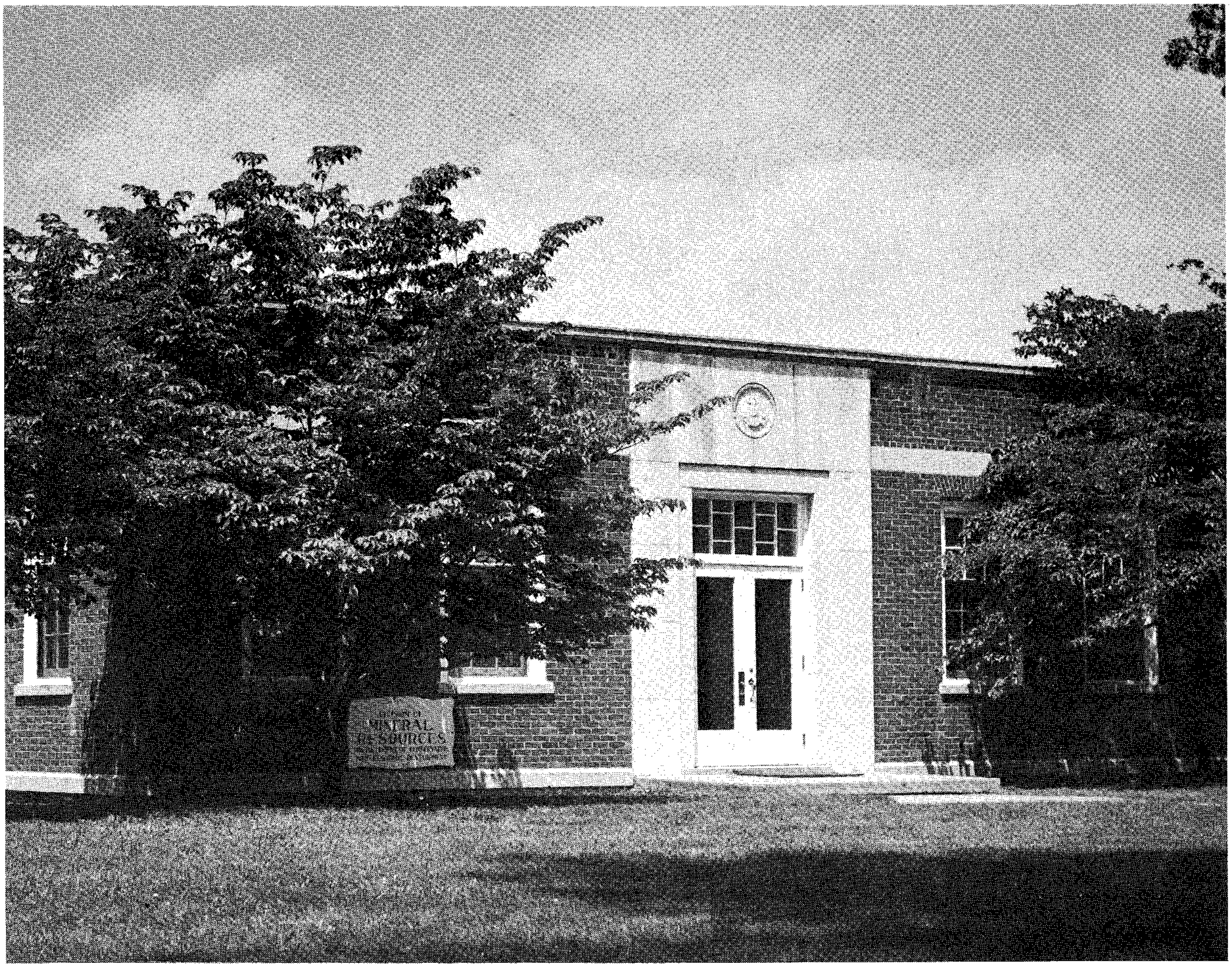
VIRGINIA DIVISION OF MINERAL RESOURCES PUBLICATION 7

CONTRIBUTIONS TO VIRGINIA GEOLOGY—III



COMMONWEALTH OF VIRGINIA
DEPARTMENT OF CONSERVATION AND ECONOMIC DEVELOPMENT
DIVISION OF MINERAL RESOURCES
James L. Calver, Commissioner of Mineral Resources and State Geologist

CHARLOTTESVILLE, VIRGINIA
1978

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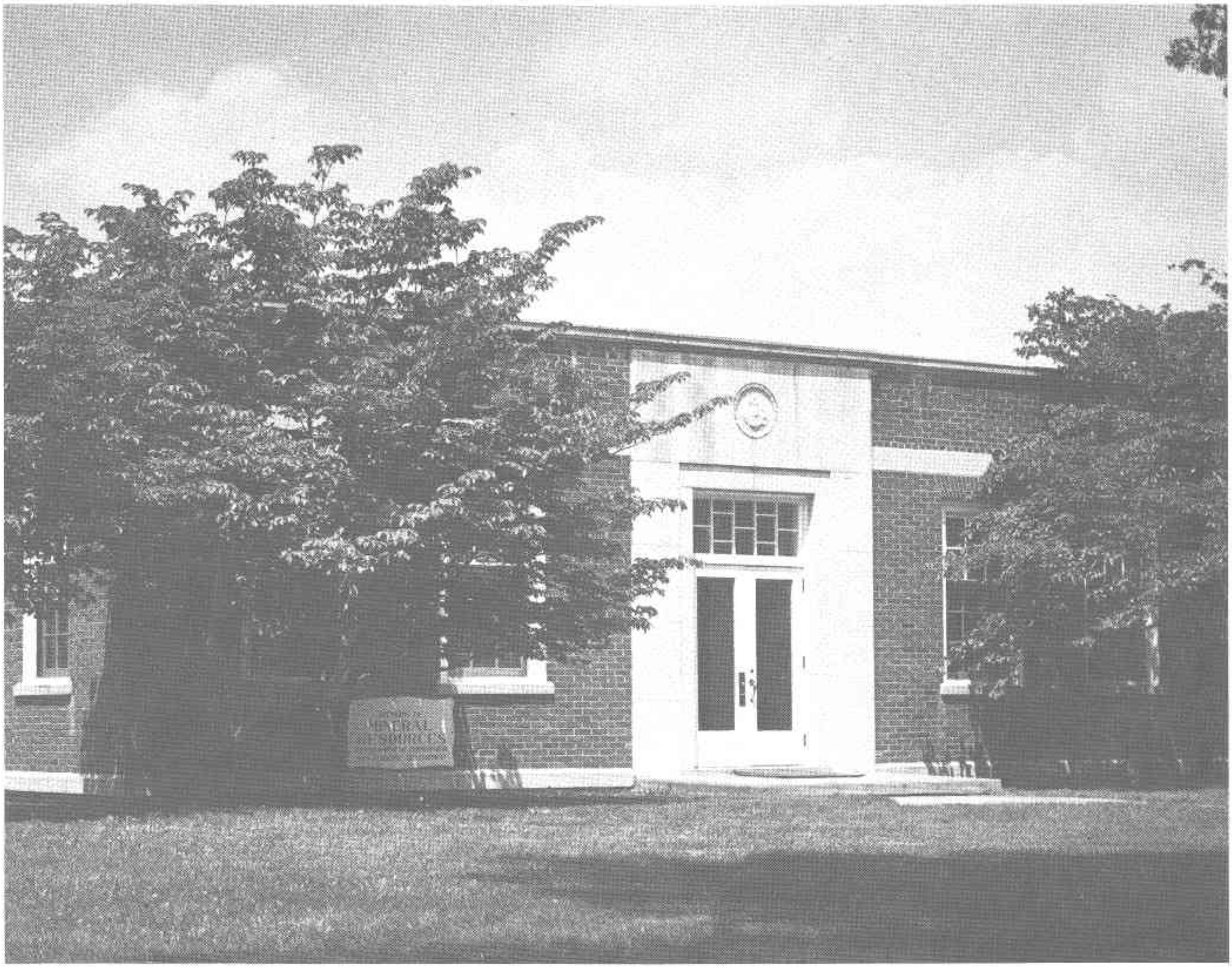

COMMONWEALTH OF VIRGINIA

DEPARTMENT OF CONSERVATION AND ECONOMIC DEVELOPMENT

DIVISION OF MINERAL RESOURCES

James L. Calver, Commissioner of Mineral Resources and State Geologist

CHARLOTTESVILLE, VIRGINIA

1978

FRONT COVER: Offices of the Virginia Division of Mineral Resources in the west wing of the Natural Resources Building, McCormick Road, Charlottesville, Virginia.

VIRGINIA DIVISION OF MINERAL RESOURCES PUBLICATION 7

CONTRIBUTIONS TO VIRGINIA GEOLOGY—III

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COMMONWEALTH OF VIRGINIA
DEPARTMENT OF PURCHASES AND SUPPLY
RICHMOND
1978

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The recommended form for individual citations is noted in each contribution.

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TOPOGRAPHIC MAPPING

In Cooperation with the U.S. Geological Survey

PREFACE

The major contribution to the Division of Mineral Resources' progress is the innovative and perceptive guidance given by James L. Calver in the development of geologic, mineral-resource, and topographic programs for the Commonwealth of Virginia. It is through his unceasing efforts as State Geologist during the past 21 years that the Division has become one of the outstanding geological surveys in the United States. He retires in 1978 with long involvement in a period of investigative and technological advancements. As a result a sound base has been established for future program achievements. Virginia has been enriched by his service to her citizens as well as the industrial and educational communities. The Division's staff respectfully offers, within this third contribution volume, information having to do with the agency's history of progress. Also contained within these covers are reports of geologic studies that are supportive to our present economic and scientific knowledge.

C.R.B.H.

CONTRIBUTIONS TO VIRGINIA GEOLOGY—III

CONTENTS[1]

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[1]The contents and illustrations of the individual papers are given with each contribution.

THE CALVER YEARS—1957-1978[1]

CONTENTS

FROM THE BEGINNING

Since the beginning of Virginia's first geological survey, the past 145 years have been a period of investigation and development of mineral resources. From the Geological Society of Pennsylvania in 1833 came a recommendation to the Governor of Virginia that a topographical, geological, and mineralogical survey of the State be made. The chief purpose was to determine the character and extent of mineral resources, especially coal. Early in 1835, the General Assembly approved the initiation of a geological survey of Virginia and for the next six years a reconnaissance was made of portions of the State (including part of West Virginia that gained statehood in 1863). During this period reports of studies on the distribution and characteristics of coal, iron ore, marl, and other rock materials were submitted to establish resource potential vital to basic residential and commercial needs. In 1907 the next major advance in the establishment of a data base was the publication of the "Mineral Resources of Virginia" by Thomas L. Watson. Prepared in conjunction with the tricentennial founding of the first settlement in the State at Jamestown, this source book was indeed the most comprehensive work about mineral resource occurrences in the State. The parent agency of the Division of Mineral Resources began studies within the same year. During the ensuing 50 years, studies were conducted to determine the physical and chemical properties as well as distribution and structure of rock strata that lay between the sandy shores of eastern Virginia and the coal fields in her western mountains. During this era individual reports and surveys were produced that were based on field observations and simple laboratory examination—this traditional work was well in step with evolving concepts and needs. By 1957 about 85 percent of the resulting 74 bulletins dealt with the location, use or potential of rock and mineral resources.

With growing emphasis on economic geology the parent organization was more appropriately retitled the Division of Mineral Resources. Under the guidance of a new State Geologist, James L. Calver, there followed a 21-year period of change necessitated by modern demands and technological advances. Initially several years were spent in reorganizing records, establishing procedures, developing programs, and setting up repositories as well as maintaining the day-to-day services to Virginia residents and industries.

Geologic information and resources inventory are obtained by examination of rocks, minerals, and fossils. This is part and parcel to development of data, ideas, and concepts eventually utilized directly or indirectly in economic and geologic investigations. Reference collections were started with the establishment of repositories housing rock cuttings and core from test borings made in the exploration for oil, gas, coal, water, and minerals and also in studies for construction of building, bridge, road, and tower foundations. Another repository contains rocks and minerals collected from quarries and mines operating throughout the State, as well as representative materials sampled from rock strata and abandoned mines and quarries encountered during geologic investigations of Virginia's approximately 40,000 square miles

(103,600 sq km). A third repository was started to provide a systematic assemblage of fossils that are useful in correlation of some rock strata and environments of sediment deposition.

Library holdings were reorganized so that reference material was readily available to staff and visitors. A microfilm collection of theses and dissertations related to Virginia geology was begun. As a by-product of the effort to maintain complete holdings, a continuation of the bibliographic compilation of works written prior to 1940 has been updated in three increments to 1969.

TOPOGRAPHIC MAPPING

One of the major contributions to Virginia's progress is the continuing topographic-mapping program. Through the encouragement by citizen's groups, industrial interests, and governmental agencies the first phase of an expanded cooperative program with the U.S. Geological Survey was initiated in 1962. At the time nearly 90 percent of the State was without adequate topographic maps and during the ensuing 10-year period Virginia became one of the first states to have total modern coverage with the availability and distribution of 805 maps. Even though maps for many areas were revised and surveys of those without previous coverage were made, growth in suburban portions of the State continued. A means to keep up with this change became necessary. Through the use of high-altitude photography the periodic up-dating phase of the program was initiated. This technique was employed for photo-revision inspection of Virginia every 5 years so that users might keep track on a comparative basis of the growth of residential, industrial, and commercial areas as well as new highway construction. Hundreds of uses for topographic maps have been identified and more become evident as new needs are recognized. Categorically, they have been indispensable in search and rescue missions, forest fire control, municipal planning, and property inventory and recordation, as well as recreational development.

An index of 30,000 geographic and cultural names in Virginia, which are used to locate places, water features, landforms, and religious institutions was compiled from the 805 topographic maps. The Division's role in the cooperative program has been one of advisement, assistance in design, and monitoring the compilation and distribution of various map products. In recognition of basic user needs pilot projects were established and as a result the first orthophotoquads, slope maps, county maps, and orthophoto maps in Virginia were published.

With the distribution of the revised 1:500,000 scale State topographic map the first incorporation of State parks and forests was made. Through a series of cartographic workshops those who determine map content were brought together with the users to single out particular needs and how to include them in a variety of new or redesigned formats.

GEOPHYSICAL STUDIES

Geophysical techniques are an integral part of geologic investigation where there is a need to interpret subsurface structures and map the multitude of existing rock units. Beginning in 1962 regional aeromagnetic surveys were scheduled to be flown over all the State area west of the 78th meridian. Results from the surveys were used to verify the location of geological structures, some of which are obscured by soil cover, and to delineate features either sketchily identified or hitherto unknown. By 1972 the total area flown approximated 28,000 square miles (72,520 sq km) or 70 percent of the State. Major structural features, such as faults of large magnitude, folded or domal basement, and thickness and rock type configuration, have become apparent from studies of the aeromagnetic maps. Several federal agencies contributed into the compilation of aeromagnetic information for the area east of the 78th meridian. In a nonfunded cooperative arrangement the Division and the U.S. Geological Survey published the first aeromagnetic map of Virginia in 1978.

A statewide gravity survey was initiated and the first regional report was distributed in 1971. In order to depict gravity measurements obtained during field studies, it was necessary to devise a computer program for gridding and contouring random data into map form. A Virginia Gravity Base Net was constructed and tied into the U.S. National Gravity Net stations at Dulles International Airport. The final regional survey was completed in 1977 with the statewide establishment of more than 11,000 stations. A composite map of all the regional work was published a year later. An unknown elongate northeastward-trending gravity anomaly in the eastern portion of the Piedmont was discovered; this extensive anomaly may be indicative of mineralization in the area. By comparing gravity and aeromagnetic data gathered from Coastal Plain studies, it was determined that the buried surface of rocks underlying the coastal sediments have considerable more relief than previously suspected.

The first aeroradiometric survey was flown over north central Virginia in 1975; an adjoining area to the west was completed in 1976 making a total coverage of about 4,200 square miles (10,880 sq km). As a remote-sensing tool these surveys are used to locate areas having concentrations of uranium, thorium, and associated elements. They also serve as a record for monitoring the natural radiation at the earth's surface. Aeroradiometric contour maps have been useful in distinguishing various rock units, thus providing a means to partially define their distribution prior to detailed geologic-mapping studies.

In 1974 the Division started using a three-component, short-period seismograph, which operates 24 hours a day, 7 days a week. Keyed to a national network, the unit is used to pinpoint seismic events in Virginia, though its effectiveness is applicable throughout the eastern United States as far west as the Mississippi River. This is an initial effort to measure the magnitude of seismic activity and eventually to establish an earthquake history useful in planning for land-use modification as well as construction projects.

ECONOMIC GEOLOGY

Response to public inquiry about Virginia's mineral resources necessitated a reorganization of file data in the late 1950's. In particular oil and gas records were systematized and periodic visitation of mines and quarries was established. The collection of background information was started to assist individuals and company representatives to locate potential resource sites or expand existing operations. To bring about awareness of raw materials used in construction and industrial processes, the first sets of rocks and minerals were distributed mainly to secondary schools throughout the State. A second edition was made available for sale in 1971. As maps are one of the best ways geographically to depict occurrences of rock units containing commercial deposits, a mineral resource map was compiled and distributed in 1963. A revised edition was released in 1971.

Several commodity studies have been made over the past two decades. They were generated chiefly by repetitive requests for the same resource information or by user demands for a specific commodity. Resources in the Gossan Lead district of the southwestern Piedmont were investigated intermittently between 1928 and 1939. It wasn't until 1957 that the report on the occurrence and distribution of rocks of possible economic value was made available. They include barite, kyanite, magnetite, and minerals containing titanium, copper, lead, and zinc. Limestone, an important raw material for construction and chemical purpose, ranks fourth in production value. The fourth in a series of limestone bulletins was published in 1958 providing useful data on geographic location, strata thickness, and chemical analyses. An exhaustive compilation of descriptions for more than two hundred mica and feldspar mines and prospects was made available in 1962. The main portion of field work for this project was done between 1942 and 1945 when mica and feldspar were considered strategic materials. For many uses naturally occurring mica is now superceded by a synthetic form and various feldspar minerals are still important ingredients in the manufacture of glass, paints, ceramics, coatings, and fillers. In 1957 a study to delineate and evaluate clay, shale, and related materials on a statewide basis was entered into with the U.S. Bureau of Mines. Division geologists methodically collected samples that were later subjected to laboratory tests to determine potential ceramic and nonceramic uses. Chief among these are the manufacture of brick, tile, and lightweight aggregate. By 1973 five reports had been distributed and in 1976 a summary was prepared listing the potential uses of 485 samples of clay material. Another commodity that has drawn particular interest is silica sand which is sought for abrasive, glass, chemical, metallurgical, and refractory uses. In 1972 the first study of sand and quartzite of moderate to high purity was published beginning with the northwestern Virginia area. An inventory guide of base- and precious-metal and related ore deposits was made available for exploration purposes. Nearly 500 mines and prospects were described with data related to minerals containing gold, copper, silver, tin, lead, zinc, tungsten, and other elements. A geochemical report prepared from a study of the copper-, lead-, and zinc-bearing minerals in the Staunton quadrangle area was published once the geologic survey had been made. Areas having anomalous amounts of zinc in B-horizon soils that occur over carbonate rocks compared favorably with abandoned mining sites in the vicinity.

Virginia moved over the billion dollar threshold in total value of mineral production for the first time in 1974. This was the twelfth consecutive year that values increased. Mineral fuels generally make up 75 percent or more of the total annual receipts. The Division is the first public agency to make a regional study of coal beds in southwestern Virginia. Released in 1974 this work is the framework for detailed investigations of the State's number one mineral commodity—coal. Well logs prepared from repository samples from test borings generally averaging 5,000 feet (1,525 meters) in depth were compared with geophysical data. The possible extent of the coal beds was interpreted to give an indication of their subsurface distribution. Because of the critical need for energy resources a two-year grant arrangement was entered into with the U.S. Geological Survey in 1975 to collect coal samples for determination of physical and chemical properties. Analyses are made to incorporate over 70 trace elements. As part of an extensive program, coals are being evaluated for effective and optimum use. This data adds to present knowledge of the State's resources and is entered into a computerized system known as the National Coal Resources Data System. Information is to be available for studies on coal quality and reserves. Energy resources of oil and gas may be present in the area of the outer continental shelf of the Atlantic Ocean. In 1974 the Secretary of Commerce and Resources established an Outer Continental Shelf Program, the initial responsibility for which was assigned to the Division of Mineral Resources. Information about offshore drilling operations was gathered and assistance was rendered in setting up a procedure for making assessments of the effect oil and gas development might have on eastern Virginia. Within two years the exploratory phase of investigation by a consortium of 31 oil companies and the U.S. Department of Interior was under way to drill stratigraphic test wells to determine subsurface structure and correlation. Federal leases in the Atlantic Ocean for the first commercial test wells were approved and drilling is to begin in 1978.

GROUND-WATER STUDIES

From its inception the Division of Mineral Resources was responsible for the State ground-water program. As in other areas of systematizing records and initiating the collection of data, first priority was given to compiling a general appraisal of ground-water conditions in each of Virginia's counties and independent cities. Simultaneously assistance was rendered to municipalities, industry, government, subdivisions, and individual residents. Because some of the most valuable geologic data is obtained from boreholes, a mutually beneficial liaison was established with the well-drilling industry. Arrangements were made for the Division to receive on a continuing basis well cuttings that can be used to help determine potential water-bearing strata. From the accumulation of borehole information and development of geologic data, ground-water conditions were described in a series of county and city summary reports. Between 1963 and 1967 several State parks were investigated to determine a sufficient source of ground-water for future expansion. They included Douthat, Claytor Lake, Fairystone, Mt. Rogers (Grayson Highlands), Westmoreland, Pocahontas, Hungry Mother, and Prince Edward State parks. Additionally, automatic water-level recorders were installed in 18 locations throughout the State to provide permanent records of static water level. Several of these were placed in parks. A unique contract arrangement was entered into when the National Park Service solicited the Division's aid in making a ground-water study of the Shenandoah National Park. Water was needed for present and future lodging, campsite, and maintenance facilities. This study was pursued for the better part of 10 years until 1969. At that time, the Division's ground-water activities were transferred over a period of 2 years to the State Water Control Board in a move to consolidate all water associated responsibilities in the State. Honoring prior commitments, two summary reports were prepared; one released in 1972 contains descriptions of the water resources and the other distributed in 1976 is the first complete geologic study of the area.

GEOLOGIC MAPPING

Geologic maps are of fundamental importance in providing a knowledge of currently or potentially useful rock and mineral materials and an inventory base for land modification and sequential land use. In the past traditional geologic maps with explanatory texts were furnished on topographic and planimetric bases with a variety of scales. These bases are considered inadequate by modern standards. To test this point of view the data from older geologic maps was mechanically transferred to modern base maps. Resistant rock units that are known to occur as mountains and ridges were plotted in valley areas; the reverse was true for nonresistant rocks. Because of these discrepancies a project to transfer by inspection all available preexisting information to new topographic bases was begun. Aerial photographs that were being made in conjunction with the expanded topographic mapping program were inspected to help make a "best fit." Within 10 years the data for most of the area examined west of the Blue Ridge Mountains was recorded to be used in future mapping projects as well as a source of background information for response to public inquiry.

From a review of geologic mapping prior to the 1960's it became evident that nearly ninety geologic maps of local and regional areas could be used to update the 1928 edition of the 1:500,000 scale "Geologic Map of Virginia." Included in the compilation was information from maps published between 1927 and 1962 as well as file data and other source material that were not being utilized. For industrial, educational, and planning purposes the map was an illustration of the distribution of 108 rock units and their structure throughout the State. Companies seeking new locations or expanding those in operation could use the map as a general reference to determine additional areas containing similar rock units. As new specifications for process and design are identified raw materials, hitherto not considered as being of value, gain economic significance.

With the expansion of the topographic-mapping program in 1962 topographic bases upon which geologic field data is compiled became available for 7.5-minute quadrangle studies in many of Virginia's urban and suburban areas. The 1:24,000-scale bases are recognized as the optimum coverage on which to depict geology in sufficient detail for land-use planning and mineral-resource inventory. Greater detail can be developed at larger scales where specific needs necessitate on-site analysis related to construction, quarry and mine expansion, property appraisal, and so forth. As mapping progressed it became the policy of the Division to investigate adjoining quadrangles to provide a continuity in rock correlation and structure. During 1963 the first 1:24,000-scale geologic quadrangle map in the State was published by the Division and during a period of 21 years 75 quadrangles representative of over 4,000 square miles (10,360 sq km) were distributed.

As of the mid-1950's only general and regional surveys of the Coastal Plain had been published. In order to appraise the status of geologic knowledge, a bibliography of Coastal Plain references was compiled in 1965. Another important factor of the appraisal was the preparation of borehole logs made from rock cuttings collected and submitted to the Division by well drillers. The information gained therefrom was used to construct a framework for the correlation of sedimentary units and determination of subsurface structure. By 1973 about 10 years after the beginning of the project, a summary of Coastal Plain geology was published. Concurrent with the latter portion of this work a systematic investigation of 7.5-minute quadrangle areas began with studies originally funded by the Office of Naval Research. The prime target of these early efforts was to provide information for the major urban areas of Norfolk, Newport News, and Hampton. Through these studies more has been learned about ancient depositional environments, including the location of old stream beds, shorelines, and beach features. Such data is useful in the search for ground-water resources and in foundation construction for buildings and transportation routes. Along the Fall Line the eastern portion of metropolitan Richmond was mapped and the first thrust to collect environmental geological data was made.

One of the areas for which there was the least known geologic information was the Piedmont section of the State. Complex structures, distorted and reconstituted rocks, and a general scarcity of exposures has made this a difficult area to deal with. Beginning with some of the known geology of the neighboring state of North Carolina, a quadrangle by quadrangle project was initiated to identify rock units and their structure in the southwestern Piedmont. Heretofore unrecognized folds and faults were mapped; their geographic distribution, and hence structural elements, were compared successfully with magnetic trends determined from aeromagnetic surveys. The use of this technique gave rise to further assistance in deciphering geology in adjoining quadrangles as well as others in the Piedmont. Earlier studies of Triassic rocks were continued; in particular, those in the Danville and Leesburg portions of the State were investigated and the unsuspected presence of intermediate felsic volcanic rocks was established. Zones of cataclastic rocks that may be transport indicators of crustal masses have been identified in the southwestern and west central portion of the Piedmont.

Prior to 1957 the Valley and Ridge area west of the Blue Ridge Mountains had received perhaps the greatest attention in geologic investigations primarily because of the occurrence of such mineral resources as coal, oil, gas, limestone, shale, manganese oxide, and lead and zinc sulfide. Most of this work was achieved using 1:62,500 or smaller scale base maps. Reports about local and regional geologic mapping surveys, usually contained a section on the past and present economic development of the mineral industry for areas studied as well as descriptions of any raw materials of potential value. Since the publication of the "Geology of the Clinchport Quadrangle" in 1963 there has been a continuous flow of completed maps at a scale of 1:24,000. Because greater detail can be illustrated at this scale, the maps can have more meaningful application in the planning stages for residential, commercial, industrial, municipal, and governmental needs. The geologic mapping program for the Valley and Ridge portion of Virginia was and continues to be centered around urban and suburban areas including those of Bristol, Abingdon, Salem, Roanoke, Staunton, Waynesboro, Woodstock, Strasburg, Front Royal, and Berryville. Quadrangles depicting these cities and towns form the nucleus around which known data is projected and mapped into adjacent quadrangles. (These procedures apply throughout the State.) In order to translate information that traditionally was described in technical language an effort has been made in recent years to furnish data in a less complex style. This approach was started when it became apparent geologic factors that partially govern land modification needed to be described in simple words. The first environmental geologic maps and accompanying reports distributed in 1975 and 1976 had information related to the Front Royal, Strasburg, and Toms Brook quadrangles. The first release of a new publication series was made in 1978. It supercedes the Division's series of bulletins, reports, and circulars and has been redesigned into an 8.5 x 11 inch format.

COMMENT

The Division of Mineral Resources has had and continues to have a vital role in developing, interpreting, and reporting geologic and topographic information for Virginia. It functions as an economically oriented public service agency with responsibilities in the inventory of mineral resources, the determination of geologic conditions, and the translating of mineral resource and geologic data into useful information. During the past 21 years the Division has experienced continual and significant growth. Past records were organized, reviewed, and utilized to set up a working data base. Major programs in geologic and topographic mapping were established, new techniques employed, and scientific advancements achieved—all done while providing response to public needs and inquiry. The framework has been furnished upon which to build a viable and lasting service to the citizens of Virginia.

C.R.B.H.

PRODUCTION OF MINERAL RESOURCES IN VIRGINIA[1]

By
D.C. Le Van

CONTENTS

TABLES

[1]Portions of this contribution may be quoted if credit is given to the Virginia Division of Mineral Resources. It is recommended that reference be made in the following form:

Le Van, D.C., 1978, Production of mineral resources in Virginia, *in* Contributions to Virginia geology—III: Virginia Division of Mineral Resources Publication 7, p. 7-21.

ABSTRACT

A wide range of mineral resources is present in Virginia. Utilization of some of these materials began as early as Colonial time and at present more than 30 different mineral resources are produced. The value of mineral production in 1976 exceeded a billion dollars, of which mineral fuels contributed about 84 percent, nonmetallic minerals about 15 percent, and metallic ores slightly less than 1 percent. The principal mineral fuel commodity is bituminous coal, which accounted for about 83 percent of the total value of mineral output in 1976; natural gas and a small amount of oil are also obtained. Nonmetallic resources produced include crushed and dimension stone, raw materials for cement and lime, sand and gravel, clay materials, kyanite, gypsum and anhydrite, feldspathic rock (Virginia aplite), silica sand, mineral pigments, talc and soapstone, marl, shells, and specimen and lapidary materials. Production of metallic ores is currently limited to mining of lead and zinc minerals at one locality. Summary information is given for the various commodities, including history, scope of activity, source of materials, uses, tables of tonnage and value where available, and selected references. Other resources that have been recovered in the past are outlined briefly.

INTRODUCTION

Virginia extends across parts of five major physiographic provinces—the Coastal Plain, Piedmont, Blue Ridge, Valley and Ridge, and Appalachian Plateaus. Surface exposures range from igneous and metamorphic rocks of Precambrian age to sediments of Quaternary age. As a result of this diversity the State has a wide variety and abundance of mineral resources (Le Van and Harris, 1971). Production of these resources began shortly after the settlement of Jamestown when English colonists undertook the mining and smelting of local iron minerals. This early iron activity survived for only a short time, but represents the initial step in the development of the State's mineral wealth. Various types of rock for building purposes and clay for brick-making were important to the people of Colonial Virginia. Early development of other resources followed, including coal in the early 1700's, lead ore by about 1756 (Brown and Weinberg, 1968), and gold by about 1829. Deposits of metallic and nonmetallic minerals and mineral fuels were found at many localities and developed for local use or to supply commercial markets. Some of these commodities, such as coal, have been important to the State's mineral economy for many years; others, such as manganese ores, pyrite, and titanium minerals were significant in the past but are not now mined because of changing technologies, markets, or economic factors.

The overall commercial development of Virginia's mineral resources has been carried out so successfully that by 1974 the value of annual production exceeded a billion dollars for the first time. In that year Virginia ranked thirteenth among the states in value of mineral output. The annual value in Virginia almost doubled from 1973 to 1974, chiefly because of a sharp increase in the price of the principal commodity, bituminous coal, and has remained above or near the billion-dollar level since that time. In 1975 bituminous coal alone contributed more than a billion dollars to the annual total. The value of mineral production for the period 1956-1976 and the relative importance of coal are shown in Table 1.

At the present time more than 30 different mineral resources are produced. The total value of resources produced or processed in 1976 was reported as $1,160,645,000 by the U.S. Bureau of Mines (1978); mineral fuels—bituminous coal, natural gas, and oil—accounted for about 84 percent. The diverse group of nonmetallic commodities other than fuels contributed about 15 percent of the value and the metallics (lead and zinc) accounted for less than 1 percent. A total of 985 coal mines were reported in operation by the Virginia Department of Labor and Industry (1977a). In addition 257 companies or individual operators were listed as engaged in the production or processing of resources other than coal as of March 15, 1976 (Le Van, 1976). More than 20,000 people were employed by the mining industry during that year.

MINERAL FUELS

COAL

Coal has accounted for more than half of the annual value of mineral output in Virginia since 1916. About 1,940 square miles (5,025 sq km) or 5 percent of the State is underlain by coal-bearing rocks (Averitt, 1975). The coal occurs in four areas: the currently active Southwest coal field in the Appalachian Plateaus province, the inactive Valley coal fields in the Valley and Ridge province, and the inactive Richmond and Farmville basins in the Piedmont province. A summary description of these coal-bearing areas, production data through 1949, and reserve estimates as of 1951 for the Southwest and Valley fields are contained in Brown and others (1952).

Table 1.—Production of mineral resources in Virginia, 1956-76 (compiled from Mineral Industry Surveys and Minerals Yearbooks of the U.S. Bureau of Mines).

	Value of All Commodities (Dollars)	Value of Coal (Dollars)	Coal Production (Short tons)	Value of Noncoal Commodities (Dollars)	Percentage of Total Value Represented by Coal
1976	1,160,645,000	964,669,000	39,996,000	195,976,000	83
1975	1,261,974,000	1,081,587,000	35,510,000	180,387,000	86
1974	1,056,569,000	856,099,000	34,326,000	200,470,000	81
1973	545,401,000	377,679,000	33,961,000	167,722,000	69
1972	489,791,000	344,061,000	34,028,000	145,730,000	70
1971	385,161,000	254,870,000	30,628,000	130,291,000	66
1970	374,321,000	246,181,000	35,016,000	128,140,000	66
1969	317,527,000	192,802,000	35,555,000	124,725,000	61
1968	295,663,000	178,946,000	36,966,000	116,717,000	61
1967	283,685,000	171,183,000	36,721,000	112,502,000	60
1966	274,297,000	153,341,000	35,565,000	120,956,000	56
1965	267,977,000	139,291,000	34,053,000	128,686,000	52
1964	237,415,000	123,123,000	31,654,000	114,292,000	52
1963	229,064,000	120,972,000	30,531,000	108,092,000	53
1962	222,494,000	117,560,000	29,474,000	104,934,000	53
1961	225,298,000	126,121,000	30,332,000	99,177,000	56
1960	203,887,000	122,723,000	27,838,000	81,164,000	60
1959	222,501,000	139,224,000	29,769,000	83,277,000	63
1958	203,277,000	130,319,000	26,826,067	72,958,000	64
1957	227,108,000	153,959,000	29,505,579	73,149,000	68
1956	208,806,000	138,127,000	28,062,775	70,679,000	66

Cumulative reported production of coal from Virginia through 1976 is approximately 1.355 billion tons (1.229 billion metric tons). It is known that the reserve estimates are not based on modern work and the U.S. Geological Survey recognizes that "no coal-bearing area in the U.S. has been adequately inventoried because of the varied classification and reporting preferences of the investigating scientists and agencies and because responsible authorities did not view assessment as necessary considering the magnitude of the resource and the commonly accepted belief that coal's day was over." (U.S. Geological Survey, 1977).

Most of the coal resources and all of the current production are in the Appalachian Plateaus province in an area of about 1,552 square miles (4,020 sq km) (Brown and others, 1952). It includes all or parts of Buchanan, Dickenson, Lee, Russell, Scott, Tazewell, and Wise counties and constitutes the Southwest coal field. Numerous commercially important beds of bituminous coal of Pennsylvanian age occur in the Pocahontas, Lee, Wise, Norton, and New River formations. Large reserves of low-sulfur coal are present. The rocks are essentially flat-lying to gently dipping, except along the southern boundary of the Appalachian Plateaus province or near the edges of the Cumberland thrust sheet, of which much of the Southwest coal field is a part. Several other structural features are also present.

Coal shipments from the Southwest coal field began in 1883 with the extension of rail facilities into Tazewell County (Harnsberger, 1919). Subsequent building of railroads into the other coal-bearing counties brought about rapid development of the field. Shipment from Buchanan County, the last to be developed, began in 1932 and that county now ranks first in Virginia in coal output. Coal production from the seven counties of the field in 1976 is shown in Table 2; cumulative production through 1976 is about 1.340 billion tons (1.215 billion metric tons).

Coal is produced by both underground and surface-mining methods in southwestern Virginia. Of the 985 coal mines reported in operation in 1976 by the Virginia Department of Labor and Industry (1977a), there were 59 tipple mines, 432 truck mines, 399 strip mines, and 95 auger operations. The deepest production is in Buchanan County where several mines developed since 1961 recover the Pocahontas No. 3 coal at depths of about 1,300 feet

(396 m). Strip mining has increased rapidly in importance in recent years.

Table 2.—Coal production in 1976 in Virginia (from Virginia Department of Labor and Industry, 1977).

County	Short Tons
Buchanan	15,803,507
Dickenson	5,298,606
Lee	1,300,172
Russell	1,708,030
Scott	12,685
Tazewell	3,582,656
Wise	12,289,890
Total Production	39,995,546

Table 3.—Relative importance of strip-mine production in Virginia, 1956-76 (compiled from Annual Reports of the Virginia Department of Labor and Industry. Production data differ slightly from those of the U.S. Bureau of Mines reported in Table 1 because of different methods of reporting information used by the two agencies).

	Production By All Methods (Short tons)	Production By Strip Mines (Short tons)	Percent of Total Production by Strip Mines
1976	39,995,546	12,959,491	32.4
1975	35,505,780	11,159,798	31.4
1974	34,283,753	10,048,467	29.3
1973	33,869,387	8,703,152	25.7
1972	33,995,841	8,296,742	24.4
1971	30,624,954	7,176,755	23.4
1970	34,974,724	5,103,462	14.6
1969	35,651,536	3,492,639	9.8
1968	36,865,703	4,046,205	11.0
1967	36,415,214	4,078,515	11.2
1966	35,572,928	3,648,982	10.3
1965	34,063,404	3,077,148	9.0
1964	31,773,217	2,451,649	7.7
1963	30,389,798	2,108,495	6.9
1962	29,469,945	1,794,819	6.1
1961	28,156,370	1,409,229	5.0
1960	26,706,285	1,373,906	5.1
1959	28,223,508	1,753,466	6.2
1958	25,030,954	1,590,085	6.4
1957	26,528,081	1,797,151	6.8
1956	26,004,732	1,749,454	6.7

About one third of the State tonnage was produced by this method in 1976. Contour mining is done extensively and mountain top removal is also used in this area of hilly terrain. Reclamation of lands that have been surface-mined for coal has been mandated by State law since 1966 and is administered by the Virginia Division of Mined Land Reclamation.

Table 4.—Consumer use of bituminous coal from Virginia mines, 1976 (from U.S. Bureau of Mines, 1978).

	Thousand Short Tons	Percent of Total Shipments
Electric utilities	15,190	37.7
Coke	8,272	20.5
Other industrial retailers	6,247	15.5
All other uses	3,787	9.4
Exports	6,835	16.9

Coal mined in the Southwest field in 1976 was shipped to domestic and export markets (Table 4). Large tonnages of coking coal are produced and beehive coke plants were formerly operated at numerous localities in this coal field. At the present time one coke plant in Buchanan County that utilizes nonrecovery Mitchell-type and other ovens is active.

The geology and coal resources of the individual counties of the Southwest coal field were described in detail in bulletins published between 1918 and 1925 by the Virginia Geological Survey. The stratigraphy of the coal-bearing rocks has been discussed and interpreted in numerous other papers, including Brown and others (1952), Englund and DeLaney (1966), Miller (1969), and Miller (1974). Geologic maps for a few quadrangles in this field have been published or placed on open file by the U.S. Geological Survey. Maps that show coal outcrops and mined-out areas in the Southwest field on 7.5-minute topographic quadrangle bases have recently been published (Southwest Virginia 208 Planning Agency, 1977). Yearly statistical data on coal mines and production are published in the Annual Reports of the Virginia Department of Labor and Industry as well as in the Minerals Yearbooks of the U.S. Bureau of Mines.

One of the objectives of the Virginia Division of Mineral Resources is to see that the Southwest Coal Field is mapped at a scale of 1:24,000 at an early date.

In the Valley and Ridge province 10 small coal fields in the area extending from Smyth to Rockingham counties are known collectively as the Valley Coal fields. The coal is of Mississippian age and is chiefly semianthracite, although some is stated to be bituminous in rank by Brown and others (1952), who give reserve estimates for 6 of the 10 fields. Mining began in the Valley fields prior to the Civil War and ceased in 1971; cumulative production is about 7 million tons (6 million metric tons). The

Valley fields were described in detail by Campbell and others (1925).

Coal of Triassic age is present in the Richmond basin in parts of Amelia, Chesterfield, Goochland, Henrico, and Powhatan counties. It is mostly bituminous, but some natural coke occurs due to the presence of igneous intrusions. Data are lacking on the thickness, extent, and continuity of the coal beds in the deeper parts of the basin. Mining began in the Richmond basin in the early 1700's and continued until the early 1900's; production is also reported for the years 1910-13, 1921-23, and 1940-41 by Brown and others (1952). Cumulative production is reported by them to be slightly more than 8 million tons (7 million metric tons). Triassic coal also occurs in Cumberland County in the Farmville basin. Mining was done near Farmville in the late 1800's and since that time there has been prospecting, but detailed records are not available. The Richmond coal basin has been discussed in many 19th Century reports, such as Shaler and Woodworth (1899); later reports include those by Roberts (1928) and Brown and others (1952) (both also describe the Farmville basin) and by Goodwin (1970).

The Dismal Swamp Peat of Holocene age is present in the Coastal Plain of southeastern Virginia. A small quantity of peat was produced from this formation for use as fuel during the 19th century.

Methane associated with the Pocahontas No. 3 coal bed in Buchanan County in the Southwest field has been the subject of methane-control studies by the U.S. Bureau of Mines. As techniques for recovery are developed and problems of ownership are resolved, the methane in this and other coal beds may ultimately become a useful energy resource. Interest is also being shown in the possibility for coal-gasification plants in the State. A coal-sampling program begun in 1975 by the Division of Mineral Resources, in conjunction with analytical work performed by the U.S. Geological Survey and U.S. Bureau of Mines, is providing new data on characteristics and composition of coal in Virginia.

NATURAL GAS AND OIL

More than 600 test wells have been drilled in the search for natural gas and oil in Virginia since the first test was drilled in Wise County in the 1890's. Drilling has been concentrated largely in the southwestern counties and commercial production of gas and oil has been limited to this area. Natural gas is currently produced in Buchanan, Dickenson, Tazewell, and Wise counties and a small amount of oil is produced in Lee County. Production of natural gas and oil for the period 1956-76 is shown in Table 5. Exploration and production data are summarized in the Annual Reports of the Virginia Department of Labor and Industry. Drilling activity to the 1950's has been reviewed by Huddle, Jacobsen, and Williamson (1956) and Le Van (1959). A listing of wells drilled through 1961 was reported by Le Van (1962).

