STATE OF DELAWARE
UNIVERSITY OF DELAWARE
DELAWARE GEOLOGICAL SURVEY

OPEN FILE REPORT NO. 11

EFFECTS OF EARTHQUAKES AND EARTH TIDES ON WATER LEVELS IN SELECTED WELLS IN THE PIEDMONT OF DELAWARE

BY
JOHN H. TALLEY

NEWARK, DELAWARE
FEBRUARY 1980

EFFECTS OF EARTHQUAKES AND EARTH TIDES ON WATER LEVELS IN SELECTED WELLS IN THE PIEDMONT OF DELAWARE

John H. Talley

INTRODUCTION

Examination of continuous water-level hydrographs from two artesian observation wells in the Piedmont near Newark, Delaware reveals water-level fluctuations caused by earthquakes and by earth tides. The effects of 14 distant earthquakes with MS (surface wave) magnitudes between 6.7 and 8.0 and MB (body wave) magnitudes between 5.9 and 7.0 (National Earthquake Information Service, 1975-1977) have been recorded over a two-year and ten-month period.

The oscillations recorded appear as sharp marks on the charts lasting from a few minutes to several hours. They result from dilitation and compression of the aquifer and vertical motion of the well-aquifer system (Cooper et al., 1965). The largest amplitude oscillations are probably caused by long period Rayleigh waves, which are surface waves that force the rock particles to move in an elliptical orbit in the vertical plane of the path of the waves (Spall, 1978). Amplitudes generated by the 14 recorded events ranged from 0.015 feet (0.46 cm) to 0.215 feet (6.55 cm).

Earth tide-induced fluctuations result from the response of the solid earth to the same forces that produce ocean tides:

(1) the force of gravitation exerted by the moon and sun on the earth;

(2) centrifugal forces produced by the revolution of the earth and moon (and earth and sun) around their common center of gravity.

Earth tides are generally characterized by semidiurnal fluctuations (two minima per day) that correspond to the moon's transit at upper and lower culmination. The larger amplitude and more regular fluctuations coincide with the new and full moon phases while smaller amplitude fluctuations of less regular character occur during first and third.

GEOLOGIC SETTING

Figure 1 shows the location of wells Ca45-39 and Cb41-10 in the Delaware Piedmont. Well Ca45-39 is adjacent to the flood plain of White Clay Creek; well Cb41-10 is 1,350 feet (411 m) to the southeast and and close to a small tributary of White Clay Creek. The area is underlain by crystalline rocks of the Wissahickon Formation of the Glenarm Series. Woodruff and Thompson (1974) have divided the Wissahickon Formation into metagraywacke (Wmg) and pelitic facies (Wp) as shown on Figure 1. Both wells are completed in the metagraywacke facies, which consists of interbedded quartz-biotite-oligoclase feldspar gneiss and schist.

WELL CONSTRUCTION AND AQUIFER COEFFICIENTS

Well Ca45-39 is 6 inches (15.24 cm) in diameter and 360 feet (109.7 m) deep. It is cased through a zone of weathered gneiss and schist to 92 feet (28 m) below the land surface and is finished beneath the casing as an open hole in the crystalline rocks. A water-bearing fractured rock zone was identified between 172 feet (52.4 m) and 230 feet (70.1 m) and yielded about 200 gallons per minute (12.6 L/s). The lithologic, caliper, and gamma-ray logs from the well are shown in Figure 2. Analysis of drawdown and recovery data acquired from a 24-hour aquifer pumping test, at a discharge of 100 gallons per minute (6.3 L/s), yielded a transmissivity of 3,700 (gal/d)/ft (gallons per day per foot) (45.8 m^2/d) and a specific capacity of 4.9 (gal/min)/ft (gallons per minute per foot) [1.01 (L/s)/m] of drawdown. The water in well Ca45-39 occurs under confined conditions.

