Determination of Rock Properties by Borehole-Geophysical and Physical-Testing Techniques and Ground-Water Quality and Movement in the Durham Triassic Basin, North Carolina

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By CHARLES E. BROWN

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SYMBOLS AND ABBREVIATIONS

Symbol	*Definition*
cm^3	cubic centimeter
°C	degree Celsius
°F	degree Fahrenheit
Δt	interval traveltime from sonic log
Δt_f	interval traveltime from sonic log for fluid
Δt_{ma}	interval traveltime from sonic log for matrix
F	formation factor
f	fluid
g	gram
g/cm^3	gram per cubic centimeter
γAPI	gamma radiation reading, in American Petroleum Institute units
HD	hole diameter, in centimeters
Hz	hertz
ILD	deep induction log
ILM	medium-induction log
K	constant related to absolute temperature
km	kilometer
kPa	kilopascal
LL8	shallow reading laterolog (laterolog 8)
L/s	liter per second
M	lithology parameter based on interval traveltime and density
m	meter
ma	rock matrix
μg/L	microgram per liter
μm^2	intrinsic permeability, in square micrometers
μmho	micromho
μs	microsecond
μs/ft	microsecond per foot
mg/L	milligram per liter
mV	millivolt
Ωm	ohm-meter
N	lithology parameter based on neutron-log porosity and density-log porosity
pH	negative log of hydrogen-ion activity porosity
ϕD	density-log porosity, in percent
ϕn	neutron-log porosity
ϕn_f	neutron-log reading for fluid
R_{mf}	resistivity of mud filtrate
R_o	resistivity of formation sample 100 percent saturated with fluid of R_w
R_w	resistivity of fluid in formation
R_{we}	Equivalent resistivity of water for high concentrations of NaCl
Rt	true resistivity of a formation
ϱb	bulk density of logged interval
ϱf	fluid density
s	second
SP	spontaneous potential
SSP	static *SP* (the deflection under ideal conditions opposite a nonshaly formation)
TDS	total dissolved solids
V_{ma}	matrix sonic velocity

CONVERSION FACTORS

Multiply metric unit	*by*	*To obtain inch-pound unit*
	Length	
millimeter (mm)	0.3937	inch (in)
centimeter (cm)	.3937	inch
meter (m)	3.2808	feet (ft)
kilometer (km)	.6214	mile (mi)
	Volume	
cubic centimeter (cm^3)	0.06102	cubic inch (in^3)
liter (L)	61.03	cubic inches
liter	2.113	pints (pt)
	1.057	quarts (qt)
	.2641	gallon (gal)
	Weight	
gram (g)	0.002205	pound, avoirdupois (lb avdp)
	.035	ounce, avoirdupois (oz avdp)
milligram (mg)	.000035	ounce, avoirdupois
	Conductance	
micromho (μmho)	1.0	microsiemen (μS)
	Specific combinations	
liter per second (L/s)	0.03531	cubic foot per second (ft^3/s)
meter per second (m/s)	3.281	feet per second (ft/s)
kilogram per second (km/s)	3,281	feet per second
gram per cubic centimeter (g/cm^3)	62.43	pounds per cubic foot (lb/ft^3)
milligram per liter (mg/L)	.05841	grain per gallon (gr/gal)
microgram per liter (μg/L)	.00005841	grain per gallon
	Temperature	
degree Celsius (°C)	$[(1.8 \times {}^\circ C) + 32]$	degrees Fahrenheit (°F)

DETERMINATION OF ROCK PROPERTIES BY BOREHOLE-GEOPHYSICAL AND PHYSICAL-TESTING TECHNIQUES AND GROUND-WATER QUALITY AND MOVEMENT IN THE DURHAM TRIASSIC BASIN, NORTH CAROLINA

By CHARLES E. BROWN

ABSTRACT

Ground water in the Durham Triassic basin in North Carolina is present in suitable amounts for domestic supplies. Water for domestic supplies is usually confined to the upper 90 meters of porous and permeable Triassic rock. Below 90 meters only smaller amounts of additional potable water can be obtained. Ground water in Triassic rocks near the surface is in interstices that have been enlarged by weathering and by leaching of mineral cement. Chemical analyses indicate that water in the basin is a calcium bicarbonate-sodium sulfate type. The apparent resistivity of formation water in the Sears No. 1 test well indicates that water having a dissolved-solids concentration of less than 5,000 milligrams per liter is present in parts of the basin to a depth of at least 1,000 meters. However, the yield of water from the rocks at 1,000 meters or more is extremely small, and major supplies of ground water probably are not available at depths of more than 300 meters in the Durham Triassic basin.

Rocks in the basin consist chiefly of argillites and mudstones that have a high density and low matrix sonic velocity. Resistivity logs indicate an alternating-cyclic sequence of sandstones and massive shales. The average resistivity of the shale in the Sears No. 1 well is 40 to 50 ohm-meters; the sandstones and conglomerates have 5 to 10 times greater resistivity values. On the basis of gamma-ray logs, most of the sandstones have gamma-ray values of from 50 to 80 American Petroleum Institute units. The mean porosity, determined from the density log, is approximately 6 percent; the mean porosity laboratory value, determined from cores, is approximately 5 percent. The temperature gradient in the rocks of the Sears No. 1 well was estimated to be 1 degree Celsius per 66 meters. Borehole-geophysical data were very important in determining both the quantity and quality of water in potential aquifers of the Durham Triassic basin. These techniques can be used to investigate subsurface hydrogeologic conditions in other basins.

INTRODUCTION

The U.S. Geological Survey began a study to determine the effectiveness of borehole geophysical and physical rock properties analyses to define ground-water circulation and quality within the Durham Triassic basin. Borehole geophysics provided rapid geologic and hydrologic evaluation of aquifers. When these techniques are combined with laboratory analyses of rock properties and with other hydrologic tests, they can provide a comprehensive evaluation of ground-water movement and occurrence. This study is a part of a larger study begun in 1972 to investigate the feasibility of storing liquid wastes in Triassic rocks of the Durham Triassic basin[1] of the Eastern United States.

PURPOSE AND SCOPE

This report presents the results of an investigation to (1) define the lithologic character and subsurface distribution of hydrogeologic units in the Durham Triassic basin, North Carolina, (2) identify and describe specific properties of rocks in the basin, and (3) describe water quality and circulation of ground water in the basin. These objectives were accomplished primarily by borehole-geophysical and laboratory analyses of rock and aquifer properties.

Although the study area encompasses the entire Durham Triassic basin of North Carolina, most geophysical and physical properties analyses were made from logs and cores of the Sears No. 1 test well, located east of the Wake County-Chatham County line in the central part of the basin.

DESCRIPTION OF STUDY AREA

LOCATION

Triassic basins are distributed along the Atlantic seaboard from Nova Scotia to Florida where they exist as buried basins. The basins extend eastward beneath the Cenozoic rocks onto the Continental Shelf where they are located by exploratory drilling and geophysical investigations. Figure 1 shows the location of east coast basins subparallel to the Appalachian trend. The Durham Triassic basin in North Carolina, which contains rocks of Upper Triassic age, is the southernmost exposed basin.

[1]Some of the east coast Triassic basins are now considered Triassic and Jurassic age but, for the purpose of this report, are called Triassic basins.

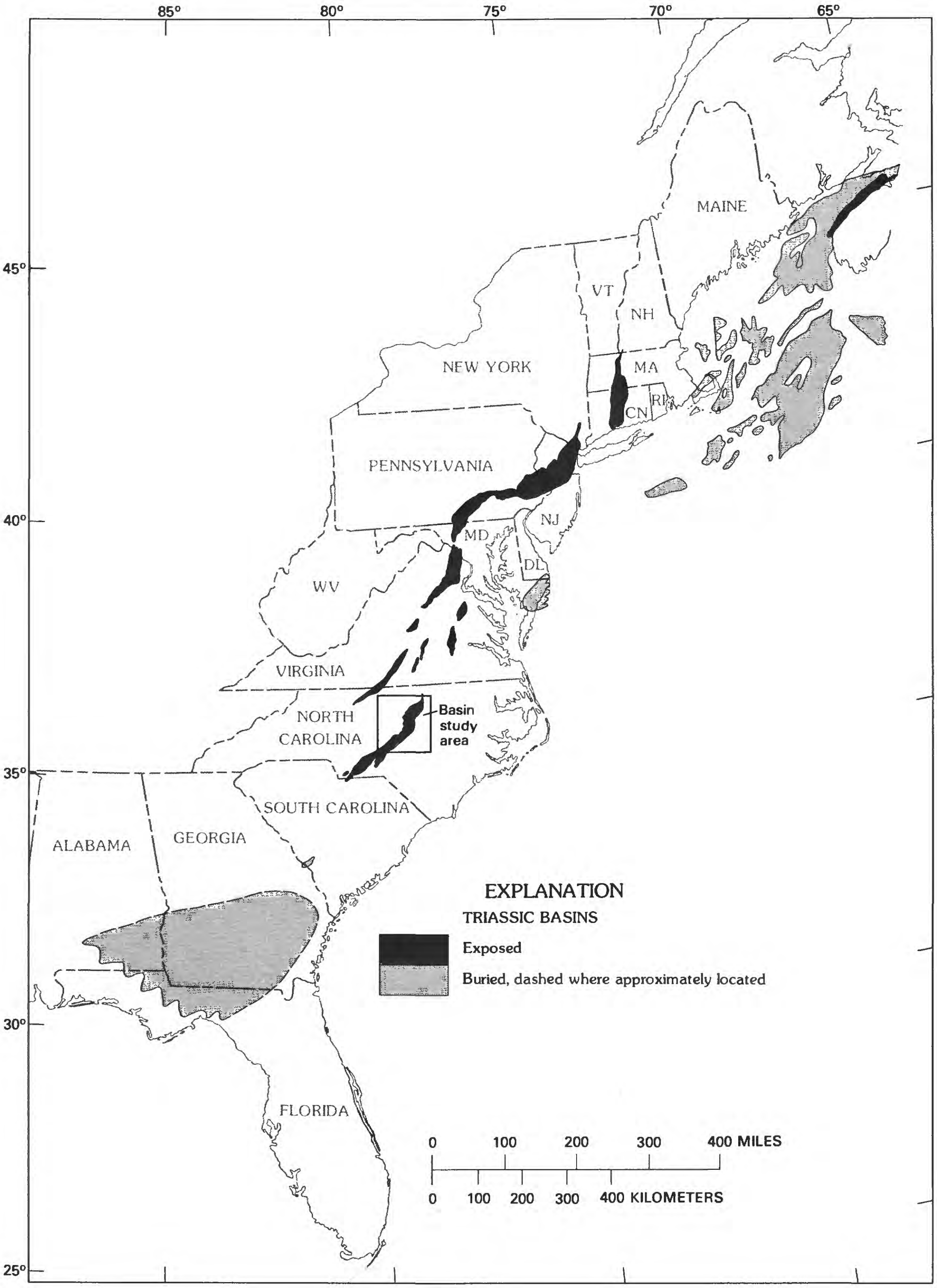

FIGURE 1.–Distribution of east coast Triassic basins.

GEOLOGIC SETTING

The east coast Triassic basins are mostly half grabens or tilted grabens that contain sedimentary rocks of fluvial origin. The Durham Triassic basin is bounded on the east and southeast by a high-angle normal-fault zone known as the Jonesboro fault (fig. 2). The basin trends southwestward between the borders of North Carolina-Virginia and North Carolina-South Carolina. The basin is about 226 km long and averages about 16 km wide. The Durham Triassic basin is traditionally divided into four substructures, which from north to south are the Durham subbasin, the Colon cross structure, the Sanford or Deep River subbasin, and the Wadesboro subbasin (fig. 2).

DESCRIPTION OF TEST WELL

A deep test well was drilled by the U.S. Geological Survey in 1976 to a depth of 1,142 m in the Durham subbasin near New Hill, on the property of W.H. Sears (Sears No. 1). The test well was specifically designed and drilled to (1) verify surface and airborne geophysics data, (2) gain a knowledge of the subsurface geology, and (3) obtain hydrogeologic information on aquifer properties and fluids.

The lithologic log shown on plate 1 was prepared by using descriptions of drill cuttings sampled at 1.5-m intervals. Cores were taken at five different intervals for determinations of physical properties. Results of physical-property tests are described and summarized in the section Determination of Rock Properties by Physical-Testing Techniques. Borehole logs obtained at the completion of drilling (pl. 1) include temperature, neutron porosity, gamma ray, gamma-gamma density, sonic, dual-induction laterolog, micrologr, caliper, and acoustic televiewer. Two zones in the test well were isolated with hydraulic packers to collect reservoir fluids for chemical analysis and to determine aquifer characteristics (Bain and Brown, 1981, for aquifer test data). Physical-property-test procedures by Terra Tek, Inc.[2] (D.O. Ennis and S.W. Butters, written commun., 1976), are described in the section discussing laboratory analyses. The Triassic rocks drilled in the Sears No. 1 well can be grouped into at least three rock stratigraphic facies, from bottom to top: (1) a lower argillite-graywacke-conglomerate facies at least 122 m thick, (2) a 670-m-thick sequence of massive mudstone, argillite, and quartz conglomerate, and (3) a 640-m-thick sequence of arkosic sandstone, siltstone, and mudstone. These units do not necessarily correlate with the traditional boundaries of the Pekin, Cumnock, and Sanford Formations in another part of the Durham Triassic basin (Reinemund, 1955; Bain and Brown, 1981; and McKee and others, 1959).

The rocks drilled have low porosity and permeability, high average density, high velocity, high resistivity, and low gravity in contrast to the Piedmont crystalline rocks (pl. 1 and Bain and Brown, 1981).

[2]Use of brand and trade names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

DETERMINATION OF ROCK PROPERTIES BY BOREHOLE-GEOPHYSICAL TECHNIQUES

DESCRIPTION AND INTERPRETATION OF GEOPHYSICAL LOGS

SPONTANEOUS-POTENTIAL LOG

The spontaneous-potential (*SP*) log measures the natural electrical potential between the borehole fluid and the surrounding rock. Generally, the conductivity of the borehole fluid is less than that of the surrounding rock and causes apparent negative *SP* deflections to the left opposite clean sand and to the right opposite shale. The *SP* log of the Sears No. 1 well shows several zones above 640-m depth where negative anomalies up to 40 mV mark the occurrence of more permeable sandstones (pl. 1).

Between depths of 640 m and 990 m, the *SP* log shows little contrast between the rock and borehole fluid and indicates increasing shaliness in the rocks. The lithologic log shows that the zone between 640 and 990 m consists of mudstone, massive argillite, and minor occurrence of conglomerate. Thus, the subdued character of the *SP* curve in the 640-m to 990-m interval is caused by the shale content of the rock. A similar but much thinner facies occurs between depths of 308 and 338 m. The negative *SP* anomalies on the log below 990 m correspond to conglomerate on the lithologic log.

The *SP* contrast between borehole and formation fluids is used elsewhere in this paper to predict total dissolved-solids (*TDS*) content of the formation waters. The general subdued character of the *SP* curve indicates that formation fluids are not much more saline than the fluid in the borehole. Because the dissolved-solids content in the drilling mud was less than 300 mg/L throughout the drilling, the Sears No. 1 well probably did not penetrate rock containing extremely saline fluids.

RESISTIVITY LOGS

The resistivity of a rock depends on the resistivity of the rock-mineral matrix and its contained fluids. Rocks that are composed primarily of quartz and feldspar, which are poor conductors, contain water that is usually a better conductor. Thus, the resistivity of a sandstone generally is largely related to the amount and the geometry of its pore space and to the salinity of its contained

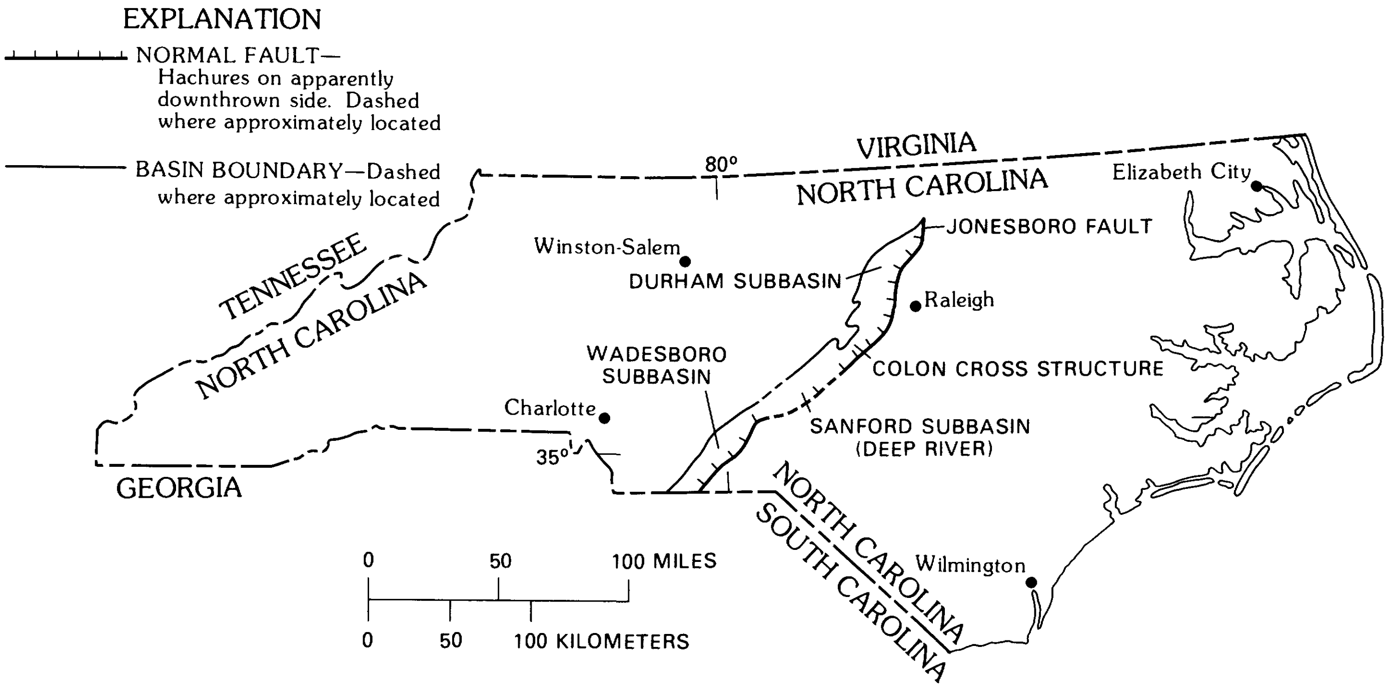

FIGURE 2.—Durham Triassic basin and tectonic features. See figure 11 for well and town locations.

fluid. As rock porosity decreases, formation resistivity on the whole increases, assuming that the resistivity of the formation fluid remains constant.

