Geology, Geochemistry, and Tectonostratigraphic Relations of the Crystalline Basement Beneath the Coastal Plain of New Jersey and Contiguous Areas

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Geology, Geochemistry, and Tectonostratigraphic Relations of the Crystalline Basement Beneath the Coastal Plain of New Jersey and Contiguous Areas

By Richard A. Volkert, Avery Ala Drake, Jr., and Peter J. Sugarman

GEOLOGIC STUDIES IN NEW JERSEY AND EASTERN PENNSYLVANIA

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1565–B

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New Jersey Geological Survey

Pre-Mesozoic metasedimentary and metaigneous rocks beneath the New Jersey Coastal Plain resemble those of tectonostratigraphic terranes in both the central and northern Appalachians

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METRIC CONVERSION FACTORS

Multiply	By	To obtain
inch (in)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer

Geology, Geochemistry, and Tectonostratigraphic Relations of the Crystalline Basement Beneath the Coastal Plain of New Jersey and Contiguous Areas

By Richard A. Volkert,[1] Avery Ala Drake, Jr.,[2] and Peter J. Sugarman[1]

ABSTRACT

Cretaceous and Cenozoic sediments of the New Jersey Coastal Plain are underlain by basement rocks that may range in age from Middle Proterozoic to Mesozoic. Buried pre-Mesozoic crystalline rocks in New Jersey are important because they link rocks of the central and northern Appalachians. The peak metamorphic grade recorded in aluminous rocks from beneath the Coastal Plain is in the amphibolite facies.

The inner Coastal Plain is underlain dominantly by pelitic and psammitic schist and minor amounts of mafic rock that are correlative with the Potomac terrane in Maryland, Delaware, Pennsylvania, and Virginia. Gravity and magnetic highs within this part of the Coastal Plain probably result from mafic rock in a rootless pluton or a thrust slice. The alignment of these inferred mafic rocks along the same structural trend suggests that they may be related. These bodies may be equivalent to rocks in the Wilmington terrane in Delaware or the Bel Air-Rising Sun terrane in Maryland. Wells drilled in the northern and central outer Coastal Plain returned graphitic, two-mica schist and marble along a trend that is coextensive with the Brompton-Cameron terrane in southern Connecticut. The southern Coastal Plain may be underlain by rocks equivalent to the Chopawamsic terrane (James Run Formation) and to the south, rocks of the Roanoke Rapids terrane (Eastern slate belt). Although drill-hole data are sparse in this part of New Jersey, wells to the west in northern Delaware penetrated chlorite schist, biotite schist, and quartzite. Pyroxenite from this part of the Delaware Coastal Plain may be correlative with the Bel Air-Rising Sun terrane, or more likely it is a separate fragment of ultramafic rock correlative with the Roanoke Rapids terrane (Eastern slate belt). Metagabbro from the southernmost part of New Jersey may be coextensive with gabbro and associated greenschist-facies rocks in the Chesapeake block (Eastern slate belt). Gravity and magnetic data suggest the possible presence of small rift basins of early Mesozoic age beneath the southern Coastal Plain, but thus far no wells have drilled rock identified as Mesozoic. Most central and some northern Appalachian terranes appear to be present beneath the New Jersey Coastal Plain.

INTRODUCTION

Cretaceous and Cenozoic sediments of the New Jersey Coastal Plain are underlain by crystalline rocks of Middle Proterozoic to Paleozoic age and sedimentary and igneous rocks of Mesozoic age. These form a basement complex, which remains poorly understood because of limited direct sampling. In general, wells penetrating basement were drilled for water, for petroleum exploration, or as stratigraphic tests for Coastal Plain sediments, and the retrieval and study of basement rock were considered unimportant.

Recently, the geology of the subsurface crystalline rocks has come under increased study because the rocks were identified as possible repositories for high-level radioactive waste (Bredehoeft and Maini, 1981). Lloyd and others (1985) summarized and evaluated data pertaining to the ground-water hydrology of the Coastal Plain sediments and their relation to possible waste disposal in the subsurface basement. They identified a zone worthy of further study at a depth of 1,000 to about 4,000 ft below sea level in the crystalline basement of New Jersey and other States.

In separate areas of research, hypotheses concerning the tectonics of the Appalachian orogen (for example, Cook and others, 1979) benefit from expanded knowledge of the crystalline basement complex beneath the Atlantic Coastal Plain. New Jersey is important in this regard because it occupies a critical position linking the central and northern Appalachians. Additionally, the identification of onshore and offshore buried rift basins of early(?) Mesozoic age has taken on importance, both economically in the search for oil and gas reserves and scientifically in providing data on the opening of the Atlantic Ocean.

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This study presents available geologic information on the buried basement, primarily in New Jersey. Descriptions of the crystalline rocks are both those of previous workers and new descriptions of core and cutting samples collected during this study. A tentative correlation of basement terranes is presented based on geologic information and gravity and magnetic data. The information presented here should be useful to geologists, hydrogeologists, geophysicists, and others interested in the pre-Cretaceous subsurface basement in this part of the northern central Appalachians.

ACKNOWLEDGMENTS

We are grateful to R.N. Benson, who made the samples of basement rocks from Delaware available for inspection and provided a list of the Delaware wells. D. Smolensky provided a list of the Long Island wells, and J. Sorel loaned the sample from the Brooklyn Union Gas Company well. M.E. Wagner generously shared unpublished geochemical analyses from Delaware and Pennsylvania with Volkert. L. Jacoby digitally plotted all of the well points on a preliminary version of figure 10, and L. Allar and D. Hogan typed the appendix. Volkert and Sugarman appreciate conversations with R.E. Sheridan on the geophysics of the Piedmont. This report benefited from reviews by D.L. Daniels, W.C. Burton, I.G. Grossman, and numerous staff members of the New Jersey Geological Survey.

REGIONAL GEOLOGY

NEW JERSEY COASTAL PLAIN SEDIMENTS

The New Jersey Coastal Plain (fig. 1) is underlain principally by unconsolidated and semiconsolidated siliciclastic sediments of Cretaceous and Cenozoic age. In general, these sediments constitute a northeast-striking, gently southeastward-dipping, seaward-thickening wedge that reaches a maximum thickness exceeding 6,300 ft in southeastern New Jersey. Coastal Plain sediments accumulated along the Atlantic continental margin and contain a mixture of nonmarine, marginal marine, and marine deposits. Nonmarine and marginal marine deposits are primarily of deltaic origin, whereas marine deposits originated on the shelf.

Coastal Plain sediments in New Jersey unconformably overlie a bedrock basement. Most of the sediments directly above basement belong to the Potomac Formation. The Potomac consists of several major lithofacies, including interbedded light-colored sand, drab, varicolored, silty clay and clayey silt, and very gravelly sand. Each lithofacies varies widely in thickness and lateral extent. Along the Fall Line from Trenton to Perth Amboy, the basement is overlain by sediments of the Raritan and Magothy Formations.

Sediments in the New Jersey Coastal Plain were deposited in two large basins (fig. 2): the Raritan embayment to the north and the larger Salisbury embayment to the south (Owens and others, 1988). Both basins are landward extensions of the Baltimore Canyon trough. These basins are separated by the South Jersey high, an area of thinner sedimentary deposits that resulted from relative uplift and (or) lack of deposition (Owens and Gohn, 1985).

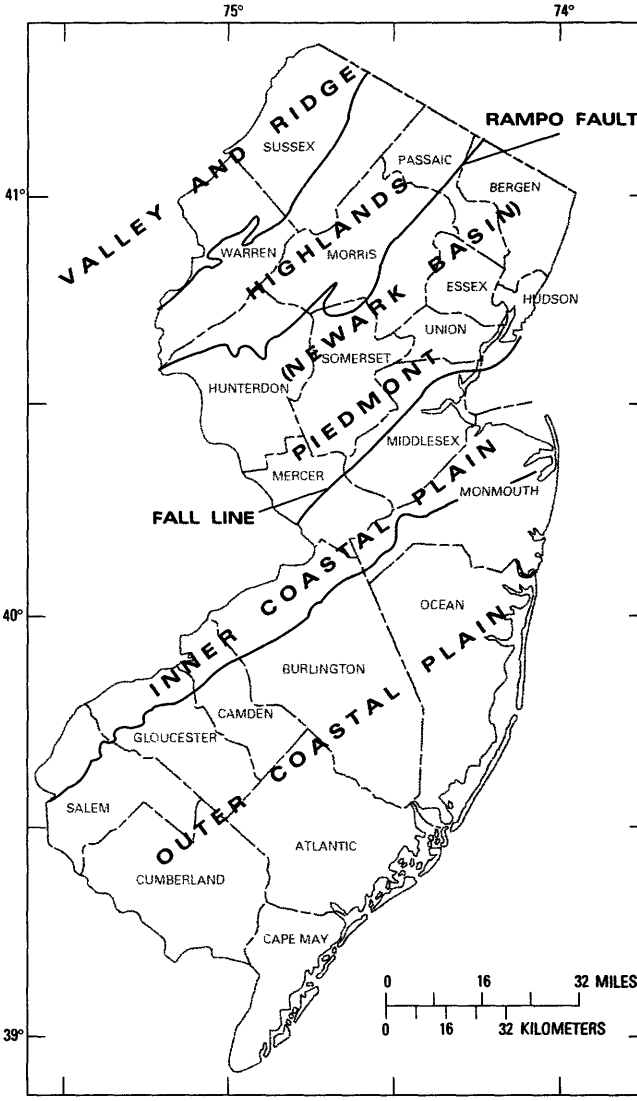

Figure 1. Physiographic provinces of New Jersey.

These sedimentary basins underwent differential movement through time. In general, the Salisbury embayment appears to have deepened in a northward direction during the Early Cretaceous, whereas the Raritan embayment was downwarped in the Late Cretaceous (Owens and others, 1988). The northward deepening appears to have continued until the late Paleogene and was reversed in the Neogene. Consequently, the modern basin configuration is a composite of several small tectonic events.

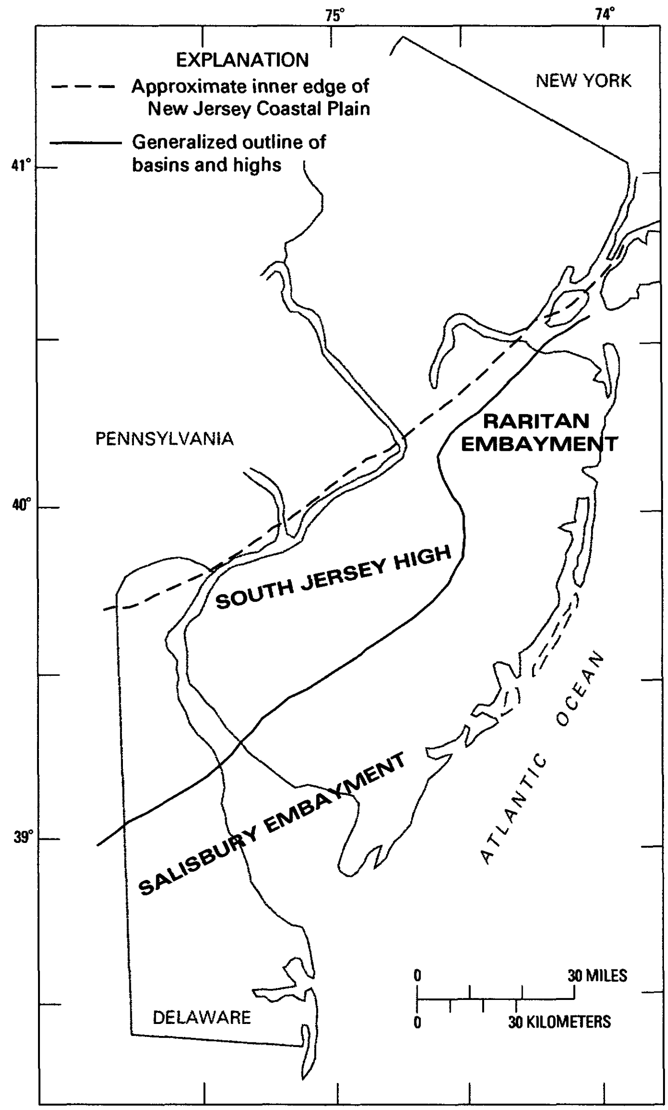

Figure 2. Tectonic setting of the New Jersey Coastal Plain.

MESOZOIC ROCKS OF THE NEWARK BASIN

Rocks of the Newark Supergroup in New Jersey occur in a broad northeast-trending basin, which extends from the Delaware River to the New York State line (fig. 1). This basin is one of a series of unconnected rift basins of Triassic age extending along eastern North America from Nova Scotia to South Carolina. In New Jersey, Newark basin strata are in fault contact on the northwest with Middle Proterozoic rocks of the New Jersey Highlands and unconformably overlie klippen of Ordovician rocks. On the southeast, they are unconformably overlain by unconsolidated Cretaceous deposits of the inner Coastal Plain and Quaternary sand and gravel.

The Newark basin contains a maximum thickness of about 20,000 ft of Upper Triassic to Lower Jurassic nonmarine conglomerate, sandstone, siltstone, argillite, shale, and interbedded continental tholeiitic basalt (Van Houten, 1969). Fanglomerates of Triassic and Jurassic age, containing clasts of various Middle Proterozoic rocks, Paleozoic sandstone, dolomite, shale, and conglomerate, and Jurassic basalt locally occur adjacent to the Ramapo fault, which bounds the Newark basin on the northwest (fig. 1). Diabase of Jurassic age occurs in thick sills in Newark basin strata and in smaller dikes and other intrusive bodies. Newark basin sedimentary rocks are commonly thermally altered where intruded by diabase.

From Trenton to near Princeton, the Stockton Formation unconformably overlies the pre-Mesozoic crystalline rocks along the southeast side of the basin, but nowhere is the contact between them exposed. Much of the basal part of the Stockton is arkosic sandstone derived from the underlying crystalline rocks. It contains 50 to 70 percent quartz and 15 to 40 percent feldspar, plagioclase being more abundant than potassium feldspar (Van Houten, 1980). Bascom and others (1909) described an exposure of the Stockton at Cadwalader Park in Trenton, which consisted of arkosic conglomerate containing large clasts of quartz and feldspar.

Northeast of Princeton, both the Stockton Formation and the older crystalline rocks are overlain by the Cretaceous Raritan and Magothy Formations and by sand and gravel of the Bridgeton and Pensauken Formations. The Stockton emerges from beneath this cover north of Raritan Bay, where it unconformably overlies the serpentinite on Staten Island and the Manhattan Schist. There is no evidence to suggest that the Stockton is absent in the covered area.

EXPOSED MIDDLE AND LATE PROTEROZOIC AND PALEOZOIC CRYSTALLINE ROCKS

Poorly exposed crystalline rocks of the New Jersey Piedmont crop out in a thin, east-northeast-trending wedge, which underlies Mesozoic and Cenozoic rocks immediately northeast of Trenton. Crystalline basement rocks are exposed near Hoboken, N.J., and on Staten Island, N.Y., where serpentinite crops out. Bedrock outcrops in the Trenton area are sparse, and most are along the west shore of the Delaware River at Morrisville, Pa. Bascom and others (1909) showed an isolated body of crystalline rocks south of Princeton Junction, but field mapping by Volkert in 1988 showed that these outcrops no longer exist.

Exposed pre-Mesozoic crystalline rocks in the Trenton, N.J., area (fig. 3) consist of Middle Proterozoic rocks to the north, which are unconformably overlain to the south by the Cambrian Chickies Quartzite. The Chickies is, in turn, bounded on the south by the southeast-dipping Huntingdon Valley fault (Bascom and others, 1909). This fault thrusts Middle Proterozoic rocks from the south onto the Chickies and, farther to the northeast, onto other Middle Proterozoic rocks. The Late Proterozoic to Lower Cambrian Wissahickon Formation has been thrust onto this sequence of

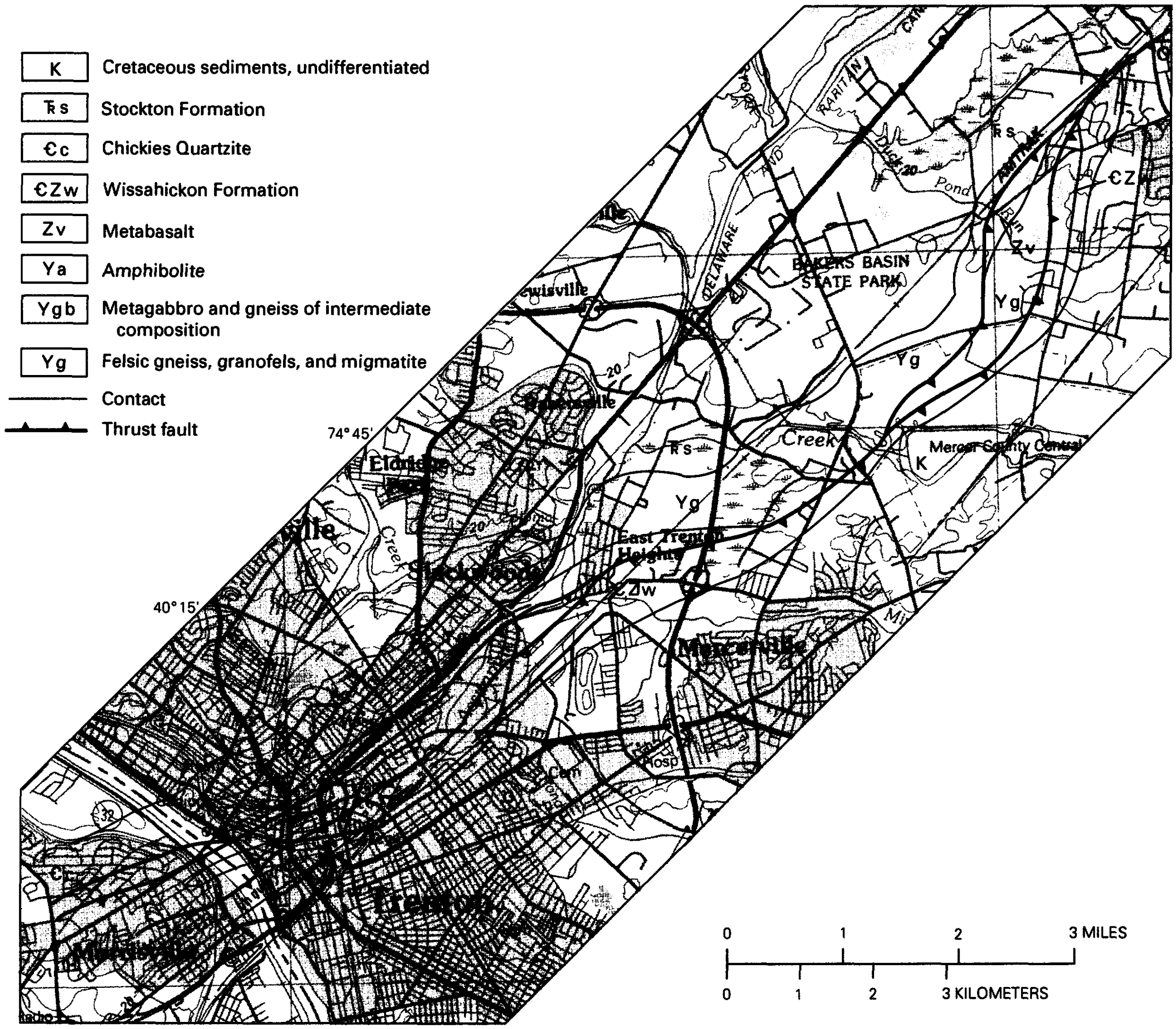

Figure 3. Geologic map of the exposed pre-Mesozoic crystalline rocks in the Trenton, N.J., area. Compiled from Widmer (1965) and R.A. Volkert and A.A. Drake, Jr. (unpub. data).

rocks along a southeast-dipping splay of the Huntingdon Valley fault, which Volkert and Drake (1993) have named the Morrisville thrust fault. These geologic relations are shown in figure 3. The Middle Proterozoic rocks consist of a heterogeneous sequence of biotite- and clinopyroxene-bearing quartzofeldspathic gneiss, hornblende- and clinopyroxene-bearing felsic to intermediate gneiss, metagabbro, meta-andesite and amphibolite (Volkert and Drake, 1993). One small body of marble in these rocks is known from boring logs for the State Department of Education building in downtown Trenton (lithologic logs on file in the office of the New Jersey Geological Survey, Trenton, N.J.). Many of these gneisses contain characteristic blue quartz and trace to moderate amounts of garnet and, according to Bascom and others (1909), locally are graphitic. No graphite was seen in any of the exposed rocks in the Trenton area.

The Chickies Quartzite, as exposed west of Trenton (fig. 3), is fine-grained, light-gray to light-greenish-gray, massive to well-bedded, locally crossbedded, tourmaline-bearing sericite-quartz schist, quartzite, and quartz pebble conglomerate. The quartz pebbles are stretched down the

DELAWARE AND ADJACENT PENNSYLVANIA		MANHATTAN PRONG		SOUTHERN NEW ENGLAND	
GEOLOGIC AGE	UNIT	GEOLOGIC AGE	UNIT	GEOLOGIC AGE	UNIT
Cambrian and (or) Late Proterozoic	Peters Creek Schist and "Wissahickon Formation"	Ordovician(?) and Cambrian	Hartland Formation	Ordovician(?) and Cambrian	Rowe Schist
	Thrust fault		Thrust fault		Thrust fault
Cambrian and (or) Late Proterozoic	Octoraro Phyllite	Cambrian and (or) Late Proterozoic	Manhattan Schist	Cambrian and (or) Late Proterozoic	Allochthonous Hoosac Formation
	Thrust fault		Thrust fault		Thrust fault
	Equivalent rocks not present	Ordovician	Walloomsac Formation	Ordovician	Walloomsac Formation
Cambrian	Vintage Dolomite through Conestoga Limestone	Ordovician and Cambrian	Inwood Marble	Ordovician and Cambrian	Stockbridge Marble
Cambrian	Chickies Formation	Cambrian	Lowerre Quartzite	Cambrian	Cheshire Quartzite
	Not recognized		Not recognized	Cambrian and (or) Late Proterozoic	Dalton Formation
	Unconformity		Unconformity		Unconformity
Middle Proterozoic rocks		Middle Proterozoic rocks		Middle Proterozoic rocks	

Figure 4. Generalized sequence of rock units from the north-central and southern northern Appalachians. Compiled from Hall (1976, in press), Berg and others (1983), Stanley and Ratcliffe (1985), Lyttle and Epstein (1987), and Brock (1989).

dip of the schistosity. No outcrops of Chickies occur east of the Delaware River.

Exposed to the south of the Chickies Quartzite is another section of Middle Proterozoic rocks (fig. 3) consisting of amphibolite, potassic feldspar augen gneiss, biotite schist and gneiss, calc-silicate gneiss, and biotite-quartz-feldspar gneiss. Many of these same lithologies also crop out north of the Chickies (Volkert and Drake, 1993). The augen gneiss and biotite gneiss association is similar to associations in Middle Proterozoic rocks from throughout the U.S. Appalachians, such as those of the Blue Ridge complex described by Sinha and Bartholomew (1984), the Baltimore Gneiss in the Maryland Piedmont (Hopson, 1964), and numerous other occurrences described by Rankin and others (1989). We accordingly interpret this augen gneiss and associated schist and gneiss to be Middle Proterozoic in age and therefore older than the Wissahickon Formation; thus, not all of the schist and gneiss south of the Huntingdon Valley fault is Wissahickon.

Crystalline rocks farther to the northeast include the serpentinite at Hoboken, N.J., and Staten Island, and the Fordham Gneiss, Yonkers Gneiss, Manhattan Schist, Inwood Marble, Walloomsac Formation, and Hartland Formation of the Manhattan prong. Stratigraphic correlations between these rocks and Piedmont rocks in adjacent States are shown in figure 4. The Middle Proterozoic Fordham Gneiss and Late Proterozoic Yonkers Gneiss are unconformably overlain by lower Paleozoic clastic and shelf carbonate rocks of the Lowerre Quartzite, Inwood Marble, and Walloomsac Formation (Hall, in press). The Walloomsac is equivalent to the Manhattan Schist, member A, of Hall (1976). The pelitic rocks and amphibolite of the Manhattan Schist (members B and C of Hall, 1976) were emplaced on the shelf sequence by the Elmsford thrust fault (Hall, in press). This sequence of basement, autochthonous, and parautochthonous cover is the North American Craton terrane of Zen and others (1989). The Ordovician(?) Hartland Formation is a sequence of metamorphosed interlayered clastic and volcanic rocks, which were thrust onto the Manhattan Schist along Cameron's Line thrust fault (Hall, in press). The Hartland Formation commonly contains serpentinite (Baskerville, 1990). These rocks constitute the western part of the Brompton-Cameron terrane of Zen and others (1989) and are interpreted to be fragments of obducted ocean crust.