Well Cb41-10 is 355 feet deep (108.2 m) and contains 52 feet (15.9 m) of 6-inch (15.24 cm) diameter steel casing. A relatively thick intermittently fractured rock zone that yielded 150 gallons per minute (9.5 L/s) while drilling was penetrated between 130 feet (39.6 m) and 178 feet (54.2 m).

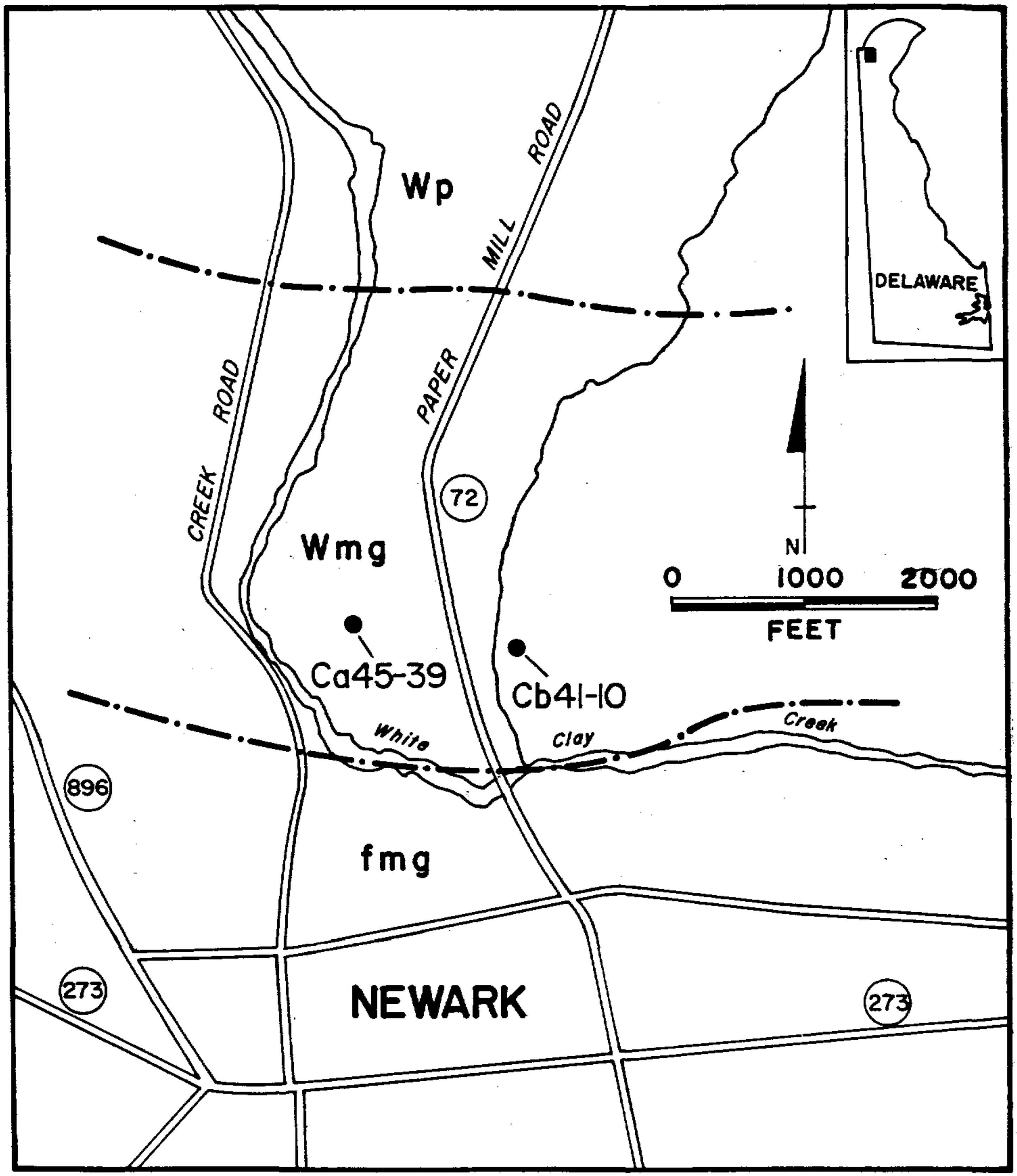

Figure 1. Location and geologic setting of wells Ca45-39 and Cb41-10.