Five separate types of resistivity logs were run in the Sears No. 1 well: microlog, microlaterolog, laterolog 8 (LL8), medium-induction log (ILM), and deep-induction log (ILD). Resistivity on these logs is expressed in square ohm-meters per meter or, more commonly, ohm-meters (Ωm).

The microlog depicts the resistivity of the mudcake covering a permeable zone. The laterolog and medium- and deep-induction logs depict resistivities for zones away from the borehole. The deep-induction log is used to provide a more reliable value for the true rock resistivity in those situations where invasion by drilling fluid has occurred in the rock. In some cases, resistivity of the flushed zone next to the borehole can be determined from a microlaterolog (available for Sears No. 1 well).

The log response to the difference in resistivity of different lithologies is useful in determining the vertical distribution and thickness of rock types. Conventionally, some type of resistivity curve (pl. 1) is recorded with the *SP* log. The *SP*-resistivity log combination is useful in ground-water investigations for identifying the more permeable, water-yielding zones. In an area of fresh ground water, a water-yielding zone has a large negative (left) deflection on the *SP* curve. Examples of such opposing deflections occur on the logs of Sears No. 1 well at 192-, 229-, and 250-m depths (pl. 1).

In permeable zones, drilling mud enters the formations and displaces the formation fluid because the drilling mud maintains a higher hydrostatic head. Thus, the depth of mud invasion is a qualitative measure of permeability. The four types of logs shown on plate 1 have different depths of investigation. The dual (medium- and deep-) induction-laterolog combination is specifically designed to determine the depth of mud invasion. In table 1 the known effect of mud invasion on the true resistivity (Rt) of the formation is compensated for by using the ratio of the resistivities of the ILD, ILM, and LL8 to each other (see Schlumberger, Ltd., 1977, p. 50). In columns 2 and 3 of table 2, the values for the LL8 and ILD give a qualitative estimate of invasion of the formation by the drilling fluid, when resistivity values from the ILD and LL8 are different. The resistivity values from the ILD and LL8 will be approximately equal when no drilling fluid invasion has occurred.

The resistivity logs reveal a cyclic or alternating sequence of sandstones and massive shales. The average resistivity of shale on the deep-induction log curve is about 40 to 50 Ωm throughout the well. The sandstones and conglomerates, however, are typically 5 to 10 times more resistive. One sandstone or conglomerate is 10 m thick near a depth of 793 m, but the vast majority of the sandstones are 0.67 to 3 m in thickness. If the lithologies of the well are arbitrarily divided into sandstone and shale, the ratio of sandstone to shale is approximately 2:3 (pl. 1).

TABLE 1.–*Log data from the Sears No. 1 well, North Carolina*

Log depth, center of zone (m)	True resistivity, from deep-induction log (Ωm)	Sonic velocity (km/s)	Bulk density (g/cm³)	Porosity (percent)
155	140	3.79	2.45	14
192	220	3.72	2.48	10.2
220	200	3.91	2.46	13
229	120	3.72	2.45	13.4
233	50	3.86	2.45	13
242	55	4.12	2.55	8
248	28	3.46	2.42	16
258	45	3.81	2.50	11
273	25	3.81	2.4	15.5
279	39	3.57	2.42	16
289	69	4.18	2.46	13
339	65	4.42	2.5	8
350	75	4.18	2.65	2
353	95	4.12	2.45	12
378	38	4.23	2.48	10.1
399	64	4.12	2.46	13.6
414	65	4.26	2.56	8.3
440	90	4.48	2.50	10
477	47	4.45	2.45	13
508	190	4.84	2.58	5
527	120	4.88	2.60	3
570	100	4.84	2.57	6
583	140	4.84	2.57	7
610	170	5.00	2.70	1
633	130	4.92	2.55	8
999	100	5.17	2.67	.6
1,020	150	5.21	2.68	0
1,041	250	5.35	2.67	-.1
1,056	375	5.40	2.68	0
1,082	160	5.54	2.69	-1.5
1,096	63	4.62	2.70	-1
1,105	200	5.00	2.72	-3
1,119	150	4.92	2.65	1.8
Mean =	116	4.45	2.55	7.48
Standard deviation =	76.3	.586	.101	5.90
No. of samples =	33	33	33	33

The lithologic log and the gamma-ray logs also exhibit a cyclic pattern. This pattern is most pronounced at depths between 732 and 793 m and depths between 915 and 960 m where the micr関log shows an inverted stairstep character. Cycle frequency on the log is about 5.5 m, and resistivity amplitude is about one order of magnitude. The cycles start at the bottom of the well at a very resistive conglomerate that becomes fine grained progressively upward into massive red argillite or mudstone. Similar cycles are also apparent higher in the hole, such as at the 518-m-depth to 427-m-depth interval.

Cycles on the logs having a frequency of 3 to 6 m can also be identified in the upper, more sandy part of the well. Here, however, the change in grain size from coarse to fine is much more abrupt, and the sandstones are better sorted.

The conglomeratic-argillite sequence probably formed as a normal consequence of sedimentary debris settling out of periodic influxes of coarse sediment into standing water. These periodic influxes might be caused by the erosion of an uplifted fault block. The abrupt change from coarse to fine in the upper part of the hole could result from changes in stream deposition and channel erosion processes (Reinemund, 1955; Bain and Brown, 1981).

DENSITY-POROSITY LOG

The gamma-gamma density log measures the apparent density of the borehole environment by recording the loss of gamma radiation caused by collision with electrons of the rock matrix and contained fluids. The attenuation of gamma radiation from the tool source depends on the electron density of the formation. Bulk density in grams per cubic centimeter depends, therefore, on porosity and the electron density of the rock matrix and fluid. In practice, a shielded gamma-ray source is pressed against and moved along the borehole wall. The attenuated radiation is received at two points at different distances from the source to adjust for the effect of mud thickness and irregular hole diameter. The density-porosity curve of plate 1 has been adjusted electronically for mud thickness and hole diameter changes, except where large washouts of wellbore have occurred.

The density log confirms the dense nature of the rocks and their characteristically low porosity. Recorded densities range from an average 2.55 g/cm³ to 2.70 g/cm³ below a depth of 610 m. The massive argillaceous rocks are the densest beds above the 610-m depth. Below 610 m in depth, the sandstones and siltstones appear to be as dense if not more dense than the argillaceous rocks.

Bulk density and corresponding porosity have been selected from the density log at points where the borehole is relatively free of washouts. These values are presented in table 2 for direct comparison with porosity determined from the neutron and sonic logs.

The density log indicates very little primary porosity between 655 and 905 m. Sandstones and conglomerate at depths of 833, 911, 1,020, 954, 1,110, and 1,131 m have low apparent porosities of up to 4 percent. The *SP*-log response for these points indicates that water is present in the formation.

NEUTRON-POROSITY LOG

The neutron-logging tool (in this case, the sidewall neutron-porosity tool) consists of a neutron source and a shielded neutron detector that are pressed against and moved down the borehole. The principle of neutron logging is that high-energy, electrically neutral particles are emitted from a radioactive source and collide with the nuclei of atoms of the surrounding environ-

TABLE 2.—*Log crossplot data for the Sears No. 1 well, North Carolina*

[LL8, laterolog 8; ILD, deep-induction log; *HD*, hole diameter, in cm; γ API, gamma radiation, in API units; ϕD, density-log porosity, in percent; ϱb, bulk density, in g/cm³; Δt, interval traveltime from sonic log, in μs/ft; ϕn, neutron-log porosity, in percent; *M*, parameter calculated: $((189 - \Delta t)/(\varrho b - 1.0)) \times 0.01$; *N*, parameter calculated: $(1.0 - \phi n)/(\varrho b - 1.0)$; sonic-log porosity calculated: $((\Delta t - \Delta t_{ma})/(\Delta t_f - \Delta t_{ma}))$; *ma*, rock matrix; *f*, fluid; *SP*, spontaneous potential; –, no data]

Log depth (m)	Resistivity (Ωm) LL8	Resistivity (Ωm) ILD	*HD*	γ API	ϕD	ϱb	Δt	ϕn	*M*	*N*	Sonic-log porosity (percent) For Δt_{ma} = 4.7 km/s	5.3 km/s	6.0 km/s	Remarks
153.6	1,800	45	–	120	14	2.45	81	14	0.74	0.59	12.9	18.2	21.7	
158.6	125	70	–	80	14	2.45	81	13	.74	.60	12.9	18.2	21.7	
160	80	40	–	175	5	2.60	69	14	.75	.54	3.2	9.1	8.7	Limy.
163.2	120	50	–	110	9	2.55	76	13	.73	.56	8.9	14.4	18.1	Fractured.
166.4	55	60	–	110	−1.5	2.7	71	8	.69	.54	4.8	10.6	14.5	
170.7	40	40	–	120	3	2.64	72	12	.71	.54	5.6	11.4	15.2	
172.2	48	30	–	100	16	2.42	85	17	.73	.58	16.1	21.2	24.6	
181.2	40	20	–	222	18	2.37	103	31	.63	.50	30.6	34.8	37.7	Fractured.
184.4	75	55	–	120	15	2.43	81	14	.76	.60	12.9	18.2	21.7	
187.7	65	95	–	260	8.5	2.54	93	13	.62	.56	22.6	27.3	30.4	
191.1	950	210	–	80	11	2.47	98	12	.62	.60	26.6	31	34	
197.5	40	40	–	105	17	2.40	85	15	.74	.61	16.1	21.2	24.6	
200.5	30	30	–	225	0	2.69	79	10	.65	.53	11.3	16.7	20.2	Anhydrite.
206	70	30	–	140	10	2.50	100	15	.59	.57	28.2	32.6	35.5	
208.5	240	80	–	80	11	2.49	80	10	.73	.60	12.1	17.4	21	
215.2	80	90	–	140	4	2.60	64	5	.78	.59	−0.8	5.3	9.4	Limy.
220	700	700	–	80	13	2.46	80	9.5	.75	.62	12.1	17.4	21	
221.6	60	60	19.8	180	4	2.60	78	12.5	.69	.55	10.5	15.9	19.6	Shaly.
224	60	60	19.3	220	2	2.64	70	9.5	.73	.55	4	9.8	13.8	High γ, low *SP*.
228.6	1,200	120	18.8	85	13.5	2.46	82	11	.73	.61	13.7	18.9	22.5	Sandstone.
239.6	280	60	19.1	110	11	2.50	75	9	.76	.61	8.1	13.6	17.4	Sandstone.
249	350	45	–	80	14	2.47	86	12	.70	.60	16.9	22	25.4	Sandstone.
271.3	35	30	–	215	4	2.60	82	18	.67	.51	13.7	18.9	22.5	High γ.
275.7	30	45	24.9	180	18.5	2.23	87	31	.83	.56	17.7	22.7	26.1	Gypsum?, low γ.
279.2	24	40	22.4	80	17	2.39	83	16	.76	.60	14.5	19.7	23.2	Low *SP*, sandstone.
289.2	900	70	18.8	54	12	2.48	73	12.5	.78	.59	6.5	12.1	15.9	Sandstone fracture.
296.6	22	50	33	190	10	2.50	101	32	.59	.45	29	33.3	36.2	Low *SP*, sandstone.
306.9	80	800	19.3	73	10	2.50	102	12.6	.58	.58	19.8	34	37	Anhydrite.
326.4	45	60	21.1	110	8	2.55	67	9	.79	.59	1.6	7.6	11.6	?
328.9	40	40	21.6	140	4	2.62	76	15	.70	.52	8.9	14.4	18.1	Shale.
329.2	50	40	21.1	120	10	2.51	74	18	.76	.54	7.3	12.9	16.7	Shale.
331.6	50	50	23.9	150	14	2.52	75	24	.75	.50	8.1	13.6	17.4	Shaly.
334.0	40	40	22.1	95	16	2.35	76	9	.84	.67	8.9	14.4	18.1	Sandstone.
335.9	60	60	21.6	110	−2	2.70	68	11	.71	.52	2.4	8.3	12.3	Shale.
338.9	65	190	19.1	110	9	2.52	69	12	.79	.58	3.2	9	12	Sandstone.
342	100	60	19.1	80	8	2.55	73	7.5	.75	.60	6.5	12.1	15.9	Siltstone.
344.4	100	80	19.1	115	6	2.57	66	5	.78	.60	.8	6.8	10.9	
352	800	85	19.1	50	14	2.44	75	13	.79	.60	8.1	13.6	17.4	Sandstone, high *SP*.
357.8	45	45	22.4	165	2	2.64	76	15	.69	.52	8.9	14.4	18.1	Shale.
360	90	60	20.1	95	12	2.48	70	12	.80	.59	4	9.8	13.8	Sandstone.
377.6	130	40	20.3	65	11	2.48	73	11	.78	.60	6.5	6	15.9	
394.1	180	70	19.3	65	9	2.52	69	6.5	.79	.62	3.2	9	12	Cycle skip, radioactive.
398	500	80	19.1	150	13	2.46	72	12	.80	.60	5.6	11.4	15.2	Sandstone.
417.9	80	80	19.6	250	3	2.72	64	6	.73	.55	−.8	5.3	9.4	
419.4	80	60	19.6	325	3	2.72	65	7	.72	.54	0	6	10.1	

TABLE 2.—*Log crossplot data for the Sears No. 1 well, North Carolina*—Continued

Log depth (m)	Resistivity (Ωm) LL8	ILD	*HD*	γ API	*ϕD*	*ρb*	*Δt*	*ϕn*	*M*	*N*	Sonic-log porosity (percent) For Δt_{ma} = 4.7 km/s	5.3 km/s	6.0 km/s	Remarks
440.4	90	70	19.3	55	10	2.50	69	9	0.80	0.61	3.2	9	13	
449.2	50	60	21.9	60	14	2.45	75	14	.79	.59	8.1	13.6	17.4	Low *SP*, sandstone.
465.1	80	80	20.3	80	15	2.60	64	7	.78	.58	–.8	5.3	9.4	
488.9	60	50	19.1	70	11	2.49	67	10.5	.82	.60	1.6	7.6	11.6	Sandstone.
495.9	50	60	19.8	150	2	2.64	67	13	.74	.53	1.6	7.6	11.6	Shaly.
498.9	80	90	18	230	9	2.53	67	7	.80	.61	1.6	7.6	11.6	Sandy.
500.8	80	60	18	76	9	2.52	63	7	.83	.61	–1.6	4.5	8.7	Sandstone.
508.4	120	120	18	90	2	2.7	59	4	.81	.60	–4.8	1.5	5.9	Limy, sandstone.
526.1	70	100	18	220	0	2.68	64	8	.74	.55	–.8	5.3	9.4	High γ.
534.6	70	90	19.1	90	10	2.54	65	6	.80	.61	0	6	10.1	Sandstone.
549.8	50	50	19.1	60	12	2.49	64	11	.84	.60	–.8	5.3	9.4	Sandstone.
550.4	300	60	30.5	140	22	1.85	82	45	1.27	.67	13.7	18.9	22.5	Fractured.
569.3	90	90	19.3	215	2	2.63	67	11	.75	.55	1.6	7.6	11.6	High γ.
570.9	100	100	18.3	250	16	2.42	72	15	.82	.60	5.6	11.4	15.2	High γ.
576.3	70	80	18.8	225	1	2.65	64	7	.76	.56	–.8	5.3	9.4	High γ.
581.5	60	70	18	90	9	2.52	66	6	.81	.62	.8	6.8	10.9	Siltstone.
585.2	120	125	17.8	220	9	2.54	62	5	.82	.62	–2.4	3.8	8	Sandstone.
596.8	200	140	18.6	80	8	2.55	61	9	.83	.59	–3.2	3	7.2	Siltstone.
609.6	300	170	17.8	70	–2	2.70	57	3	.78	.57	–6.5	0	4.3	
619.3	50	55	19.6	140	0	2.68	73	10	.69	.54	6.5	12.1	15.9	Shale.
624.5	70	80	18.0	75	8	2.54	65	7	.80	.60	0	6	10.1	Sandstone.
638.2	200	130	18.3	100	0	2.70	59	3.5	.76	.57	–4.8	1.5	5.8	
639.4	50	60	18.3	130	0	2.67	70	12	.71	.53	4	9.8	13.8	Shale.
641.9	100	105	–	70	7	2.58	61	5	.81	.60	–3.2	3	–7.2	Very low *SP*, sandstone.
654.7	70	90	–	100	–1	2.70	62	6	.75	.55	–2.4	3.8	8	Siltstone.
670.5	120	120	17.3	70	1	2.67	59	5.5	.78	.57	–4.8	1.5	5.8	Conglomerate.
694.9	70	65	19.6	100	1	2.68	68	14	.72	.51	2.4	8.3	12.3	Shale.
696.7	180	90	18	65	2	2.65	59	5	.79	.58	–4.8	1.5	5.8	Limy, conglomerate.
715.6	80	65	20.3	90	4	2.6	63	9	.79	.57	–1.6	4.5	8.7	Shale.
742.5	50	50	20.3	95	6	2.55	72	16	.75	.54	5.6	11.4	15.2	Shale.
743.1	35	45	21.3	100	0	2.65	71	15	.72	.52	4.8	10.6	14.5	Shale.
743.7	50	50	19.3	85	0	2.68	65	12	.74	.52	0	6	10.1	Shale.
744.3	70	70	18.8	85	0	2.68	62	8	.76	.55	–2.4	3.8	2	
744.9	100	100	18.3	60	3	2.62	64	8	.77	.57	–.8	5.3	9.4	
788.9	150	120	17.8	60	1	2.66	60	5	.78	.57	–4	2.2	6.5	Conglomerate.
828.4	110	110	17.3	60	1	2.66	59	6	.78	.57	–4.8	1.5	5.8	Conglomerate.
853.4	70	80	18.3	90	–1	2.70	64	9.5	.74	.53	–.8	–5.3	9.4	
882.7	160	70	16.8	70	3	2.52	59	6	.86	.62	–4.8	1.5	5.8	
907	100	80	17.3	60	4	2.61	59	9	.81	.57	–4.8	1.5	5.8	
917.1	50	50	17.8	95	0	2.70	65	9.5	.73	.53	0	6.0	10.1	
925.3	190	110	17.3	60	5	2.60	57	4	.82	.60	–6.5	0	4.3	Conglomerate.
936.9	50	60	–	100	–1	2.69	66	10	.73	.53	.8	6.8	10.9	
946.1	500	210	–	60	1	2.66	57	4	.80	.58	–.65	0	4.3	
976.8	40	30	–	105	50	1.65	76	42	1.74	.89	8.9	14.3	18.1	
1,019.2	600	150	–	70	0	2.68	59	7	.77	.55	–4.8	1.5	5.8	
1,039.3	1,200	240	–	70	0	2.68	56	6	.79	.56	–.73	–.8	3.6	
1,055.2	1,200	40	16.8	70	–1	2.69	55	5	.79	.56	–8.1	–1.5	2.9	
1,061.3	90	70	–	125	–4	2.74	67	14	.70	.49	1.6	7.6	11.6	
1,079.2	–	120	16.8	80	3	2.63	63	7.5	.77	.57	–1.6	4.5	8.7	
1,109.1	–	160	16.5	70	3	2.63	61	7	.78	.59	–3.2	3.0	7.2	
1,115.5	–	105	16.5	135	–3	2.72	66	12	.72	.51	–.8	6.8	10.1	Shale?
1,125.3	–	100	16.5	175	–3	2.72	72	16	.68	.49	–5.6	11.4	15.2	
1,130.8	–	300	16.3	–	4.5	2.60	63	5.5	.79	.59	–1.6	4.5	8.7	Cycle skip.

