GEOPHYSICAL PROPERTIES OF THE BASEMENT ROCKS OF INDIANA

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AUTHORS OF THIS REPORT

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Geophysical Properties of the Basement Rocks of Indiana

By Albert J. Rudman and John A. Rupp

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GEOPHYSICAL PROPERTIES OF THE BASEMENT ROCKS OF INDIANA

By Albert J. Rudman and John A. Rupp

ABSTRACT

Measurements of the physical properties of the basement complex from well samples, cores, and geophysical logs of deep tests in Indiana, Illinois, and Ohio show: (1) density values from 2.57 to 2.81 gm/cm^3 for granites, 2.86 gm/cm^3 for basalt, and 2.70 to 2.90 gm/cm^3 for andesites; (2) low magnetic susceptibility for basement rocks (generally less than 0.001 emu), with the highest value 0.010 emu for a gabbro in LaGrange County, Ind.; (3) seismic velocities ranging from 14,113 to 18,868 ft/sec; and (4) apparent electrical resistivity of 7 to 1,000 ohm-meters for the logged intervals.

Geophysical surveys of basement features depend in part on predicting contrasts in physical properties between the basement and the overlying Mount Simon Sandstone (Cambrian). Studies of electrical resistivity, porosity, velocity, and gamma-ray logs show that the contact between the Mount Simon Sandstone and the basement complex is a mappable horizon in the northern and eastern parts of Indiana.

The density contrast between the Mount Simon Sandstone and the basement complex ranges from 0.1 to 0.2 gm/cm^3, and magnetic-susceptibility contrasts range from 0.0 to approximately 0.007 emu. These low contrasts indicate that only major topographic features on the basement are observable by gravity and magnetic surveys. Therefore, the principal sources of gravity and magnetic anomalies observed throughout the state are considered to be lithologic contrasts within the basement complex. If the sources of the anomalies are near the top of the basement complex, the basement structural configuration can be obtained by standard depth calculations. Velocity contrasts between the Mount Simon and the basement complex were used to generate synthetic seismograms that demonstrate that the contact is a seismically mappable horizon in selected areas.

INTRODUCTION

To better understand the Precambrian basement structure and lithologies of Indiana, samples and wire-line logs from 24 boreholes that penetrated the basement within the state (table 1) were analyzed to determine density, magnetic susceptibility, acoustic velocity, and resistivity values. Geophysical definition of the contact between rocks of the concealed Precambrian basement and the overlying basal Paleozoic clastic sediments depends on a knowledge of the physical properties of these rocks. Additionally, understanding the contrast in physical properties between these two rock types is necessary in various types of investigations that are targeted at quantitatively defining the structure and lithologic composition of the upper crust.

The basement complex in Indiana is entirely concealed by Phanerozoic sediments, and therefore only a simplified model of this complex has been proposed. Because the basement is present only in the subsurface, a more detailed conceptualization of specific structural features and lithologic distributions within the complex requires the use of geophysical investigations along with the results from analyses of the sparse core samples that exist. These two sources of data permit a more detailed and accurate assessment of the evolution, structure, and composition of the upper crust.

PREVIOUS INVESTIGATIONS

Basement evolution, lithologic and structural complexities, and the relationships with overlying sedimentary strata have been investigated for many years in the state, where the depth to the basement is approximately 3,000 to 14,000 feet (900 to 4,300 m) below the surface and the scarcity of wells has made interpretation of the basement complex difficult.

Some preliminary values for density and magnetic susceptibility for the basement rocks in Indiana were previously reported by Rudman and Blakely (1965).

Regional geophysical studies of the basement complex in Indiana began with a statewide aeromagnetic survey, which resulted in 92 county aeromagnetic maps that were published as Geophysical Investigations Maps of the U.S. Geological Survey between 1949 and 1952. These aeromagnetic data were interpreted to obtain both regional (Henderson and Zietz, 1958) and local basement geology (Andreasen and Zietz, 1965). The Indiana Geological Survey mapped the state with a regional gravity survey on the basis of one station per one township (Mead and others, 1953). More detailed gravity, magnetic, and seismic (reflection and refraction) surveys were then made for some of the more prominent anomalies and interpreted to obtain depth and lithologic information (Rudman and Blakely, 1965; Rudman and others, 1971; Lam, 1989). Regional seismic-reflection investigations of the basement began with a survey in southwestern Indiana (Rudman, 1960) and were then extended to include the entire southern half of the state (Rudman, 1963). Synthetic seismogram studies were made concurrently (Biggs and others, 1960) to establish the nature of the basement surface as a reflecting horizon. Electrical surveys of the basement were conducted with magnetotelluric measurements (Renick, 1969).

Rudman and Blakely (1965), Rudman and others (1972), O'Hare (1981), Denison and others (1984), and Van Schmus and others (1987) used geophysical surveys and well data to summarize the basement geology of Indiana as part of a

Table 1. Precambrian

No.	Operator and well name	Completion Date	County	Sec.	Location T.	R.	Total depth (ft)
1	Tecumseh No. 1 Gibson	1947	Allen	33	29N	12E	3,524
2	NIPSCO No. 1 Leuenberger	1968	Allen	14	29N	14E	3,672
3	Hoskins Mfg. No. 1 Hoskins Mfg.	1984	Elkhart	21	35N	6E	4,132
4	Gulf No. 1 Scott	1965	Fayette	32	13N	13E	3,955
5	NIPSCO No. 2 Pheil	1967	Fulton	32	29N	1E	4,056
6	Ohio No. 1 May	1945	Henry	12	16N	11E	3,664
7	Kokomo No. 1 Greentown	1911	Howard	32	24N	5E	3,996
8	Petroleum No. 1 Binegar	1940	Jay	29	24N	13E	3,404
9	Farm Bureau No. 1 Binegar	1944	Jay	29	24N	13E	3,395
10	Shell Western No. 1-24 F & P Inc.	1982	Lagrange	24	38N	10E	4,737
11	Inland No. WD 1 Inland	1967	Lake	14	37N	9W	4,363
12	Inland No. WD 2 Inland	1984	Lake	14	37N	9W	4,385
13	Farm Bureau Texas No. 1 Brown	1959	Lawrence	20	5N	2E	6,806
14	NIPSCO No. 1 Ames	1969	Marshall	21	34N	3E	4,082
15	Stoltenberg No. WD-1 Indiana	1969	Porter	16	35N	5W	4,548
16	Pfizer Chem No. 2 Pfizer Chem	1981	Porter	16	35N	5W	4,528
17	Bethlehem No. WD-1 Bethlehem	1963	Porter	28	37N	6W	4,304
18	Bethlehem No. WD-2C Bethlehem	1968	Porter	29	37N	6W	4,301
19	Midwest No. WD-1 Midwest	1964	Porter	25	37N	7W	4,308
20	Swager No. 1 Swager	1970	Steuben	15	38N	14E	6,866
21	Ashland No. 1 Collins	1965	Switzerland	4	2N	1W	4,000
22	Ashland No. 1 Sullivan	1985	Switzerland	20	2N	2W	4,151
23	Ashland No. 1 Hudson	1965	Wabash	25	29N	6E	3,685
24	Gordon No. 1 Doddridge	1950	Wayne	23	15N	13E	3,908