Table 5.—Production of Natural Gas and Oil in Virginia, 1956-76 (compiled from Annual Reports of the Virginia Department of Labor and Industry).

	Natural Gas (Thousand Cubic Feet)	Oil (Barrels)
1976	6,937,326	2,696
1975	6,722,837	3,002
1974	7,096,443	2,790
1973	5,129,289	0
1972	2,801,913	97
1971	2,632,976	594
1970	2,869,102	917
1969	2,845,846	842
1968	3,388,788	2,583
1967	3,827,447	3,491
1966	4,249,340	1,073
1965	4,210,086	3,617
1964	1,881,780	5,828
1963	2,084,946	3,466
1962	2,488,226	2,757
1961	2,465,910	2,996
1960	2,455,947	2,024
1959	2,351,313	3,992
1958	2,670,156	4,450
1957	2,596,370	4,517
1956	3,048,155	4,454

The first commercial gas discovery was made in 1931 in the Valley and Ridge province by a test drilled to a depth of 3,613 feet (1,101 m) in Scott County on the Early Grove anticline. Additional wells were drilled in Scott County and adjacent Washington County on this anticline, and gas production was developed from sandy zones in the Little Valley limestone of Mississippian age (Averitt, 1941). Gas from the Early Grove field was supplied to the city of Bristol by a small-diameter pipeline from 1938 until about 1958 when the field was abandoned.

Drilling in the Appalachian Plateaus province resulted in discoveries of natural gas in Buchanan County in 1948, Dickenson County in 1949, Wise County in 1953, Russell County in 1955, Tazewell County in 1961, and northern Scott County in 1976. The gas occurs principally in the Greenbrier Limestone ("Big Lime") and the Berea and other sandstones of Mississippian age, and in Devonian shale. Of the wells drilled in Virginia for natural gas and oil about 450 have been in the Appalachian Plateaus, and gas production has been established over extensive parts of the province. Production from Buchanan, Dickenson, and Tazewell counties is supplied to pipelines in Kentucky and West Virginia. Gas in Wise County is used in a local coal-preparation plant, and gas in Russell County has been used in the past for local industrial purposes. Production in Virginia in 1976 was reported at 6,937,326 mcf (194,245 thousand cubic meters) from 180 wells operated by seven companies (Virginia Department of Labor and Industry, 1977b).

In the Valley and Ridge province natural gas has been found in the Devonian Ridgeley Sandstone from the Bergton-Crab Run anticline in northern Rockingham County. Drilling began in this area in the 1930's and between 1951 and 1956 five tests were completed as gas wells in the Ridgeley at depths of about 2,985 to 3,800 feet (910 to 1,158 m). The field is not on a pipeline, and no gas has been produced commercially. The geology of the Bergton field has been described by Young and Harnsberger (1955).

The first commercially significant oil discovery was made in 1942 when a test drilled in Lee County found oil at a depth of 1,110 feet (338 m) in the Trenton limestone of Ordovician age. Independent operators drilled numerous wells in and around a group of fensters in the Cumberland thrust sheet along the axis of the Powell Valley anticline, and thus the Rose Hill oil field was developed. The early history of the field and a detailed description of the geology have been reported by Miller and Fuller (1954). Production has been chiefly from the Trenton limestone. The oil has a gravity of about 44.4° API, a paraffinic wax-bearing base, and very little associated gas. The peak annual production was in 1947 when the output was reported at 61,000 barrels of oil by the U.S. Bureau of Mines. In 1976 production was 2,357 barrels from six wells (Virginia Department of Labor and Industry, 1977b). Cumulative oil production from the Rose Hill field through 1976 is about 278,000 barrels. A second small oil discovery was made in 1963 in the Trenton limestone near Ben Hur in Lee County, about 20 miles (32 km) northeast of the Rose Hill field. The Ben Hur field is in and near the Sulphur Springs fenster of the Cumberland thrust sheet on the Chestnut Ridge anticline; the geology of this part of Lee County has been described by Miller and Brosge (1954). Production in 1976 was 339 barrels of oil from one well. Cumulative production from the Ben Hur field through 1976 is about 9,000 barrels of oil.

Oil produced in the Rose Hill and Ben Hur fields is trucked to a refinery in Kentucky. At present the only refinery in Virginia is on the York River near Yorktown. This facility has a capacity of 53,000 barrels per day and processes crude oil imported from foreign sources. Two additional refineries are currently proposed for the Hampton Roads area.

Only a few exploratory tests have been drilled in the Coastal Plain province in Virginia and no significant oil or gas shows have been encountered. Principal interest in the Mid-Atlantic Outer Continental Shelf, as reflected by recent tract nominations for Federal offshore leasing, lies in the Baltimore Canyon trough north of the waters off the Virginia coast. As exploration of the trough proceeds, drilling activity and perhaps production may ultimately take place in Federal waters on the portion of the shelf that lies east of Virginia.

NONMETALLIC COMMODITIES

The second major segment of the mineral industry in Virginia, production and processing of nonmetallic materials exclusive of fuels, accounted for about $179,000,000 or slightly more than 15 percent of the total mineral output in 1976 according to the U.S. Bureau of Mines. These varied commodities, usually included in the group termed industrial minerals, provide a wide range of raw materials and products that are essential to everyday activities. The resources presently utilized include limestone and dolomite, marl, oyster shells, sandstone, quartzite, quartz, clay, shale, granite and related rocks, diabase and basalt, amphibolite, ultramafic rock, schist, slate, talc and soapstone, kyanite, sand and gravel, gypsum and anhydrite, iron-oxides (considered as industrial minerals in this report because of their end use), aplite, and specimen and lapidary materials.

STONE

The production and processing of various types of rock for crushed stone and dimension-stone products is commonly classified under the general heading "stone," for purposes of discussion and statistics. Stone is the second most important commodity produced in Virginia, being exceeded only by coal in value of output. A total of 36,132,000 short tons (32,771,724 metric tons) of stone with a value of $91,723,000 were sold or used by producers in 1976 (U.S. Bureau of Mines, 1978). Limestone, dolomite, marl, sandstone, quartzite, quartz, shale, granite and related rocks, diabase, metabasalt, amphibolite, ultramafic rock, slate, soapstone, and feldspathic rock were all quarried for stone. About 150 quarries were active in the production of a wide range of raw materials or finished stone from these rocks. Most of the rock produced is used for various types of crushed stone. In 1974, for example, more than 97 percent of the output value of stone represented crushed or broken stone, and the remainder was attributed to dimension stone (Vannoy, 1977). In that year Virginia ranked seventh in the total value of crushed and dimension-stone shipped or used by producers. The tonnage and value of stone output in Virginia for the period 1956-1976 is shown in Table 6.

Table 6.—Production of stone in Virginia, 1956-76 (compiled from Mineral Industry Surveys and Minerals Yearbooks of the U.S. Bureau of Mines. Some variation exists in commodities that have been included under the category of stone by the Bureau over the period 1956-76).

	Value in Dollars	Short Tons
1976	91,723,000	36,132,000
1975	84,204,000	35,384,000
1974	95,988,000	44,176,000
1973	82,719,000	43,895,000
1972	74,090,000	39,987,000
1971	63,482,000	34,643,000
1970	60,477,000	35,415,000
1969	58,713,000	33,461,000
1968	53,533,000	31,217,000
1967	52,470,000	31,324,000
1966	55,550,000	34,151,000
1965	59,397,000	36,350,000
1964	52,153,000	30,407,000
1963	45,529,000	27,653,000
1962	43,121,000	25,766,000
1961	39,206,000	22,934,000
1960	33,019,000	19,358,000
1959	31,447,000	17,787,000
1958	27,504,000	15,412,947
1957	21,158,000	14,243,510
1956	23,076,000	14,081,904

Crushed Stone

The principal market for crushed stone produced in Virginia is the construction industry, which utilizes these materials for highway building and maintenance, paving, concrete aggregate, ballast, drain fields, manufactured stone sand, and many other purposes. Much of the crushed stone marketed for construction is prepared to size and gradation specifications. Crusher-run material is also used extensively. Larger, irregular pieces of stone are marketed for riprap, jetties, and similar uses. Many quarries that produce crushed stone for the construction industry are permanent installations that have served their respective market areas for decades. The use of portable crushing plants that are moved to new or intermittent quarry sites near highway construction or other large projects has become common in recent years. Some of the quarry sites that are worked with portable plants are abandoned after tonnage requirements for a specific nearby project are met. Other sites may remain as full time or intermittent operations if warranted by market demand. In some cases companies rotate one crushing plant among two or more alternately operated quarry sites, or employ a single crew to operate plants at two or more quarries alternately. The crushed-stone industry received considerable impetus in recent years from demand created by the Federal Interstate Highway System and the Virginia arterial highway program. Large tonnages of crushed stone for construction are shipped from quarries in the Piedmont into the Tidewater area, where there are few sources of material suitable for crushing other than gravel. Physical test data determined for potential aggregate sources at many sites in Virginia have been reported by Parrott (1954); test data for rock supplied by operating quarries were listed by Gooch, Wood, and Parrott (1960), and are reported periodically by the Department of Highways and Transportation.

Extensive occurrences of carbonate rocks, including high-calcium limestones and high-magnesium dolomites, are present in the Valley and Ridge province; more restricted deposits of carbonates occur in the Piedmont. In addition to their use in the construction field, large tonnages of carbonate rocks in Virginia are crushed and used for specific purposes such as the manufacture of lime and cement; for agricultural liming and mineral-feed supplements; for mine dusting; as raw materials in the steel, glass, and chemical industries; and for many other industrial applications. A limited amount of marl is also produced for agricultural use and for fill. Numerous analyses of carbonate rocks have been reported in a series of publications on industrial limestones and dolomites in western Virginia (Cooper, 1944, 1945; Edmundson, 1945, 1958).

High-silica sandstone and quartzite are present in several formations in western Virginia. The Ridgeley Sandstone of Devonian age has been quarried and processed for glass sand at a site in western Frederick County for many years. In the past glass sand has also been produced from sandstone of Silurian age at other localities in the State, and metallurgical quartzite has been obtained from the Erwin Formation of Cambrian age. Chemical and physical test data for high-silica resources in western Virginia have been reported by Lowry (1954) and Harris (1972).

A few types of rock are quarried in Virginia to meet a demand for ornamental aggregate. White vein quartz in the Piedmont is crushed and used as exposed aggregate in precast concrete panels, and black limestone of the Edinburg Formation is used in terrazzo. Both vein quartz and light-colored carbonate rocks are crushed and marketed for decorative purposes in landscaping and horticulture. Other varieties of rock may also be used for ornamental purposes.

Dimension Stone

The quarrying of rock for dimension stone in Virginia began in Colonial times. Over the years, quarries have been opened at numerous localities to supply demand ranging from local construction needs to extensive commercial markets. Cretaceous sandstone from northern Virginia was used, for example, in construction of several early government buildings in Washington, including the White House and Capitol (Watson, 1907). Granitic rocks from the Piedmont were widely used for monuments, paving blocks, curbing, and general building stone in the past. Carbonate rocks and sandstone in western Virginia were also utilized extensively for building purposes. Slate quarrying began in the late 1700's (Redden, 1961) and has remained an important industry to this time. Soapstone has also been an important dimension stone material for many years. Other types of rock, such as schist, gneiss, and metabasalt with a wide range of appearance, workability, and durability, have been used for various building purposes.

At present the various types of dimension stone produced in Virginia account for less than 3 percent (Vannoy, 1977) of the total value of stone produced. In Buckingham County two companies quarry and prepare slate of the Arvonia Formation of Ordovician age for roofing, flooring, building facings, and similar uses. Broken and unused slate that results from the dimension-slate operations is crushed and marketed as a crushed-stone product. Soapstone from quarries operated by a company in Albemarle and Nelson counties is finished for laboratory bench tops and various special-order products. Diabase of Triassic age in Culpeper County is quarried for monumental and building stone and granitic gneiss in Hanover County is used for building stone. Quartzite of the Mt. Athos Formation in Campbell County (Redden, 1963, p. 89) and quartzite in Fauquier and Prince William counties are quarried for building purposes such as facing stone, walls, and flagstone.

CEMENT

Cement was the third most important mineral commodity in Virginia in 1976 although only three plants are in operation. Portland and masonry cement are manufactured at a plant in Botetourt County that began operation in 1951. This plant utilizes limestone and calcareous shale of the Edinburg Formation and limestone of the Lincolnshire and New Market formations (McGuire, 1976) of Ordovician age as basic raw materials. Major plant expansion was completed in 1976 that approximately doubled capacity at that site. Limestone of the Edinburg Formation (Rader and Biggs, 1975) is used at a plant in Warren County at which masonry cement has been manufactured since about 1928. The crushed limestone is calcined to lime, hydrated, and mixed with purchased portland cement to make the masonry product. A third plant is operated in the City of Chesapeake to grind imported cement clinkers for the manufacture of Ca-Al cement. This plant formerly used shell marl and clay from Suffolk as raw materials for cement. A new facility to be completed at the Chesapeake operation in 1978 will also produce specialty cement. Middle Ordovician limestone quarried in Scott County is shipped by rail to a cement plant in Kingsport, Tennessee, where it is used as a raw material. In the past carbonate rocks and shale of Devonian age in Augusta County have been used in the manufacture of portland and masonry cement. Natural cement has been produced from rocks of Cambrian age in Rockbridge County (Watson, 1907). An early report by Bassler (1909) described the cement resources of Virginia.

LIME

Lime was the fourth-ranking mineral commodity produced in Virginia in 1976. A total of 878,000 short tons (796,346 metric tons) of quicklime and hydrated lime, valued at $25,993,000, was produced in that year. The high-calcium New Market Limestone was quarried and calcined for lime at two sites in Frederick County and one site in Shenandoah County. Two firms in Giles County operate underground mines to produce high-calcium Five Oaks limestone of Ordovician age for manufacture of lime in on-site plants. Lime from Virginia plants is marketed to the steel and paper industries, for water purification, sewage treatment, agriculture, and for other uses. A plant in Isle of Wight County operates intermittently, burning oyster shells to produce lime for agricultural use. In the past, lime plants have been operated at many other localities in the State. Lime produced by calcining limestone of the Edinburg Formation in Warren County is used in the manufacture of masonry cement at that site. Production of lime in Virginia for the period 1956-1976 is shown in Table 7.

Table 7.—Production of lime in Virginia, 1956-76 (compiled from Mineral Industry Surveys and Minerals Yearbooks of the U.S. Bureau of Mines).

	Value in Dollars	Short Tons
1976	25,993,000	878,000
1975	20,192,000	705,000
1974	18,929,000	895,000
1973	12,205,000	782,000
1972	11,739,000	758,000
1971	11,049,000	759,000
1970	14,090,000	1,046,000
1969	13,653,000	1,072,000
1968	11,138,000	919,000
1967	10,345,000	829,000
1966	10,486,000	840,000
1965	10,584,000	847,000
1964	9,781,000	780,000
1963	8,058,000	639,000
1962	7,668,000	615,000
1961	7,375,000	657,000
1960	8,028,000	711,000
1959	8,168,000	765,000
1958	5,533,000	471,313
1957	6,029,000	510,216
1956	5,926,000	512,346

SAND AND GRAVEL

Sand and gravel are important mineral commodities in Virginia, ranking fifth in value in 1976. In that year the output, excluding industrial sand and gravel, was reported at 10,191,000 tons, valued at $23,089,000 (U.S. Bureau of Mines, 1978). Production is largely from the Coastal Plain, which makes up approximately one-fourth of the State. In this area production is obtained from deposits of marine, fluvial, and estuarine origin. Gravel is abundant in the western portion of the Coastal Plain near the Fall Line, and in general it becomes finer in size and less abundant eastward. In other parts of the State sand and gravel are obtained along streams such as the James, New, Dan, and Shenandoah rivers. Approximately 125 commercial or captive producing operations were recorded active on a full time or intermittent basis in 35 counties and 6 major independent cities during 1976 (Le Van, 1976). Other sites are used as material is needed by the Department of Highways and Transportation or other consumers. Much of the production is in the vicinity of the larger markets near Fredericksburg, Richmond, Petersburg, and the Virginia Beach area.

The sand and gravel are recovered by operations that range from high-volume plants producing a range of washed and screened materials to small pits that supply bank-run material for local use. Equipment utilized includes dredges or pumps in streams and artificial ponds, draglines, shovels, and front-end loaders. Gravel is crushed at some operations to provide a source of coarse aggregate. Many of the producing sites are operated seasonally or intermittently in accordance with demand and weather conditions.

Large quantities of material are produced in the area east of Fredericksburg and shipped by rail into the northern Virginia-Washington, D.C. market area. Some sand and gravel produced along the James River below Richmond are shipped by barge for use in the Norfolk area. Shipments are also made westward to and beyond the Piedmont by rail and truck. In addition to the production described, manufactured sand is obtained by crushing sandstone and quartzite. Sand is recovered from residual deposits formed by weathering of those rocks at some localities. In 1974 the State ranked 20th in the value of sand and gravel materials produced. The U.S. Bureau of Mines reports (Vannoy, 1977) that in that year about 80 percent of the output from Virginia was used commercially and 20 percent was used for publicly funded projects; about 87 percent of the output tonnage was reported to be processed material. Production during the period 1956-1976 is shown in Table 8. The output is used chiefly in various phases of the construction industry, including concrete aggregate and masonry work, paving and other road work, and fill material; for concrete products; for ice-control; for traction sand; and for filter sand. Some quartz gravel in the Coastal Plain is marketed for use as ornamental aggregate in cast concrete panels. Regional descriptions of sand and gravel resources in the Coastal Plain of Virginia have been made by Wentworth (1930) and Onuschak (1973). A modern summary discussion is presented by Sweet in a contribution elsewhere in this volume. Physical test

Table 8.—Production of sand and gravel in Virginia, 1956-76 (compiled from Mineral Industry Surveys and Minerals Yearbooks of the U.S. Bureau of Mines).

	Value in Dollars	Short Tons
1976	*23,089,000	*10,191,000
1975	24,776,000	9,895,000
1974	29,270,000	14,314,000
1973	26,246,000	14,511,000
1972	21,696,000	14,085,000
1971	20,201,000	12,796,000
1970	15,229,000	11,126,000
1969	15,954,000	12,140,000
1968	13,644,000	10,859,000
1967	12,494,000	9,863,000
1966	16,635,000	17,191,000
1965	18,019,000	15,322,000
1964	13,722,000	10,588,000
1963	17,752,000	10,400,000
1962	16,375,000	9,745,000
1961	14,697,000	9,839,000
1960	11,432,000	7,666,000
1959	12,369,000	8,452,000
1958	10,834,000	7,158,228
1957	9,877,000	7,046,869
1956	9,240,000	7,783,103

*Excludes industrial sand and gravel.

data for sand and gravel at numerous sites in the Coastal Plain have been published by Parrott (1954) and Gooch, Wood, and Parrott (1960). Test data for fine-size aggregate from operating plants are summarized and distributed periodically by the Virginia Department of Highways and Transportation.

CLAY MATERIALS

The production of clay materials for use in the manufacture of ceramic and nonceramic products is an important segment of the mineral industry in Virginia. The reported output of clay materials in 1976 was 862,000 tons, valued at $1,210,000. Clay, shale, schist, and slate were produced for ceramic products from open-pit operations in 15 counties and the City of Richmond. The manufacture of bricks has been prominent since Colonial days, and brick construction has been fundamental to much of the traditional architecture of the State. Brick plants were operated at numerous localities, many on a local basis. The trend over the years has been to fewer, modern, high-capacity plants. At present nine brick plants are in operation in the State. Raw materials that are used include shale of Cambrian, Devonian, and Triassic age, schist of Precambrian or Paleozoic age, and clay derived from various sources. A wide range of coatings, colors, and textures is marketed.

The manufacture of lightweight aggregate is also an important part of the clay-material industry in Virginia. Three plants currently produce aggregate by the rotary-kiln method and one plant utilizes the sintering method. Slate of the Hampton Formation is used as raw material by a plant in Amherst County and slate from the Arvonia Formation by a plant in Buckingham County. Slate used in the manufacture of lightweight aggregate is included under stone for statistical purposes by the U.S. Bureau of Mines. Triassic shale and related rocks from an adjacent quarry in North Carolina is the raw material used at a plant in Pittsylvania County. Shale from the Rome Formation is utilized to produce sintered aggregate in Botetourt County. The aggregates are marketed under company trade names and are widely used in the manufacture of lightweight building blocks, concrete, and elsewhere in the construction industry. In the past shale that was recovered at a coal-preparation plant in Russell County has also been used as a raw material for lightweight aggregate.

Clay in James City County is used intermittently in the manufacture of pottery. Clay mined in Tazewell County is extruded to make dummies that are used in coal mining to tamp shot holes, and clay from Russell County is used to seal oven doors at a coke plant in Buchanan County. Production of clay materials for the years 1956-1976 is shown in Table 9.

The Division of Mineral Resources has carried out a program of sampling and testing of clay materials in Virginia since 1957 in conjunction with the U.S. Bureau of Mines. Preliminary testing of fired and unfired samples by the Bureau indicates a wide range of potential uses for the various materials, including brick, tile, pottery, lightweight aggregate, refractories, fillers, whiteware, and other products. Summary information for 485 samples of clay materials at selected localities that have a potential for ceramic or nonceramic products was published by the Division (Sweet, 1976).

KYANITE

Virginia is the leading state in the production of kyanite. The mineral is mined in the Piedmont by surface operations at Willis Mountain, Buckingham County and Baker Mountain, Prince Edward County, where it occurs in quartzites of late

Table 9.—Production of clay materials in Virginia, 1956-76 (compiled from Mineral Industry Surveys and Minerals Yearbooks of the U.S. Bureau of Mines).

	Value in Dollars	Short Tons
1976	1,210,000	862,000
1975	1,152,000	819,000
1974	2,614,000	1,957,000
1973	1,886,000	1,646,000
1972	1,783,000	1,634,000
1971	1,800,000	1,710,000
1970	1,672,000	1,633,000
1969	1,504,000	1,677,000
1968	1,714,000	1,462,000
1967	1,623,000	1,382,000
1966	1,813,000	1,486,000
1965	1,657,000	1,415,000
1964	1,614,000	1,440,000
1963	1,558,000	1,410,000
1962	1,444,000	1,464,000
1961	1,332,000	1,406,000
1960	1,395,000	1,348,000
1959	1,397,000	1,346,000
1958	1,143,000	1,152,850
1957	986,000	893,255
1956	1,033,000	1,000,019

Precambrian or Early Cambrian age. At Willis Mountain mining operations are conducted on a prominent monadnock formed by the resistant kyanite quartzite. The kyanite is beneficiated by means of flotation and magnetic separation of iron oxides at processing plants near the mine sites in the two counties. Most of the beneficiated kyanite is converted to synthetic mullite by calcination. The finished kyanite and mullite products are marketed in bulk or in bags and are used chiefly as super duty refractories in the metallurgical and glass industries. Fine-grained quartzite obtained during the milling process is marketed as sand for a variety of industrial uses. Magnetic iron oxides separated in processing are stockpiled for possible future use. Production of kyanite began at Baker Mountain in the early 1920's (Johnson, 1967) and at Willis Mountain in 1957. Recent expansion of mining and milling facilities will expand production at Willis Mountain by 100 percent (personal communication, C. Kay, 1978). Other occurrences of kyanite, none of which has been exploited commercially, are found in Buckingham, Prince Edward, and Charlotte counties and elsewhere at scattered localities in the Piedmont. The kyanite occurrences have been described by Jonas (1932), Espenshade and Potter (1960), and Johnson (1967).

EVAPORITES

Gypsum, anhydrite, and salt are present in rock strata that trend southwestward across northern Smyth and Washington counties. The evaporites occur in the Maccrady Formation of Mississippian age, which is locally thickened in this area. The geologic setting and the origin of the evaporites have been interpreted by Stose (1913), Withington (1965), and Cooper (1966). Gypsum has been mined at numerous sites along this trend since about 1830 (Withington, 1965). At present two underground mines are operated near Plasterco, Washington County and Locust Cove, Smyth County. The gypsum and anhydrite are processed at a plant in Plasterco for gypsum wallboard and agricultural gypsum, and for use in portland cement. This company also operates a plant in Norfolk to process gypsum that is imported from Nova Scotia.

Salt was recovered from brines near Saltville as early as the 1700's (Withington, 1965). Beginning about 1895 a large chemical complex was developed at Saltville, based upon salt recovered by dissolution from brine wells and upon high-purity limestones quarried in the area, for the manufacture of numerous chemical products. Recovery of salt and the operation of the related chemical facilities were terminated in 1972.

MINERAL PIGMENTS

Deposits of iron oxides, including ocher, sienna, and umber, are found in Pulaski County. They are considered as industrial minerals in this report because of their end use in pigments. The oxides occur near the contact of the Erwin and Shady formations of Cambrian age (Johnson, 1964). These materials have been mined since about 1921 near Hiwassee, where ocher, sienna, and umber are currently recovered by surface mining at various sites. These raw materials are processed and blended into a wide range of natural pigment products in a plant at Hiwassee. Iron-oxide pigments are also manufactured from purchased raw materials at a plant in Henry County. Natural iron-oxide pigments have been obtained at other localities in six counties. Titanium-dioxide pigments were manufactured from ilmenite mined in Amherst County and rutile pigment has been produced from rutile mined in Hanover County. Iron and titanium mineral-pigment materials in Virginia have been described by Johnson (1964).

APLITE AND FELDSPAR

The term "aplite" is used commercially to describe intrusive feldspathic rocks that are mined and processed in the Piney River area of Nelson and Amherst counties, and in Hanover County, Virginia. Mining of aplite began in the Piney River area in about 1938 (Brown, 1962), and in Hanover County in 1960. It is currently produced by open-pit mining and processed on-site by firms in Nelson and Hanover counties. The processed aplite is marketed to the glass and brick industries. This feldspathic rock is also quarried by a company in Amherst County and crushed for use as construction aggregate. The commerical use of aplite has been discussed by Feitler (1967) and by Rogers and Neal (1975). The rock mined in the Piney River area was classified as anorthosite by Ross (1941) and has been discussed by a number of other writers, including Watson and Taber (1913) and Herz (1968). Titanium minerals that occur with feldspathic and associated rocks in the Piney River and Hanover County areas have been mined. Feldspar has been obtained from some of the numerous pegmatite bodies that occur in several areas of the Piedmont; the most recent production, which ceased in 1972, was in Bedford County. Occurrences of feldspar in Virginia have been described by several authors, including Pegau (1932) and Brown (1962).

GROUND TALC AND SOAPSTONE

Intermittent surface mining is done by one company from a pod of talc-chlorite-dolomite schist (Henika, 1971) in Franklin County. The rock is pulverized at a nearby plant and marketed for foundry facings and other industrial uses. Soapstone in the Schuyler area of Nelson and Albemarle counties has also been pulverized for industrial purposes, in addition to the current use as dimension stone.

VERMICULITE

Vermiculite occurrences have been reported in six areas of the Piedmont by Gooch (1957), who cited western Louisa County as having promise for possible development. In that area the vermiculite is associated with the Green Springs intrusive. Two companies have indicated their intent to begin surface mining in Louisa County and initial operations by one of these firms were underway in early 1978.

SPECIMEN AND LAPIDARY MATERIALS

A variety of rock, mineral, and fossil materials are collected in Virginia by dealers and hobbyists. Some localities are open on a fee basis. Staurolite, clear quartz, amethyst, unakite, garnets, amazonstone, cleavelandite, moonstone, prehnite, coquina, and other specimen and lapidary items are collected.

OTHER ACTIVITY

Certain other nonmetallic commodities, which originate outside the State, are currently processed at plants in Virginia. These include muscovite from domestic and foreign sources that is used in mica-fabricating and plate-mica operations in Newport News and perlite from the western United States that is expanded for use in insulating board at a plant in Shenandoah County.

PAST PRODUCTION OF OTHER NONMETALLIC RESOURCES

Some other nonmetallic resources that are not currently being recovered have been produced in Virginia in the past. Diatomaceous earth, glauconitic or greensand marl, and marine shells have been obtained from the Coastal Plain. Pegmatites in the Piedmont have been sources of muscovite, feldspar, kaolin, quartz, and small quantities of beryl and other minerals. Asbestos and emery have also been mined in the Piedmont and apatite from the Piney River district has had commercial usage. Barite has been mined at numerous sites in the Piedmont and Valley and Ridge provinces, and a small amount was recovered in the Blue Ridge; Virginia was the leading producing state for many years (Edmundson, 1938). Kaolin deposits have been exploited in several areas, and travertine has been quarried in western Virginia.

METALLIC ORES

LEAD AND ZINC

Production of metallic ores constituted slightly less than 1 percent of the total output value of Virginia mineral resources in 1976. The only production is in the Austinville-Ivanhoe area of Wythe County, where underground mining of lead and zinc ore is done by one company. The ore minerals, principally sphalerite and galena, occur in carbonate rocks of the Shady Formation of Cambrian age in a stratabound deposit. The geology and mining activity at Austinville-Ivanhoe are described by Brown and Weinberg (1968) who state that mining of lead ore began at Austinville in about 1756 and that the recovery of zinc was started shortly after the Civil War. The Austinville mine is reported to be the oldest continuously worked mine in the United States and to have production of about 2,200 short tons (1,995 metric tons) of ore per day

(Gulf and Western Resources Group, 1977). The recoverable content of zinc produced during 1976 was 11,241 short tons (10,196 metric tons) valued at $8,319,000 and of lead, 1,946 short tons (1,765 metric tons) valued at $899,000, according to the U.S. Bureau of Mines (1978). Production of lead and zinc for the period 1956-76 is shown in Table 10.

Table 10.—Production of lead and zinc in Virginia, 1956-1976 (compiled from Mineral Industry Surveys and Minerals Yearbooks of the U.S. Bureau of Mines.*

	Lead		Zinc	
	Value in Dollars	Short Tons	Value in Dollars	Short Tons
1976	899,000	1,946	8,319,000	11,241
1975	1,097,000	2,551	11,818,000	15,151
1974	1,398,000	3,106	12,346,000	17,195
1973	859,000	2,637	6,894,000	16,683
1972	1,034,000	3,441	5,960,000	16,789
1971	934,000	3,386	5,419,000	16,829
1970	1,048,000	3,356	5,534,000	18,063
1969	1,000,000	3,358	5,462,000	18,704
1968	944,000	3,573	5,199,000	19,257
1967	960,000	3,430	5,088,000	18,846
1966	930,000	3,078	5,123,000	17,666
1965	1,139,000	3,651	5,942,000	20,491
1964	1,010,000	3,857	5,700,000	21,004
1963	756,000	3,500	5,725,000	23,988
1962	747,000	4,059	6,141,000	26,479
1961	769,000	3,733	6,726,000	29,163
1960	504,000	2,152	5,142,000	19,885
1959	637,000	2,770	4,662,000	20,334
1958	687,000	2,934	3,808,000	18,472
1957	899,000	3,143	5,277,000	23,080
1956	953,000	3,035	5,181,000	19,196

* Recoverable metal content of ores and concentrates, etc.

Pulverized dolomite that is produced during milling of the ores is marketed for agricultural purposes. The U.S. Bureau of Mines reported (1978) that an unspecified quantity of silver was recoverable by smelting Virginia lead and zinc during 1976. In the past lead and zinc ores have been mined at other localities in the Valley and Ridge province and the Piedmont.

OTHER ACTIVITY

A few other metallic minerals, which are mined outside the State, are processed in Virginia. Magnetite from domestic and foreign sources is ground at a plant in Giles County and marketed as a coal-preparation medium. Foreign manganese ores are graded at a plant in Newport News and used in battery products. A plant in Shenandoah County produces ferrovanadium from out-of-State raw materials.

Mining companies have shown renewed interest in exploration for base metals and other metallic ores in Virginia during the past few years. Recent exploratory activity by companies, including geochemical and geophysical surveys, geologic mapping, and drilling, has been concentrated in the Piedmont province. Underground drifting and bulk sampling for base metals and associated minerals was recently conducted at a site in Louisa County.

PAST PRODUCTION OF OTHER METALLIC RESOURCES

A wide range of other metallic minerals that are not now recovered has been produced in the past. Iron ores, including hematite, limonite, magnetite, and carbonate ore, and manganese ores were mined at numerous localities in the Piedmont, Blue Ridge, and Valley and Ridge provinces. Past production of iron ore was estimated at approximately 26 million long tons (26 million metric tons), about half of which was mined in the Alleghany-Bath limonite district (Gooch, 1954). Furnaces were operated at many sites in Virginia to process the local iron ores. The State was an important source of manganese ore for many years; Gooch (1955) notes that Virginia produced 55 percent of the total manganese ore mined in the United States up to 1916. Titanium minerals have been produced in the Piney River area of Nelson and Amherst counties, and in Hanover County. Gold has been mined from numerous lode and placer deposits in the Piedmont and from placers in Floyd and Montgomery counties.

Pyrite in Louisia, Stafford, and Prince William counties and pyrrhotite in the Gossan Lead district in Carroll County have been mined extensively, chiefly for the manufacture of sulfuric acid; Virginia was a leading producer. Copper has been recovered from various deposits, including massive sulfide bodies in the Gossan Lead and Gold-Pyrite districts and in Floyd County, and quartz veins of the Virgilina district in Charlotte and Halifax counties. Efforts have also been made to exploit scattered occurrences associated with the Catoctin greenstone along the Blue Ridge and in Triassic sedimentary rocks. Arsenopyrite has been mined in Floyd County, and limited mining has been done for tungsten ore in the northern portion of the Hamme district in Mecklenburg County, and for tin ore in Rockbridge County. A small tonnage of bauxite was produced in Augusta County. Minor amounts of

columbite and tantalite have been recovered from pegmatites in the Piedmont. Luttrell (1966) has presented summary information and references on 496 mines and prospects in base, precious-metal, and related ore deposits in Virginia; only the lead and zinc operations at Austinville-Ivanhoe are active.

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GEOPHYSICAL CHARACTERISTICS OF THE BLUE RIDGE ANTICLINORIUM IN CENTRAL AND NORTHERN VIRGINIA[1]

By
Stanley S. Johnson and Thomas M. Gathright, II

CONTENTS

ILLUSTRATIONS

TABLE

[1]Portions of this contribution may be quoted if credit is given to the Virginia Division of Mineral Resources. It is recommended that reference be made in the following form:

Johnson, S.S., and Gathright, T.M., II, 1978, Geophysical characteristics of the Blue Ridge anticlinorium in central and northern Virginia, *in* Contributions to Virginia geology—III: Virginia Division of Mineral Resources Publication 7, p. 23-36.

ABSTRACT

Evaluation of regional aeromagnetic, aeroradiometric, and simple Bouguer gravity maps and detailed gravity profiles of the Blue Ridge anticlinorium in central and northern Virginia provides greater insight into the structure and distribution of rock units depicted on existing geologic maps. Characteristic radioactivity and magnetic signatures of known rock units can be traced into adjacent areas and will aid future detailed geologic mapping of these areas. The geophysical data is used to interpret gradational relationships between the major metamorphosed plutonic rock units within the anticlinorium and to delineate smaller felsic intrusives. Aeroradiometric data provides insight into the location of cataclastic and sedimentary rock units that could possibly be overlooked in normal field mapping. Magnetic intensity gradually decreases northeastward over the metamorphosed igneous rocks whereas radioactivity increases in the same direction. This is caused by a gradual change in the lithology northeastward—uranium, thorium, and potassium increases as the igneous rocks become more felsic. Detailed gravity data provides valuable information on the near surface and deep structural features such as the large, low density rock body beneath overturned quartzite beds at the Shady-Antietam contact.

Aeromagnetic, aeroradiometric, and detailed gravity data provide an additional dimension to geologic investigations. The use of these data in defining the structural framework and distribution of near-surface rock units permits a more competent interpretation of the geology.

INTRODUCTION

This geophysical study was made within an area outlined by Staunton, Zion Crossroads, Leesburg, and Winchester (Figure 1). The area is in the Piedmont, Blue Ridge, and Valley and Ridge physiographic provinces.

Maps and profiles from regional aeromagnetic, aeroradiometric, and gravity surveys are compared with the stratigraphy and structure in the Blue Ridge anticlinorium of central and northern Virginia. Within the Blue Ridge anticlinorium rock-unit relationships are locally obscured by thick alluvial deposits and structural complications in the core of the anticlinorium and by Triassic rocks on the eastern flank. The relationship between the various plutonic rock units and the presence and extent of cataclastic rock zones in the core of the anticlinorium are not well defined. The geophysical anomalies shown on the maps and profiles are indicative of the continuation of known rock units into unmapped or reconnaissance-mapped areas. Interpretation of the data also suggests that a re-examination of some rock-unit boundaries is needed and that the geophysical signature of many rock units can be traced southwestward within the Blue Ridge anticlinorium aiding future detailed mapping.

The Blue Ridge anticlinorium is a long, relatively narrow arch or upwarp that includes the rocks of the Blue Ridge on its west flank and rocks of Southwestern Mountain and Catoctin Mountain on its east flank in northern and central Virginia. The core of the anticlinorium contains two suites of plutonic rocks that were metamorphosed in Precambrian time (Figure 2). The western suite forms the Blue Ridge and is composed of granulite gneiss, charnockite, and metamorphosed granite of the Precambrian Pedlar Formation and Old Rag Granite (Table 1, Figure 2, units 2 and 3 respectively). The eastern suite forms the Ragged Mountains and other discontinuous ridges east of the Blue Ridge and is composed of biotite-rich augen gneiss and granite of the Lovingston and Marshall formations and the granite of the upper Precambrian Robertson River Formation (Table 1, Figure 2, units 1 and 4 respectively).

The core of the Blue Ridge anticlinorium is flanked by a thick sequence of resistant, metamorphosed clastic sedimentary and volcanic rocks of late Precambrian(?) and Early Cambrian age. This sequence lies unconformably on the older Precambrian plutonic rocks and is conformably overlain by younger rocks of Paleozoic age. The upper Precambrian(?) and Lower Cambrian rock units on the west flank are the Swift Run and Catoctin formations, the Chilhowee Group, and younger Cambrian and Ordovician carbonates and clastic rocks. On the east flank, the Lynchburg, Swift Run, and Catoctin formations sequentially overlay older plutonic rocks. Rock units examined by geophysical methods in this paper are listed in Table 1.

GEOPHYSICAL SURVEYS

The aeroradiometric data (Figure 3) is part of a survey done by the Virginia Division of Mineral Resources in 1976. Data from a 1975 survey by the Virginia Division of Mineral Resources is additionally used in the geophysical profiles. Both surveys were flown in an east-west direction with traverses spaced 0.5 mile (0.8 km) apart at an altitude of 500 feet (152 m) above terrain. The 1975

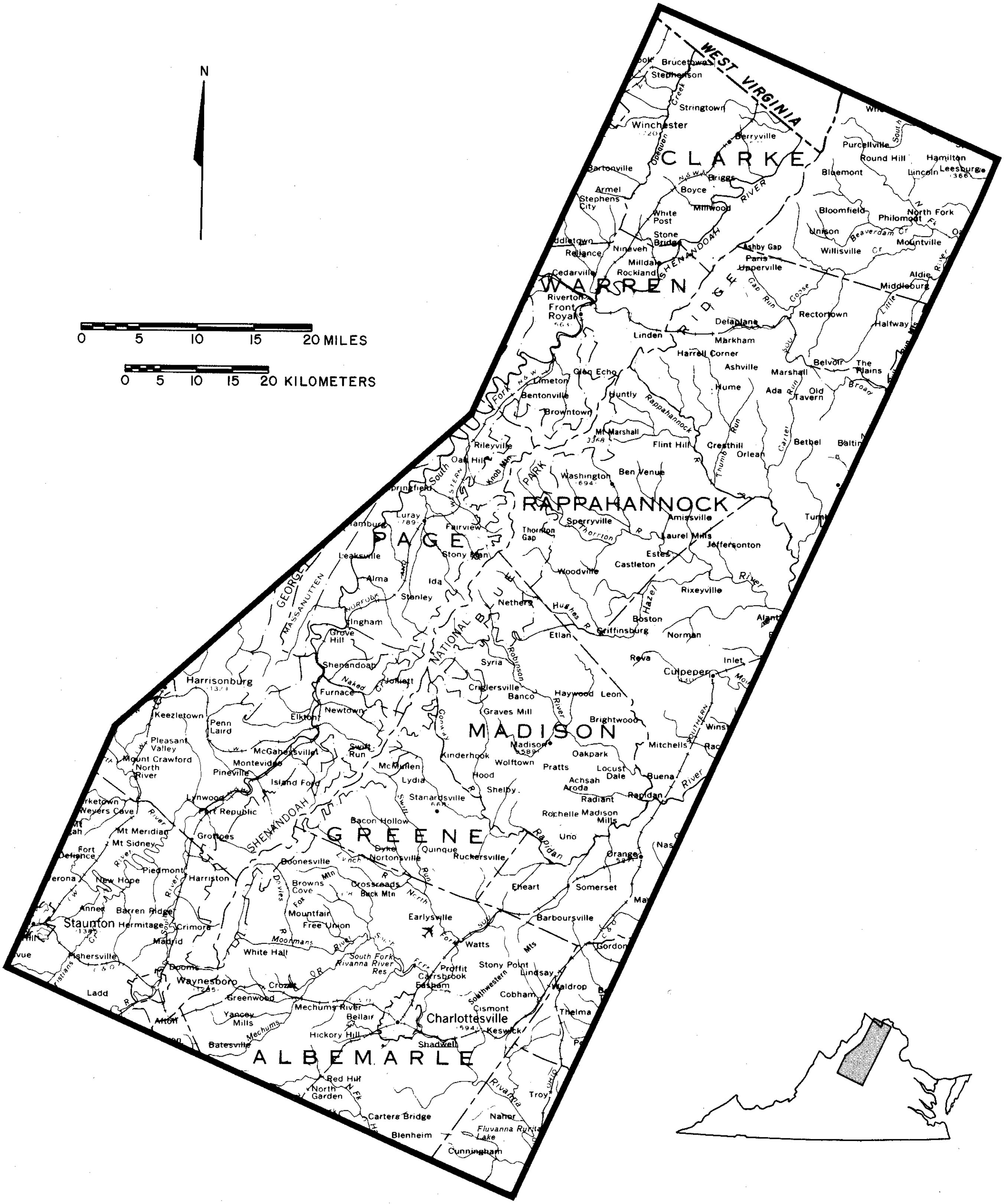

Figure 1. Index map showing area of study. (Base is part of a map of State of Virginia published by U.S. Geological Survey in 1973.)