ment. Greatest loss of energy occurs when the neutrons collide with particles of similar mass, such as hydrogen. These particles having reduced energy are called thermal neutrons. The neutron tool is generally designed to count either thermal neutrons or the gamma radiation resulting from neutron capture by hydrogen (Schlumberger, Ltd., 1972b). The recorded porosity must be corrected for gases, lithologies other than limestone, and fluids other than water.

In clean (nonshaly) formations, the neutron log is a measure of liquid-filled porosity. For shaly formations and for minerals such as gypsum ($CaSO_4 \cdot 2H_2O$), the indicated porosity is in error because the logging tool also measures the hydrogen associated with bound water and crystallization water. The neutron-porosity log in plate 1 is scaled linearly in percent porosity. The tool is designed to calculate a porosity from a signal that would result if the rock were limestone that contained water (Schlumberger, Ltd., 1972b).

Uncorrected apparent limestone porosity (ϕn) is presented in table 2 (col. 9). Care was taken to select porosity values from the neutron log opposite points in the borehole where the caliper log indicated the hole was reasonably smooth. Much of the shift toward higher apparent porosities in zones, such as those at depth intervals from 305 to 355 m, 445 to 449 m, and 796 to 826 m, is due to formation shaliness. Most porosity spikes were caused by poor contact between the logging tool and the borehole wall, opposite fractures and washouts. However, spikes indicating high porosity at depths of 181, 201, and 274 m occur opposite evaporate-rich beds. There is a slight but overall decrease in minimum porosity with depth. The lowest porosity value, however, occurs at depths of 610 m in a dense, 1.8-m-thick bed that appears, from cuttings, to be cherty and quartzose. Minimum neutron porosities average 4 percent in sandstones that are thought to have no porosity. This apparent discrepancy is probably caused by the increased clay content of some sandstones. Porous zones that are greater than 5 m thick at depths greater than 150 m occur throughout the well (table 3). Table 4 shows data for selected intervals in the Sears No. 1 well.

TABLE 3.—*Porous zones (greater than 5 m thick) below 150-m depth in the Sears No. 1 well, North Carolina*

[Analysis of gamma-ray, density, neutron, and sonic logs]

Depth to top of zone (m)	Approximate thickness of zone (m)	Average effective porosity[1] (percent)	Average bulk density[2] (g/cm³)
189	9	11.40	2.66
216	18	8.49	2.66
341	12	6.83	2.67
391	8	7.86	2.67
434	9	6.70	2.67
497	18	5.27	2.67
565	6	5.29	2.67
622	18	4.46	2.69
783	12	[3]3.66	2.70
826[4]	21	2.92	2.70
933[4]	15	1.86	2.71

[1]Average porosity is clay-free porosity.
[2]Higher density zones indicate an increase of clay with sandstone matrix at depth.
[3]Lower porosities result from compaction.
[4]Porosities below 4 percent are effectively zero for sandstones.

TABLE 4.—*Rock characteristics processed from logs for the Sears No. 1 well, North Carolina*

Depth (m)	Water saturation (percent)	Total porosity (percent)	Secondary porosity (percent)	Shale content (percent)	Matrix bulk density (g/cm³)
153	100	7.8	–	39	2.66
167	100	1.6	–	46	2.80
184	100	9.3	–	28	2.66
198	100	10.7	–	17	2.66
214	100	0	–	44	2.66
229	100	12.9	–	0	2.66
249	100	7.5	–	26	2.67
259	100	10.6	–	0	2.65
275	100	7.2	–	44	2.65
290	100	10.8	–	17	2.66
306	100	9.5	–	26	2.66
322	100	3.2	–	41	2.80
336	100	2	–	47	2.80
351	100	9.7	–	0	2.66
367	100	4.8	–	40	2.66
381	100	0	–	49	2.77
396	100	8.6	–	3	2.67
412	100	.9	–	41	2.65
428	100	3.4	–	29	2.67
442	100	6.1	–	16	2.67
472	100	0	–	47	2.65
489	100	11	–	3	2.67
526	100	1.1	0.3	39	2.65
550	100	6.9	.5	13	2.66
580	100	6.3	–	7	2.69
617	100	8	–	0	2.67
762	100	1.3	–	37	2.72
917	100	3.6	–	37	2.69
1,067	100	7.2	–	3	2.71
1,129	100	4.4	–	1	2.72

SONIC LOG

Because sonic-log response is dependent on porosity and is independent of fluid content for lower porosities, it is an excellent means of estimating porosity. Shaliness tends to increase interval traveltime from sonic log (Δt) because the characteristic velocity of shale matrix is slower than that of sandstone. Thus, porosities calculated for shaly sandstones on the basis of a clean sandstone-matrix velocity tend to yield porosity values that are high.

The speed of sound in rock is determined principally by the lithology and porosity of the rock. Indurated sandstone, limestone, and dolomite have high compressional sonic velocities. Salt, gas, and water have relatively low velocities. The sonic log on plate 1 is a record-

TABLE 5.–*Sonic velocities and traveltimes for common materials and rocks of the Durham Triassic basin*

[Modified from Gerhart-Owens, Inc., 1974.–means no value given]

	Matrix velocity (km/s)	Matrix velocity (ft/s)	Interval travel-time (μs/ft)	Interval travel-time (μs/m)
Sandstones	5.49–5.9	18,000–19,500	55.5–51.0	182.1–167.3
Limestones	6.4–7.0	21,000–23,000	47.6–43.5	156.2–175.5
Dolomites	7.0	23,000	43.5	147.7
Anhydrite	6.1	20,000	50.0	164.0
Salt	4.6	15,000	66.7	218.8
Shale	1.8–4.9	6,000–16,000	–	–
Water	1.6	5,000–5,300	189.0	620.1
Oil	1.3	4,300	238.0	780.8

ing of a compressional wave's traveltime through the rock parallel to the wellbore. The log is recorded in microseconds per foot (μs/ft), which is the reciprocal of the compressional wave velocity; this value is called the interval traveltime (Δt). Values of traveltimes for common rock types and fluids in the Durham Triassic basin are presented in table 5.

The sonic-logging tool has two transmitters that are pulsed alternatively. The received signals are integrated over time to give the recorded interval traveltime and integrated traveltime. The traveltime between any two depths in the hole may be computed by adding each millisecond pulse (indicated by tick marks) between the desired depths.

The first signal arriving at the sonic receiver is generally the compressional wave that has traveled through the rock adjacent to the borehole. However, if that signal is attenuated by gas, salt, or fractures in the formations, the receiver will record some altered arrival time. The result is a large displacement of the log curve to the left toward lower velocities (higher Δt) called "cycle skipping." In the Sears No. 1 well, a caliper (borehole-diameter) log indicates that this phenomenon occurs opposite enlarged parts of the wellbore.

Below a depth of 848 m, the sonic log has several sharp spikes or deflections to the right. Although these spikes could represent thin-bedded anhydrite zones having high velocity, the recorded traveltime is shorter than normal for anhydrite; therefore, these spikes are assumed to be noise spikes caused by cable and tool noise triggering the sonic receiver in a low-signal area of the borehole.

The sonic log, which is matrix-velocity dependent, is a good tool for determining lithology and is commonly used for correlation purposes. The overall character of the Sears No. 1 sonic log confirms the cyclic character of the sedimentary rocks and correlation of the 793-m-depth to 1,134-m-depth interval with the 1,174-m-depth to 1,524-m-depth interval of the Groce No. 1 well (pl. 1).

Wyllie and others (1956, 1958) and Wyllie (1963) have developed a formula that can be used to calculate porosity from interval traveltime for shale-free sandstone:

$$\text{porosity of sandstone} = \frac{\Delta t - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}}$$

where:

Δt = the interval traveltime from the sonic log (μs/ft);
Δt_{ma} = the interval traveltime for the rock matrix (μs/ft); and
Δt_f = the interval traveltime from the sonic log for fluid (μs/ft).

Porosities were calculated from the sonic log by the Wyllie formula for selected intervals of the Sears No. 1 well and are presented in table 2. The accuracy of these calculated porosities depends on the accuracy of estimated matrix velocity obtained from the sonic log. An error difference of 1.0 μs/ft changes the calculated porosity about 0.5 percent.

Crossplots showing the relation of sonic velocity to bulk density, sonic velocity to neutron porosity, and bulk density to apparent limestone porosity were constructed from logs (figs. 3–5) to investigate the lithologic properties of layers in the Sears No. 1 well. The major portion of the points in figures 3–5 are plotted in the limestone-sandstone range, with matrix sonic velocities from 5.5 km/s to 6.4 km/s (Δt_{ma} = 55.5 to 47.6 μs/ft). Most of the points on the density-sonic velocity crossplot are plotted in the dolomite range. The rocks associated with these points are identified as mudstones and argillites. The displacement of data points into the dolomite region of figure 3 is not the result of their having a dolomite matrix, but rather a result of high density-low matrix sonic velocity (higher Δt_{ma}). The measured high densities also indicate that the shales penetrated in the Sears No. 1 well do not have anomalous high-hydrostatic pressure or overpressure. Overpressured shales tend to be less compacted and have higher porosity and lower density.

GAMMA-RAY LOG

The gamma-ray log is a measure of the natural emission of gamma-ray particles from decay of radioactive minerals in rocks around the borehole.[3] Measurement

[3]The American Petroleum Institute uses a standard calibration test pit to measure certain log parameters such as gamma-ray emission and porosity. API units are standard geophysical industry measures.

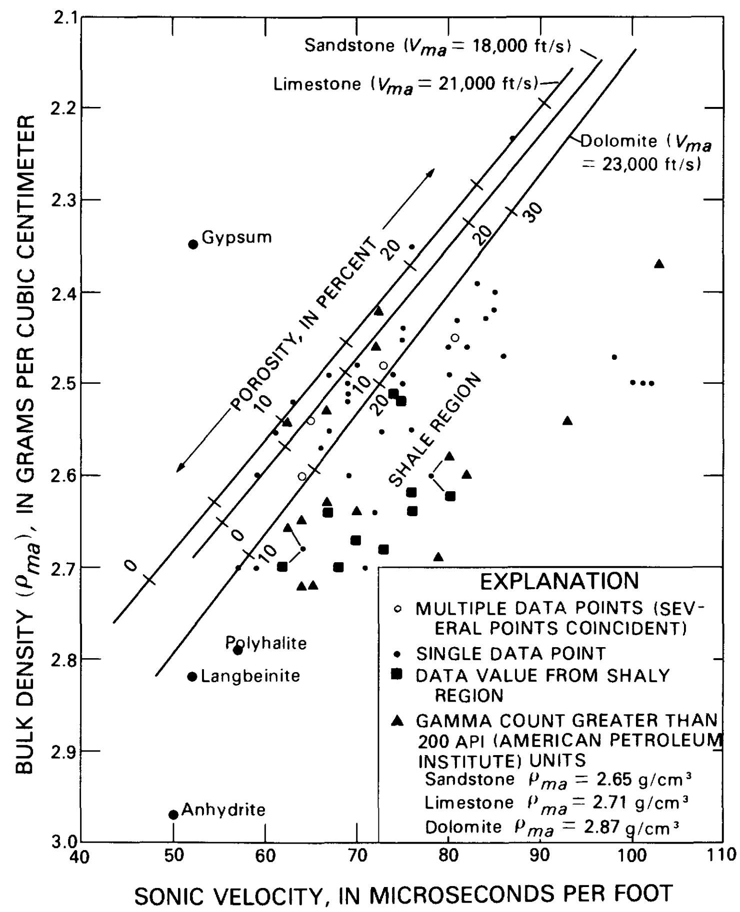

FIGURE 3.–Relation of bulk density to sonic velocity for rocks in the Sears No. 1 well, North Carolina (from Bain and Brown, 1981). Sonic log was recorded in μs/ft, or interval traveltime, which is the reciprocal of matrix sonic velocity (V_{ma}), recorded in ft/s. See table 5 for correlation. Points not plotted on solid lines represent rocks composed of more than one lithologic type.

is generally made with a borehole scintillation counter and recorded in American Petroleum Institute (API) units (Wyllie, 1963, p. 118), as in plate 1. Gamma-ray radiation is random; therefore, a time constant and logging speed are chosen to give a good average measurement. One API gamma-ray unit is defined as 1/200 of the difference between the deflections produced on a log by the radiation from two standard formations in a test pit in Houston (Wyllie, 1963).

The gamma-ray curve and the resistivity and sonic logs illustrate the alternating pattern of sandstone and shale in the Sears No. 1 well. The cleaner sandstones occur at depths of 289, 351, 537, and 782 m and have radiation values of 50 to 55 API units. Most of the units identified on the sample log as sandstones have radiation levels of 60 to 80 API units. The *SP* curve opposite the sandstone zones has a higher negative deflection, indicating that the rocks are filled with water and are more permeable. The lack of a good *SP* deflection opposite the 782-m zone indicates that the zone's water chemistry is close to that of the drilling mud and (or) that this sandstone contains no water. The gamma-gamma density log indicates that the porosity of sandstone is less than or equal to 2 percent.

The shaly rocks in the Sears No. 1 well consist predominantly of massive argillite and mudstone. Small amounts of thinly laminated fissile shale are present in some cuttings. The radiation level of the gray, massive argillaceous unit between a depth of 308 and 338 m is a good example of the shale radiation level of the upper rock of the Sears No. 1 well. The red mudstone and argillite facies below a depth of 640 m, however, has a lower radiation level about 100 API units.

The upper 610 m of this log has several anomalous gamma-ray peaks that have intensities of more than 200 API units. The largest of these intensities occurs at 420 m.

The gamma-ray log anomalies at depths of 161, 188, 398, 499, 571, and 585 m appear, from sample logs and log crossplots, to occur in sandstone that is shaly or radioactive. Some anomalies definitely occur at the base of the sandstones. The sandstone at 161 m is calcareous.