Wp = pelitic facies, Wissahickon Formation;
Wmg = metagraywacke facies, Wissahickon Formation;
fmg = felsic and mafic gneiss, Wilmington Complex;
— · — = geologic contact

The results of a 43-hour aquifer pumping test at 198 gallons per minute (12.5 L/s) show that the transmissivity is 1,700 (gal/d)/ft (21.1 m^2/day) and the specific capacity is 2.6 (gal/min)/ft [0.54 (L/s)/m] of drawdown. Water occurs under confined conditions in well Cb41-10.

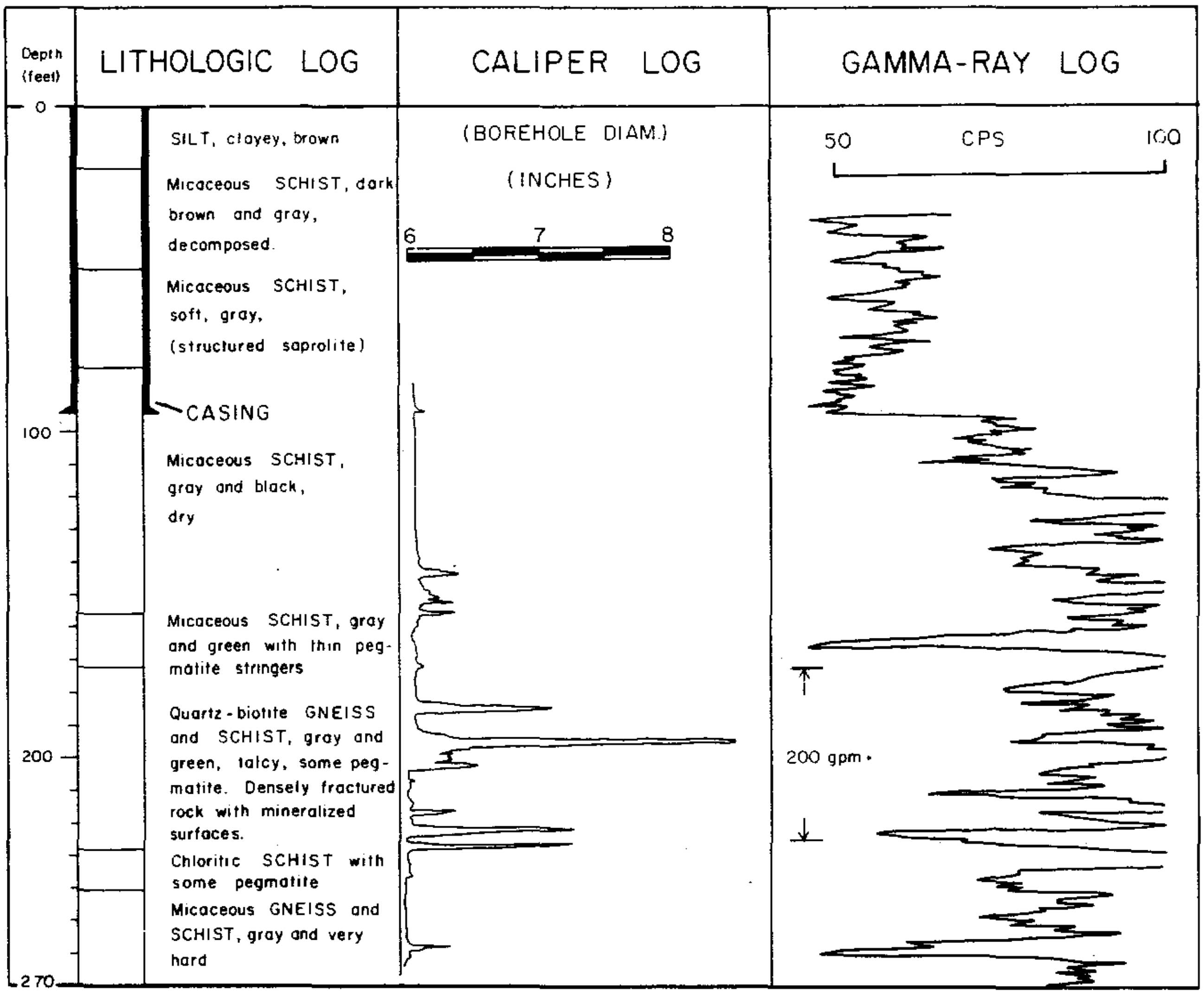

Figure 2. Lithologic, caliper, and gamma-ray logs of well Ca45-39 (After Talley, 1974).

DISCUSSION

Fluctuations Resulting from Earthquakes

The seismic waves recorded in well Ca45-39 between February 1975 and November 1977 were caused by earthquakes that occurred in various parts of the world: northeastern China, the Philippine Islands, Romania, the eastern Indian Ocean, the southwest Pacific Ocean, the Solomon Islands, and off the coast of northern California. Most of these earthquakes were recorded by seismograph station NED (Newark, Delaware) which is also operated by the DGS. Pertinent data pertaining to each of the 14 events are presented in Table 1.

Several earthquakes have occurred in northern Delaware (Jordan et al., 1972; Woodruff et al., 1973), however, none during the period of this investigation.