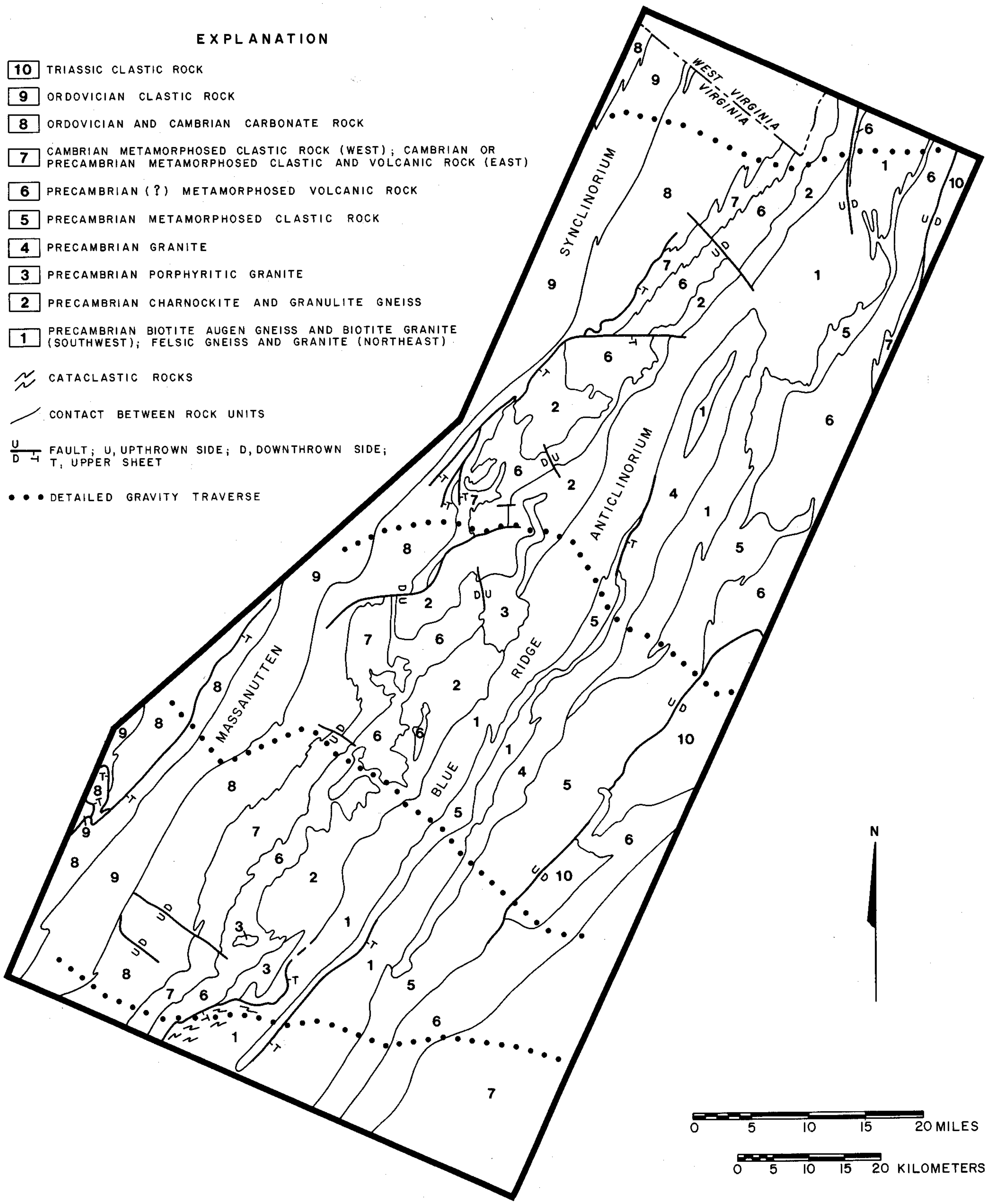

Figure 2. Generalized geologic map of the Blue Ridge anticlinorium and adjacent areas in central and northern Virginia (modified from the "Geologic Map of Virginia" published by the Virginia Division of Mineral Resources in 1963.)

Table 1.—Composite rock units in the Blue Ridge anticlinorium and Massanutten synclinorium in central and northern Virginia.

Rock Unit	Description
10	Triassic sandstone, shale, and conglomerate with diabase sills and stocks locally (mapped as Manassas sandstone, Bull Run shale, and Border conglomerate by Roberts, 1928).
9	Ordovician sandstone, slate, and calcareous argillite of the Martinsburg Formation.
8	Ordovician and Cambrian carbonate rock of the Lincolnshire, New Market, Beekmantown, Chepultepec, Conococheague, Elbrook, Waynesboro, and Shady formations.
7	Cambrian metamorphosed clastic rock of the Antietam, Harpers, and Weverton formations of the Chilhowee Group on the west flank of the Blue Ridge anticlinorium; Cambrian or upper Precambrian metamorphosed clastic and volcanic rocks of the Candler (Loudoun of Nelson, 1962) and Everona formations on the east flank of the anticlinorium.
6	Upper Precambrian(?) metamorphosed basalt, tuffs, and clastic sedimentary rock of the Catoctin and Swift Run formations.
5	Upper Precambrian metamorphosed clastic rock of the Rockfish, Lynchburg, Johnson Mill, Charlottesville, Fauquier, and Mechum River formations.
4	Upper Precambrian granite of the Robertson River Formation.
3	Precambrian porphyritic granite of the Old Rag Granite and similar bodies in Albemarle County.
2	Precambrian charnockite and granulite gneiss of the Pedlar Formation.
1	Precambrian biotite augen gneiss and biotite granite of the Lovingston Formation (southwest portion of anticlinorium) and felsic gneiss and granite of the Marshall Formation (northeastern portion of the anticlinorium).

survey was made using a gamma-ray spectrometer with a crystal volume of 252 cubic inches, the 1976 survey, 450 cubic inches.

The total intensity aeromagnetic data (Figure 4) is from the "Aeromagnetic Map of Virginia" (Zietz, Isidore, and others, in press). The original data used to compile the portion of the map shown in Figure 4 is from three surveys: two by the Virginia Division of Mineral Resources in 1971 and 1972 and one by U.S. Geological Survey in 1960. The 1971 survey (Piedmont-Blue Ridge) was flown in an east-west direction with traverses spaced at 0.5 mile (0.8 km) apart at an altitude of 500 feet (152 m) above terrain. The 1972 survey (Valley and Ridge) was flown in an east-west direction with traverses spaced at 3.0 miles (4.8 km) apart at an altitude of 5,000 feet (approximately 1,500 m) above sea level. The 1960 survey was flown in an east-west direction with traverses spaced at 1.0 mile (1.6 km) apart at an altitude of 500 feet (152 m) above terrain (personal communication, Isidore Zietz, 1978). The detailed observations and correlations utilized 1:62,500-scale contour maps (open file, Virginia Division of Mineral Resources, 1971 and 1972.

The regional gravity data (Figure 5) is from the "Gravity Map of Virginia: Simple Bouguer Anomaly" published by the Virginia Division of Mineral Resources (1977). A supplemental detailed gravity survey was made along four traverses across the Blue Ridge anticlinorium (Figure 2). The traverses were made along Interstate Highway 64 from Zion Crossroads to Staunton; along U.S. Highway 33 from Gordonsville to Harrisonburg; along State Highway 3, U.S. Highway 522, and U.S. Highway 211 from Lignum to Hamburg; and along State Highway 7 from Leesburg to Winchester. A gravity station was established and measurements taken every 0.25 mile (0.40 km). Elevations for these stations were determined from centerline elevations obtained from highway construction profiles. Elevations on these profiles and actual location of the gravity station on the highway are generally within 1.0 foot (0.3 m) accuracy; 4.0 feet (1.3 m) in mountainous terrain. The 0.25 mile (0.40 km) stations were located by using highway construction profiles and plan views, topographic maps, and a precision odometer with an accuracy of 3 feet (1 m) per mile. All of the gravity data was tied to the Virginia Gravity Base net (1972). A density of 2.67 gm/cm^3 was used to determine Bouguer anomaly values.

Three traverses (profile A, Figure 6; profile B, Figure 7; profile C, Figure 8) contain gravity, magnetic, and radiometric data. A fourth traverse (profile D, Figure 9) contains only magnetic and gravity data. The geophysical data is presented on

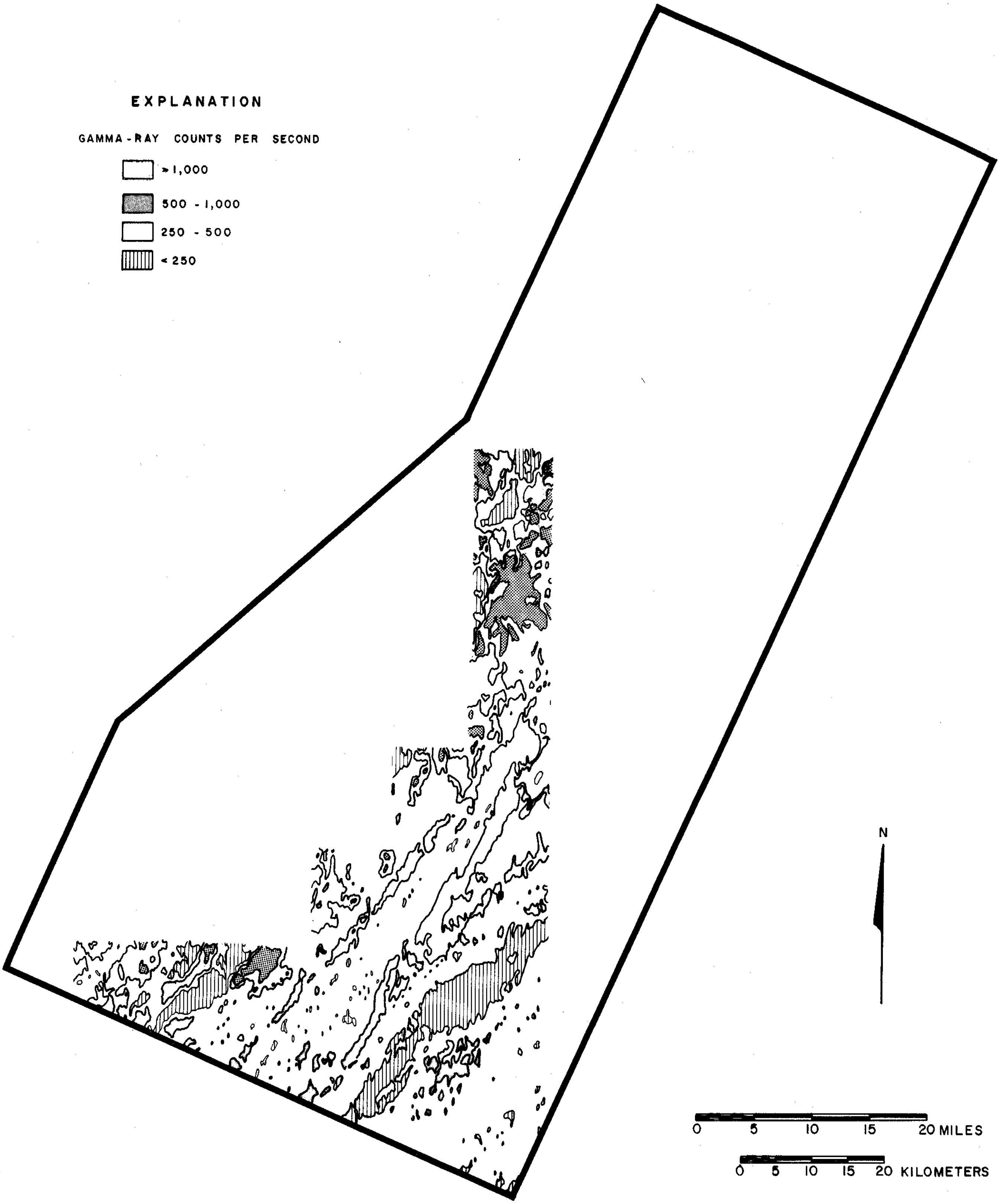

Figure 3. Aeroradiometric map of the Blue Ridge anticlinorium and adjacent areas in central and northern Virginia (simplified from "Aeroradiometric Contour Map" prepared in 1976 for the Virginia Division of Mineral Resources).

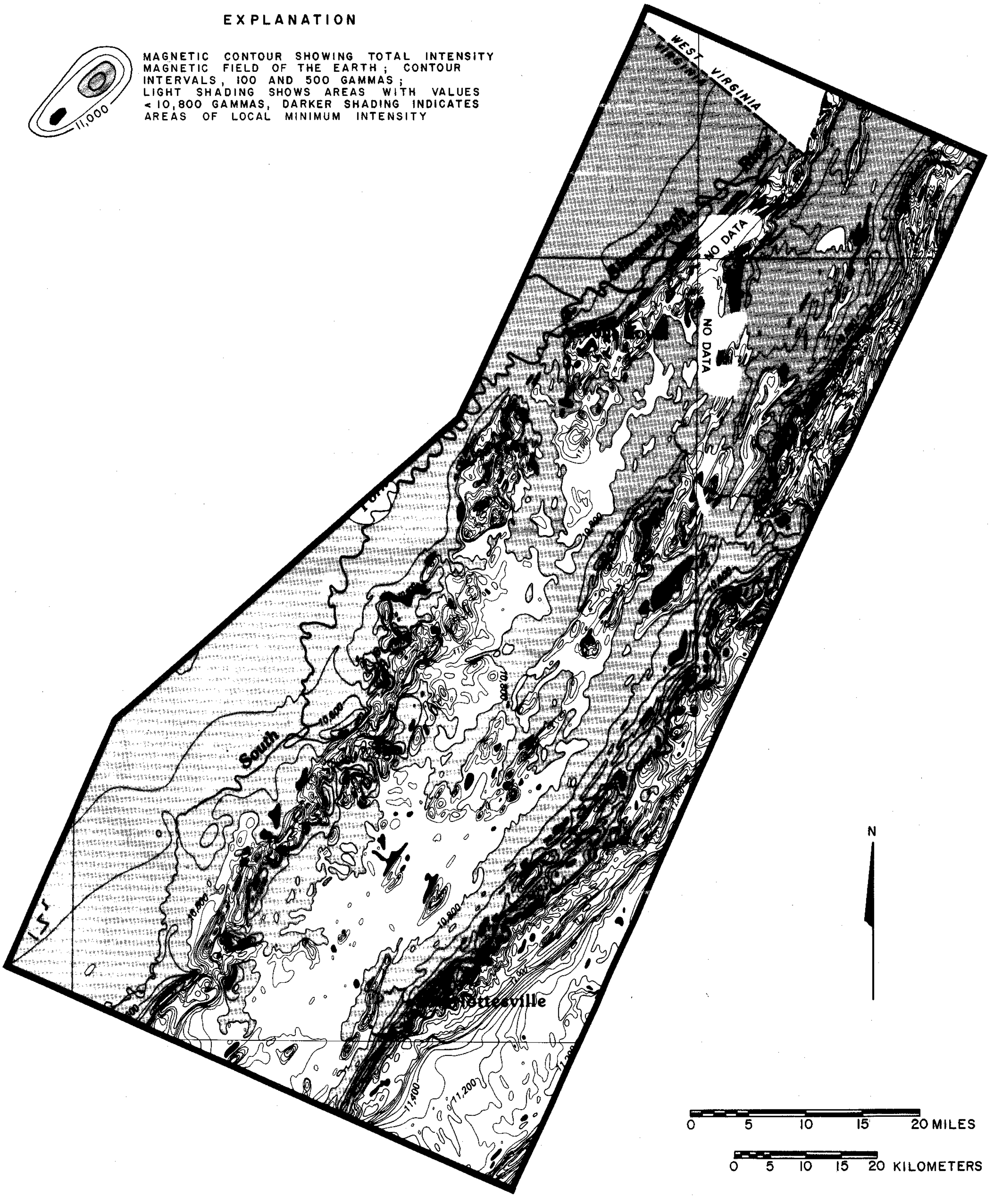

Figure 4. Aeromagnetic map of the Blue Ridge anticlinorium and adjacent areas in central and northern Virginia (from "Aeromagnetic Map of Virginia" – Zietz and others, in press).

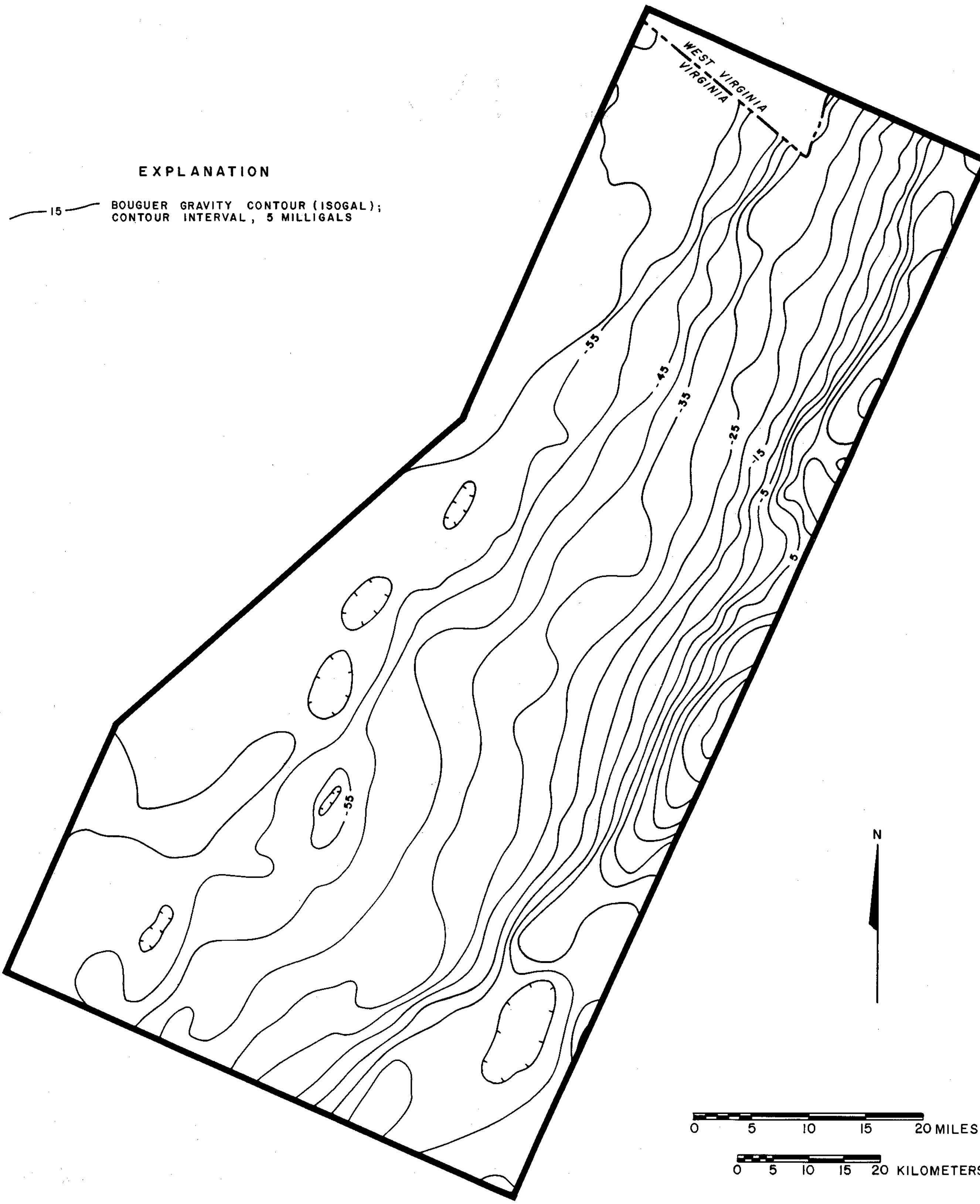

Figure 5. Simple Bouguer gravity map of the Blue Ridge anticlinorium and adjacent areas in central and northern Virginia (from "Gravity Map of Virginia: Simple Bouguer Anomaly" published by the Virginia Division of Mineral Resources in 1977).

east-west profiles. The plan view of the highway was projected to an east-west profile line. Geology obtained from available sources was plotted at the same scale on the profiles (Figures 6, 7, 8, 9).

To further determine the formational changes and contacts, profiles of the magnetic and radiometric data (from 1:62,500-scale contour maps) were made along the same detailed gravity traverses previously mentioned.

REGIONAL GEOPHYSICAL ANALYSIS

AERORADIOMETRIC MAP

The aeroradiometric contour map (Figure 3) when compared with the geologic map (Figure 2) is a means by which visual correlation may be made between contour shape and values and mapped geologic units within the Blue Ridge anticlinorium. Areas with low values (count per second) along the flanks of the anticlinorium correlate directly to major outcrop areas of Catoctin metabasalt (Unit 6). Elliptical or irregularly shaped areas of high values in the core outline felsic intrusive bodies such as the Old Rag Granite (Unit 3) associated with the Pedlar Formation (Unit 2). The linear distribution of metasedimentary rocks of the Mechum River Formation (Unit 5) and granite of the Robertson River (Unit 4) are also shown by linear areas of high values.

The rocks of the Chilhowee Group (Unit 7) are devisable into two units; a stratigraphically lower one with relatively high values which are related to the fluvial and marginal marine sedimentary rocks of the Weverton and Harpers formations, and an upper unit with low values which is comprised of the nearly pure quartzite of the Antietam Formation. The granulite gneiss, biotite augen gneiss, and granitic rocks of the Lovingston Formation are characterized by low to moderate values in Albemarle and Nelson counties. Values are higher where these rocks may be intimately mixed with or grade into metamorphosed granites of the Marshall Formation to the northeast. Biotite augen gneiss with Lovingston Formation affinities persists northeastward beyond the area of the 1976 radiometric survey into areas dominated by granite and granite gneiss of the Marshall (?) Formation in the northeastern portion of the anticlinorium. Radiometric highs in the Waynesboro area correlate with areas having a higher percentage of exposures of the Elbrook Formation.

In examining the profiles that show radiometric data, one must keep in mind that the aeroradiometric data is projected from adjacent flight lines and may not accurately reflect the regional radiometric characteristic of the rock unit shown in Figure 3. Anomalies in local areas are influenced by outcrop distribution, depth of weathering and soil development, and redistribution of weathered rock material by alluvial and colluvial processes. Variations in local patterns may be caused by either primary or secondary geologic processes that can be recognized only through detailed studies.

AEROMAGNETIC MAP

The aeromagnetic contour map (Figure 4) shows high magnetic anomalies over the Catoctin Formation on (Unit 6) on both flanks. The only metamorphosed igneous rock unit within the core of the Blue Ridge anticlinorium that has a distinctive positive magnetic signature is the Robertson River Formation (Unit 4), which is mostly granite. This signature is not present over all of the area mapped as Robertson River. The remainder of the metamorphosed igneous units in the core have small, isolated magnetic highs. Magnetic intensity gradually decreases northeastward over the metamorphosed igneous rocks whereas radioactivity increases in the same direction.

The metasedimentary rocks (Unit 5) of the Precambrian Mechum River, Rockfish, Lynchburg, Fauquier, Charlottesville, and Johnson Mill formations have magnetic intensities that are locally higher but generally compatible with the adjacent metamorphosed igneous rocks from which they were derived. The local presence of negative magnetic anomalies northwest of positive magnetic anomalies in the Mechum River and Robertson River formations (Units 4, 5) are indicative that the rock units are southeastward-dipping tabular bodies in many areas.

The apparent random distribution of magnetic highs and lows within the Catoctin Formation (Unit 6) is probably related to internal fold structures, interbedded magnetic and less magnetic units, and the discontinuous or lenticular nature of the volcanic rock. Northwestward-trending linear magnetic lows in the Catoctin occur over northwestward-trending faults. Structurally, rocks of the Catoctin Formation are overturned at Rockfish Gap (Figure 6); near vertical at Swift Run Gap (Figure 7); and upright at Thornton Gap (Figure 8) on the east, but are overturned at the Chilhowee Group contact. The Catoctin is folded at Snickers Gap (Figure 9), but the fold envelope inclined to the west.

SIMPLE BOUGUER GRAVITY MAP

The simple Bouguer gravity map (Figure 5) is

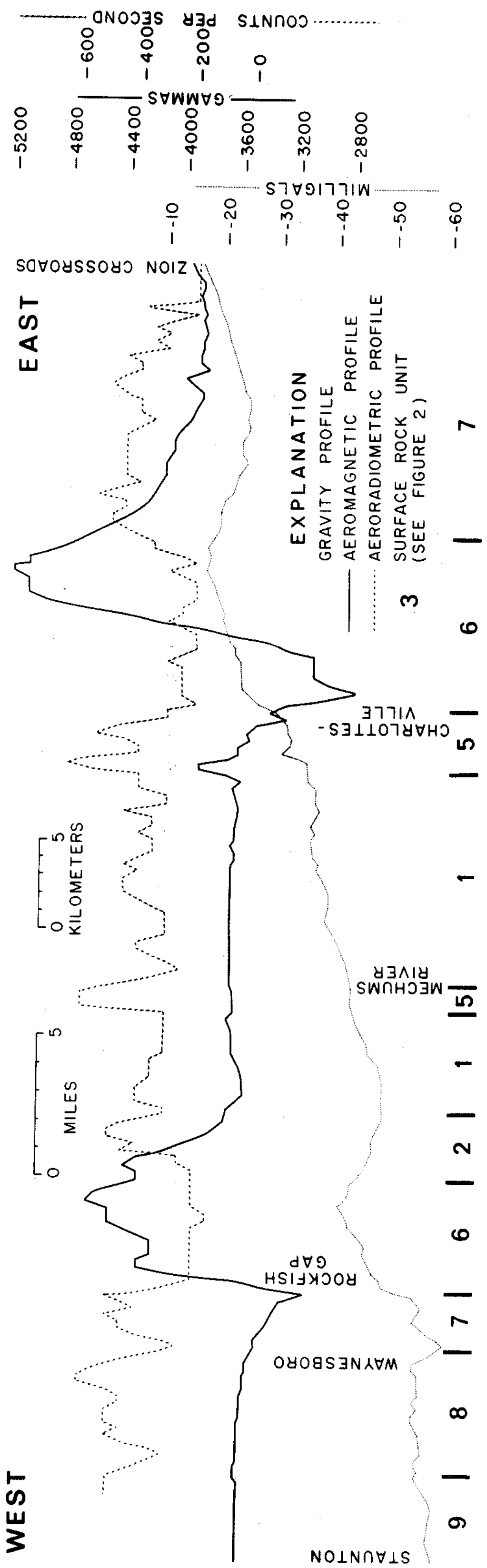

Figure 6. Profile A showing detailed gravity with magnetic and radiometric contour data from Zion Crossroads westward to just south of Staunton.

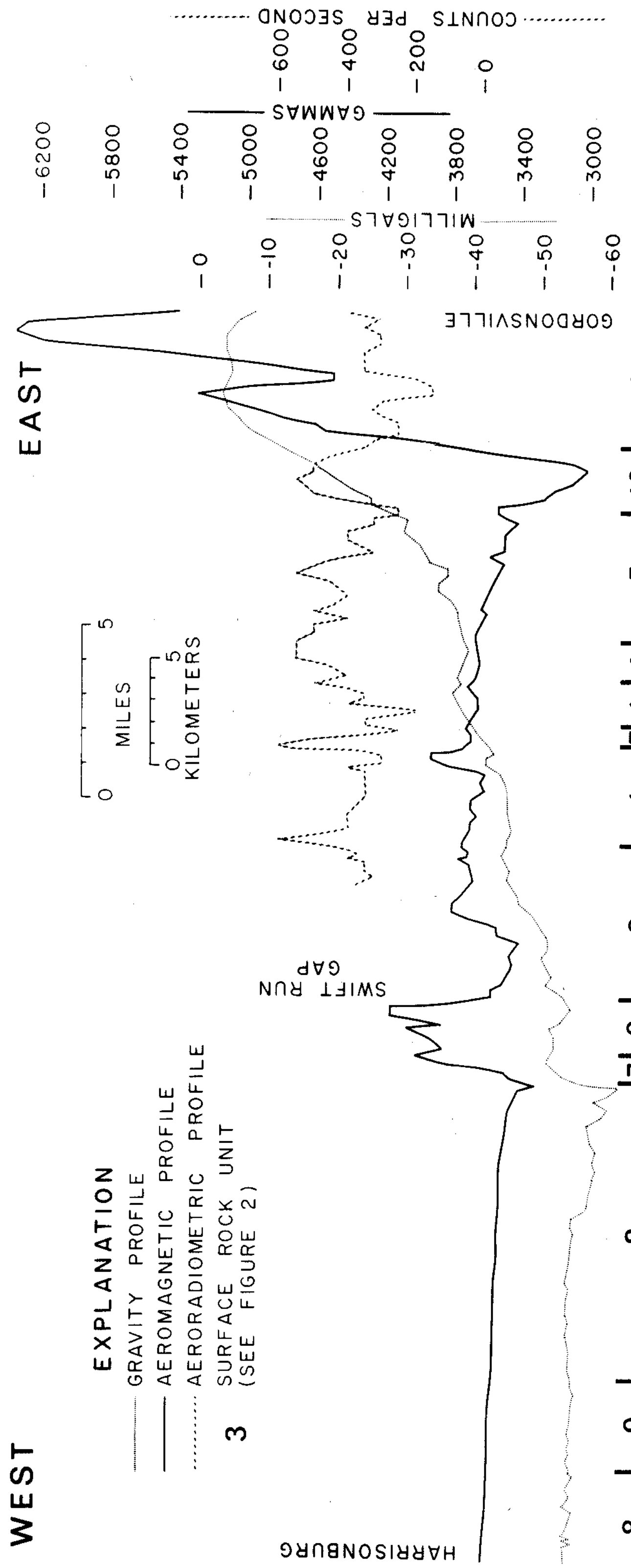

Figure 7. Profile B showing detailed gravity with magnetic and radiometric contour data from Gordonsville westward to just east of Harrisonburg.

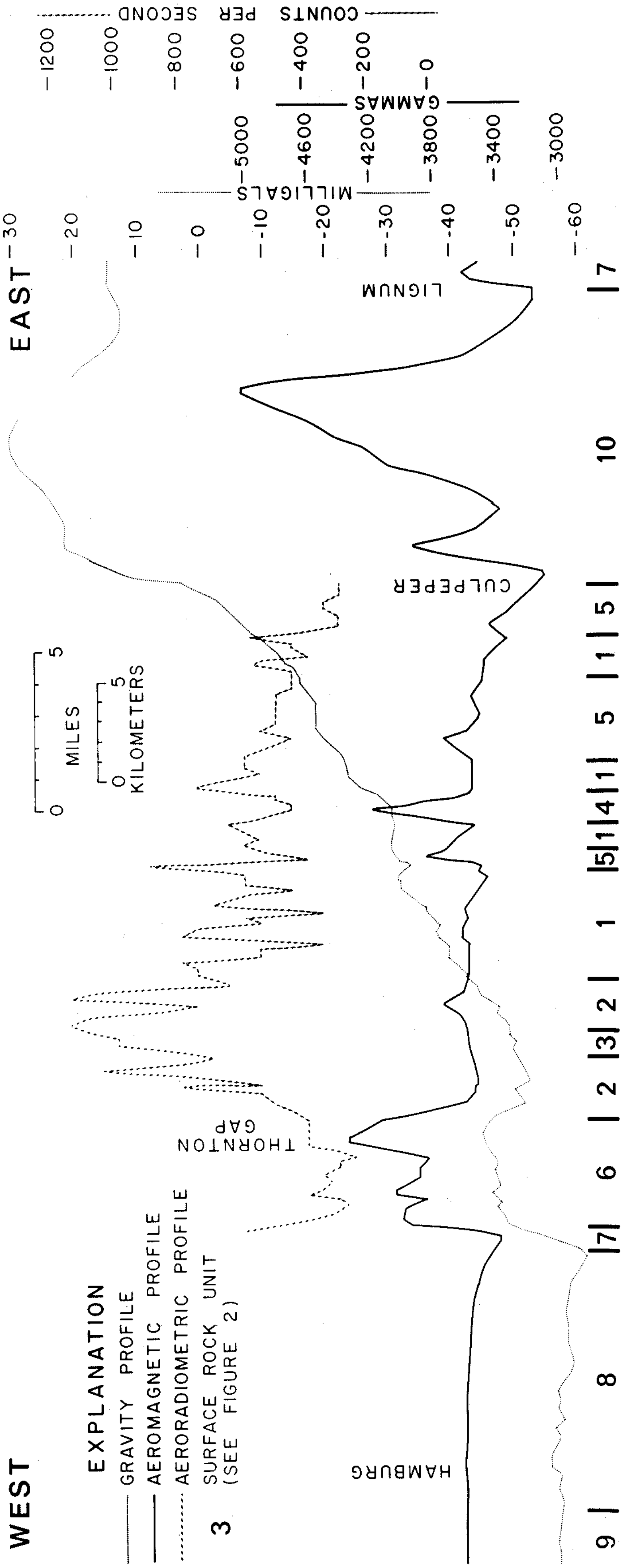

Figure 8. Profile C showing detailed gravity with magnetic and radiometric contour data from Lignum westward to just west of Hamburg.

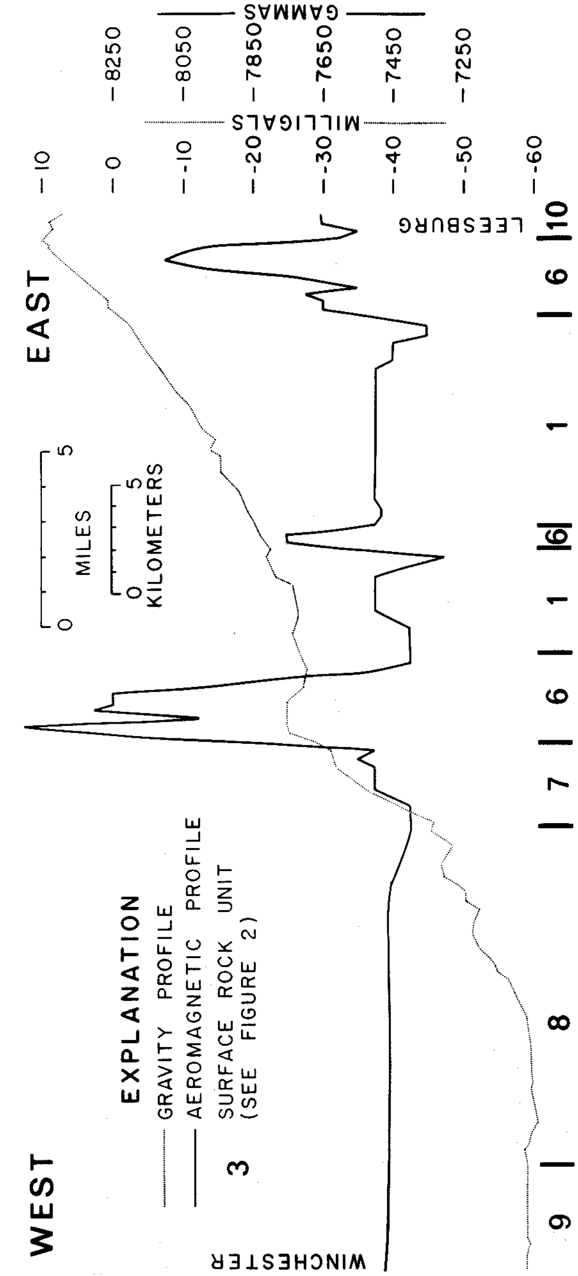

Figure 9. Profile D showing detailed gravity with magnetic contour data from Leesburg to just east of Winchester.

useful in locating deep crustal structures on a regional basis. The interpretation of these subsurface structures is based on the densities of specific rock types. The high-density metabasalt of the Catoctin Formation produces gravity anomalies that are useful for deep structural interpretation.

The steep westward-sloping gravity gradient that lies along the outcrop belt of the Catoctin Formation (Unit 6) on the east flank of the Blue Ridge anticlinorium appears to relate directly to the thick eastward-dipping, high-density metabasalt unit. A similar but less pronounced gradient marks the trace of the Catoctin Formation on the west flank of the anticlinorium between Front Royal and the Potomac River to the northeast. In this area a very thick folded sequence of metabasalt is inclined steeply into the Massanutten synclinorium. Both anomalies appear as steep linear zones on the westward-sloping regional gravity field that dominate this portion of the Blue Ridge anticlinorium. West-northwestward-trending gravity highs and lows lie across the trend of the anticlinorium in the southern half of the area (Figure 5). As they do not correlate well with the structural culminations and depressions that are inferred from the salients and embayments along the west flank of the anticlinorium (Figure 2), they probably relate to deep crustal structures. The western faults bounding the Culpeper basin lie within or parallel to the steep gravity gradient on the east limb of the anticlinorium. In the Leesburg area where the basin probably has its greatest depth, a local reversal in the gravity gradient marks the fault.

GRAVITY PROFILE ANALYSIS

Comparison of the detailed gravity profiles with aeroradiometric, aeromagnetic, and geologic profiles provides insight into the structure of the Blue Ridge anticlinorium. The gravity profiles also may be used to infer the vertical distribution of rock units having contrasting densities.

CARBONATE ROCKS

Cambrian and Ordovician limestone and dolomite above the Chilhowee Group and below the Martinsburg Formation have similar densities. They exhibit 1 to 2.5 milligal negative anomalies on the gravity profiles. These anomalies generally coincide with alluvial or colluvial deposits suggesting deep local weathering of the carbonate rocks (Hack, 1965).

CATOCTIN FORMATION

Examination of the Catoctin Formation is most advantageous in evaluating the structure of the Blue Ridge anticlinorium, since the major density contrast occurs between the Catoctin and adjacent rock units. Along profiles A, B, and C (Figures 6, 7, 8, respectively), the gravity gradients across Shenandoah Valley are nearly horizontal west of the Catoctin Formation.

The Catoctin is known to become radically thinner or "pinch-out" to the west along the west flank of the anticlinorium in the area south of the Thornton Gap vicinity (King, 1950; Bloomer and Werner, 1955). The flat gravity field along profiles A, B, and C may be indicative of the absence of the Catoctin beneath the east limb of the Massanutten synclinorium. Conversely, the Catoctin has a greater thickness to the northeast. Along profile D (Figure 9), the gravity field slopes westward toward the axis of the Massanutten synclinorium and is an indication that the Catoctin extends westward beneath the synclinorium.

On profiles A, B, and C (Figures 6, 7, and 8, respectively), the Catoctin is vertical or sharply overturned at its contact with the Chilhowee Group. The westward-sloping gravity gradients are steep near this contact and appear to reflect the structure of the overturned sequence.

The steepest eastward-sloping gravity gradient corresponds to the fault through Thornton Gap on profile C (Figure 8) where the Catoctin is downthrown by the fault.

METAMORPHOSED IGNEOUS AND METAMORPHOSED SEDIMENTARY ROCKS

The gravity gradient across the core of the Blue Ridge anticlinorium is not definitive. Many rock unit contacts coincide with changes in aeromagnetic and/or aeroradioactivity characteristics (Figures 3, 4, 6, 7, 8, 9). The granite of the Robertson River Formation partially coincides with a slight gravity depression or deflection of the gravity gradient. Similar small anomalies occur within other rock units and appear to define lithologic changes.

CATACLASTIC ROCKS

A zone of cataclastic gneiss, schist, and phyllonite is present at the east foot of the Blue Ridge as shown on profile A (Figure 6). The cataclastic rock zone and southeastward inclined thrust fault along its west edge separate the rocks of the Lovingston Formation to the east from the Pedlar, Swift Run, and Catoctin formations to the west. The zone is defined by a broad featureless depression in the gravity gradient. The depression can be attributed to the lower density of the cataclastic rocks as compared to the adjacent unsheared metamorphosed igneous rocks. The gradual increase in the gravity field toward the unsheared rocks can be attributed to the gradational nature of the cataclastic fabric into the metamorphosed igneous rocks.

Aeroradiometric anomalies over the cataclastic zone reflect the composition of the parent rock. Areas with high values along the western edge reflect the incorporation of felsic granite close to that edge of the zone near Crozet (Figure 2). Areas with low values on the east edge of the zone reflect the low radiometric character of the adjacent Lovingston Formation. Cataclastic rock zones are abundant near the boundary between the Lovingston Formation and the Pedlar Formation, but are generally too narrow to be identified on the detailed gravity profiles.

ANTIETAM-SHADY FORMATIONAL CONTACT

Anomalous gravity lows are present at the west foot of the Blue Ridge across the Antietam-Shady formational contact (Figures 6, 7, 8). The contact and the Shady Formation are concealed beneath alluvium or talus in most localities in central and northern Virginia. Several boreholes have been drilled through the alluvium into the carbonate rock of the Shady Formation. Depths to this rock range from 100 to 500+ feet (30 to 152+ m), which is indicative of deep solution and the subsequent filling of the resulting voids by rock debris from the Blue Ridge. Where the rocks are overturned and possibly faulted, stratigraphically younger Shady carbonate rock is beneath or against older Antietam quartzite (Figures 6, 7, 8). Masses of brecciated quartzite, which are cemented with iron or manganese oxides or autobrecciated and disintegrating massive quartzite beds occur at or near the contact and in other areas where the contact is inverted. The maximum gravity low occurs within the Antietam Formation and is indicative of low density rocks beneath the inverted quartzite where higher density dolomite and limestone should occur in inverted stratigraphic succession. The presence of locally intense brecciation that postdates Appalachian folding and the apparent westward rotation of the axial surfaces of small folds (Gathright, Henika, and Sullivan 1977) occur in areas that coincide with the gravity anomaly. Solution of the underlying carbonate rocks possibly resulted in the subsequent collapse of the inverted quartzite into solution cavities. Clay residuum, which was derived from the solution of carbonate rock beneath the quartzite, and greatly increased fracture permeability within the brecciated quartzite would tend to reduce the average density near the contact and produce the anomaly. No appreciable gravity low occurs at this contact on the northern traverse (Figure 9). The Shady Formation is exposed on State Highway 7 only a few tens of feet west of Antietam quartzite. In this area the Shady Formation is protected from the acid ground-water runoff from the Blue Ridge by the Shenandoah River. On the other traverses (Figures 6, 7, 8) acid groundwater moving down the western slope of the Blue Ridge encounters the Shady carbonates east of the Shenandoah River. This results in deep solution at the clastic-carbonate rock interface.

A detailed geophysical survey of the Antietam-Shady formational contact with local stratigraphic control supplied by boreholes should provide valuable geologic information especially, on the depth and distribution of the deep solution activity. This may lead to determination of the possible presence of economic clay deposits, the potential for ground-water development, and the sensitivity of the area to urban or industrial development.

TRIASSIC ROCKS

The Blue Ridge anticlinorium is partially bounded on the east by Triassic rocks that are present in the Culpeper and Leesburg areas. Coinciding positive magnetic and gravity anomalies occur in the central part of the Culpeper basin at Culpeper (Figure 8). The anomalies are indicative of a large rock body at depth that is probably denser than the diabase known to be present in the Culpeper basin.