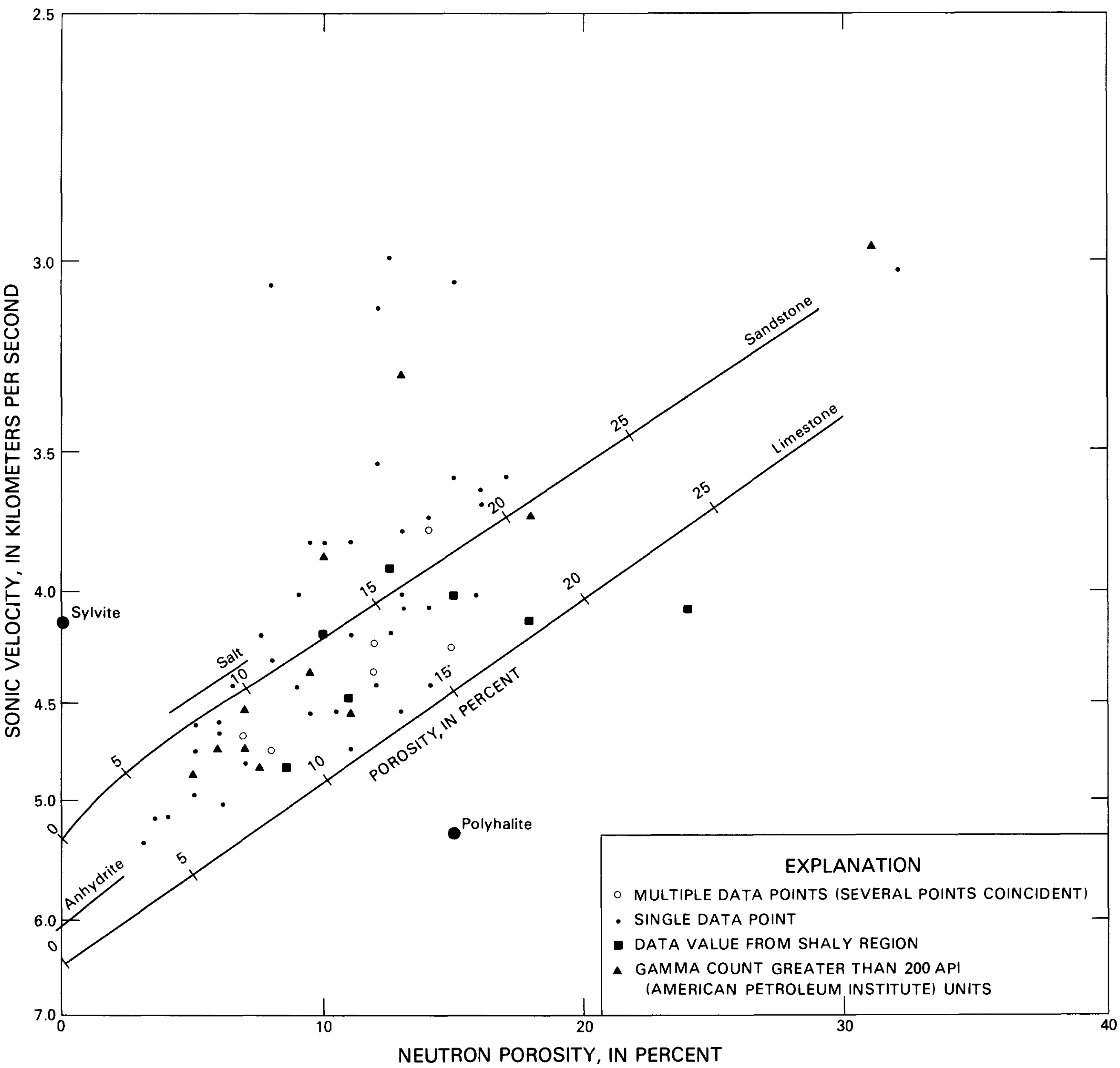

FIGURE 4.—Relation of neutron porosity to sonic velocity for Triassic rocks in the Sears No. 1 well, North Carolina (from Bain and Brown, 1981). Points plotted between solid lines represent rocks composed of more than one lithologic type.

Anomalies at depths of 181, 271, 418, and 420 m correspond to shale. The anomaly at a depth of 201 m may correspond to siltstone. Some of the anomalies, such as at depths of 181 and 188 m, correspond to washouts of the hole, which affect the gamma-ray readings.

TEMPERATURE LOG

A thermal gradient exists between the Earth's core and surface. The temperature near the surface generally increases about 1°C for every 55 m of depth. Departure from this average gradient is caused by differences in the thermal conductivity of rocks, the degree of water circulation, and the depth of magma.

Borehole-temperature logging is accomplished with a sonde having a thermistor whose internal resistance changes in response to temperature change. In addition to determining gross thermal gradients, the temperature log is used to detect inflow and outflow of liquids and gases in the borehole, thermal conductivity of indi-

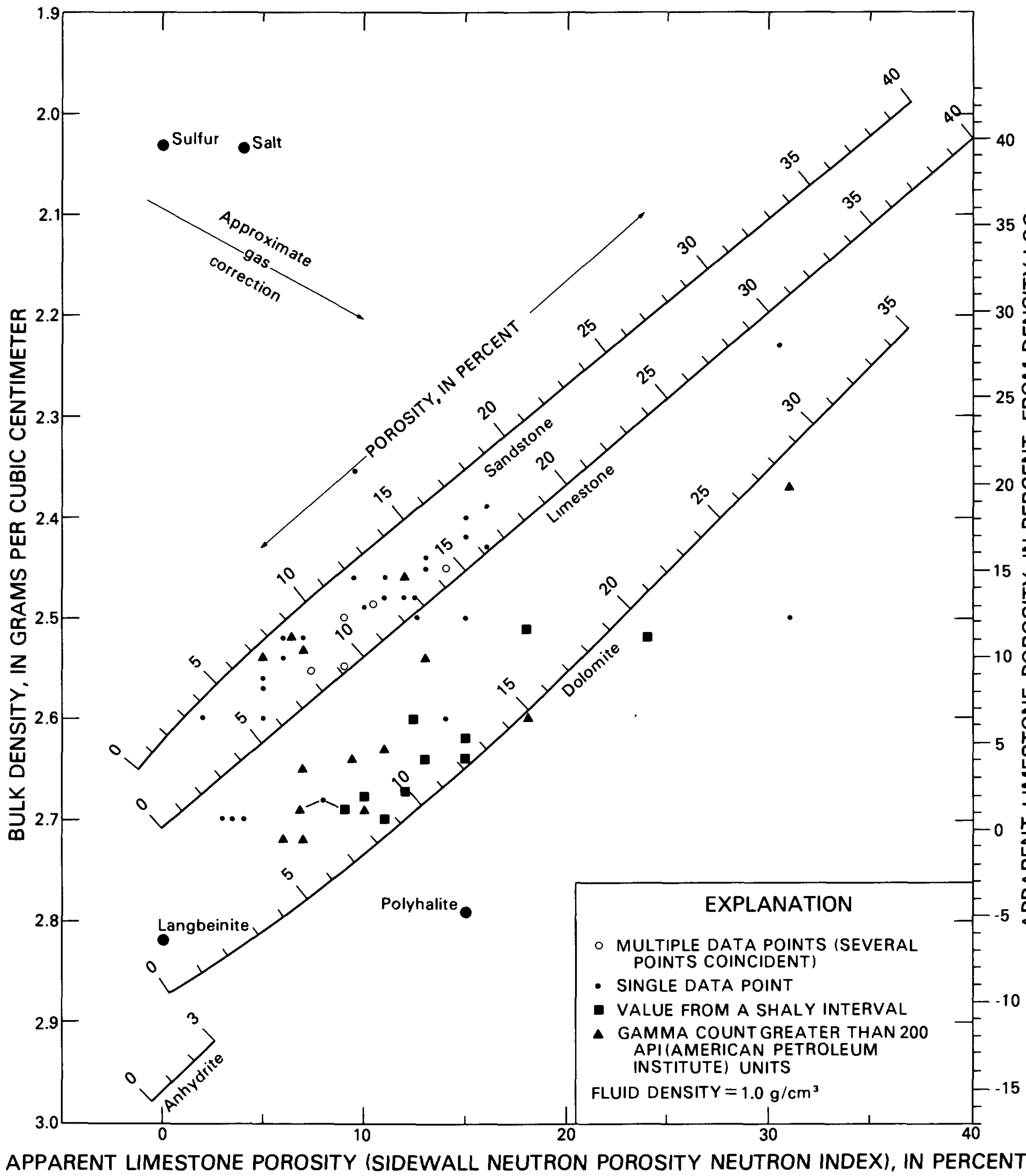

FIGURE 5.—Relation of bulk density to apparent limestone porosity for rocks of the Sears No. 1 well, North Carolina (from Bain and Brown, 1981). Points between solid lines indicate mixtures of lithologic types.

vidual beds, and location of new cement grout behind casings.

The temperature log of the Sears No. 1 well is presented in plate 1 and figure 6. The temperature log in figure 6 is plotted beside the caliper log and a log of drilling samples to facilitate interpretation of the temperature anomalies. The temperature gradient at the Sears No. 1 well is 1°C/66 m.

Most of the temperature anomalies in the Sears No. 1 well that occur above a 500-m depth appear to be caused by cooler water moving down the wellbore and outflow into more permeable sandstones. Most of the anomalies below 500 m appear opposite points identified on the caliper log as fractures. The relatively small temperature gradient of this well compared to that of the Groce No. 1 well may indicate deep circulation of ground water. Additional discussion of borehole-temperature logging is found in Keys and MacCary (1971).

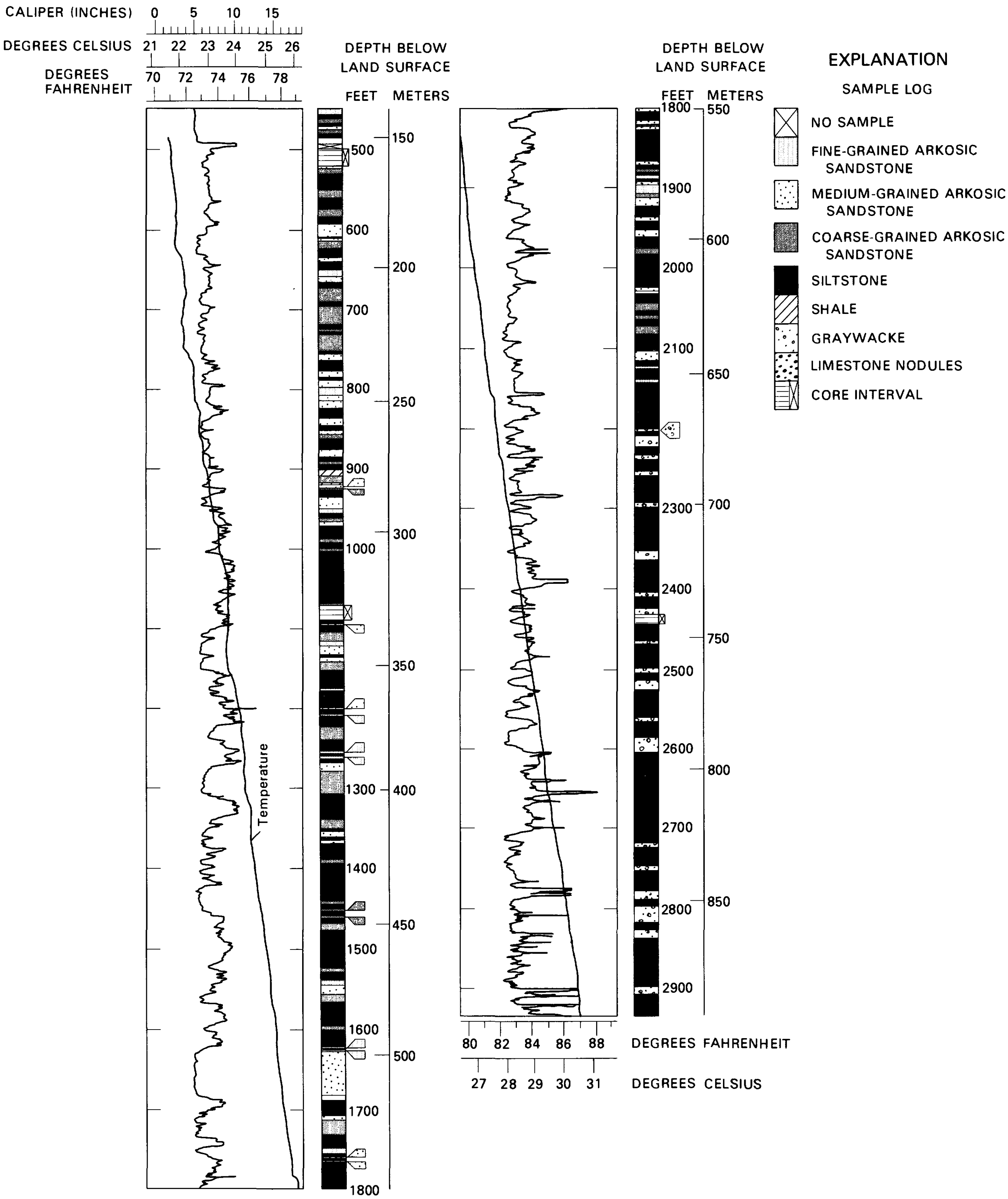

FIGURE 6.–Correlation of temperature log with caliper and drilling sample logs.

ACOUSTIC-TELEVIEWER LOG

An acoustic televiewer was used to examine the detailed physical character of the Sears No. 1 well wall-rock in areas having temperature and caliper-width anomalies. The acoustic-televiewer log shows (1) areas of high reflectivity (light-colored areas on the log) that indicate dense layers and (2) areas of low reflectivity (dark-colored areas on the log) that indicate fractures or openings in the rock. Bright areas on the log are a function of the reflected energy from the wellbore. The acoustic-televiewer tool spins or rotates from north to south as it is lowered into the borehole. Figure 7 illustrates the fractures and washouts observed between 590-m to 620-m depth and 650-m to 660-m depth in the Sears No. 1 well. Vertical drill-bit marks and horizontal and dipping fractures (dark areas on log) can be observed on the televiewer log. Most caliper and televiewer anomalies are coincident with temperature anomalies (Keys and others, 1979) for the Sears No. 1 well.

APPLICATION OF LOG DATA

DETERMINATION OF LITHOLOGY

The data from sonic, density, and neutron logs are sometimes crossplotted to give additional information on mineral composition of rocks. Figure 8 is a sonic-density crossplot of data for sandstones from the Sears No. 1 well. Figures 9 and 10 are *M-N* parameter crossplots of the log data from the Sears No. 1 well.

Equations for M and N, from Schlumberger, Ltd. (1972), are

$$M=\frac{\Delta t_f-\Delta t}{\varrho b-\varrho f}\times 0.01$$

and

$$N=\frac{\phi n_f-\phi n}{\varrho b-\varrho f}$$

where

Δt_f = interval traveltime from sonic log for fluid (189 μs/ft for fresh mud and 185 μs/ft for salt mud);
Δt = interval traveltime from sonic logs, in μs/ft;
ϱb = bulk density of logged interval;
ϱf = density of fluid (1.0 for fresh mud and 1.1 for salt mud);
ϕn_f = neutron-log porosity for fluid (use 1.0);
ϕn = percentage neutron porosity of logged interval from compensated neutron or sidewall neutron-porosity log;
0.01 = multiplication factor;
M = lithology-dependent quantity derived by using density- and sonic-log values; and
N = lithology-dependent quantity derived by using density- and neutron-log values.

The data points on figures 7 and 8 are a result of lithology-dependent values, M and N, in which the effects of the rock matrix are calculated if sonic-log values are divided by density-log values and neutron-log values are divided by density-log values. The value M is derived by dividing the porosity component (interval traveltime difference) of the sonic log by the porosity component (density-value difference) of the density log. The value N is derived by dividing the porosity component (neutron-value difference) of the neutron log by the porosity component (density-value difference) of the density log (Schlumberger, Ltd., 1972, p. 73). Because the porosities determined from the logs are different, the calculations are characteristic of the matrix effects measured by the logging instruments. The multiplication factor 0.01 applied in determining the value M makes M and N of the same order of magnitude.

Because the position of plotted points depends on mineralogy, the binary mineralogy mixtures under ideal conditions should plot along lines connecting any two minerals, and trinary mineralogy mixtures should plot in the triangular areas connecting the respective end points. The presence of gas or evaporite rocks in the well causes a shift in the plot of data values to the upper right, and shaliness causes a shift in the plot of data values to the graph's lower center. Figure 8 indicates that the upper 640 m of the Sears No. 1 well contains some quartz, calcite, and anhydrite. Other data points are closer to the shale region on the graph, indicating the rocks are shaly in this interval. This interpretation agrees with the sample data shown in plate 1.

DETERMINATION OF SECONDARY POROSITY

Normally, the porosity determined from a neutron-sonic velocity crossplot and from a neutron-density crossplot differs; this difference reflects secondary porosity, which tends to shift a point upwards on *M-N* plots (figs. 9 and 10). This relation is caused by the tendency of the sonic-velocity signal to overlook or skip over larger openings in the rock and to record only intergranular porosity. Neutron- and density-logging tools respond to total porosity, regardless of porosity type. However, a sonic log tends to ignore vugs, because the sound energy is propagated through the surrounding matrix and bypasses the vugs. Therefore, a sonic log used in conjunction with a density and (or) neutron log can provide an estimate of the secondary porosity, as well as intergranular porosity, of a formation of known lithology (Schlumberger, Ltd., 1972, p. 6). The effects of secondary porosity are small or negligible, as shown on figures 9 and 10.