Serpentinite crops out on Castle Point in Hoboken, it underlies much of Staten Island, and one body is known on Manhattan Island. The serpentinite at Hoboken is a tectonic melange containing disrupted blocks of serpentinite as much as several feet across within a matrix of scaly-cleaved, fine-grained serpentinite and talc schist. The Manhattan Schist is known from boring logs to occur in the Jersey City area but is not exposed there. At Jersey City, and elsewhere along the Hudson waterfront, serpentinite appears to have been thrust over the Manhattan Schist (Lyttle and Epstein, 1987; Baskerville, 1990; R.A. Volkert, unpub. data) on the Cameron's Line thrust fault (fig. 5). The Cameron's Line thrust fault must continue southward and then cut between the serpentinite exposed on northern Staten Island and the schist along the Hudson waterfront to the immediate north (fig. 5). From here, it apparently continues southwestward beneath the eastern edge of the Newark basin, merging with, or becoming, the Huntingdon Valley-Morrisville fault system northeast of Trenton (fig. 3). Small bodies of serpentinite also occur within the Wissahickon Formation and the Peters Creek Schist in the Pennsylvania Piedmont immediately west of the New Jersey border. The fault separating these rocks from the autochthonous cover therefore may be a continuation of Cameron's Line.

In the part of Pennsylvania adjacent to New Jersey, basement rocks of Middle Proterozoic age crop out in numerous detached massifs of variable size. Rocks in the West Chester prong occur south of the Cream Valley-Huntingdon Valley fault system and are unconformably overlain by a lower Paleozoic succession of clastic and carbonate rocks of the Setters Formation and Cockeysville Marble. These are overlain by pelitic and psammitic schists containing ultramafic rocks and amphibolite layers usually referred to as the Wissahickon Formation. However, Drake (1986) suggested that the term "Wissahickon" actually refers to several distinct lithotectonic units. These include the allochthons containing the Piney Branch Complex, Peters Creek Schist, and Annandale Group in Virginia and Maryland of Late Proterozoic or Early Cambrian age, and the high-grade Wissahickon (in a strict sense) in Philadelphia of probable Late Proterozoic and (or) Early Cambrian age. These compose the Potomac terrane (fig. 6) of Horton and others (1989). A more conservative interpretation of the "Wissahickon" was previously taken in the Pennsylvania Piedmont, where it was mapped as stratigraphically overlying the Cockeysville Marble. However, recent workers (for example, Crawford and Mark, 1982; Wagner and Srogi, 1987; Faill and MacLachlan, 1989) recognized that the "Wissahickon" may be allochthonous and composed of several distinct lithologic units. Crawford (1991) stated that the current interpretation for the "Wissahickon" in Pennsylvania and Delaware is that it probably represents a sequence of deepwater marine sediments that contains volcanic rocks and tectonically emplaced slices of ultramafic rocks. Thus, rocks south of the Cream Valley fault are termed Wissahickon or Peters Creek Schist, depending on their stratigraphic position. Faill and MacLachlan (1989) assigned all of the rocks south of the Cream Valley-Huntingdon Valley fault system and east of the West Chester prong to the Philadelphia terrane and those rocks to the west to the Brandywine terrane (collectively, the Potomac terrane of Horton and others, 1989).

In the Maryland Piedmont, the Middle Proterozoic Baltimore Gneiss crops out in a series of domelike structures. It is unconformably overlain by a lower Paleozoic succession of clastic and shelf carbonate rocks, which are the Setters Formation and the Cockeysville Marble, respectively (Hopson, 1964; Crowley, 1976). The Baltimore Gneiss, Setters Formation, and Cockeysville Marble constitute the Baltimore terrane of Horton and others (1989) (fig. 6).

These are tectonically overlain by the Loch Raven Schist and the Oella Formation (Crowley, 1976), an interlayered sequence of meta-arenite and schist. Both units contain blocks of ultramafic rock. At different places, the thrust sheet containing the Loch Raven Schist and Oella Formation overlies either the Baltimore Gneiss, the Setters Formation, and (or) Cockeysville Marble (map in Crowley, 1976). It also overlies the Laurel Formation, a precursory sedimentary melange that contains olistoliths of Loch Raven Schist and Oella Formation (Fleming and others, 1994; A.A. Drake, Jr., unpub. data).

To the west of the Baltimore terrane, the Loch Raven thrust sheet is tectonically overlain by the Sykesville Formation, a precursory sedimentary melange (Drake, 1986). A thrust sheet of ultramafic rock, the Soldiers Delight Ultramafite, lies between these thrust sheets in central Maryland (A.A. Drake, Jr., unpub. data). The Sykesville Formation is tectonically overlain by the Mather Gorge Formation that was miscorrelated with the Peters Creek Schist by Drake and Morgan (1981). All these units are part of the Potomac terrane of Horton and others (1989). The Potomac terrane is tectonically underlain by rocks of the Westminster terrane (Drake, 1986; Horton and others, 1989) (fig. 6).

To the east of the Baltimore terrane, rocks of the Potomac terrane are tectonically overlain by the mafic and ultramafic rocks of the Baltimore Complex (Bel Air-Rising Sun terrane of Horton and others, 1989; this report, fig. 6). Crowley (1976) interpreted the James Run Formation (Chopawamsic terrane of Horton and others, 1989; this report, fig. 6) to tectonically overlie the Baltimore Complex. In exposures along the Patapsco River near Relay, Md., however, the units are separated by a zone of west-dipping mylonitic foliation, suggesting that the Baltimore Complex overlies the James Run Formation (A.A. Drake, Jr., unpub. data). Tectonostratigraphic relations of the various terranes adjacent to New Jersey are shown in figure 7.

The Wilmington Complex crops out in the Delaware and Pennsylvania Piedmont just west of Salem and

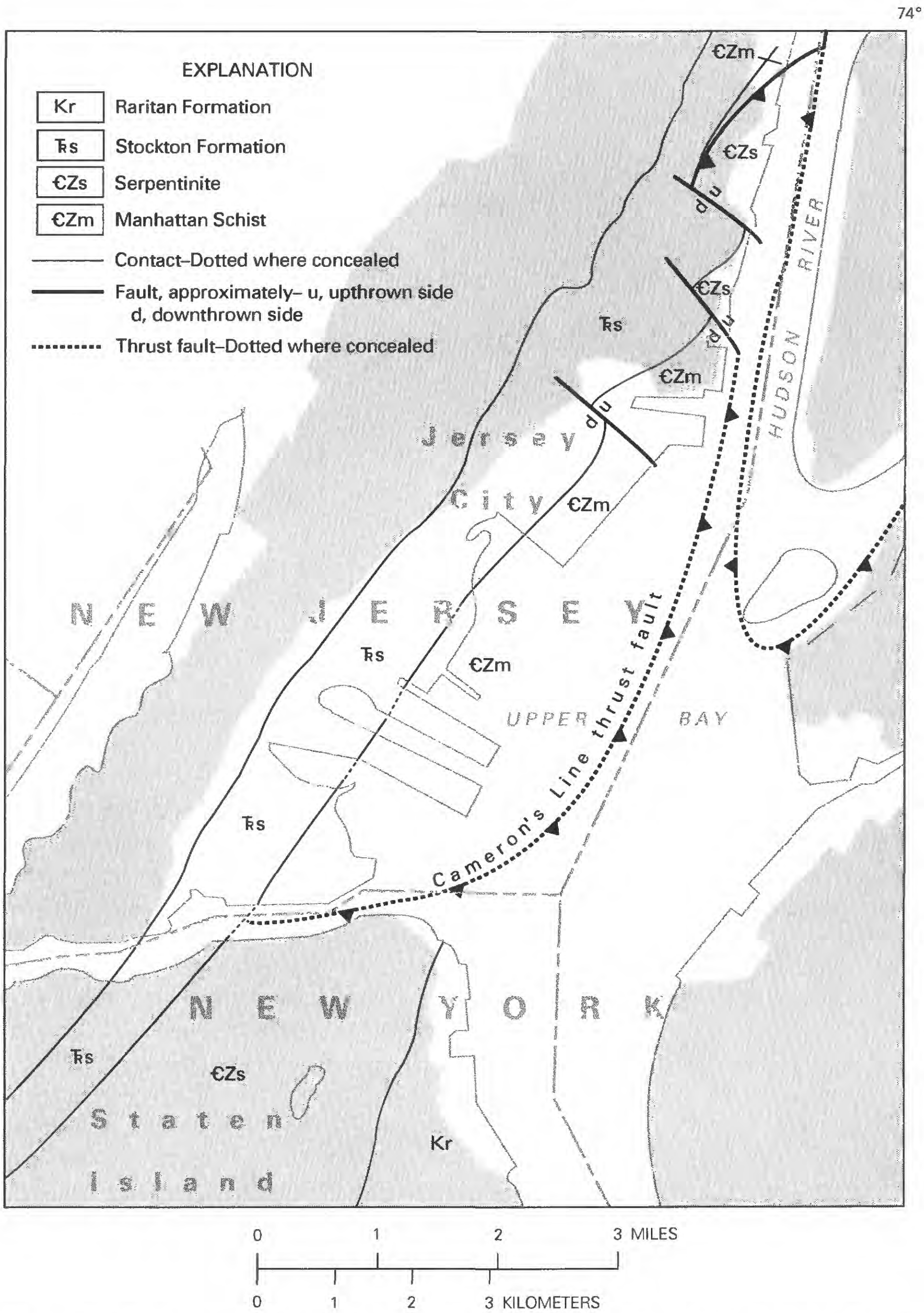

Figure 5. Geologic map of the Hoboken, N.J., area. Compiled from Mueser Rutledge Consulting Engineers (1986), Lyttle and Epstein (1987), Tams Consultants, Inc. (1988), R.A. Volkert (unpub. data), and unpublished New Jersey Geological Survey permanent notes (undated).

Gloucester Counties in New Jersey (fig. 6). As mapped by Ward (1959) and Woodruff and Thompson (1975), the Wilmington Complex consists of a sequence of mafic rocks of gabbroic, noritic, anorthositic, and charnockitic composition (Arden pluton), as well as a sequence of layered, two-pyroxene-bearing gneisses (Wagner and Srogi, 1987). The gneisses were intruded by the Arden pluton from which Foland and Muessig (1978) obtained a Rb-Sr whole-rock age of 502 Ma, suggesting that it is Cambrian or older. Layered gneisses associated with the Wilmington Complex have been interpreted to be metavolcanic and volcaniclastic by several Piedmont geologists (for example, Southwick, 1969; Higgins, 1972; Crawford and Crawford, 1980) who have correlated them with rocks of the Cambrian James Run Formation in Maryland, the Chopawamsic Formation in Virginia, and other Cambrian rocks of island arc affinity in the Piedmont. Horton and others (1989) disagreed with this correlation and interpreted the layered gneisses of the Wilmington Complex to be Cambrian or older, perhaps even Middle Proterozoic in age, and speculated that the

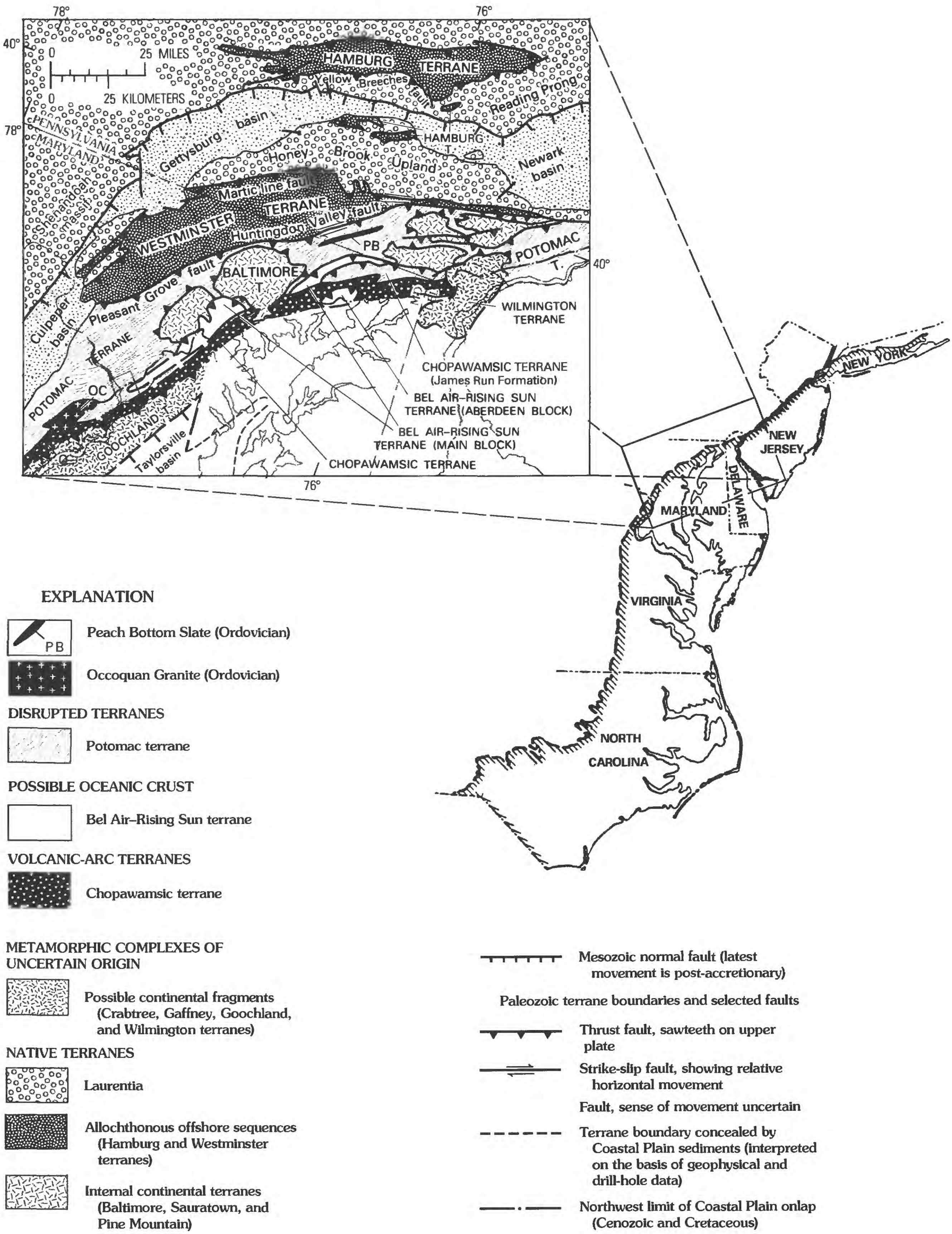

Figure 6. Tectonostratigraphic terrane map of the central Appalachians. Modified from Horton and others (1989).

Goochland terrane

Montpelier metanorthosite
Maidens Gneiss
Sabot amphibolite
State Farm Gneiss

Wilmington terrane

Arden Pluton
Layered gneisses

Chopawamsic terrane

Chopawamsic Formation
James Run Formation

Bel Air–Rising Sun terrane

Baltimore Mafic Complex

Potomac/Philadelphia/Brompton–Cameron terrane

Sykesville Formation
Peters Creek Schist
Piney Run Formation
Oella Formation
Wissahickon Formation (sensu stricto)
plus
rocks in Connecticut Valley Synclinorium east of Cameron's Line

Westminster terrane

Pretty Boy Schist
Octoraro Phyllite
allochthonous Hoosac Formation
plus
Manhattan Schist B and C (?)

Baltimore/North American Craton terrane

Walloomsac Formation
Stockbridge Marble
Inwood Marble
Cheshire Quartzite
Dalton Formation
Lowerre Quartzite
Yonkers Gneiss
Fordham Gneiss
plus
Loch Raven Schist
Cockeysville Marble
Setters Formation
Baltimore Gneiss

← **Figure 7.** Tectonostratigraphic sequence showing generalized relation of terranes of the north-central and southern northern Appalachians. Compiled from Crowley (1976), Hall (1976), Crawford and Mark (1982), Stanley and Ratcliffe (1985), Drake (1986), Faill and MacLachlan (1989), Horton and others (1989), and Zen and others (1989). Terranes are listed in their inferred stacking order with the highest thrust sheet at the top and the lowest thrust sheet at the bottom.

Wilmington terrane (fig. 6), which they envisioned to be thrust over rocks of the Chopawamsic terrane, may be an extension of the Goochland terrane (fig. 6). Horton and others (1989), however, showed these terranes separately on their map.

It is tempting to correlate the exposed crystalline rocks in the Manhattan prong with those in the Pennsylvania and Maryland Piedmont. There are, however, problems in doing so. Some workers (for example, Higgins, 1972; Muller and Chapin, 1984) thought that the Setters Formation and Cockeysville Marble, the cover rocks that overlie Grenville basement, were Late Proterozoic or earliest Cambrian in age, hence older than the Lowerre and Inwood in the Manhattan prong. Other workers (for example, Crowley, 1976) considered them to be Cambrian to Ordovician in age. The age of rocks called "Wissahickon" Formation has been a problem. For example, Drake (1986), Lyttle and Epstein (1987), and Horton and others (1989) interpreted them to be Late Proterozoic or earliest Cambrian in age. Others (for example, Higgins, 1972; Muller and Chapin, 1984) thought that the "Wissahickon" ranged in age from Late Proterozoic to Ordovician but was mostly Cambrian. We think that the autochthonous cover sequence rocks overlying Proterozoic basement, namely the Lowerre and Inwood, and the Setters and Cockeysville are correlative, whether Late Proterozoic or early Paleozoic, because of their respective structural relations, their stratigraphy, and lithologic descriptions in Hopson (1964), Crowley and others (1975), Muller and Chapin (1984), and Hall (1976; in press). All of them are included here in the Baltimore terrane of Horton and others (1989) and its equivalent, the North American Craton terrane of Zen and others (1989).

We agree that rocks in the Potomac terrane have been thrust westward over the Laurentian craton and its cover as suggested by some workers (for example, Crawford and Crawford, 1980; Wagner and Srogi, 1987; Horton and others, 1989). We think that rocks in the Manhattan prong at least through the Inwood Marble would structurally underlie rocks equivalent to the Wissahickon Formation (in a strict sense) and other parts of the Potomac terrane. This interpretation suggests that the Manhattan Schist as used by Hall (in press), the allochthonous Hoosac Formation and equivalent units in New England, and the Octoraro Phyllite in Pennsylvania are correlative and structurally underlie Potomac terrane rocks. This correlation is supported by the fact that in New England, the Rowe Schist, which contains ultramafic rocks and basaltic amphibolite, was thrust westward over albite schist and phyllite of the allochthonous Hoosac Formation (Stanley and Ratcliffe, 1985). Similarly, the Peters Creek Schist and "Wissahickon" both contain mafic and ultramafic rocks and were interpreted by Lyttle and Epstein (1987) to have been thrust westward over albite schist and phyllite (Prettyboy Schist and Octoraro Phyllite, respectively). However, once again, age is a problem, as the Peters Creek and "Wissahickon" are considered to be Late Proterozoic to earliest Cambrian in age, whereas analogous rocks in the Manhattan prong (Hartland Formation) and in New England (Rowe Schist) are considered to be Ordovician in age (Stanley and Ratcliffe, 1985; Hall, in press). We note, however, that the ages of these rocks are not well constrained.

GEOPHYSICAL DATA

Gravity and aeromagnetic maps constitute the principal geophysical data sets available for interpretation of the basement rocks beneath the Coastal Plain of New Jersey. Gravity maps by Bonini (1965) and the Society of Exploration Geophysicists (1982) and aeromagnetic maps by the U.S. Geological Survey (1979) and Zeitz and Gilbert (1981) were used.

GRAVITY DATA

Bouguer gravity maps of the New Jersey Coastal Plain display generalized patterns, which are part of the more extensive Appalachian trends (fig. 8). The most obvious gravity feature is the linear negative-positive couplet, which is part of the Appalachian gravity gradient (AGG) (Cook and others, 1979). This feature consists of a gravity low on the northwest, which reaches a minimum value of −100 milligals in the Valley and Ridge province, and an adjacent gravity high. This high trends from Staten Island south through the Raritan Bay, peaking near Prospertown, N.J., at more than 40 milligals; it continues southwestward through Deptford, N.J., and to the Wilmington Complex in Delaware. Bonini (1965) referred to this positive gravity anomaly as the trans-New Jersey gravity high.

The AGG is interpreted to result from the transition of rifted, thinned, and intruded continental crust into denser oceanic crust (Cook and others, 1979). Crustal thinning and extension preceded the opening of the Iapetus Ocean basin during the Late Proterozoic and early Paleozoic. Regional gravity models in Virginia (Pratt and others, 1988) and in New Jersey (Sugarman, 1981) demonstrated that shallowing of the mantle from a depth of 25 to approximately 18.6 mi is sufficient to achieve the observed Bouguer gravity anomaly pattern.

Southeast of the AGG, a more intricate series of gravity anomaly patterns contains two oval gravity lows, which are separated near Tabernacle, N.J. The northern gravity low extends offshore of the northern part of the New Jersey Coastal Plain, whereas the southern low continues under the Delaware Coastal Plain to the south of the Wilmington Complex. Southeast of this gravity low is a gravity high that exceeds 30 milligals near Manahawkin, N.J. This anomaly may be part of the broader positive feature that extends from North Carolina to New Jersey and is associated with a linear positive magnetic anomaly. However, just north of Leonardtown, Md., there is a sharp termination of both the gravity and magnetic anomalies, and it is unclear whether any anomalies to the north are a continuation (D.L. Daniels, written commun, 1993). Southeast of this positive anomaly, the Bouguer gravity anomaly decreases to a low of −25 milligals at Cape May, N.J.

Sheridan and others (1991) interpreted the gravity high to result from high-density thrust slices of ophiolite, metavolcanic rock, and melange. According to their interpretation, the gravity low to the northwest marks the location of a buried Mesozoic basin. No density variations were needed below a 5 mi depth, as seismic-reflection data (Sheridan and others, 1991) do not indicate any large lateral velocity contrasts.

AEROMAGNETIC DATA

Aeromagnetic maps are excellent tools for studying the basement, as the sediments of the Coastal Plain have very weak magnetic susceptibilities in contrast to susceptibilities of some of the crystalline rocks. Consequently, it is assumed that the major aeromagnetic anomalies result from compositional and structural contrasts in the basement and that their gross trend is controlled by the regional grain of the basement rocks.

In general, the aeromagnetic map (fig. 9) shows two basic anomaly patterns beneath the New Jersey Coastal Plain: (1) in the inner Coastal Plain, an area characterized primarily by short-wavelength anomalies typical of the exposed Piedmont and (2) in the outer Coastal Plain, an area of broader, lower amplitude anomalies, which reflect the greater depth to basement.