G - gamma-ray
E - electric
N - neutron
D - density
S - sonic
a - no samples
b - no cores

regional study of the midcontinent. Geochronologic studies of the Midcontinent basement complex were conducted by Goldich and others (1966), Lidiak and others (1966), Hoppe and others (1983), and Denison and others (1984). Understanding of the regional structural configuration on the top of the basement has been continually refined in maps prepared by the American Association of Petroleum Geologists Basement Rocks Project Committee, which initiated the basement

basement tests in Indiana

Surface elevation (ft)	Depth to basement (ft)	Basement rock type	Geophysical logs	Sample set no.	Interval (ft)	Core no.	Interval (ft)
822	3,476	Andesite	E	2066	0-3,517	b	
797	3,484	Andesite	G E N S D	8941	65-3,672	438	3,129-3,672
829	4,109	Andesite	G E D	12282	30-4,132	b	
959	3,914	Arenite	E S	8055	170-3,955	304	1,372-1,416
762	3,920	Granite	G E N	8730	0-4,056	417	4,049-4,056
1,060	3,649	Granite		1509	0-3,670	b	
821	3,945	Granite		589	65-3,995	b	
948	3,351	Andesite		4728	973-3,404	b	
949	3,333	Andesite		4727	190-3,395	b	
944	4,670	Gabbro	G E N S D	12293	50-4,735	675	2,455-4,737
608	4,333	Granite	G E N S	8719	100-4,360	415	2,260-3,953
607	4,330	Granite	G E N D	a		b	
800	6,641	Basalt	G E N S	6088	10-6,806	179	6,800-6,806
789	3,900	Gneiss	G E N S D	9003	100-4,077	455	3,020-4,077
784	4,533	Granite	G N	9110	0-4,540	465	4,450-4,473
786	4,510	Granite	G E N D	1909	350-4,520	b	
625	4,248	Granite	G E N S D	7697	100-4,304	80	4,300-4,304
624	4,270	Granite	G N D	8865	180-4,290	b	
615	4,252	Granite	G E N S	7900	0-4,308	280	3,445-4,308
1,058	4,930	Granite	G E N S D	9356	600-6,866	b	
880	3,974	Arenite	G E N D	8209	50-4,000	b	
794	4,040	Arenite	G E N S D	12541	0-4,150	b	
787	3,654	Granite	G E N S	8032	10-3,685	301	3,680-3,685
857	3,435	Granite		3379	35-3,970	b	

map of North America (Flawn, 1967). More recent versions of this map (Cohee, 1974; Muehlberger and Tauvers, 1988) have shown an increased understanding of detailed basement topography.

Recent geophysical surveys in Indiana aided by this type of baseline physical-properties data include: an east-west seismic-reflection profile in southwestern Indiana conducted by the Consortium for Continental Seismic Profiling

(COCORP)(Kaufman and others, 1988; Pratt and others, 1989), a series of seismic-reflection profiles in the area of the Wabash Valley Fault System (René and others, 1989), and various gravity and magnetic crustal modeling studies (Campbell, 1983; McPhee, 1983; Leosewski, 1985; Lucius and Von Frese, 1988; Lam, 1989). These studies have improved the understanding of the basement influence on Phanerozoic sedimentation patterns and tectonic control of hydrocarbon and mineral accumulations.

GEOLOGIC SETTING

The basement complex of Indiana lies approximately 3,000 to 14,000 feet (900 to 4,300 m) below a thick sedimentary cover of Paleozoic rocks (fig. 1). In Indiana only 24 wells have penetrated the basement (table 1), and all but three of these lie along the Cincinnati and Kankakee Arches, where the depth to the basement is less than 4,600 feet (1,400 m). The knowledge of the basement rocks, therefore, is necessarily based on extrapolation of geologic data from these few available test wells and on interpretation of geophysical data obtained from gravity, magnetic, electrical, and seismic surveys.

Figure 1 shows the locations of all basement tests in Indiana and selected basement tests from the surrounding states. The generalized structural configuration of the Precambrian basement complex in the Midwest is also shown. In this region the structural style at the top of the basement is characterized by low-relief basins and arches (fig. 1). Although the structural configuration of the later Paleozoic sediments generally follows the contours of the basement structure, many of the smaller scale structures defined on shallower horizons are not evident on the basement surface because of the lack of detailed well control. Many of the structures evident in later Paleozoic sediments may ultimately be derived from flexure of the basement (Flawn, 1965; Hinze and Zietz, 1985). Indirect evidence for basement influence on early Paleozoic sedimentation can be inferred from facies changes and thinning of strata across known basement structures, for example, the La Salle Anticlinal Belt (Nelson, 1990).

The surface rocks of the Precambrian basement complex in Indiana and surrounding areas (fig. 2) define three generalized yet distinct lithologic provinces: an anorogenic granitic or felsic intrusive terrane (Central Granite-Rhyolite Province), a metamorphic terrane (Grenville Province), and a Keweenawan or younger series of intermediate to mafic terranes with accompanying sediments (Michigan arm of the Midcontinent Rift System, Ft. Wayne Rift, Wabash Valley Rift, Rough Creek Graben, Reelfoot Rift, St. Louis Rift). Both the Grenville and Central Granite-Rhyolite Provinces are well defined by drilling. The presence of the mafic terranes, which may have formed in response to Keweenawan rifting events (Braile and others, 1982, 1986; Lidiak and others, 1985; Hinze and Kelly, 1988), is interpreted from gravity, magnetic, seismic, and earthquake-epicenter data and is supported by sparse subsurface data. The isotopic-age dating of the basement rocks indicates that the Central Granite-Rhyolite Province is the oldest (average 1.3 Ga) and is followed by the basaltic rift zones of middle Keweenawan age (1.0 to 1.2 Ga). Some of this rifting is interpreted to be possibly late Precambrian or Early Cambrian in age (Braile and others, 1986; Kolata and Nelson, 1988). The latest event is the emplacement of the Grenville Province (0.8 to 1.0 Ga) (Hoppe and others, 1983; Denison and others, 1984). Two wells, IN-21 and IN-22 (table 1), in southeastern Indiana and a series of wells in southwestern Ohio, including an Ohio Division of Geological Survey well in Warren County, Ohio, have encountered dense arkosic quartz arenites below the Mount Simon. The crystalline basement may be more than 5,000 feet (1,500 m) below these pre-Mount Simon rocks (Wickstrom and Shrake, 1989).

Basement lithologies were first described in Illinois by Bradbury and Atherton (1965), in Ohio by Summerson (1962), and in Indiana by Greenberg and Vitaliano (1962) and Kottlowski and Patton (1963). Summaries of basement lithologic characteristics for the entire Midwest have been presented by Rudman and others (1971), Denison and others (1984), and Van Schmus and others (1987). All found a regional predominance of granitic rocks.

Although most of the wells penetrate a minimal amount of the top of the basement complex, most of the lithologies encountered are generally consistent through the entire interval penetrated. Cuttings from IN-7, IN-8, and IN-9 (table 1) were initially identified as metasedimentary rocks (Rudman and Blakely, 1965) on the basis of short intervals and fine-grained samples but have been reinterpreted to be weathered granite and andesites.

The Mount Simon Sandstone, a section of marginal-marine siliciclastics 200 to 2,500 feet (60 to 750 m) thick, unconformably overlies the crystalline rocks of the basement complex throughout Indiana except possibly in the Wabash Valley rift area in southwestern Indiana and also in southeastern Indiana in the southern extension of the Ft. Wayne rift where pre-Mount Simon clastics (late Precambrian or Early Cambrian) may be present (Sexton and others, 1986; Kaufman and others, 1988; Pratt and others, 1989). The Mount Simon is the oldest known (confirmed through drilling) Paleozoic rock unit in Indiana and is assumed to be St. Croixan (Late Cambrian) in age (Gutstadt, 1958; Droste and Patton, 1985).

The above summary is based on sparse well data generally concentrated in areas of shallow basement, especially along the broad crest of the Cincinnati Arch and its northwestward extension, the Kankakee Arch (fig. 1). The only wells that penetrated the basement complex off these arches are a hole in south-central Indiana, where a deep test reached the basement at a depth of 6,650 feet (2,000 m) below the surface, and two wells in the extreme northeastern part of the state. Several deep tests in the southern part of Illinois also penetrated the basement complex.