The geophysical data delineates the basin quite well. The eastern boundary is an unconformity marked by a sharp, steep magnetic gradient and a shallow gravity low. The western fault boundary is marked by steep gradients on both the magnetic and gravity profiles (Figure 8). The steepest portion of the gradient coincides with the western fault. A gradient reversal coincides with the fault trace (Toewe, 1966) at Leesburg. The gravity high correlates well with the unbroken magnetic high that is present over the Catoctin Formation to the southwest (Zietz and others, 1977). This magnetic high coincides with the magnetic high in profile C (Figure 8). The magnetic high lies just east of the gravity high; which is a similar relationship to that seen in Profile A (Figure 6) over the Catoctin Formation. From these relationships it seems that the gravity and magnetic highs are related to the Catoctin metabasalt and probably not to diabase.

CONCLUSIONS

Geophysical maps and profiles are useful tools for mapping the Blue Ridge anticlinorium and adjacent structures. They provide information on the probable distribution of rock units and aid in the identification and delineation of the mappable units or important segregations within existing ones. The geophysical maps are useful in establishing and understanding regional relationships among the metamorphosed igneous rock units within the core of the anticlinorium. The gradual northeastward decrease in magnetic intensities and increase in radioactivity of the Lovingston and Marshall formations are indicative of gradational changes in lithology from the southwest to the northeast. The rocks in the northeastern part of the anticlinorium are more felsic than those to the southwest. The occurrence of uranium, thorium, and potassium commonly increases with an increase in the felsic content of igneous rocks and probably explains the increase in radioactivity to the northeast. Similarly, a northeastward increase in felsic minerals is indicative of a decrease in mafic minerals thus correlating with the observed northeastward decreasing magnetic field. From examination of the aeroradiometric maps small felsic intrusive rock units are probably present within the complex plutonic terrane. Regional Bouguer gravity maps are useful for analysis of deep subsurface structures, and detailed Bouguer gravity profiles are valuable for providing information not only about these structures but near-surface geology as well. This is particularly so in the case of the Antietam-Shady formational contact where gravity anomalies reflect the presence of a large, low density rock body probably consisting of unconsolidated sand, clay, and quartzite fragments beneath overturned quartzite beds. The positive gravity anomaly over the Triassic sedimentary rocks in the Culpeper basin may be an indication of the location of Catoctin metabasalt beneath the western portion of the basin.

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TOPOGRAPHIC MAPS OF VIRGINIA[1]

By
Harry W. Webb, Jr.

CONTENTS

ILLUSTRATIONS

ABSTRACT

Topographic maps have been produced for portions of Virginia at different scales from 1890 to date. Due to the completion of a cooperative Virginia Division of Mineral Resources-U. S. Geological Survey mapping program detailed 1:24,000-scale maps are available for all of the Commonwealth. Maps of growth areas are being updated from inspection of aerial photography each 5 years. Topographic maps are prepared from information derived from aerial mapping photographs, geodetic control, and from data observed and obtained from the area being shown. Maps are especially useful for engineers, foresters, geologists, planners and for recreation such as fishing, hiking, and hunting. By-products of the mapping program are aerial photographs and geodetic control. Four different scale series are available to show features of the State. These range in use from depiction of small areas in much detail to large areas with little detail. Map products are available for some parts of the State as orthophotoquads and as slope, county, orthophoto, and land-use maps.

INTRODUCTION

The importance of topographic maps is indicated by the more than 800 uses that have been determined. This article was written to describe the

[1] Portions of this contribution may be quoted if credit is given to the Virginia Division of Mineral Resources. It is recommended that reference be made in the following form:

Webb, Harry W., Jr., 1978, Topographic maps of Virginia, *in* Contributions to Virginia geology—III: Virginia Division of Mineral Resources Publication 7, p. 37-49.

mapping-program history, how the maps are made, their uses, useful by-products and types of maps available. Helpful suggestions on map preparation and content were made by members of the Eastern Mapping Center, Topographic Division, U. S. Geological Survey, Reston, VA. Mark Phillips of the Division of Mineral Resources aided in making this report more understandable.

HISTORY OF TOPOGRAPHIC MAPS FOR VIRGINIA

The importance of maps was shown as early as 1815 by an act of the Virginia General Assembly directing the preparation of county maps in which elevations of mountain pinnacles and gaps as well as the locations of waterways were to be determined. The first topographic map for Virginia, the Christiansburg quadrangle, was printed by the U. S. Geological Survey in 1890 (Figure 1). It depicted the shape and elevations of mountains, the configurations of streams, the locations of roads and railroads, and the positions of towns. It must have been of considerable aid in determining the best way to reach the resort springs that were shown. Features were shown at the scale 1:125,000 so that 1.00 inch (2.54 cm) on the map represents about 2 miles (3 km) on the earth. The quality of these early reconnaissance-type maps was often dependent upon the map maker's skill in artistic sketching and woodsmanship.

In 1900 with the realization of the need for maps showing the land surface in greater detail and with more accuracy the 1:62,500-scale series was initiated (Figure 2). Each map of this series depicts one-fourth of the area shown on the 1:125,000-scale maps but in far greater detail. One inch (2.54 cm) on the map portrays about 1 mile (1.6 km) of earth surface. Additional information to that of the older series is the extent of woodland, classification of road types, location of all residential buildings, spotting of benchmarks, and depiction of schools and churches.

Within the acts of the General Assembly of 1908 establishing a state geological survey the preparation of topographic maps was authorized. It was stated that it "is hereby authorized to arrange with the director . . . of the United States Geological Survey . . . topographic . . . work . . . as may be deemed necessary and of advantage to the State." In 1909 the Commonwealth with an expenditure of $1,750 became one of the first states to begin a cooperatively funded mapping program with the U. S. Geological Survey. This program is still in effect today.

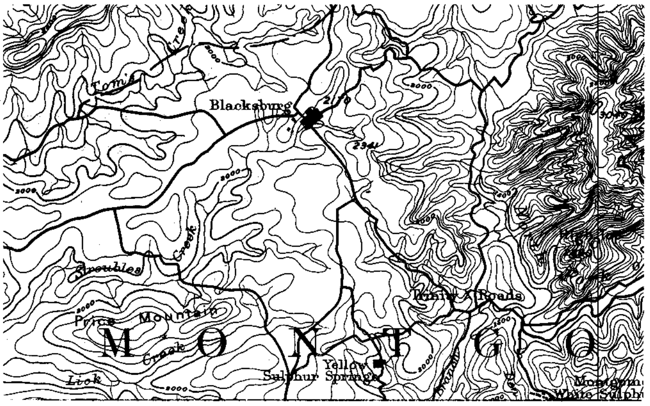


Figure 1. First Virginia topographic map, portion of Christiansburg 1:125,000-scale quadrangle, 1890, Montgomery County.

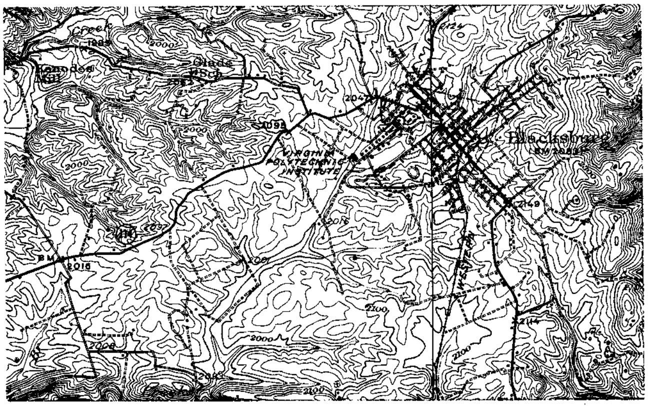


Figure 2. Intermediate-scale map, portion of Blacksburg 1:62,500-scale quadrangle, 1937, Montgomery County. Compare map detail and cultural growth with similar area in Figure 1.

Figure 3. Detailed map, portion of Blacksburg 1:24,000-scale quadrangle, 1970, Montgomery County. Compare map detail with similar areas of Figures 1 and 2.

With the need for more accurate and detailed maps in the late 1930's, the present series of mapping at the 1:24,000-scale was initiated (Figure 3). Maps of this series depict one-fourth of the area shown on that of the 1:62,500-scale. Information derived from aerial photographs combined with on-site investigations became a better way of making these maps than former field methods. Each map of this series depicts about 60 square miles (155 sq km) of the Commonwealth; 805 are available to illustrate the entire State. One inch (2.54 cm) on the map represents 2,000 feet (610 m) on the earth. Growth areas shown on the 1:24,000-scale series are being updated once each 5 years.

Maps at scale of 1:62,500 and 1:125,000 are gradually being phased out of use as they are withdrawn from sale because they are not kept up-to-date.

Realizing the importance of topographic maps for the well being of the people of the Commonwealth, James L. Calver, State Geologist and Commissioner of the Virginia Division of Mineral Resources in 1962 initiated a plan to completely map the State. This multiyear plan was cooperatively funded with the Topographic Division, U. S. Geological Survey, who would make the maps. Dr. Calver indicated that maps are fundamental to agriculture and forestry, in industrial development, communications, disaster relief, sports and recreation, and in other activities.

The need for maps was stressed by officials of chambers of commerce, railroads, planning agencies, and industry at an Advisory Legislative Council hearing in 1961. A Norfolk and Western Railway representative in a Roanoke newspaper article stated "many localities quickly fall out of the running in attempting to sell industrial sites, because they don't have maps quickly available to show the advantages of their sites." The State Highway Commissioner said in a Richmond newspaper article "up-to-date topographic maps would be of great assistance in highway planning." The executive director of the State Chamber of Commerce said that "maps are used in agriculture, forestry, mining, geology, scouting, education, recreation, military, transportation, and utilities."

With the support of these Marvin Sutherland, Director, Virginia Department of Conservation and Economic Development; the Virginia Federation of Business and Professional Women's Clubs; and others the cooperative plan to prepare maps was presented to the 1962 meeting of the General Assembly. Governor Albertis S. Harrison, Jr., in his inaugural address to that Assembly stated that topographic maps ... "are useful for industrial development, planning in connection with highway construction, watershed projects, and related purposes. Virginia should proceed at once to appropriate the necessary matching funds to provide these maps." State funds appropriated by this and succeeding assemblies totaled over $4 million which were matched by Federal funds over a 10-year period. By November 1972 Virginia became the tenth State to have complete detailed 1:24,000-scale topographic map coverage. Dr. Calver and Mr. R. H. Lyddan, Chief Topographic Engineer for the U. S. Geological Survey described the mapping program in a 1972 press release as "an outstanding example of Federal-State cooperation in efforts aimed at helping to solve complex resource and environmental problems."

In 1968 additional funds to keep existing maps up-to-date were requested and obtained from the General Assembly. Inquiry was made of various State agencies for names of maps needing revision. Maps selected were revised from changes noted on aerial photographs. These changes which are printed in purple, illustrate growth patterns with the dimension of time now being shown. Beginning Spring 1972 a periodic method of inspection of maps to determine which one needed to be revised was developed. Each portion of the Commonwealth is to be examined once each 5 years from high-altitude aerial photography. In addition to keeping growth areas with up-to-date maps, aerial photography will be available each 5 years for the Commonwealth.

The Division by means of mail-outs, conferences, and consultations has developed information on the use of maps in the State. As response to effectiveness of new products that can be obtained through these processes, the Federal map makers have initiated several pilot programs to put before the public innovative map products. These include county maps, orthophotoquads, slope maps, and orthophotomaps. A first-of-its kind sales index map with accompanying map catalog was developed to portray availability of Virginia maps.

An ongoing program to publicize the more than 800 uses of topographic maps is in progress. This includes liaison with State agencies, the planning district commissions, educational institutions, county and city planning officials, and industrial and commercial firms.

HOW VIRGINIA TOPOGRAPHIC MAPS ARE MADE

Topographic maps are prepared from information derived from aerial-mapping photographs, geodetic control, and data observed and obtained from the area being shown (Figure 4). Initially contours, drainage, vegetation, and man-made features are stereoscopically compiled from inspection of overlapping aerial photographs. During an on-the-spot examination cultural features, vegetation, and drainage are classified and best names are iden-

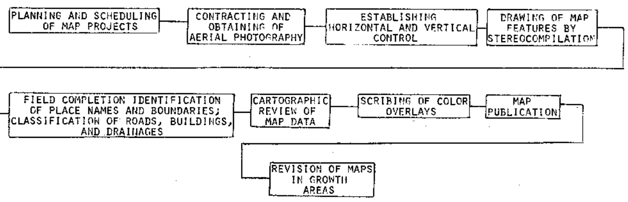


Figure 4. Steps in preparing topographic maps.

tified. Uncertain information derived from aerial photographs is also checked at this time. After a multiediting of the accuracy and clarity of the data shown, the map is printed and made available for sale.

Aerial photographs are taken and serve as a major source of map information for areas chosen to be mapped. Quad-centered high-altitude photography consists of black and white overlapping photographs. Of these there is a single photograph centered on each 1:24,000-scale map area that is flown over. In acquiring vertical photographs, the optical axis of the camera is oriented perpendicular to the ground. Flight paths and altitudes are chosen as to the amount of detail needed for the map. Aerial photographs are taken on clear days when the sun is at least 3 hours above the horizon when no leaves are on the trees, and in general with no snow on the ground. This photography is produced under contract by commercial companies.

Geodetic control is used to relate features on the maps derived from the aerial photographs with the same features on the ground. Reference points such as road intersections, bridges, and mountaintops are located. These points, together with those surveyed, are used to orient the map, correct photographic distortions, and verify elevations. Selected surveyed monumented control stations are shown on published maps as triangulation stations (a small unfilled triangle) for horizontal control and benchmarks "x BM" for vertical control (Figure 5).

Horizontal control permits the map maker to accurately plot all physical and cultural features in their correct positions on a horizontal plane of reference. The usual number of horizontal control points required for a 1:24,000-scale quadrangle is four, one near each corner.

The elevations of photoidentifiable points of vertical control are needed so that the map maker can accurately compile a contour map showing the landforms of an area. Vertical control involves the establishment of a network of elevation marks along roads, especially those bordering the quadrangle boundaries, to which supplemental control points

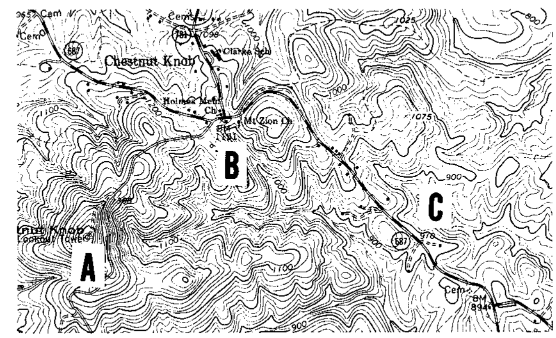


Figure 5. Geodetic control symbols, portion of Price 1:24,000-scale quadrangle, 1964, Henry County. Symbols are indicated at A, triangulation station by unfilled triangle for horizontal control; B, bench mark, BM x, for vertical control; C, spot elevation, 910, for supplemental vertical control.

can be tied. These elevations are obtained approximately every 0.5 mile (0.8 km) at a photoidentifiable point whereas bench mark posts are set every 2 to 3 miles (3 to 5 km). The elevations of all photoidentifiable points along a line of traverse are marked on aerial photographs and are used in the stereocompilation of contours.

Stereocompilation is the procedure by which map details are plotted from photographs. By a systematic orientation of overlapping aerial photographs in a plotting machine, an optical model of the terrain to be mapped is produced. This results in a three-dimensional view. By means of a "floating" mark located within the viewing system, which can be set at various elevations, the contours or shape and altitude of the land surface are drawn (Figure 6). Also roads, streams, buildings, and woodland can be properly identified, located, and drawn on the base sheet.

Field completion adds information obtained in the area being mapped that cannot be obtained from photographs. This includes identifying place names and boundaries and in classifying the type of roads, buildings, and drainages. The data obtained from the photographs is checked for completeness and accuracy. Supplemental control is often obtained.

By means of cartographic editing the manuscripts are checked periodically to assure that the information presented is accurate, complete, and conforms to accepted standards. This information includes examination of drainage patterns, contour treatment, names, and determination of the quadrangle name. All data to be shown on the map are verified by the editor. This material is then furnished the scribers, who prepare the overlays for printing. An overlay is scribed for each color to be printed on the final map. These sheets are then carefully checked to assure that one color does not

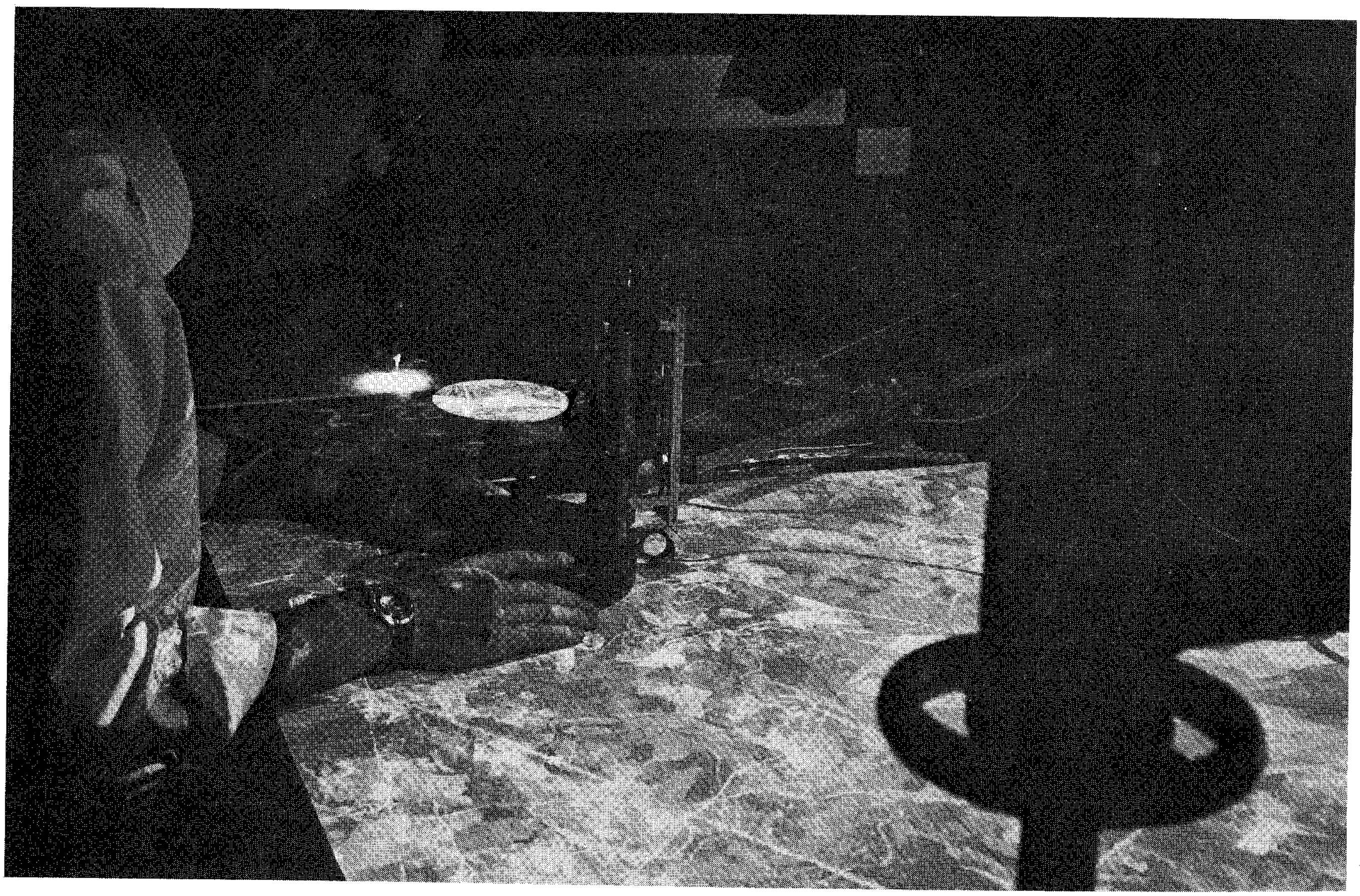


Figure 6. Contour lines being prepared by stereocompiler by tracing "floating marks," which has been set at a predetermined elevation along 3-dimensional projected view of the landscape.

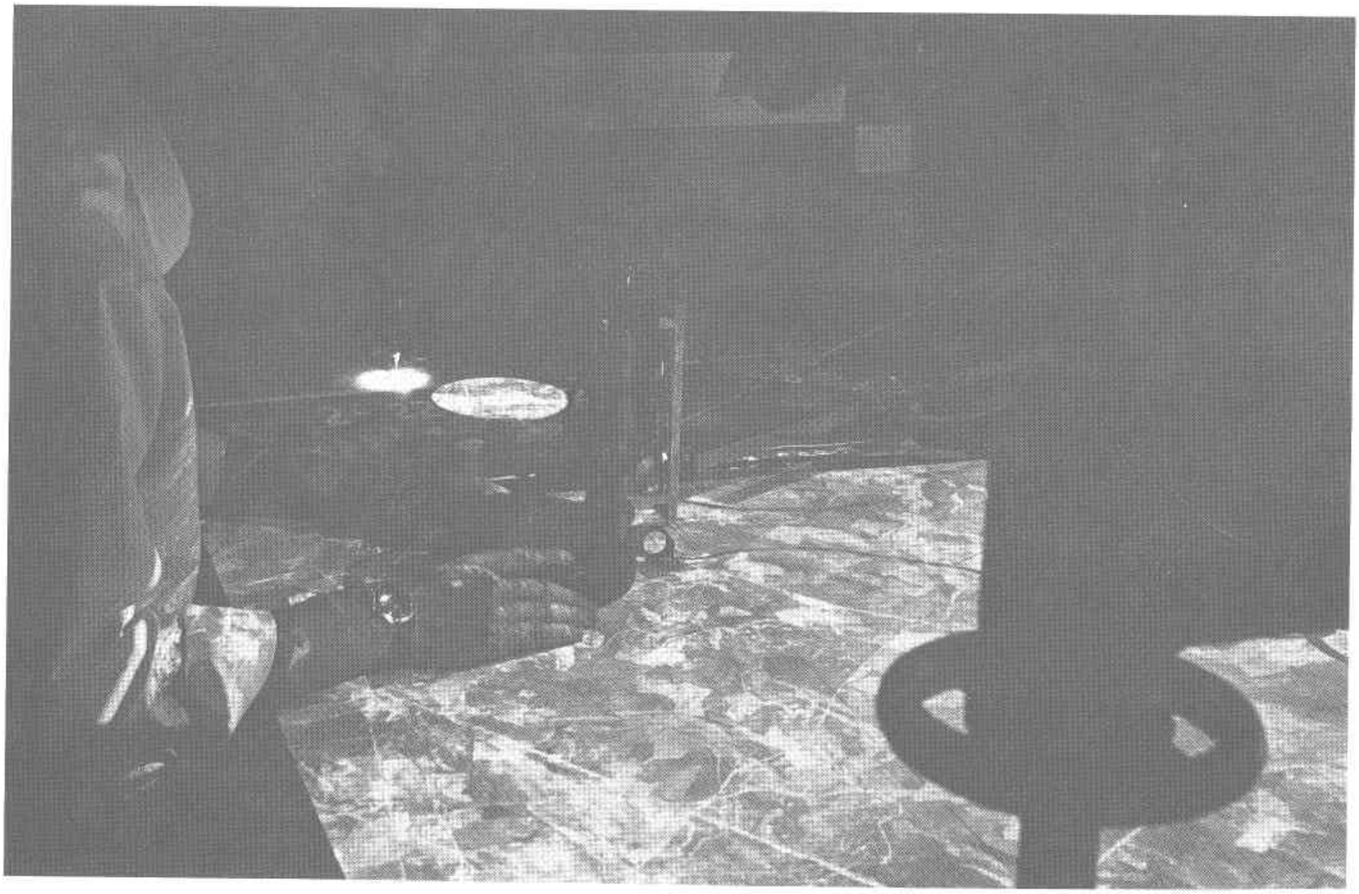
interfere with another. After the composite proof of all the colors has been finished, it is carefully reviewed and submitted for publication.

Revision is commonly necessary as maps become outdated because of natural or man-made changes. River courses may be altered, dams will impound lakes, new buildings are erected and old ones are destroyed, and new roads may be constructed and old ones altered. In order to maintain 1:24,000-scale map coverage in an up-to-date status, a program of photoinspection to determine revision need was started. Under this program the State is divided into five sectors of about 160 quadrangles each. New aerial photography is obtained over one sector each year so that there will be coverage of the entire State every 5 years. The aerial photography is then photoinspected for new features to determine which quadrangles actually need to be revised or updated. For those quadrangles not selected for revision, growth features can be interpreted from the photographs.

In photorevision cultural and drainage feature changes which have occurred since the date of a previous map edition are obtained by comparison of information on that map with the newly acquired aerial photographs. All additions and changes are printed in purple on the revised map. The purple color adds a new dimension—time—to the map since it clearly shows any changes or developments that have occurred since the previous edition (Figure 7). This provides a historical comparison that is useful to planners, geographers, earth scientists, engineers, and other map users in any field of activity involving the surface of the earth. Maps not selected for photorevision when reprinted will have the statement "photoinspected" which means that no major cultural or drainage changes were observed on the photographs. This innovative approach to map revision was implemented under the cooperative mapping program between the State of Virginia and the U. S. Geological Survey. The effectiveness of the program has been proven to the extent that similar programs are being established by other States.

MAP USES

Over 800 uses of topographic maps in 22 different categories have been listed. They are especially



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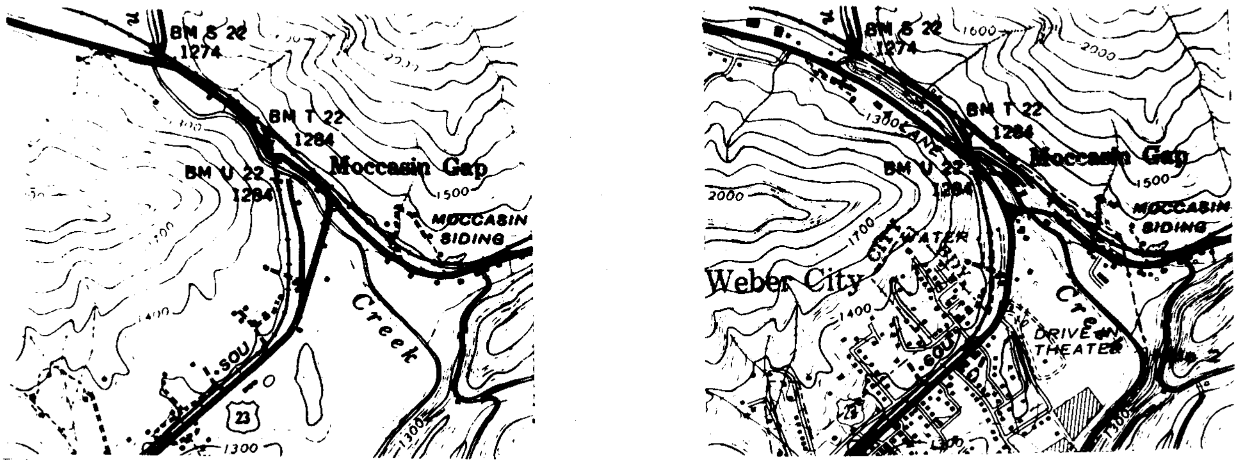

Figure 7. Urban growth depicted in purple on photorevised edition of Gate City quadrangle. New buildings, water tower, trail, roads, and drive-in theater were constructed in southern Scott County within a 30-year period (left map, 1938; right map, 1968).

useful to engineers, foresters, geologists, geographers, planners, and developers and for recreation such as hunting, fishing, and hiking. For construction the availability of these maps for planning the location of buildings, drainage, sewers, water, roads, and utility lines has resulted in substantial savings.

In most *engineering studies* involving the surface of the earth these maps aid in the planning and construction phases. These studies include construction of airports, buildings, communication towers, dams, drainage systems, highways, pipelines, transmission lines, and tunnels. They assist in the location of property boundaries and the selection of sites for quarries and industrial or commercial plants.

From the maps information can be obtained on the shape and elevation of the land surface, availability of water, location of roads and railroads, amount of cleared areas, and proximity to towns where goods can be sold or a labor supply obtained. Examination of contour lines enables the engineer to determine topographic relief for making preliminary studies for the excavating or filling or tracts of land for building sites, road construction, or drainage control. Data from these lines also aids in development of projects for flood control, land reclamation, and minimizing erosion of soil.

Elevations above sea level that are important in forecasting weather conditions can be determined from the contour-line values; these can be more readily seen by coloring in different contour intervals such as every 100 feet (30 m). From the orientation of slopes it can be determined whether they will face toward the sun for use in agriculture or solar home heating. Access to an area is shown by railroads, roads, and trails. Ease of driving is indicated by the road classification. Trails are differentiated as to whether they are passable by four-wheel-drive vehicle or only by foot. Studies of sites for power plants include inspection of topographic maps to determine favorable terrain. Knowledge of drainage patterns and terrain profiles obtained from the maps can be used to estimate the amount of water power that is available and the volume of reservoir that will occur behind planned dams. The most efficient and economical placement of a power plant is affected by the locations of customers, which are shown on maps as metropolitan and industrial areas and as houses.

As tributary streams usually join main streams in a downstream direction the flow direction can be determined. Wet swamp areas difficult to cross by foot or with a vehicle are indicated by a symbol. Dredged channels, maintained for navigation are indicated in coastal areas.

Maps are useful to plan the locations of microwave towers and transmission lines. Knowledge of the land surface is needed to obtain the most economical construction route, which will require the fewest numbers of towers and least amount of wire for transmission lines. Sites for microwave towers can be spotted on high elevations, where surrounding hills will not block transmissions. Telephone company engineers use maps to plan lines by noting the locations of potential customers and the most economical way to reach them. A telephone company engineer by using maps found that he could accomplish in a few hours at the office what would take a week in the field.

A study of topographic maps is the initial step in highway construction to determine the cheapest, safest, and most usable location for the planned road. Information for cost estimates as to how many bridges, the number of cuts and fills, and how much right-of-way needed can be obtained from examining the maps. A consulting engineer stated that the use of a topographic map in selecting a bridge site resulted in a saving of 40 percent of the cost of the bridge.

Foresters use these maps to determine best routes for reaching tree stands for the purpose of study, selective cutting, or fire fighting. The locations of roads, buildings, and utility lines for recreational areas can be planned. Then the position of campgrounds, trails, and lakes are shown on topographic maps as an aid to the public.

Geologists and geographers examine maps to better understand processes that are shaping the surface of the land and to obtain clues on subsurface composition. *Geologists* use these maps as bases on which to depict information on the type and position of bedrock as well as the location of present and potential mineral resources (Figure 8). An analysis of contour shapes and drainage courses will show the relative resistance to erosion of the bedrock.

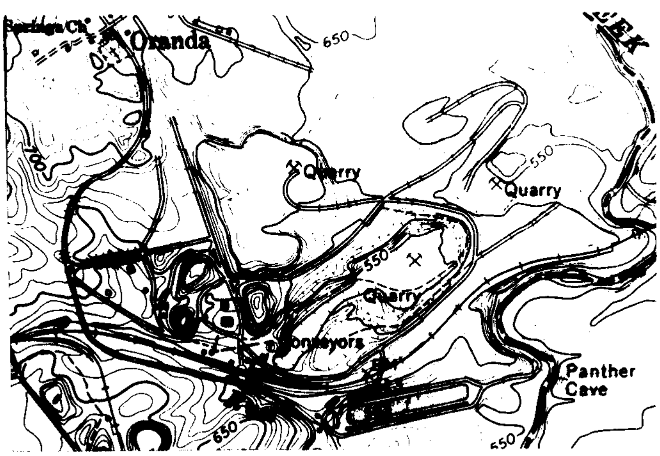

Figure 8. Depiction of quarries; shown are the locations of quarries, rock waste piles, and processing equipment, northeastern Shenandoah County on portion of Middletown 1:24,000-scale quadrangle, 1972.

Geographers note the effect of the landscape on the positions of towns. These are often located at gaps through the mountains, near rapids at the upstream end of a navigable river, and in areas where hills afford protection from the weather. Interesting highlights on the history of an area can be obtained by noticing the names used on maps.

Outdoorsmen use topographic maps extensively for hunting, fishing, hiking, camping, picnicing, and sightseeing (Figure 9). Out-of-the-way, little used areas where game and fish may be found can be determined. Access to these can be planned as maintained roads and trails are shown. Clearings where game may come to feed are shown on the maps. New lakes generally are shown with underwater contours and the former channel of the stream is marked, which assists in deciding where the fish might be.

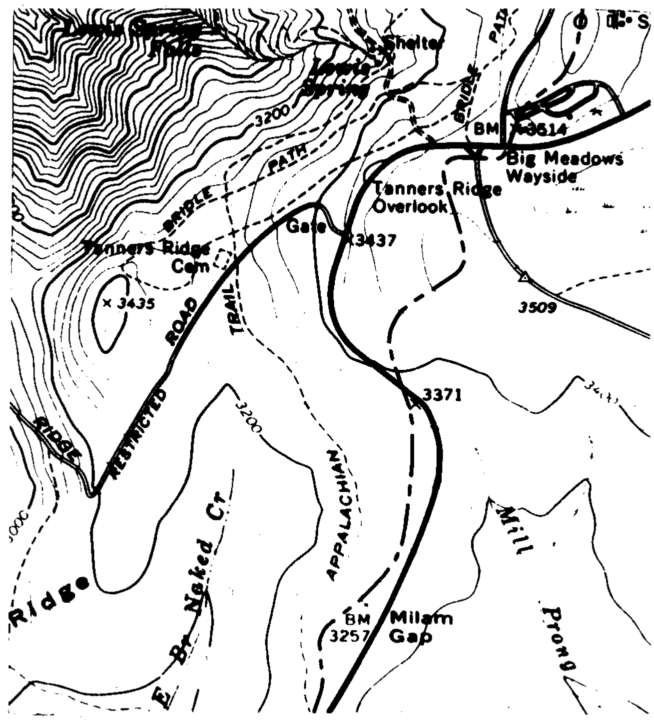

Figure 9. Recreational facilities; a spring, waterfalls, horse and foot trails, fire road, shelter, and overlook are adjacent to the Skyline Drive, Shenandoah National Park. Portion of Big Meadows 1:24,000-scale quadrangle, Page and Madison counties, 1972.

Trails are shown in Federal and State parks and forests which are suitable for hiking. Access by road and major springs are indicated. By examining the spacing of the contour lines, their values, and the crossing of the trail by streams, the degree of difficulty of walking the trail can be determined before the walk begins. From overlooks along the trail the map will help in understanding what is being seen.

Most public campgrounds and their access roads as well as the surroundings of the campground are shown. Picnic tables in public areas are denoted by a special symbol. From features seen on the map one can often find things to see or do after the picnic. Though few significant historical or natural features are labeled as such on topographic maps, roads along rivers or in mountainous areas may reveal things of interest to the sightseer. The type of terrain as shown by the contour lines can be of help in locating areas of natural beauty. Where roads intersect streams, boats and canoes can be launched or removed from the water. As the top of the map is true north it can be used with a compass to navigate.

County and city planners use topographic maps to assist in zoning areas most suitable for industrial, commercial, and residential development (Figure 10). The most usable locations for fire stations, police departments, water reservoirs, and schools can be determined. The cheapest and most efficient routes for new streets and sewerage, electric, and gas conductors can be planned. The locations of election, fire, and tax districts can be added to these maps for ready reference of man-made features.

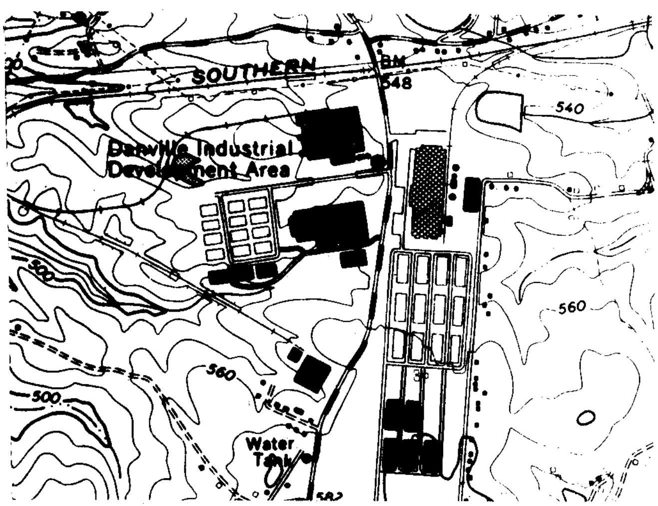

Figure 10. Industrial-site planning, portion of Ringgold 1:24,000-scale quadrangle, 1970, Pittsylvania County. The relation of industrial buildings to the transportation network is shown.

Sinking streams or sinkholes usually are indicative of caverns and solution openings in carbonate rocks. Because of possible collapse or water-supply pollution, construction activities must be planned with care in these areas. Man's use of the land can be determined from the number and position of buildings. Populated places are marked by many houses close together, whereas farms have few houses and many outbuildings. Industrial areas commonly have railroad spurs. Level land adjacent to streams generally is indicative of an area that will normally be flooded during times of heavy rains. Restrictions in the width of the flood plain by ridges or fills can commonly act as temporary dams during flooding. The flat or gently sloping areas above streams are terraces which are usually above flood-level and can be used for building-sites or farm fields. Delta-shaped landforms adjacent to mountains are alluvial fans formed by downslope wash. They may be good sources of water but may be unstable for building sites due to their loose, heterogeneous composition. Closely spaced contour lines indicate steep slopes on which landslides or rockfalls may occur.

The water table is generally close to the surface where swamps or streams are shown. These will impede movement by vehicle or foot. The number and orientation of streams can give information on the type of bedrock and how much it has been deformed. The configuration of landforms can also yield information on the type of bedrock. As north is at the top of the map the effect of sun and elevation on temperature and moisture conditions of various slopes can be interpreted. The ability to travel off roads and trails can be determined from the steepness of the land and position of streams. Cuts, fills, and disturbed areas show where the land surface no longer has natural characteristics. By relating the elevation of a location to the surrounding elevations it can be determined which features are visible and which are hidden behind nearby hills.

Farmers use maps to determine which slopes face toward the sun to assist in knowing where to plant crops. Drainage systems can be planned for the collection or dispersal of water. Aerial crop-dusting flight lines can be located. Farm land and acreage-allotment appraisers use maps as bases on which to plot information.

Police, firemen, and rescue squads use topographic maps for emergency services to determine quickest access routes to aid victims. Locations of people needing help can be best identified from such maps. If the Universal Transverse Mercator grid is drawn across the map and each square assigned a number, individuals can then identify their location by number. Streams and ponds as water sources for fire control are shown. Damaged housing can be located on sites determined from inspections of maps, and favorable locations for control and prevention of damage from wind, fire, and water can be planned.

Among other uses for maps *realtors* determine favorable areas for development and use them to indicate the regional setting to prospective clients. *Bank officials* determine the topographic setting of property or buildings as a part of making assessments for loans. *Attorneys* use them as a source of information on the ground surface and streams which affect cases dealing with man's misuse of the environment. Out-of-print editions can be used to show locations of superceded names or former stream courses which may have marked property lines. *Water-well drillers* determine access routes and preliminary sites to drill. *Ministers* in rural areas can mark parishioners houses for reference. *Salesmen* plan how to effectively service their territories by considering the road network and their client's buildings. *Teachers* use maps as visual aids in the study of how man is affected by his natural environment. *Military uses* for topographic maps include planning sites for airfields, forts, training areas, munitions manufacture and storage, firing and bombing ranges, and maneuver areas.

Many *State agencies* use these maps to either obtain information or to portray data. The Division of Mineral Resources publishes detailed geologic data on topographic map bases. These maps are used for planning field traverses to gather information on the type and distribution of rocks; this data is keyed to the map. Hunters can obtain maps from the Commission of Game and Inland Fisheries showing game management areas. Those features selected as historical landmarks are listed on reference maps at the Commission on Historical Landmarks. Many maps used extensively in the public schools to teach map and chart skills are supplied by the Department of Education. During the planning of highway locations and bridges maps are examined by the Department of Highways. Enlargements of topographic maps are used in the process of preparing county tax maps by the Department of Taxation. In fighting fires the type of terrain and the position of streams is noted from maps to assist in planning how to get equipment in by the Division of Forestry. The Division of Industrial Development uses maps to illustrate and to determine the position and surroundings of potential industrial sites. To assist counties in developing regional plans the Division of Intergovernmental Affairs uses maps to determine slope information. As an aid in planning for roads and recreational facilities maps are used by the Division of Parks. The Office of Emergency Services finds maps an aid in locating access routes to disaster victims.

Planners from the regional planning district commissions composite maps together to portray the terrain, drainage systems, and houses within the district. Slope values derived from the contours aid in classifying land usage for comprehensive plans and in zoning decisions. From noting the positions of streams and intervening ridges drainage divides can be determined. The location of houses can be identified for surveys about house type and condition.

MAPPING BY-PRODUCTS

Important by-products of the mapping program are aerial mapping photographs and geodetic control. To determine which quadrangles need to be revised *high-altitude quad-centered aerial photography* is flown by private companies under contract to the U.S. Geological Survey. This photography taken from an altitude of about 40,000 feet (12,192 m) consists of a series of over-lapping black and white 9 x 9 inch (23 x 23 cm) photographs. By means of viewing similar points on overlapping photographs with a stereoscope the land surface is given a 3-dimensional appearance, which aids in interpreting features that are seen. Within the series of photographs there are single photographs which are uniquely centered on each 1:24,000-scale topographic map area. These quad-centered photographs, if enlarged 3-times, afford good visual comparisons with their corresponding map. The map and photograph together will aid in interpreting features shown on both and will make more information available on the area that is shown than if only one is used.

Aerial photographs are useful for portraying features of individual properties, for interpreting land use and extent of pine forests, and for gaining a better idea of the area around one's home. New features shown on aerial photographs are added to maps on photorevised editions. Where maps have not been selected for revision they can be updated by the user by examining the applicable aerial photographs. Information on availability and enlargements of this type of photography as well as for other types for Virginia can be obtained from the National Cartographic Information Center, U.S. Geological Survey, Reston, VA 22092.

Geodetic control survey data includes information on places of known horizontal or vertical position. Horizontal control (triangulation) stations are indicated by a small unfilled triangle; vertical control is designated by "BM" and an "x" (bench marks) with the elevation indicated to the nearest foot (Figure 5). At some locations both horizontal and vertical control has been established. This control is necessary in the making of precise maps to present features in their correct relationship to each other and to the earth's surface. Surveyors use bench marks as reference locations from which to conduct land surveys. Lists describing available horizontal or vertical control can be obtained from the National Cartographic Information Center-East, U.S. Geological Survey, Reston, VA. 22092 by indicating the area needed by the names of the 1:24,000-scale maps.