The amplitudes of the anomalies on the aeromagnetic map generally correlate with the configuration of the basement surface. In areas of high-amplitude anomalies, the basement surface is high relative to the surrounding basement. For example, Sugarman (1981) studied the positive magnetic and residual Bouguer gravity anomalies near Marlboro, N.J. (figs. 8, 9), and suggested the presence of mafic rocks either in a pluton or a thrust slice. A regional basement structural high (fig. 10) is associated with these anomalies. A similar model was proposed for the Iron Hill in Delaware by Maguire (1980) and the Staten Island Serpentinite by Yersak (1977). Another short-wavelength magnetic anomaly, or series of anomalies, occurs near Mount

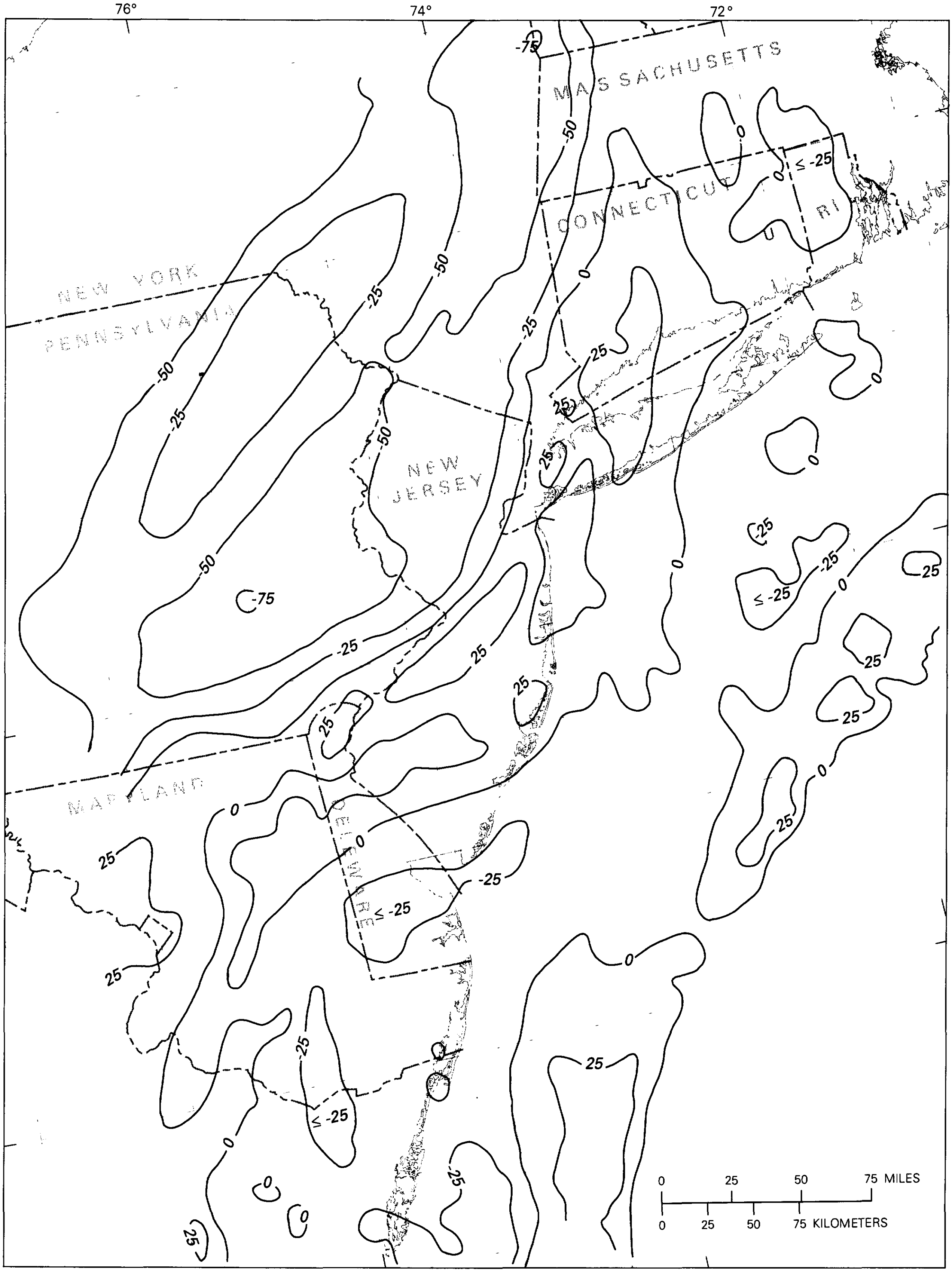

Figure 8. Bouguer gravity anomaly map of New Jersey and contiguous areas. Modified from Society of Exploration Geophysicists (1982). Contour interval 5 milligals.

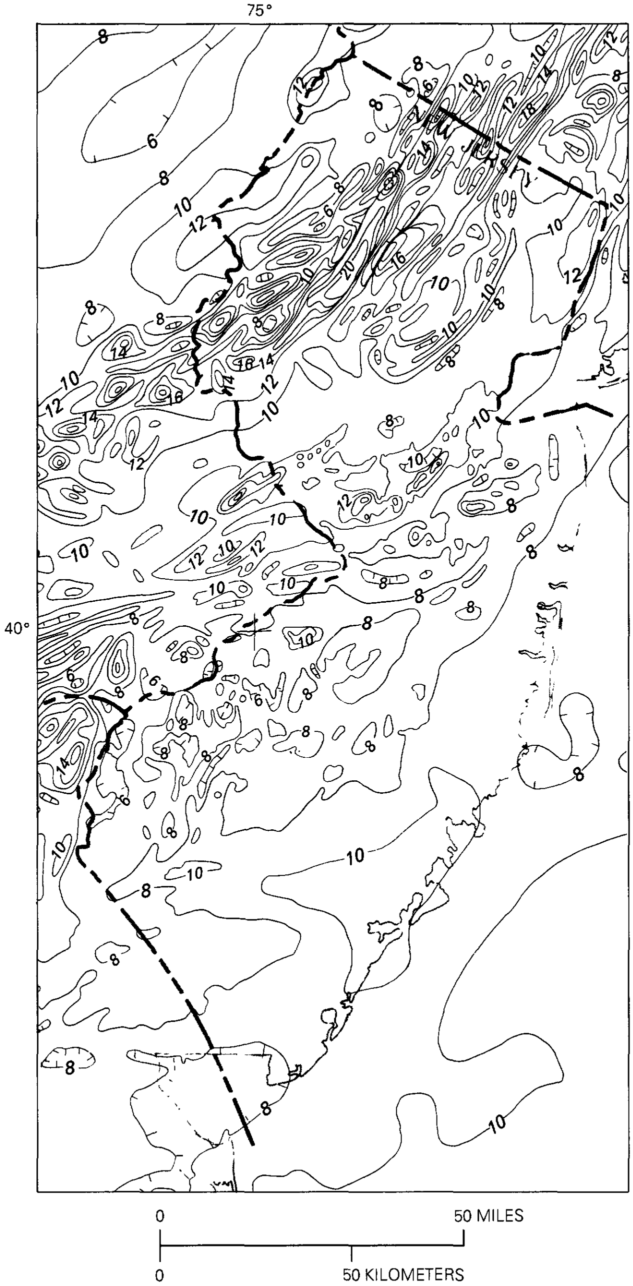

Figure 9. Aeromagnetic map of New Jersey and contiguous areas. Total intensities are shown in hundreds of gammas. Modified from Zietz and Gilbert (1981). Contour interval 200 gammas.

Holly in northwestern Burlington County. These anomalies are along the western part of the South Jersey high (fig. 1) and also are associated with a regional basement high (fig. 10). We interpret the anomalies and disruption in the basement seen in the basement surface contours in figure 10 near Mount Holly to be due to mafic rocks in a pluton or thrust slice similar to that proposed for the body near Marlboro.

DESCRIPTION OF WELL SAMPLES

INTRODUCTION

Most of the wells in New Jersey penetrating crystalline basement are concentrated along the northwestern edge of the Coastal Plain where bedrock is encountered at relatively shallow depths (fig. 10). To the south and east, deep wells are fewer and are widely separated. Except for the few published reports (Southwick, 1964; U.S. Geological Survey, 1967; Daniels and Leo, 1985), lithologic descriptions from this part of the State are known mainly from nondescript water well records. Where samples are available, many are saprolitic. Saprolite thicknesses of as much as 150 ft have been encountered beneath the New Jersey Coastal Plain, with the result that few fresh basement samples are available for study. Consequently, these basement rocks have remained poorly understood, and prior attempts to correlate them with distantly outcropping crystalline rocks elsewhere were problematic and conjectural at best (for example, Southwick, 1964).

As one objective of this study, well samples of fresher rock were analyzed petrographically where possible in order to define their gross mineralogy (table 1). This included the analysis of thin sections as well as rotary cuttings. The following county-by-county descriptions involve only new data resulting from this study and older data based on reliable sources. A complete listing of all wells used in this study that penetrate basement rock is given in the appendix.

CAPE MAY COUNTY

The deepest well that encountered basement in New Jersey for which samples are available is the Anchor Gas Dickinson well (appendix, well no. 104), which penetrated rock at a depth of about 6,300 ft below land surface. The samples remaining from the original well cuttings are of a fine-grained, grayish-black to greenish-black gabbro containing plagioclase, hornblende, trace amounts of biotite and sulfide, and minor amounts of quartz. No other wells to basement are known from Cape May County.

CUMBERLAND COUNTY

The Anchor Gas Ragovin well (appendix, well no. 103) drilled a fine-grained, quartz-rich rock containing trace amounts of accessory garnet. No feldspar was seen in the washed cuttings. However, a few small rock fragments from a depth of 3,700 to 3,710 ft contained chalky, fine-grained, highly altered feldspar. This appears to be a metaquartzite, possibly feldspathic in part. Most of the sample from the bottom of this well was of a coarse, angular quartz sand containing siderite nodules, probably representative of the Potomac Formation. The very bottom of the well appears to

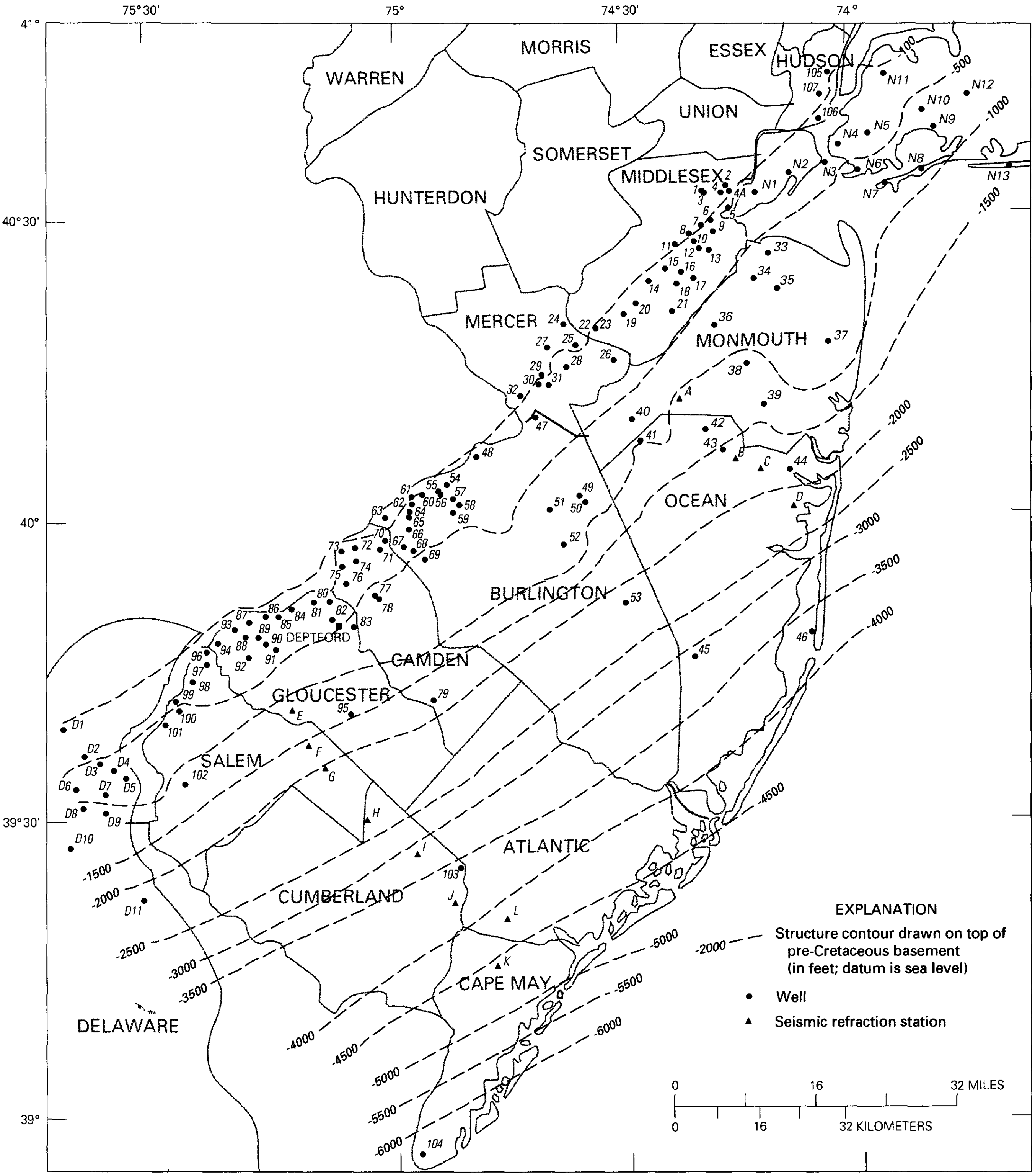

Figure 10. Location map of wells penetrating basement rock in New Jersey and contiguous areas. Structure contours are drawn on top of basement surface. Well numbers are same as in appendix.

Table 1. Modal analyses of selected basement rocks.

[Analyses are based on 1,200 points. Analyst: R.A. Volkert; —, no data]

Mineral	CL	SH	S&S	GAV–22	IBP	DUR–246	DUR–199	GAV–17
Plagioclase	39.8	35.95	36.2	28.5	40.4	36.6	53.7	45.6
Quartz	37.7	35.90	45.5	45.0	34.4	22.1	.4	.7
Biotite	18.5	18.50	14.6	16.2	18.6	29.6	2.6	—
Muscovite	2.8	8.30	—	8.6	.7	—	—	—
K-feldspar	—	.75	—	—	3.6	—	—	—
Hornblende	—	—	—	—	—	7.6	36.9	48.9
Garnet	.5	trace	.1	.4	.1	1.5	—	—
Tourmaline	.1	—	—	—	trace	—	—	—
Sillimanite	trace	—	—	trace	—	trace	—	—
Opaque[1]	.4	.2	1.9	.9	.2	2.4	5.1	3.1
Chlorite	trace	trace	.4	trace	.1	trace	.3	.4
Apatite	.1	.2	.1	.3	.2	.2	trace	trace
Zircon	.1	.2	.2	.1	trace	trace	trace	trace
Other[2]	trace	trace	1.0	trace	1.7	trace	1.0	1.3
Total	100	100	100	100	100	100	100	100

[1]Opaque minerals include magnetite, ilmenite, and pyrite.

[2]Includes alteration products and carbonate, plus trace amounts of titanite and epidote.

Description of samples

CL	Psammitic schist from Chemical Leaman well (appendix, well no. 89)
SH	Pelitic schist from Shoemaker Farm well (appendix, well no. 92)
S&S	Psammitic schist from S&S Auction well (appendix, well no. 90)
GAV–22	Psammitic schist from Gaventa Farms well (appendix, well no. 88)
IBP	Average of five thin sections from 3,873 ft to 3,881 ft below land surface. Based on 6,337 points from Southwick (1964) from the U.S. Geological Survey Island Beach State Park well (appendix, well no. 46)
DUR–246	Basaltic andesite from DuPont Repauno Works well (appendix, well no. 85)
DUR–199	Amphibolite from DuPont Repauno Works well (appendix, well no. 85)
GAV–17	Amphibolite from Gaventa Farms well (appendix, well no. 88)

have barely penetrated the basement surface. No additional wells into basement are known from Cumberland County.

ATLANTIC COUNTY

No wells into basement are known from Atlantic County.

OCEAN COUNTY

The U.S. Geological Survey test well (appendix, well no. 46) drilled at Island Beach State Park in the 1960's penetrated basement at a depth of about 3,800 ft. Southwick (1964) described the rock as a medium-grained, locally migmatitic, garnet-muscovite-microcline-biotite-quartz-plagioclase gneiss. His description omits a medium-grained garnet-hornblende-biotite-quartz-feldspar gneiss recovered from the bottom of the hole at a depth of 3,890 ft. The thickness of the hornblende-bearing phase of the gneiss is unknown because only a single piece of core exists. Its contact with the overlying gneiss is conformable and gradational. The foliation at 3,890 ft dips at about 35°.

The Oxly 1A well (appendix, well no. 45), drilled in the southern part of Ocean County, encountered a light-pinkish-tan saprolite of decomposed schist or gneiss containing chlorite, muscovite, biotite, quartz, highly altered feldspar (plagioclase?), trace amounts of sulfide, and a few grains of graphite.

The most noteworthy well from Ocean County is the W.&K. Oil Company well (appendix, well no. 42) drilled about 1920 at Jacksons Mills. New Jersey Geological Survey permanent notes by former State Geologist Henry Kümmel dated February 1922 state:

> gneiss was penetrated at about 1,900 ft in well no. 2 and limestone and sandstones found in which were Paleozoic fossils (Ordovician)... At the contact of the gneiss on the supposed Ordovician there was a 5-ft bed of clayey material containing bits of gneiss and limestone, the description indicating a fault breccia or "gouge" in a vein. The data appear to indicate the occurrence of an overthrust mass of gneiss on Ordovician strata.

Unfortunately, no description of the Paleozoic section drilled or the fossils contained within it exists, nor is there any reference to who identified them or the current whereabouts of the fossils. We know that Kümmel was never permitted direct access to the drilling site and relied on indirect information for his interpretation. If this report is valid, the thrust fault would have to exist between 1,900 and 3,000 ft below land surface. Reexamination of the cuttings from the 3,000- to 4,850-ft interval for this study indicates that the rock is a medium-fine-grained schist containing biotite, quartz, altered feldspar, sparse pale pink garnet, and trace amounts of sulfide. The section from 4,832 to 4,840 ft contains trace amounts of graphite. At 4,850 ft, the rock is a medium-fine- to medium-grained biotite-chlorite-muscovite-quartz-feldspar schist containing trace amounts of garnet and possible sillimanite. Apparently, the samples from below 4,851 and above 3,000 ft no longer exist.

The other wells in Ocean County (appendix, well nos. 41, 43, and 44) all encountered nondescript saprolite or bedrock.

MONMOUTH COUNTY

Most of the samples obtained from wells in Monmouth County are of micaceous schist or gneiss containing muscovite, biotite, quartz, and altered, chalky feldspar. The U.S. Geological Survey Freehold observation well (appendix, well no. 38) cut a weathered, medium-fine-grained schist containing abundant biotite, quartz, and altered, chalky feldspar, as well as sparse amounts of pink garnet and trace amounts of graphite. Schistosity in the core dips at a moderate angle.

The New Jersey Highway Authority well (appendix, well no. 35) encountered weathered, fine- to medium-fine-grained chlorite-biotite-muscovite-quartz-feldspar schist containing trace amounts of staurolite and graphite.

The Levitt & Sons, Inc., well (appendix, well no. 34) drilled a saprolitic mica schist that, according to the description (F.J. Markewicz, unpub. lithologic log), either was locally migmatitic or was intruded by granite.

MIDDLESEX COUNTY

Limited information is available from wells in Middlesex County. The lithologic descriptions are mostly of saprolitic material. The Madison Water Company well (appendix, well no. 17) penetrated micaceous greenish-gray saprolite. The two Clifford Stultz wells (appendix, well nos. 22 and 23) encountered saprolite containing quartz and feldspar that was called "Wissahickon" by Johnson (1961). One sample contained hornblende. These three wells are in the southeastern part of the county. Most of the wells in central and eastern Middlesex County are in rocks of the Newark basin. The Chevron Oil Company well (appendix, well no. 4a) in the northeastern part of the county drilled serpentinite (reported as "soapstone" by Gronberg and others, 1989), apparently a continuation of the outcropping body on Staten Island.

MERCER COUNTY

Most of the available well data from southern and eastern Mercer County list micaceous schist or gneiss labeled "Wissahickon" on the well records; the constituent mineralogy is not recorded. However, given the geographic location of these wells, a correlation with the Wissahickon Formation is certainly reasonable. In the south-central part of the county, the 270-ft-deep New Jersey Geological Survey Mercer County Park test hole (appendix, well no. 27) encountered a variety of rock types dominated by medium-grained, light-greenish-gray hornblende-pyroxene-quartz-biotite-plagioclase gneiss containing sparse sulfide. Above the gneiss is massive, light-tan clinopyroxene-quartz-microperthite granulite. Intruding the gneiss is massive, pinkish-white-weathering, medium- to coarse-grained micro-perthite alaskite containing blue quartz. The contact between the gneiss and these granitic rocks is sharp and conformable with gneissic foliation. Also intruding the gneiss at a depth of 226 to 260 ft is greenish-gray, fine-grained to aphanitic, retrogressively metamorphosed metabasalt. Foliation dips at an angle of about 35°–40° throughout the sampled interval. A thin ductile shear zone was observed at a depth of about 147 ft. Mineralized brittle fractures overprint this shear zone at a high angle. Several other sheared intervals were encountered deeper in the hole. These rocks probably are part of the heterogeneous Middle Proterozoic basement exposed near Trenton.

BURLINGTON COUNTY

Most of the wells concentrated along the northwestern edge of Burlington County and at least as far east as those at McGuire Air Force Base (appendix, well nos. 49 and 50) penetrated micaceous schist or gneiss. Where mineralogical descriptions are given, the rock consists dominantly of biotite, quartz, and weathered feldspar. The schistose gneiss from the Cinnaminson well (appendix, well no. 64) is a saprolitic, gray, medium-fine- to medium-grained rock that contains muscovite subordinate to biotite and sparse pink garnet. The dominant feldspar is plagioclase.

The Butler Place test well (appendix, well no. 53), drilled in the easternmost part of this county, penetrated a fine-grained, greenish-gray rock consisting of 40 percent carbonate plus phlogopite, chlorite, clay minerals, and minor quartz (U.S. Geological Survey, 1967). Unfortunately, samples of this core no longer are available. This well is particularly noteworthy in that carbonate rock was not encountered elsewhere in the New Jersey subsurface. The dimensions of this carbonate unit, as well as companion lithologies, remain unknown since no other wells to basement were drilled nearby. The closest wells are the Burlington County Institution well (appendix, well no. 52) to the northwest and the Oxly 1A well (appendix, well no. 45) to the southeast. Both wells are over 10 mi from the Butler Place well, and lithologic descriptions are lacking from the Burlington County Institution well.

CAMDEN COUNTY

As in Burlington County, most of the wells along the western and northern edges of Camden County were drilled in micaceous schist or gneiss. An exception is the Pennsauken SLF well (appendix, well no. 70) that returned a yellowish-tan decomposed schist or gneiss containing muscovite, quartz, and kaolinite.

The U.S. Geological Survey New Brooklyn Park well (appendix, well no. 79) in the southwestern part of the county drilled a pale-greenish-gray, fine- to medium-grained biotite-muscovite-quartz-plagioclase schist or gneiss that locally contains abundant pink garnet. No sillimanite was seen in the core in this study, although the U.S. Geological Survey (1967) reported sillimanite in some of the core. The garnet must occur locally as well, as the U.S. Geological Survey did not mention it in the sample USGS workers studied.

GLOUCESTER COUNTY

The freshest samples examined during this study were of core from a series of wells along the western edge of Gloucester County. These include the Gaventa Farms, Lopes Farm, and Shoemaker Farm wells (appendix, well nos. 88, 91, and 92, respectively) and the Chemical Leaman, S&S Auction, and DuPont Repauno Works wells (appendix, well nos. 89, 90, and 85, respectively). The U.S. Geological Survey Deptford and Clayton wells (appendix, well nos. 83 and 95, respectively) returned somewhat more weathered rotary cuttings.

The Gaventa Farms well (appendix, well no. 88) drilled (from top to bottom) a layered sequence of metapelite, amphibolite, and metagraywacke. The metagraywacke is medium fine to medium grained and contains muscovite, biotite, quartz, and plagioclase, with minor amounts of garnet and trace amounts of sillimanite and sulfide (table 1). The metapelitic schist is medium grained and contains essentially the same mineralogy plus minor K-feldspar. The foliated amphibolite dominantly contains hornblende and plagioclase (table 1). Contacts between the metapelite and the metagraywacke are gradational, whereas the schist/amphibolite contacts are sharp. All of the contacts observed in the core are conformable with schistosity. Schistosity is gently dipping throughout the section and ranges from subhorizontal to about 20°.

The Lopes Farm well (appendix, well no. 91) encountered a medium-grained schist containing muscovite, biotite, quartz, and plagioclase. No garnet or sillimanite was noted in the small amount of core from this well. The Shoemaker Farm well (appendix, well no. 92) drilled a medium-grained pelitic schist similar to that from the Gaventa Farms well. It contains muscovite, biotite, quartz, and plagioclase with minor amounts of K-feldspar and trace amounts of garnet and sulfide (table 1). This core is locally migmatitic, containing 0.1-in.-thick leucocratic seams of quartz and plagioclase. Schistosity is crenulated but dips at an average of about 40°.

The Chemical Leaman well (appendix, well no. 89) returned a layered sequence of (top to bottom) schistose metapelite and metagraywacke. A sample of medium-fine- to medium-grained metagraywacke contains muscovite, biotite, quartz, and plagioclase, with minor amounts of garnet and tourmaline and trace amounts of sillimanite and sulfide (table 1). Contacts between the pelitic and psammitic parts of the section appear to be gradational. Schistosity is uniformly subhorizontal throughout the core.

The S&S Auction well (appendix, well no. 90) encountered medium-grained schistose metagraywacke composed of biotite, quartz, and plagioclase with minor amounts of garnet (table 1). The core from a depth of 401 ft is cut by brittle fractures and by a 6-in.-thick vein of quartz that dips about 35° to 40° and that is subparallel to the dip of the schistosity.