CORRELATION OF STRATIGRAPHIC UNITS IN BASIN

Log data from the Sears No. 1 well and from the Groce No. 1 well (location shown on fig. 11) were compared

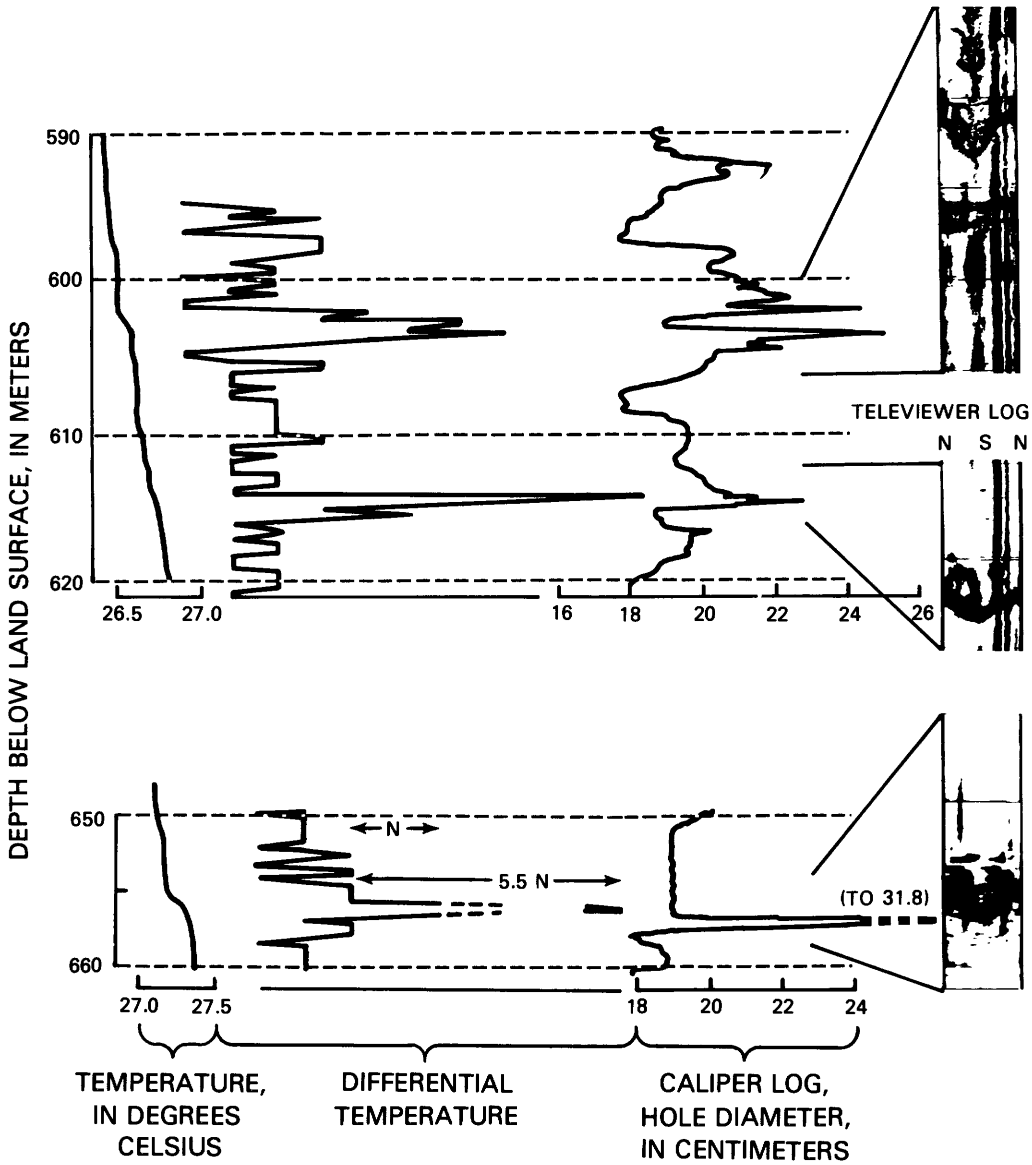

FIGURE 7.–Temperature, differential temperature, caliper, and acoustic-televiewer logs, Sears No. 1 well, North Carolina (Keys and others, 1979).

to show how log data could be used to define stratigraphic relationships between two areas of the basin (pl. 1). The bottom 350 m of the Sears No. 1 well correlates with the bottom 396 m of the Pekin Formation in the Groce No. 1 well of the Sanford area on the basis of similar response in the dual induction-laterologs of the two wells (pl. 1). These logs suggest that as much as 590 m of the bottom part of the Sears No. 1 well may correlate with the bottom 640 m of the Groce No. 1 well. There is no indication of the presence of a unit in the Sears No. 1 well that is equivalent to the carbonaceous, coal- and oil-shale-bearing Cumnock Formation or to the Sanford Formation of the Groce No. 1 well. The stratigraphic relations between the two wells suggest that the environments of deposition were similar in both the Durham and Sanford areas during Pekin time and possibly into early Cumnock time (Bain and Brown, 1981). Thereafter, a stable, swampy, reducing environment having a slow rate of sediment accumulation prevailed in the Sanford area, while a higher energy environment was creating channel sands and point bars in the fine-grained alluvial-fan deposits in the New Hill area. In the Sanford area, the paludal deposits were succeeded by reddish, poorly sorted, detrital materials. In the New Hill area, a different source area contributed increasingly greater amounts of gray to buff detrital granitic material to the sediment being deposited (Bain and Brown, 1981, fig. 3).

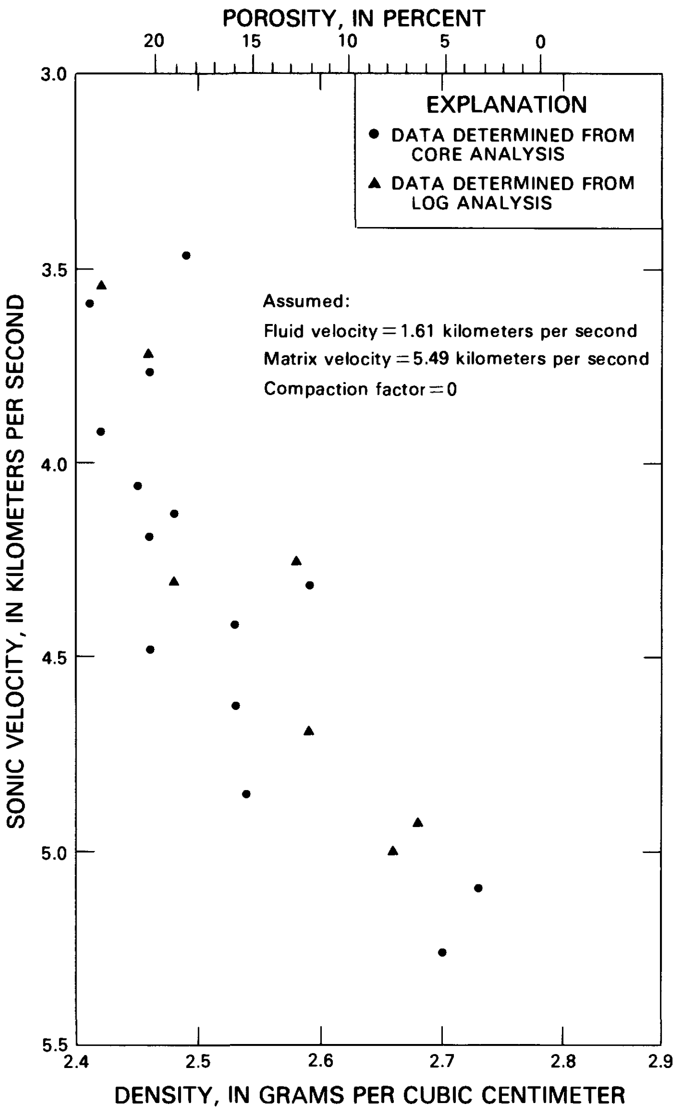

FIGURE 8.—Relation of density to sonic velocity of cores of selected sandstone intervals.

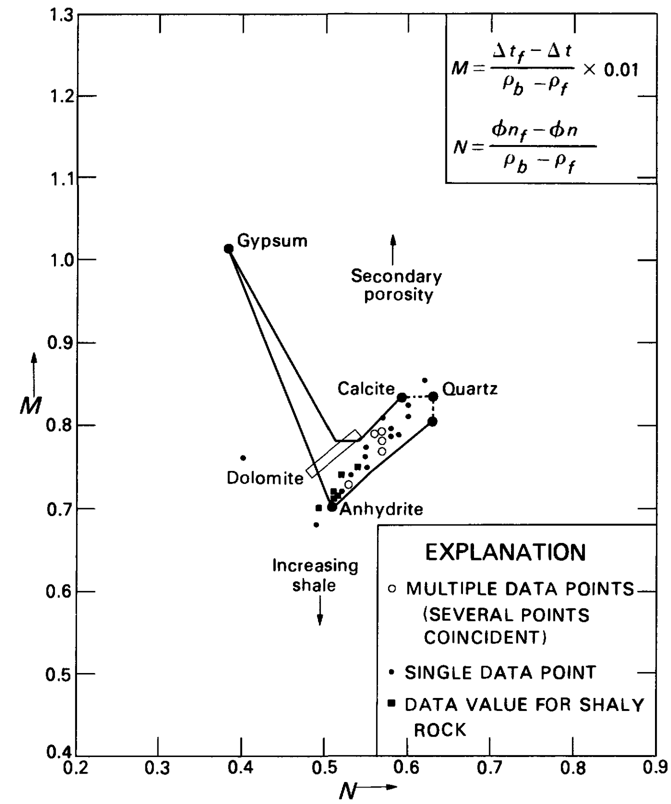

FIGURE 9.—Plot of M and N parameters derived from geophysical logs for 640-m-depth to 1,140-m-depth interval. Data points between solid lines indicate mixtures of lithologic types for depth interval. (See p. 14 for explanation of equations for M and N.)

DETERMINATION OF ROCK PROPERTIES BY PHYSICAL-TESTING TECHNIQUES

The Triassic rocks of the Durham Triassic basin have low porosity and permeability because they were deposited as continental sediments; therefore, the rocks are poorly sorted. Much of the initial or primary porosity has been lost through compaction, lithification, and diagenesis. Consequently, ground-water yields are low—generally less than 2.6 L/s in shallow domestic wells (Bain and Thomas, 1966). Laboratory testing determined porosity, permeability, bulk density, moisture content, sonic velocity, resistivity, and mechanical strength.

Results of physical tests of representative core samples from the Sears No. 1 test well and of core samples from the Deep River coal study (Reinemund, 1955) in the Sanford area are summarized in tables 6 and 7, respectively. The following sections describe the test procedures performed on Sears No. 1 well cores by Terra Tek, Inc., of Salt Lake City, Utah (written commun., 1976).

BULK DENSITY, MOISTURE CONTENT, AND EFFECTIVE POROSITY

Physical-properties tests were performed to determine the bulk density, moisture content, and effective porosity of each core sample. Samples for the physical-property tests were obtained by breaking two fragments of approximately 30 cm³ each from a core. The bulk-density measurements were made by using a Ruska Mercury Porometer, which determines volume by mercury displacement. The densities obtained by this method are accurate to ± 0.005 g/cm³.

The moisture content is expressed as a percentage of the wet weight and is determined by measuring the weight loss of a crushed sample during oven drying for 24 hours at 105°C. The accuracy of this method is 0.1 percent.

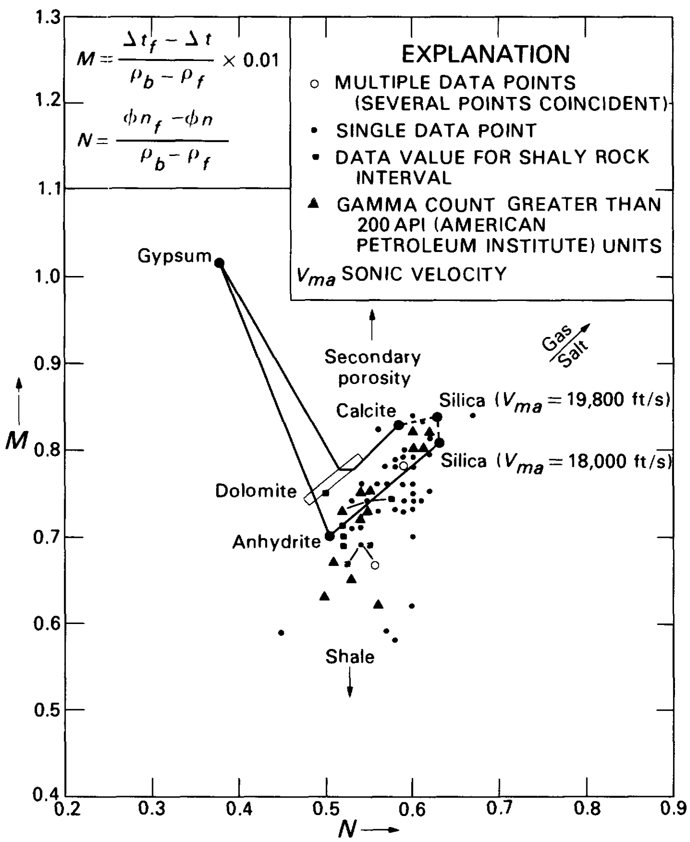

FIGURE 10. – Plot of M and N parameters derived from geophysical logs for 152-m-depth to 640-m-depth interval. Data points between solid lines indicate mixtures of lithologic types for depth interval. V_{ma}, matrix sonic velocity. (See p. 14 for explanation of equations for M and N.)

The effective-porosity determinations were made by using a Beckman Gas Pycnometer. The effective porosity is essentially a measure of the connected pore volume. The Beckman technique uses helium gas to impregnate the sample and to measure the volume of the connected pores. The bulk volume is then determined by sealing the sample surface and determining the total volume of the sample. With this technique, measurements of effective porosity are accurate to ± 0.05 percent.

The samples that were analyzed contain very little moisture. The largest moisture content measured was 1.1 percent in a sample from a depth of 745 m. The effective porosities measured were relatively low; the largest porosity observed was 6.2 percent for the sample from a 745-m depth. Samples from 744-m and 1,141-m depths had effective porosities of less than 1 percent.

PERMEABILITY

Permeability was measured on cylindrical samples 2.54 ± 0.013 cm in diameter and 0.635 ± 0.051 cm in length. The test cylinders were sealed and confined at a confining pressure equal to 4.73×10^4 g/cm^2 per centimeter of depth. A pore pressure equal to 50 percent of the confining pressure was then established at each end of the sample. These pressures were maintained for a period of 4 hours to allow the pore pressure to stabilize. At the end of this period, the two ends of the sample were isolated from one another, and a pressure step of approximately 4.62 g/cm^2 was applied to one end of the sample. The differential pressure change across the sample was monitored over a period of approximately 15 hours. This differential pressure change allowed time for the system to establish a uniform differential pressure-decay rate.

The pore and driving water were estimated to contain 500 mg/L *TDS*. A value of 500 mg/L was considered to be a reasonable approximation of the reservoir water chemistry.[4] The dissolved solids were primarily sodium chloride. Use of 500-mg/L *TDS* water solution should result in slightly higher permeabilities than when using pure water, because the sample permeated with pure water experiences more clay swelling and therefore lower permeability.

An upper limit for water permeability tests was established by an unconfined gas permeability test on the sample from 1,141-m depth. A gas permeability of $9.9 \times 10^{-8} \mu m^2$ was obtained.

The permeability-test results show agreement with the effective porosity measurements. The samples from a 157-m depth had the highest permeability and also the largest effective porosity. Samples from 960-m and 1,138-m depths had similar permeabilities and almost identical effective porosities. Samples from 744-m and 1,141-m depths had the lowest permeabilities and the lowest effective porosities.

The permeabilities obtained for the Sears No. 1 well by using water of 500 mg/L *TDS* are listed in table 6.

SONIC VELOCITY

The technique used to measure the sonic velocities of the various stratigraphic intervals is best described as the "through transmission system." The system can determine small delay times to a high degree of accuracy (Terra Tek, Inc., written commun., 1976).

The frequency synthesizer used is extremely stable; signal error is 1 part in 10^7. A signal that passes through the test sample is compared with a signal coming directly from the synthesizer. The delay experienced by the signal in passing through the sample is then determined by comparing waveforms on an oscilloscope. The path

[4] Reservoir chemistry was determined from a U.S. Geological Survey Central Laboratory water-quality analysis that accompanied sample cores (lab ID No. 131010; Record No. 39928).

TABLE 6.—*Physical properties of core samples from the Sears No. 1 well, North Carolina*

Sample depth (m)	Bulk density (g/cm³)	Water content (percent)	Gas porosity (percent)	Permeability (μm^2)		Velocity (km/s)		Formation resistivity (Ωm)	Formation factor $(F=R_o/R_w)$[1]	Unconfined strength (kPa×10⁴)	Lithology
				Liquid	Air	Longitudinal	Shear				
154	(2)	--	5	4.55×10^{-10}	10^{-4}	--	--	[3]58	[4]2.74	--	Sandstone.
154	--	--	2.3	--	--	[5]3.73	--	--	--	--	Do.
157	--	--	8.9	2.18×10^{-3}	10^{-2}	--	--	[3]422	[4]24.1	--	Do.
157	--	--	12	--	--	[5]3.82	--	--	--	--	Do.
329	--	--	1.3	--	--	[5]3.28	--	--	--	--	Gray argillite.
329	--	--	--	Sample failed.	9.9×10^{-6}	--	--	--	--	--	Do.
330	--	--	4.7	4.85×10^{-9}	1.98×10^{-5}	--	--	[3]80	[4]3.64	--	Siltstone.
330	--	--	2.2	--	--	--	--	--	--	--	Do.
330	--	--	2.8	--	--	[5]4.26	--	--	--	--	Do.
744	2.65	0.6	.9	1.98×10^{-9}	--	4.50	2.37	72	[6]6.5	8.8	Red sandstone.
745	2.60	1.1	6.2	1.7×10^{-8}	--	4.71	2.60	130	12	11.4	
960	2.65	.5	2.8	4.95×10^{-9}	--	5.14	3.04	1,060	[6]96	13.9	Conglomerates.
1,138	2.66	.1	2.5	6.93×10^{-9}	--	5.14	3.02	736	[6]67	11.1	Do.
1,141	2.73	.1	.9	3.96×10^{-9}	9.9×10^{-8}	4.55	2.36	195	[6]18	12.2	Graywacke.

[1]*F*, formation factor; R_o formation resistivity; R_w, resistivity of fluid in the formation.
[2]No value determined in some cases when more than one sample from same depth was tested.
[3]Calculated from $R_o=F\times R_w$.
[4]Measured at 15,169 kPa.
[5]At 13,790 kPa.
[6]At overburden pressure.