Fluctuations with a maximum amplitude of 0.168 feet (5.09 cm) in well Ca45-39 resulting from the August 19, 1977 earthquake of MS (surface wave) magnitude of 7.9 in the eastern Indian Ocean south of Sumbawa Island are shown in Figure 3. These fluctuations persisted for approximately two hours and twenty minutes. During that time the amplitude gradually increased to a maximum and then gradually receded to zero. Superimposed upon earthquake fluctuations was a rise in the "undisturbed" water level of 0.035 feet (1.07 cm) caused by earth tides.

Seven verified seismic events have been recognized in records for well Cb41-10 between August 1976 and August 1977. Several events recorded in well Ca45-39 were not detected in well Cb41-10; well Cb41-10 appears to be less sensitive than well Ca45-39. The amplitudes recorded in well Cb41-10 were in all instances smaller than those recorded for corresponding events in well Ca45-39. For example, the earthquake that occurred August 19, 1977 south of Sumbawa Island was also recorded in Cb41-10 (Figure 4). However, the amplitude in Cb41-10 was smaller than the amplitude in Ca45-39: 0.065 feet (1.98 cm) vs. 0.168 feet (5.09 cm). It is interesting to note that the transmissivity calculated from Ca45-39 test data is larger than the transmissivity calculated from Cb41-10. The larger amplitude fluctuations studied occur in the aquifer with higher transmissivity.