The DuPont Repauno Works (appendix, well no. 85) actually consists of a cluster of nine wells that returned dominantly metapelite and metagraywacke schist having a mineralogy quite similar to that of the aforementioned well samples with or without garnet and sillimanite locally. Contacts between the metapelite and metagraywacke are everywhere gradational and conformable. Also encountered was a medium-grained schist containing biotite, hornblende, quartz, and plagioclase, with minor amounts of garnet and sillimanite (table 1, sample DUR–246) that has the composition of basaltic andesite (table 2). The meta-andesite occurs in thin to thick layers with metapelite, with which it has a conformable contact. No contacts between the meta-andesite and metagraywacke were noted in these wells.

Two principal types of amphibolite were seen in samples from the DuPont Repauno Works wells. They include medium-grained, foliated, grayish-black gneiss to schistose gneiss containing hornblende and plagioclase with minor amounts of biotite (table 1) and medium-fine- to medium-grained, grayish-black to black, less foliated, locally mottled gneiss to schistose gneiss containing dominantly hornblende and plagioclase. Despite the similar mineralogy, these amphibolites have a markedly different chemistry that will be discussed further on in this report.

Schistosity in the core from these wells is variable in dip due to folding and ranges from about 10° to subvertical. Dips in core from wells to the west generally are steeper, ranging from about 30° to 90°, whereas dips toward the east are gentler and range from about 10° to 50°. Folds have locally been refolded into type 2 dome-crescent-mushroom

Table 2. Chemical analyses of selected basement rocks.

[Major-oxide compositions except FeO were determined by X-ray fluorescence. FeO was determined by wet chemical methods. Trace-element abundances were determined by X-ray fluorescence. Rare earth element abundances and Th, Hf, and Ta were determined by instrumental neutron activation. All analyses by XRAL Activation Services, Ann Arbor, Mich. —, no data]

	CL	SH	S&S	GAV–21	DUR–398	DUR–256	IBP
Major-oxide composition, in weight percent, and loss on ignition (LOI)							
SiO_2	76.80	63.40	65.00	64.70	60.90	67.30	68.60
TiO_2	.55	.90	.85	.77	.88	1.20	.56
Al_2O_3	10.90	15.80	14.20	15.40	18.10	13.30	14.50
Fe_2O_3	1.11	2.69	2.28	1.82	2.90	2.94	1.53
FeO	2.20	4.30	4.30	4.10	4.50	3.70	3.30
MgO	1.28	2.77	2.83	2.49	2.81	1.66	2.01
CaO	1.37	1.28	2.78	2.09	.74	3.01	2.37
Na_2O	3.11	2.52	2.29	4.39	1.88	3.24	3.51
K_2O	1.58	4.20	2.48	2.36	4.26	1.68	2.31
P_2O_5	.18	.17	.12	.08	.16	.22	.11
MnO	.10	.17	.09	.12	.20	.14	.09
LOI	.46	1.23	1.39	.62	1.77	.39	.93
Total	99.64	99.43	98.61	98.94	99.10	98.78	99.82
Trace-element abundances, in parts per million							
Ba	330	670	510	770	860	800	540
Co	—	—	—	—	—	—	—
Cr	50	80	100	70	90	60	20
Hf	—	—	—	—	—	—	—
Nb	10	40	20	20	30	20	30
Ni	—	—	—	—	—	—	—
Rb	100	230	110	120	180	80	100
Sc	—	—	—	—	—	—	—
Sr	110	90	160	220	110	270	160
Ta	—	—	—	—	—	—	—
Th	—	—	—	—	—	—	—
V	—	—	—	—	—	—	—
Y	10	40	<10	30	30	30	20
Zr	210	190	230	210	190	620	180
Rare earth element abundances, in parts per million							
La	—	—	—	—	—	—	—
Ce	—	—	—	—	—	—	—
Nd	—	—	—	—	—	—	—
Sm	—	—	—	—	—	—	—
Eu	—	—	—	—	—	—	—
Tb	—	—	—	—	—	—	—
Yb	—	—	—	—	—	—	—
Lu	—	—	—	—	—	—	—

Description of samples

CL	Psammitic schist from Chemical Leaman well (appendix, well no. 89)
SH	Pelitic schist from Shoemaker Farm well (appendix, well no. 92)
S&S	Psammitic schist from S&S Auction well (appendix, well no. 90)
GAV–21	Psammitic schist from Gaventa Farms well (appendix, well no. 88)
DUR–398	Pelitic schist from DuPont Repauno Works well (appendix, well no. 85)
DUR–256	Psammitic schist from DuPont Repauno Works well (appendix, well no. 85)
IBP	Migmatitic gneiss from the U.S. Geological Survey Island Beach State Park well (appendix, well no. 46)

Table 2. Chemical analyses of selected basement rocks—Continued.

	DUR–199	MCP–228	DUR–206	GAV–17	DUR–185	DUR–137	DUR–246
Major-oxide composition, in weight percent, and loss on ignition (LOI)							
SiO_2	48.70	49.00	49.50	49.50	49.60	46.70	56.10
TiO_2	3.77	3.67	3.70	1.63	2.06	1.95	1.93
Al_2O_3	12.70	12.60	12.50	13.50	13.00	13.90	15.70
Fe_2O_3	8.10	5.30	7.70	7.40	3.20	4.40	3.50
FeO	9.80	10.60	9.30	9.40	10.60	10.00	7.90
MgO	4.78	4.30	4.33	6.04	5.86	7.35	3.18
CaO	7.85	8.15	7.86	8.75	9.74	11.10	5.26
Na_2O	1.70	2.94	1.89	1.26	2.59	2.67	2.69
K_2O	.65	.86	.38	.38	.25	.34	1.78
P_2O_5	.54	.50	.55	.22	.20	.19	.29
MnO	.26	.26	.24	.25	.21	.21	.19
LOI	.39	.31	.39	1.62	.93	1.20	.46
Total	99.24	98.49	98.34	99.42	98.24	100.01	98.98
Trace-element abundances, in parts per million							
Ba	250	350	120	90	200	40	430
Co	76	71	—	80	—	—	83
Cr	40	12	30	52	80	130	90
Hf	9.2	7.8	—	3.7	—	—	6.4
Nb	50	50	30	30	20	30	20
Ni	56	68	—	61	—	—	68
Rb	20	10	20	10	30	20	60
Sc	31.2	30.2	—	40.3	—	—	29.6
Sr	230	250	330	100	220	230	290
Ta	2.0	1.7	—	.5	—	—	1.1
Th	3.9	2.2	—	1.3	—	—	4.3
V	400	420	—	320	—	—	260
Y	40	20	50	50	40	20	50
Zr	340	280	350	170	140	100	270
Rare earth element abundances, in parts per million							
La	32.5	28.7	—	5.8	—	—	27.2
Ce	73	65	—	14	—	—	59
Nd	40	37	—	10	—	—	29
Sm	9.84	9.0	—	2.88	—	—	6.2
Eu	2.7	3.37	—	1.11	—	—	2.1
Tb	1.7	1.3	—	.70	—	—	1.1
Yb	4.31	3.52	—	3.08	—	—	3.11
Lu	.61	.49	—	.48	—	—	.45

Description of samples

DUR–199 Metabasalt from DuPont Repauno Works well (appendix, well no. 85)
MCP–228 Metabasalt from Mercer County Park well (appendix, well no. 27)
DUR–206 Metabasalt from DuPont Repauno Works well (appendix, well no. 85)
GAV–17 Metabasalt from Gaventa Farms well (appendix, well no. 88)
DUR–185 Metabasalt from DuPont Repauno Works well (appendix, well no. 85)
DUR–137 Metabasalt from DuPont Repauno Works well (appendix, well no. 85)
DUR–246 Basaltic andesite from DuPont Repauno Works well (appendix, well no. 85)

Table 2. Chemical analyses of selected basement rocks—Continued

	DUR–246A	DUR–405	AGD–6407
Major-oxide composition, in weight percent, and loss on ignition (LOI)			
SiO_2	52.70	56.10	49.20
TiO_2	2.48	1.25	2.55
Al_2O_3	16.10	16.60	13.70
Fe_2O_3	13.50*	3.80	4.50
FeO	—	6.40	9.20
MgO	3.82	3.97	4.98
CaO	4.99	3.65	8.09
Na_2O	2.62	2.95	3.24
K_2O	2.42	2.68	.62
P_2O_5	.28	.26	.26
MnO	.18	.35	.22
LOI	.93	1.20	1.62
Total	98.99	99.21	98.18
Trace-element abundances, in parts per million			
Ba	620	280	170
Co	—	—	—
Cr	99	50	50
Hf	—	—	—
Nb	30	50	20
Ni	—	—	—
Rb	90	150	20
Sc	—	—	—
Sr	430	570	450
Ta	—	—	—
Th	—	—	—
V	—	—	—
Y	40	40	30
Zr	260	190	210
Rare earth element abundances, in parts per million			
La	—	—	—
Ce	—	—	—
Nd	—	—	—
Sm	—	—	—
Eu	—	—	—
Tb	—	—	—
Yb	—	—	—
Lu	—	—	—

*Total Fe as Fe_2O_3.

Description of samples

DUR–246A Basaltic andesite from DuPont Repauno Works well (appendix, well no. 85)

DUR–405 Basaltic andesite from DuPont Repauno Works well (appendix, well no. 85)

AGD–6407 Metagabbro from Anchor Gas-Dickinson well (appendix, well no. 104)

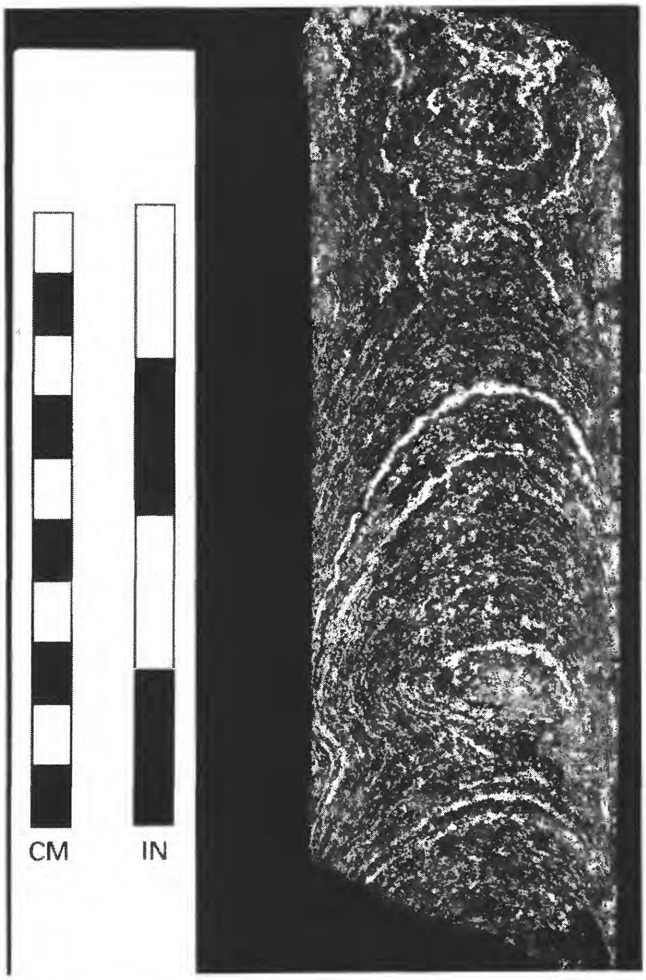

Figure 11. Type 2 dome-crescent-mushroom fold interference patterns in amphibolite from the DuPont Repauno Works well.

interference patterns (Ramsey and Huber, 1987); one such refolded fold in amphibolite is pictured in figure 11. This type of superimposed folding is common where recumbent fold nappes have been refolded by a fold phase having a steeply dipping axial surface (Ramsey and Huber, 1987).

The U.S. Geological Survey Deptford well (appendix, well no. 83) penetrated medium-grained, decomposed schist composed of muscovite, biotite, quartz, and altered, chalky feldspar, with minor amounts of garnet and trace amounts of sulfide. The U.S. Geological Survey Clayton well (appendix, well no. 95) encountered similar schist containing biotite and abundant quartz, with sparse amounts of altered feldspar and trace amounts of garnet and sulfide.

SALEM COUNTY

Typically, the wells along the northwestern edge of Salem County encountered micaceous schist or schistose gneiss. The most complete description is from well no. 7 at the DuPont Carney Point Works (appendix, well no. 100) that returned a decomposed, medium-fine- to medium-grained gneiss composed of quartz, plagioclase, biotite, and chlorite, with minor amounts of muscovite (U.S. Geological Survey, 1967). It is of interest that none of the rocks of the Wilmington Complex as mapped by Woodruff and Thompson (1975) were observed in any of the wells immediately across the Delaware River in New Jersey. The aeromagnetic pattern of the Wilmington Complex seen in figure 9 suggests that it is confined mainly to Pennsylvania and Delaware. It may project into the extreme western end of Salem County; however, descriptions of basement are lacking from the Pennsville well (appendix, well no. 101).

HUDSON COUNTY

Extensive borings along the eastern edge of Hudson County for a variety of development projects (appendix, well nos. 105, 106, 107) disclosed serpentinite extending south to a point east of Jersey City and then schist from that point southward to the waterfront area east of Bayonne (fig. 5). Serpentinite crops out immediately to the south of the waterfront on the northern end of Staten Island. The serpentinite east of Jersey City terminates abruptly, and plots of the available boring logs (R.A. Volkert, unpub. data) suggest that a series of northwest-trending normal faults cut the Stockton Formation and crystalline rocks west of the Hudson County waterfront (fig. 5). These faults step the Stockton Formation successively farther to the east as one goes south. Therefore, the serpentinite and Manhattan Schist contacts have been offset also, as has been the Cameron's Line fault, which is displaced to the east into the Hudson River (fig. 5).

DELAWARE

As in New Jersey, most wells penetrating subsurface basement in Delaware are concentrated along or near the Fall Line and were drilled to shallow depths. Most noteworthy of the Delaware wells are those drilled to the west and south of the southern half of Salem County, N.J. These include Ec 14–07, Eb 23–22, Eb 44–08, and Gd 33–04 (appendix, well nos. D5, D6, D8, and D11, respectively). Wells Ec 14–07 and Eb 23–22 both returned weathered cuttings of light-green chlorite schist composed of quartz, plagioclase, chlorite, and muscovite. Well Eb 44–08 (appendix, well no. D8) drilled a medium-grained, dark-grayish-green pyroxenite from a depth of 1,142 ft to the bottom of the hole at 1,159 ft (Dames and Moore, 1974). This rock is dominantly composed of clinopyroxene with minor amounts of amphibole and some alteration products. A well drilled approximately 1 mi to the northwest encountered saprolite composed of quartz and feldspar (Dames and Moore, 1974). Well Ec 32–7 (appendix, well no. D7), drilled about 3.3 mi northeast of Eb 44–08, penetrated mica schist. However, well Ec 41–10 (appendix, well no. D9), drilled about 1.8 mi east-southeast of Eb 44–08, encountered saprolitic green clay. This may represent weathered rock developed on a continuation of the same pyroxenite body drilled at Eb 44–08. Well Gd 33–04 (appendix, well no. D11) is the southernmost of the Delaware wells for which basement samples are available. The sample from this well at a depth of between 2,291 ft and 2,300 ft is weathered, fine-grained, light-green- to grayish-green schistose gneiss composed of chlorite, quartz, and plagioclase and a fine-grained, dark-green, quartz-poor rock largely altered to chlorite. These lithologies appear to have all of the aspects of a sequence of altered metavolcanic rocks. Their relation to the pyroxenite from well Eb 44–08 is unknown since these wells are separated by a distance of approximately 7 mi and no other wells were drilled to basement between Gd 33–04 and Eb 44–08.

METAMORPHIC GRADE

Most of the aluminous basement rocks from the New Jersey subsurface examined during this study consist essentially of the mineral assemblage quartz+biotite+plagioclase with or without muscovite and garnet. Sillimanite, K-feldspar, tourmaline, staurolite, and graphite occur locally. The peak metamorphic grade of these rocks is within the sillimanite-almandine-muscovite subfacies of the amphibolite facies (Turner and Verhoogen, 1960). No evidence of granulite-facies metamorphism was seen in any of the New Jersey well samples.

Metamorphic isograds (contours showing metamorphic grade) were drawn for the subsurface pelitic and psammitic basement rocks in New Jersey and are shown in figure 12. The highest metamorphic grade occurs in northern Gloucester and western Camden Counties as defined by the sillimanite isograd. Metamorphic grade decreases to the immediate north and south, with isograds displaying an apparent bilateral symmetry. Sillimanite-grade rocks are seen again in southern Monmouth County, but it is doubtful that this sillimanite isograd is continuous with the one in Gloucester and Camden Counties. It is interesting to note that the trend of the metamorphic isograds is crudely parallel to the Bouguer gravity contours and also to the aeromagnetic contours.

Most of the New Jersey well samples contain both muscovite and biotite, but saprolite from the Pennsauken SLF well (appendix, well no. 70) contains only muscovite, reflecting lower metamorphic grade (fig. 12). No kyanite, andalusite, or cordierite was observed in any of the well samples.

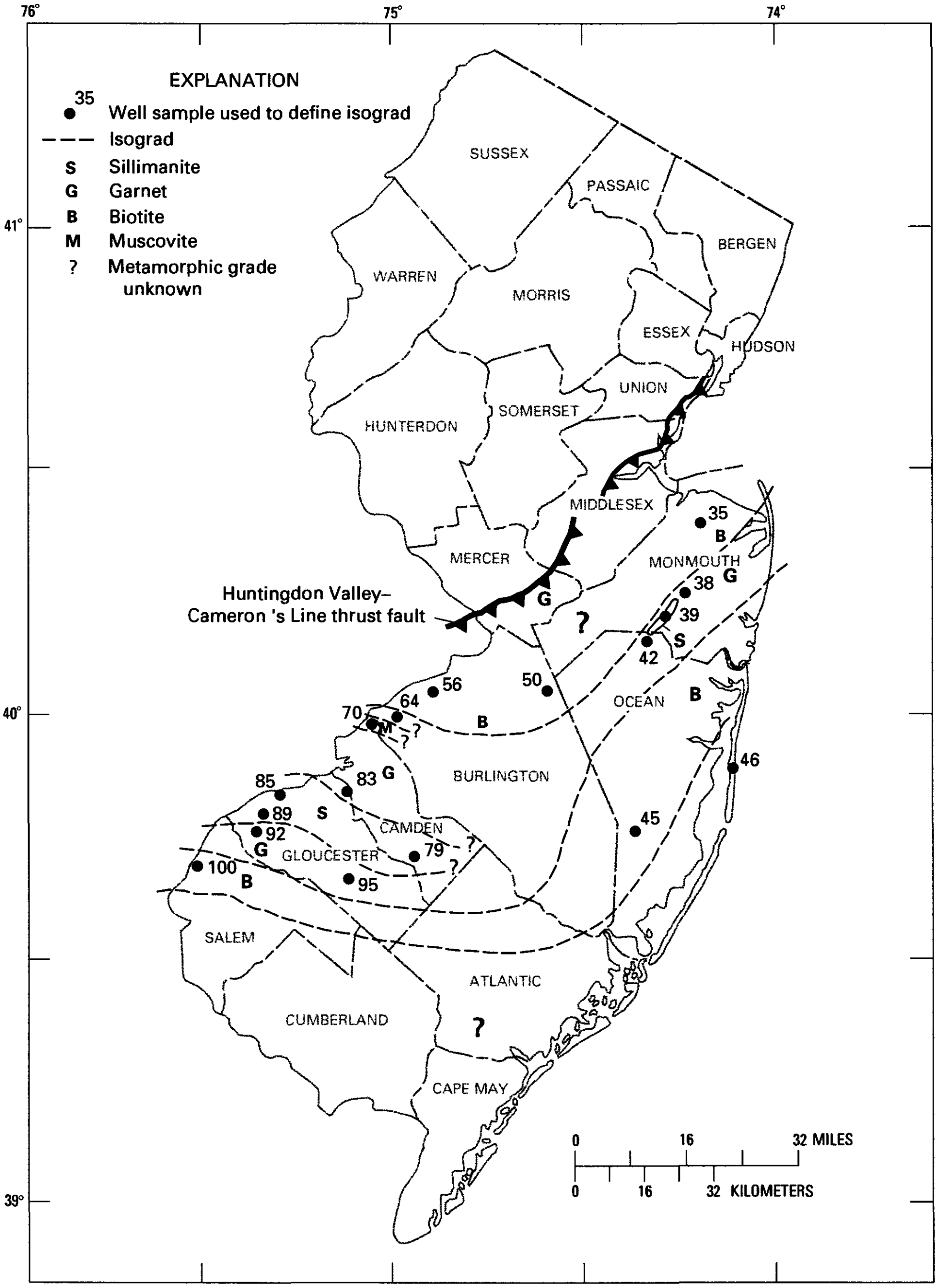

Figure 12. Metamorphic isograds shown in the pre-Mesozoic crystalline basement of New Jersey.

GEOCHEMISTRY

Despite the similar mineralogy of the schist and schistose gneiss encountered beneath the New Jersey Coastal Plain, there is a marked difference in the chemistry of many of these rocks. Geochemical analyses were obtained on the freshest samples available to determine their protolith and to assign them to an appropriate tectonic setting. They were then able to be correlated with rocks originating in similar tectonic settings from terranes in areas adjacent to New Jersey. Major-oxide and trace-element contents of rocks sampled for this study are given in table 2.

METAPELITE AND METAGRAYWACKE

Wells from Gloucester County consistently returned pelitic and psammitic schists that fall within the field of mudrock and graywacke, respectively (fig. 13). The psammitic schists sampled typically contain 34 to 45 modal percent quartz and 65 to 77 weight percent SiO_2 and have K_2O/

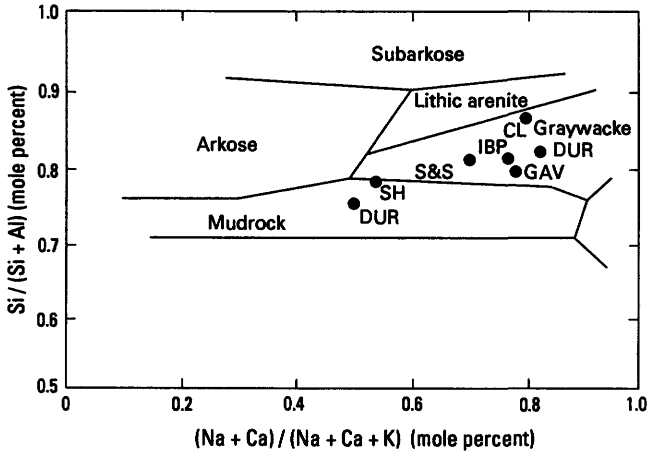

Figure 13. Si/(Si+Al) versus (Na+Ca)/(Na+Ca+K) diagram of pelitic and psammitic schist from beneath the New Jersey Coastal Plain. Diagram from Garrels and McKenzie (1971). Sample abbreviations are CL, Chemical Leaman; IBP, Island Beach State Park; DUR, DuPont Repauno Works; GAV, Gaventa Farms; S&S, S&S Auction; and SH, Shoemaker Farm.

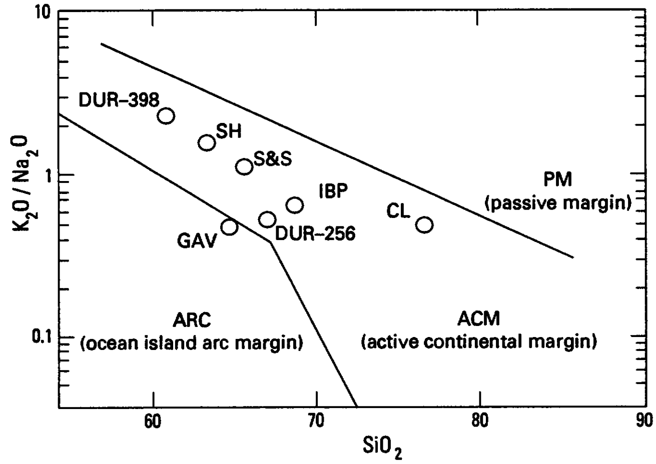

Figure 14. K_2O/Na_2O versus SiO_2 diagram of pelitic and psammitic schist from beneath the New Jersey Coastal Plain. Diagram from Roser and Korsch (1986). Sample abbreviations as in figure 13.

Na_2O ratios <1. These rocks correspond to the quartz- intermediate graywackes of Crook (1974) characteristic of tectonically mobile continental margins and are undoubtedly of marine origin.