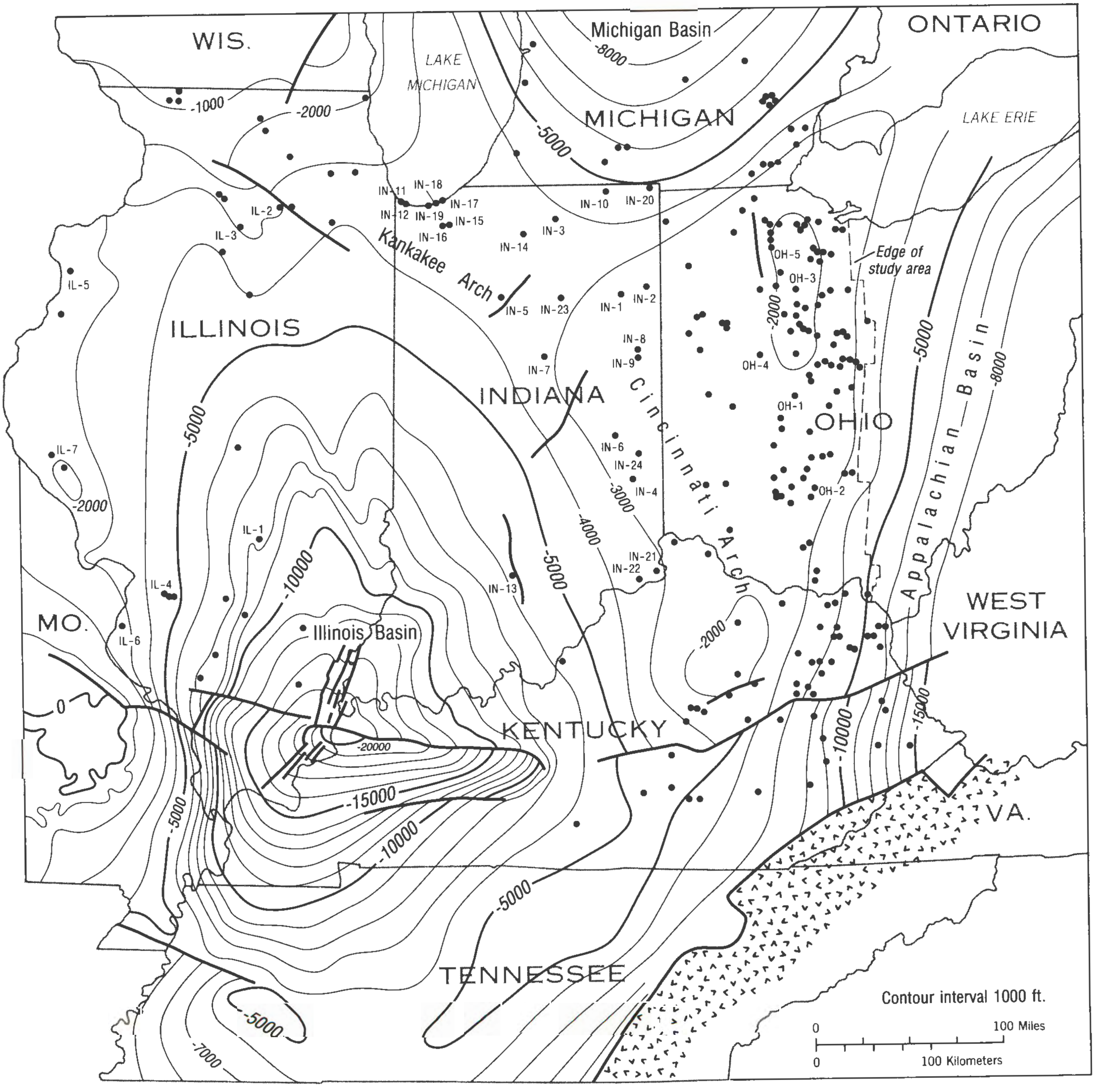


Figure 1. Map of the Midwest showing the locations of basement tests, regional basin and arch systems, and structure on top of the Precambrian basement complex in feet below sea level. Pattern indicates the deformed rocks of the Valley and Ridge Province. Precambrian rocks are exposed in the St. Francis Mountains of Missouri. Numbered wells are listed in Tables 1 and 3. Modified from Buschbach, 1984.

EXPLORATION POTENTIAL

The deeper pre-Silurian sediments, which represent about half of the total volume of sediments in the state, are relatively untested. In particular, the Cambro-Ordovician sequence is considered a valid target for oil exploration (Bond and others, 1971). In Indiana the top of the Knox Supergroup (Cambro-Ordovician) ranges in depth from 1,000 feet (300 m) along the Cincinnati Arch to 8,000 feet (2,400 m) in the southwestern part of the state. Oil was found in the top of the Knox in Jay County as early as 1904. Oil has also been discovered in the rocks of Cambrian age in Ohio (Calvert, 1964). There has

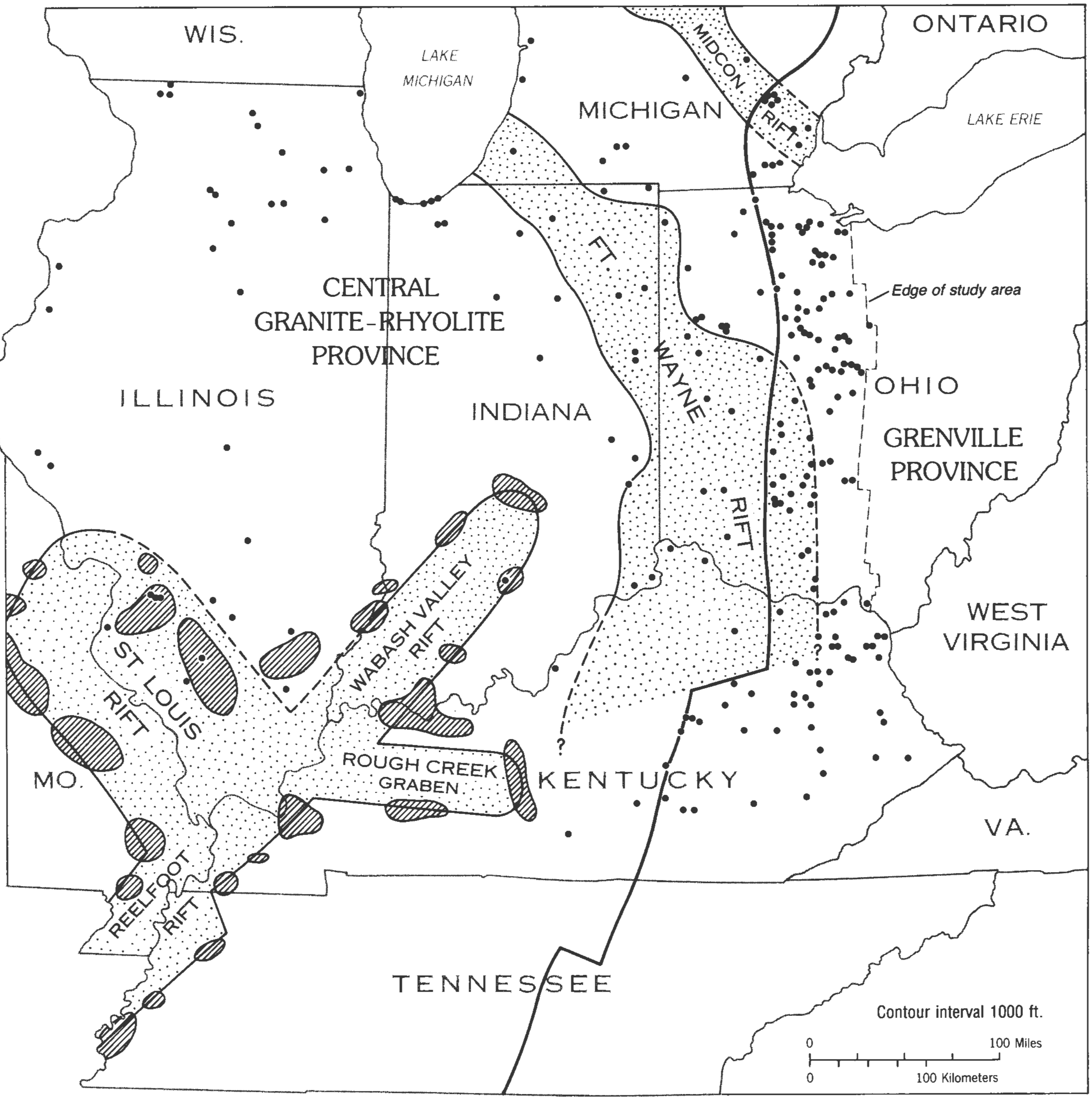


Figure 2. Map of the Midwest showing the locations of basement tests and interpreted provinces based on lithology. Modified from Braile and others, 1982; Denison and others, 1984; and Lucius and Von Frese, 1988.

been successful exploration of the lower part of the Ordovician in southern Kentucky (Carpenter and others, 1983). In Indiana exploration for Cambrian oil has been slowed by the greater depths that must be drilled. For example, the Mount Simon Sandstone ranges in depth from 2,500 feet (750 m) on the Cincinnati Arch to about 9,000 feet (2,700 m) along the western margin of the state.