For specialized uses stable-base composites, feature separates, and out-of-print map copies can be obtained on order from the Center. *Stable-base composites* are black and white copies of topographic maps, usually without woodland information, printed on translucent plastic. These are useful as bases onto which several data overlays can be referenced. Paper copies, which can change dimension with changes in temperature and humidity, are less desirable for overlays. From stable-base composites inexpensive ozalid copies can be obtained.

Feature separates can be obtained in black and white if any single type of map data such as contours, streams, or woodland are needed. These features can also be combined. These are useful for studies where only certain types of information on the map need to be emphasized.

For most areas of the Commonwealth there are several maps of different ages on which historical features can be seen or growth can be traced. Black and white paper copies of these *out-of-print* maps are also available from the Center. The older maps generally show less detail.

Black and white copies of all maps at a given scale are available on rolls of microfilm. Libraries and companies which need map information for the Commonwealth but have little storage space find these rolls especially useful for ready reference.

Contours from certain map series have been digitized. These values are available on magnetic tapes. They are useful for computer programs that involve planned changes in the landscape. Information on availability of these can be obtained from the Center.

Page-size reductions in black and white of 1:24,000-scale maps, when bound together by county area, are a convenient portable reference to the features of large areas. As contour values and names of features are quite small a magnifying glass may be needed to see them. Several regional planning commissions have made these reductions available, often in multicolor editions. Real-estate and emergency service organizations have found these useful.

MAP SERIES AVAILABLE FOR VIRGINIA

Four different topographic map series at the scales of 1:1,000,000, 1:500,000, 1:250,000, and 1:24,000 are available to portray all of the Commonwealth (Figure 11). Each series has its own use. Base maps that show the entire State on either one or two map sheets are available at the scales of 1:1,000,000 and 1:500,000; the other series require

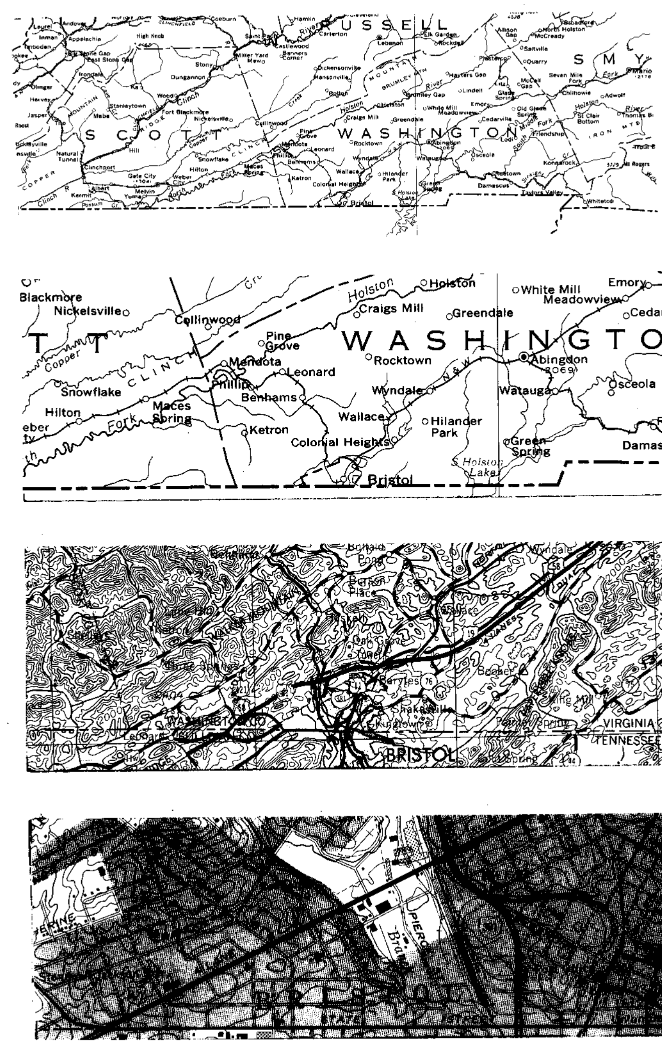

Figure 11. Portions of maps of different scales showing Bristol area suitable for various uses. The 1:1,000,000-and 1:500,000-scale maps present an overview of the entire State. The 1:250,000-scale map shows a birds-eye view of portions of the Commonwealth. The most up-to-date and detailed maps are those of the 1:24,000-scale series.

many different sheets. Copies of all types of topographic maps and products are available from the Virginia Division of Mineral Resources, P. O. Box 3667, Charlottesville, VA 22903.

Two types of maps are available in the *1:1,000,000-scale series*. The first is a State base map in black and white, which shows county boundaries and names, railroads, cities, streams, large water bodies, airports with scheduled service, major landform names with some spot elevations, and some place names including county seats. The map is 16 x 32 inches (41 x 81 cm) in size.

The second type available at the scale of 1:1,000,000 consists of two maps of the International Map of the World series. These multicolor maps measuring 26 x 26 inches (65 x 65 cm) divide the Commonwealth along a line trending through Culpeper and Blackstone and show portions of adjoining States as well as Delaware, New Jersey, Ohio, and Pennsylvania. They show county boundaries, major place names and roads, railroads, rivers, lakes, and locations of national forests and parks. Elevations above sea level are depicted in meters by color tint and contour lines. One inch (2.54 cm) on the map represents about 16 miles (26 km) at the scale of 1:1,000,000. Both of these two types of maps are useful where a general overview of the entire State is needed in a relative small size whether it be for wall mounting or as a base map for reports.

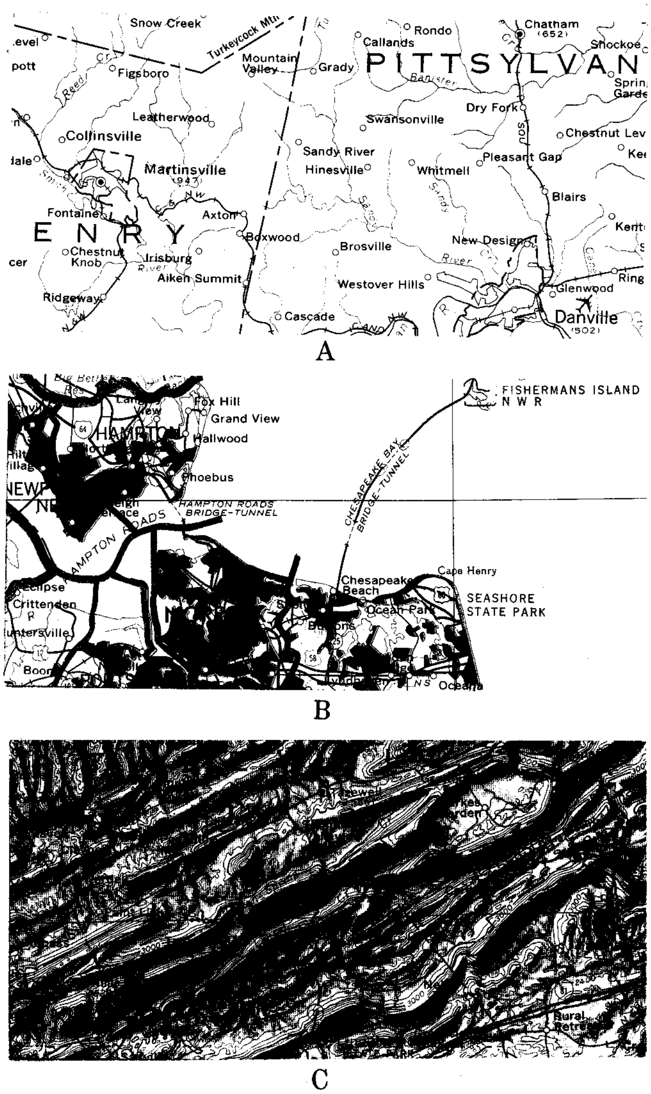

Figure 12. Portions of different maps showing the entire State at the scale of 1:500,000. The base edition (A) is useful to show counties, towns, and cities. The topographic edition (B) in multicolor depicts the shape of the landscape by contour lines. The shaded-relief edition (C) gives a 3-dimensional aspect to major landforms.

Three maps in the *1:500,000-scale series* (1 inch or 2.54 cm on the map represents about 8 miles or 13 km), which show the entire State are available (Figure 12). Each map is 30 x 64 inches (76 x 162 cm). The first of these, the State base edition, has the same information as that of the 1:1,000,000-scale State base map except by being larger and by having the streams and water bodies in blue it is more readable.

The second, the State topographic edition, is a multicolor presentation of the information shown on the State base together with highways and landform shape, and elevation shown by contour lines. Built-up areas, and State and Federal parks and forests, are color coded.

The third, the State shaded-relief edition, is a multicolor map with the information of the topographic edition on which land forms are given a three-dimensional aspect by means of brown shading. All three maps are suitable for wall mounting where the geographic features of the entire State can be viewed.

The State base should be chosen if the location of major streams with their tributaries and large water bodies are needed. The topographic edition depicts public recreational areas, urban areas, and county locations. The shaded-relief edition best shows the positions of major landforms. Mountains and valleys from the Blue Ridge westward are especially prominent.

The *1:250,000-scale series* consists of portions of 14 maps needed to show the Commonwealth. Each map depicts an area of about 7,700 square miles (19,943 sq km) bounded by 2 degrees of longitude and 1 degree of latitude. Most of these maps are 24 x 34 inches (61 x 86 cm) in size and show portions of adjoining states. These multicolor maps show roads, railroads, towns, cities, urbanized areas, major power lines, quarries, mines, airports, streams, ponds, lakes, and reservoirs. Roads are shown by symbols that indicate the relative ease with which they can be driven. Boundaries of cities, counties, and State and Federal parks and forests are indicated. Many features are named. The elevation and shape of the land is shown by contour lines. The extent of woodland and landmark buildings and man-made structures, such as schools, churches, water tanks, and lookout towers, are also depicted. These maps are drawn to scale so that 1 inch (2.54 cm) on the map equals about 4 miles (6 km) of the earth's surface. The Universal Transverse Mercator Reference grid in 1,000-meter squares is printed on the map as an aid for locating features.

These maps are especially suited for use in the car or airplane for obtaining the bird's-eye view of your home or vacation area. Trips to places of interest can also be planned from studying these maps. If the Virginia portion of these maps are composited together they make for an attractive 4 x 10 foot (1 x 3 m) wall display of the features of the Commonwealth. Plastic raised-relief editions of most of the maps of this series are available, which show a 3-dimensional view of the State. Mt. Rogers, the highest point in the State, extends about 0.5 inch (1.3 cm) above the surrounding country.

The *1:24,000-scale series* has the most detail and up-to-date map coverage. Each map shows about 60 square miles (155 sq. km) and is bounded by 7.5-minutes of longitude and latitude. Portions of 805 quadrangle maps are needed to completely show the Commonwealth. Most maps measure 22 x 27 inches (56 x 69 cm). They are drawn to scale so that 1 inch (2.54 cm) on the map represents 2,000 feet (610 m) on the ground. These multicolor quadrangles show a detailed presentation of natural and man-made features such as roads and railroads, houses, schools, churches, cemeteries, industrial and commercial buildings, streams, dams, lakes, ponds, reservoirs, bench marks, and city, town, and county boundaries. The shape and elevation of the land surface is shown by contour lines and spot elevations. All maintained roads have their route numbers indicated. Many unimproved roads and trails are shown. Woodland areas are indicated by a green overlay. Buildings inhabited by man are denoted as black squares or rectangular outlines according to the shape of the particular building. Many outbuildings used for protection of animals, machinery, or materials are depicted by outlined squares only.

Ticks for latitude-longitude, Virginia coordinate, and Universal Transverse Mercator reference systems are located on the map margins. Points can easily be identified or located by comparison with lines drawn by connecting ticks of equal value across the map. Names of map features are those used by the local residents. Often there are many name variants for features. Note that different sizes and style of type on the map can be a guide to names of different types of features. This map series is the most useful for the State because of its great amount of information.

Portions of the Commonwealth are covered by multicolor maps at the scales of 1:100,000 and 1:50,000 which depict the man-made and natural features of the State. They are compiled from and show much of the information of the 1:24,000-scale series. Those at the *1:100,000-scale series* are regional maps measuring 29 x 36 inches (74 x 91 cm) and show the position of features at the ratio of one inch (2.54 cm) on the map to about 1.5 miles (2.4 km) on the earth's surface.

The *1:50,000-scale series* is used to depict individual counties. On these one inch (2.54 cm) portrays about 0.8 mile (1.3 km). These are useful for showing county areas in detail for planning, hunting, fishing, or hiking trips or for just a better understanding of the county. Inquiry should be made for maps of specific areas as State coverage is not available at these scales.

Map products prepared from the 1:24,000-scale maps or from aerial mapping photographs include orthophotoquads, slope maps and orthophoto maps. *Orthophotoquads* are black and white aerial photographic depictions of 1:24,000-scale topographic map areas. Distances between points can be measured as one inch (2.54 cm) on the map equals 2,000 feet (610 m) on the earth's surface. The same grid reference ticks as those on the topographic series are around the periphery of the map. There are grid lines for the Universal Transverse Mercator metric reference system across the orthophotoquad. This product measures 22 x 27 inches (56 x 69 cm). A few of the more important features such as towns and highways are named or numbered.

These are suited for a birds-eye view of each map areas, for locating individual properties, and for interpreting land use and coniferous trees. When used with the corresponding topographic map of the same name much useful information can be obtained (Figure 13). If the orthophotoquad is placed underneath the map so that the corners labeled with latitude and longitude are above each other and then folded, similar points between the two can be compared.

Slope maps are 1:24,000-scale topographic maps in black and white on which inclination of the land surface are shown in percent slope categories by means of black and white patterns (Figure 14). The steeper the slope the darker the pattern. These maps measure 22 x 27 inches (56 x 69 cm). They are especially useful in planning for the use of land where slope could be a factor.

Orthophoto maps are multicolor depictions of topographic map information on a photographic base of 1:24,000-scale map areas. These are especially useful in wetlands areas as an aid in navigation and interpreting types of vegetation. Inquiry should be made for specific areas as State coverage is not available for these products.

Land-use maps are being prepared for Virginia on the areas depicted by the 1:250,000-scale topographic map series. Uses are classified from in-

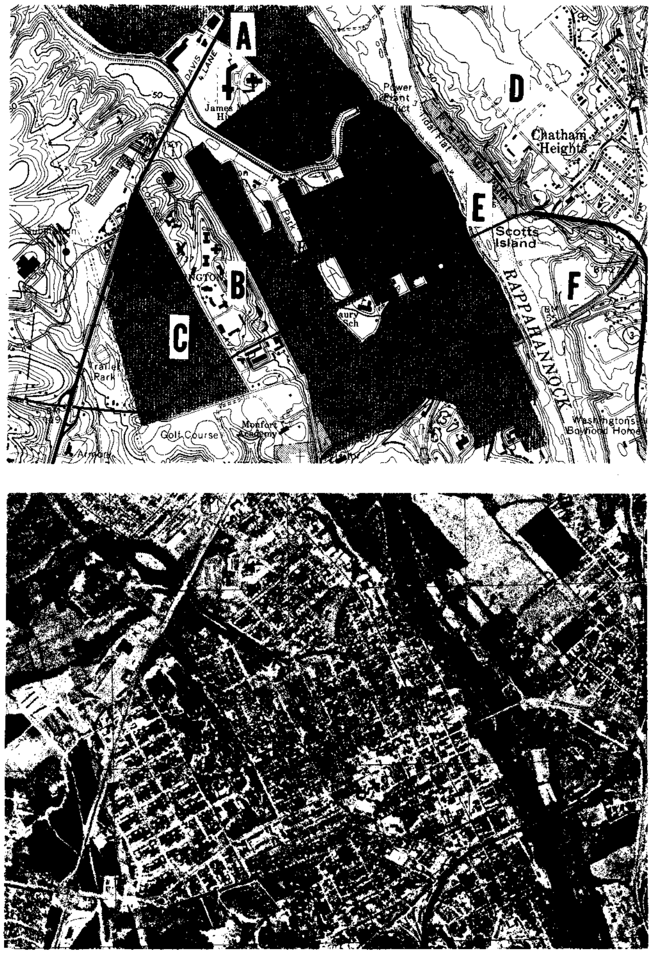

Figure 13. Comparison of information shown on 1:24,000-scale topographic quadrangle, 1971, and orthophotoquad, 1972, of Fredericksburg. Compare features at A, major road; B, college campus; C, residential subdivision; D, cleared field; E, bridge; and F, railroad.

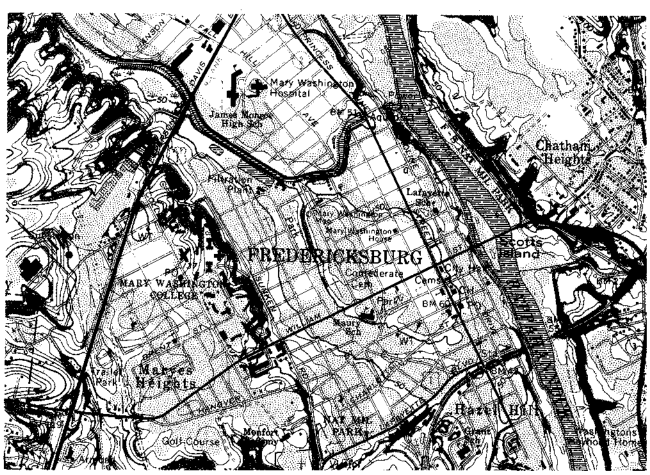

Figure 14. Slope map of a portion of the Federicksburg 1:24,000-scale quadrangle, 1971. Slope groups are shown with the steeper slopes in darker patterns than the more gently, nearly flat areas that are indicated in white. Compare this portion with that shown in Figure 13.

terpretation of aerial photography, LANDSAT imagery, and other sources. Basically features are classified and number coded as either urban or built-up land, agricultural land, rangeland, forest land, water, wetland, barren land, tundra, and perennial snow or ice.

These categories are divided into some 37 subcategories. As an example forest land is subdivided into deciduous, evergreen, and mixed forest land. These uses are composited together and appear as outlined, numbered areas on an overlay; the numbers are identified on the overlay legend. In addition the following other overlays to the 1:250,000-scale map areas will be available: political boundaries showing counties and cities with census reference number; census county and standard metropolitan statistical areas with reference numbers; and hydrologic units on which major watershed are outlined and numbered. Information on the land-use classification system is contained in "A Land Use and Land Cover Classification System for Use with Remote Sensor Data" by J.R. Anderson and others, U.S. Geological Survey Professional Paper 964, 1976. The availability of the various overlays can be obtained from the National Cartographic Information Center-East, U.S. Geological Survey, Reston, VA 22092.

ORDOVICIAN SHELF-TO-BASIN TRANSITION SHENANDOAH VALLEY, VIRGINIA[1]

By
Eugene K. Rader and William S. Henika

CONTENTS

ILLUSTRATIONS

TABLES

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[1]Portions of this contribution may be quoted if credit is given to the Virginia Division of Mineral Resources. It is recommended that reference be made in the following form:

Rader, E.K., and Henika, W.S., 1978, Ordovician shelf-to-basin transition, Shenandoah Valley, Virginia, *in* Contributions to Virginia geology—III: Virginia Division of Mineral Resources Publication 7, p. 51 - 65.

ABSTRACT

Detailed mapping and petrographic study of Ordovician carbonate and siliciclastic lithofacies in the Shenandoah Valley provide the data from which depositional units can be related. Lithofacies that are characteristic of the standard facies belts of Wilson (1975) are recognized. Utilizing the standard facies-belt distribution, an Ordovician depositional strike east of the present structural strike can be defined. An Ordovician shelf-to-basin transition is recognized throughout the Shenandoah Valley. Areal and vertical distribution of lithofacies can be related to a gently subsiding carbonate platform that existed from Middle Cambrian through early Middle Ordovician time. In early Middle Ordovician time the platform began to collapse in isostatic response to rising tectonic highlands to the southeast. Collapse of the platform edge was differential both in space and time and occurred earliest and most precipitously in rocks now exposed along the southeastern limb of the Massanutten synclinorium.

INTRODUCTION

Although geologic mapping has been relatively continuous in the Shenandoah Valley of north-central Virginia during the past 50 years the major emphasis has been on stratigraphic subdivision of the rocks rather than on interpretation of depositional environments that the mapped lithologic units represent. Recent detailed mapping of 7.5-minute quadrangles at the scale of 1:24,000 (Edmundson and Nunan, 1973; Gathright, Henika, and Sullivan, 1977 and personal communication, Grottoes, Mount Sidney, Fort Defiance, and Crimora quadrangles, 1978; Rader, 1967, 1969; Rader and Biggs, 1975, 1976; Young and Rader, 1974) has provided direct physical proof of the complex interrelationships among the lithofacies of carbonate rocks and has stimulated the search for rational explanations of these relationships by the application of depositional environmental models.

The purpose of this paper is threefold: (1) to describe the complex interrelationships between lithofacies, (2) to relate the lithofacies to a depositional model that may be used to predict the location of high-calcium limestone and reef porosity which may have potential as hydrocarbon reservoirs, and (3) to describe the general lithofacies distribution.

The area of this study is in the Shenandoah Valley from south-central Augusta County northeastward to the Virginia-West Virginia boundary (Figure 1). The stratigraphy was classically described by Butts (1933, 1940-41) and was in part revised by Cooper and Cooper (1946). The stratigraphy summarized in Figure 2 essentially follows that of Cooper and Cooper (1946) with revisions by the writers to eliminate time-rock units that have not been distinguished in mapping lithostratigraphic units since that publication. These revisions also include the recognition of the intertonguing relationship between Martinsburg and Edinburg lithofacies, and the subdivision of the Beekmantown Group in the southwestern part of the area into four unnamed units (Cooper and Cooper, 1946, p. 85; Gathright, Henika, and Sullivan, 1977 and personal communication, Grottoes, Mount Sidney, Fort Defiance, and Crimora quadrangles, 1978). Conodont data was supplied by Anita Harris of the U.S. Geological Survey.

The lithofacies that are used in determining the depositional environmental model that is applied to the area are summarized in Table 1. Briefly, the lithofacies include cyclically interbedded limestone and dolomite (Beekmantown Group), laminated limestone and bird's-eye limestone (New Market Limestone), cherty calcarenite (Lincolnshire Formation), rhythmically bedded limestone and slate[2] (or shale, Liberty Hall limestone, Edinburg Formation); nodular bedded limestone and shale (Lantz Mills limestone, Edinburg Formation); calcareous slate (black slate, Martinsburg Formation), interbedded calcareous argillite, slate, and limestone (calcareous turbidite, Martinsburg Formation) and lithoclastic sandstone, argillite and slate (siliciclastic turbidite, Martinsburg Formation).

COMPARISON OF CARBONATE ROCKS OF THE SHENANDOAH VALLEY TO THE STANDARD FACIES BELTS

Descriptions of carbonate rocks in Table 1 are presented in terms of standard microfacies (SMF, Wilson, 1975) as based on the study of hand specimens, acetate peels, and thin sections. The depositional environment can be inferred for a particular suite of samples by using a combination of standard microfacies and sedimentary structures. Depositional environments combined with the spatial relationships of the lithofacies allow the assignment of standard facies belt (SFB) designations (Wilson, 1975). Rock that is charac-

[2]Slate as used in text is a compact, fine-grained metamorphic rock formed from such rocks as shale and volcanic ash, which possesses the property of fissility along planes independent of the original bedding (slaty cleavage) whereby they can be parted into plates that are lithologically indistinguishable (Am. Geol. Inst., 1972).

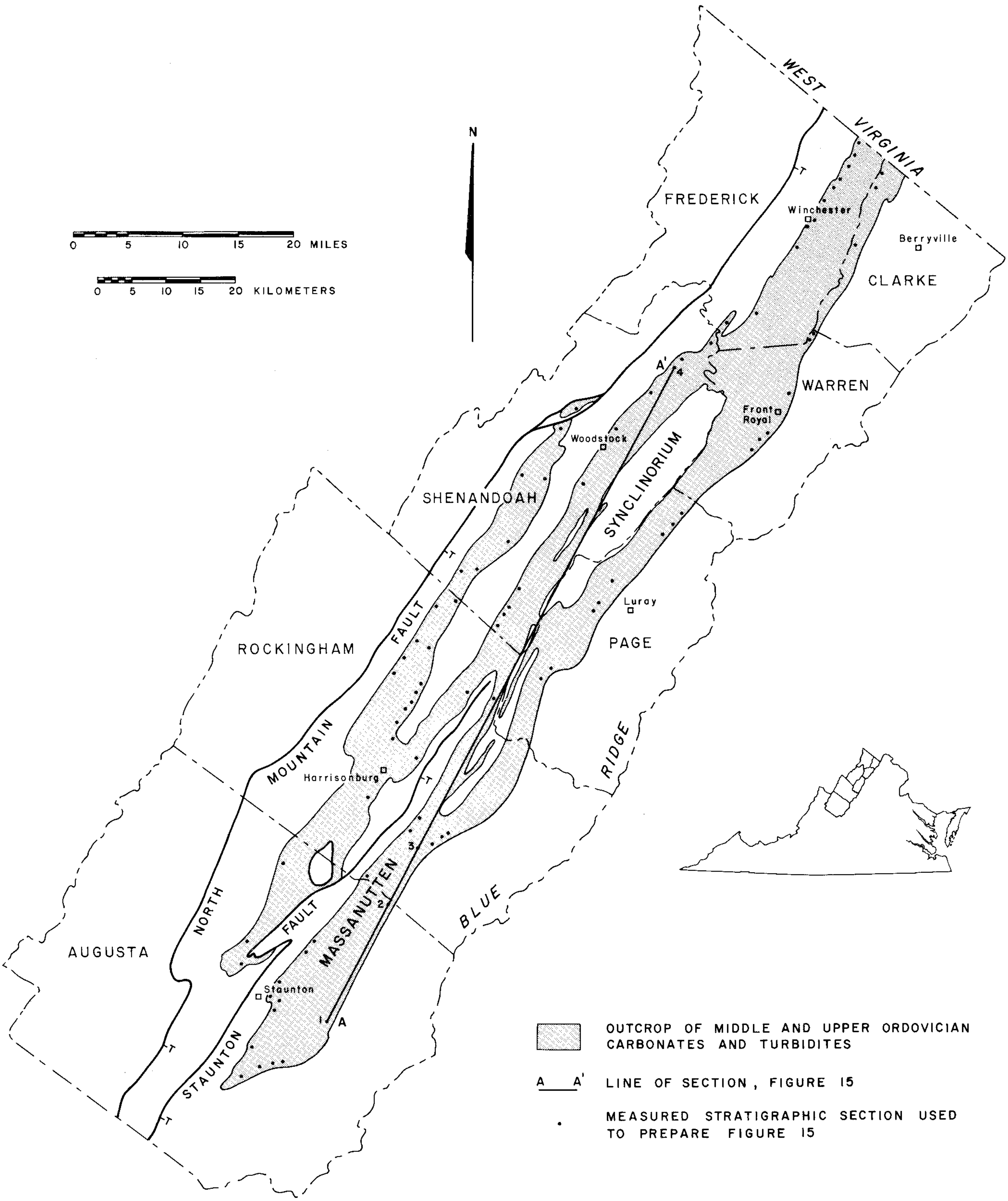

Figure 1. Location map showing the area of study, location of measured stratigraphic sections, structural framework, and areal extent of outcrop belts of Middle and Upper Ordovician carbonate rock and turbidite (modified from Virginia Division of Mineral Resources Geologic Map of Virginia, 1963).

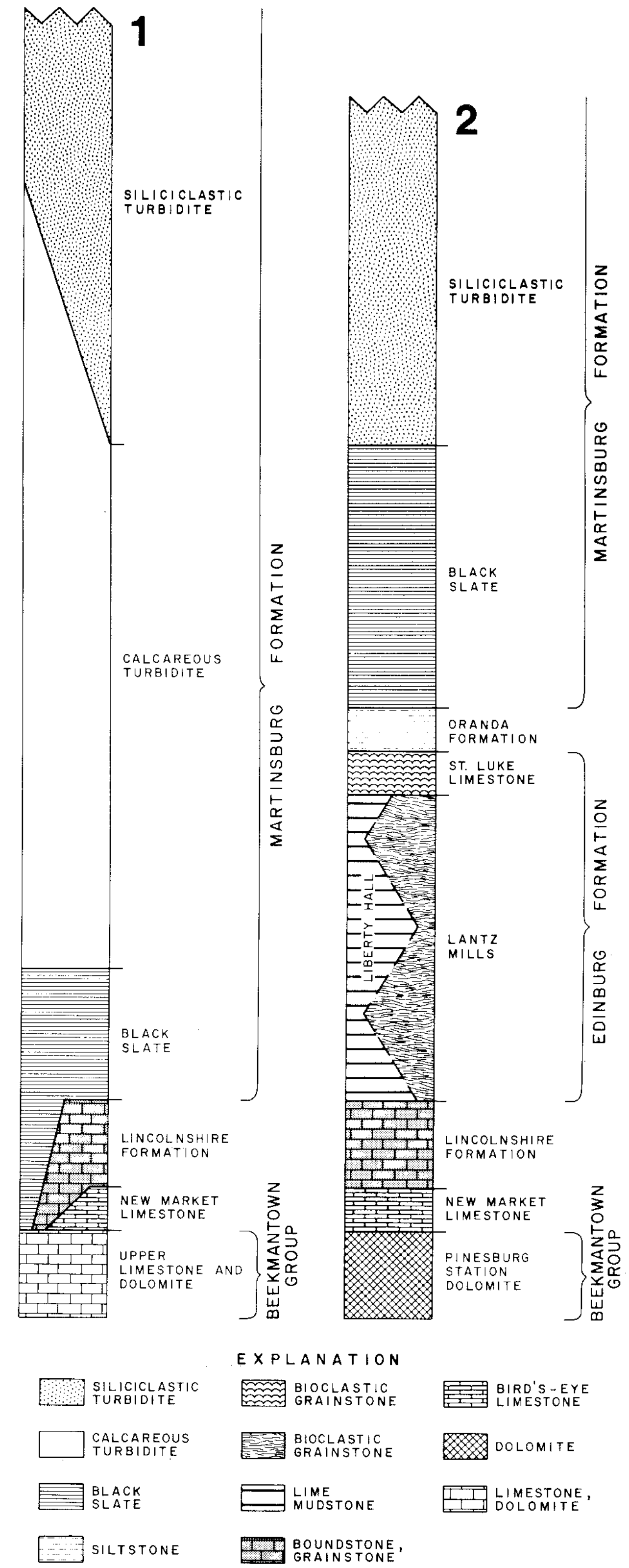

Figure 2. Columnar sections illustrating stratigraphic nomenclature and related lithologies. Section 1 is from the eastern limb of the Massanutten synclinorium in eastern Augusta County. Section 2 is from the western limb of the Massanutten synclinorium in northeastern Shenandoah County.

teristic of the standard facies belts can be recognized in the Ordovician carbonate rocks of the Shenandoah Valley of Virginia (Table 2).

Pelagic mudstone (slate and argillite), calcareous turbidite (Figure 3), and siliciclastic turbidite (Figure 4) are the lithofacies that were deposited in a basin at some distance from the source of siliciclastic sediment (SFB 1). The general stratigraphic sequence from oldest to youngest is pelagic mudstone that is gradational upwards into calcareous turbidite, which is succeeded by siliciclastic turbidite. The sequence shows a transition from an euxenic basin to an open-shelf environment in which distal siliciclastic turbidite is interbedded with calcareous turbidite. The siliciclastic turbidite contains medial and minor amounts of proximal turbidite beds that show graded bedding, cross-ripple laminations, flute casts, groove casts, and load casts. The fauna consists principally of graptolite genera *Climacograptus* and *Orthograptus*.

Rhythmically interbedded, black-lime mudstone with black slaty partings (Figure 5) comprise SFB 2. Turbidite layers are interstratified with thin fossil-debris beds derived from the open-shelf fauna or washed down a foreslope from a carbonate buildup. Gross-bedding aspect corresponds to bedding Type A of Wilson (1969, p. 9, fig. 1); however, on the microscopic-scale, individual limestone beds show complete to base cut-out Bouma cycles. Slump-folded beds are common and may be storm related.

The nodular limestone lithofacies that is characteristic of standard facies belts 3 and 4 consists of black-lime mudstone and bioclastic wackestone (Figure 6) that contain soft-sediment slump features, primarily sedimentary boudinage, which developed after deposition on a paleoslope (Figure 7). Abundant bioclastic material derived from the edge of the platform is a characteristic of this foreslope facies. The diverse fauna includes brachiopods, trilobites, bryozoans, ostracodes, crinoids, and algae.

The cherty calcarenite lithofacies that is characteristic of these standard facies belts 5 through 7 includes skeletal grainstone, bioclastic wackestone, and algal-bryozoan boundstone associated with organic-reef structures and carbonate buildups (Figure 8). Massive calcarenite associated with reef frameworks is generally light to medium gray whereas medium-bedded, cherty calcarenite of reef flanks and more open marine platform environments is dark gray with nodular to wavy bedding and red to purple bedding partings. Rocks of this lithofacies probably were deposited from the crestal portion of a foreslope (carbonate

Table 1.—Formations and lithofacies in Ordovician rocks, Shenandoah Valley, Virginia.

Stratigraphic Unit	Standard Microfacies	Lithofacies	Standard Facies Belts	Depositional Environment
Martinsburg Formation		siliciclastic turbidite calcareous turbidite pelagic (slate and argillite)	SFB 1 SFB 1 SFB 1	basinal basinal basinal
Oranda Formation		calcareous turbidite	SFB 1	basinal
Edinburg Formation				
St. Luke Member	SMF 12	calcarenite	SFB 6	shoal, agitated-water
	SMF 9	calcarenite	SFB 7	shelf, open circulation
Lantz Mills limestone	SMF 4	nodular limestone	SFB 3	toe of slope and foreslope
Liberty Hall limestone	SMF 1-4	rhythmic limestone	SFB 2	open shelf to toe of slope
Lincolnshire Formation	SMF 5, 9, 11, 12	cherty calcarenite	SFB 4-7	foreslope to open platform
New Market Limestone	SMF 20, 21, 23 SMF 20	bird's-eye limestone laminated limestone	SFB 8 SFB 8	restricted platform tidal flat
Beekmantown Group				
Upper limestone and dolomite[1]	SMF 19, 20, 23	limestone-dolomite	SFB 8-9	tidal flat to supratidal
Pinesburg Station Dolomite[2]	SMF 19, 20, 23	dolomite	SFB 9	supratidal to tidal flat

buildup) across an open-marine platform as carbonate sand shoals, beaches, and bars as well as patch-reef complexes that were interspersed with areas of quiet, shallow water (lagoons), which were characterized by deposition of lime mudstone. The fauna includes incrusting red algae and bryozoans, corals, sponges, gastropods, cephalopods, brachiopods, ostracodes, trilobites, and rarely graptolites.

Dove gray, thick-bedded to massive lime mudstone (Figure 9) with thin, lenticular beds of bioclastic wackestone, bioclastic packstone, pelsparite, and biopelsparite (Figure 10) constitute the bird's-eye limestone lithofacies and a major portion of the limestone-dolomite lithofacies (SFB 8 and 9). Medium- to thin-bedded laminated algal lime mudstone (Figure 11) with tan dolomite laminae constitute the laminated limestone lithofacies. They are important interbeds in the limestone-dolomite lithofacies (Figure 12). Dessication features such as fenestral fabric, bird's-eye structure, and mudcracks are common in the lime mudstones of these facies. Algal matte lamination and stromatolitic structures reflect variable intertidal conditions during deposition. Burrow-mottled, dolomitized limestone (Figure 13), forming a thin-bedding structure, are major interbeds in the limestone-dolomite lithofacies. Dolomite is generally thin-bedded to laminated with abundant mudcracks, crystalline vugs, and collapsed breccia zones. The vugs and breccia zones suggest dissolution of evaporite beds or lenses. Pink, red, and tan dolomitic mudstone and shale that are interbedded in the limestone-dolomite facies may represent terrigenous clastic and wind-blown sediment that accumulated on tidal mud flats in the supratidal and inland pond environments. The fauna of the three lithofacies included in SFB 8 and 9 is restricted to solitary corals, ostracodes, gastropods, and abundant algal stromatolites.

RELATIONSHIP OF FACIES BOUNDARY TRENDS TO STRUCTURAL TRENDS

The major structure in the Shenandoah Valley is the Massanutten synclinorium. Several folds involving Middle and Upper Ordovician rocks occur to the northwest of the synclinorium. The Staunton fault that extends along a portion of the northwestern limb of the synclinorium is within the larger thrust sheet, which is bounded to the northwest by the North Mountain fault. These struc-

[1]Upper unit of the Beekmantown Group in southern Shenandoah Valley.

[2]Upper formation of the Beekmantown Group in northern Shenandoah Valley.

Table 2. — Characteristics of standard facies belts in Ordovician rocks, Shenandoah Valley, Virginia.

	Standard Facies Belt				
	1	2	3	4	5
Inferred depositional environment	Flysch basin gradational from initially euxenic basin	Open shelf	Deep shelf margin (toe of slope)	Foreslope	Carbonate buildup (organic reef)
Rock types	Siliciclastic turbidite, pelagic slate and argillite, thin, spiculitic limestones	Carbonate turbidite, lime mudstone, skeletal packstone, and wackestone with slate (shale) and argillite (siltstone or claystone) interbeds			Biocalcarenite and boundstone masses
Color	Dark brown, black	Dark gray to black			Light gray
Grain types and relict textures	Coarse to fine lithoclasts, fine siliciclastic matrix, lime mud, fine calcisilt, and calcispheres	Siliciclastic silt, calcisilt, lenticular bioclastic wackestone-packstone, lithoclasts of varying sizes			Boundstones and channel fillings of grainstone-packstone
Bedding and sedimentary structures	Planar millimeter lamination, Bouma cycles, flute, groove and load casts, scour and fill, convolute and cross ripple lamination	Planar millimeter lamination, calcareous Bouma cycles, sedimentary boudins, localized bioclastic lenses, convolute bedding and slump structures			Massive, organic structure
Fossil flora and fauna	Graptolites, sponge spicules, crinoids, brachiopods, ostracodes, trilobites, conodonts	Bryozoans, algae, brachiopods, ostracodes, graptolites, sponge spicules, trilobites, conodonts			Encrusting algae, corals and bryozoans (frame builders). Trilobites, ostracodes, brachiopods, crinoids, gastropods, and cephalopods, conodonts

	Standard Facies Belt			
	6	7	8	9
Inferred depositional environment	Platform edge	Platform, lagoon with open circulation	Restricted circulation platform, tidal flat	Supratidal evaporative flats
Rock types	Biocalcarenite, calcarenite (wackestone, packstone and skeletal grainstone)	Calcarenite (wackestone and skeletal packstone), lime mudstone	Laminated lime mudstone, dolomite and wackestone	Microcrystalline laminated dolomite
Color	Gray	Light gray to gray	Light gray to gray	Gray, tan to pink
Grain types and relict textures	Grainstone, moderately well sorted, well sorted, and well rounded, partly recrystallized	Variety of grain types and textures	Peloidal fragments, onkoids, bioclasts of varying sizes	Fine crystalline texture, some fine silica sand grains
Bedding and sedimentary structures	Massive structure, structureless or recrystalline (marble). Bioclastic and peloidal relics (microscopic)	Bedding plane burrows, imbricated clasts, localized patch and pinnacle reefs	Bird's-eye structure, stromatolitic lamination, cross lamination, dessication cracks	Lamination, mud cracks, crystal casts, and vugs. Chaotic zones and breccias suggestive of dissolution of evaporites
Fossil flora and fauna	Worn and abraded coquinite of forms living at or on slope and organic reef flanks	Brachiopods, algae, crinoids, bryozoans, trilobites, cephalopods, conodonts	Algae, gastropods, cephalopods, solitary corals, ostracodes, conodonts	Algae, conodonts

Figure 3. Laminated argillite of calcareous turbidite, Martinsburg Formation, approximately 0.6 mile (1.0 km) northwest of Tinkling Springs Church along State Road 636, Waynesboro West 7.5-minute quadrangle.

tures and the distribution of the Ordovician carbonate rocks are shown on Figure 1.

Examination of the lithofacies distribution within a given strike belt of folded rocks allows for the determination of the trend of the original facies boundary. If the beds depicted in Figure 14 are folded along X-X′ or Y-Y′ and eroded the resulting outcrop belts would show the relationship between facies boundaries and structural trend. Figure 14A illustrates a structural trend east of the trend of the facies boundaries. In this example the progression of facies belts is tidal flat to basin. In Figure 14B where the structural trend is west of the facies boundary trend the progression of lithofacies from southeast to northwest is from basin to tidal flat. The upper Beekmantown Group lithofacies in the Shenandoah Valley along the southeastern limb of the Massanutten synclinorium (structural trend N. 35° E.) shows the following progression of depositional environments from the southwest toward the northeast: open platform (SFB 7), restricted-platform tidal flat (SFB 8), and platform evaporites of the supratidal zone (SFB 9). Such a progression of facies belts is indicative of a facies boundary trend that was east of the present-day structural trend.

TECTONICS OF THE BASIN

Ordovician rocks in the Shenandoah Valley north of Harrisonburg (Figures 1 and 15, locality 4) show a normal transgressional sequence. Supratidal dolomite beds are overlain in succession by tidal-flat algal and bird's-eye limestone, platform biocalcarenites, foreslope lime mudstones, bioclastic wackestones, and open-shelf lime mudstones and slates. During deposition sediment production exceeded the rate of subsidence, and progradation of foreslope and toe-of-slope deposits occurred. This was followed by a rapid transgression of basinal sedimentation (black pelagic slate) and siliciclastic turbidites. In this area the development of the basin appears to have been that of a slowly subsiding carbonate platform in which subsidence exceeded the rate of carbonate sedimentation. This marks a change from the very stable to progradational nature of the earlier Cambro-Ordovician platform. The minor progradation reflects a pause in the collapse of the marginal platform.