Various attempts have been made to correlate the mineralogy and chemical composition of ancient sandstones with a particular tectonic setting (for example, Dickinson and Suczek, 1979; Bhatia, 1983; Roser and Korsch, 1986). Some of these discriminants were used with the Gloucester County schists. On a diagram of K_2O/Na_2O versus SiO_2 (fig. 14), all psammitic and pelitic schists, except for the sample from the Gaventa Farms well, fall within the active continental margin field. The Gaventa Farms sample plots in the ocean island arc margin field but close to the active continental margin field. Although a variety of basin settings are included in the active continental margin field, sediments are chiefly derived from continental margin magmatic arcs or dissected magmatic island arcs (Roser and Korsch, 1986). Comparison of the quartz, plagioclase, and K-feldspar ratios for the psammitic schists on a ternary diagram after Dickinson and Suczek (1979) (not shown) also supports a model of sediment derivation from a transitional to dissected magmatic arc along a continental margin or island arc. By using the geochemical discriminants of Bhatia (1983) (Fe_2O_3+MgO, TiO_2, Al_2O_3/SiO_2, K_2O/Na_2O, and $Al_2O_3/[CaO+Na_2O]$), psammitic schists from the Gaventa Farms, S&S Auction, and DuPont Repauno Works wells are classified as oceanic island arc sandstones. The Chemical Leaman sample, which has lower contents of Fe_2O_3+MgO and TiO_2 and a lower Al_2O_3/SiO_2 ratio, is an active continental margin sandstone from an "Andean type setting." The high contents of plagioclase (29 to 41 modal percent) and Na_2O (2.3 to 4.4 wt. percent) in the Gloucester County psammitic schists support the interpretation that they were receiving abundant volcanic detritus from a magmatic arc source.

METABASALT

As discussed above, Gloucester County pelitic and psammitic schists are intercalated with amphibolite, and at the DuPont Repauno Works well, with mafic schist that is meta-andesite. On the basis of major- and trace-element compositions, all amphibolites are metabasalt and form two distinct geochemical groups, referred to as type 1 and type 2. Amphibolite from the Gaventa Farms well is very similar geochemically to some amphibolite from the DuPont Repauno Works well (table 2), and together they define type 1 basalts. Compared to type 2 basalts, they are characterized by higher contents of MgO (5.86–7.35 percent), CaO (8.75–11.10 percent), and Cr (52–130 ppm) and lower contents of TiO_2 (1.63–2.06 percent), P_2O_5 (0.19–0.22 percent), and Zr (100–170 ppm).

Type 1 basalts have compositions that are similar to those of moderately fractionated tholeiitic basalt and show typical tholeiitic Fe enrichment on an AFM diagram (fig. 15). They are hypersthene normative, but the Gaventa Farms well sample contains normative olivine, whereas the DuPont Repauno Works well samples contain normative quartz. They all have relatively low Mg' values (100(Mg/[Mg+Fe^{2+}]) atomic), ranging from 49.6 to 56.7, together with generally low Cr and Ni contents. On the basis of one analysis (GAV–17), total concentrations of rare earth elements (REE's) are low, and these rocks have $(La/Yb)_N$ of

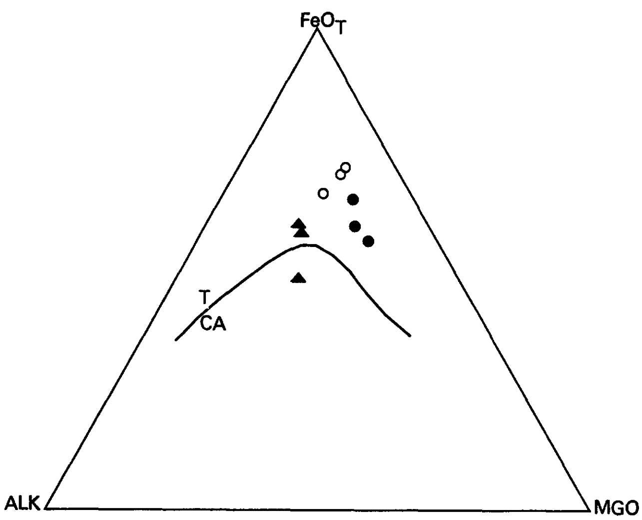

Figure 15. Plot of metabasalt and meta-andesite from beneath the New Jersey Coastal Plain on an AFM diagram. Dividing line shows the boundary of Irvine and Baragar (1971) between tholeiitic (T) and calc-alkaline (CA) rocks. Solid circle, type 1 basalt; open circle, type 2 basalt; triangle, meta-andesite.

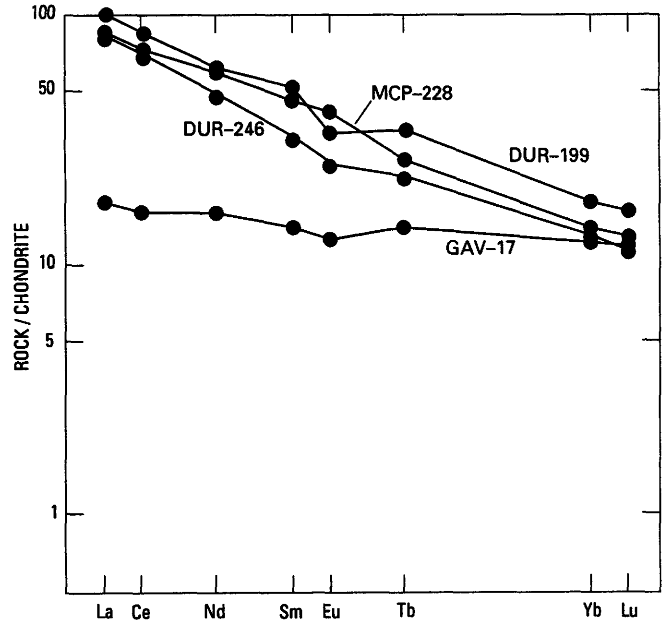

Figure 16. Chondrite-normalized rare earth element patterns for New Jersey metabasalt and meta-andesite. Normalization values from Shimizu and Masuda (1986). Sample numbers as in table 2. MCP, Mercer County Park well sample. Other sample abbreviations as in figure 13.

1.26. Compared with chondritic values, La is enriched 17.7× and Yb 14×. Type 1 basalt displays a relatively flat, slightly light-REE enriched pattern (fig. 16) with a small negative Eu anomaly. The REE pattern is similar to REE patterns of marginal basin basalts and also island arc basalts. Basalts from these two settings differ in their chondrite-normalized concentrations of Ba. Island arc basalts have Ba_N equal to or enriched relative to La_N, while marginal basin basalts are depleted in Ba_N (Basaltic Volcanism Study Project, 1981). Type 1 basalt has Ba_N ranging from 5.8 to 13, clearly depleted relative to La_N, and therefore more like that of marginal basin basalts.

Various discrimination diagrams involving immobile elements were used to correlate type 1 basalts with a specific tectonic setting. These samples fall dominantly in the field of midocean ridge basalt (MORB) on diagrams of Zr/Y versus Zr (fig. 17) and Nb-Zr-Y (fig. 18), as well as a number of other diagrams (not shown), but also over- lap into the within-plate field. However, the chemistry of type 1 basalts is less like the chemistry of normal MORB (N-MORB) and more closely resembles that of enriched MORB (E-MORB). Type 1 basalts have higher overall concentrations of incompatible elements compared to N-MORB and ratios of $(La/Sm)_N$ (1.25), Th/Hf (0.35), Zr/Nb (3.33–7), Ta/Yb (0.16), Zr/Y (3.4), Hf/Ta (7.4), and Ti/Zr (104) are more consistent with the composition of E-MORB (Sun and others, 1979; Wood and others, 1979, 1981; Wilson, 1989).

On a MORB-normalized incompatible-element diagram (fig. 19), type 1 basalt (GAV–17) has a pattern that, except for P and Ti, is variably enriched in the more incompatible elements. This pattern is unlike that of N-MORB or

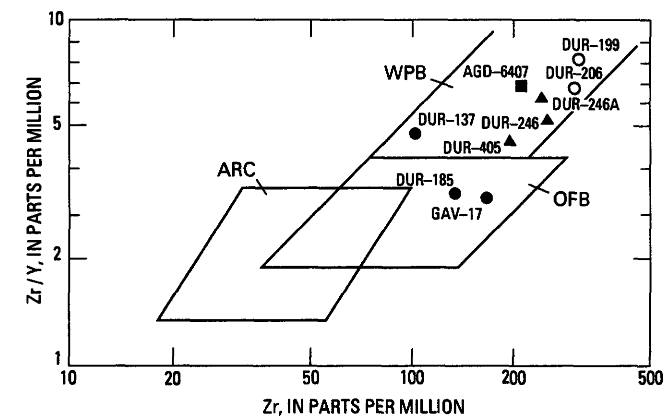

Figure 17. Plot of Zr/Y versus Zr for mafic rocks from beneath the New Jersey Coastal Plain. Fields are WPB, within-plate basalt; OFB, ocean floor basalt; and ARC, island arc basalt. Diagram from Pearce and Norry (1979). AGD, Anchor Gas-Dickinson well sample. Other sample abbreviations as in figure 13. Open square, metagabbro. Other symbols as in figure 15.

that of island arc basalts. The latter are typically depleted in the elements Th to Yb and enriched in Sr to Ba (Pearce, 1983) and have a much flatter pattern from Th to Yb with normalized values <1. Wood and others (1979, 1981) pointed out that island arc basalts are enriched in Cs, Rb, Ba, Th, U, La, and Sr relative to N-MORB. Type 1 basalts have generally low concentrations of these elements. Furthermore, island arc basalts display a distinct Ta–Nb trough (Pearce, 1983), whereas type 1 basalts are enriched in Ta–Nb and display a peak in this part of the pattern. On figure

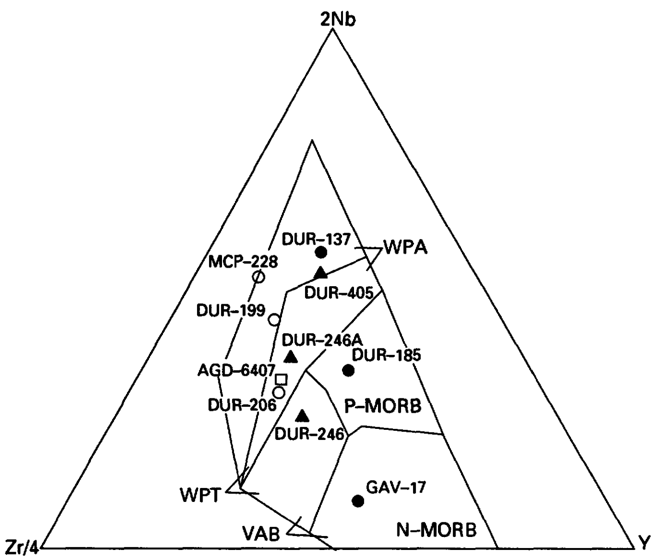

Figure 18. Plot of mafic rocks from beneath the New Jersey Coastal Plain on a Nb-Zr-Y ternary diagram from Meschede (1986). Fields are WPA, within-plate alkalic; WPT, within-plate tholeiitic; VAB, volcanic arc basalt; N-(normal) MORB; and P-(enriched plume) MORB. Symbols and sample abbreviations as in figure 17.

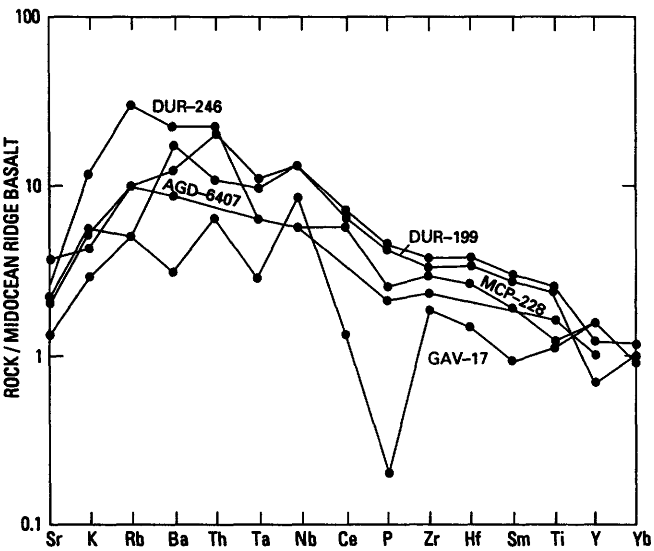

Figure 19. MORB-normalized incompatible-element diagram for metabasalt and meta-andesite. Normalization values from Pearce (1983). Sample abbreviations as in figure 17.

19, type 1 basalt displays some characteristics typical of N-MORB, but enrichment of high-field-strength elements superimposed on the pattern is responsible for its atypical appearance.

Type 1 basalts have a Ti/V ratio of 33 that overlaps the fields of MORB and back-arc basin basalts on the Ti versus V diagram of Shervais (1982) (not shown). Island arc basalts typically have Ti/V ratios of <20 (Shervais, 1982). Scandium contents of 40 ppm for type 1 basalts and La/Nb ratios of 0.19 are also more consistent with the composition of MORB than of island arc basalt. Therefore, the geochemical evidence appears to preclude an island arc origin for type 1 basalts. They seemingly have a MORB affinity but are more fractionated and closer in composition to E-MORB. Wood and others (1979) stated that E-MORB can be distinguished from ocean island basalt and off axis (within plate) basalt in that the latter have ratios of Hf/Ta <2 and Zr/Y >4.5. Type 1 basalt has Hf/Ta of 7.4 and Zr/Y of 3.4, further supporting its MORB affinity. The MORB-like composition of type 1 rocks suggests that the magma that produced these basalts tapped a similar shallow mantle source and underwent considerable fractionation of mafic minerals plus plagioclase prior to emplacement.

Type 1 basalts are chemically dissimilar to Eastern North American basalt and diabase of Jurassic age in the Newark basin. They are also chemically dissimilar to basalts in the Cambrian Chopawamsic Formation or amphibolites of the Ta River Metamorphic Suite in Virginia described by Pavlides (1981) or to basalts in the Cambrian James Run Formation (Gilpins Falls Member) in Maryland described by Higgins and Conant (1990). Type 1 basalts are higher in TiO_2, P_2O_5, FeO^t, Zr, Hf, and Th and lower in CaO, Sc, Ni, and Cr than metabasalt in the James Run Formation. On a diagram of TiO_2 versus Zr/P_2O_5 (fig. 20), type 1 basalts plot away from the fields defined by basalts of the Chopawamsic, Ta River, and James Run. The REE pattern of type 1 basalts is also dissimilar to those of the occurrences just mentioned. However, type 1 basalts have major- and trace-element compositions and REE abundances very similar to those of basaltic rocks of Late Proterozoic to early Paleozoic age (Hancock Member of the Pinney Hollow Formation) (Coish and others, 1985) and early Paleozoic age (Stowe Formation) (Coish and others, 1986) in Vermont. On figure 20, they partially overlap, or fall close to, the field of type 1 basalts.

Type 2 basalts are defined by samples from the DuPont Repauno Works well and from the Mercer County Park well. As shown above, these rocks are typically lower in MgO (4.33–4.78 percent), CaO (7.85–8.15 percent), and Cr (10–50 ppm) and higher in TiO_2 (3.67–3.77 percent), P_2O_5 (0.50–0.55 percent), and Zr (280–350 ppm) than type 1 basalts. They contain slightly lower abundances of transition metals than type 1 basalts. Type 2 basalts have compositions that are hypersthene normative and similar to those of fractionated tholeiitic basalt. They show typical tholeiitic Fe enrichment on an AFM diagram (fig. 15) at slightly higher Fe contents than type 1 basalt. Type 2 basalts have Y/Nb ratios of 0.6–1.67, reflecting their overlap toward transitional and even slightly alkalic composition. They have relatively low Mg' values of 44–46.5, which suggests that they are more fractionated than type 1 rocks, and generally low contents of Cr and Ni. On MgO variation diagrams (fig. 21), type 2 basalts consistently fall along the same fractionation

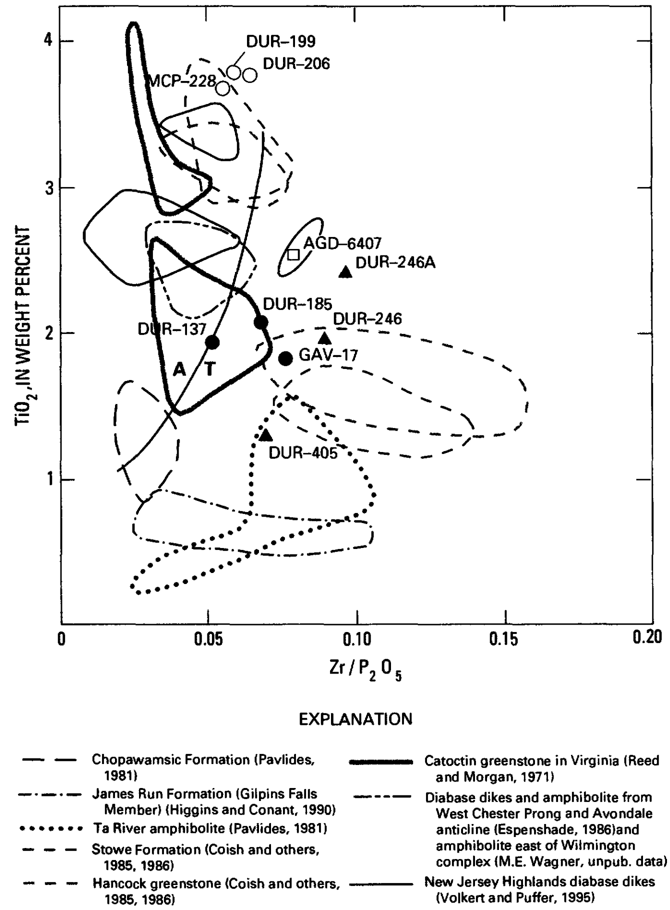

Figure 20. Plot of mafic rocks from the New Jersey subsurface (indicated by symbols and sample abbreviations) compared with mafic rocks from the north-central and northern Appalachians on a diagram of TiO_2 versus Zr/P_2O_5. Dividing line is between alkalic (A) and tholeiitic (T) rocks. Diagram from Winchester and Floyd (1976). Symbols and sample abbreviations as in figure 17.

trend as type 1 basalts, suggesting that the two types are petrogenetically related.

Total concentrations of REE's are higher in type 2 basalts than in type 1; the former have $(La/Yb)_N$ of 5.06. Lanthanum is enriched 89–101× relative to chondrite in type 2 basalts, reflecting their more fractionated composition. The REE patterns (fig. 16) of type 2 basalts are similar to each other, although the DuPont Repauno Works well sample has slightly higher total REE abundances. Similar REE patterns are seen in basalts from continental and oceanic, within-plate tectonic settings (Basaltic Volcanism Study Project, 1981; Wilson, 1989).

Type 2 basalts fall consistently in the within-plate field on diagrams of Zr/Y versus Zr (fig. 17) and Nb-Zr-Y (fig. 18), as well as numerous other diagrams (not shown). A within-plate setting is further supported by incompatible-element ratios of Zr/Nb (5.6–11.7), Hf/Ta (4.6), Zr/Y (7–14) (Wood and others, 1979), and La/Nb (0.6–0.8) (Basaltic Volcanism Study Project, 1981). On a diagram of Th/Yb versus Ta/Yb (fig. 22), type 2 basalts cluster in the field of enriched, within-plate basalts. There is no geochemical evidence suggesting they have experienced much crustal contamination or enrichment by subduction zone fluids, which, according to Pearce (1983), would enrich them in Th.

On a MORB-normalized incompatible-element diagram (fig. 19), type 2 basalts have similar overall patterns that nearly overlap from Ta to Yb. The "humped" shape of their pattern is characteristic of basalts from within-plate settings (Pearce, 1983). Type 2 basalts have higher overall concentrations of incompatible elements than type 1 but have similar enrichments and depletions. The type 1 pattern of GAV-17, therefore, mimics the type 2 patterns, especially from Nb to Ti. The greater amount of fractionation of type 2 basalts probably is a result of their derivation from a deeper mantle source region and (or) lower amounts of partial melting prior to emplacement than type 1 rocks.

Type 2 basalts have Ti/V ratios of 52.4–56.5 that are slightly higher than ratios in type 1 rocks and plot in the field of continental and oceanic tholeiitic to alkalic basalts on the Ti versus V diagram of Shervais (1982). Tholeiitic basalts have Ti/V ratios of 30–50, and transitional to alkalic basalts, 35–70 (Shervais, 1982). By this criterion, type 2 rocks are transitional to alkalic. This interpretation is consistent with their Y/Nb ratios.

Type 2 basalts have major- and trace-element compositions and REE abundances that, like those of type 1 rocks, are dissimilar to those of Eastern North American Jurassic basalt and diabase and also to those of metabasalts of the Chopawamisic, Ta River, and James Run. However, type 2 chemistry is very similar to that of high-TiO_2 amphibolites in the "Wissahickon" Formation east of the Wilmington Complex (M.E. Wagner, unpub. data), and also to that of metabasalt of Late Proterozoic to early Paleozoic age in the Underhill Formation as used by Coish and others (1985), and the early Paleozoic Stowe Formation (Coish and others, 1986) in Vermont and Late Proterozoic or Early Cambrian metabasalt in the Nassau Formation in eastern New York and western Massachusetts (Ratcliffe, 1987a). It also has major- and trace-element abundances nearly identical to those of metabasalt of the Late Proterozoic Catoctin Formation in Virginia (Reed and Morgan, 1971; Espenshade, 1986) and Pennsylvania (Smith and others, 1991) and to those of Late Proterozoic diabase dikes in the southern Blue Ridge (Goldberg and others, 1986), New Jersey Highlands (Puffer and others, 1991; Volkert and Puffer, 1995), and the New York Hudson Highlands (Ratcliffe, 1987b). On figure 20, type 2 basalt overlaps or plots close to these other occurrences.

META-ANDESITE

Spatially associated with type 2 basalt in the DuPont Repauno Works well is metamorphosed andesite having the composition of basaltic andesite. These rocks contain 52.7 to 56.1 percent SiO_2. They are consistently hypersthene normative, contain normative quartz, and are dominantly

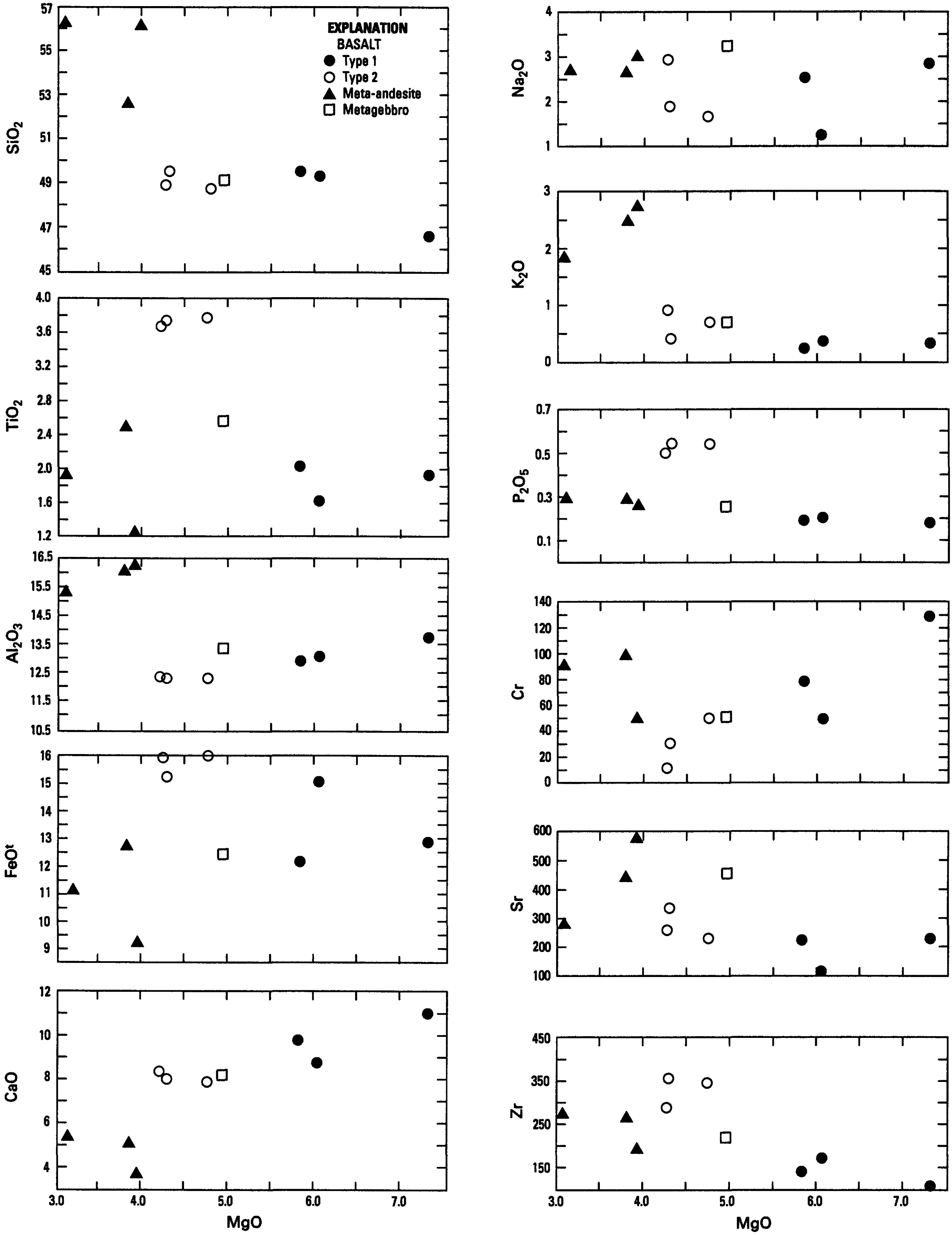

Figure 21. MgO variation diagrams of major and selected trace elements for mafic rocks from beneath the New Jersey Coastal Plain. Major elements in weight percent; trace elements in parts per million. Symbols as in figure 17.