Geophysical prospecting is an economically feasible approach toward a successful exploration program of deep strata. Because structures and sedimentation patterns in the lower Paleozoic portion of the section may be controlled by topography and (or) structure on the Precambrian surface (Rudman and Blakely, 1965; Hamburger and Rupp, 1988; Nelson, 1990), geophysical mapping of the basement surface is an essential step in exploring for deep oil and gas reservoirs in Indiana. It is hoped that the parameters summarized in this study will facilitate such mapping.

PHYSICAL PROPERTIES

Geophysical studies of the basement complex of Indiana have been based primarily on data from seismic, gravity, and magnetic surveys, although some efforts have been directed toward magnetotelluric investigation (Renick, 1969) and earthquake seismogram analyses (Sexton and others, 1977). The successful interpretation of geophysical data depends partly on previous knowledge of the physical properties of the basement rocks, especially density, magnetic susceptibility, seismic velocity, and electrical resistivity. Lidiak and others (1985) found poor correlation between basement lithology and both gravity and magnetic maps. Among the causes that they list is "lack of definitive geophysical properties." If such knowledge is lacking, geophysical interpretation is weakened by the use of assumed approximate values for these physical properties. Some density and magnetic-susceptibility measurements of the basement rocks have been reported for the Midwest by Rudman and Blakely (1965), Lucius and Von Frese (1988), and Dutch and others (in preparation). The physical properties discussed in this report include data from the basement rocks encountered in 24 test wells in Indiana. Additionally, the geophysical logs from seven wells in Illinois and five wells in Ohio (table 3) were examined for resistivity and seismic-velocity characterization. The well data are presented in tables 1, 2, and 3. The values used in figure 3 for the recognized lithologic types are weight averaged on the basis of the footage of basement rock penetrated by each borehole.

As with many geologic investigations of this kind, it is recognized that much, if not all, of the data presented in this report may not be totally accurate in terms of absolute values. The significant differences in the conditions between the physical environment of the subsurface and the laboratory present a series of problems. The most notable of these parameters that differ are pressure, temperature, and fluid saturation. The changes in the petrophysical character of the samples when moved from the deep subsurface environment to the laboratory are significant but probably consistent, so that the relative values of the physical properties measured are preserved. In situ measurements by means of downhole logging present similar measurement problems ranging from changes in the rock column influenced by drilling to difficulties in the actual measurement in the borehole by the logging tool. Despite these difficulties, the values reported here should be sufficiently accurate to interpret gravity, magnetic, and seismic data obtained in surface surveys.

DENSITY

The statewide gravity map of Indiana (Mead and others, 1953) is useful for delineating the major lithologic trends within the basement complex. Detailed studies of basement depths, lithology, and structure, on the other hand, depend on analysis of more localized gravity anomalies, that is, areas of intense gravity gradients. Most prominent gravity anomalies in Indiana are interpreted as resulting from the density contrast between basic rock intruded into granitic country rock (Lidiak and others, 1985; Hinze and Braile, 1988). Quantitative interpretation depends on the estimation of a reasonable density contrast for each locale.

The specific gravity of 18 samples of the basement rock (table 2) were measured with a Jolly balance using distilled water at 70°F. Although the measurements with a Jolly balance yield dimensionless values of specific gravity, by convention the data are presented as density (gm/cm^3). Precision is excellent for large chips or core samples (standard deviation less than 0.01 gm/cm^3) but can be poor (s.d. 0.3 gm/cm^3) for badly crushed samples. Five of the samples had grain sizes too small to permit meaningful measurements. In samples from wells in Indiana densities of basement rocks (fig. 3a) are from 2.57 to 2.81 gm/cm^3 for granites (average = 2.65), 2.81 gm/cm^3 for gneiss, 2.70 to 2.90 gm/cm^3 for andesites (average = 2.79), 2.86 gm/cm^3 for basalt, 3.0 gm/cm^3 for gabbro, and 2.53 to 2.69 gm/cm^3 for arenite (average = 2.64). Accordingly, basic rock (basalt or gabbro) intruded into granitic country rock could yield a density contrast from 0.05 to 0.43 gm/cm^3. On the basis of an average granite density of 2.65 gm/cm^3, the contrast with basalt or gabbro would be 0.21 to 0.35 gm/cm^3. The depths to the basement calculated from gravity anomalies based on an expected density contrast between basalt and granite of 0.2 gm/cm^3 have yielded values that are consistent with seismic surveys and nearby well data. The contrast among various types of basement rock in Indiana is shown in figure 3a.

Measurements of density were also obtained for samples from the lower 200 feet (60 m) of the Mount Simon Sandstone. Eleven samples from five wells in Indiana yielded an average density of 2.50 gm/cm^3 for Mount Simon rocks. Assuming an average density of 2.6 to 2.7 gm/cm^3 for the granitic basement, we can expect a density contrast of approximately 0.1 to 0.2 gm/cm^3.

Some geophysical logs can also yield bulk-density values after appropriate borehole rugosity and mudcake corrections have been applied. For example, the corrected gamma-gamma log (density log) in the Bethlehem WD-1 well in Porter County (No. 17, table 1) shows an average value of approximately 2.4 gm/cm^3 for the lower part of the Mount Simon and approximately 2.6 gm/cm^3 for the granitic basement. Although these measured values may not be absolutely

Table 2. Geophysical properties of the basement rocks from wells drilled in Indiana

No.	Density of basement rocks (gm/cm^3)		Magnetic susceptibility of basement rocks (emu)		Seismic velocities: Lower 100 feet of sedimentary sequence		Seismic velocities: Basement rocks		
	Mean	s.d.	Mean	s.d.	Interval (ft.)	Average velocity (ft./sec.)	Interval (ft.)	Average Velocity (ft./sec.)	Average resistivity of basement rocks (ohm-meters)
1	2.90 a, b	0.3	0.0072	0.0011					150
2	2.77 c		0.000083	0.000015	3,385-3,484	14,485	3,485-3,658	15,136	50
3	2.70 d	0.030	0.00034	0.00033					15
4	2.69	0.09	0.00029	0.00025	3,818-3,914	13,954	3,914-3,950	14,833	15
5	2.62 c	0.012	0.00014						700
6	e		0.00016						
7	2.81	0.05	0.00030	0.00012					
8	e		0.00038	0.00071					
9	e		0.00016						
10	3.0	0.11	0.010	0.00044	4,570-4,670	15,385	4,680-4,725	18,868	1,000
11	2.65		0.000056	0.000023	4,236-4,332	11,997	4,332-4,358	14,113	125
12	No samples or core								500
13	2.86 c	0.06	0.00130	0.00012	6,544-6,640	14,928	6,640-6,780	16,320	50
14	2.81 c		0.00054	0.00085	3,798-3,900	12,977	3,900-4,068	15,544	50
15	e		0.00015	0.000012					
16	2.57 a, b		0.00051						7
17	2.68 c	0.005	0.00064		4,150-4,248	13,070	4,248-4,290	17,964	600
18	2.59	0.028	0.000081	0.000040					
19	2.64 c	0.006	0.000034		4,150-4,250	13,212	4,250-4,294	17,544	150
20	2.65 b, d	0.37	0.00014	0.00012	4,815-4,914	14,706	4,915-6,832	18,518	800
21	2.53 c	0.01	0.00024	0.00023					15
22	2.67 d	0.12	0.00018	0.000082	3,940-4,039	13,889	4,040-4,125	14,925	15
23	2.72 c	0.008	0.00095	0.00016	3,556-3,654	13,707	3,654-3,680	15,526	35
24	e		0.00026	0.000088					

a - some bit contamination
b - some lithic contamination
c - core sample
d - additionally computed from density logs
e - cuttings too fine grained for analysis
s.d. - standard deviation