In the Shenandoah Valley south of Harrisonburg the tectonic history of the basin was quite different. The rocks at localities 1, 2, and 3 (Figures 1 and 15) show a sequence of lithofacies considerably different from those in the northern Shenandoah

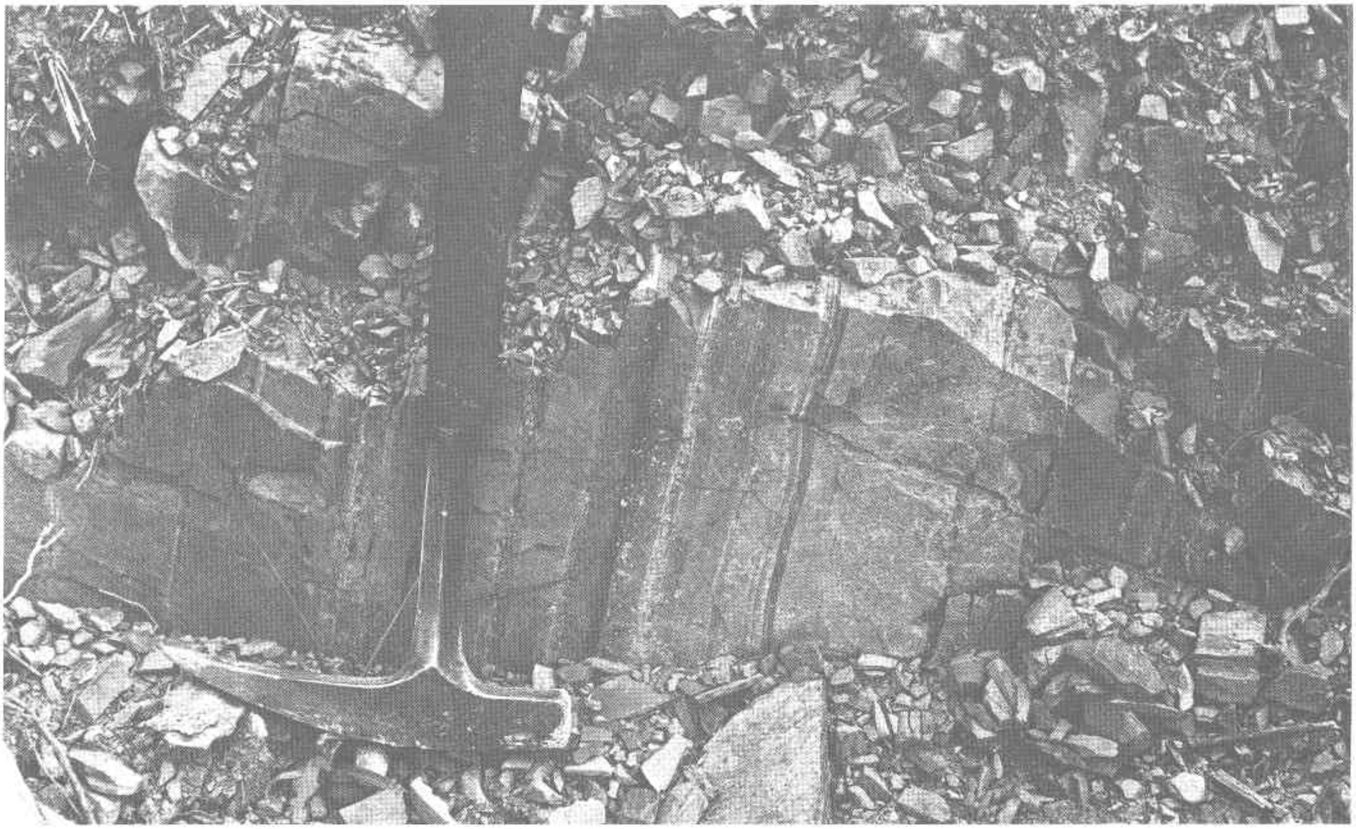

Figure 3. Laminated argillite of calcareous turbidite, Martinsburg Formation, approximately 0.6 mile (1.0 km) northwest of Tinkling Springs Church along State Road 636, Waynesboro West 7.5-minute quadrangle.

tures and the distribution of the Ordovician carbonate rocks are shown on Figure 1.

Examination of the lithofacies distribution within a given strike belt of folded rocks allows for the determination of the trend of the original facies boundary. If the beds depicted in Figure 14 are folded along X-X′ or Y-Y′ and eroded the resulting outcrop belts would show the relationship between facies boundaries and structural trend. Figure 14A illustrates a structural trend east of the trend of the facies boundaries. In this example the progression of facies belts is tidal flat to basin. In Figure 14B where the structural trend is west of the facies boundary trend the progression of lithofacies from southeast to northwest is from basin to tidal flat. The upper Beekmantown Group lithofacies in the Shenandoah Valley along the southeastern limb of the Massanutten synclinorium (structural trend N. 35° E.) shows the following progression of depositional environments from the southwest toward the northeast: open platform (SFB 7), restricted-platform tidal flat (SFB 8), and platform evaporites of the supratidal zone (SFB 9). Such a progression of facies belts is indicative of a facies boundary trend that was east of the present-day structural trend.

TECTONICS OF THE BASIN

Ordovician rocks in the Shenandoah Valley north of Harrisonburg (Figures 1 and 15, locality 4) show a normal transgressional sequence. Supratidal dolomite beds are overlain in succession by tidal-flat algal and bird's-eye limestone, platform biocalcarenites, foreslope lime mudstones, bioclastic wackestones, and open-shelf lime mudstones and slates. During deposition sediment production exceeded the rate of subsidence, and progradation of foreslope and toe-of-slope deposits occurred. This was followed by a rapid transgression of basinal sedimentation (black pelagic slate) and siliciclastic turbidites. In this area the development of the basin appears to have been that of a slowly subsiding carbonate platform in which subsidence exceeded the rate of carbonate sedimentation. This marks a change from the very stable to progradational nature of the earlier Cambro-Ordovician platform. The minor progradation reflects a pause in the collapse of the marginal platform.

In the Shenandoah Valley south of Harrisonburg the tectonic history of the basin was quite different. The rocks at localities 1, 2, and 3 (Figures 1 and 15) show a sequence of lithofacies considerably different from those in the northern Shenandoah

Figure 4. Siliciclastic turbidite of the Martinsburg Formation along the Chesapeake and Ohio Railway, 0.2 mile (0.3 km) northwest of State Road 636 underpass, Waynesboro West 7.5-minute quadrangle. This photograph illustrates a typical base cut-out Bouma cycle; the light-gray sandstone to the right is a cross ripple laminated unit; to the right center the sandstone is a parallel laminated unit, and to the left a pelagic unit occurs (Photograph courtesy Paul G. Nystrom, Jr.).

Valley. At Locality 1 supratidal and tidal-flat facies are succeeded by a carbonate-mound buildup (organic reef) and associated shoal deposits. Immediately overlying the carbonate buildup are basinal black slates. These black slates are followed by open-shelf carbonate turbidites which are in turn overlain by siliciclastic turbidites.

At Locality 2 the supratidal and tidal-flat deposits are overlain by thin platform deposits of biocalcarenite. The biocalcarenite in this area is overlain by relatively thick basinal black slate, open-shelf calcareous turbidites, and siliciclastic turbidites.

Farther to the north at Locality 3 the supratidal to tidal-flat deposits are overlain by thicker platform deposits of biocalcarenite which are in turn overlain by intertonguing open shelf, rhythmically bedded, lime mudstone and slate and basinal black slate. Basinal black slate, calcareous turbidites, and siliciclastic turbidites complete the sequence in this area.

In contrast to the Shenandoah Valley north of Harrisonburg the area to the south was part of a rapidly collapsing marginal platform. In some areas such as Locality 1 carbonate buildups were able to balance the rate of subsidence, but at Locality 2 the

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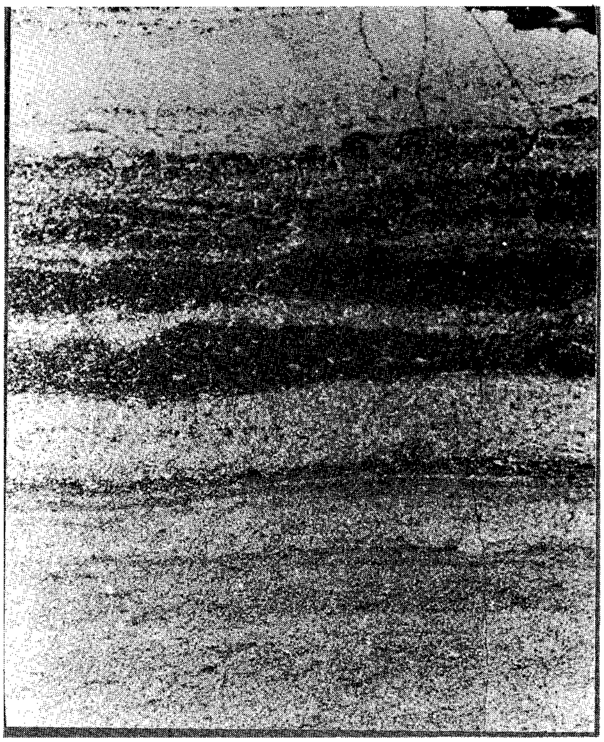


Figure 5. Acetate peel of turbiditic lime mudstone with graded calcisilt and wackestone laminae; Frazier quarry, just west of Harrisonburg, approximately 4.2x.

Figure 6. Photomicrograph of bioclastic wackestone (slope facies, SFB 3-4), approximately 1.5 miles (2.4 km) southwest of Mount Crawford, Mount Sidney 7.5-minute quadrangle; plain light; approximately 4.0x.

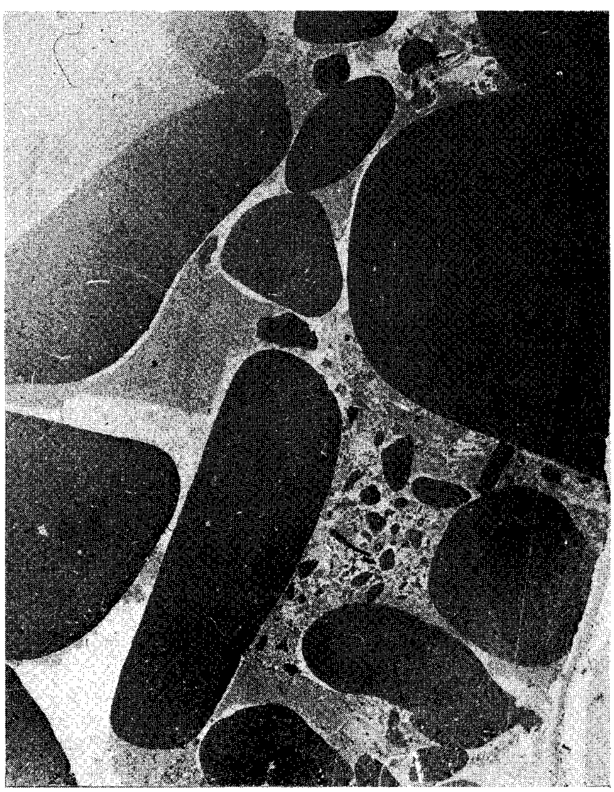


Figure 7. Photomicrograph of packstone conglomerate (slope facies, SFB 3-4) from Fort Defiance, Fort Defiance 7.5-minute quadrangle; plain light; approximately 3.9x.

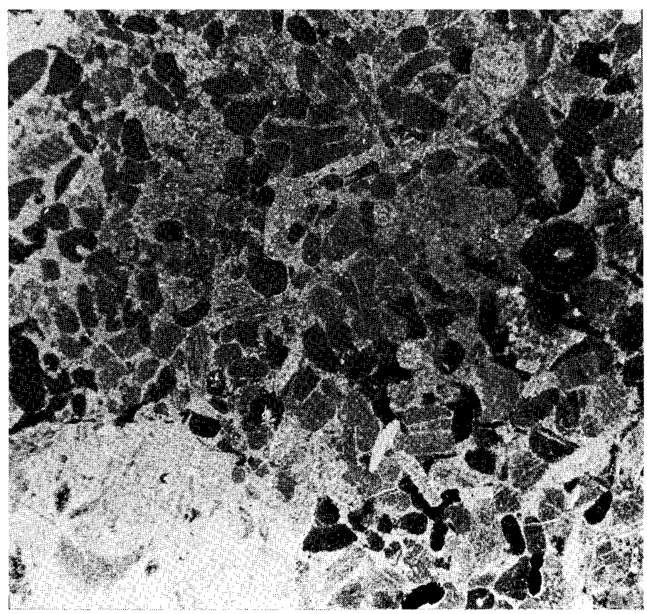
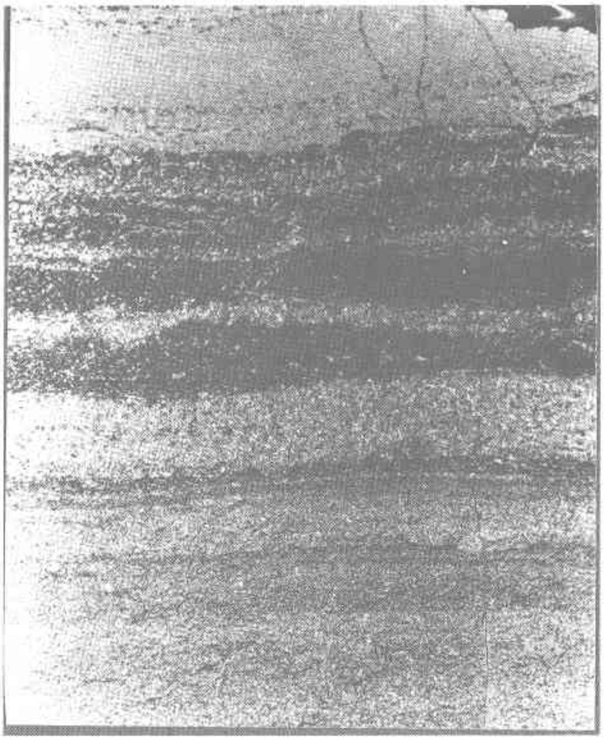


Figure 8. Acetate peel of skeletal grainstone from carbonate buildup just southeast of intersection of State Roads 796 and 782, Fort Defiance 7.5-minute quadrangle. Skeletal fragments derived from bryozoans, crinoids, and algae; algal boundstone, light gray area in lower left-hand portion of photograph; approximately 4.0x.



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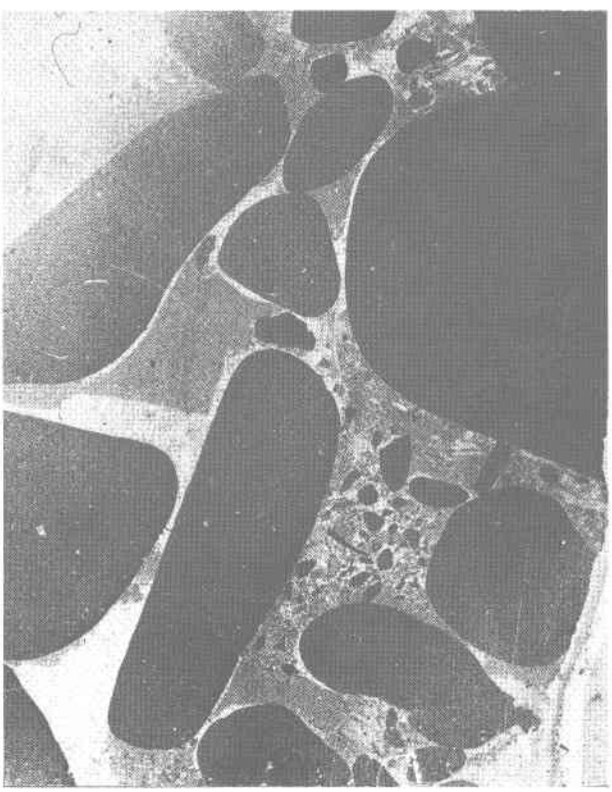

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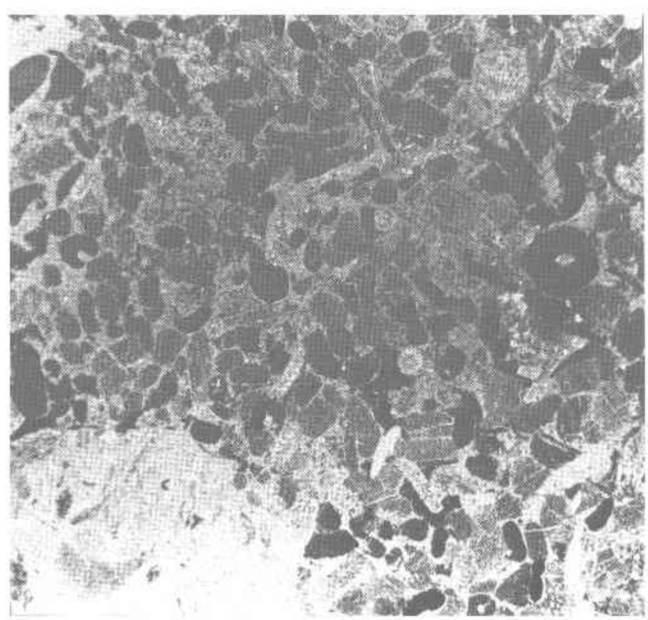

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Figure 9. Photomicrograph of bioclastic wackestone (tidal-flat facies, SFB 7) from southeastern one-ninth of the Strasburg 7.5-minute quadrangle; plain light; approximately 4.0x.

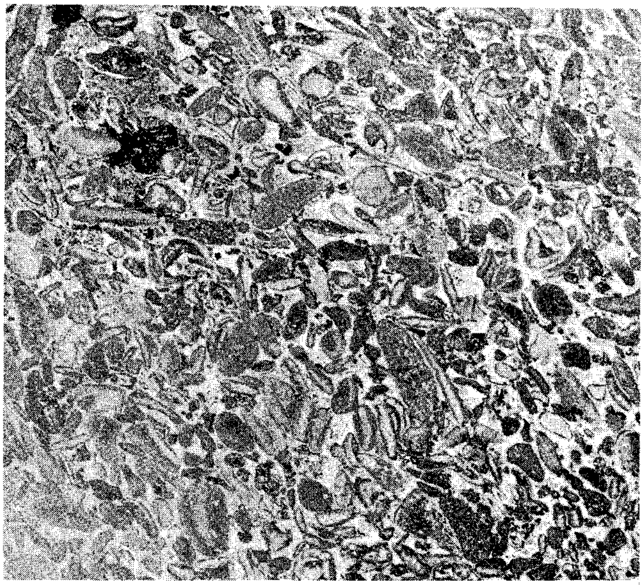


Figure 10. Photomicrograph of biopelsparite (R-6136, shoal facies, SFB6) from southeastern one-ninth of the Strasburg 7.5-minute quadrangle; plain light; approximately 5.0x.

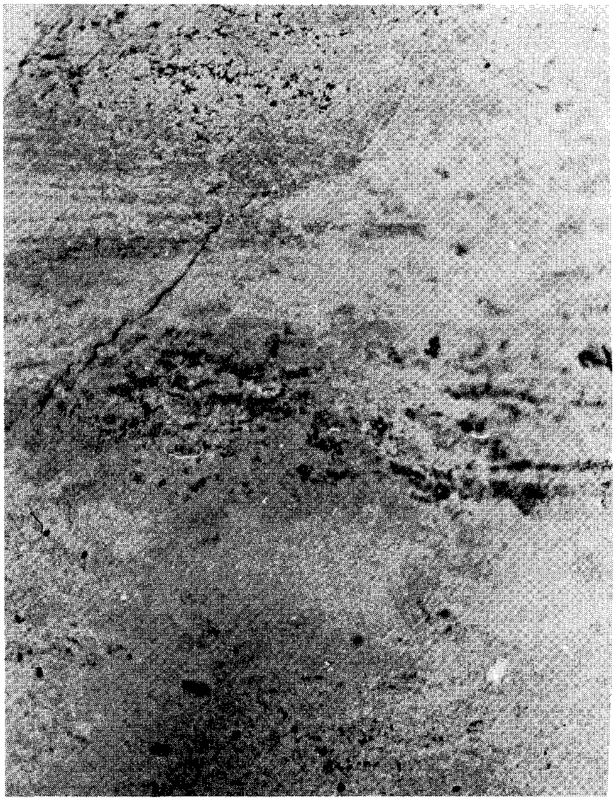


Figure 11. Acetate peel of algal stromatolite lime mudstone (tidal flat to evaporative flat, SFB 7-8), southern environs of Woodstock, Woodstock 7.5-minute quadrangle; approximately 4.6x.

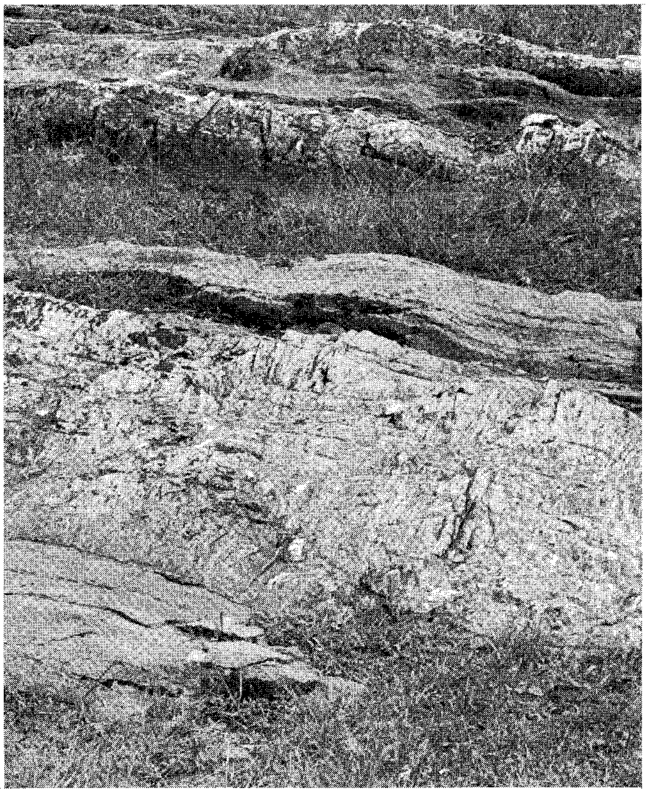
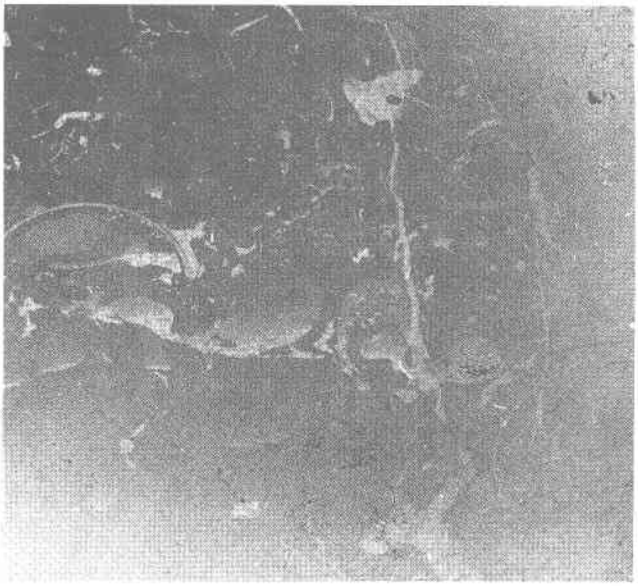


Figure 12. Typical interbedded limestone (dark) and butcher-block weathering dolomite (light); upper Beekmantown Group, Waynesboro West 7.5-minute quadrangle (photo courtesy Paul G. Nystrom, Jr.).



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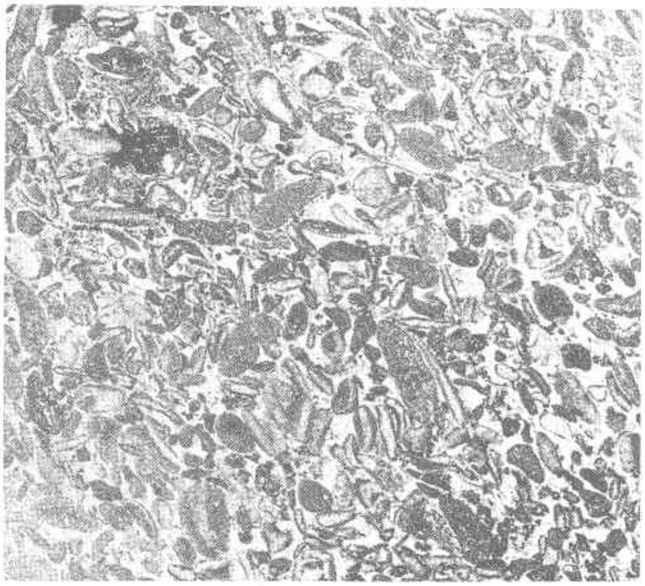

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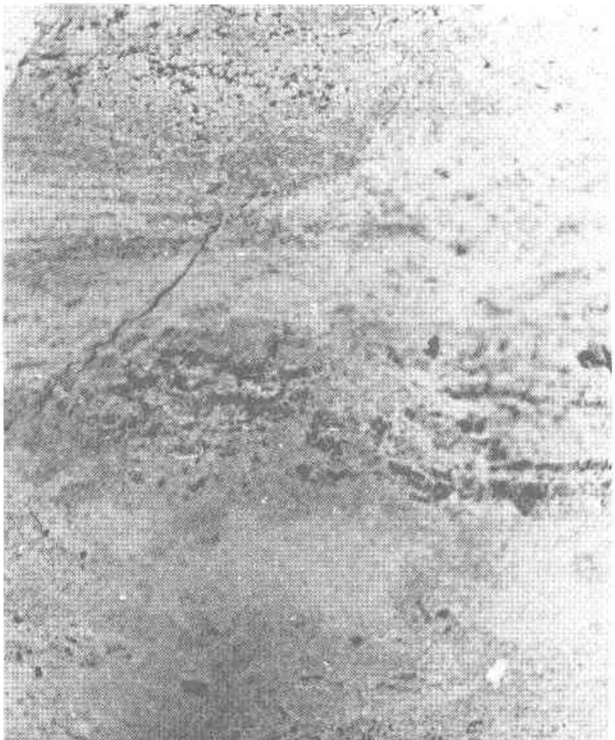

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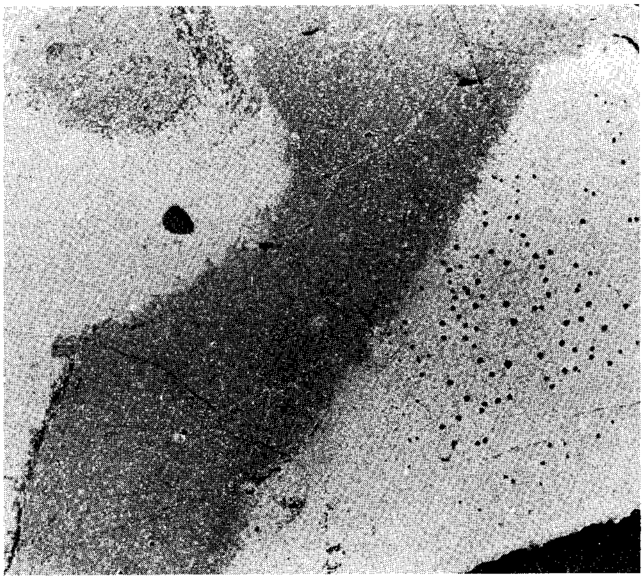


Figure 13. Acetate peel of burrow-mottled dolomite (tidal-flat facies, SFB 7-9); Prison quarry, Clarke County; approximately 4.4x.

rate of subsidence far exceeded the rate of carbonate-sediment production; thus basinal deposits overlie the platform-edge carbonates. Locality 3 reflects the transition between the more stable northern and the rapidly subsiding southern portion of the Shenandoah Valley.

Based on an analysis of Figure 15 a series of maps has been constructed to depict the areal relationships of the lithofacies. These maps (Figure 16) were constructed from 85 measured sections as described by Edmundson (1945), Cooper and Cooper (1946), Neuman (1951), and Brent (1960) and from 20 7.5-minute geologic quadrangle maps (Edmundson and Nunan, 1973; Rader and Biggs, 1975, 1976; Young and Rader, 1974; Rader, 1967, 1969; Nystrom, 1977; Gathright, Henika and Sullivan, 1977, and personal communication, Grottoes, Mount Sidney, Fort Defiance, and Crimora quadrangles). All sections were reexamined in the field by the writers and nine sections were remeasured. The maps in Figure 16 were prepared on a palinspastic base (Pedlow, 1976) utilizing data derived from the analysis of the vertical sections considering the derived depositional strike and the application of Walther's law.

The seven serial lithofacies maps Figure 16 show the development of the basin in time and space. "A" of the figure illustrates the sediments that formed the rock types of a stable marginal platform during early Ordovician time. In this figure a supratidal evaporative flat represented by the dolomite lithofacies lies to the northwest of a facies boundary that had a trend of approximately N.45° E. Southeast of this boundary there was a tidal flat represented by the interbedded limestone and dolomite lithofacies.

Initiation of collapse of the continental margin is illustrated in "B" of Figure 16. To the northeast transgression of platform deposits over the tidal flat and supratidal zone is shown by the superposition and northwestward migration of the cherty calcarenite lithofacies and the appearance of isolated carbonate buildups (patch reefs). To the southwest large carbonate buildups (organic reefs) were flanked by grainstone blankets of the cherty calcarenite lithofacies.

A continued northwestward transgressive sequence in the northeast is illustrated in "C" of Figure 16 by the open-shelf deposits (rhythmic limestone lithofacies). To the southwest subsidence accelerated and the pelagic black slate lithofacies is superimposed on platform and carbonate-mound buildups. At some localities (Figure 17) isolated areas of carbonate buildups seem to have kept pace with the precipitous subsidence of the platform edge and to have built pinnacle reef structures that

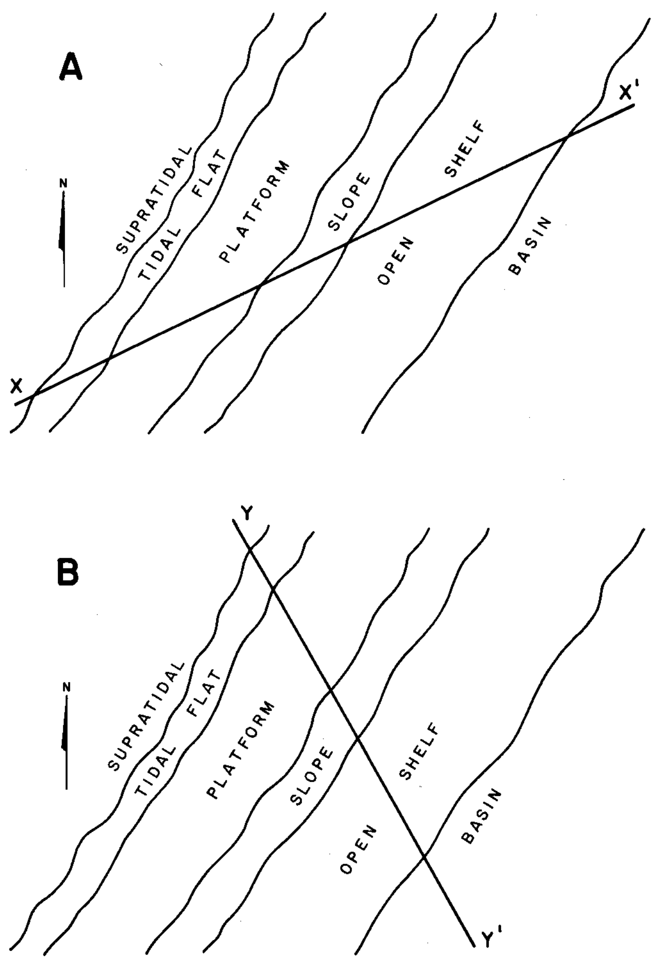
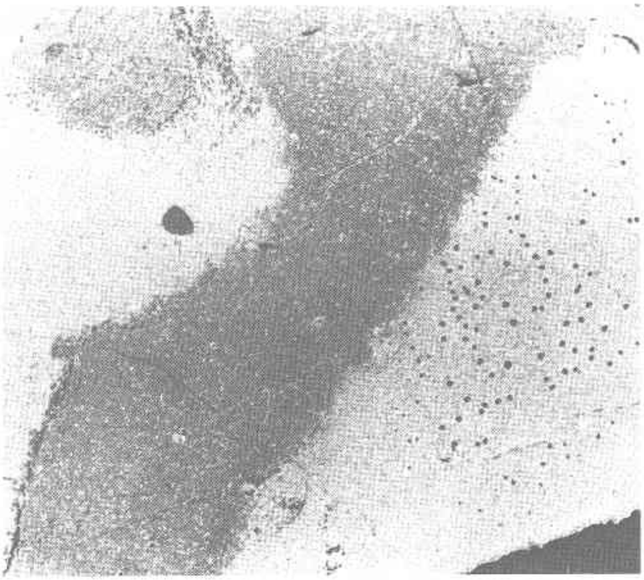


Figure 14. Illustrations of two possible relationships between facies boundary trends and structural trends; refer to text for discussion.



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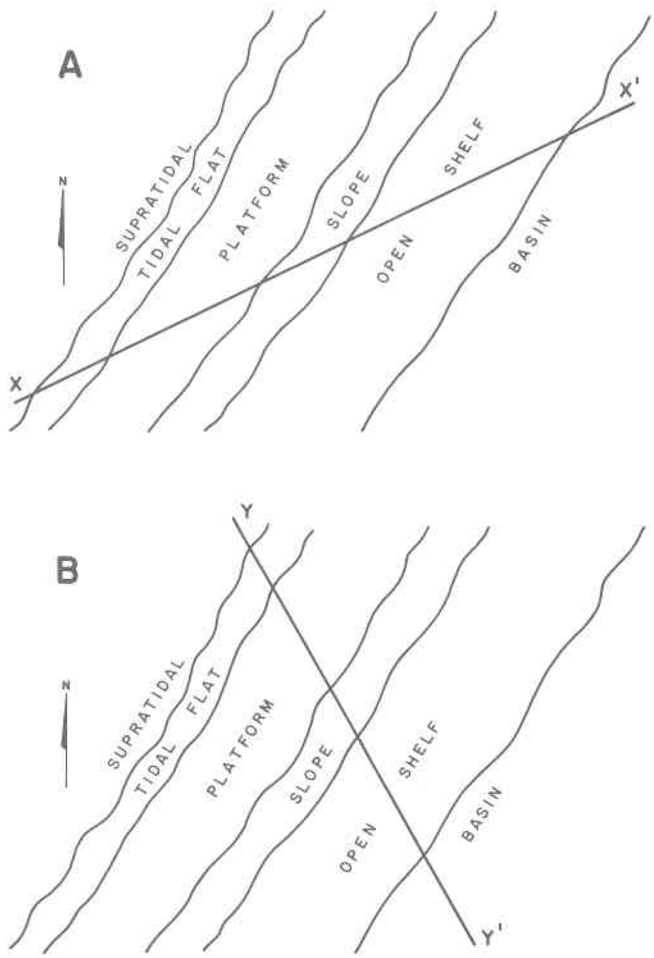

Figure 14. Illustrations of two possible relationships between facies boundary trends and structural trends; refer to text for discussion.

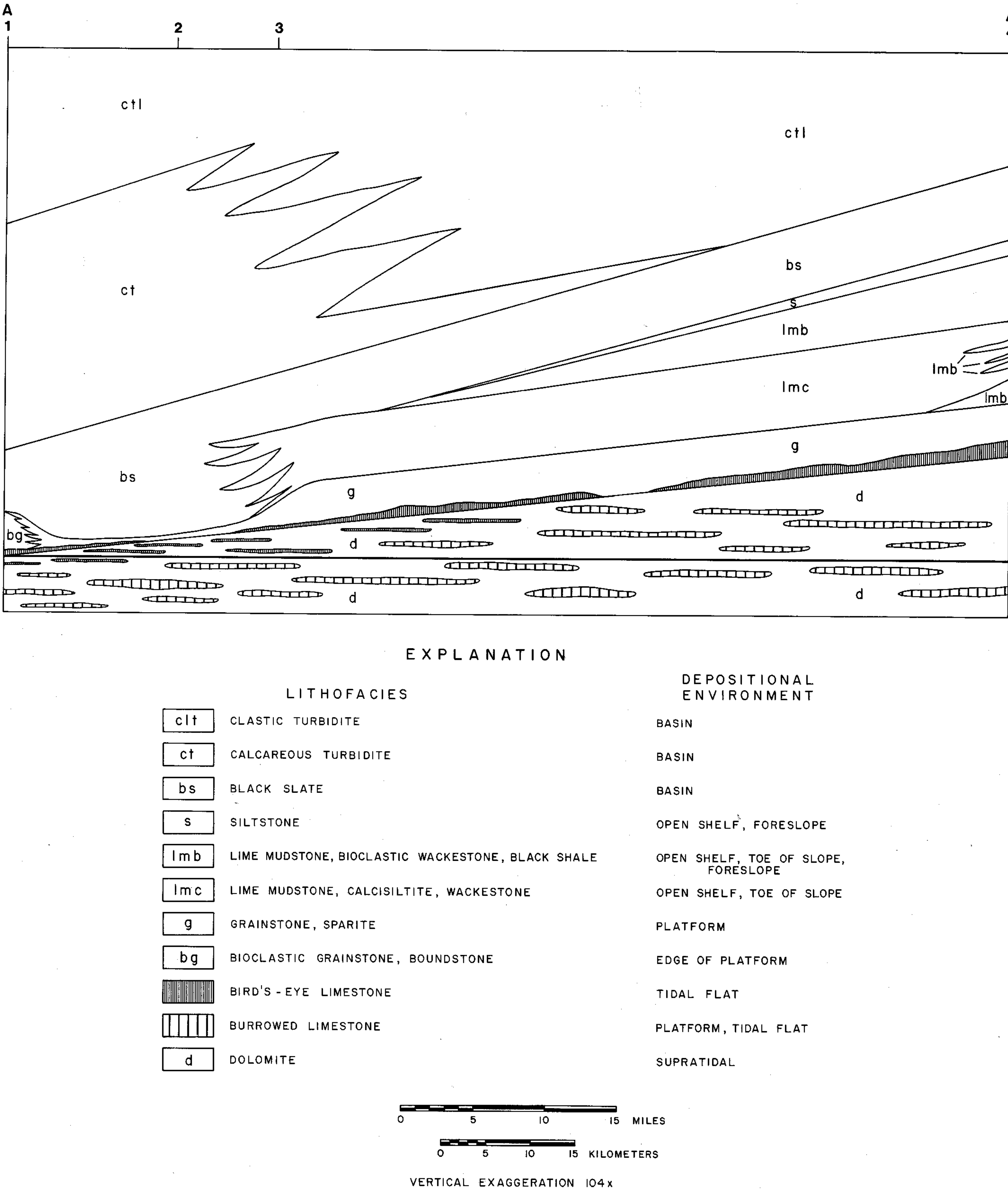

Figure 15. Schematic diagram illustrating lithofacies relationships along line A-A' (see Figure 1 for location). Heavy horizontal line is a biostratigraphic correlation horizon based on conodonts.

maintained localized shallow-water conditions for some time after the initial subsidence. In "C" of Figure 16 the irregular facies boundary between basinal and platform deposits show rapid and precipitous subsidence and possibly the formation of submarine canyons. Figure 18 depicts the contact between the pelagic black slate lithofacies and the cherty calcarenite lithofacies in the Fort Defiance and Crimora quadrangles. At this locality a tongue of black slate can be traced eastward across the trend of the underlying tidal flat limestone and dolomite units and has been interpreted as a channel or arm of deep water deposition connected with the main body of pelagic slate to the west (personal communication, Gathright, Henika, and Sullivan, 1978). Within the suspected channel a coarse conglomeratic limestone (slope facies) lies between the basinal black slate and the intertidal limestone and dolomite.

In the northeast submarine fans and channels developed along the slope between the platform and the open shelf as shown on Figure 16 (D). Transgression continued, but at a slower rate, during this time interval and a distinct slope developed. To the southwest basinal deposits expanded and a more distinct channel-like configuration was formed.

Figure 16(E) shows a minor southward progradation in the northern part of the area. To the south basinal deposits expanded to the extent that carbonate mound buildups were excluded and distinct "submarine canyons" are no longer recognizable. Figure 16(F) shows the initiation of turbidite sedimentation in the basin and the rapid transgression of the basinal black slate lithofacies over the western part of the area. In the southwestern part calcareous turbidite sedimentation began and to the northeast along the eastern margin of the area siliciclastic turbidites were being deposited. Siliciclastic sedimentation increased (Figure 16, G) and calcareous turbidite sedimentation decreased. The siliciclastic sedimentation continued until the basin was filled.

In summary, lithofacies of Ordovician carbonate formations in the Shenandoah Valley can be directly related to standard facies belts as described by Wilson (1975). Areal and vertical distribution of lithofacies in measured sections shows that their depositional systems can be related to a gently subsiding carbonate platform that existed from mid-Cambrian through the early Middle Ordovician. During that time carbonate facies belts showed depositional strikes to the east of the later tectonic axes and subsidence was approximately equal to the rate of carbonate deposition. At some time during the early Middle Ordovician the platform began to collapse, possibly in response to rising highlands to the southeast. Collapse of the platform edge was differential both in space and time and occurred earliest and most precipitously in rocks now exposed along the southeastern limb of the Massanutten synclinorium of eastern Augusta County.

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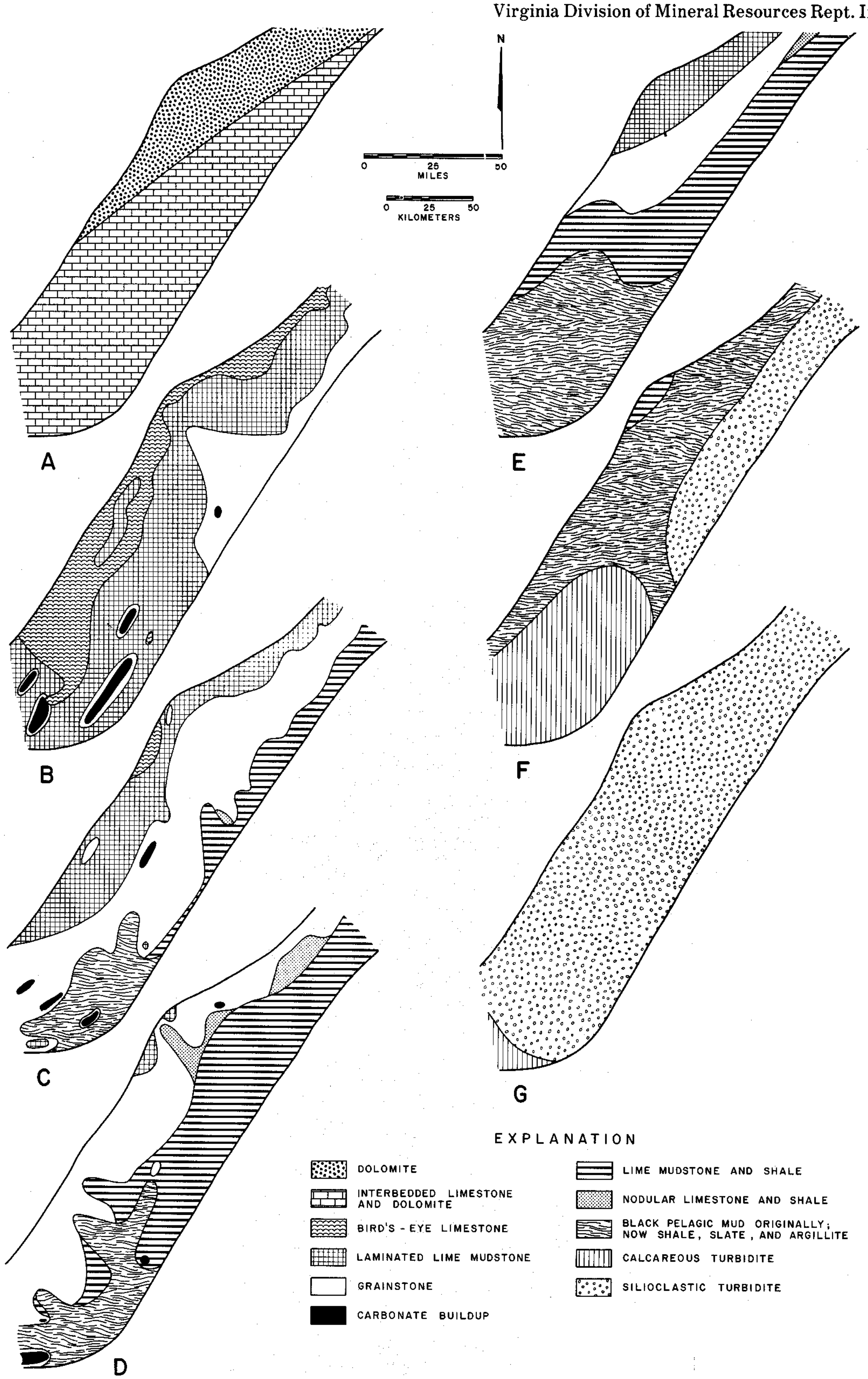

Figure 16. Serial lithofacies maps showing the shifting of sedimentological elements with time, Middle and Upper Ordovician, Shenandoah Valley, Virginia.