TABLE 1

Summary of Earthquakes and Corresponding

Water-Level Fluctuations in Wells Ca45-39 and Cb41-10

DATE UTC	ORIGIN TIME UTC			GEOGRAPHIC COORDINATES		REGION	DEPTH (KM)	MAGNITUDES GS		NO. STA.	PDE NO.	WELL RESPONSE	AMPLITUDE (FT)
	Hr	Min	Sec	Lat.	Long.			MB	MS				
Feb. 2, 1975	08	43	39.1	53.1N	173.5E	Near Islands Aleutian Islands	10	6.1	7.6	205	11	Ca45-39	0.215
July 27, 1976	19	42	54.6	39.57N	117.98E	Northeastern China	33	6.3	8.0	248	15	Ca45-39	0.084
July 28, 1976	10	45	34.1	36.69N	118.42E	Northeastern China	33	6.3	7.4	315	19	Ca45-39	0.035
Aug. 16, 1976	16	11	05.9	6.26N	124.02E	Mindanao, Philippine Islands	24	6.4	7.9	231	21	Ca45-39 Cb41-10	0.058 0.015
Nov. 26, 1976	11	19	23.1	41.35N	125.77W	Off coast of northern California	33	6.0	6.8	209	21	Ca45-39 Cb41-10	0.031 0.015
Nov. 30, 1976	00	40	57.4	20.60S	68.95W	Northern Chile	88	6.5	---	269	24	Ca45-39	0.018
Dec. 20, 1976	20	33	07.9	48.81N	129.34W	Vancouver Island	33	5.9	6.7	210	21	Ca45-39 Cb41-10	0.046 0.018
Mar. 4, 1977	19	21	54.1	45.77N	26.76E	Romania	94	6.4	---	301	8	Ca45-39	0.028
April 2, 1977	07	15	22.7	16.70S	172.10W	Somoa Islands	33N	6.8	7.6	181	13	Ca45-39 Cb41-10	0.065 0.025
April 21, 1977	04	24	09.6	9.97S	160.73E	Solomon Islands	33N	6.6	7.5	176	11	Ca45-39 Cb41-10	0.055 0.020
June 22, 1977	12	08	33.4	22.88S	175.9W	Tonga Islands	65	6.8	---	331	12	Ca45-39 Cb41-10	0.087 0.045
Aug. 19, 1977	06	08	55.2	11.08S	118.46E	South of Sumbawa Island	33	7.0	7.9	176	16	Ca45-39 Cb41-10	0.168 0.065
Oct. 10, 1977	11	53	53.6	25.86S	175.41W	South of Tonga Islands	33N	6.6	7.2	151	16	Ca45-39	0.017
Nov. 23, 1977	09	26	25.7	31.05S	67.75W	San Juan Province, Argentina	12	6.3	7.4	255	19	Ca45-39	0.035

UTC - Universal Coordinated Time

Hr Min Sec - Hour, Minute, Second

KM - Kilometers

GS - U. S. Geological Survey

MB - Body wave magnitudes

MS - Surface wave magnitudes

No. Sta. - number of stations reporting P or P' phases used in computation

PDE No. - refers to the issue of the "Preliminary Determination of Epicenters" and "Earthquake Data Report" in which the computation was originally published.

N - depth was restrained at 33 KM for earthquakes whose character on seismograms indicates a shallow focus but whose depth is not satisfactorily determined by the data.