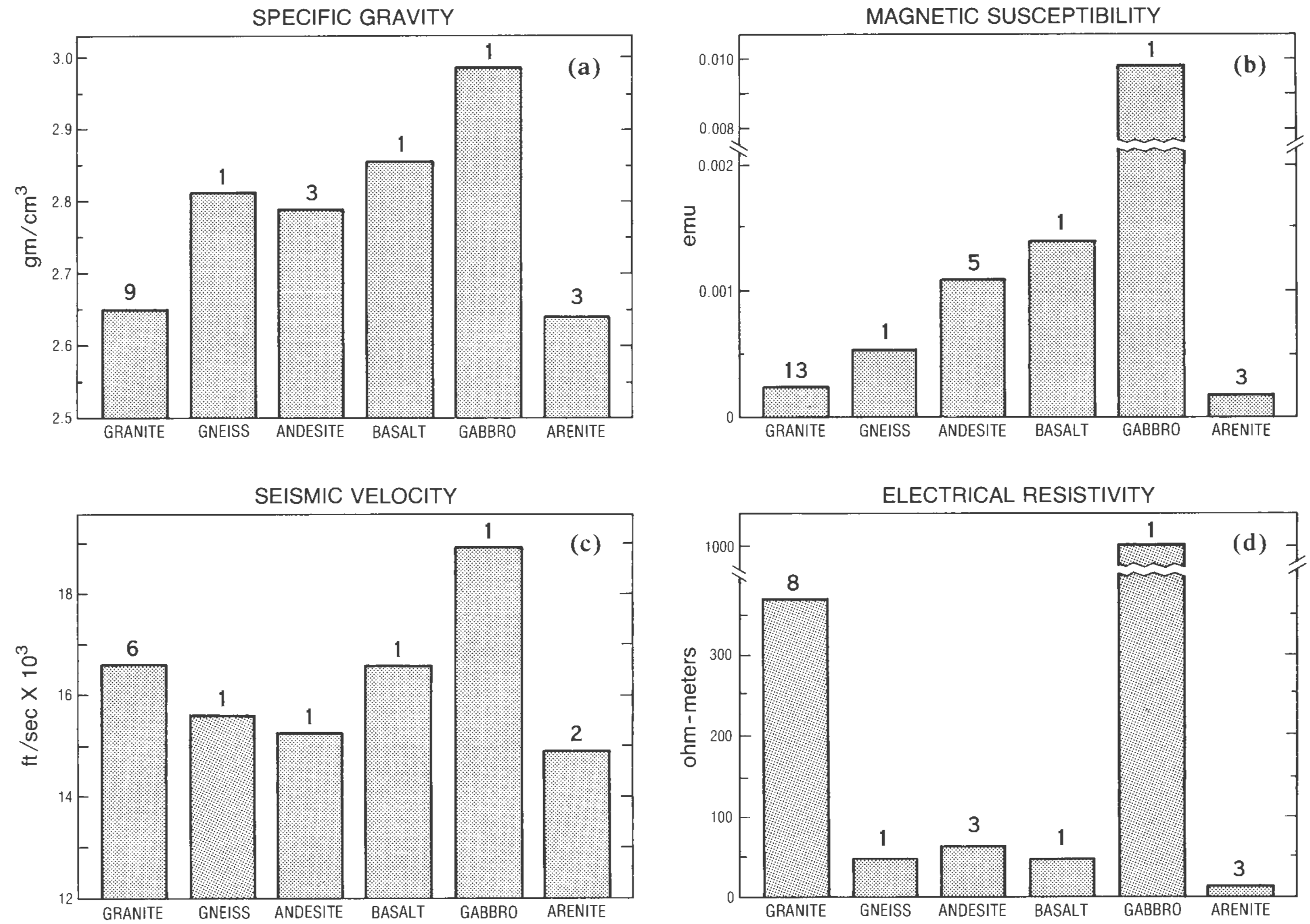


Figure 3. Graphs of weight-averaged values for the four physical properties of basement rocks of Indiana investigated. The number over each bar indicates the number of samples (wells) in each lithology.

precise, the contrast of 0.2 gm/cm^3 is thought to be representative of the true in situ value.

MAGNETIC SUSCEPTIBILITY

Previous investigations of magnetic anomalies have been interpreted to indicate lithologic contrasts within the basement, although such interpretation also depends on some prior assumptions of magnetic susceptibility for expected rock types. The magnetic susceptibility of chip samples was measured with a susceptibility bridge in a magnetic field of the same order of magnitude as the earth's field. The results for 13 basement wells in Indiana that encountered rocks of the Central Granite-Rhyolite Province show that the mean susceptibility of the granitic rock is low, generally less than 0.001 emu (table 2; fig. 3b). Measurements in Illinois and Ohio (Rudman and Blakely, 1965) similarly show low susceptibility for the granitic rocks. The values are 0.000034 to 0.00095 emu for granites (average = 0.00026), 0.00054 emu for gneiss, 0.000083 to 0.0072 emu for andesites (average = 0.0011), 0.0013 emu for basalt, 0.010 emu for gabbro, and 0.00018 to 0.00029 emu for arenites (average = 0.00024). The average values for the different lithologies are compared in the bar graph shown in figure 3b. The granite from the test well in Steuben County (No. 20, table 2) shows an anomalously high magnetic susceptibility (0.0014 emu), which may be an artifact caused by magnetic induction and (or) contamination while drilling. Gabbro in the Lagrange County well (No. 10, table 2), however, has a substantially higher magnetic susceptibility (0.010 emu) than any other basement rock tested in Indiana. The intrusion of similar basic rocks into a granitic country rock may typify the geologic situation for many magnetic anomalies in Indiana.

In certain areas the strength and direction of remanent magnetization can also be important in interpreting magnetic surveys. Some preliminary measurements of remanent magnetization on file at the Indiana Geological Survey were made on selected samples by using a spinner magnetometer. The

Table 3. Geophysical logs for selected Illinois and Ohio wells

State	No.	Operator and well name	County	Basement rock type[a]	Geophysical logs[b]
Illinois	1	Humble No. 1 Weaver-Horn	Fayette	Granite	G E N S
Illinois	2	Lawinger No. 1 Miller	LaSalle	Granite	G E N
Illinois	3	Vickery No. 1 Mathesius	LaSalle	Granite	G E N
Illinois	4	Maryland No. S-1 Kircheis	Madison	Granite	G E N S
Illinois	5	Kelley No. 1 Fullerton	Mercer	Granite	E
Illinois	6	Miss. No. A15 Theobold	Monroe	Granite	G E N
Illinois	7	Hendron No. 1 Campbell	Pike	Granite	E
Ohio	1	Edmund No. 1 Brown	Clark	Gabbro	E S
Ohio	2	Kewanee No. 1 Hopkins	Fayette	Gneiss	G E N
Ohio	3	Edmund No. 1 Jones	Hardin		E S
Ohio	4	Ohio oil No. 1 Jones	Logan	Rhyolite	E
Ohio	5	O'Neill, Jr. No. 1 Peek	Wood	Gneiss	G E N

[a]Basement rock types for Illinois are from Sargent and Buschbach (1985).
Basement rock types for Ohio are from Lucius and Von Frese (1988).

[b]G - gamma-ray
E - electric
N - neutron
D - density
S - sonic

results indicate that the remanence has not influenced overall magnetic-susceptibility measurements on the basement samples. Moreover, the fact that reasonable depths to the basement have been calculated without compensating for remanent magnetization indicates that remanence may not be a significant factor in Indiana. Problems resulting from induction of magnetism as an artifact of the drilling or coring process do not appear to be a factor in the Indiana basement samples.

SEISMIC VELOCITY

The seismic-reflection method is currently the most useful tool for studying the structural or topographic configuration of the basement surface in Indiana. Within certain practical limits, seismic data can yield the depth to reflecting horizons with some certainty. This is in marked contrast to potential-field interpretations, which can never be considered to have a unique geologic solution. But calculations of seismic depth depend in part on how closely the average vertical velocity from a datum to the desired horizon can be estimated. Fortunately, continuous-velocity (sonic or acoustic) logging now enables the geophysicist to compute reliable velocities.

There are 11 basement tests in Indiana with available continuous-velocity logs. The velocities from these wells are summarized in table 2. Interval transit times for the basement rocks and the overlying sediments were read directly from the log at 2-foot intervals and then averaged. Seismic interval velocities showed a wide range (14,113 to 18,518 ft/sec) for granites. The gabbro sample showed the highest velocity (18,868 ft/sec) and an arenite showed one of the lowest velocities (14,925 ft/sec). Average seismic velocities for the different lithologies are shown in figure 3c.