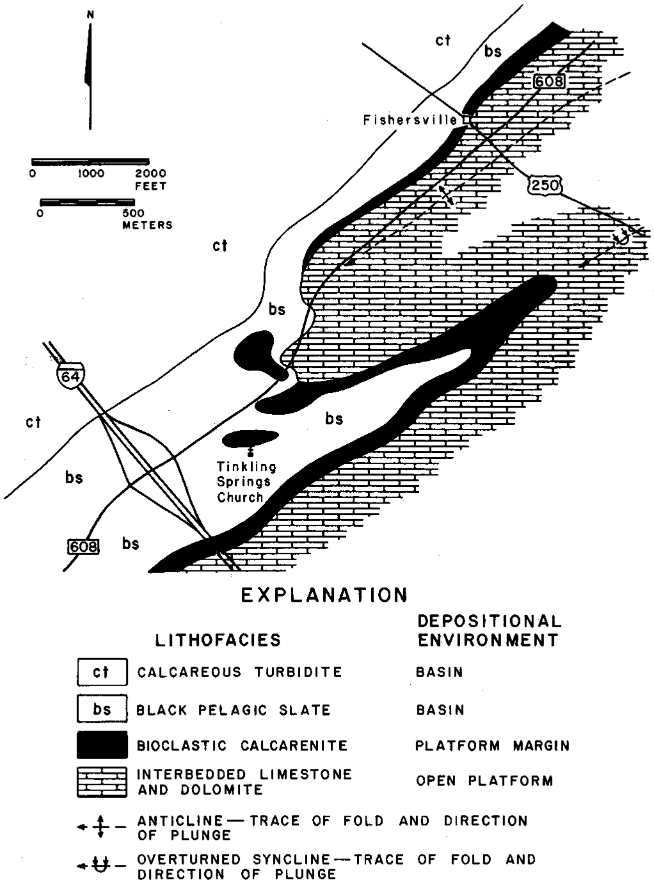

Figure 17. Sketch map of a portion of the Waynesboro West 7.5-minute quadrangle (geology by Paul G. Nystrom, Jr. in Gathright, Henika, and Sullivan, 1977) showing contact relationships between basinal and open-platform lithofacies on the southeastern limb of the Massanutten synclinorium.

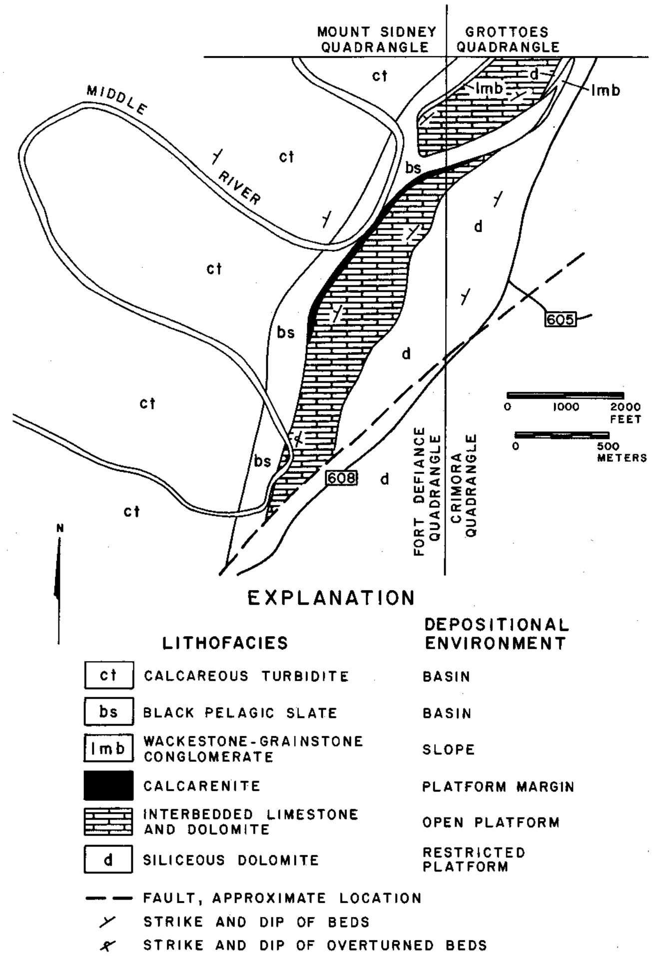

Figure 18. Sketch map of a portion of the Fort Defiance and Crimora 7.5-minute quadrangles showing contact relationships between basinal and open-platform lithofacies along the southeastern limb of the Massanutten synclinorium.

SAND AND GRAVEL RESOURCES IN VIRGINIA[1]

By
Palmer C. Sweet

CONTENTS

ILLUSTRATIONS

TABLE

[1]Portions of this contribution may be quoted if credit is given to the Virginia Division of Mineral Resources. It is recommended that reference be made in the following form:

Sweet, P. C., 1978, Sand and gravel resources in Virginia, *in* Contributions to Virginia geology—III: Virginia Division of Mineral Resources Publication 7, p. 67-74.

ABSTRACT

In Virginia more than one-third billion short tons of sand and gravel have been produced during the 20th century. Sand has been produced for use as an abrasive, building, paving, engine (traction), fill, filter, fire (furnance), foundry (molding) and glass sand and for ice control, golf courses, railroad ballast, pottery, and other industrial sands. Gravel resources have been produced for use in building, fill, paving, railroad ballast, and miscellaneous products.

Fluvial, marine, and residual sand and gravel deposits in Virginia are discussed in this article. There are 134 active or intermittently active commercial sand and gravel producers in Virginia; 101 of these are located in the Coastal Plain province of eastern Virginia.

Figures on the average cost of some sand and gravel products over the last 40 years as well as some requirements for concrete aggregate are provided. A graph depicts the quantity and value of sand and gravel resources produced by year. Some mention of specifications, governmental regulations and restrictions, and reclamation requirements that sand and gravel producers encounter is also made.

INTRODUCTION

Sand is a loose, noncohesive granular material whose grains are generally in only tangential contact and thus the sand has high porosity. Lenhart (1960, p. 734) states that sand of good commercial quality has 28 to 35 percent void space between grains and weighs 105 to 120 pounds per cubic foot. By definition sand consists of detrital material with fragments ranging from particles retained on a 230-mesh U. S. sieve (0.0625 mm) to those passing through a 10-mesh U. S. sieve (2.0 mm). In Virginia it consists mainly of quartz, but may also contain feldspar, mica, clay, chert, and heavy minerals such as magnetite, olivine, and garnet. For the purpose of this paper most sand and gravel resources includes those of sand- and gravel-size material formed by geologic processes; sandstone and quartzite that are utilized for silica products and whose tonnages are included under sand and gravel production figures are considered in the end use for these resources in Virginia.

Resources of sand in Virginia are or have been produced for use as abrasive, building, paving, engine (traction), fill, filter, fire (furnace), foundry (molding), and glass sand. Other uses include sand for ice control, golf courses, railroad ballast, pottery, and other industrial sands.

SAND USES

ABRASIVE SAND

Abrasive sand is used to clean metal castings; remove paint and rust; clean oil and gas storage tanks and pipelines; sandblast stone, brick walls, or concrete products, and to etch glass and plastics. Requirements are not strict except for clean, hard grains of a particular size; grades usually range from 40- to 10-mesh U. S. Sieve (0.4 to 2.0 mm) size. Angular grains may be preferred because they cut faster but rounded grains are preferred by some because they produce a smoother finish and last longer. The cutting power of sand is the most important quality and is determined by the shape and size of the grain and toughness (ability to resist crushing and shattering) of the sand. Sand may be used repeatedly until the grains become worn or too fine.

BUILDING AND PAVING SAND

For concrete and masonry, as well as paving sand, the material should be free of dirt, mica, and organic matter. Disseminated clay may be harmful if it is difficult to remove; only a small amount of silt is usually allowed. Size of sand grains should be variable with no abundance of any particular size; this is important for paving as well as building sand. Overall grain size in masonry sand is usually smaller than that of concrete sand. Subrounded to rounded grains without any clay, calcium carbonate, or iron oxide coatings are the most desired. Flat or elongated grains may cause the accumulation of excess water and a weak aggregate-cement bond; coatings on the sand grains may also cause a weak bond and the material may be chemically unstable as well.

ENGINE (TRACTION) SAND

This material is generally used by the railroads and mines for greater traction on wet, slippery rails. Requirements include a clean sand with a minimum silica content of 90 percent and material free of clay, loam, mica, and other rocks, minerals, and debris in order to allow rapid and steady flowage. Uniform grain size (generally between 80 and 20 mesh, 0.18 to 0.84 mm) is important; almost any shape of grain, subangular to rounded, with satisfactory noncaking properties may be used.

FILL SAND

A fill-sand material should have a percentage of clay and silt that will allow the material to hold together and pack well; silica content is not critical.

Deposits of loam gravel with clay-loam matrix, found extensively in eastern Virginia are some of the best material for this product.

FILTER SAND

Filter sand, which is used to remove undissolved solids and bacteria from water supplies, must be free of clay, lime, and organic matter. Grain-size uniformity and chemical inertness is important; the sand should be a well-sorted, hard, durable material that is high in quartz content (at least 98 percent) and free of any grain coatings. Grain-shape requirements are not critical although the number of flat or elongated grains should be less than 1.0 percent.

FIRE (FURNACE) SAND

This sand is used to line the floors of open hearth furnaces and also to form the bottom of copper-refining and reverberatory copper-smelting furnaces (McLaws, 1971, p. 26). High silica content (95 percent or more), a small amount of bonding material, and refractory properties are necessary. Grain size of the sand should grade from coarse to fine instead of uniform-sized grains.

FOUNDRY (MOLDING) SAND

Foundry sand is used in iron and steel foundries to make molds and cores for metal castings. Material must have refractoriness to withstand the heat of the molten metal; enough cohesiveness to hold together when moist (5 to 10 percent fireclay or bentonite make a good bond); strength, which depends on bond and moisture content; the ability to resist the pressure of the metal, permeability to allow gases and water vapor to escape from the metal mold, and satisfactory composition, so the mold will produce a smooth surface on the casting.

GLASS SAND

Basic criteria for glass sand are chemical composition and grain size. The type of glass to be made will generally determine the specifications needed; a higher silica (SiO_2) content is required for better grades of glass. Generally material should pass through a 20-mesh U. S. sieve (0.84 mm) and a total of 95 percent or more of the material should be retained on a 100-mesh U. S. sieve (0.15 mm); excessive fines tend to carry impurities and may cause foaming. Grain shape is not a prime consideration. Sand should also be free of inclusions, coatings, stains, and heavy minerals.

A small amount of iron oxide may cause tinted or opaque glass. Larger amounts of total iron (Fe_2O_3), up to 0.20 percent, can be used as the need for crystal quality lessens, such as in amber and green bottles. Sands for making optical glass should generally have less than 0.008 percent iron oxide. Alumina (Al_2O_3) in the form of feldspar is most easily dissolved; it should be uniform and not exceed 0.1 percent in the best grades of glass. Small quantities of magnesium oxide (MgO), (less than 1.0 percent) are not usually detrimental. Titanium oxide (TiO_2) content should be less than 0.03 percent; 0.0002 percent cobalt will produce a distinct tint in the glass. Other undesirable minerals in the silica melt include magnetite, ilmenite, zircon, hornblende, garnet, tourmaline, and rutile because of iron content. Mica will cause spots and holes in the glass. Mineral coatings and stain (oxides of chromium, manganese, nickel, copper) also should be avoided. Trace amounts of some of these elements (nickel, chromium, copper, and cobalt), while deleterious because of high colorant properties, are often added to the glass batch under highly controlled conditions (Murphy, 1975, p. 1045). Lime (CaO) may be added as needed to provide durability of glasses against attack by water and to depress the melting temperature.

MISCELLANEOUS SAND USES

Other sand products that are or have been produced in Virginia include those used for ice control by the Department of Highways and Transportation, railroad ballast, and pottery sand. Another important product of sand not produced in Virginia, is fracturing (frac) sand, which is used in wells, and must have a high-silica content with only minor carbonates or other oxides. Fracture sand is pumped with water under high pressure into the rock strata; the pressure will open the bedding planes, causing partings in the rock which are kept open by the sand grains when the pressure is removed. Round grains are usually required with a size grading of 90 percent of the material between a 20 and 40-mesh U. S. sieve (0.84 to 0.42 mm). A better permeability into a rock unit is given by a uniformly graded sand.

Sands may also be exploited for rare minerals and elements that they contain, such as gold, gems, platinum, uranium, tin (cassiterite), tungsten (wolframite), zircon (zirconium), and rutile (titanium). Sandstones are an important reservoir for fluids such as fresh water, brine, petroleum, and natural gas and also act as conduits for artesian water; they are also used for storage of natural gas and fresh water.

GRAVEL USES

Gravel consists of rounded fragments larger than 2 mm, classified as follows: granules (2-4 mm), pebbles (4-64 mm), cobbles (64-256 mm) and boulders (>256 mm). Gravel in Virginia has been produced for use in building, as fill, paving, railroad ballast (cobble size-material), and miscellaneous products. Gravels may contain many types of rock fragments ranging from soft to hard and resistant. Hard rock material is best for resistance to abrasion, freezing and thawing, and wetting and drying; most suitable material includes fresh granitic rocks, quartz, and hard limestone and dolomite. Porous and fractured rock material is not sound enough. Chert pebbles are not suitable for use in concrete as the pebbles react with the alkalis in cement and have poor resistance to freezing and thawing. Good sources of gravels usually occur with sand; quartz gravels are regarded as some of the better material. For example conglomeratic material of Pliocene age (Brandywine) is a good source of gravel in Virginia.

Clean silica gravels or crushed quartzite are used as a component in the preparation of silicon alloys and as a flux in the preparation of elemental phosphorous. Rigorous specifications include alumina of less than 0.4 percent, total iron to no more than 0.2 percent, and combined base oxides not more than 0.3 percent. Ignition loss should be kept below 0.3 percent. Size limits are usually 0.5 inch (1.3 cm) to as much as 8-inches (20 cm) in size. A strong material free from fractures and one that will not break down into fines is required. Crushed quartzite (Erwin Formation) from Rockbridge County was formerly produced for this use.

A possible use for some high quality silica gravel in Virginia may be refractory pebble material to be used as a raw material for super duty acid refractories. General requirements include clean silica in gravel sizes, with a maximum of 0.4 percent alumina, total iron between 0.2 to 0.4 percent, and less than 1.0 percent lime. Alkalies should not exceed 0.5 percent and there must be a minimum of titanium. Opaline silica would not be suitable, as it may spoil or disintegrate in the kiln; ignition loss should be kept below 0.5 percent.

SAND AND GRAVEL DEPOSITS

FLUVIAL

Resources consist of numerous sand and gravel deposits that range greatly in size and confined to stream and river channels and flood plains along major drainage systems. Most of these deposits are generally poorly sorted and consist of heterogenous material. Sands from granitic rock sources may have a higher porosity than those rich in argillaceous rock fragments, which tend to be flat and flow into pores forming a barrier to fluid movement and reducing storage capability.

Stream-channel sand and gravel deposits are usually easily accessible and easy to mine. The nature of the deposited material is determined by the source. Abrasive action of moving water and rolling of the material removes the soft rock; material is usually subrounded to rounded and the deposit is continually being replenished. Flood plain sand and gravel deposits consist of material deposited on plains that border the streams; they are formed by the occasional overflow of the streams. These deposits may be overlain by finer material (silty sand) because of intermittent flooding. Terrace deposits of sand and gravel consist of benches of material that border, but are above the level of the present flood plain through which the stream cuts. Material in flood plain deposits is also developed by erosion and redeposition of material from former terraces or already emplaced higher elevation sediments.

Most concrete sand is recovered from river sediments in Virginia. Grains are usually angular to sub-angular, not too fine and free of salt coatings that are commonly present on marine sediments. Sand and gravel for general purpose construction materials, including building and masonry sand are present in deposits along most of the rivers, east of the contact with the Piedmont province around Richmond, in the Coastal Plain province along the banks of the Potomac, Rappahannock, York, Mattaponi, Pamunkey, James, Chickahominy, Blackwater, Nottoway and Meherrin rivers.

Fluvial-estuarine deposits may be formed during regression of the sea. After a new surface was exposed to erosion, streams extended across the new surface and graded into estuaries near the sea; point bars, levees, and flood-plain deposits related to the streams were formed. In these deposits, material is usually poorly sorted and porosity and permeability are lower. In some cases property with this type of deposit would not be suitable as real estate because of nonsuitability for drain fields in successful septic tank operation.

MARINE

Marine deposits of material, whose immediate source is from the sea, includes those that were formed during the transgression of sediments onto the land. Clean, well-sorted, rounded sand grains with clay and silt are characteristic of the landward limit of the marine sediments in Virginia. The material is very valuable as fill material, but because of the roundness of the grains, clay content and salt coatings on the grains there is no use for the material in buildings and construction. Onuschak (1973, p. 134) states that sizable quantities of this material are present north of Newport News, around the area of Grafton, York County. Marine sediments are also present but unavailable for mining in the urban area of southeast Newport News and around Cape Henry. So-called marine-estuarine deposits include those along the Atlantic Ocean, Chesapeake Bay, and other estuaries, bays, tidal flats, and lagoons and their associated sediments (Onuschak, 1973, p. 121). A large part of these deposits would probably have to be dredged, although power shovels and draglines may also be used.

RESIDUAL

Residual deposits of sand and gravel consist of colluvial (debris from sheet erosion deposited by unconcentrated surface runoff or slope wash, together with talus and mass-movement accumulations) and partly consolidated to unconsolidated deposits of material from the weathering of sandstone and quartzite beds. Such material is presently being mined in southeastern Augusta County where a large quantity of sand was derived from the weathering of the Erwin Formation to the east and south at higher elevations. Sand is removed with a front-end loader and a dragline; material is washed and marketed for use as masonry sand. Highly weathered rock are also present in western Rockbridge County, central Bath County, and south-central Smyth and Wythe counties. Some of these units have been and/or are presently being worked, mainly for construction sand material.

SAND AND GRAVEL INDUSTRY IN VIRGINIA

Sand and gravel production in Virginia is primarily by open-pit mining and dredging, and by crushing sandstone and quartzite; some is recovered as a by-product from a kyanite mine.

The first year in which United States sand and gravel statistics were kept was 1902. The first reported figures available for production in Virginia was 1904, when 339, 534 short tons were produced. Through 1977 more than one-third billion short tons have been produced during the 1900's. The largest output to date was 17,191,000 short tons in 1966 (Figure 1). This large production was due to in-

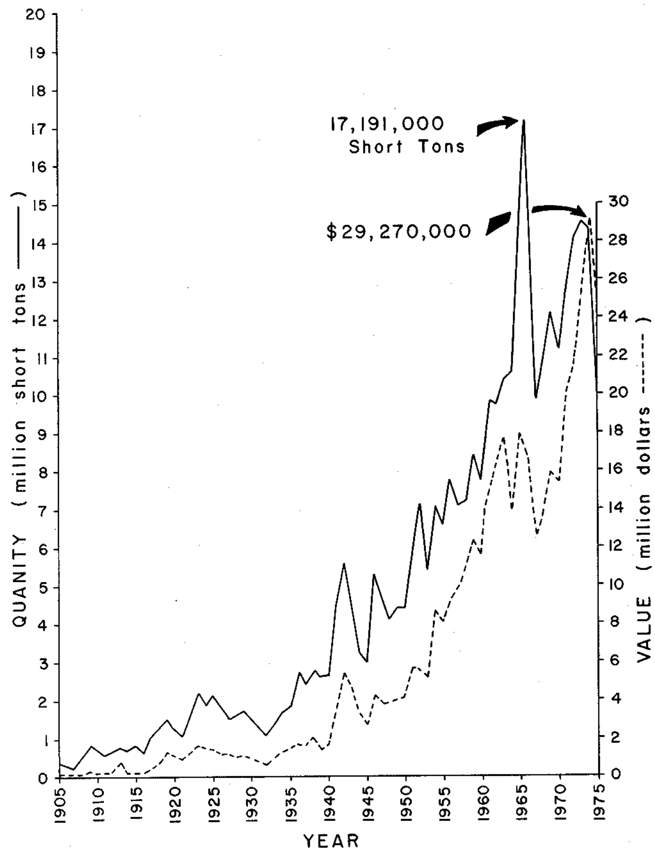

Figure 1. Sand and gravel production in Virginia.

creased demand for building and road construction material; the following year, production decreased by 43 percent. In 1974 when production of sand and gravel in Virginia was 14,313,949 short tons, eight commercial sand and gravel operations each had an output of at least 500,000 short tons. In order of total output and according to the U. S. Bureau of Mines figures, the five leading producing areas in Virginia during 1974 were Chesterfield, Henrico, Virginia Beach (City of), King George, and Prince George counties. In 1975 when production dropped to 9,894,772 short tons only four companies produced at least 500,000 tons of sand and gravel. As of March 15, 1977 there were 134 active or intermittently active commercial sand and gravel operations; 101 are located in the Coastal Plain province (Figure 2). Some brief information on the general characteristics and kinds of sand and gravel operations present in each province follows.

COASTAL PLAIN PROVINCE

The Coastal Plain province has sand and gravel operations in 25 counties and 5 cities. Most building (masonry and concrete) sand and gravel and at present all engine, foundry, and filter sand is produced from this province. Most of this material is produced from Pleistocene sand and gravel deposits that occur as beaches and dunes along the coast. Large amounts of fill material as well as sub-base gravel have been and are being produced.

Much of the marine material in the eastern part of the Coastal Plain and away from the river estuaries is used only for fill or sub-base material due to the high degree of rounding of the constituents and salt coatings. A poorly sorted loam gravel material in this province contains clay- to boulder-size fragments of material with a sticky, ferruginous clay-loam matrix. With enough pebble- to cobble-size gravels, the material can be used as a sub-base for roads. The Eastern Shore of Virginia (Accomack and Northampton counties) is an area of marine terraces and the basic sand and gravel is a sandy gravel with a slightly sticky ferruginous matrix. This material is very suitable as fill. Sand and gravel were produced in the Eastern Shore of Virginia in 1974 for a value of $152,000.

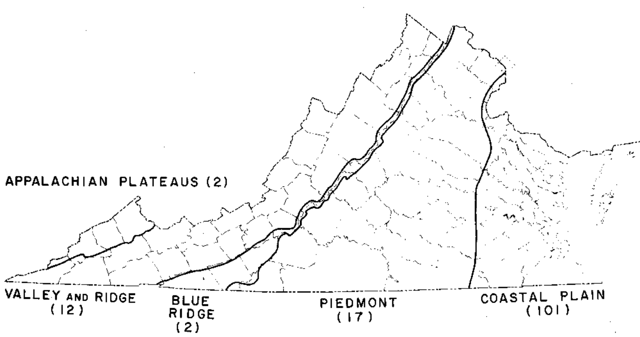

Figure 2. Location of the five physiographic provinces in Virginia and number of active sand and gravel operations as of March 15, 1977 in each province (base map from Dietrich, 1970, p. 103).

There may possibly be economic deposits of high quartz gravel of metallurgical grade in the north-central and western edge of the Coastal Plain province. These clean quartz pebbles are highly prized for use as exposed aggregate, especially on precast wall panels.

PIEDMONT PROVINCE

Sand and gravel is produced from 10 counties in the Piedmont province, the majority of which is from fluvial sediments in flood plains along rivers and streams. Most of the material can be used for paving sand as well as concrete sand; it is also very good for ice-control sand. Some may be used for masonry sand. Angular sand (ground quartzite) is produced as a by-product from a kyanite-mining operation; most of this is used for golf-course sand. In the past, residual deposits of sand-quartzite were worked commercially in the Piedmont province.

Sand and gravel deposits in the province are numerous, vary in size, and are confined to flood plains and stream channels along major drainage systems. In areal distribution, deposits are erratic; sands are generally poorly sorted, consisting of heterogenous fragments of rocks.

BLUE RIDGE PROVINCE

In the Blue Ridge province, sand resources are presently produced in Grayson County. Material is dredged from the New River and sold for use as construction (masonry and concrete) sand, paving sand, local sand, and ice-control sand. No gravel is presently being produced in this province although there has been production in the past.

VALLEY AND RIDGE PROVINCE

In the Valley and Ridge province sand and gravel is produced from 10 counties. Gravel occurrences are large whereas good deposits of alluvial sand are restricted. Most available sand is limited to stream channels; in places the gravel consists of chert from the limestone and is not suitable for building and construction purposes because the chert pebbles may react with the alkalis in cement and cause poor resistance to freezing and thawing. Concrete and masonry sand and gravel, paving sand and gravel, and glass sand are produced in this province. Production is from fluvial and residual deposits. Carter (1968, p. 352) states that in western Virginia (Valley and Ridge and Blue Ridge provinces) the Clinch, Erwin (Antietam), Keefer, Ridgeley, and Tuscarora formations are potential sources of high-grade silica. The Erwin (Antietam) Formation has been worked for many years along the eastern edge of the Valley and Ridge province. Sandstone and quartzite beds in many of the ridges throughout this province have been worked in the past; furnace (fire) sand was produced until about 2 years ago. Resources have been produced from geologic units of Cambrian, Silurian, and Devonian age. The Clinch (Tuscarora) Formation of Silurian age has been quarried near Kermit and Silica in Scott County and at Price Gap in Washington County on Clinch Mountain, which is a narrow ridge in southern Tazewell County extending southwestward through Russell, Scott, Smyth, and Washington counties in Virginia. The sandstone was used in the manufacture of glass; the material, where harder, was utilized for ferrosilicon. This formation as well as the younger Clinton Formation of Silurian age may have good clean, well-sorted, friable sandstone near their base.

Metallurgical-grade quartzite was produced from the Valley and Ridge province in the past. Present production in Wythe County is only for construction sand, but is probably suitable for glass sand and furnace material. Localities of many sandstone and quartzite exposures have been examined to determine if they may have any potential for high-silica sand or a metallurgical material. Harris (1972) examined and evaluated sandstone and quartzite exposures in parts of the northern Valley and Ridge and Blue Ridge provinces in Virginia. Data and various analyses on many such localities are available in several publications and work is continuing on the evaluation of high-silica materials.

Appalachian Plateaus Province

Sand is produced from Buchanan and Wise counties in the Appalachian Plateaus province; building (masonry and concrete) sand, traction sand for use in the coal mines, local general purpose sand, and sand for ice-control are produced. In Buchanan County production is from a river deposit with a dredge, and in Wise county it is with a power shovel from a residual deposit. Little or no gravel is present in the area, and concrete aggregate and road material, are supplied by limestone quarries as crushed stone. Sand and gravel deposits are found in only small flood plains and in river channels along drainage, as most of the area is mountainous with numerous narrow valleys. Flood stage waters are common in such topography and the river channels may be cleaned of valuable sand and gravel resources after such an act of nature; a flood may also add sand and gravel resources to the river channel.

POTENTIAL AND EVALUATION OF THE SAND AND GRAVEL RESOURCES

Increases in energy, production, and labor costs, as well as governmental regulations, over the last few years have correspondingly increased the cost of sand and gravel. In November 1977 building sand in central Virginia cost about $10.00 per ton plus haulage cost. Most of this sand is transported about 100 miles (160 km) from the area east of Richmond. Comparative average costs of sand and gravel have increased over the past two decades (Table 1).

The sand and gravel industry is continually facing financial problems. The material has a low unit value and a high transportation cost today. Other problems, which are common with the mineral industry, include changes in specifications and market area, new zoning legislation, and only seasonal production in many cases. Alternate building supplies such as crushed stone, furnace slag, and fly ash may take the place of sand and gravel in some cases. Maintaining adequate supplies of water with the disposal of waste and waste-water is also a continuing problem. Some large companies may, in an effort to reduce transportation cost for a short-time market, set up portable plants closer to the market areas. Today, it is obvious that planning officials must understand the importance of our sand and gravel resources; satisfactory means must be determined so that we can make the best use for the available tracts of land where the resources are.

Table 1.—Average cost of sand and gravel in Virginia (cost per short ton in dollars, data from the average of figures supplied by the U. S. Bureau of Mines).

Product	1935	1955	1975
Glass sand	$0.65	$2.15	$6.15
Engine sand	0.40	1.10	5.00
Foundry (molding) sand	0.75	3.00	7.00
Furnace (fire) sand	—	—	2.50
Filter sand	—	1.50	5.75
Building (concrete and mortar sand)	0.50	1.00	3.00
Paving sand	0.50	0.50	2.00
Concrete and paving gravel	0.90	0.95	2.00

Sand and gravel, a low cost and high volume commodity, cannot be transported for economically; cost of material will also vary greatly from area to area depending on the speciality and quality of the material. Thus, major guidelines for a potential producer of sand and gravel, in addition to a large deposit, include proximity to market, socioeconomic restrictions including zoning, ease of obtaining a mining permit, and public acceptance. Examination of sand and gravel resources includes:

1) Visual inspection and examination of exposure and/or samples from borings.
2) Laboratory tests and sieving the sand to help determine the size of the grains, the degree of sorting and aggregates of grains that have not been freed. Hardness and reactivity of material can also be determined in the laboratory.
3) Petrographic examination to determine rock type, physical condition, particle shape, coatings, and undesirable constituents.

The results of various tests on aggregates with good service records in concrete has resulted in some minimum requirements that aggregates are expected to meet. Goldman and Reining (1975, p. 1033-1034) state that new material will be satisfactory for most uses if it meets the following minimum standards, which are a general average of requirements recommended by the American Society for Testing and Materials, California Division of Highways, U.S. Army Corps of Engineers, and the U. S. Bureau of Reclamation.

Abrasion—The abrasion loss should be less than 30 percent.
Soundness—The in loss the sodium sulfate test should be less than 10 percent.
Specific gravity—The specific gravity should be greater than 2.55.
Size and grading—(a) The deposit has proper grading so that the fine aggregate should contain no more than 45 percent of the material between two consecutive sieve sizes; (b) the fineness modulus should be between 2.3-3.1; (c) no more than 5 percent of the material should pass the no. 200 sieve.
Reactivity—A mortar bar containing the aggregate should have an expansion less than 0.10 percent in a year with 0.8 percent alkali-cement content.
Absorption—The absorption should not exceed 3 percent.
Durability—The concrete containing the aggregate should not have a loss in the modulus of elasticity exceeding 50 percent in the freeze-thaw test.
Sand Equivalent—The fine aggregate should have a sand equivalent of not less than 75.

The complexity of specifications to be met when marketing products is a major consideration in the evaluation of a deposit. Specifications may be such that it would not be economically feasible to mine a particular deposit; at another time, however, conditions such as availability, demand, and development may be right for starting operations. Final evaluation of suitable sand and gravel consists of determining competition, a suitable market, transportation and labor cost, plant equipment requirements and various environmental regulations on the local, State, and Federal governmental level. Sand and gravel producers in Virginia are required to obtain a mining permit from the Division of Mines and Quarries (Department of Labor and Industry); a bond is required by the Division of Mined Land Reclamation (Department of Conservation and Economic Development).

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STREAM-SEDIMENT GEOCHEMISTRY OF THE IRISH CREEK TIN DISTRICT, ROCKBRIDGE COUNTY, VIRGINIA[1]

By
Oliver M. Fordham, Jr.

CONTENTS

ILLUSTRATIONS

TABLES

[1]Portions of this contribution may be quoted if credit is given to the Virginia Division of Mineral Resources. It is recommended that reference be made in the following form:

Fordham, O.M., Jr., 1978, Stream-sediment geochemistry of the Irish Creek tin district, Rockbridge County, Virginia, *in* Contributions to Virginia Geology—III: Virginia Division of Mineral Resources Publication 7, p. 75-85.

ABSTRACT

Results of a geochemical reconnaissance survey of the Irish Creek tin deposits in the Blue Ridge physiographic province of Virginia indicate that tin-bearing greisen can be detected and located on a reconnaissance basis using stream sediments. Sediments were analyzed for Be, Co, Cu, Fe, Mn, Ni, Pb, and Zn by atomic absorption, for Sn, Ti, and Zr by X-ray fluorescence, and for heavy-mineral percentage by heavy-liquid separation.

The concentration of Be, Ti, Fe, and heavy minerals in stream sediments is shown by factor analysis to be correlated with the concentration of tin and thus useful as pathfinders. Statistical evaluation of Co, Cu, Mn, Ni, Pb, and Zn in the iron-manganese oxide coatings on the sediments proved these elements to be independent of the tin content and unrelated to tin mineralization.

X-ray fluorescence analysis is a precise and rapid technique for the determination of tin; the 4 ppm detection limit is sufficient to detect all known tin-bearing areas in the Irish Creek district. The two size fractions of sediment analyzed, 60-80 mesh and 80-230 mesh, show only minor differences in their average elemental content, but they show major differences in the spacial distribution and association of those elements. Tin and beryllium in the 80-230 mesh stream sediment fraction were found to be the best variables tested for outlining greisen containing tin mineralization. An area unrelated to previous mining activity or known tin veins was located that has anomalous tin and beryllium concentrations.

INTRODUCTION

In 1973 a reconnaissance stream-sediment survey was done in the Irish Creek drainage basin of Rockbridge County, Virginia, as a pilot study for future geochemical mapping and exploration projects. Several size fractions of sediment and several analytical techniques were tried in order to optimize the information obtainable from the samples. Factor analysis was used to help interpret the geological and chemical processes that caused the variance in the analytical data.

David Hubbard and Wayne Marshall assisted in sample collection and Jacqueline Kennamer assisted in preparing and analyzing the samples.

DESCRIPTION OF THE AREA

The Irish Creek tin district is located in the northeastern portion of Rockbridge County, Virginia, near its boundary with Nelson and Amherst counties (Figure 1). The abandoned tin mines are 5.6 miles (9.0 km) southeast of Steeles Tavern and 15.9 miles (25.6 km) east-northeast of Lexington. Irish Creek drains an area of about 25 square miles (65 sq. km) on the western slope of the Blue Ridge and the study area is entirely within the Blue Ridge physiographic province. The topography

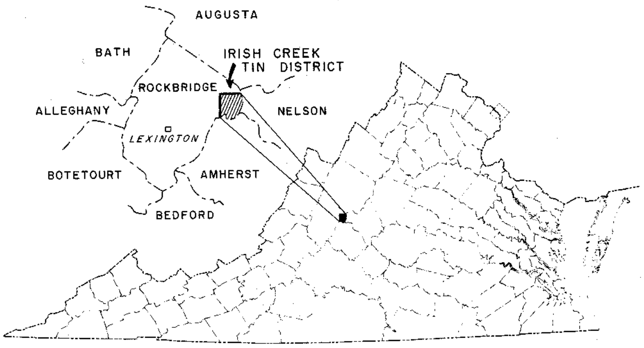

Figure 1. Index map showing location of the Irish Creek tin district (IC), Virginia.

of the heavily forested basin has considerable relief with many hills and ridges. Rock outcrops are scarce because of weathering and a deep soil cover; they are more readily exposed along streams. Major rock types are granodiorite, granite, and granitic gneiss of the Precambrian Pedlar Formation. Sedimentary rocks of the Cambrian Weverton and Harpers formations form ridges in the northwestern portion of this area (Ferguson, 1918; Werner, 1966). The gneiss and granite are intruded by the granodiorite, which in turn is cut by small aplite and mafic dikes (Koschmann and others, 1942) (Figure 2).

Cassiterite (tin oxide) was discovered along Irish Creek in 1846, but it was not until 1884 that active prospecting and development of the deposits began. Production was limited and it is estimated that less than 1,000 tons (907 metric tons) of ore came mainly from the workings along Panther Run, a small tributary near the headwaters of Irish Creek (Koschmann and others, 1942). The region has been actively worked for tin ore during the periods 1883-1885, 1889-1892, and 1918-1919. Koschmann and others (1942) state that "cassiterite has been found in an area of about 12 square miles along the headwaters of Irish Creek, at altitudes ranging from about 2,300 to 2,800 feet." They also note that cassiterite is the only tin-bearing mineral found in these deposits and as far as is known its occurrence is restricted to the granodiorite. Tin occurs in quartz veins bordered on both sides by greisen which is a hydrothermal alteration of the

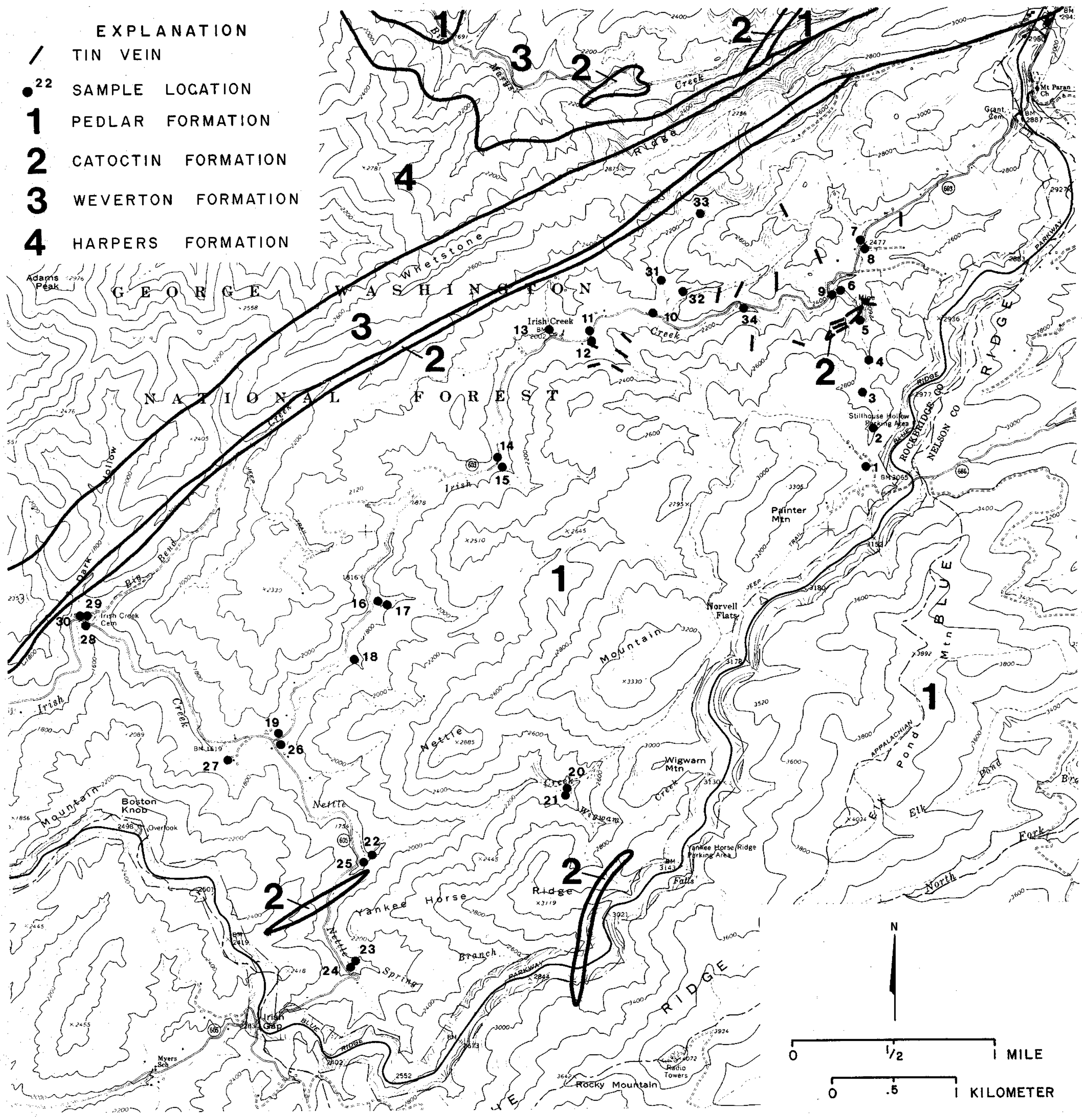

Figure 2. Generalized geology and sample locations on part of the topographic map of the Montebello 7.5-minute quadrangle.

surrounding granodiorite. The greisen grades into the granodiorite from which it was formed by replacement (Koschmann and others, 1942). Cassiterite occurs as coarsely crystalline masses in veinlets and scattered pockets adjacent to the quartz veins that cut the granodiorite and as small grains disseminated through the greisen. Lesure and others (1963) describe the veins as "irregular in trend and ranging in thickness from an inch to several feet. The greisen, which forms a narrow zone 1 inch to several feet thick between the quartz and unaltered granodiorite, consists of muscovite, quartz, and fluorite with smaller amounts of cassiterite, beryl, wolframite, and other minerals."

The unfractured quartz and the unaltered granodiorite are both barren. The greisen has been reported to contain from 0.11 to 3.78 percent tin in the Number 1 workings, the average being about 1 percent (Koschmann and others, 1942). There are 46 minerals that have been reported from these deposits (Glass and others, 1958).

SAMPLE COLLECTION AND PREPARATION

Thirty four stream sediment samples were collected from Irish Creek and its tributaries. All samples were taken from the center of actively flowing streams to assure uniformity in sampling and to assure that the sediments were in chemical equilibrium with the stream waters. Sediments from these streams are used because they act as integrators of the chemistry and mineralogy of the entire upstream catchment area.