TABLE 7.—*Physical properties of core samples from the Deep River coal field, North Carolina*

Well No. [1]	Specimen No.	Depth (m)	Specific gravity (g/cm³)	Bulk density (g/cm³)	Porosity (percent)	Permeability (μm^2)	Tensile strength (kPa)
DH-2	1	290	2.64	2.58	2.04	4.9×10^{-5}	12,170
	2	324	Sample broken.	--	--	--	--
	3	434	2.62	2.53	3.35	4.0×10^{-5}	(3)
	4A	443	2.65	2.62	.88	3.0×10^{-5}	14,286
	[2]4B	--	--	--	--	--	17.596
	5	409	(3)	--	--	--	--
	6	53	2.65	2.37	10.7	4.3×10^{-4}	5,191
BH-11	7	68	2.66	2.53	4.82	(3)	4,385
	8	75	2.68	2.49	7.11	4.3×10^{-4}	9,970
BH-10	9	19	2.71	2.00	26.4	2.1×10^{-3}	4,999
	10	32	2.71	2.49	8.00	9.9×10^{-5}	7,502
BH-7	11A	352	2.66	2.64	.83	2.0×10^{-5}	12,549
	[2]11B	--	--	--	--	--	9,998
BH-9	[4]12	145	2.68	2.37	11.8	5.9×10^{-4}	5,440

[1]Refer to Reinemund, 1955, for well locations.
[2]Duplicate tested tensile strength only.
[3]Specimen unable to be extracted from core.
[4]Oil saturation 3.25 percent.

length divided by the elapsed time of the signal passing through the sample gives the resulting acoustic velocity for that medium. The longitudinal wave is designated the "P wave," and the shear wave is designated the "S wave."

The samples for sonic testing were 2.54 ± 0.013 cm in diameter and 2.54 ± 0.05 cm in length. Prior to testing, all test samples were saturated in an aqueous solution of 500 mg/L *TDS* (see footnote 4, in the Permeability section).

The samples were then confined at a pressure equal to 4.73×10^{-4} g/cm² per centimeter of burial. P-wave and S-wave velocities for each depth interval were obtained. These velocities are accurate to ±1 percent.

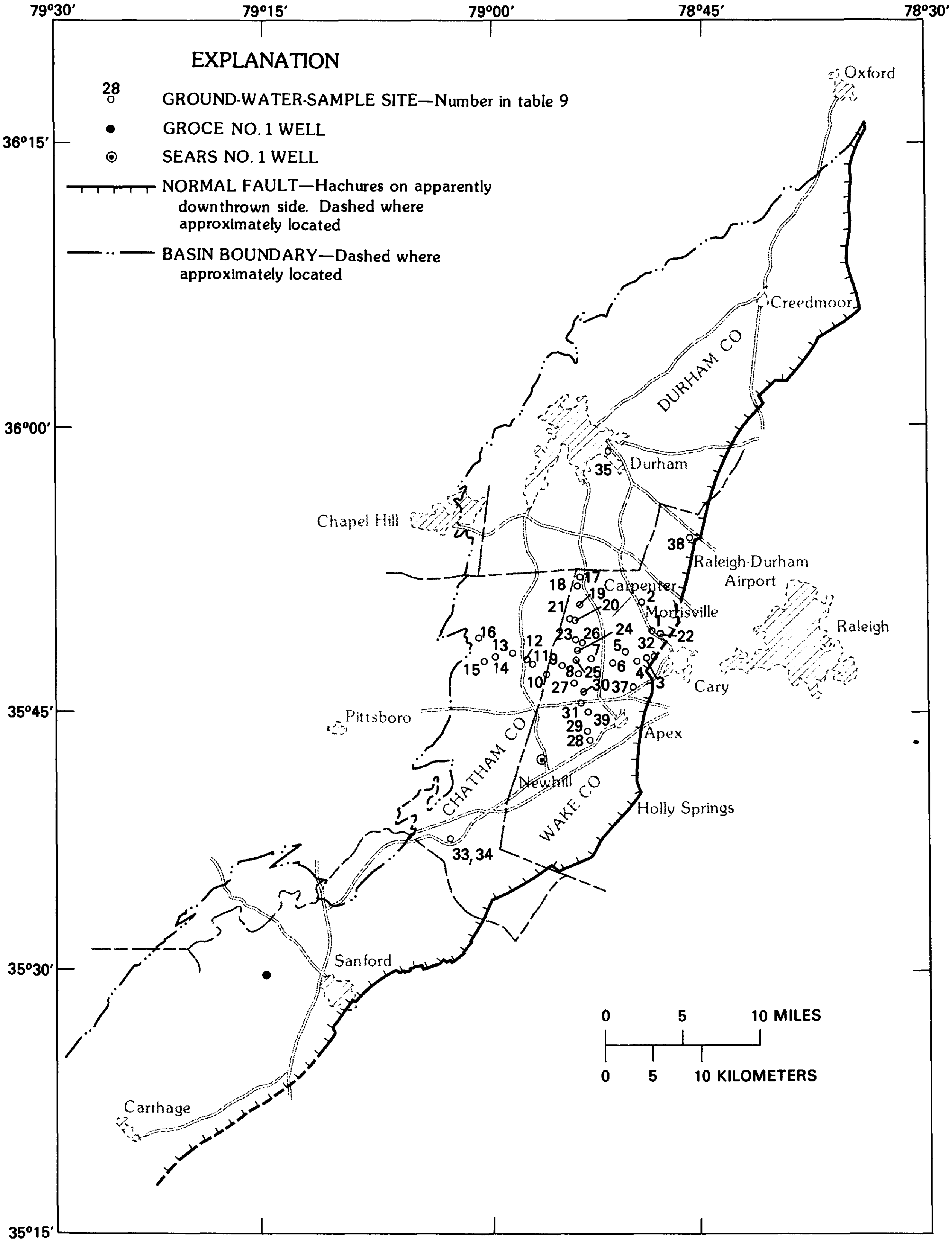

FIGURE 11.—Ground-water-sample site locations in Durham Triassic basin and Sears No. 1 well and Groce No. 1 well locations, North Carolina.

Samples from 960-m and 1,138-m depths that appeared to be composed of similar materials had virtually identical sonic velocities. A summary of the sonic-test results for the Sears No. 1 well is given in table 6.

ELECTRICAL RESISTIVITY

The electrical-resistivity measurements were made on the same samples used in the sonic velocity test. The samples were saturated in an aqueous solution containing 500 mg/L *TDS*.[5] The resistivity of this solution was measured and determined to be 11 Ωm. The saturated samples were then covered with a jacket to isolate ends of the sample and confined at a pressure equivalent to 4.73×10^{-4} g/cm² per centimeter of burial depth. A 30-Hz source voltage was applied at the ends of the cylindrical sample. The resistance of the sample to this voltage was then determined. From this resistance, the resistivity of the sample was calculated and expressed in ohm-meters,

A summary of the resistivity values for each of the Sears No. 1 samples is contained in table 6. The resistivity values are accurate to ± 5 percent.

MECHANICAL STRENGTH

Unconfined compression tests were performed on all Sears No. 1 well samples to determine compressive strength. The samples were cylinders 3.81 ± 0.05 cm in length and 1.91 ± 0.013 cm in diameter. Sample ends were ground to within 0.00002-mm flatness. Samples were tested with the "as-received" moisture content.

All loadings were applied quasi-statistically by using a constant displacement rate of 3.65 ± 10^{-3} cm. No strain measurements were taken. The transducer used to measure axial load is accurate to 2 percent.

The relation of axial stress to time graph for the various loadings was recorded. All samples, except the sample from 960 m, demonstrated a similar response, and all samples experienced a brittle failure. There was no apparent increase in strength with increasing depth. A summary of the mechanical behavior is given in table 6.

EVALUATION OF POROSITY AND PERMEABILITY MEASUREMENTS

POROSITY

Continuous porosity values for the Sears No. 1 well are available from the neutron-porosity and gamma-gamma density logs of plate 1. In addition, porosity values calculated for different matrix sonic velocities of 4.7 km/s, 5.3 km/s, and 6.0 km/s are presented in table 2.

The porosity determined from the geophysical logs differs from laboratory-determined porosity values of cores from equivalent depths. There are some differences among density-log, neutron-log, and sonic-log porosity values in table 2. The Sears No. 1 borehole wall is irregular and washed out, and the resulting effects of variable hole diameter may cause the discrepancies among porosity values determined by different techniques. The neutron-log response is particularly influenced by the shaly matrix of the Triassic rocks.

In table 3, average effective porosities determined from the porosity logs represent depth intervals where the borehole is reasonably smooth and is not washed out. Explanations for the apparent inconsistencies among the porosities determined from logs are given in the "Remarks" column of table 2. The gamma-gamma density and neutron-porosity values for sandstone intervals generally agree within 15 percent. If the lithology of an interval is shale, the neutron-porosity value for that interval is high. The sonic-porosity value believed to be more accurate is calculated by using the lowest matrix velocity and is about equal to the gamma-gamma density value.

Laboratory-porosity values are lower, and the lack of consistency between laboratory-measured values and geophysical-log values is not understood. Factors that could cause such differences include

1. The laboratory test core sample was not representative of the volume of rock being sampled by the logging tool.
2. Crystal-structure changes had occurred in the rock core between the time the rock was cored and the time it was tested in the laboratory.

Laboratory-determined gas porosities for Sears No. 1 well and Deep River coal field samples below 152 m range from 0.83 percent to 12 percent, as shown in tables 6 and 7. The average is about 3.5 percent.

PERMEABILITY

Laboratory air-permeability tests (tables 6 and 7) of core samples from the Sears No. 1 well and of drill hole samples from the Deep River coal field illustrate the low permeabilities characteristic of the Triassic rocks below the zone of weathering. Most values are in the square micrometer $\times 10^{-5}$ range. Attempts to determine liquid permeability with water having *TDS* similar to that of water pumped during packer tests of the Sears No. 1 well resulted in rupture of some samples having low permeability. The apparent sensitivity to the water composition

[5] Based on water-quality analysis.

indicates swelling of clays (or other mineralogic changes) caused by the use of water of probable different chemistry than that of formation water. Montmorillonite, which is highly expandable, is the most abundant clay in samples from the Sears No. 1 well. Also the water used in laboratory tests may not be truly representative of the formation water and could have the correct salinity but the wrong ionic composition.

DETERMINATION OF GROUND-WATER QUALITY AND MOVEMENT

WATER QUALITY

CHEMICAL ANALYSIS OF WATER SAMPLES

Water samples obtained from most shallow ground water (less than 90 m deep) are predominantly a calcium-bicarbonate type. Dissolved-solids contents are generally less than 250 mg/L. However, shallow ground water having a high dissolved-solids content (greater than 1,600 mg/L) is present in the area west and northwest of Cary, N.C., and north of Carpenter, N.C. From Cary, near the eastern border fault and basinward, sodium- and calcium-sulfate types change progressively to calcium-chloride and sodium-chloride types. North of Carpenter, near the common corners of Durham, Chatham, and Wake Counties, some waters have a high (greater than 800 mg/L) dissolved-solids content.

The wells that have a high dissolved-solids content are on the northwestern side of major faults and penetrate red mudstone or conglomerate having a red mudstone maxtrix. Thus, all the wells may be in a similar hydrogeologic situation at the discharge end of the basin's subsurface flow system. Water having high (greater than 1,600 mg/L) dissolved solids present in shallow wells in the conglomerate and fanglomerate near Cary occurs near the deeper downfaulted parts of the basin.

Water from a depth of 115 m in the Sears No. 1 well (table 8) appears to be a sodium-chloride type similar to water from shallow depths in sample sites 4 and 38 (fig. 11). The water from the Sears No. 1 well 247-m-depth to 264-m-depth interval is similar to water from sample sites 4 and 38 in that there is only a slight increase in the amount of calcium over sodium-ion concentration. The Sears No. 1 well water sample from the 1,009-m-depth to 1,143-m-depth interval; although higher in dissolved-solids content and calcium content than the water from either the 115-m-depth, 247-m-depth to 264-m-depth interval, or the drilling water, is known to be a blend of the drilling (mud filtrate) water and the formation water. A single inflatable packer was used to isolate a zone between the 1,009-m-depth and the bottom of the well at 1,143 m. The small amount of water that did move into the test packer assembly from the 1,009-m-depth to 1,143-m-depth interval is probably a mixture of drilling-mud water and formation water (Bain and Brown, 1981).

The similarity of the chemical composition (chiefly sodium-calcium chloride types) of water from the buried Dunbarton, S.C., Triassic basin to that of the water of the Durham basin is striking. In contrast, ground water from the Culpeper, Va., basin to the northeast is a calcium-sulfate water, presumably caused by the widespread presence of gypsum. Water from sample 32 (table 9) near Cary (fig. 11) contains an ionic composition characteristic of water from the gypsum-bearing Permian Castile Formation near Jumping Springs, N. Mex., and the Triassic redbeds of the Newark basin, New Jersey. This similarity implies that gypsum may be present to influence the geochemistry of water near Cary.

GEOPHYSICAL ANALYSIS

General Quality

The borehole-geophysical logs were used to check the accuracy of properties measured from samples taken from the 247-m to 264-m and 1,009-m to 1,143-m zones and to give additional information on the water chemistry in the remainder of the hole.

Salinity

The formation resistivity factor, also called the formation factor (*F*), is defined as the electrical resistance of a rock that is saturated with a conducting electrolyte divided by the resistivity of the electrolyte; this factor is useful in analyzing the conductivity of fluids in rocks.

The salinity of formation waters is commonly estimated from the geophysical logs by using one or both of the following relationships (Alger, 1966; Schlumberger, Ltd., 1974, p. 34):

$$1.\ SP = -K \log \frac{R_{mf}}{R_w}$$

where:

SP = the spontaneous potential, in millivolts;
K = a constant related to absolute temperature;
R_{mf} = the resistivity of the drilling mud filtrate, in ohm-meters at a specified temperature; and
R_w = the resistivity of the formation water, in ohm-meters at a specified temperature.

TABLE 8.—*Chemical analysis of ground water*

[Latitude 35°41′33″, longitude 78°56′35″. Dissolved con-

Depth of sample (m)	Date	Sequence No.	Alkalinity (total $CaCO_3$)	Bicarbonate (HCO_3)	Cadmium[1] (Cd)	Calcium (Ca)	Carbonate (CO_3)	Chloride (Cl)	Cobalt[1] (Co)	Copper (Cu)	Fluoride (Fl)	Noncarbonate hardness
115	12/21/75	11	--	--	--	--	17	--	--	--	--	--
Mudline	04/04/76	12	--	--	--	--	15	--	--	--	--	--
259	04/16/76	1	85	104	0	18	0	93	0	1	0.5	0
259	04/16/76	4	0	0	3	62	0	83	32	300	.8	170
1,018	04/17/76	8	0	0	4	30	0	41	14	130	.5	84
1,018	04/17/76	9	0	0	1	96	0	200	31	420	.9	250
1,018	04/18/76	10	0	0	--	--	0	75	--	--	1.4	--

[1]Dissolved constituent in micrograms per liter.

TABLE 9.—*Chemical analysis of ground*

[Modified from Bain and Brown, 1981.

Sample site No.[1]	Well depth (m)	Yield (L/s)	Sample date	Latitude[2]	Longitude[3]	Sequence No.	Alkalinity (total $CaCO_3$)	Bicarbonate (HCO_3)	Calcium (Ca)	Carbonate (CO_3)	Chloride (Cl)	Conductance (μmho)	Fluoride (Fl)
1	61	0.01	05/09/73	362832	784856	01	179	218	150	0	650	2,420	0.3
2	30	.06	05/09/73	351708	794802	01	153	186	56	0	110	660	.3
3	67	.32	05/09/73	354721	794904	01	230	280	230	0	920	3,330	.4
4	53	.32	05/09/73	354704	794927	01	197	240	28	0	280	1,300	.4
5	30	1.1	--	354739	795145	01	143	174	22	0	18	330	.2
6	53	.13	05/10/73	354549	785408	01	115	140	11	0	4	240	.2
7	78	.13	05/10/73	350708	785208	01	128	156	24	0	10	270	.2
8	43	.32	05/10/73	354610	783357	01	164	200	31	0	10	330	.1
9	23	.76	05/10/73	355631	795514	01	167	204	42	0	56	500	.2
10	37	1.9	05/10/73	354624	791606	01	11	13	3.5	0	5	67	.1
11	--	--	05/10/73	364650	791718	01	67	82	12	0	24	220	.3
12	38	4.7	05/10/73	351650	781729	01	125	152	35	0	42	370	.2
13	59	.32	05/10/73	350737	790825	01	190	232	52	0	80	650	.3
14	37	.63	05/11/73	350722	790948	01	146	178	40	0	48	435	.3
15	34	--	05/11/73	360648	792025	01	179	218	35	0	22	420	.3
16	30	.44	05/11/73	350831	792057	01	161	196	78	0	130	740	.2
17	41	.32	--	351144	782349	01	331	404	140	0	250	1,410	.3
18	--	--	05/11/73	350108	785403	01	105	168	42	0	10	300	.3
19	30	.25	05/11/73	351012	781357	01	312	380	80	0	100	850	.2
20	12	--	05/11/73	350920	791412	01	20	24	40	0	100	570	.1
21	24	.32	05/11/73	350922	790425	01	218	266	60	0	82	710	.3
22	145	.19	05/12/73	361822	784822	01	92	112	74	0	210	2,400	.4
23	32	.32	05/14/73	791408	791408	01	125	125	19	0	6	253	.3
24	53	.38	05/14/73	354705	791400	01	200	244	35	0	28	470	.2
25	30	1.4	05/14/73	350651	791415	01	30	36	3.7	0	4	80	.1
26	34	.16	05/14/73	352735	781400	01	154	188	21	0	16	339	.2
27	76	.13	05/14/73	353556	785109	01	154	188	11	0	14	335	.6
28	46	.32	05/14/73	360244	791312	01	62	76	8.8	0	5	140	.3
29	99	.09	05/14/73	350305	791329	01	108	132	18	0	11	250	.6
30	24	1.1	05/15/73	352517	792340	01	116	142	18	0	4	230	.3
31	33	.63	05/15/73	350442	791348	01	116	142	21	0	3.5	230	.3
32	122	.95	05/15/73	351002	790940	01	87	106	100	0	4	620	.3
33	183	.63	--	355615	792254	01	154	188	5.2	0	36	415	.7
34	107	.95	05/18/73	355615	792254	01	80	98	11	0	7	190	.2
35	91	.76	05/21/73	355440	792050	01	75	92	11	0	3	160	.2
36	232	.38	05/23/73	351556	795100	01	105	128	15	0	18	285	.2
37	152	.19	05/23/73	355407	791604	01	190	232	36	0	300	1,350	.5
38	88	.09	06/04/73	360548	792025	01	149	182	16	0	3.4	300	.3
Mean							140.5	171.6	43		96	635	0.287
Standard deviation							68	82.9	46.4		185	705	.136
Median							144.5	176	29.5		20	354	.300
Maximum							311	404	23.0		920	3,300	.700
Minimum							11	13	3.5		3	67	.100