The average vertical velocities of the basal 100 feet (30 m) of sedimentary section on top of the basement were also determined. The velocities for the overlying sedimentary rocks ranged from approximately 12,977 to 15,385 ft/sec although one well (IN-11) showed an anomalously low velocity of 11,997 ft/sec. These variations were due primarily to the thinning and thickening of major lithologic units overlying the basement and to lateral changes in the porosity and permeability that affect the acoustic properties of the strata.

The velocity data can also be used to determine theoretically if the basement surface is a reflecting horizon. Reflections can be expected only if a significant acoustic-impedance

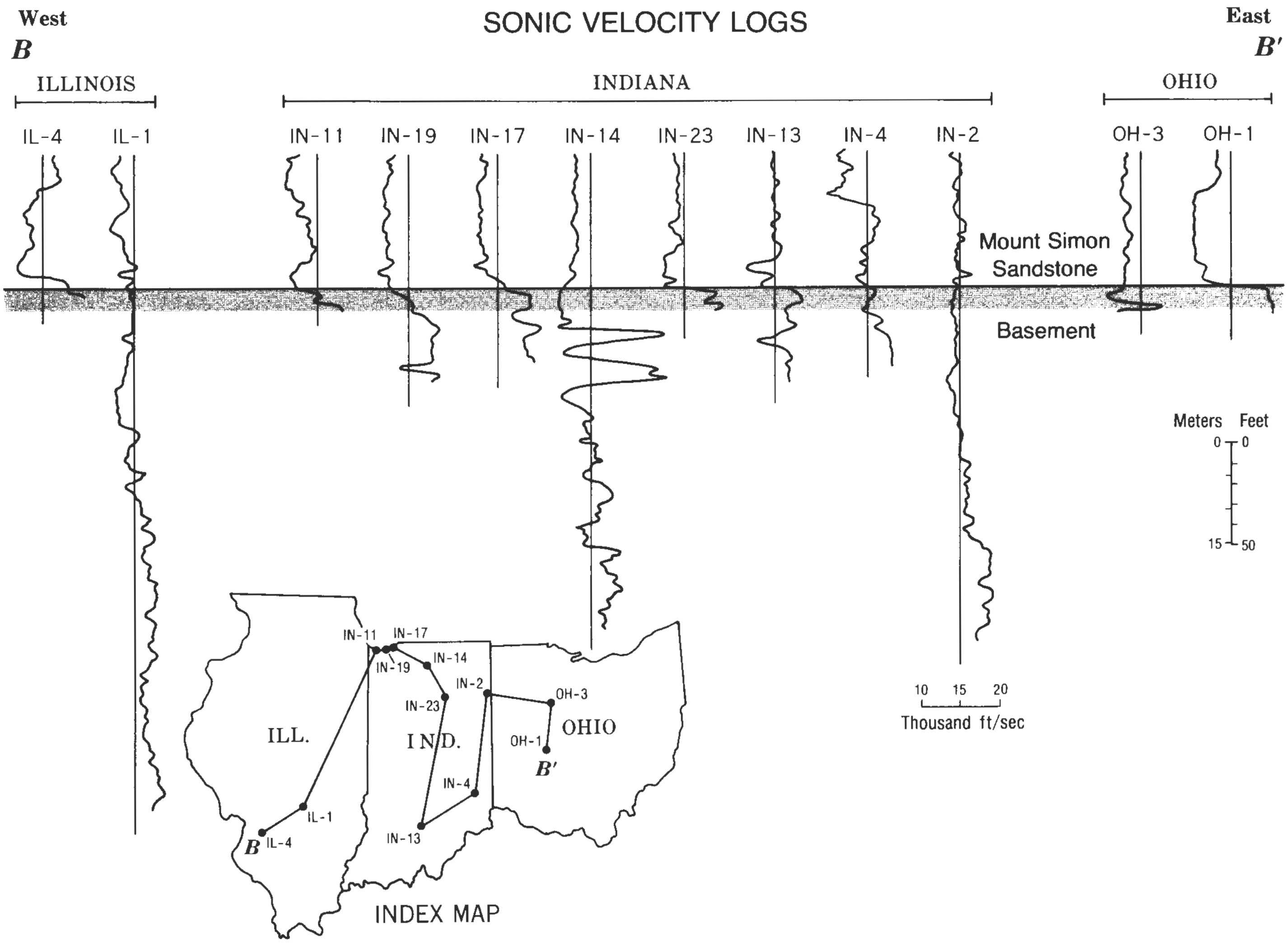


Figure 4. Cross-section of continuous velocity (sonic) logs demonstrating the contrast in acoustic velocity across the Precambrian basement-Phanerozoic boundary. Datum is the top of the Precambrian basement complex.

contrast exists between the basal Mount Simon Sandstone and the basement rocks. The velocity contrasts between the granites and andesites and the overlying sedimentary rocks ranged from 1,400 to 4,900 ft/sec. The velocity contrast in one well (IN-2) was as low as 650 ft/sec. The contrasts between the mafic rocks and the overlying sediments were much higher (1,800 to 3,500 ft/sec), and the contrasts with the arenites were lower (879 to 1,817 ft/sec). Very few continuous-velocity logs span the Mount Simon Sandstone-basement contact in Indiana, but most available logs exhibit a marked velocity contrast near the contact (fig. 4). For comparison, figure 4 includes a few logs known to penetrate the basement granite in Illinois and Ohio. (See also table 3.)

Most of the continuous-velocity logs exhibit a distinct decrease in velocity within 50 feet (15 m) of the basement contact. This decrease is attributed to a marked increase in the porosity in the basal sandstone near the contact (fig. 4). This decrease in velocity contrasts strongly with the observed marked velocity increase beginning in the top of the basement rocks. Some exceptions include the Allen County, Indiana well (IN-2) and the Fayette County, Illinois well (IL-1), both of which show little change at the contact but a moderate, gradual increase in velocity beginning approximately 100 feet (30 m) below the basement surface. Some of the wells (IN-17 and OH-1) show a localized increase in velocity above the contact. These variations may be attributed to increased feldspar cementation in the basal part of the Mount Simon Sandstone (Kersting, 1982) and adularia in the top of the basement complex (Hoholick and others, 1984; Lidiak and Ceci, 1988).

Interval velocities for the basement rocks of Indiana range from as low as 14,113 ft/sec for a granite in Lake County (IN-11) to 18,868 ft/sec for the gabbro in Lagrange County (IN-10). Some of the velocities listed in table 2 were substantiated by using basement cores in laboratory measurements of bar velocities.