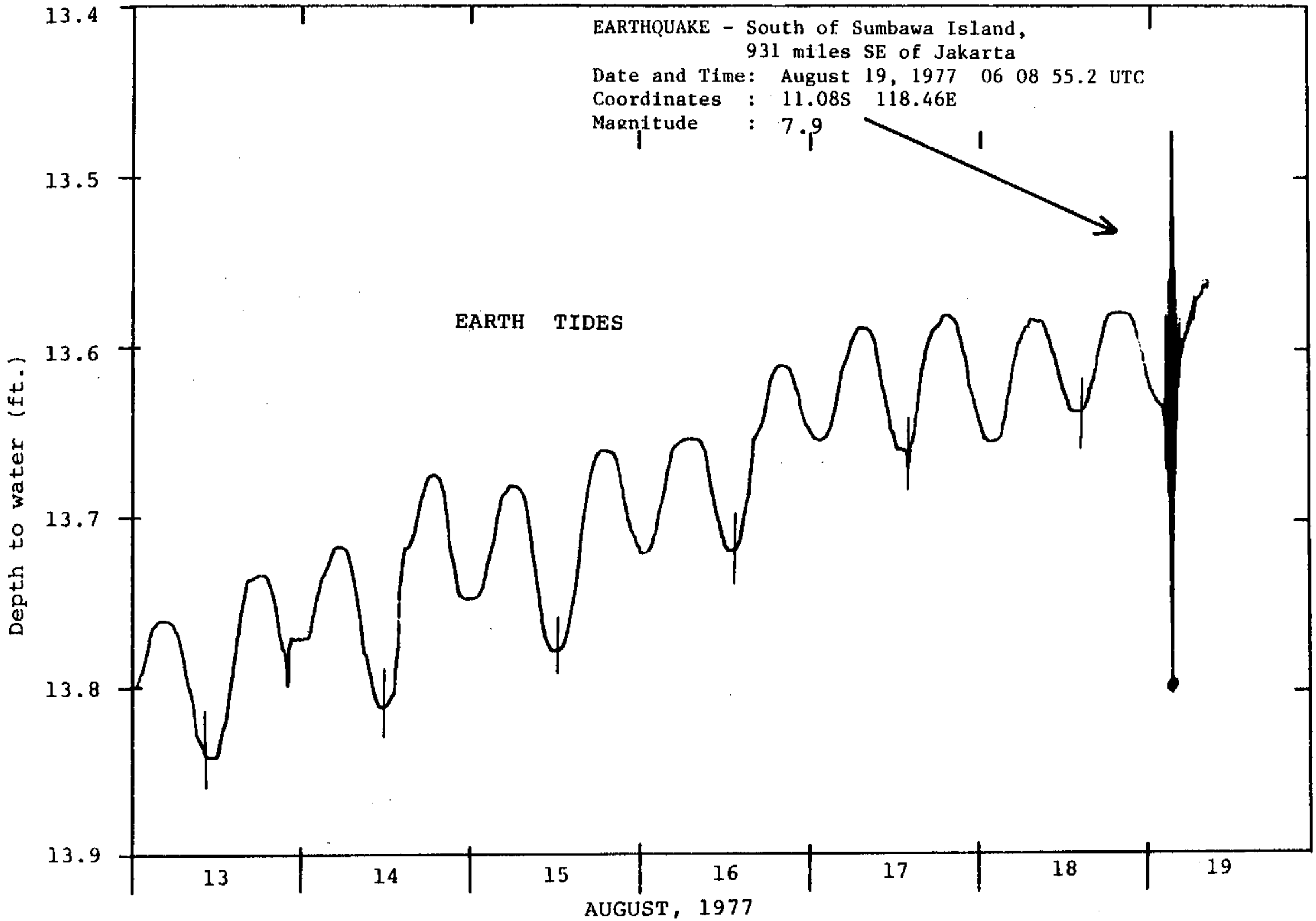

Figure 3. Short-period fluctuations of ground-water levels in well Ca45-39 caused by an earthquake and earth tides. Maximum amplitude of the earthquake is 0.168 feet while the maximum amplitude of earth tides is 0.070 feet. Upper culminations of the moon are shown by short vertical lines.