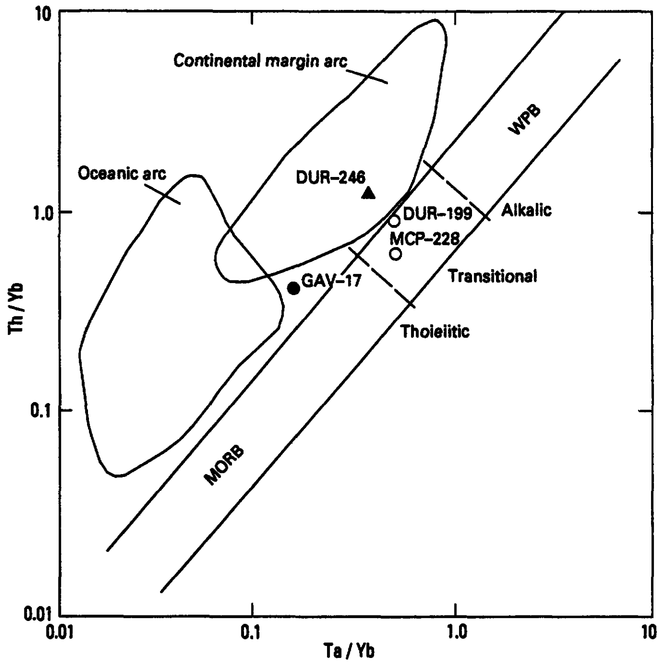

Figure 22. Th/Yb versus Ta/Yb diagram for metabasalt and meta-andesite. MORB, midocean ridge basalt; WPB, within-plate basalt. Diagram modified from Pearce (1982, 1983).

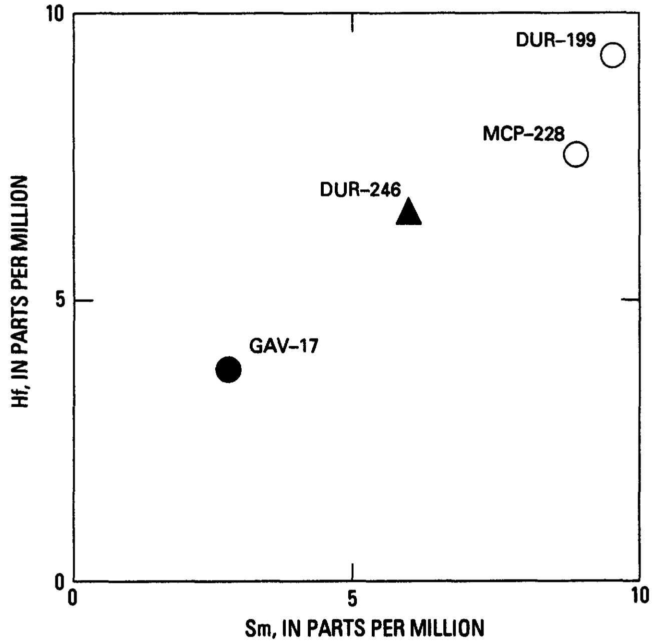

Figure 23. Hf versus Sm diagram for metabasalt and meta-andesite. Symbols and sample abbreviations as in figure 17.

tholeiitic in composition, although Y/Nb ratios of 0.8 to 2.5 suggest that they range to slightly alkalic. They show typical tholeiitic Fe enrichment on an AFM diagram (fig. 15) with exception of sample 405, which contains less Fe and falls within the calc-alkaline field. The three meta-andesites sampled for this study contain 15.7 to 16.6 percent Al_2O_3 and 1.78 to 2.68 percent K_2O. Compared to type 2 basalts, they are lower in MgO, CaO, FeO^t, and P_2O_5. However, they have TiO_2 contents, trace-element abundances, and Mg' values (41.8–52.5) that overlap those of both type 1 and type 2 basalts. Concentrations of Cr are somewhat higher (50–99 ppm) than in type 2 samples, as are the other transition metals, and similar to abundances in type 1 rocks.

Meta-andesites sampled have relatively high total REE concentrations (La/Yb_N=6.33) and are light-REE enriched with La=84.5× chondrite. The REE pattern (fig. 16) is similar to that of type 2 basalts. The same is seen on a MORB-normalized incompatible-element diagram (fig. 19), with data for meta-andesite and type 2 basalts display- ing similar "humped" patterns and incompatible-element enrichments. However, meta-andesite is further enriched in K, Rb, Ba, and Th. Pearce (1983) has proposed that enrichment in these elements, superimposed on a within-plate pattern, may indicate a contribution from a subduction zone component. It may also be attributable to the effects of crustal contamination. However, this seems less likely given the close spatial association with type 2 basalts, which show little evidence of contamination. Enrichment in K, Rb, and Ba may also be the result of low-pressure fractionation as proposed by Dostal and others (1982). We favor this as the cause for the enrichment in basaltic andesites for reasons discussed below.

By use of selected major- and trace-element abundances and trace-element-ratio discriminants of Bailey (1981), meta-andesite from the DuPont Repauno Works well has characteristics of both orogenic and non-orogenic andesite. On the basis of Th versus La/Yb and Sc/Ni versus La/Yb diagrams, which Bailey (1981) stated are the most sensitive for discriminating tectonic settings, meta-andesite falls consistently in the continental margin arc field. These rocks similarly plot in the continental margin arc field on a diagram of Th/Yb versus Ta/Yb (fig. 22). On diagrams of Zr/Y versus Zr (fig. 17) and Nb-Zr-Y (fig. 18) and other diagrams not shown, meta-andesite plots consistently in the within-plate field.

Several lines of evidence suggest a possible petrogenetic relation between meta-andesite and type 2 basalt. These include (1) their overlapping spatial and temporal association in the DuPont Repauno Works well, (2) similar REE and incompatible-element concentrations, (3) other trace-element similarities, and (4) consistent plot in within-plate tectonic setting on various discrimination diagrams. On diagrams of Hf versus Sm (fig. 23) and La/Sm versus La/Yb (fig. 24), meta-andesite falls along the same trend as types 1 and 2 basalt. The correlation of all three rock types on these diagrams is noteworthy and seems to imply a petrogenetic relation. On figure 23, these rocks define a linear progression from olivine tholeiite to quartz tholeiite to transitional alkalic to alkalic. However, meta-andesite does not consistently fall along the same fractionation trend as types

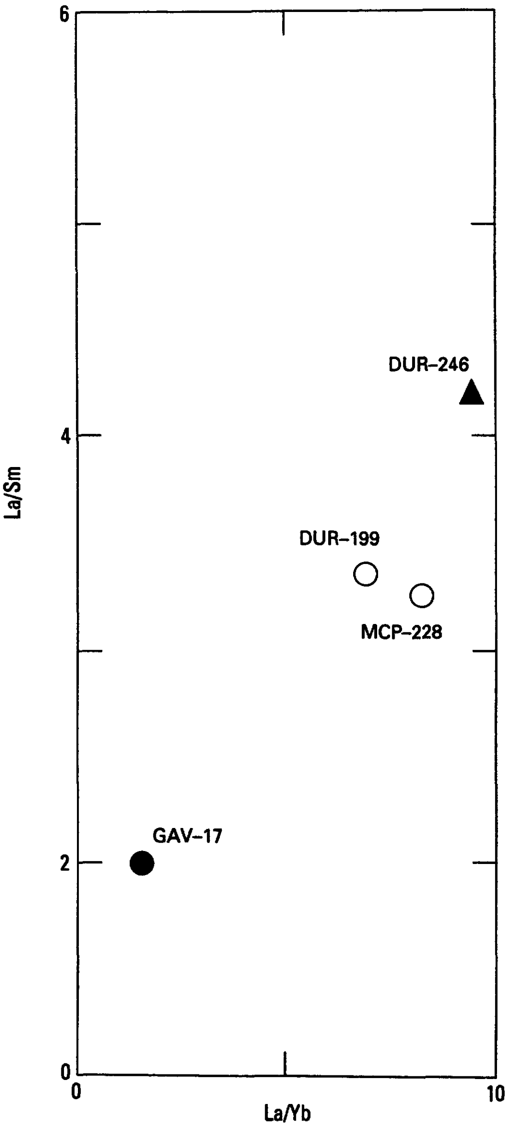

Figure 24. La/Sm versus La/Yb diagram for metabasalt and meta-andesite. Symbols and sample abbreviations as in figure 17.

1 and 2 basalt on MgO variation diagrams (fig. 21). Nor does it lie along the trend of the metabasalts on a Th versus Hf diagram (not shown). Ratios of Hf/Th for the two basalt types overlap and range from 2.36 to 3.77, whereas meta-andesite has a much lower Hf/Th ratio of 1.49. Nevertheless, the evidence suggests that basaltic andesite and type 2 basalt are related. We interpret the former to have been derived principally through fractional crystallization from type 2 basalt prior to emplacement. Fractionation mainly involved olivine, clinopyroxene, and, to a lesser extent, plagioclase. This is supported by the low Mg' values, low CaO/Al_2O_3 ratios, low Sc contents, inverse correlation of Sr with MgO (fig. 21), and small Eu anomalies (fig. 16) present in both rock types. This interpretation is further supported by the experimental work of Ringwood (1977) who reported that basaltic andesite may be produced through fractionation from a parental basalt; the resulting rock will be enriched in light rare earth elements and depleted in heavy rare earth elements.

METAGABBRO

Fine-grained metagabbro from the Anchor Gas Dickinson well is somewhat similar geochemically to type 2 basalts but differs in having lower contents of FeO^t (12.33 percent), Nb (20 ppm), and Zr (210 ppm) and higher contents of Na_2O (3.24 percent) and Sr (450 ppm). This rock is hypersthene normative and contains normative quartz but substantially less than type 2 basalt and meta-andesite. Metagabbro is distinctly tholeiitic in composition and has Y/Nb of 1.5. It has a relatively low Mg' of 49.4 and low Cr content (50 ppm). A complete suite of trace elements and REE's could not be obtained on this sample. However, sufficient elements were obtained to construct a partial pattern on a MORB-normalized incompatible-element diagram (fig. 19). The metagabbro data clearly display an enriched pattern with a "humped" shape roughly similar to and intermediate between the shapes of data for type 1 and type 2 basalts. Incompatible-element abundances are closer to those of type 2 from Sr to Ba but closer to those of type 1 from P to Yb.

With the exception of SiO_2, CaO, K_2O, and Cr contents, metagabbro data fall outside of the fractionation trend defined by type 1 and 2 basalts on MgO variation diagrams (fig. 21). The same is seen on a diagram of TiO_2 versus Zr/P_2O_5 (fig. 20), with metagabbro plotting away from the fields of either type 1 or type 2 basalt. On diagrams of Zr/Y versus Zr (fig. 17) and Nb-Zr-Y (fig. 18), metagabbro consistently falls in the within-plate field. It straddles the fields of within-plate and volcanic arc basalts on a diagram of Y versus Cr (not shown). We think that the geochemical differences between metagabbro and types 1 and 2 basalt are sufficient to preclude a petrogenetic relation. Metagabbro from the Anchor Gas Dickinson well is a moderately fractionated tholeiite with an affinity toward a within-plate tectonic setting. Whether this setting was continental or oceanic is impossible to say at this time.

METAGRAYWACKE AT ISLAND BEACH STATE PARK

Schistose gneiss from the U.S. Geological Survey Island Beach State Park well falls within the field of graywacke on figure 13. This sample contains about 30 percent modal quartz and 68 weight percent SiO_2 and has a K_2O/Na_2O ratio <1, values that correspond to the quartz-intermediate graywacke of Crook (1974). It falls within the active continental margin field on a diagram of K_2O/Na_2O versus SiO_2 (fig. 14). In these respects, the chemistry of this rock is similar to that of psammitic schist from the wells in Gloucester County. However, a comparison of the geochemical discriminants of Bhatia (1983) shows that the Island Beach State Park well sample has somewhat lower Fe_2O_3+MgO and TiO_2 contents and a slightly higher Al_2O_3/(CaO+Na_2O) ratio than the Gloucester County samples. It is also lower in Cr and slightly higher in Nb. Therefore, it is classified as a continental island arc sandstone. Sediments in this type of setting are deposited in basins adjacent to island arcs developed on continental crust or on thin continental margins (Bhatia, 1983). The high contents of modal plagioclase (40 percent) and Na_2O (3.51 weight percent) suggest that the Island Beach State Park sample was receiving felsic volcanic/plutonic detritus from a magmatic source. A similar interpretation was discussed above for the Gloucester County metagraywacke.

DISCUSSION

Correlating the subsurface pre-Mesozoic crystalline basement rocks in New Jersey with outcropping rocks in adjacent States and in distant terranes is hindered by the overall structural complexity of the exposed rocks, as well as by the limited amount of subsurface data available for New Jersey. However, it is logical to assume that subsurface crystalline rocks in New Jersey are a continuation of the complex structures of the exposed Piedmont of adjacent States and therefore represent a composite of different lithotectonic units contained in a series of stacked thrust sheets. The following interpretations are based largely on drill-hole, geochemical, and potential field geophysical data.

No intrusive rocks, nor any of the layered, two-pyroxene gneisses of the Wilmington Complex, were observed in any of the well samples studied. Rocks of the Wilmington terrane appear to be largely confined to southeastern Pennsylvania and northern Delaware and extend into New Jersey only along the western tip of Salem County (Volkert and Drake, 1991). The gravity data (fig. 8) and aeromagnetic data (fig. 9) also support this interpretation.

All of the amphibolite-facies pelitic and psammitic schist and schistose gneiss occurring along the Fall Line and extending at least to the western edge of Monmouth County probably are equivalent to the "Wissahickon" Formation, which is included in the Potomac terrane of Horton and others (1989) and the Philadelphia terrane of Faill and MacLachlan (1989) in Pennsylvania. Volkert and Drake (1991) interpreted these rocks to be equivalent also to the western part of the Brompton-Cameron terrane of Zen and others (1989) in New England (fig. 7). Rankin (1994) suggested that the correlation of the Potomac terrane with the Brompton-Cameron terrane is incorrect because the Brompton-Cameron terrane lacks the pre-Taconic deformation characteristic of the Potomac terrane. A boundary between these terranes is probably present in the subsurface. In New Jersey, these pelitic and psammitic rocks represent a sequence of "eugeoclinal" sediments deposited in a slope and basin setting. Alternating shale and graywacke layers of varying thickness recovered from drill holes in Gloucester County probably are turbidite deposits. A similar interpretation has been suggested for high-grade rocks like the "Wissahickon" in the Potomac terrane in Maryland and Pennsylvania (Drake and others, 1989; Muller and others, 1989; Crawford, 1991). The basin in which these sediments were deposited must have been situated east of the North American continental margin. We interpret this basin as having been a marginal, perhaps back arc, basin, as did Crawford and Mark (1982) and Pavlides (1989).

The occurrence of type 1 basaltic rocks having a MORB-like chemistry with marine sediments points to the likelihood that a small spreading center existed within the basin. The areal extent and thickness of type 1 basalts in New Jersey are unknown due to the paucity of basement samples from outside of Gloucester County. However, similar low- to intermediate-TiO_2 basalts having MORB and island arc affinities are known west of the Wilmington Complex in southeastern Pennsylvania (M.E. Wagner, unpub. data) within schist and schistose gneiss similar to the "Wissahickon." Closely associated with pelitic and psammitic schist and also type 1 basalt is type 2 basalt. Basaltic rocks that are chemically identical to type 2 rocks are known from artificial exposures and from drill holes in the Trenton prong in New Jersey (Volkert and Drake, 1993; R.A. Volkert, unpub. data). Some of these basalts may be dikes and some sills. We interpret these high-TiO_2 and incompatible-element-enriched basalts to be correlative with Late Proterozoic diabase dikes that intrude Middle Proterozoic rocks in the New Jersey Highlands (Puffer and others, 1991; Volkert and Puffer, 1995) and other Late Proterozoic metabasalt from throughout the Appalachians. In this regard, they record tholeiitic and minor alkalic magmatism generated during crustal extension related to Iapetan rifting. If this correlation is correct, then the ages of the pelitic and psammitic schist protoliths in this basin range from Late Proterozoic to early Paleozoic. Similar age estimates were advanced by Drake (1985, 1986) for Potomac terrane rocks in Virginia, by Higgins (1972) and Muller and Chapin (1984) for rocks in Maryland, and by Crawford (1991) for rocks in southeastern Pennsylvania.

The close spatial and temporal association of type 1 and 2 basalt and meta-andesite within the same sediment package is intriguing. The association of transitional to alkalic basalts with tholeiitic MORB basalts is not uncommon and is known from modern ocean ridge settings (for example, Shibata and others, 1979). The more fractionated type 2 basalts probably were generated from a deeper mantle source through small amounts of partial melting. Less fractionated type 1 basalt (E-MORB) may have originated from a shallower mantle source that had undergone greater amounts of partial melting than type 2 source rocks. These two basalt types possibly intruded the spreading center along a "leaky" transform fault or at some location along the flank of the ridge. Less enriched type 1 basalt is more typical of MORB erupted in a back arc basin setting. Whether the more fractionated type 1 basalt is similar MORB that underwent mixing with type 2 magma or is from a different, more enriched source region is difficult to say at this time. As discussed above, type 2 basalt likely was a parental magma to meta-andesite. We interpret meta-andesite to have been derived from type 2 basalt principally through fractionation involving olivine, clinopyroxene, and, to a lesser extent, plagioclase. Conformable contacts between meta-andesite and pelitic schist suggest that the former may have intruded as sills. Type 2 basalts may have intruded as dikes and (or) sills; contact relations are not clearly known. The major- and trace-element compositions of type 2 basalt and basaltic andesite suggest that they are mantle derived. Any model relating their magmatism to a subduction zone setting seems unlikely, as their emplacement was clearly in an extensional tectonic setting and unrelated to subduction. No evidence of associated rocks of dacitic or rhyolitic composition was seen within rocks of this marginal basin. Petrogenetic conditions apparently prevented magma intruding the basin from fractionating further to produce rocks of a more evolved composition. Perhaps these conditions were due to the presence of a relatively thin crust in this part of the Appalachians at this time.

Sedimentary melange deposits were recognized and mapped in the Potomac terrane in Virginia (Drake, 1985) and Maryland (Muller and others, 1989; Higgins and Conant, 1990). However, no such rock was encountered in any of the drill holes from the Potomac terrane in New Jersey. While noteworthy, this lack of data may have little meaning bcause basement wells are much less abundant immediately southeast of the inner Coastal Plain.

Recognition of possible nappe-stage folds in psammitic schist and amphibolite from Gloucester County is significant in documenting the possible presence of nappe structures in New Jersey involving rocks of the Potomac terrane. Similar structural interpretations have been proposed for Grenville-age basement cored "domes" in Maryland (Muller and Chapin, 1984) and also in Pennsylvania (Wagner and Srogi, 1987). It is generally accepted that emplacement of these nappes and northwestward-directed transport of Potomac terrane rocks along thrust faults over rocks of the North American craton and its cover rocks occurred in the Ordovician during the Taconic orogeny.

Lack of drill-hole data leads to uncertainty whether rocks of the James Run Formation (Chopawamsic terrane) extend into New Jersey. Such rocks, if present, should be outboard of the Potomac terrane. However, interpreted Potomac terrane rocks in New Jersey occur farther southeast than exposed occurrences of the James Run in northeastern Maryland and northern Delaware (fig. 25). Therefore, the James Run would have to trend southeast through northern Delaware and then into central Salem County, N.J. Geologic mapping in northeastern Maryland (Higgins and Conant, 1990) shows that many of the units do have a east-southeast trend. To an extent, the aeromagnetic contours are also east-southeast-trending through northern Delaware (fig. 9). Insufficient information exists to interpret whether this structural divergence is related to possible displacement along north-trending faults, or to arcing of the regional structural grain in a trend that is subparallel to the Salisbury embayment. Regardless, it is possible that the James Run extends into New Jersey. Unfortunately, reliable sample descriptions are lacking from the only well in central Salem County for which information is available (appendix, well no. 102).

Although Volkert and Drake (1991) initially correlated metabasalt and meta-andesite in some Gloucester County wells with similar rocks in the Chopawamsic terrane, it is now clear from the geochemistry that these rocks are not the same as the Chopawamsic Formation or the James Run Formation and instead are part of the Potomac terrane. Wagner and Srogi (1987) suggested that the Wilmington Complex represents the root of a volcanic arc, and Pavlides (1989) proposed that the Wilmington Complex may be the northeastern extent of a volcanic arc represented by the Chopawamsic and James Run volcanic arc. We tentatively extend the James Run into central Salem County (fig. 25), but we recognize that it could also taper and end, along with the base of the arc, in northern Delaware. Our reason for extending this terrane is largely influenced by the chemistry of the pelitic and psammitic rocks from the inner Coastal Plain. Their highly sodic composition suggests a magmatic arc source that shed abundant volcanic detritus into the basin. The lack of K-feldspar in these rocks precludes an uplifted continental block (either part of the North American craton or a separate fragment thereof) as a sediment source.