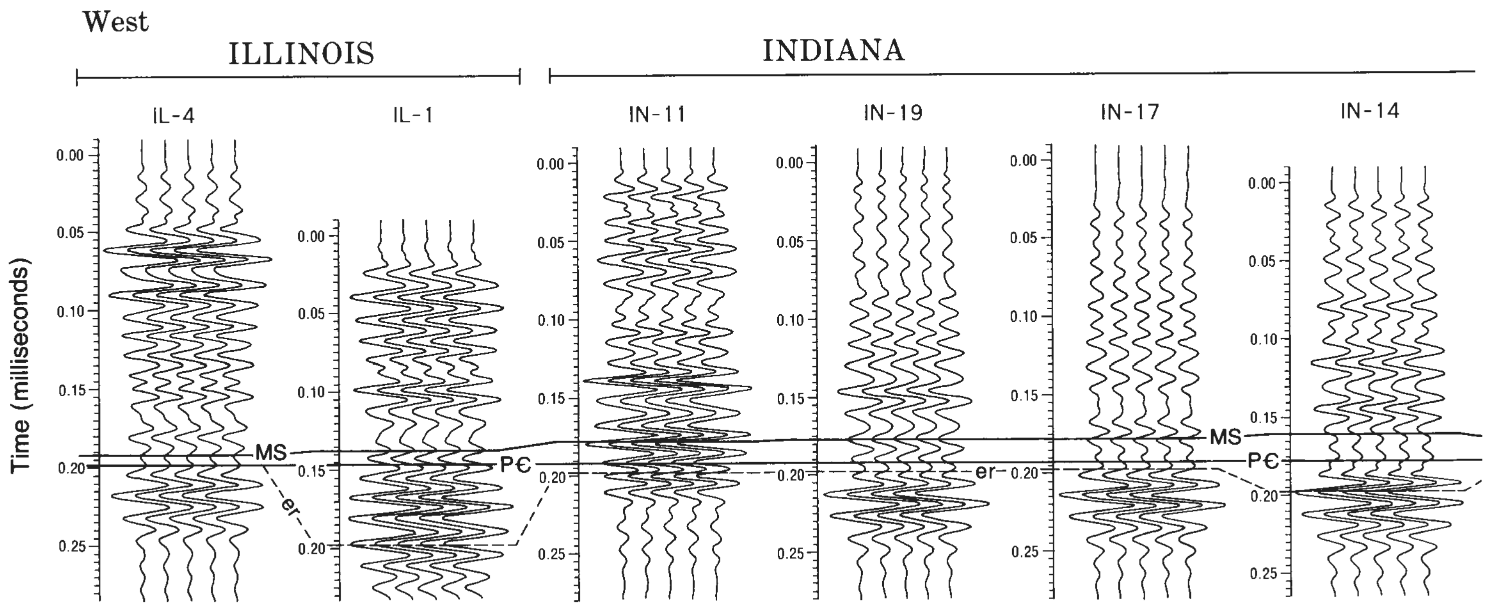
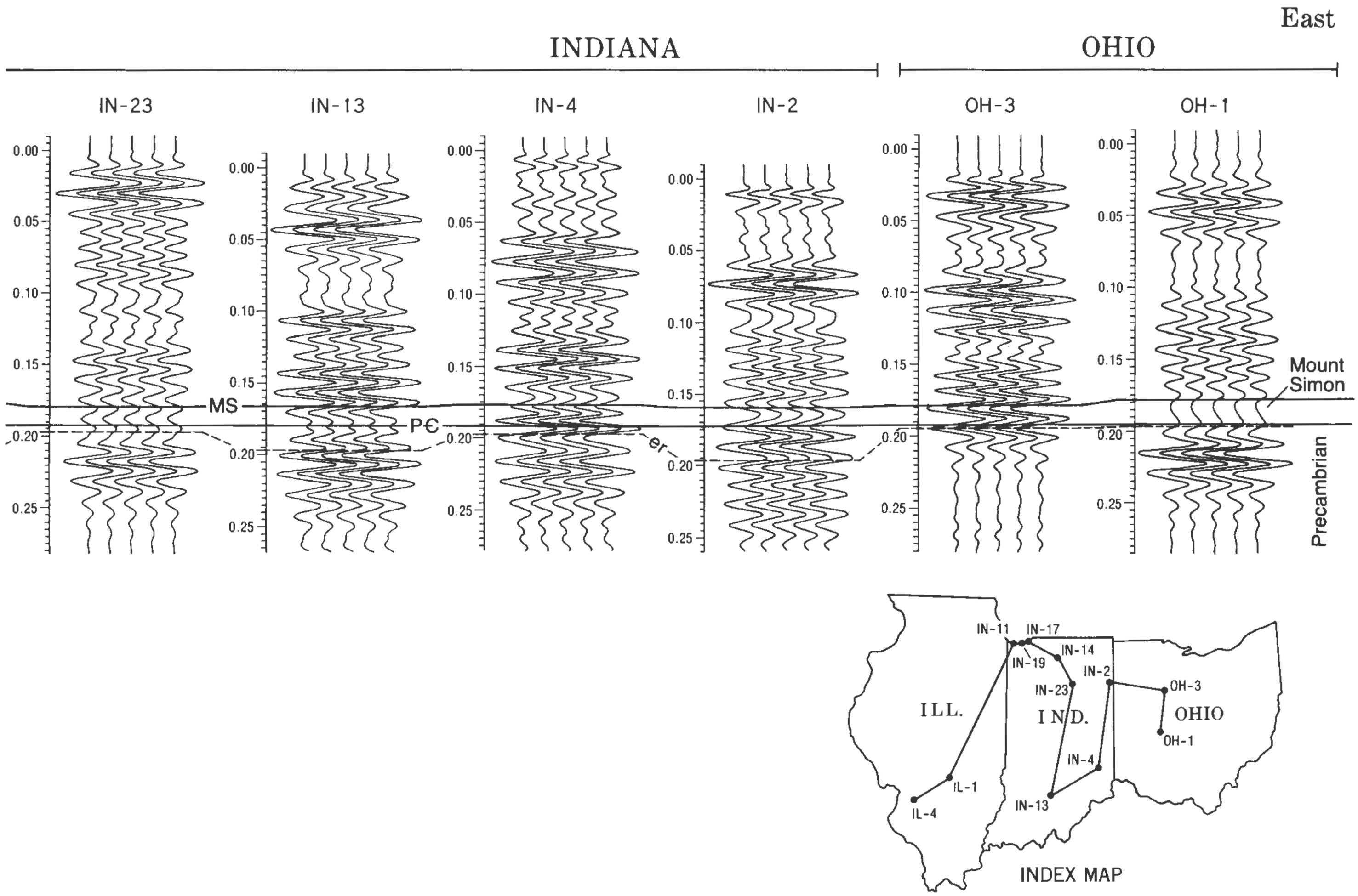


Figure 5. Cross-section composed of synthetic seismograms generated from sonic logs (see fig. 4) showing reflections at the Precambrian basement-Phanerozoic boundary. MS identifies the time equivalence of 100 feet above the Mount Simon-Precambrian contact, PC identifies the top of the Precambrian, and er identifies the end of the continuous velocity log data. Reflections below er may not be significant. Seismograms include multiples and are band-

An interpretation of seismic data can be facilitated by using velocity data to construct theoretical (synthetic) seismograms (fig. 5) and then comparing reflections on the synthetic record with those observed on seismic-reflection data. Such considerations led Biggs and others (1960) to demonstrate that the contact of sedimentary rocks and basalt in Lawrence County yields an observable reflection. Calculated reflection coefficients demonstrate that the contact of the Mount Simon Sandstone and the granite can be a strong reflecting horizon (for example, IN-23). Although the contact is clearly evident on some velocity logs and synthetic seismograms (for example, IN-17), a distinct contrast is absent on others (for example, IN-2). Although the marked velocity contrast between the dense granite and the overlying porous sandstone readily explains the prominent reflections produced on the synthetic seismograms, subdued reflections on other seismograms are more difficult to explain. Although some studies (Sexton and others, 1986; Kaufman and others, 1988; Pratt and others, 1989) have interpreted the position of the crystalline basement by using seismic-reflection data in the Illinois Basin, much ambiguity about the actual position of the basement is primarily due to the lack of data from drill holes and continuous-velocity logs. The relation between the crystalline basement and the potential overlying late Precambrian or Early Cambrian in proposed structural basins or rifts of Keweenawan age (southwestern and southeastern Indiana and northwestern Ohio) remains enigmatic.

Synthetic seismograms were constructed for some of the wells in Indiana that have velocity logs and for selected wells in Illinois and Ohio (fig. 5). The seismograms were generated by a computer using a Fortran program, VISP (Frazer and others, 1985). Only the lower portions of the seismograms are displayed here, as the essential purpose is to test whether the basement is a mappable horizon in this area. The seismograms from wells IL-1, IL-4, IN-2, IN-13, IN-14, IN-17, IN-19, IN-23, and OH-1 display recognizable basement reflections at approximately the position of the basement complex. A comparison of the seismograms and their cor-



passed filtered for 60-80 Hz with 72 db/octave. Records from wells IN-2, IN-4, IN-13, and IN-23 are enhanced with a simulated automatic gain control. Datum is the Precambrian surface PC. Records are truncated approximately 0.20 sec. above the basement to show only the significant portion of the log.

responding velocity logs (figs. 4 and 5) is consistent, and the velocity contrasts can therefore be approximately correlated to the reflections.

The seismograms from IN-4, IN-11, IN-13, and OH-3 show reflections from above the basement contact and probably result from combinations of the velocity contrasts. The reflections from near the basement for the Lawrence County well (IN-13) were studied in detail and were shown to originate from a sequence of slightly metamorphosed sedimentary rocks lying above the basement complex and from the basalt (Biggs and others, 1960). Unusually dense, well-cemented intervals in the basal portion of the Mount Simon probably account for some of these distinct velocity contrasts.

ELECTRICAL RESISTIVITY

The electrical resistivities of rocks vary enormously. This variance depends not only on the mineral content and structure of the pore system but also more importantly on the salinity of the contained water. The resistivity for anisotropic rocks (stratified or schistose) can vary according to the direction of measurement and the complexity of the sedimentary structures or the microfabric of the pore system. The utility of tabulating absolute values of resistivity has therefore been questioned for some time, because these data are not essential (invariable) rock properties. Nevertheless, even an approximate resistivity can be useful in interpreting magnetotelluric measurements and in making stratigraphic correlations.