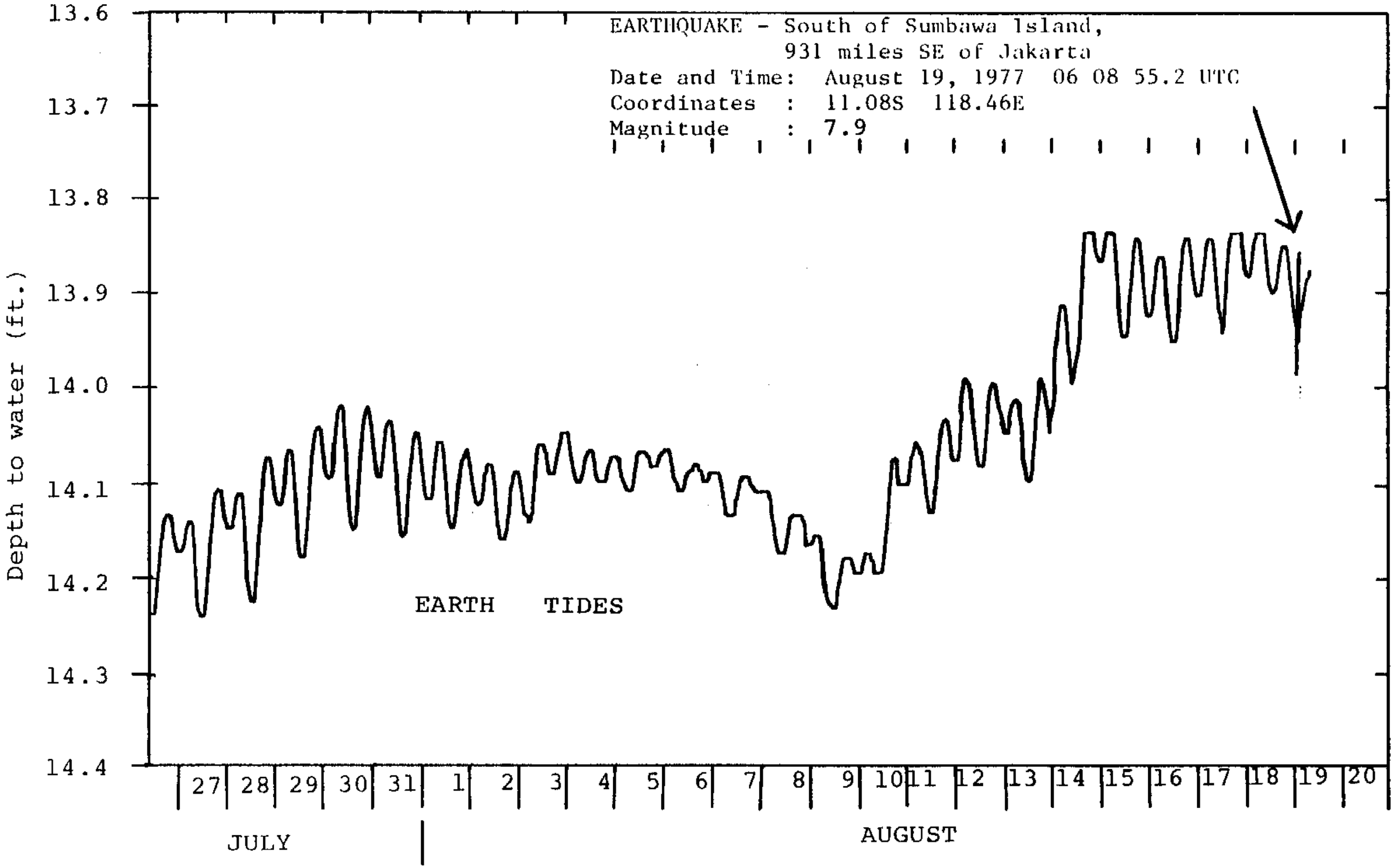

Figure 4. Short-period fluctuations of ground-water levels in well Cb41-10 caused by an earthquake and earth tides. Maximum amplitude of the earthquake is 0.065 feet while the maximum amplitude of earth tides is 0.077 feet.

The recorded duration of this event was probably similar in both wells. However, the duration in well Cb41-10 was difficult to determine because of the small time scale: 0.3 inches (0.762 cm) per day.

Fluctuations Resulting from Earth Tides

Fluctuations caused by earth tides are evident in Figures 3 and 4. Two minima (troughs) occur each day and coincide with the upper and lower culmination of the moon. Both troughs occur during high earth tides, at which time this portion of the earth is expanded, aquifer pressure is reduced, and water levels decline in the well. As can be seen in Figure 3, during any semidiurnal fluctuation there are two troughs, one of which is deeper than the other. The deepest troughs, which are marked by short vertical lines in Figure 3, indicate times of upper culmination of the moon when the tide-generating influence is at a maximum. These times occur approximately 50 minutes later each day in response to lunar retardation as the tidal day has an average period of 24 hours and 50 minutes.

The peaks occur at low tide when the tide-generating forces are at a minimum. During this period of time this portion of the earth is compressed, the water is under increased pressure, and the water level rises in the well.