Pyroxenite encountered in well Eb 44–08 in Delaware (appendix, well no. D8) may be correlative with pyroxenite in the Bel Air-Rising Sun terrane (Baltimore Complex) in northeastern Maryland. However, the pyroxenite in well Eb 44–08 is more than 15 mi southeast of the exposed James Run Formation in Maryland, whereas the main block of the Bel Air-Rising Sun terrane is northwest of the exposed James Run. Gabbro and serpentinite are exposed south of the exposed James Run in northeastern Maryland (Higgins and Conant, 1990). Similar gabbro at Iron Hill and serpentinite, which was returned in nearby wells, occur north of the pyroxenite in northern Delaware. Higgins and Conant (1990) tentatively correlated these rocks with metagabbro at Aberdeen, Md. Horton and others (1989) referred to this as the Aberdeen block and interpreted it to be part of the Bel Air-Rising Sun terrane, which was structurally emplaced onto the James Run Formation. Pyroxenite in well Eb 44–08 is surrounded to the immediate north by wells returning a diversity of lithologies; these include chlorite schist, biotite

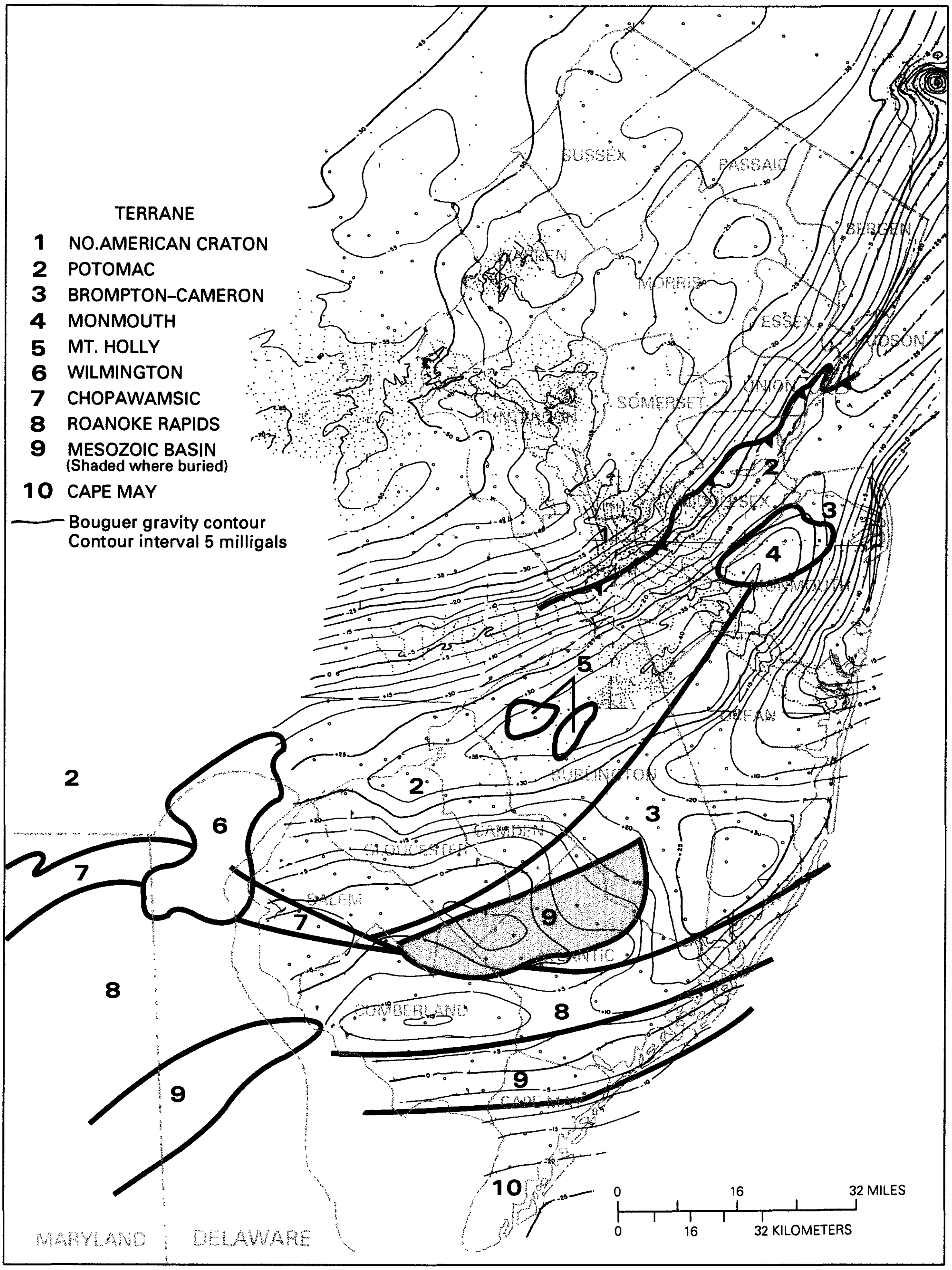

Figure 25. Speculative assignment of pre-Cretaceous basement rock in New Jersey to central and northern Appalachian terranes. Terranes are superimposed on Bouguer gravity anomaly map of New Jersey modified from Bonini (1965). Location of inferred, buried Mesozoic basin from Sheridan and others (1991); inferred Mesozoic basin in Delaware from Benson (1992).

schist, and quartzite. This association is dissimilar to that of rocks in the Bel Air-Rising Sun terrane. The pyroxenite may have been thrust over this sequence of rocks and may represent another fragment of the Bel Air-Rising Sun terrane. Alternatively, the pyroxenite may be ultramafic rock preserved in a structurally higher thrust sheet unrelated to this terrane. In this regard, the pyroxenite represents a small sliver of oceanic crust emplaced within rocks having a volcanic arc affinity. Therefore, the pyroxenite, chlorite schist, biotite schist, and quartzite are related and would be part of the same terrane. Limited subsurface data available in this part of the Delaware Coastal Plain prohibit a more definitive interpretation. Our preference at this time is to interpret the pyroxenite as a separate fragment of ultramafic rock since it is south of, and seemingly unconnected to, the metagabbro farther north in Delaware. Hence, we do not think it is another detached fragment of the Bel Air-Rising Sun terrane. We interpret the pyroxenite, chlorite schist, biotite schist, and quartzite to be related, and we correlate them with similar rocks in the Roanoke Rapids terrane of Horton and others (1989). This terrane, as described by Boltin and Stoddard (1987), consists of greenschist-facies metavolcanic and metasedimentary rocks and associated ultramafic rocks of the Eastern slate belt and amphibolite facies gneisses of the Raleigh belt. By our interpretation, rocks correlative with the Roanoke Rapids terrane would extend through central Salem and Cumberland Counties and into Atlantic County (fig. 25). This is consistent with the interpretation of Sheridan and others (1991) whose gravity model suggests that this part of the New Jersey Coastal Plain may be underlain by ophiolite, metavolcanic rock, and melange.

The metaquartzite drilled in the Anchor Gas-Ragovin well (appendix, well no. 103) was seen in no other New Jersey wells. However, one well penetrating basement in Delaware, Eb 23–22 (appendix, well no. D6) encountered muscovite-free metaquartzite. No other wells in New Jersey are close enough to permit direct correlation with the Anchor Gas-Ragovin quartzite. In Delaware, several wells were drilled near Eb 23–22. Most penetrated a soft, light-green chlorite schist. One well (Ec 32–07) to the immediate east returned mica schist, and well Eb 44–08 just to the south returned pyroxenite (appendix, well nos. D7 and D8, respectively). Metaquartzites are ubiquitous throughout the Appalachians and occur in several lithologic sequences from Middle Proterozoic through Paleozoic in age. There is nothing distinctive about the quartzite from the Anchor Gas-Ragovin well in terms of its mineralogy. Neither its thickness nor its lithologic associations are known.

If the quartzites from the Anchor Gas-Ragovin well and well Eb 23–22 in Delaware are coeval, then several possible interpretations exist as follows: (1) the association of pyroxenite and quartzite (metamorphosed chert?) could represent a partial ophiolite sequence; (2) the quartzites may not be valid units but may be thick quartz veins perhaps associated with shear zones; or (3) the pyroxenite may be part of a more extensive mafic/ultramafic body that was structurally emplaced with the quartzite, chlorite schist, and biotite schist that occur to the immediate north. As stated above, we interpret the quartzite, chlorite schist, and biotite schist from Delaware to be related and to be part of a volcanic arc sequence that includes the pyroxenite. The Anchor Gas-Ragovin well appears to be along the same gravity trend (fig. 8) as the pyroxenite, quartzite, and surrounding wells in Delaware; it is located north of a pronounced gravity high.

The sequence of chlorite-quartz-plagioclase schist/gneiss and altered metavolcanic rock penetrated in well Gd 33–04 in northern Delaware (appendix, well no. D11) occurs south of the pyroxenite in well Eb 44–08. No basement rock samples are available for the intervening area in Delaware. However, several wells along strike in eastern Maryland returned similar lithologies. Descriptions from wells KE-DB 40 and KE-BG 33 are of quartz-plagioclase gneiss containing chlorite with some associated quartzite and highly altered schist or gneiss containing chlorite and sericite, respectively (Hansen and Edwards, 1986). These same authors described another well farther to the west, CH-BE 57, which drilled chlorite-quartz-plagioclase schist. These Maryland wells are surrounded by wells that dominantly returned biotite-quartz-plagioclase gneiss or schist. In New Jersey, quartzite from the Anchor Gas-Ragovin well is on strike with the Maryland and Delaware wells. Well Gd 33–04 in Delaware, the Maryland wells, and the New Jersey quartzite all occur in an area of slightly positive gravity anomalies (fig. 8) but subdued aeromagnetic expression (fig. 9). The similarity of the chlorite schist, biotite schist, and quartzite drilled north of the pyroxenite to rocks in some of the Maryland wells and the quartzite from the Anchor Gas-Ragovin well is striking, and we interpret them to be correlative. Therefore, we interpret that part of southern New Jersey and northern Delaware including the pyroxenite in well Eb 44–08 and the gravity high in central Cumberland County (fig. 25) is underlain by rocks correlative with the Roanoke Rapids terrane.

The rocks beneath the central part of the Coastal Plain are much more difficult to interpret because of the lack of data. The positive gravity (fig. 8) and aeromagnetic (fig. 9) anomalies in Monmouth and Burlington Counties occur along the same general structural and geophysical trend as anomalies that define the Wilmington Complex and the Baltimore Complex. Both complexes consist largely of mafic rock. The gravity and magnetic anomalies in Monmouth and Burlington Counties probably result from mafic rock of similar composition occurring at or beneath the basement surface. Sugarman (1981) modeled the Monmouth County body as rootless and extending no deeper than 0.8 mi. However, thus far, no wells have penetrated these bodies. In keeping with the interpretation of the Baltimore Complex (Crowley, 1976) and the Wilmington Complex (Crawford and Mark, 1982; Wagner and Srogi, 1987; Horton and others, 1989) as allochthonous, we suggest that the Monmouth County and Burlington County mafic bodies are allochthonous also. They are herein named the Monmouth terrane and the Mount Holly terrane, respectively. Whether they are correlative with rocks in the Bel Air-Rising Sun terrane, or perhaps the Wilmington terrane, or whether they are bodies of mafic rock unrelated to either terrane or even to each other is difficult to say. Therefore, at this time, they are shown as separate terranes on figure 25.

The graphite in the New Jersey Highway Authority well (appendix, well no. 35) and the U.S. Geological Survey Freehold observation well (appendix, well no. 38) in Monmouth County, N.J., the W.&K. Oil Company well (appendix, well no. 42) and the Oxly 1A well (appendix, well no. 45) in Ocean County, N.J., and the Brooklyn Union Gas Company well (appendix, well no. N9) in Queens County, N.Y., is significant, as these wells all occur in a linear north-northeast-trending belt. The closest exposed crystalline rocks that are lithologically similar and contain graphite are the following rocks of the Manhattan prong: (1) the Middle Proterozoic Fordham Gneiss (unit V of Brock, 1989); (2) the informal Late Proterozoic and Cambrian Ned Mountain formation of Brock (1989), which is correlated with the Pound Ridge Granite and Yonkers Gneiss; and (3) the Ordovician Walloomsac Formation (Brock, 1989; Hall, in press). These units are within the North American Craton terrane of Zen and others (1989). One problem with correlating any of these rocks with the New Jersey well samples is that rocks between the Fordham and Walloomsac occur west of the Cameron's Line thrust fault, whereas these wells project to the east of the Cameron's Line thrust fault (fig. 12). Other possible correlations in southwestern Connecticut include The Straits Schist (equivalent to the Goshen Formation in Massachusetts), the Wepawaug Schist (equivalent to the Waits River Formation in Massachusetts), the Hawley Formation, or the Harrison Gneiss (Rodgers, 1985), all of which are graphite bearing and occur east of the Cameron's Line fault. They occur within the Brompton-Cameron terrane of Zen and others (1989) but to the east of rocks in this terrane correlative with those of the Potomac terrane. Each of the aforementioned wells is located along gravity (fig. 8) and aeromagnetic (fig. 9) trends that are more similar to trends of the Brompton-Cameron terrane than to trends of the cover-sequence rocks in the Manhattan prong (North American Craton terrane). Therefore, the best correlation appears to be with the graphitic schists in southern Connecticut. Unfortunately, none of the graphitic well samples is fresh enough for geochemical analysis. These carbonaceous schists likely represent a sequence of metamorphosed graywacke and minor pelitic rocks that were deposited in a locally restricted marine basin.

During the 1960's, pelmatozoan fragments were discovered at the base of the Walloomsac near its contact with the Inwood Marble in the Verplanck Point Quarry in the Manhattan prong (Ratcliffe and Knowles, 1968). This fossiliferous unit is underlain by a white dolostone. It is possible that the schist drilled in the W.&K. Oil Company well at Jacksons Mills (appendix, well no. 42) may be Walloomsac and that the "fossils" (Henry Kummel, New Jersey Geological Survey permanent notes, 1922) recovered from this well (if there is any validity to this report) occur in the same basal part of the formation. Because each of these central Coastal Plain wells is outboard of the Potomac terrane, interpreting the schist in the W.&K. Oil Company well as Walloomsac would require the Walloomsac to occur in a window beneath accreted terranes exposed farther to the west. Our preference is to interpret the rock drilled in these wells as being correlative with schists in the Brompton-Cameron terrane for reasons already stated.

The phlogopitic marble from the Butler Place well (appendix, well no. 53) may correlate with the phlogopitic metalimestone member of the Cockeysville Marble (Crowley and others, 1975) in the Maryland, Delaware, and Pennsylvania Piedmont, with the Inwood Marble, or with the phlogopitic marble member (Hall, in press) of the Walloomsac Formation in the Manhattan prong, or with siliceous marble in the Waits River or Gile Mountain Formations in southern New England. As stated above, the association of pelitic schist and marble from bedrock wells in the central Coastal Plain suggests that these rocks may be spatially related and equivalent to cover-sequence rocks cropping out in the Manhattan prong or in the Connecticut Valley synclinorium to the northeast. If they are correlative with the basement and cover-sequence rocks in the Manhattan prong, then the rocks in this part of the Coastal Plain would occur in a window beneath the thrust sheet(s) that transported rocks of the Potomac terrane farther to the west. However, because rocks in the Manhattan prong do not appear to be along the same gravity and aeromagnetic trend as the Butler Place well, or any of the wells penetrating graphitic schist, and because the Butler Place well is outboard of Potomac terrane rocks, the best correlation appears to be with rocks in the Connecticut Valley synclinorium (Brompton-Cameron terrane). The associated schist and marble in the central Coastal Plain are shown as a component of this terrane on figure 25.

The outermost edge of the New Jersey Coastal Plain was penetrated only by the U.S. Geological Survey Island Beach State Park well (appendix, well no. 46) and the Anchor Gas-Dickinson well (appendix, well no. 104). The migmatitic quartzofeldspathic gneiss from the Island Beach State Park well is important in that it is the easternmost sample of basement available. It occurs just west of the projected trend of several exposed and inferred early Mesozoic basins. These include the Hartford basin in Connecticut; the inferred New York Bight basin south of Long Island (Hutchinson and others, 1986); an inferred, unnamed basin in southern Cumberland and Atlantic Counties, N.J. (Benson, 1992); the Queen Anne basin in eastern Maryland

(Hansen, 1988), which Benson (1992) extended into north-central Delaware; and the Taylorsville basin in Virginia. The Taylorsville Basin is in contact on the northwest with rocks of the Goochland terrane along the Hylas fault zone (Farrar, 1984). As described by Farrar, rocks of the Goochland terrane consist of the State Farm Gneiss, which crops out in a series of domelike structures, overlain by the Sabot Amphibolite, Maidens Gneiss, and meta-anorthosite of Montpelier, which contain relict granulite-facies mineral assemblages overprinted by amphibolite-facies assemblages.

As stated above, chemistry of the Island Beach State Park well sample from a depth of 3,890 ft reveals that this rock is metagraywacke. The State Farm Gneiss is similar mineralogically, but it is characterized by abundant titanite, whereas the metagraywacke from this well contains only trace amounts of titanite (table 1) and a low TiO_2 content (table 2). Parts of the Maidens Gneiss are also similar mineralogically to this well sample; however, the latter displays no evidence of relict granulite-facies assemblages. Unfortunately, no chemistry, published or unpublished, exists for rocks in the Goochland terrane (L. Glover, oral commun., 1990), making any correlation with lithologies in the Maidens Gneiss largely speculative. No rocks fitting the description of Goochland lithologies were encountered in New Jersey in any of the wells for which samples are available. Therefore, at this time, we doubt that rocks having an affinity to the Goochland terrane extend into New Jersey. This interpretation receives support from a reexamination of the potential-field data by D.L. Daniels (written commun., 1993), suggesting that gravity and magnetic trends similar to those of the Goochland terrane may not continue into New Jersey.

The Island Beach State Park well is along the same structural and magnetic trend as rocks in the Connecticut Valley synclinorium (Brompton-Cameron terrane) occurring west of the Hartford basin in southern Connecticut. The closest well in New Jersey is the Oxly 1A well (appendix, well no. 45) to the west. The graphitic schist/gneiss from this well appears to have an affinity to some of the sulfidic, carbonaceous rocks in the Brompton-Cameron terrane. The location of the Island Beach State Park well west of the projection of several inferred, buried, early Mesozoic basins from Connecticut to Maryland suggests that it is likely part of the Brompton- Cameron terrane also. This is more consistent with the lithologic association of nearby wells in New Jersey and also exposed rocks along strike in southern Connecticut than a correlation with Goochland terrane lithologies. Therefore, for reasons stated, as well as the closeness of the Island Beach State Park well to the rocks in southern Connecticut, we propose that the eastern edge of New Jersey is underlain by rocks correlative with the Brompton-Cameron terrane (fig. 25).

Fine-grained metagabbro from the bottom of the Anchor Gas-Dickinson well (appendix, well no. 104) has a distinctly enriched tholeiitic composition (fig. 20) that is unlike that of eastern North American Jurassic basalt or diabase. Thus, correlation with a flow or dike in a buried Mesozoic rift basin can be ruled out. Metagabbro contains major-element abundances similar to those of microgabbro and quartz gabbro from the Baltimore Mafic Complex described by Hanan and Sinha (1989) and Higgins and Conant (1990). Unfortunately, no published trace-element abundances for these rocks are available for comparison.

The occurrence of gabbro in the Anchor Gas-Dickinson well in an area of negative gravity expression (−20 milligals, fig. 8) and moderate aeromagnetic expression (600 to 800 gammas, fig. 9) is enigmatic. Hansen and Edwards (1986) described similar gabbro from well WO–CE 12 (Mobil Bethards No. 1) in the eastern shore of Maryland just south of Delaware. This well is along the same gravity and aeromagnetic trend as the Anchor Gas-Dickinson well. These wells are approximately 40 mi apart, yet they returned identical rocks. The absence of positive gravity and magnetic anomalies in this part of New Jersey suggests that gabbro in the Anchor Gas-Dickinson well may be preserved as a very thin thrust slice above more felsic rocks or that it occurs very locally in a volcanic arc sequence. The latter interpretation is supported by the occurrence of low-grade metamorphic rocks, namely volcaniclastic phyllite and calcareous metasiltstone, to the south of WO–CE 12 in Maryland and Virginia (Hansen and Edwards, 1986). If this mixture of rock types is related, then they may be correlative with Eastern slate belt rocks (Chesapeake block of Horton and others, 1991). These consist of greenschist- grade metasedimentary and metavolcanic rocks locally intruded by gabbro. The Anchor Gas-Dickinson well, WO–CE 12, and the Eastern slate belt occur along similar gravity and aeromagnetic trends. Because the Anchor Gas-Dickinson well occurs outboard of the Delaware well that returned pyroxenite, correlation with the Bel Air-Rising Sun terrane seems unlikely. It is possibly coextensive with other gabbro and greenschist-facies metamorphic rocks in the Chesapeake block as described by Horton and others (1991). However, because this terrane is distanced from the Anchor Gas-Dickinson well, gabbro from it may represent a separate terrane fragment. We, therefore, tentatively name this the Cape May terrane.

Several workers (for example, Hutchinson and others, 1986; Benson and Doyle, 1988; Sheridan and others, 1991; Benson, 1992) have proposed that buried Mesozoic rift basins containing rocks correlative with those in the Newark basin occur beneath the Coastal Plain in New Jersey and adjacent States, as well as offshore. With the exception of Mesozoic rocks encountered in wells along the Fall Line in New Jersey, only a few wells, none of which are in New Jersey, have definitively penetrated Mesozoic sedimentary or igneous rocks, and the presence of such rocks has been inferred largely from seismic-reflection profiles and gravity modeling. Several wells beneath the Maryland Coastal Plain summarized in Hansen and Edwards (1986) penetrated red sedimentary rocks occurring along a northeast trend. A seismic-reflection profile to the east of these wells imaged what Hansen (1988) has tentatively named the Queen Anne basin. By using aeromagnetic data, Benson (1992) inferred the presence of a separate, but parallel, buried, early Mesozoic basin in southern Cumberland County, N.J., south of a gravity high (fig. 25). Sheridan and others (1991) interpreted parts of southern Gloucester and Camden Counties and northern Atlantic County to be underlain by a buried, early Mesozoic basin, which they have named the Buena basin. Their interpretation is based on a seismic-reflection profile and gravity modeling. The locations of these inferred basins are shown on figure 25.

The Anchor Gas-Dickinson well in New Jersey encountered a 140-ft-thick sequence of pale-pinkish-tan, angular to subangular quartz sand and clayey silt directly overlying crystalline basement. It is possible that this is sandstone of Mesozoic age as suggested by Doyle (lithologic log, on file in the office of the New Jersey Geological Survey, Trenton, N.J.). It is also possible that this material is from the Potomac Formation. Although the sediment thickness is anomalous for a buried rift basin, that the margin of one was drilled cannot be totally discounted. If this is, in fact, the margin of a buried rift basin, it is south of the inferred basin of Sheridan and others (1991) and also south of the projected subsurface trace of the Queen Anne basin (Benson, 1990, 1992) and the unnamed basin of Benson (1992). However, we interpret this quartz sand to be part of the Potomac Formation and do not think that crystalline basement was penetrated at this depth in the Anchor Gas-Dickinson well.

CONCLUSIONS

1. The crystalline basement complex in New Jersey is overlain along the Fall Line by the Stockton Formation and to the southeast by unconsolidated sediments mainly of the Potomac Formation. Saprolite was encountered in nearly every well and locally is more than 150 ft thick.
2. The pre-Mesozoic subsurface basement in New Jersey likely consists of a stack of thrust sheets representing a composite of accreted terranes.
3. The inner Coastal Plain is underlain dominantly by amphibolite-facies pelitic and psammitic schists of the Potomac/Philadelphia terrane. These rocks are probably equivalent, at least partially, to the western part of the Brompton-Cameron terrane in southern New England. In New Jersey, these rocks were deposited in a marginal, perhaps back arc, basin to the east of the North American craton. Amphibolites associated with these schists in Gloucester County, N.J., are geochemically divisible into two basalt types. Type 1 basalts have N-MORB and E-MORB affinities and were erupted at, or proximal to, a small spreading center in this marginal basin. Type 2 basalts are chemically similar to other occurrences of Late Proterozoic basalt and diabase from throughout the Appalachians and are therefore interpreted by us also to be Late Proterozoic in age. They may have intruded along a leaky transform fault. Amphibolites of basaltic andesite and type 2 basalt compositions are associated with pelitic and psammitic schists as sills and dikes. Major- and trace-element abundances suggest that basaltic andesite fractionated from type 2 basalt. Type 1 basalt is less fractionated and tapped a separate, possibly shallower, mantle source.
4. Rocks of the James Run Formation (Chopawamsic terrane) may extend into New Jersey into central Salem County. The absence of drill-hole data in this area, as well as in southern Gloucester County, provides neither proof nor disproof of the occurrence of the James Run Formation in New Jersey.
5. Pyroxenite encountered in the Delaware subsur- face may be related to ultramafic rocks in the Bel Air-Rising Sun terrane (Aberdeen block) or may be a separate fragment in a structurally higher slice. It is tentatively interpreted as being the latter and is correlated with similar rocks of the Roanoke Rapids terrane (Eastern slate belt).
6. Quartzite in the Anchor Gas-Ragovin well is on strike with, and north of, the same gravity high as quartzite, chlorite schist, biotite schist, and altered metavolcanic rock from wells in northern Delaware and eastern Maryland. These rocks may represent a volcanic arc sequence. We interpret them to be correlative with rocks of the Roanoke Rapids terrane (Eastern slate belt).
7. The associated gravity and aeromagnetic anomalies in Monmouth County and Burlington County coincide with a structural high in the basement. Thinning of Coastal Plain sediments here reflects structural complexities in the basement. Gravity and magnetic data permit the interpretation of high-density mafic rock that occurs either in a rootless pluton or in a thrust slice extending to a depth of less than 1 mi. The alignment of the Baltimore Complex and Wilmington Complex with these bodies along the same structural trend and gravity high suggests that they may be related. The Monmouth County body is herein named the Monmouth terrane, and the Burlington County bodies are herein named the Mount Holly terrane.
8. Graphitic schists from the northern part of the Coastal Plain are probably related to marble and carbonaceous schist encountered farther to the south. We suggest a possible correlation with rocks of the Brompton-Cameron terrane because they are along the same gravity and aeromagnetic trend. The assignment of these rocks

east of the occurrence of Potomac terrane rocks is consistent with the assignment of similar rocks occurring east of Hartland or Manhattan in southern New England and New York. If the graphitic schist and marble correlate with the Walloomsac Formation and rocks of the North American Craton terrane, then they are outboard of rocks in the Potomac/Philadelphia terrane and may be exposed in a window through accreted terranes transported farther to the west.

9. The reported occurrence of Ordovician fossils from beneath schist at the W.&K. Oil Company well at Jacksons Mills, N.J., is scientifically intriguing but unsubstantiated. The available facts suggest there may be little validity to this report.
10. Metagabbro from the Anchor Gas-Dickinson well is herein named the Cape May terrane. It may be a continuation of gabbro and associated greenschist-facies metamorphic rocks from eastern Maryland. It is possible that these rocks correlate with rocks of the Chesapeake block (Eastern slate belt).
11. Rocks of Mesozoic age were penetrated by wells along the Fall Line in Middlesex and Mercer Counties. To the south, evidence for early Mesozoic buried rift basins beneath the New Jersey Coastal Plain is equivocal; thus far no well has drilled rock that can be definitively identified as Mesozoic. However, there are areas in southern New Jersey untested by drilling where gravity and magnetic data suggest the possible presence of small, buried, early Mesozoic basins.