From the foregoing discussion one can conclude that it is meaningful to speak of the order of magnitude of resistivity only for a particular rock, and, wherever possible, these data should be obtained from a measurement in situ. A conventional electric log yields resistivity values that are an average of the mud column, the mud cake, the invaded zone, and several feet of rock surrounding the sonde system. Electrical tools with a large depth of investigation, such as a 64-inch normal and an 18-foot and 8-inch lateral induction log, can record the true formation resistivity, provided the values are

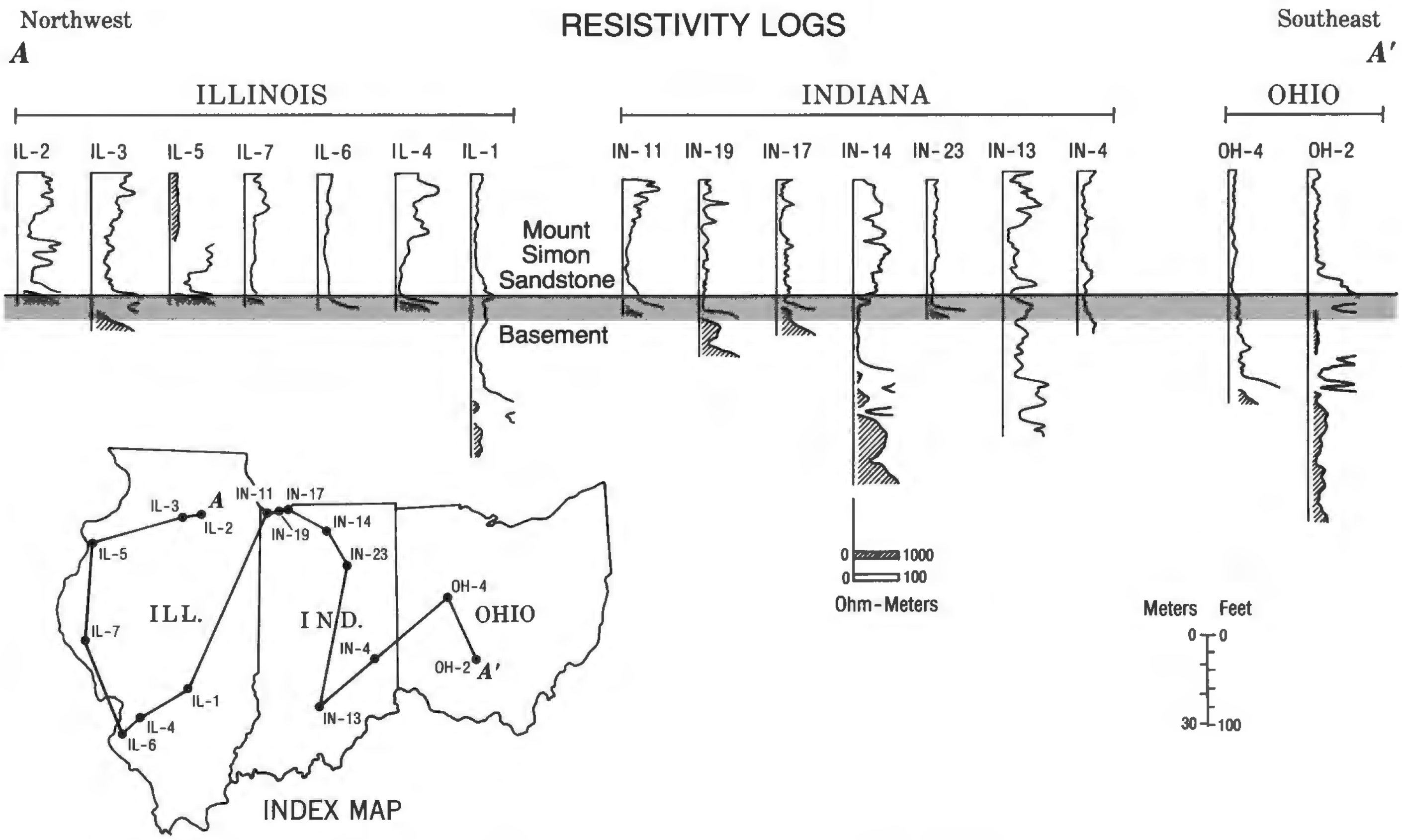


Figure 6. Cross-section of resistivity logs showing the various degrees of contrast at the Precambrian basement-Phanerozoic interface. Datum is the top of the Precambrian basement complex.

between 2 and 40,000 ohm-meters (Schlumberger, 1987, p. 76).

The variations in the electrical resistivity of rocks as recorded in boreholes have long been used in correlating strata from one area to another. Control was established for this study by using primarily 16- and 64-inch normal resistivity data. Although there is a large amount of variability in the resistivities of the different basement lithologies, there is generally a sharp contrast with the resistivities of the overlying porous sandstones of the Mount Simon Sandstone. A fivefold to tenfold increase in resistivity marks the top of the basement in most wells (fig. 6), and therefore this contact is an easily recognized marker that can be used effectively in correlation.

Some wells do not display an increase in resistivity at the contact of the Mount Simon and the basement. Wells IL-1, IN-14, and OH-4 show an increase approximately 50 to 100 feet (15 to 30 m) below the contact. This observation may be related to altered zones in the basement. Other wells (IN-4 and IN-13) show no obvious increase in resistivity across the contact. Both of these wells differ, however, from other basement-rock types at the contact. IN-4 is an extremely weathered lithic arenite and IN-13 is a sequence of metamorphosed sediments overlying basalt (table 1).

The ranges of measured resistivities for intervals penetrating the basement complex in Indiana are shown in table 2. The resistivities range from 7 ohm-meters for a granite to 1,000 ohm-meters for a gabbro. The average values for the different lithologies are graphed comparatively in figure 3d. The resistivities in the Mount Simon are extremely variable and range from more than 1 ohm-meter to more than 200 ohm-meters.

CONCLUSIONS

A knowledge of the physical properties of the basement rocks in Indiana is essentially limited to data obtained from geophysical logs and a limited number of sample sets and cores. Unfortunately, most of the well data are from the shallower areas concentrated along the Cincinnati Arch. Despite this selective sampling, some general observations can be made:

1. The density of the granitic basement is approximately 2.6 to 2.7 gm/cm^3. Therefore a contrast of 0.1 to 0.2 gm/cm^3 exists between the Mount Simon Sandstone and the basement. Similarly, a contrast of 0.2 gm/cm^3 can be expected between the granitic country rock and the anomalous areas of basalts.

Depending on the depth and size of the anomalous area, gravimetric methods can detect such variations.

2. The magnetic susceptibility of the rocks that make up the basement complex ranges from a low of 0.000034 emu for a granite to 0.010 emu for a gabbro. Magnetic surveys are best suited for differentiating contrasts in rock types.

3. Seismic velocities generally increase at or near the contact between the basement and the Mount Simon Sandstone. Many of these velocity contrasts ranging from 1,500 to 3,500 ft/sec generate basement reflections of sufficient amplitude to be mapped seismically. But there are sufficient velocity variations within the lower Mount Simon and within the basement to cause some variability in the arrival times of the reflections and the possibility for misidentification of basement reflectors. The altered zones within the basement and the overlying siliciclastic section may be the cause of some of these problems.

4. Electrical resistivity increases at the Mount Simon-basement contact. Although this increase (generally on the order of 100 to 300 ohm-meters) is obscured in some places by an altered zone near the top of the basement, the observed resistivity contrast is present in most wells.

Future studies of geophysical logs and samples from the basement are needed to establish predictable lithologic and structural patterns. Given sufficient data, it may be possible to show that the zones of weathered basement are concentrated in certain geographic areas relative to the basins and arches. Although the granitic rock of the basement complex has displayed consistent physical properties throughout the study area, additional data will possibly demonstrate that the granitic terrane may not be as consistent. New data from wells and surface geophysical surveys are needed before distribution patterns of rock types in the basement can be effectively interpolated throughout the state.

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