correct. A value for velocity of ground water movement was obtained by simply dividing the distance between sample points by the difference in C^{14} ages (Table 1). We could not obtain such a value for velocity between sample points 4 and 5 because of the apparent anomaly of age reversal. This enigma is readily resolved, however, by examining the experimental uncertainty inherent in δC^{14} determinations, ± 20 per mil. At the low C^{14} concentrations present in samples from 4 and 5, the apparent age reversal is well within experimental error. Thus, the C^{14} data present a reasonable picture of the hydrologic system; the C^{14} content of the water decreases in a systematic manner away from the area in which the water enters the aquifer, and velocities determined from C^{14} measurement seem reasonable. It is possible to check this last statement without referring to the C^{14} determinations by calculating groundwater velocities from hydrologic measurements.

The quantity of water, Q, flowing through water-saturated material is given by

$$Q = pAv \qquad (1)$$

where p is the porosity, A is the cross-sectional area, and v is velocity. The quantity of water flowing is also given by a simplified form of Darcy's law:

$$Q = kAi \qquad (2)$$

where k is the coefficient of permeability in Meinzer's units (gal day^{-1} ft^{-2}), A is cross-sectional area, and i is the dimensionless hydraulic gradient. By combining Eqs. 1 and 2,

$$v = \frac{ki}{p} \qquad (3)$$

Within the area of study it is estimated that the principal artesian aquifer of central Florida has a transmissibility of 250,000 gal day^{-1} ft^{-1}, a thickness of 1000 feet, and a porosity of 10 percent. The hydraulic gradient, in feet of head per foot of horizontal distance in the aquifer, may be obtained from the piezometric map (Fig. 1) and is shown in Table 1. The permeability, k, equals transmissibility divided by thickness, or 250 gal day^{-1} ft^{-2}. Dividing this value by the number of gallons per cubic foot (7.48) gives k = 33.4 ft day^{-1} (10.2 m day^{-1}). Putting the above values into Eq. 3 and changing from days to years gives us the velocity in feet per year from hydrologic parameters.

If we compare $v_{\text{hydrologic}}$ with $v_{C^{14}}$ we see that the two independent determinations are in excellent agreement and generally agree within a factor of two (Table 1). Over the longest travel distance, from points 1 to 5, the agreement is almost exact.

Several simplifying assumptions had to be made in order to calculate the velocity of groundwater flow from hydrologic information. One assumption is that the porosity is constant at 10 percent; actually it may range from 5 to 20 percent over the study area. From Eq. 3 we see that this will change $v_{\text{hydrologic}}$ by a factor of two.

Although the wells sampled were chosen so as to be progressively lower than one another in a hydraulic gradient, they cannot be connected by one orthogonal flow line, and water flowing from Polk City to Cleveland does not pass through the intervening sample points. If the aquifer is assumed to be isotropic to horizontal flow [it must be to calculate velocity from equation (3)] then this does not affect the $v_{C^{14}}$ calculations because the isopleths of the piezometric surface and of C^{14} ages are probably approximately parallels.

Much work remains to be done before it is possible to establish absolute age of ground water using C^{14}. However, this study indicates that relative C^{14} ages are probably quite reliable and that C^{14}-determined velocities are in essential agreement with traditional hydrologic calculations.

BRUCE B. HANSHAW
WILLIAM BACK
MEYER RUBIN

U.S. Geological Survey,
Washington, D.C. 20242

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