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APPENDIX

Appendix. Selected Coastal Plain wells and seismic stations in New Jersey and contiguous areas that penetrate basement rock

[Location of wells is shown in figure 10. Elevation was estimated in feet above sea level from USGS 7.5-min topographic map. Sample type symbols: D, driller's log; G, geologists' log; GT, geologic description from this study. USGS, U.S. Geological Survey; Do. (do.), ditto; Fm., Formation]

Well no.	Owner or name	Latitude	Longitude	Elevation (ft)	Depth to basement (ft)	Sample type		Description	Reference
				MIDDLESEX COUNTY					
1	Harold Kuhn	40 32 20	74 18 33	170	+10	Cuttings	(G)	Passaic Formation Red Mesozoic shale.	Johnson (1961).
2	American Cyanamid	40 32 33	74 16 20	15	58	do.	(D)	Greenish-gray baked Mesozoic shale.	Kasabach and Scudder (1961).
3	Stephen Futo	40 32 07	74 18 20	150	20	do.	(D)	Dusky-red, finely micaceous, slightly calcareous Mesozoic shale.	Do.
4	California Refining Co.	40 32 07	74 16 47	50	89	do.	(D)	Metamorphosed hard gray Mesozoic shale.	Do.
4a	Chevron Oil Co. #11	40 32 11	74 16 12	14	83	do.	(D)	"Soapstone"	Gronberg and others (1989).
5	R & H Chemical Co.	40 30 47	74 16 07	30	145	do.	(D)	Red Mesozoic shale	Kasabach and Scudder (1961).
6	Duhernal Water Board	40 29 40	74 18 07	10	115	do.	(D)	Mesozoic diabase	Do.
7	DuPont #13	40 29 00	74 19 13	8	91	do.	(D)	Mesozoic rock	([1])
8	Man & Engine Co. #29	40 28 20	74 20 47	23	51	do.	(D)	Mesozoic diabase	Do.
9	National Lead Co.	40 28 33	74 18 07	140	200	do.	(D)	Red Mesozoic shale	Do.
10	Man & Engine Co. #3	40 27 40	74 20 33	100	165	do.	(D)	Mesozoic rock	Do.
11	Water Policy Comm.	40 27 40	74 22 07	5	86	do.	(D)	Mesozoic diabase	Kasabach and Scudder (1961).
12	Hercules #2	40 27 00	74 20 07	50	235	do.	(D)	Red Mesozoic shale	([1])
13	DuPont	40 27 00	74 19 13	100	259	do.	(D)	Mesozoic sandstone	Kasabach and Scudder (1961).
14	Laurence Smith	40 24 07	74 26 07	115	115	do.	(D)	Stockton Formation "Light-colored sandstone."	Do.
15	Middlesex Development Co.	40 24 33	74 24 33	90	170	do.	(D)	Mesozoic Stockton Fm.	Do.
16	Anheuser-Busch	40 24 33	74 22 07	20	292	do.	(D)	Basement	Do.
17	Madison Water Co.	40 23 53	74 20 47	40	330	do.	(D)	Basement	Do.
18	Duhernal Water Co.	40 23 40	74 22 47	10	302	do.	(D)	Basement	Do.
19	Kimberly-Clark Co.	40 21 00	74 29 40	125	208	do.	(G)	Red Mesozoic shale fragments.	Johnson (1961).
20	Stauffer Chemical #7	40 21 25	74 28 25	128	180	Core	(GT)	Red clay and weathered Mesozoic shale.	
21	State Home for Boys	40 20 33	74 23 26	100	405	Cuttings	(D)	Basement	Kasabach and Scudder (1961).
22	Clifford Stultz	40 18 33	74 34 07	90	90	do.	(G)	Decomposed "Wissahickon"	Johnson (1961).
23	Clifford Stultz	40 18 47	74 33 53	95	105	do.	(G)	Weathered "Wissahickon" (granitic).	Do.
				MERCER COUNTY					
24	Heyden Chemical (1946)	40 19 30	74 37 52	55	+31	do.	(D)	Stockton Formation—Light sandstone and interbedded Mesozoic shale; "Wissahickon" at 377 ft below sea level (granitic).	Do.
25	Wing Hing	40 17 40	74 36 07	100	+18	do.	(D)	Pre-Mesozoic basement	Kasabach and Scudder (1961).
26	Peddie Inst.	40 15 53	74 31 26	108	374	do.	(D)	Pre-Mesozoic basement	Do.

Appendix. Selected Coastal Plain wells and seismic stations in New Jersey and contiguous areas that penetrate basement rock—Continued

Well no.	Owner or name	Latitude	Longitude	Elevation (ft)	Depth to basement (ft)	Sample type		Description	Reference
27	Mercer County Park	40 17 05	74 39 00	62	15	Core	(GT)	Medium-grained, moderately foliated, pale-weathering, light-greenish-gray hornblende-pyroxene-quartz-biotite-plagioclase gneiss with trace sulfide. Quartz is colorless to blue. Minor medium- to coarse-grained, pinkish-white weathering, afoliate microperthite alaskite with 2 feldspars & blue quartz. Also minor greenish-gray, fine-grained to aphanitic metabasalt.	
28	Robbinsville Hotel	40 15 13	74 37 40	120	240	Cuttings	(D)	Pre-Mesozoic basement	Kasabach and Scudder (1961).
29	Hamilton Sq. Water Co.	40 14 33	74 40 20	75	79	do.	(D)	Pre-Mesozoic basement	Do.
30	F. Agabiti	40 13 53	74 40 47	90	66	do.	(D)	Pre-Mesozoic basement	Do.
31	Hamilton Sq. Water Co.	40 13 53	74 39 53	100	115	do.	(G)	Highly weathered "Wissahickon" schist.	Johnson (1961).
32	Cocavio Bros.	40 12 33	74 43 13	60	82	do.	(D)	Weathered mica gneiss	Kasabach and Scudder (1961).
				MONMOUTH COUNTY					
33	Union Beach Water Dept.	40 26 32	74 10 51	10	599	do.	(D)	Pre-Mesozoic basement	Lloyd and others (1985).
34	Levitt & Sons, Inc., PH 1	40 23 53	74 12 47	90	607	Core	(G)	Clay, mostly decayed mica schist with zones of white granite. Schist is dark red, white, and green with zones of black speckling.	F.J. Markewicz, unpublished lithologic log.
35	New Jersey Highway Authority.	40 23 13	74 10 33	215	743	Cuttings	(GT)	Pale-olive, highly weathered, fine- to medium-fine-grained chlorite-biotite-muscovite-quartz-feldspar schist with trace staurolite and graphite.	
36	Gordons Corner Water Co.	40 19 13	74 18 07	160	718	do.	(D)	Weathered pre-Mesozoic basement.	([1])
37	RH Macy TH 1	40 17 27	74 03 13	60	811	do.	(D)	Bedrock(?), weathered	Daniels and Leo (1985).
38	USGS Freehold observation well.	40 15 17	74 13 51	205	1065	Core	(GT)	Highly weathered, medium-fine-grained, moderately well foliated, graphitic garnet-biotite-quartz feldspar schist.	
39	USGS NJ Water Supply Manasquan Reservoir.	40 11 05	74 12 02	110	1390	Cuttings	(G)	Weathered biotite schist	Brown and Zapecza (1990).
40	Punk Bros.	40 10 05	74 29 39	129	659	do.	(D)	Pre-Mesozoic basement	Lloyd and others (1985).
				OCEAN COUNTY					
41	W.S.Driver Oil Co.	40 07 40	74 28 07	110	990	do.	(D)	Pre-Mesozoic basement	Kasabach and Scudder (1961).
42	W.&K. Oil Co.	40 09 00	74 19 13	110	1226	do.	(GT)	Total depth is 5,022 ft.; 3,000 ft to 4,832 ft—medium-fine-grained garnet-bioite-quartz-feldspar schist with trace sulfide. 4,832- ft to 4,840 ft—the same with accessory graphite. 4,850 ft—medium-fine- to medium-grained garnet-biotite-chlorite-muscovite-quartz-feldspar schist.	

Appendix. Selected Coastal Plain wells and seismic stations in New Jersey and contiguous areas that penetrate basement rock—Continued

Well no.	Owner or name	Latitude	Longitude	Elevation (ft)	Depth to basement (ft)	Sample type		Description	Reference
43	Jackson Twp. MUA #9	40 06 52	74 17 17	135	1515	do.	(D)	Clay, weathered	Lloyd and others (1985).
44	Brick Twp. MUA #9	40 04 31	74 08 32	8	1776	do.	(D)	Weathered zone	([1])
45	Oxly 1A	39 45 55	74 21 39	138	3082	do.	(GT)	Pale-olive, highly weathered, medium-grained chlorite-muscovite-biotite-quartz-feldspar schist or gneiss with accessory sulfide and trace graphite. Feldspar chalky.	
46	USGS Island Beach State Park.	39 48 29	74 05 35	10	3793	Core	(G, GT)	Migmatitic garnet-muscovite-microcline-biotite-quartz-plagioclase gneiss (Southwick, 1964) and medium-grained garnet-hornblende-biotite-quartz-feldspar gneiss (this study).	Southwick (1964).
	BURLINGTON COUNTY								
47	U.S. Engineering Corps	40 10 33	74 42 07	70	240	Cuttings	(D)	Basement	([1])
48	National Gypsum #2	40 06 20	74 49 40	15	142	do.	(D)	Mica rock	Kasabach and Scudder (1961).
49	McGuire AFB #A	40 02 07	74 36 07	124	936	do.	(D)	Weathered basement	Do.
50	McGuire AFB #2	40 01 40	74 35 26	160	940	do.	(G)	"Wissahickon"; contains biotite, quartz, and some feldspar.	Johnson (1961).
51	Helis Stock Farm	40 00 54	74 40 00	96	891	do.	(D)	"Wissahickon"(?): hard sandstone, probably weathered bedrock.	Daniels and Leo (1985).
52	Burlington County Institution #1.	39 58 12	74 38 36	59	711	do.	(G)	"Wissahickon"(?)	Do.
53	Butler Place test well-Lebanon State Forest.	39 51 27	74 30 20	132	2096	Core	(G)	Fine-grained, greenish-gray, laminated carbonate rock composed of 40% carbonate plus phlogopite, chlorite, and an aggregate of montmorillonite, illite, and chlorite.	U.S. Geological Survey (1967).
54	Levitt & Sons Adm.	40 03 13	74 53 40	33	209	Cuttings	(G)	Decayed basement rock	([1])
55	Levitt & Sons, Inc., #8	40 02 33	74 54 33	39	196	do.	(G)	Mica schist—"Wissahickon"	Do.
56	Levitt & Sons, Inc., #21	40 02 20	74 54 20	15	260	do.	(G)	Schistose gneiss and biotite schist.	Do.
57	Levitt & Sons, Inc., DCB–25	40 01 53	74 52 33	27	331	do.	(G)	Highly weathered "Wissahickon" gneiss.	Do.
58	Levitt & Sons, Inc., DCB–27	40 01 40	74 52 07	40	371	Core	(G)	Weathered "Wissahickon" schist.	Do.
59	Levitt & Sons, Inc., DCB–12	40 00 33	75 52 47	55	445	do.	(D)	Pre-Mesozoic basement	Kasabach and Scudder (1961).
60	Delaware River Water Company #17	40 02 20	74 56 47	20	115	do.	(D)	Pre-Mesozoic basement	Do.
61	Delaware River Water Co.	40 02 07	74 57 40	20	71	do.	(D)	Weathered rock—"Wissahickon"(?).	Do.
62	Shell Chemical Company	40 01 13	74 58 33	20	125	Cuttings	(D)	Pre-Mesozoic basement	Do.
63	Riverton-Palmyra Water Co. #8	40 00 47	74 01 40	10	86	do.	(D)	Weathered rock—"Wissahickon."	Do.
64	Cinnaminson MW F–2	40 00 36	74 58 35	65	185	do.	(GT)	Saprolitic, gray, garnet-muscovite-biotite-quartz-plagioclase schist or gneiss.	
65	Sanitary Landfill GM–4	40 00 20	74 58 33	60	+40	Core	(G)	Micaceous bedrock with layers of fine sand.	([1])
66	Riverton-Palmyra W.C. #10	39 59 27	74 59 13	80	226	Cuttings	(D)	Weathered pre-Mesozoic basement.	Do.

Appendix. Selected Coastal Plain wells and seismic stations in New Jersey and contiguous areas that penetrate basement rock—Continued

Well no.	Owner or name	Latitude	Longitude	Elevation (ft)	Depth to basement (ft)	Sample type		Description	Reference
67	Maple Shade WD MSWD #5	39 57 25	74 59 14	20	474	do.	(D)	Pre-Mesozoic basement	Do.
68	Moorestown WD #1	39 57 00	74 57 48	20	476	do.	(D)	"Wissahickon"	Daniels and Leo (1985).
69	Mount Laurel Water Co.	39 56 06	74 56 30	30	564	do.	(D)	Weathered "Wissahickon"	Do.
					CAMDEN COUNTY				
70	Pennsauken SLF 11D	39 59 53	75 02 26	20	85	Core	(GT)	Buff to yellowish-tan saprolite containing muscovite, quartz, and kaolinite.	
71	Merchantville-Penns WC-#1	39 57 27	75 02 33	60	232	Cuttings	(D)	Mica rock—Pre-Mesozoic basement.	Kasabach and Scudder (1961).
72	Camden City #6	39 57 13	75 05 40	50	130	do.	(D)	Pre-Mesozoic basement	Do.
73	U.S. Gasket Company	39 57 13	75 07 13	20	121	do.	(D)	Weathered pre-Mesozoic basement.	Do.
74	Camden City #5	39 55 53	75 05 40	40	237	do.	(D)	"Wissahickon" schist	([1])
75	Camden City Sewage Plant #1.	39 55 23	75 07 29	9	192	do.	(D)	"Wissahickon"	Do.
76	Gloucester City	39 53 53	74 07 13	5	271	do.	(D)	Pre-Mesozoic basement	Kasabach and Scudder (1961).
77	NJ Water Company #14	39 52 47	75 03 26	85	517	do.	(D)	White mica rock	([1])
78	NJ Water Company	39 52 33	75 03 00	70	557	do.	(D)	Highly weathered basement	Kasabach and Scudder (1961).
79	USGS New Brooklyn Park #1.	39 42 07	74 55 53	110	1831	Core	(GT)	Highly weathered, pale-greenish-gray, fine- to medium-grained biotite-muscovite-quartz-plagioclase schist or gneiss. Accessory garnet and sillimanite. Feldspar chalky and altered.	
					GLOUCESTER COUNTY				
80	Texas Co. # 3	39 52 07	75 09 26	10	278	Cuttings	(D)	Pre-Mesozoic basement	Kasabach and Scudder (1961).
81	National Park Boro. #3	39 51 40	75 11 00	25	263	do.	(D)	Pre-Mesozoic basement	Do.
82	City of Woodbury	39 50 07	75 08 47	30	403	do.	(D)	"Wissahickon"—weathered mica rock.	Do.
83	USGS Deptford observation well.	39 49 57	75 05 30	35	643	do.	(GT)	Medium-grained schist composed of muscovite, biotite, quartz, and partially altered feldspar, sparse accessory garnet, and trace sulfide.	
84	Vacuum Oil Co.	39 51 00	75 15 13	10	308	do.	(D)	Pre-Mesozoic basement	Kasabach and Scudder (1961).
85	DuPont Repauno Works	39 50 33	75 16 33	20	118	Core	(GT)	Schist and gneiss composed of muscovite, biotite, quartz, and plagioclase with sparse accessary garnet and trace sillimanite. Some schist contains hornblende. Also medium-grained amphibolite composed of hornblende and plagioclase.	
86	DuPont Repauno Works TH#4.	39 50 33	75 17 40	20	95	do.	(G)	Mica schist and amphibolite	F.J. Markewicz, unpub. lithologic log.
87	Hercules Powder Co.	38 49 53	75 19 26	10	210	Cuttings	(D)	Pre-Mesozoic basement	Kasabach and Scudder (1961).

Appendix. Selected Coastal Plain wells and seismic stations in New Jersey and contiguous areas that penetrate basement rock—Continued

Well no.	Owner or name	Latitude	Longitude	Elevation (ft)	Depth to basement (ft)	Sample type		Description	Reference
88	Gaventa Farms	39 48 02	75 19 09	10	240	Core	(GT)	Muscovite-biotite quartz-plagioclase schist with trace sillimanite and sulfide. Also thin, conformably interlayered, medium-grained amphibolite.	
89	Chemical Leaman	39 47 56	75 20 01	20	240	do.	(GT)	Muscovite-biotite-quartz-plagioclase schist with accessory sillimanite, garnet, and trace sulfide.	
90	S&S Auction	39 47 43	75 18 22	12	311	do.	(GT)	Biotite-quartz-plagioclase schist with minor accessory garnet.	
91	Lopes Farm	39 47 22	75 17 32	28	398	do.	(GT)	Muscovite-biotite-quartz-plagioclase schist.	
92	Shoemaker Farm	39 47 06	75 19 43	7	333	do.	(GT)	Saprolite reportedly 78 ft thick. Muscovite-biotite-quartz-plagioclase schist with minor K-feldspar and trace garnet and trace sulfide. Locally migmatitic with layers composed of quartz and plagioclase.	
93	Monsanto Chemical Co. #2	39 48 33	75 22 33	10	143	Cuttings	(D)	Pre-Mesozoic basement	Kasabach and Scudder (1961).
94	Monsanto Chemical Co.	39 47 40	75 24 07	5	118	do.	(D)	Pre-Mesozoic basement	Do.
95	USGS Clayton well	39 40 32	75 06 07	140	1498	do.	(GT)	Schist composed of biotite and abundant quartz with sparse amounts of altered feldspar and trace garnet and sulfide.	
	SALEM COUNTY								
96	Pan American Refining Co. PT #1.	39 46 33	75 25 13	6	211	do.	(D)	Mica rock	Rosenau and others (1969).
97	Ford, Bacon & Davis	39 45 27	75 25 26	10	228	do.	(D)	Pre-Mesozoic basement	Kasabach and Scudder (1961).
98	Penns Grove Water Co.	39 43 53	75 27 53	5	205	do.	(G)	80 ft of weathered rock-micaceous gneiss, "Wissahickon"(?).	Rosenau and others (1969).
99	DuPont Chambers Works 45B	39 41 30	75 29 30	17	489	do.	(D)	Weathered basement	Leggette, Brashears, & Graham, Inc. (1979).
100	DuPont Carney Point Works #7	39 41 05	75 29 08	(?)	Sample from 542 and 555.	do.	(G)	Highly decomposed gneiss composed of quartz, plagioclase, biotite, and chlorite with minor muscovite.	U.S. Geological Survey (1967).
101	Pennsville	39 39 54	75 30 48	9	590	do.	(G)	Bedrock "pre-Cretaceous"	([1])
102	City of Salem	39 34 20	75 27 53	12	1364	do.	(G)	Weathered "Wissahickon"	Johnson (1961).
	CUMBERLAND COUNTY								
103	Anchor Gas-Ragovin #1	39 25 12	74 51 54	91	3610	do.	(GT)	Quartz-rich sand with trace amounts of reddish-brown garnet and muscovite.	
	CAPE MAY COUNTY								
104	Anchor Gas-Dickinson #1	38 56 33	74 57 26	14	6357	do.	(GT)	Very fine grained, dark-grayish to greenish-black biotite-hornblende quartz-plagioclase gneiss and a single fragment of fine-grained muscovite-quartz-feldspar gneiss.	

Appendix. Selected Coastal Plain wells and seismic stations in New Jersey and contiguous areas that penetrate basement rock—Continued

Well no.	Owner or name	Latitude	Longitude	Elevation (ft)	Depth to basement (ft)	Sample type		Description	Reference
				HUDSON COUNTY[2]					
105	Holland Tunnel test boring 31.	40 43 45	74 02 00	0	128	Core	(G)	Serpentinite	N.J. Geological Survey permanent notes (1935).
106	Passaic Valley Sewerage Commission test boring #394.	40 39 30	74 04 00	5	123	do.	(G)	Red Mesozoic sandstone	Do.
107	Liberty State Park test boring DB-8.	40 42 20	74 03 30	5	39	do.	(G)	Mica schist	Tams Consultants, Inc. (1988).
				NEW YORK WELLS					
N1	People's Pulpit Association	40 32 30	74 12 01	150	210	?		"Mica schist"	Perlmutter and Arnow (1953).
N2	Boulevard Station #1	40 33 20	74 07 40	10	309	?		"Soapstone with mica"	Do.
N3	Hoffman Island	40 34 43	74 03 16	5	450	?		Basement	Do.
N4	K718	40 37 21	74 01 21	139	294	?		Basement	DeLaguna (1948).
N5	K523	40 38 18	73 56 46	152	384	?		Basement	Do.
N6	K1	40 34 41	73 59 17	125	625	?		"Granite"	Do.
N7	Q403	40 33 52	73 54 40	5	865	?		Basement	U.S. Geological Survey, Syosset, Long Island, unpub. well record.
N8	Q1030	40 34 51	73 50 04	74	974	?		"Granite" (65% K-feldspar, 25% quartz, 10% biotite-muscovite, etc.).	Roberts (1948).
N9	Brooklyn Union Gas Co.	40 39 32	73 49 31	5	651	Cuttings	(GT)	Sample at 676 ft is light-grayish-buff-weathering clayey saprolite containing quartz, chalky feldspar, trace graphite, and muscovite and a grain or two of garnet.	
N10	Q350	40 40 22	73 50 06	78	577	?		"Mica schist"	Leggette and others (1938).
N11	Q430	40 44 09	73 54 58	121	125	?		"Fordham Gneiss"	Do.
N12	Q568	40 42 00	73 44 16	58	811	?		"Mica rock"	Do.
N13	N5308	40 35 19	73 38 28	8	1459	?		Basement	U.S. Geological Survey, Syosset, Long Island, unpub. well record.
				DELAWARE WELLS					
D1	Db 11–27	39 39 25	75 44 03	—	117	?		Basement	Rasmussen and others (1957).
D2	Db 44–04	39 36 13	75 41 21	—	340	?		do.	Do.
D3	Dc 51–04	39 35 35	75 39 49	—	543	?		do.	Do.
D4	Dc 52–01	39 35 12	75 38 12	—	639	?		do.	Delaware Geological Survey, unpub. well record.
D5	Ec 14–07	39 34 23	75 36 14	—	755	Cuttings	(GT)	Chlorite schist	Delaware Geological Survey, unpub. well record; this study.
D6	Eb 23–22	39 34 11	75 38 14	—	670	do.	(GT)	Chlorite schist and quartzite.	
D7	Ec 32–7	39 32 39	75 38 01	—	741	?		Mica schist	Rasmussen and others (1957); Dames and Moore (1974).
D8	Eb 44–08	39 31 19	75 41 16	—	1160	Core	(G, GT)	Pyroxenite	Dames and Moore (1974).
D9	Ec 41–10	39 31 01	75 39 03	—	1209	?	(G)	Saprolitic green clay	Delaware Geological Survey, unpub. well record; Dames and Moore (1974).
D10	Fb 33–06	39 27 08	75 42 57	—	1414	?		do.	Richards (1945).
D11	Gd 33–04	39 22 12	75 32 42	—	2295	Cuttings	(GT)	Altered metavolcanic rock	Otton and Mandle (1984); this study.

Appendix. Selected Coastal Plain wells and seismic stations in New Jersey and contiguous areas that penetrate basement rock—Continued

SEISMIC STATIONS

ID[3]	Location	Latitude	Longitude	Seismic depth to basement (ft)
A	Charleston Springs	40 11 36	74 22 36	1010
B	Lakewood	40 05 48	74 15 30	1410
C	Cedar Bridge	40 04 30	74 12 18	1610
D	Silverton	40 00 54	74 08 06	2210
E	Lincoln	39 41 18	75 19 30	1200
F	Pittsgrove	39 37 24	75 12 06	1540
G	Elmer	39 35 30	75 10 12	2020
H	Norma	39 30 00	75 04 36	2370
I	Millville	39 26 36	74 57 54	3350
J	Port Elizabeth	39 21 48	74 53 00	3750
K	Woodbine	30 14 30	74 48 06	4570
L	Corbin City	39 19 56	74 46 03	4231

[1]Unpublished water well record on file in the office of the Bureau of Water Allocation, Trenton, N.J.

[2]Wells are not in Coastal Plain but are used for basement surface control.

[3]A–K from Ewing and others (1939, 1940). L from Robert Sheridan, Rutgers University (written commun., 1989).

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