[1]On figure 11.
[2]For example, 36°28′32″.
[3]For example, 78°48′56″.
[4]Dissolved constituent, in micrograms per liter.

from the Sears No. 1 well, North Carolina

stituents in mg/L unless indicated otherwise. --means no data]

Total hardness	Iron[1] (Fe)	Lead[1] (Pb)	Magnesium (Mg)	Manganese[1] (Mn)	pH (field measurement)	Potassium (K)	Residue (calculated sum)	Sodium absorption ratio	Silica (SiO_2)	Sodium (Na)	Sulfate (SO_4)	Zinc[1] (Zn)
52	--	--	2.3	--	8.9	3.2	--	7.9	--	130	--	--
39	--	--	.3	--	.8	--	--	--	--	--	--	--
47	10	0	.4	380	8.5	4.8	283	5.6	3.9	88	23	30
170	26,000	2,000	2.6	3,400	8.9	10	342	3.2	28	96	16	12,000
84	12,000	2,000	2.1	1,600	9	5.7	179	1.9	19	40	14	11,000
250	31,000	4,200	3.4	4,300	9	11	535	3.6	34	130	9.7	10,000
--	--	--	--	--	8.9	--	--	--	82	--	1.4	--

water from the Durham basin, North Carolina

Dissolved constituents in mg/L, unless indicated otherwise. -- means no data]

Noncarbonate hardness	Total hardness	Iron[4] (Fe)	Magnesium (Mg)	Manganese[4] (Mn)	Nitrate (NO_3)	pH (field measurement)	Potassium (K)	Residue (calculated sum)	Residue (dissolved)	Silica (SiO_2)	Sodium (Na)	Strontium[4] (Sr)	Sulfate (SO_4)
470	650	40	66	70	--	6.8	3.4	1,300	1,580	48	220	2,200	16
120	270	10	31	0	1.8	7.5	2.1	340	384	31	19	400	.8
870	1,100	30	120	10	.4	6.8	4.2	2,020	2,410	32	220	2,800	.8
0	87	--	4	--	0	7.8	3.5	680	715	12	240	400	8.8
0	100	0	11	0	.9	6.8	1.8	200	205	30	30	340	.8
0	45	--	4.3	--	0	7.6	1.6	150	160	27	35	23	.8
0	92	--	7.7	--	2.2	7.0	2.2	180	182	32	25	460	.8
0	110	--	8.2	--	0	8.0	1.7	210	215	24	32	640	.8
0	150	--	12	--	.4	6.8	1.8	290	297	31	44	220	.8
2	13	20	.9	10	9.3	5.9	1.7	69	70	34	6.9	80	.8
0	50	--	4.8	--	.4	6.5	.8	160	174	48	27	220	5.6
0	120	--	7.4	--	.4	6.4	.9	240	241	44	29	740	.8
0	150	--	5	--	.4	7.5	.7	380	388	34	80	1,400	10
0	120	10	5.4	100	0	7.1	.7	270	262	34	45	1,100	4
0	130	170	11	370	.9	7.5	.6	250	268	30	39	600	8.4
89	250	130	13	810	0	7.4	.7	410	490	32	47	1,800	8.8
240	570	30	52	40	6.2	7.4	2.5	810	864	21	68	2,200	68
15	120	40	3.7	280	0	7.7	.9	200	208	37	19	860	1.6
0	220	60	4	90	3.1	7.5	.7	500	500	22	100	2,400	6.4
150	170	180	17	10	44	6.2	1.2	380	380	52	34	360	34
32	250	--	25	--	1.3	6.8	1.4	410	455	44	48	400	14
130	220	40	7.5	290	.3	8	3.4	417	1,500	12	430	--	700
0	67	20	4.7	30	0	7	1.4	170	167	34	31	360	.2
0	120	50	8.8	30	.3	7.8	2.2	280	287	27	56	640	4.4
0	15	700	1.3	30	1.3	6.3	.8	79	63	39	11	70	.4
0	75	30	5.4	10	.4	7.5	1.4	210	197	27	45	370	.4
0	35	0	1.8	0	.3	8.5	1.2	210	204	20	65	210	.4
0	37	2,200	3.7	80	0	6.3	1.4	120	113	44	15	120	
0	75	40	7.2	40	0	7.3	2.9	160	157	33	24	320	2
0	78	820	8	80	0	7.2	2.2	160	150	37	20	300	.4
0	77	70	5.9	30	0	7.7	3.4	150	149	29	20	360	.4
210	300	3,200	13	1,900	0	7	.6	430	461	29	10	120	220
0	16	10	.7	20	0	8.7	.8	250	254	19	90	50	5.2
0	37	30	.2	10	1.8	7.7	1.0	130	130	33	26	140	1.2
0	40	80	.2	190	.3	7.6	1.4	120	119	34	19	100	2.8
0	65	370	.2	20	8.4	7.5	1.8	190	177	37	34	130	2
0	150	30	.5	10	.9	8.7	2.6	740	724	38	220	520	10
0	52	10	.3	10	0	--	1.8	180	196	18	51	280	.8
--	164	26	12.7	158	2.38	7.3	1.72	354	408	31.32		30	641
--	206	742	3.6	374	7.47	.658	.952	366	474	9.33		117	727
--	205	40	5.6	30	.4	7.45	1.5	225	228	32		2	360
870	1,100	3,200	120	1,900	44	8.7	4.2	2,020	2,410	52		700	2,800
0	13	10	.2	0	0	5.9	.6	69	63	12		0	23

The relation of F to porosity (ϕ), formation water resistivity (R_w), and true resistivity of rocks saturated with the formation water (Rt) (Archie, 1942) is

$$2.\ F=\frac{Rt}{R_w}=\frac{1}{\phi^m},$$

where m, the cementation factor $=1.3$ to 2.6, and ϕ = porosity, in percent.

The Humble formula, $F=0.62^{-2.15}$, is commonly used for granular rocks. Water resistivity at five depths in the Sears No. 1 well derived from the relation $R_w=\frac{Rt}{F}$ is given in table 10 (col. 4). F values are determined from laboratory analyses, and Rt values are taken from the deep induction curve (ILD) of plate 1.

Table 10 shows that the calculated values of R_w ranged from about 1.0 to 14 Ωm. These data indicate that formation waters at the Sears No. 1 well site could have a dissolved-solids equivalent that ranges from about 350 to 5,500 mg/L as sodium chloride.

The analyses of water samples collected from the 247-m-depth to 264-m-depth interval indicate a dissolved-solids concentration of approximately 560 mg/L when corrected to equivalent sodium chloride. Alger (1966), Schlumberger, Ltd. (1972), and Brown (1971) indicate that, at 25°C, water containing 560 mg/L sodium chloride should have a resistivity of about 10 Ωm. No laboratory F data are available for the 247-m-depth to 264-m-depth interval; however, water resistivities calculated from F values above and below the sampled zone are approximately 10 Ωm. Similarly, R_w values from laboratory-measured porosity and Rt values from the ILD indicate that interstitial water below 960 m is not highly saline. This formation water, which has a resistivity of 1 to 2 Ωm at 25°C, is equivalent to a sodium-chloride concentration of 2,200 to 4,500 mg/L. The analysis of water sampled from the 1,018-m-depth to 1,143-m-depth interval indicates a much less saline water.

Water resistivities also were calculated (table 10, col. 7) by using F values derived from log porosities (ϕ):

$$F=\frac{Rt}{R_w}=\frac{1}{\phi^m}$$

where F, Rt, R_w, and ϕ are the notations described previously and m is the "appropriate" cementation factor (Schlumberger, Ltd., 1972). Log-derived F values determined by this equation are frequently one to two orders of magnitude lower than those calculated by using laboratory porosities. Values determined from log data give extreme F values, which can be directly related to the range of porosity values.

Figures 12 and 13 are graphs showing the relation of porosity from the density and sonic logs to resistivity from the induction log (ILD). There appears to be some correlation between the measured variables on these figures.

Apparent R_w values were calculated by Schlumberger, Ltd. (written commun., 1977), from the same ILD data and by using the same equation:

$$F=\frac{Rt}{R_w}=\frac{1}{\phi^m}.$$

The values ranging from 0.41 Ωm at 152 m to 0.35 Ωm at the bottom of the well indicate sodium chloride concentrations of about 11,000 mg/L.

The explanation for the disparity is apparently related to the assumption that $F=\frac{1}{\phi^2}$ at low dissolved-solids concentrations and low porosities. Alger (1966) states, "*** the customary relationships between F and porosity used in oil field interpretations usually do not apply to freshwater sands.*** F varies in freshwater sands not only with porosity, but also with R_w and grain size."

Data from the computation of formation water resistivity based on the relation $SP=-\mathrm{K}\log\frac{R_{mf}}{R_w}$ are presented in table 11 (Schlumberger, Ltd., 1974, p. 34). The SP values given in table 11 are calculated by using a log deflection of 5 mV per division. Formation factors calculated from the SP-log-derived R_w and from Rt from the ILD curve are given in table 12. Calculated R_w for the 247-m-depth to 264-m-depth interval ranges from 5.3 to 12.4 Ωm at 25°C (table 11, col. 8). However, the R_w values shown in table 11 increase with depth, contrary to most natural occurrences. The use of the SP deflection to obtain reliable R_w values opposite very low permeability formations may make the results less accurate in some cases.

MOVEMENT

A ground-water flow map was not completed for this study. Ground water having dissolved-solids content greater than 2,400 mg/L – chiefly calcium-sodium chloride types – occurs along the basin's eastern edge from Morrisville to Cary and southwest to Holly Springs, N.C. (fig. 11). The location of these occurrences relative to the downfaulted blocks along the east side of the basin indicates that the probable source of the high dissolved-solids-content water is from movement of water upward along fracture zones that bound the

TABLE 10.—*Formation water resistivities calculated by using laboratory measurements and porosity-log data, Sears No. 1 well, North Carolina*

[--, no data]

Depth (m)	Formation factor, F (measured in laboratory)	True resistivity, Rt, from ILD (Ωm)	Water resistivity, R_w,[1] calculated by using F derived from laboratory analyses and Rt from ILD (Ωm)	Porosity, from porosity log (percent)	Formation factor, $F = 1/(\text{porosity})^2$ (calculated from log porosity)	Water resistivity, R_w,[1 2] calculated by using Rt and F derived from logs (Ωm)
154	2.74	40	14.6	5	400	0.10
157	25.0	80	3.2	8.9	127	.63
330	3.64	50	13.7	4.7	452	.11
744	6.5	75	11.5	.9	12,346	.006
960	96	80	1.04–2.08	2.8	1,275	0.078–0.157
1,138	67	100	--	2.5	1,600	.06
1,142	18	>100	--	.9	12,346	--

[1] $R_w = Rt/F$.

[2] Small range in porosity and salinity of formation water increases error for calculation of R_w.

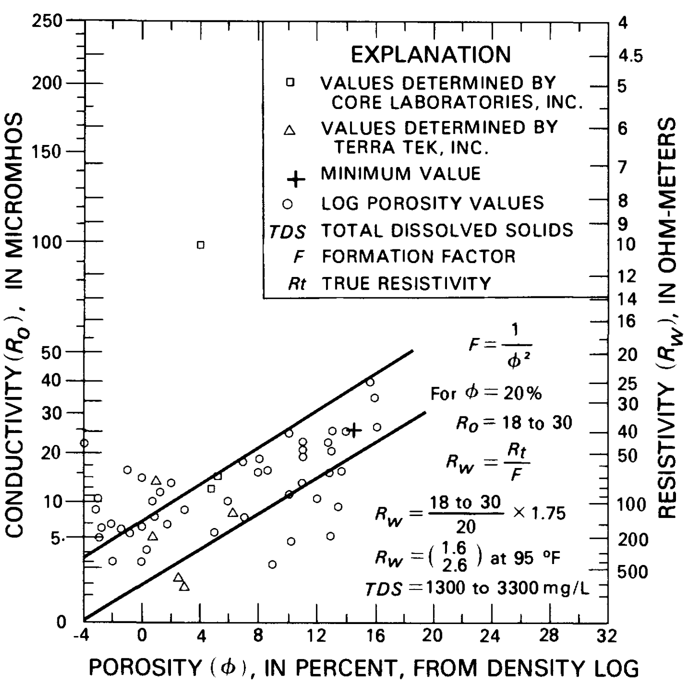

FIGURE 12.—Relation of porosity determined from density log to resistivity and conductivity of rocks in the Sears No. 1 well, North Carolina.

blocks. The temperature log, however, indicates apparent upward movement of water to the 550-m zone and downward movement to the 500-m zone. The resistivity and *SP* logs from the Sears No. 1 well indicate that the formation water is relatively fresh (<4,500 mg/L dissolved-solids contents) to the bottom of the hole. The lower gradient of the Sears No. 1 well temperature log suggests deep circulation at this site. In contrast, the temperature gradient of the Groce No. 1 well indicates poor ground-water circulation in the Sanford area (Bain and Brown, 1981).

The low values of permeabilities of the core samples and the low temperature gradient from the temperature log indicate that circulation in the unweathered rock in the subsurface may be through fractures.

CONCLUSIONS

Tests indicate that low porosities and low permeabilities for the rocks in the Durham Triassic basin are the result of the depositional environment, which limited sorting of sediment, caused extensive lithification and cementation, and possibly caused the presence of montmorillinite.

The low temperature gradient (1°C/66 m) and the presence of relatively freshwater throughout the Sears No. 1 test well are an indication of deep circulation, probably through fractures.

The lithologic log and borehole-geophysical logs from the Groce No. 1 well and the Sears No. 1 well confirm the simultaneous deposition of different facies in separate parts of the basin, the cyclic nature of sediment deposition, and the general imperviousness of the rocks. The logs from the Sears No. 1 well indicate that slightly permeable sandstones and siltstones of the tan arkosic unit interfinger with dense, essentially impervious, red mudstones and argillites. The lateral extent of these sandstones and siltstones is limited by the nearest impermeable facies and the boundaries of the individual structural blocks.

Porosity determined from the density logs is slightly higher than that determined from the laboratory analysis of core samples. The mean density-log

TABLE 11.—*Formation water resistivities calculated by using spontaneous-potential-log data, Sears No. 1 well, North Carolina*

[-- means no data]

Depth to top of zone (m)	Spontaneous potential, *SP* (mV)	Formation temperature, *SP* log		Resistivity of mud filtrate, R_{mf}, at formation temperature[1] (Ωm)	Resistivity factor[2] (when K=70) (Ωm)	Equivalent water resistivity, R_{we}, at formation temperature[3] (Ωm)	Water resistivity, R_w, from R_{we} at 25°C[4] (NaCl-type water) (Ωm)	Water resistivity, R_w, from R_{we} at 25°C ($NaHCO_3$-type water) (Ωm)	Resistivity from ILD (Ωm)
		°F	°C						
154	+10	71.5	22	21.6	0.72	30	28	49	45
191	-11	72	22	21.6	1.48	14.6	13.6	25	210
220	-17	73	23	21.4	1.70	12.6	12.2	21	700
229	-36	73	23	21.4	3.25	6.58	6.2	11	120
248	-39	74	23	21.3	3.70	5.73	5.3	9	45
257	-16	74	23	21.3	1.70	12.5	12.1	21	---
259	-21	74	23	21.3	2.03	10.4	10	18	---
262	-15	74	23	21.3	1.65	12.8	12.4	22	---
270	-18	74.5	23	21.1	1.77	11.9	11.4	20	30
278	-18	75	24	21.1	1.77	11.9	11.4	20	---
282	-15	75	24	21.1	1.65	12.8	12.4	22	---
289	-23	75	24	21.1	2.30	9.17	9	16	70
306	-17	76	24	20.9	1.70	12.3	12	21	800
338	-17	76.5	24	20.9	1.80	11.6	11.6	20	190
377	-20	78	26	20.4	1.96	10.4	10.5	18	40
398	-34	78	26	20.4	3.20	6.38	6.27	11	80
413	-20	78.5	26	20.3	1.96	10.36	10.7	19	---
440	-25	79	26	20.1	2.33	8.62	8.9	16	70
477	-15	80.5	27	19.8	1.65	13.2	14.5	25	---
478	-14	80.5	27	19.8	1.60	12.4	13	23	---
508	-4	81	27	19.7	1.11	17.7	19	33	120
526	-16	82	28	19.5	1.70	11.5	12.3	22	100
570	-7	83	28	19.3	1.20	16.1	17	30	80
582	-20	83	28	19.3	1.96	9.85	11	19	---
609	-4	84	29	19.1	1.11	17.2	19	33	---
633	-15	84.5	29	19	1.65	11.5	13.6	24	---
999	-5	93.5	34	17	1.17	14.5	17.5	31	---
1,019	-26	94	34	16.9	2.35	7.19	8.7	15	150
1,025	-14	94	34	16.9	1.60	10.6	13	23	---
1,043	-13	95	35	16.7	1.52	13.9	17	30	---
1,057	-8	95	35	16.7	1.28	13	16	28	---
1,082	-5	95.5	35	16.6	1.17	14.2	17.2	30	---
1,102	-6	96.5	36	16.4	1.20	13.7	16.8	29	---
1,108	-5	97	36	16.3	1.17	13.9	17.5	31	160

[1]Recorded from log heading.
[2]Factor in *SP* equation (see Schlumberger, Ltd., 1972, p. 79) = R_{mf}/R_{we}. K, constant related to absolute temperature.
[3]Schlumberger, Ltd. (1972, p. 79).
[4]Value estimated from Schlumberger, Ltd. (1972, fig 13-3, p. 79).

porosity was approximately 6 percent, whereas the laboratory-tested core's porosity was approximately 5 percent. However, porosities derived from the neutron and sonic logs are substantially higher than either the mean density-log porosity or the laboratory-tested core porosity. Undoubtedly, part of this difference is due to inadequately compensating for hole irregularity when making logs, and part may be due to postdrilling mineralogical changes in the core prior to testing. However, the higher porosities determined for the Sears No. 1 well are consistent with those observed for the Groce No. 1 well.