Maximum and regular fluctuations take place during the new and full moon while smaller and irregular fluctuations mark the first and third quarter phases. For example, in Figure 4, regular fluctuations of maximum amplitude coincide with the full moon (July 30, 1977) and the new moon (August 14, 1977). Like ocean tides, at new and full moon (syzygy), the sun and moon line up so that gravitational forces reinforce each other thereby producing maximum solar and lunar tides.

During the third quarter phase of the moon (August 6, 1977) the tide-producing force was at a minimum because the gravitational attraction of the sun and moon on the earth is exerted at right angles to one another with each force tending to counteract the other. As a result, fluctuations during this quarter are smaller and more irregular than at new and full moon.

CONCLUSIONS

Water-level fluctuations that occur as sharp vertical traces with amplitudes of fluctuation both above and below the "undisturbed" water level are attributable to earthquakes. A minimum MS (surface wave) magnitude of 6.7 and MB (body wave) magnitude of 5.9 for a specific event were required to cause detectable water-level fluctuations in well Ca45-39.

For a particular seismic event, the amplitudes generated in well Ca45-39 were in all instances larger (1.9 to 3.9 times as large) than those recorded in well Cb41-10. Thus, a relationship between aquifer transmissivity and amplitude is suggested as the transmissivity in Ca45-39 is 2.2 times as large as the transmissivity in Cb41-10.

The conclusion that semidiurnal water-level fluctuations are a result of earth tides is supported by the following:

(1) each day is marked by two cycles of fluctuations;

(2) large regular fluctuations occur during periods of new and full moon while smaller and irregular fluctuations coincide with first and third quarter phases;

(3) minimum water levels (troughs) coincide with high tides during the upper and lower culminations of the moon.

PERTINENT REFERENCES

Bodvarsson, G., 1970, Confined fluids as strain meters: Jour. of Geophysical Research, v. 75, p. 2711-2718.

Bredehoeft, J. D., 1967, Response of well-aquifer systems to earth tides: Jour. of Geophysical Research, v. 72, p. 3075-3087.

Cooper, H. H., Bredehoeft, J. D., Papadopulos, I. S., and Bennett, R. R., 1965, The response of well-aquifer systems to seismic waves: Jour. of Geophysical Research, v. 70, p. 3915-3926.

Jordan, R. R., Pickett, T. E., and Woodruff, K. D., 1972, Preliminary report on seismic events in northern Delaware: Delaware Geol. Survey Open File Report No. 2, 15 p.

National Earthquake Information Service, Preliminary determinations of epicenters, monthly listings, 1975-1977: U. S. Dept. of the Interior/Geological Survey.

Parker, G. G., and Stringfield, V. T., 1950, Effects of earthquakes, rains, tides, winds, and atmospheric pressure changes on the water in the geologic formations of southern Florida: Economic Geology, v. 45, p. 441-460.

Robinson, R. W., 1939, Earth tides shown by fluctuations of water levels in wells in New Mexico and Iowa: Transactions American Geophysical Union, v. 20, p. 656-666.

Spall, Henry, 1978, Water-level changes and earthquake prediction: Earthquake Information Bulletin, v. 10, no. 2, p. 55-59.

Talley, J. H., 1974, Hydrogeology of selected sites in the Greater Newark Area, Delaware: Delaware Geol. Survey Rept. of Invest. No. 22, 61 p.

U. S. Naval Observatory, The American Ephemeris and Nautical Almanac for 1976 and 1977: Nautical Almanac Office.

Woodruff, K. D., Jordan, R. R., and Pickett, T. E., 1973, Preliminary report on the earthquake of February 28, 1973: Delaware Geol. Survey Open File Report No. 3, 16 p.

Woodruff, K. D., and Thompson, A. M., 1974, Geology of the Newark area, Delaware: Delaware Geol. Survey Geologic Map Series No. 3.