Attempts to determine permeabilities with liquids in cores in the laboratory resulted in rupture of some samples. The ruptured core that contained interstitial clay was sensitive to the chemistry of the water—namely, the presence and type of dissolved solids. Later during clay analysis, montmorillonite was found to be the most abundant clay present in the Sears No. 1 well drill cuttings. The expansion of montmorillonite probably affected the results of some of the in-hole and laboratory analyses.

Insufficient data were available to construct a potentiometric map and to establish the rate and direction of movement of ground water in the basin. The low temperature gradient of the Sears No. 1 well indicates deeper circulation of ground water at the Sears No. 1 wellsite, and the sonic log does not indicate that any of the shales are overpressured. The shape of the temperature anomalies on the Sears No. 1 log suggests that there is a little water movement vertically downward above a depth of 550 m and vertically upward below a depth of 550 m. If deep circulation does occur at the Sears No. 1 well site, circulation must take place through an extensive fracture system. Acoustic-televiewer images of selected parts of the Sears No. 1 wellbore show many irregular openings that appear to be parallel to bedding and may be related to either fractures or crossbedding.

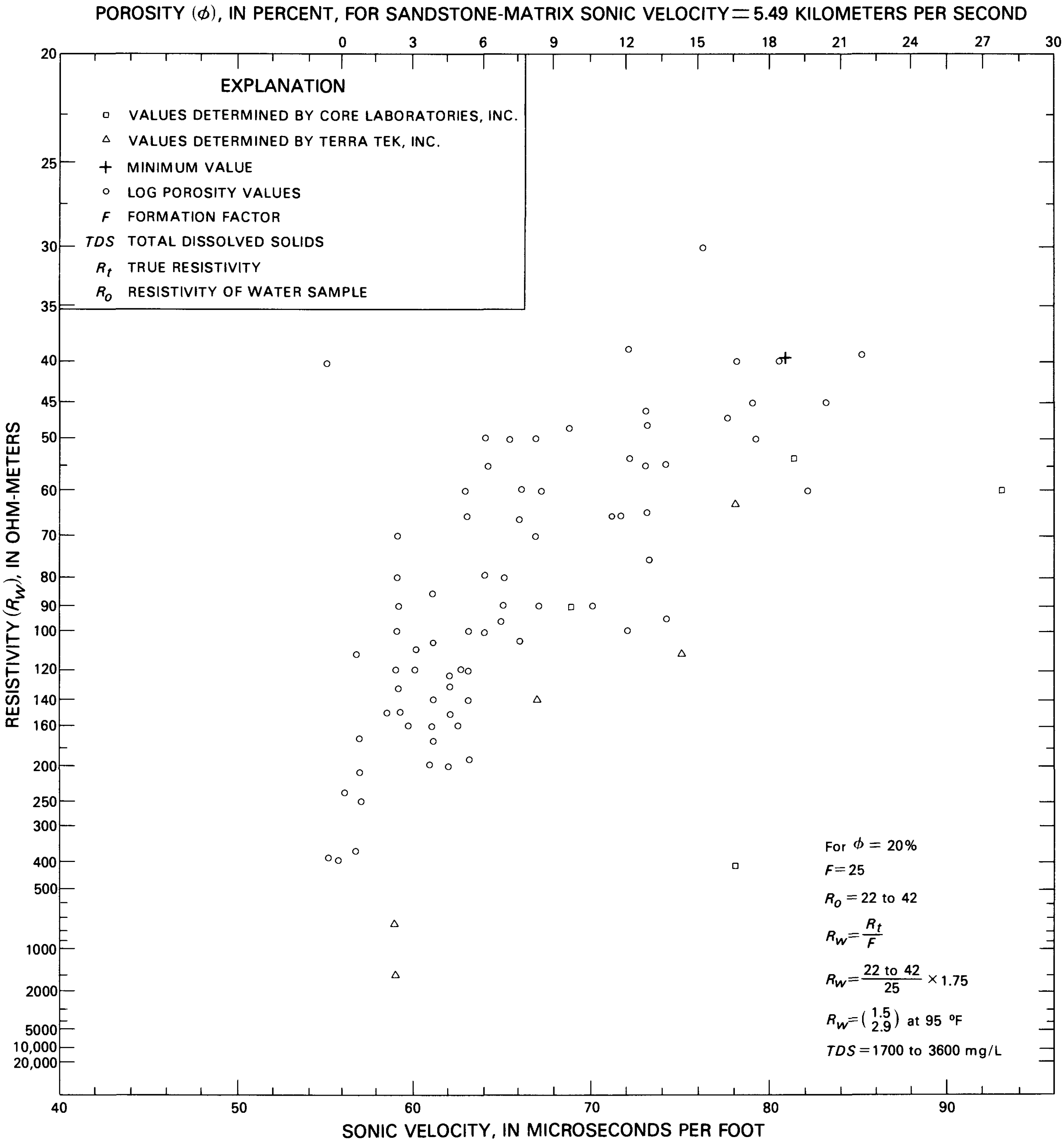

FIGURE 13.—Relation of porosity determined from sonic log to resistivity of rocks on the Sears No. 1 well, North Carolina.

TABLE 12.—*Formation factor calculated from spontaneous-potential-log-derived water resistivities and from induction-log-derived true resistivities, Sears No. 1 well, North Carolina*

[-- means no data]

Depth to top of zone (m)	True resistivity (*Rt*) from ILD at formation temperature (Ωm)	Water resistivity (R_w) from *SP* log for $NaHCO_3$ equivalent at 25°C (Ωm)	Formation factor (*F*) ($F=Rt/R_w$)	True resistivity (*Rt*) from ILD at 25°C (Ωm)	Porosity (percent)
154	>40	49	<.76	>37	14
191	>220	25	0.2-2.6	5-65	10.2
219	220	21	0.4-3.0	8-63	13
229	120	11	0.4-3.2	4-35	13.4
247	27	9	2.9	26	13-16
257	39	21	1.8	37	11
259	39	18	.94	17	13
262	57	22	2.5	54	11
273	22	20	1.	21	15.5
278	39	20	1.9	38	16
282	47	22	2.1	46	11
289	64	16	3.9	62	13
306	75	21	3.5	73	11
338	84	20	42	84	--
377	38	18	2.2	39	10.1
398	64	11	5.9	65	13.6
413	65	19	3.5	66	8.3
440	90	16	5.7	91	10
468	47	25	1.9	48	13
478	55	23	2.5	57	7
508	190	33	6.1	200	5
526	120	22	5.7	126	3
570	100	30	3.6	109	6
582	140	19	7.9	150	7
609	170	33	5.6	184	-1
633	130	24	5.8	140	.8
998	100	31	3.9	120	.6
1,019	130	15	12	180	0
1,025	100	23	5.4	125	1.5
1,042	400	30	16.5	495	-2
1,057	380	28	16.6	465	0
1,082	160	30	6.5	196	-1.5
1,101	150	29	6.4	185	-2
1,108	200	31	8.1	250	-3

The spontaneous-potential and resistivity-log responses indicate that the water in the formations at the Sears No. 1 site increases vertically downward from 350 to 5,500 mg/L *TDS*. The consistent increase with depth also suggests that some circulation takes place throughout the depth of basin.

Average resistivity values for shale in the Sears No. 1 well ranged from about 40 to 50 Ωm. Sandstones and conglomerates were found to have resistivities 5 to 10 times higher. The gamma-ray log indicated that most sandstones have gamma-ray values of from 50 to 80 API units.

Laboratory-measured values, which were used to check the accuracy of the borehole-geophysical log data, were important in determining other physical properties of rocks that could not be obtained from analysis of borehole-geophysical logs.

SELECTED REFERENCES

Ackerman, H.D., Bain, G.L., and Zohdy, A.A.R., 1976, Deep exploration of an east-coast Triassic basin using electrical resistivity: Geology, v. 4, no. 4, p. 137–140.

Alger, H.D., 1966, Interpretation of electric logs in fresh water wells in unconsolidated formations: Tulsa, Oklahoma, Society of Professional Well Log Analysts, 7th Annual Logging Symposium, May 8-11, p. CC1-CC5.

Anderson, E.M., 1951, The dynamics of faulting and dyke formation, with applications to Britain (2d ed.): Oliver and Boyd, 206 p.

Archie, G.E., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics: Transactions, American Institute of Mining, Metallurgical, and Petroleum Engineers 146, p. 54–62.

Asquith, G.B., 1980, Log analysis by microcomputer: Penn Well Pub. Co., Tulsa, 105 p.

Avary, Lee, 1977, Clay mineralogy of the Durham basin: North Carolina University at Chapel Hill, North Carolina, 14 p.

Bain, G.L., 1973, Feasibility study of east coast Triassic basins for waste storage-data availability: U.S. Geological Survey open-file report, 113 p.

———1977, Wrench-fault tectonic origin of east coast Triassic basins [abs.]: Geological Society of America Abstracts with Program, Southeastern Section, v. 9, no. 2, p. 115.

Bain, G.L., and Bisdorf, R.J., 1977, Structural reinterpretation of the Durham-Wadesboro basin, North Carolina [abs.]: Geological Society of America Abstracts with Program, Southeastern Section, v. 9, no. 2, p. 116.

Bain, G.L., and Brown, C.E., 1981, Evaluation of the Durham Triassic basin of North Carolina and techniques used to characterize its waste-storage potential: U.S. Geological Survey Open-File Report 80–1295, 132 p.

Bain, G.L., and Harvey, B.W., 1977, Field guide to the geology of the Durham Triassic basin: Carolina Geological Society field trip guidebook, North Carolina Division of Mineral Resources, 83 p.

Bain, G.L., and Thomas, J.D., 1966, Geology and ground-water in the Durham area: North Carolina Division of Mineral Resources, Ground-Water Bulletin 7, 147 p.

Bell, Henry, III, Butler, J.R., Howell, D.E., and Whallen, W.H., 1974, Geology of the Piedmont and Coastal Plain near Pageland, South Carolina, and Wadesboro, North Carolina: Soil Science State Development Board, Division of Geology (Carolina Geological Society Field Trip guidebook), 23 p.

Birch, F., 1942, Handbook of physical constants: Geological Society of America Special Paper 36, 325 p.

Brown, D.L., 1971, Techniques for quality of water interpretations from calibrated geological logs, Atlantic coastal area: Ground Water, July–August, v. 9, no. 4, 13 p.

Campbell, M.R., and Kinball, K.W., 1923, The Deep River coal field of North Carolina: North Carolina Geological and Economic Survey Bulletin 13, p. 25–28, 64–79.

Conley, J.F., 1962, Geology and mineral resources of Moore County, North Carolina: North Carolina Division of Mineral Resources Bulletin 76, 40 p.

Cornet, Bruce, 1977, The palynostratigraphy and age of the Newark super group: Pennsylvania State University, Ph.D. dissertation, 508 p.

Custer, R.L.P., 1967, Occurrence of limestones in the Durham Triassic basin [abs.]: Elisha Mitchell Scientific Society Journal, v. 84, no. 3, p. 176.

Gearhart-Owen, Inc., 1974, Formation evaluation data handbook: Fort Worth, 240 p.

Glaeser, J.D., 1966, Provenance, dispersal, and deposition environments of Triassic sediments in the Newark-Gettysburg basin: Pennsylvania Geological Survey Report G-43, 168 p.

Guyod, Hubert, 1944, Guyod's electrical well logging: Welex Bulletin A132, 103 p.

Hafner, W., 1951, Stress distributions and faulting: Geological Society of America Bulletin, v. 62, p. 373–398.

Harrington, J.W., 1951, Structural analysis of the west border of the Triassic basin: Geological Society of American Bulletin, v. 62, no. 2, p. 149–158.

Hooks, W.G., and Ingram, R.L., 1955, The clay minerals and the iron oxide minerals of the Triassic red beds of the Durham basin, North Carolina, American Journal of Science, v. 253, p. 19–25.

Hubbert, M.K., 1951, Mechanical basis for certain familiar geologic structures: Geological Society of America Bulletin, v. 62, p. 335–372.

Keys, W.S., Eggers, D.E., and Taylor, T.A., 1979, Borehole geophysics as applied to the management of radioactive waste – Site selection and monitoring, *in* Carter, M.W., and others, eds., Management of low-level radioactive waste: Elmsford, New York Pergamon Press, Inc., v. 2, p. 955-982.

Keys, W.S., and MacCary, L.M., 1971, Application of borehole geophysics to water-resources investigation: Techniques of Water-Resources Investigations of the United States Geological Survey, book 2, chap. E-1, 126 p.

Klein, G., deV., 1969, Deposition of Triassic sedimentary rocks in separate basins, eastern North America: Geological Society of American Bulletin, v. 80, p. 1825-1832.

Krynine, P.D., 1950, Petrology, stratigraphy, and origin of the Triassic sedimentary rocks of Connecticut: Connecticut Geological and Natural History Survey Bulletin, v. 73, 247 p.

Marine, I.W., and Siple, G.E., 1974, Buried Triassic basin in the central Savannah River area, South Carolina and Georgia: Geological Society of America Bulletin, v. 85, p. 311-320.

McKee, E.D., and others, 1959, Paleotectonic map of the Triassic systems: U.S. Geological Survey Miscellaneous Geological Investigations Map 1-300, 33 p., 9 pls.

McKinstry, H.E., 1953, Shears of the second order: American Journal of Science, v. 251, p. 401-414.

Moody, J.D., and Hill, M.J., 1956, Wrench-fault tectonics: Geological Society of America Bulletin, v. 67, no. 9, p. 1207-1246.

Parker, J.M., III, 1978, The geology and mineral resources of Wake County, North Carolina: North Carolina Division of Mineral Resources Bulletin 86, 122 p.

Patterson, O.F., III, 1969, The depositional environment and paleoecology of Pekin Formation (Upper Triassic) of the Sanford Triassic basin, North Carolina: Unpublished Master's thesis, North Carolina University at Raleigh, North Carolina, 104 p.

Peterson, M.N.A., and von der Broch, C.C., 1965, Chert: Modern inorganic deposition in a carbonate precipitating locality: Science, v. 149, p. 1501-1503.

Prouty, W.F., 1931, Triassic deposits of the Durham basin and their relation to other Triassic basins of Western United States: American Journal of Science, 5th ser., v. 21, p. 473-490.

Randazzo, A.F., and Copeland, R.E., 1975, The geology of the northern portion of the Wadesboro Triassic basin, North Carolina: Southeastern Geology, v. 17, no. 3, p. 115-138.

Randazzo, A.F., Swe, W., and Wheeler, W.H., 1970, A study of the tectonic influence in Triassic sedimentation – The Wadesboro basin, central Piedmont: Journal of Sedimentary Petrology, v. 40, no. 3, p. 998-1006.

Reinemund, J.A., 1955, Geology of the Deep River coal field, North Carolina: U.S. Geological Survey Professional Paper 246, 159 p.

Russell, I.C., 1892, The Newark system: U.S. Geological Survey Bulletin 85, 344 p., 13 pls.

Sanders, J.E., 1963, Late Triassic tectonic history of northeastern United States: American Journal of Science, v. 261, p. 501-524.

Schlumberger, Ltd., 1972, Log interpretation, Volume I – Principles: Schlumberger Limited, New York, 113 p.

———1974, Log interpretation, Volume II – Applications: Schlumberger Limited, New York, 116 p.

———1977, Log interpretation charts: Schlumberger Limited, New York, 83 p.

Shearer, R.D., 1927, A cross section through the Triassic basin: Unpublished Master's thesis, University of North Carolina at Chapel Hill, 23 p.

Sumner, J.R., 1977, Geophysical investigation of the structural framework of the Newark-Gettysburg Triassic basin, Pennsylvania: Geologicial Society of America Bulletin, v. 88, p. 935-942.

Vilbrant, F.C., 1927, Oil-bearing shales of Deep River valley: North Carolina Division of Mineral Resources Bulletin, Economic Paper 59, 23 p.

Whitehead, J.W., 1962, The petrology of the Sanford basin Triassic sediments, North Carolina: Missouri University, M.S. thesis, 174 p.

Wilcox, R.E., Harding, T.P., and Seely, D.R., 1973, Basic wrench tectonics: American Association of Petroleum Geologists Bulletin, v. 57, p. 74-96.

Woodworth, J.B., 1902, The Atlantic coast Triassic coal fields: U.S. Geological Survey, 22d Annual Report, pt. 3, p. 25-53.

Wyllie, M.R.J., 1963, The fundamentals of well log interpretation: Academic Press, New York, 238 p.

Wyllie, M.R.J., Gregory, A.R., and Gardner, L.W., 1956, Elastic wave velocities in heterogeneous and porous media: Geophysics, v. 21, no. 1, p. 41-70.

———1958, An experimental investigation of factors affecting elastic wave velocities in porous media: Geophysics, v. 23, no. 3, p. 459-493.

Zohdy, A.A.R., 1974, The use of Dar Zarrouk curves in the interpretation of VES data: U.S. Geological Survey Bulletin 1313-D, 41 p.

Zohdy, A.A.R., and Bisdorf, R.J., 1975, Computer programs for the forward calculation and automatic inversion of Wenner sounding curves: National Technical Information Service, PB-247265/AS, Springfield, Virginia.