Within the drainage basin, samples are taken on every tributary emptying into the main stream and at 1 mile (1.6 km) intervals on the main stream. The tributary samples were collected 100 feet (30 m) above their junction with the main stream or farther upstream if it appeared that flooding could cause contamination at that point. Mainstream samples were collected 100 feet (30 m) above tributaries at approximately 1 mile (1.6 km) intervals where practical. Follow-up sampling on a stream having anomalous tin content and on a stream draining the abandoned mine workings were taken at close intervals to help define the mineralized zones (Figure 2).

Approximately 9 pounds (4 kg) of -10 mesh sediment were collected at each sample site using a steel garden trough, a 10 mesh stainless steel sieve, and cloth bags. The material was scooped from the stream bottom and wet sieved in the field. Samples were returned to the laboratory and left several days to air dry. The sediments were oven dried at 110° C for approximately 24 hours to assure complete dryness. They were then sieved in stainless steel sieves to obtain 60-80 mesh and 80-230 mesh fractions for chemical analysis and heavy mineral studies. In all cases at least 15 grams of the 80-230 mesh fraction were obtained from the initial 9 pounds (4 kg) of coarse sand. The two fractions were washed with water and acetone, dried, and stored for analysis.

SAMPLE ANALYSIS

The analysis of total tin, titanium, and zirconium in the sediments was carried out by X-ray fluorescence (Appendices I, II). Analytical parameters and equipment for the determination of these elements are listed in Table 1. Samples were ground to -325 mesh and 1.000 gram of each sample was mixed with 1.000 gram of pure chromographic cellulose. Each was pressed under 25 tons (23 metric tons) pressure into a 1.25 inch (31.8 mm) diameter pellet for X-ray analysis. A Diano XRD 700 X-ray spectrometer was used for analysis. Because the magnitude of the matrix interference on these elements is small compared to variability inherent in geochemical sampling and because standards were made up in a matrix similar to the samples, no matrix corrections were needed for these elements. The 4 ppm detection limit (Table 2) of the X-ray procedure for tin served as a good indicator of tin mineralization. Background areas had no tin detectable above this limit whereas the known mineralized areas were all well above this level (Figure 3).

Atomic absorption was used for the analysis of Co, Cu, Fe, Mn, Ni, Pb, and Zn in the hydrated iron and manganese oxide coating on the mineral grains of the sediment (Appendices I, II). The extraction procedure consists of digesting 1.000 gram of sediment in 10 ml of 50 percent HCl in a covered teflon beaker. It is heated on a hot plate at 70° C for 1 hour with constant agitation, cooled, and diluted to 50 ml in a volumetric flask with distilled water. The detection limits for all elements analyzed are listed in Table 2. Analytical conditions are those recommended by Varian, whose AA-6 atomic absorption spectrophotometer was used in these analyses.

The mineralized component of geochemical samples can often be emphasized to the exclusion in part of the nonmineralized component by selective extraction of the type just outlined. In so doing, the magnitude and variability of the background values can be reduced and the contrast between threshold and anomaly can be increased considerably.

This attack effectively removes all iron and manganese oxide coating from the mineral grains, dissolves iron oxide and carbonate minerals completely, but has little effect on most silicate minerals. An additional benefit of this procedure is the optical examination of the "clean" residue for minerals that may be diagnostic of mineralization. The following minerals in decreasing order of abundance in stream sediments from the Irish Creek drainage basin were identified using X-ray diffraction and optical microscopy: quartz, microcline, ilmenite, hematite, andesine, muscovite, kaolinite, rutile, zircon, epidote, leucoxene, anatase, and cassiterite. All of these minerals have been reported by Glass and others (1958) from the granodiorite and greisen of the deposits, except for

Table 1.—X-ray fluorescence analysis.

Element	Analytical Line	Radiation	Crystal	Counter	Vacuum
Sn	LA1	Cr	LiF (200)	flow-proportional	yes
Ti	KA	Cr	LiF (200)	flow-proportional	yes
Zr	KA	W	LiF (200)	xenon-filled	no

Table 2.—Analytical detection limits.

Element	Method	Detection Limit (ppm)
Beryllium	AA-TA	2
Cobalt	AA-SE	5
Copper	AA-SE	1
Iron	AA-SE	1
Lead	AA-SE	4
Manganese	AA-SE	1
Nickel	AA-SE	5
Tin	XRF-TA	4
Titanium	XRF-TA	10
Zinc	AA-SE	2
Zirconium	XRF-TA	10

AA, atomic absorption; XRF, X-ray fluorescence;
SE, selective extraction; TA, total analysis.

anatase, which is reported for the first time in the present study.

Cassiterite is present in extremely small amounts in the sediments. Hand picking, heavy liquid separation, and chemical separation were necessary in order to concentrate the cassiterite for positive X-ray identification. Ferguson (1918) noted the same sparsity of cassiterite in the streams and suggested that the veins have undergone only slight erosion since Cambrian time causing very little cassiterite to enter the streams. This was inferred from the presence of small isolated areas of sediments near the workings.

From the mineralogy of the tin deposits excellent exploration guides should be provided by analyzing samples for F, Be, W, and Sn whose source is respectively in the following minerals: fluorite, beryl, wolframite, and cassiterite. Of these elements the Division of Mineral Resources only had adequately sensitive techniques for Sn and Be and they both served well in outlining mineralized zones.

A total attack procedure on the beryl-bearing sediments was used for the determination of beryllium. The procedure consists of digesting 0.5000 gram of sediment in 47 ml of $HF\text{-}HNO_3\text{-}HClO_4$ (30:15:2) acid mixture in a covered teflon beaker. It is then heated on an oscillating hot plate at 80° C for 4 hours with constant agitation. The covers are removed and the solution is evaporated to dryness. After cooling, 10 ml of 50 percent HCl is added to each sample, they are covered and heated at 70° C for one hour with constant agitation. Finally, the samples are cooled, diluted to 25 ml in volumetric flasks with distilled water, and analyzed by atomic absorption. Figure 4 shows the beryllium distribution in the 80-230 mesh sediment fraction for sample localities in the Irish Creek drainage basin.

RESULTS

Statistical analysis of the variables analyzed in the two sample fractions obtained by sieving is shown in Table 3. The means of the elements in the two fractions are only statistically different at the 5 percent significance level for beryllium and zirconium, which are higher in the fine fraction. The skewness and kurtosis of the variables show some to be a poor fit to a normal gaussian distribution, especially beryllium, lead, and tin. This is partially due to the mineralized character of these samples. The application of nonparametric statistics to this

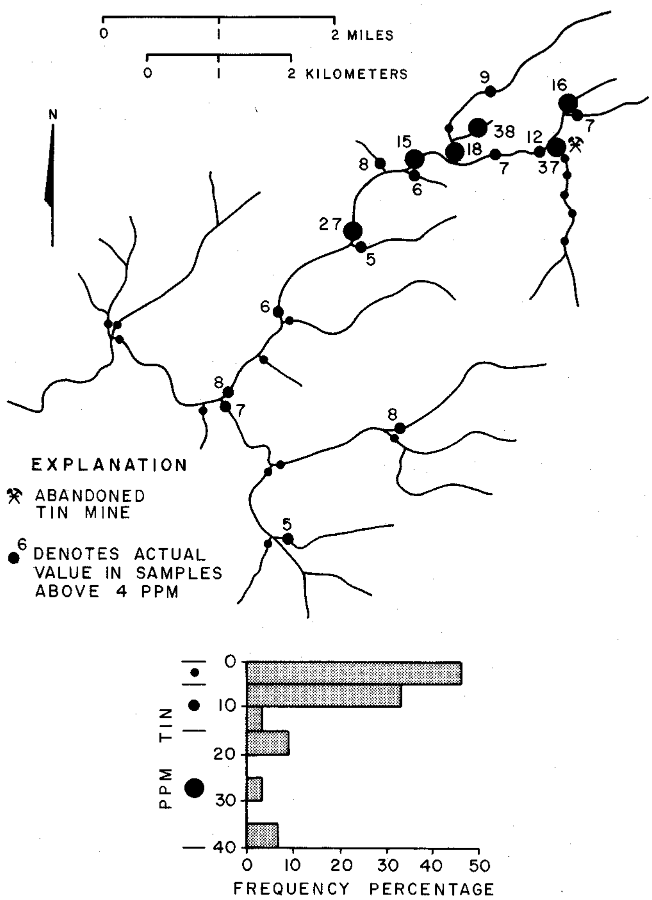

Figure 3. Distribution of tin in the 80-230 mesh stream sediment fraction.

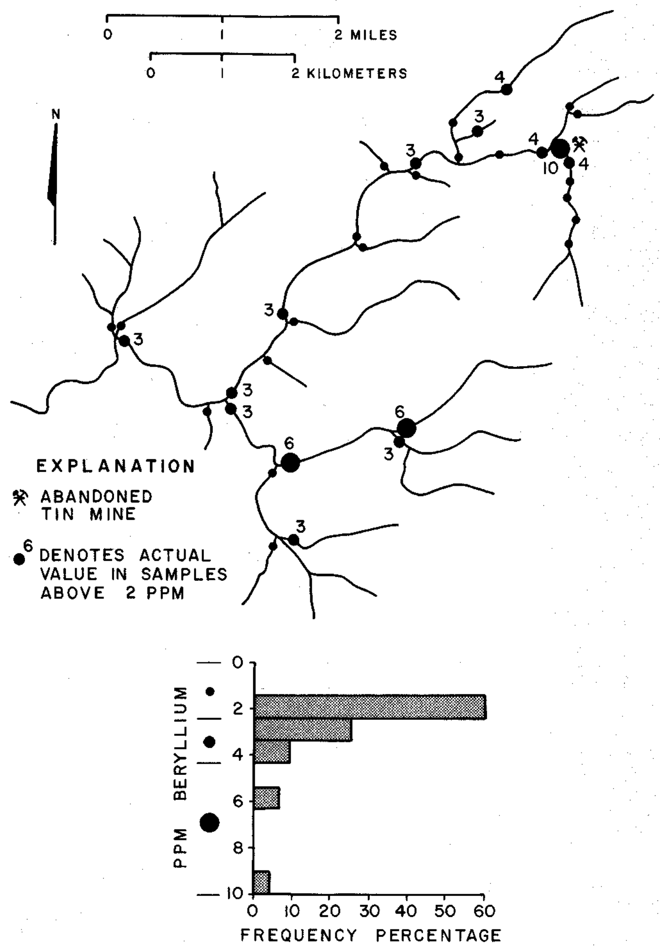

Figure 4. Distribution of beryllium in the 80-230 mesh stream-sediment fraction.

data might prove useful because of the non-normal distribution of some of its variables.

Of the 12 elements and variables analyzed, Sn, Be, Fe, Ti, and heavy mineral (HM) content are related to the tin mineralized greisens of the area as shown by correlation coefficients (Table 4) and factor analysis (Table 5). Even though the means of the variables in the two size fractions showed no significant differences except for beryllium and zirconium, there is an important difference in the spacial distribution and correlation of the variables in the fractions. Factor analysis (Table 5) graphically shows these associations. The first factor in both fractions, accounting for half of the total variance in the data, is identical. Iron oxide coatings on stream sediments coprecipitating or absorbing Ni, Co, and Cu, and Fe in hematite (heavy mineral) with the same associated trace elements are the dominant factor. The remaining factors differ significantly between the two size fractions of sediment. In the 60-80 mesh fraction, factor 2 is produced by the coprecipitation or absorption of Zn into the manganese oxide coatings on the sediment and by the heavy mineralogy of the Pedlar Formation with ilmenite, hematite, and zircon being the predominant heavy minerals; factor 3, the mineralized component, reflects the association of cassiterite with the other heavy mineral components ilmenite and hematite; and factor 4, beryllium and lead, has no clear cut interpretation but may reflect some minor association of galena and beryl in mineralized areas. In the 80-230 mesh fraction, factor 2 reflects the heavy mineralogy of the Pedlar Formation with ilmenite, hematite, and zircon being the predominant heavy minerals; factor 3 is caused by the coprecipitation or absorption of Pb and Zn into the manganese oxide coatings on the sediment, by the base metal association of Pb and Zn, and by some weak association of Zr and Be with the other elements; and factor 4, the mineralized component, shows the strong association of Sn and Be in samples from mineralized greisens. This fourth factor in the 80-230 mesh stream sediment fraction outlines tin mineralization in the Irish

Table 3.—Statistical analysis of stream-sediment samples from Irish Creek and its tributaries.

60-80 mesh fraction, N = 34

Variable	Mean (ppm)	Standard Deviation (ppm)	Skewness	Kurtosis
Heavy Minerals	23.92%	16.23%	0.96	−0.10
Beryllium	2.2	0.9	2.30	5.69
Cobalt	11.0	4.6	0.42	−0.95
Copper	6.2	2.2	0.42	0.16
Iron	4.76%	3.35%	1.49	2.13
Manganese	770.7	445.4	2.05	4.63
Nickel	7.1	4.0	0.63	0.46
Lead	20.6	6.2	2.65	9.97
Tin	6.9	8.3	3.05	11.78
Zinc	94.1	43.0	0.95	1.26
Titanium	4.03%	2.36%	1.10	1.04
Zirconium	299.3	197.5	1.69	2.68

80-230 mesh fraction, N = 34

Variable	Mean (ppm)	Standard Deviation (ppm)	Skewness	Kurtosis
Heavy Minerals	21.23%	12.11%	0.52	−0.78
Beryllium	2.9	1.6	2.97	10.40
Cobalt	11.6	4.1	−0.06	−1.10
Copper	6.9	2.7	0.94	2.36
Iron	4.38%	2.70%	1.52	2.26
Manganese	686.8	192.9	0.70	0.82
Nickel	8.5	3.2	0.76	1.20
Lead	22.6	6.7	1.48	4.38
Tin	8.0	9.4	2.19	4.51
Zinc	95.6	30.9	−0.32	0.65
Titanium	3.31%	1.82%	0.85	0.61
Zirconium	2181.0	1176.9	0.51	−0.43

Creek drainage basin better than any single element or other combination tested. The third factor in the 60-80 mesh fraction is also useful in outlining mineralization, but it is not as good as that above and requires more variables to be analyzed. Factor analysis did not show any other elemental associations in the data that would be an indication of other types of mineralization present in the area.

As a practical guide, tin above the 4 ppm detection limit is indicative of mineralized areas in the Pedlar granodiorite. This is shown by the fact that tin was undetected in 13 of the samples away from known tin veins. Additionally, 25 stream-sediment samples collected from the Saint Marys River manganese mine area, 7 miles (11 km) to the northeast of Irish Creek showed no detectable tin, despite the high concentrations of manganese and many trace elements in these samples due to the scavaging effect of manganese oxides and the heavy trace element content carried by manganese minerals. Tin and beryllium in the stream sediments of the Irish Creek drainage basin (Figures 3, 4) clearly outline the known cassiterite veins and workings (sample location numbers 5, 6, 9, 10, 11, 14, 32, 33) and show a promising new area near sample location numbers 20, 22, and 26.

X-ray fluorescence analysis of stream sediments for Sn is an accurate, economic, and rapid screening technique for outlining mineralized zones. Concentration techniques such as panning are unnecessary using this method. Total analysis of 80-230 mesh sediments for Be by atomic absorption

Table 4.—Correlation coefficients for variables of stream-sediment samples from Irish Creek and its tributaries.

60-80 mesh fraction significance level = 1 percent

	HM	Be	Co	Cu	Fe	Mn	Ni	Pb	Sn	Zn	Ti	Zr
HM			.72	.44	.81	.47	.64		.64		.95	.54
Be								.53				
Co	.72			.67	.84		.88		.44		.60	
Cu	.44		.67		.57		.67					
Fe	.81		.84	.57			.86		.63		.63	
Mn	.47									.81	.63	.72
Ni	.64		.88	.67	.86				.42		.48	
Pb		.53										
Sn	.64		.44		.63		.42				.56	.44
Zn						.81					.51	.71
Ti	.95		.60		.63	.63	.48		.56	.51		.64
Zr	.54					.72			.44	.71	.64	

80-230 mesh fraction significance level = 1 percent

	HM	Be	Co	Cu	Fe	Mn	Ni	Pb	Sn	Zn	Ti	Zr
HM			.65		.69		.48		.40		.90	.42
Be								.41	.44	.49		
Co	.65			.66	.76		.85				.48	
Cu			.66		.58		.77					
Fe	.69		.76	.58			.74					
Mn								.51		.58		
Ni	.48		.85	.77	.74							
Pb		.41				.51				.66		
Sn	.40	.44									.41	.45
Zn		.49				.58		.66				.61
Ti	.90		.48						.41			.54
Zr	.42								.45	.61	.54	

HM, heavy minerals.

while showing less contrast of anomaly to background than Sn still is very useful in locating greisen bodies and gives added strength to Sn anomalies when they occur in conjunction with them.

CONCLUSIONS

The full extent of the tin deposits and occurrences in the Irish Creek district remains undetermined. Quartz veins and especially greisen in the granodiorite are valuable guides to and indicators of tin ore. The greisen is easily distinguished from its associated granodiorite as a muscovite-fluorite rock.

Beryl in the tin deposits is sufficiently coarse grained to make it recoverable as a secondary by-product (Lesure and others, 1963). The above average beryllium content in the granodiorite rocks of the upper Irish Creek drainage basin, the beryllium enrichment of the greisen zones, and the numerous quartz-tin veins along the headwaters of the creek suggest that the area has promise for both tin and beryllium.

The tin district extends into Amherst and Nelson counties on the east side of the Blue Ridge, where cassiterite has been found from the James River to the northern boundary of Rockbridge County (Ferguson, 1918). Techniques outlined in this report should prove useful in the systematic exploration for tin and beryllium in the Pedlar Formation of central Virginia.

Table 5.—Factor analysis of variables of stream-sediment samples from Irish Creek and its tributaries.

60-80 mesh fraction

	Eigenvalue	Percentage of Variance	Variables (correlation with factor)
Factor 1	5.34	55	Ni (.92), Co(.84), Fe(.77), Cu(.76), HM(.49)
Factor 2	2.40	25	Mn(.90), Zn(.89), Zr(.72), Ti(.64), HM(.44)
Factor 3	1.19	12	Sn(.81), HM(.67), Ti(.58), Fe(.56)
Factor 4	0.78	8	Be(.80), Pb(.70)

80-230 mesh fraction

	Eigenvalue	Percentage of Variance	Variables (correlation with factor)
Factor 1	4.20	46	Ni(.96), Co(.85), Cu(.80), Fe(.78), HM(.50)
Factor 2	2.68	29	Ti(.90), HM(.85), Zr(.59)
Factor 3	1.43	16	Pb(.86), Zn(.83), Mn(.62), Zr(.42), Be(.40
Factor 4	0.83	9	Sn(.80), Be(.63)

HM, heavy minerals.

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APPENDIX I

ANALYSIS OF 80-230 MESH STREAM SEDIMENTS FROM IRISH CREEK AND ITS TRIBUTARIES.

Sample Number	Be (ppm)	Co (ppm)	Cu (ppm)	Fe (%)	Mn (ppm)	Ni (ppm)	Pb (ppm)	Sn (ppm)	Zn (ppm)	Ti (%)	Zr (ppm)	HM (%)
1	2.	7.	3.	1.87	722.	5.	19.	–	79.	2.07	3130.	9.74
2	2.	6.	3.	1.76	620.	–	21.	–	74.	1.48	2530.	7.89
3	2.	5.	4.	2.04	672.	6.	21.	–	102.	1.64	2330.	10.49
4	2.	6.	3.	1.84	677.	7.	24.	–	74.	1.29	974.	6.52
5	4.	7.	4.	2.21	763.	5.	25.	–	87.	1.62	1740.	11.33
6	10.	10.	7.	2.94	819.	7.	27.	37.	140.	2.16	2480.	12.48
7	2.	15.	7.	4.72	916.	9.	30.	16.	132.	8.67	4390.	48.53
8	2.	16.	9.	4.60	755.	11.	33.	7.	111.	3.01	1330.	16.00
9	4.	14.	9.	3.95	672.	10.	22.	12.	126.	2.47	1710.	14.76
10	2.	20.	9.	9.44	599.	15.	18.	18.	87.	3.76	2780.	32.08
11	3.	17.	7.	7.46	620.	12.	22.	15.	93.	5.66	3740.	40.62
12	2.	14.	9.	4.33	769.	10.	14.	6.	104.	5.51	3620.	35.30
13	2.	17.	16.	6.19	514.	18.	33.	8.	104.	1.53	534.	15.60
14	2.	17.	8.	8.04	769.	12.	23.	27.	100.	6.21	3220.	42.35
15	2.	14.	5.	4.36	1,020.	8.	27.	5.	102.	5.09	1970.	30.49
16	3.	14.	8.	5.84	774.	10.	20.	6.	105.	3.77	1531.	25.03
17	2.	9.	4.	2.39	651.	6.	21.	–	83.	2.36	1380.	11.97
18	2.	7.	7.	2.18	579.	8.	21.	–	59.	1.44	509.	6.43
19	3.	14.	7.	6.36	1,080.	9.	24.	8.	113.	4.01	2090.	27.18
20	6.	9.	10.	2.34	922.	6.	47.	8.	169.	2.46	4820.	16.27
21	3.	6.	3.	2.37	813.	6.	25.	–	96.	2.38	3610.	14.46
22	6.	7.	6.	2.28	672.	5.	29.	–	116.	2.67	3170.	10.12
23	3.	13.	6.	3.41	635.	10.	24.	5.	129.	3.65	2170.	21.22
24	2.	13.	7.	3.35	709.	9.	23.	–	111.	3.10	1940.	18.82
25	2.	11.	6.	2.90	418.	8.	18.	4.	80.	4.95	2260.	30.40
26	3.	9.	6.	2.94	514.	6.	19.	7.	91.	4.81	2030.	30.58
27	2.	5.	4.	1.80	470.	5.	14.	–	41.	1.13	476.	5.89
28	3.	14.	7.	5.87	1220.	11.	25.	–	129.	3.32	1980.	23.26
29	2.	11.	7.	5.51	385.	9.	18.	–	34.	1.28	677.	12.96
30	2.	16.	5.	2.68	404.	8.	11.	–	20.	.75	683.	4.36
31	2.	15.	10.	10.15	610.	13.	20.	–	67.	4.69	1230.	35.56
32	3.	11.	7.	4.03	538.	6.	15.	38.	116.	5.24	4350.	29.49
33	4.	16.	10.	13.05	668.	11.	19.	9.	64.	2.83	1130.	40.17
34	2.	11.	10.	3.74	383.	7.	17.	7.	112.	5.45	1640.	23.48

HM, heavy minerals; –, not detected

APPENDIX II

ANALYSIS OF 60-80 MESH STREAM SEDIMENTS FROM IRISH CREEK AND ITS TRIBUTARIES.

Sample Number	Be (ppm)	Co (ppm)	Cu (ppm)	Fe (%)	Mn (ppm)	Ni (ppm)	Pb (ppm)	Sn (ppm)	Zn (ppm)	Ti (%)	Zr (ppm)	HM (%)
1	2.	6.	3.	1.98	830.	5.	18.	—	82.	2.06	392.	9.62
2	2.	5.	3.	1.57	536.	—	18.	—	64.	1.94	225.	7.61
3	2.	6.	3.	1.68	554.	—	22.	—	71.	2.48	330.	8.74
4	2.	5.	3.	2.03	780.	5.	21.	—	84.	2.34	197.	9.87
5	3.	7.	4.	2.03	725.	—	23.	—	85.	1.80	186.	9.06
6	4.	7.	5.	2.66	835.	—	21.	19.	121.	2.87	322.	14.05
7	2.	17.	8.	7.25	2,400.	8.	19.	13.	216.	11.21	801.	61.08
8	2.	8.	6.	2.90	406.	6.	33.	9.	67.	3.61	204.	18.25
9	3.	13.	8.	3.33	559.	8.	18.	4.	105.	1.88	207.	10.97
10	2.	21.	8.	15.80	594.	17.	21.	44.	66.	7.39	502.	60.54
11	2.	15.	6.	8.38	698.	10.	16.	16.	85.	7.82	554.	53.14
12	2.	17.	7.	6.75	1,670.	11.	19.	6.	149.	7.33	904.	42.55
13	2.	19.	12.	9.70	499.	17.	30.	—	83.	2.74	151.	22.36
14	2.	18.	7.	10.30	1,500.	12.	20.	19.	131.	7.74	438.	49.07
15	2.	14.	6.	5.22	1,450.	9.	22.	—	121.	4.22	271.	23.00
16	2.	13.	9.	4.77	646.	8.	18.	—	83.	3.29	167.	21.34
17	2.	7.	5.	2.10	544.	5.	18.	—	69.	2.29	132.	11.15
18	2.	7.	6.	1.73	418.	6.	19.	—	50.	1.14	90.	4.76
19	2.	11.	6.	5.51	646.	9.	21.	13.	79.	5.24	246.	31.08
20	5.	8.	9.	2.62	1,050.	6.	47.	11.	192.	2.87	736.	14.34
21	2.	6.	3.	2.51	957.	—	24.	—	102.	2.88	327.	14.58
22	5.	7.	6.	2.31	698.	—	23.	7.	111.	3.11	379.	14.78
23	2.	11.	6.	3.20	625.	6.	21.	5.	126.	3.90	266.	22.04
24	—	13.	7.	3.82	887.	9.	20.	—	122.	4.00	308.	21.80
25	2.	15.	7.	5.22	1,450.	11.	22.	5.	171.	5.97	268.	33.63
26	2.	8.	4.	2.83	427.	7.	18.	9.	85.	6.38	238.	35.58
27	2.	5.	4.	1.83	509.	—	17.	—	42.	1.70	49.	6.70
28	2.	8.	6.	3.41	475.	7.	18.	—	80.	2.41	150.	14.53
29	2.	13.	5.	8.23	366.	10.	21.	—	29.	2.32	111.	20.46
30	2.	17.	6.	3.76	399.	8.	11.	—	20.	.88	149.	7.05
31	2.	13.	10.	10.04	552.	10.	18.	7.	57.	5.75	219.	48.98
32	2.	11.	6.	3.81	549.	—	14.	7.	105.	5.57	199.	32.08
33	—	14.	8.	9.50	614.	10.	16.	4.	50.	5.86	214.	39.02
34	2.	9.	9.	2.96	357.	5.	15.	6.	98.	3.96	245.	19.32

HM, heavy minerals; —, not detected.

RARE-EARTH AND THORIUM MINERALIZATION IN SOUTHEASTERN RAPPAHANNOCK COUNTY, VIRGINIA[1]

By
Christopher R. Halladay

CONTENTS

ILLUSTRATION

ABSTRACT

An aeroradiometric contour map of a portion of southeastern Rappahannock County, Virginia shows several thorium anomalies. The main anomaly, located near Woodville, is related to occurrences of rare-earth and thorium mineralization. Allanite, bastnaesite, chevkinite, thorite, rhabdophane, and florencite(?) are present in nodules and in pegmatite. Rare-earth-bearing fluorapatite occurs in magnetite-rich rock. The proximity of the rare-earth- and thorium-bearing rocks to outcrops of alkali granite suggests the mineralization is related to alkaline magmatism in the late Precambrian.

INTRODUCTION

Radioactive rare-earth and thorium minerals associated with nodules, pegmatite, and apatite-magnetite-quartz rock are present east of Woodville, Rappahannock County, Virginia, and are expressed as thorium anomalies that are shown on the Sperryville 15-minute aeroradiometric contour map (Virginia Division of Mineral Resources, 1975). Other anomalies are related to a mineralized zone extending northeastward from the anomaly near Woodville for a distance of about 9 miles (14 km) (Figure 1). X-ray fluorescence and diffraction analyses of about 50 samples collected in the vicinity of Woodville were made by G. B. Baetcke, C.R.B. Hobbs, Jr., R. S. Good, O. M. Fordham, Jr., and the writer. The assistance of Harold W. Glascock who located numerous sites where samples were collected is appreciated.

GEOLOGY

The mineralized zone that is delineated by thorium anomalies lies in the core of the northeastward-trending Blue Ridge anticlinorium. The zone occurs in Precambrian augen-bearing gneiss, which is composed of potassium feldspar porphyroblasts in a matrix of quartz, biotite, and feldspar. The thorium anomalies are adjacent to and just northwest of the contact between the augen-bearing gneiss and Precambrian metasedimentary rocks of the Mechum River Formation. Near Woodville thorium- and rare-earth-bearing minerals

[1]Portions of this contribution may be quoted if credit is given to the Virginia Division of Mineral Resources. It is recommended that reference be made in the following form:

Halladay, C.R., 1978, Rare-earth and thorium mineralization in southeastern Rappahannock County, Virginia, *in* Contributions to Virginia geology—III: Virginia Division of Mineral Resources Publication 7, p. 87-89.

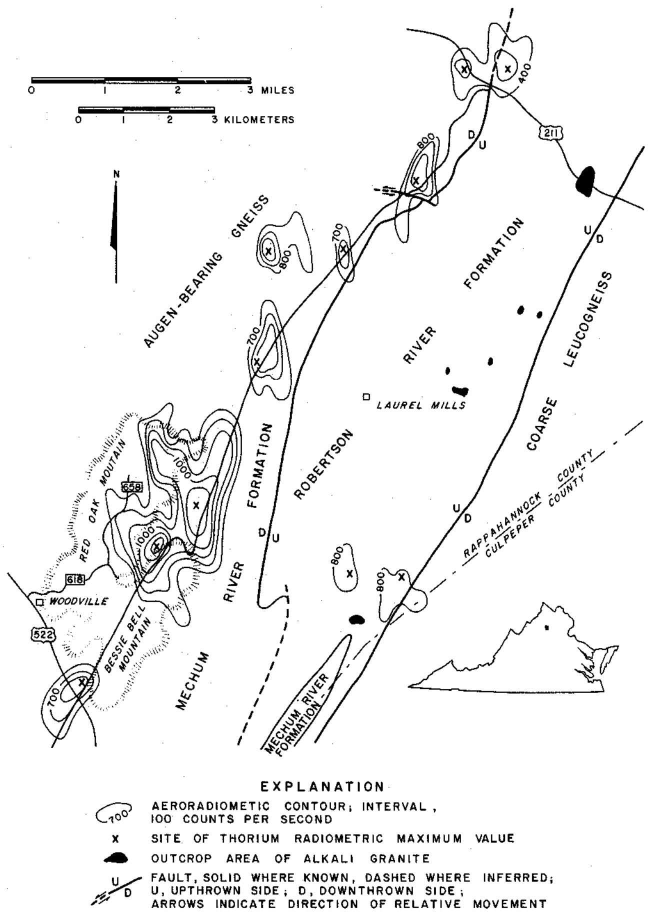

Figure 1. Sketch map showing location of thorium anomalies, Mechum River Formation, and alkali granite. Radiometric data from aeroradiometric contour map of the Sperryville 15-minute quadrangle (Virginia Division of Mineral Resources, 1975). Geology modified from mapping of the Massies Corner 7.5-minute quadrangle by M. T. Lukert and C. R. Halladay in 1977 for the Division of Mineral Resources.

are present in (1) nodules, (2) granite pegmatite, and (3) apatite-magnetite-quartz rock. All identified rare-earth minerals, including allanite, chevkinite, bastnaesite, rhabdophane, and rare-earth fluorapatite, are rich in the cerium-group earths.

Concentrations of uranium in the rocks are much lower than those of thorium or rare-earth elements. Aeroradiometric and chemical data show that there is only a very minor amount of uranium in the area. It is present possibly as a trace element in the rare-earth-bearing minerals.

NODULES

Most of the radioactive samples are massive nodules that were found in soil. The nodules are dense, irregularly shaped, and up to 5 inches (13 cm) in diameter. Colors range from black to greenish gray to light brown. Several samples consist of a black glassy core surrounded by brown or gray rims. Thin, earthy, orange or yellowish white weathering coatings are common.

The most abundant rare-earth mineral, allanite, occurs primarily in aggregates of small anhedral grains. It is commonly partially metamict, and heating samples to about 750° C is usually required to identify the mineral by X-ray diffraction. In thin section nonmetamict grains are strongly pleochroic from dark reddish brown to light brown.

Bastnaesite is common in the nodules and is often the only mineral that can be identified by X-ray diffraction without heating. In thin section black and brown fine-grained isotropic masses of metamict allanite and chevkinite contain small, disseminated, birefringent particles of bastnaesite. The bastnaesite appears to have replaced allanite and possibly chevkinite.

Metamict chevkinite was identified with X-ray diffraction only after the mineral was heated to 1000° C. At this temperature the bastnaesite and some of the allanite diffraction peaks were replaced by cerium oxide peaks.

Some of the nodules contain thorite occurring as discreet grains, about 0.1 mm in size, and as reddish-orange fracture-filling material. The identification of thorite was confirmed by X-ray diffraction of samples heated to 1000° C. A yellowish-white coating on one nodule from Red Oak Mountain is composed of halloysite, rhabdophane, and florencite (?). The orange crusts on other samples yield only bastnaesite X-ray patterns. Common accessory minerals in the nodules are quartz, sphene, and hematite.

A partial semiquantitative spectrographic analysis[2] of a moderately radioactive nodule containing quartz, allanite, chevkinite, bastnaesite, sphene, and thorite(?) is as follows (in percent): Ce, 25; Si, 20; La, 15; Ti, 8; Nd, 7; Fe, 6; Ca, 3.5; Al, 1.5; Nb, 1.25; Th, 0.7; Pr, 0.5; Sm, 0.45; Gd, 0.2; Pb, 0.2; Mn, 0.2; Y, 0.15; Dy, 0.1; and less than 0.1 of Mg, Zr, Sc, and Yb.

[2]American Spectrographic Laboratories, Inc.

PEGMATITE

Pegmatite float with rare-earth minerals is present near the southeastern part of Red Oak Mountain east of State Road 658. Blue quartz, microcline-perthite, albite, and biotite are major constituents with minor amounts of apatite, zircon, and sphene. Metamict allanite with secondary bastnaesite occurs as dark-brown to nearly opaque, fine-grained, massive fillings between quartz and feldspar grains. Thorite is present in some samples. The interstitial masses of rare-earth minerals and thorite in the pegmatite resemble in mineralogy and texture the nodules from the overlying soil. The nodules apparently have weathered out of the pegmatitic rocks.

APATITE-MAGNETITE-QUARTZ ROCK

Rare-earth-bearing apatite-magnetite-quartz rock appears to be restricted to the southwestern part of the mineralized area between U.S. Highway 522 and Bessie Bell Mountain. Qualitative analyses show major amounts of calcium, iron, and silicon, and minor amounts of titanium, magnesium, rare-earth elements, yttrium, phosphorous, and aluminum. Rare earth-bearing fluorapatite constitutes from 15 to 30 percent of the rock, occurring as cream-colored ovoid and elongate grains up to 7 mm long. In thin section the apatite grains contain abundant minute nonopaque inclusions of bastnaesite(?) and monazite(?). Analyses of apatite concentrates show cerium to be the most abundant rare-earth element; lanthanum, neodymium, yttrium, and strontium are present in minor amounts. Magnetite, ilmenite, and hematite compose about 50 percent of the rock. Magnetite fills interstices between apatite grains. Hematite is disseminated throughout the rock, giving it a purple color. In thin section ilmenite, partly altered to leucoxene, is associated with sphene and with dark-brown, pleochroic, granular aggregates of chevkinite. The rest of the rock is composed mainly of quartz, which occurs as anhedral strained grains up to 5 mm in diameter.

Parts of the rock are finer grained and have an apparent flow texture. In these parts magnetite occurs as discreet subhedral grains, less than 1 mm in size, associated with quartz, pale-green amphibole, and biotite.

OTHER RADIOMETRIC ANOMALIES

Augen-bearing gneiss is the only rock type exposed at most of the thorium anomalies northeast of the Woodville area. The gneiss samples from the anomalous areas contain an average of 38 ppm thorium. Gneiss samples from surrounding areas generally contain no thorium above the X-ray fluorescence detection limit of 7 ppm. The highest concentration of thorium, 74 ppm, was detected in a gneiss sample from an anomaly 4.5 miles (7.2 km) northeast of Red Oak Mountain. Vitreous, reddish-orange crystals, up to 0.1 mm in diameter, either of thorite or the hydrous thorium silicate, thorogummite, were identified. At one thorium anomaly near U.S. Highway 211 a pegmatitic rock was found which contains allanite, monazite, and bastnaesite. High concentrations of rare-earth elements were detected in a granitic dike cutting augen-bearing gneiss at another anomalous area. Numerous pegmatites with similar rare-earth mineralogy elsewhere in the Blue Ridge province of Virginia have been described (Mitchell, 1966).

CONCLUSIONS

Thorium and rare-earth mineralization probably took place during the development of the pegmatite and apatite-magnetite-quartz rock within the augen-bearing gneiss unit. The origin of the rare-earth and thorium mineralization may be related to the emplacement of alkali granite, containing aegirine and riebeckite, which is exposed in a zone about 3 miles (5 km) east of and roughly parallel to the zone of thorium anomalies (Figure 1). The alkali granite is considered to be a late phase of the Precambrian Robertson River Formation as based on mapping of the Massies Corner 7.5-minute quadrangle by M. T. Lukert and the writer in 1977. The pegmatite and apatite-magnetite-quartz rock were probably formed from a later rare-earth and thorium enriched fraction of the magma from which the alkali granite was derived.

The Mechum River metasedimentary rocks have been considered to represent fluvial deposits within a rift valley (Schwab, 1974). Although the Mechum River Formation apparently is fault-bounded only on the east side in the study area, it appears to be a graben-like structure along much of its length to the south. The rare-earth and thorium mineralization possibly was associated with the development of this structure.

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GEOLOGY AND GEOPHYSICS OF WARREN COUNTY, VIRGINIA[1]

by
Eugene K. Rader and Stanley S. Johnson

CONTENTS

ILLUSTRATIONS

ABSTRACT

Detailed geologic and geophysical mapping in Warren County by the Division of Mineral Resources affords the opportunity to examine the correlation of geological and geophysical data in the Blue Ridge and Valley and Ridge physiographic provinces in the northern part of Virginia. Geologic formations range from the Precambrian Pedlar Formation (quartz monzonite) to the Silurian Massanutten Sandstone. One major and several minor faults are present. The Front Royal fault in the southern part of the county has a stratigraphic throw of more than 12,000 feet (3,658 m).

Along the west slope of the Blue Ridge the Catoctin and Pedlar formations and the Chilhowee Group are readily distinguishable by their characteristic magnetic pattern. Large greenstone intrusives are well defined by linear magnetic highs in the southern part of the county. Major faults are frequently shown as a series of aligned magnetic lows. Northeast of Front Royal the aligned magnetic lows are associated with a collapse breccia zone.

A north-northwestward-trending linear extends across Warren County from near Compton Peak through Buckton. It corresponds to the abrupt Bouguer gravity gradient change. Abrupt change in strike of the Front Royal fault and Ordovician and Cambrian rocks suggests that there has been movement along the linear. The sinuous nature of the Front Royal Fault may be explained by late basement movement along the linear that warped the fault as part of a northeastward-facing monocline.

[1]Portions of this contribution may be quoted if credit is given to the Virginia Division of Mineral Resources. It is recommended that reference be made in the following form:

Rader, E.K., and Johnson, S.S., 1978, Geology and geophysics of Warren County, Virginia, *in* Contributions to Virginia geology—III: Virginia Division of Mineral Resources Publication 7, p. 91-97.

INTRODUCTION

Detailed geologic and geophysical mapping in Warren County affords the opportunity to examine the correlation of geological and geophysical data in the Blue Ridge and Valley and Ridge physiographic provinces in the northern part of Virginia. Geologic mapping of 7.5-minute quadrangles by the Division has provided geologic maps for the entire county (Edmundson and Nunan, 1973; Rader and Biggs, 1975, 1976; Gathright, 1976; Lukert and Nuckols, 1976; personal communication, Rader and Webb). Figures 1 and 2 include a sketch geologic map that is based on this mapping.

Aeromagnetic surveys were flown over the area in 1971 and 1972 as part of a regional geophysical program by the Division of Mineral Resources. The east-west flight lines were flown at 500 feet (152 m) above terrain at one-half mile intervals. The area was included in a regional gravity survey (Johnson, 1971). Additional data points were occupied in 1976 to more clearly define the configuration of the Bouguer gravity contour map.

STRATIGRAPHY

The bedrock in Warren County has been divided into six stratigraphic units for this study. They range in age from Precambrian to Silurian and include 17 formations.

PRECAMBRIAN ROCKS

Pedlar Formation

Along the Blue Ridge and to the west in the southern portion of Warren County two elliptical-shaped areas of the Pedlar Formation are exposed. The smaller is the core of a breached anticline. The upper contact is unconformable and commonly marked by a zone of unakite. The Pedlar is an assemblage of meta-igneous rocks consisting of quartzofeldspathic granulite and altered quartz monzonite. The granulite is composed of quartz, perthite, epidote, garnet, rutile, ilmenite, and leucoxene and is generally associated with the Front Royal fault and small shear zones. The greenish-gray quartz monzonite is composed of quartz, microcline, plagioclase, pyroxene altered to chlorite and pyrite, biotite, muscovite, specular hematite, pyrite and chalcopyrite.

PRECAMBRIAN(?) ROCKS

Catoctin and Swift Run Formations

The Catoctin Formation is exposed in a broad belt southwestward from the northeastern Warren County boundary to the central part of the county. Along the southeastern boundary of the county it underlies the Blue Ridge. Southeast of Bentonville the formation outlines an anticline with a Pedlar core. Small areas of metasediments of the Swift Run Formation are included in the basal part of the Catoctin. The lower Catoctin (and Swift Run) contact is unconformable with the Pedlar. The upper contact with the Chilhowie Group is also unconformable. The most common rock type is greenstone, the product of low-grade regional metamorphism of a basalt. Mineral composition of the greenstone is albite, epidote, chlorite, actinolite, and minor quartz, magnetite, specular hematite, sphene, and pyroxene. Pale yellow green, fine-grained epidosite, an early chemical-alteration product of the metabasalt, occurs as vein fillings and as a cementing agent in flow breccias and interbedded sandstones (Reed and Morgan, 1971). Mud-lump breccias consisting of angular to subangular fragments of reddish-brown argillite in a matrix of fine-grained schistose greenstone occur locally at the base of flows. Purple metatuffs are common at or near the top of the Catoctin. Meta-arkose, metalithic sandstone, and phyllite are commonly interbedded with the Catoctin flows. The thickness is estimated to be 2,000 to 2,500 feet (610 to 762 m) as based on outcrop width and general structural configuration.

CAMBRIAN CLASTIC ROCKS

Chilhowee Group

The Chilhowee Group comprises the Weverton, Harpers, and Antietam formations. It unconformably overlies the Catoctin and is conformably overlain by the Shady Formation of Cambrian age. The basal conglomerate is composed of subangular to rounded quartz and flat clay clasts in a matrix of quartz and lithic fragment sand that is cemented by quartz, sericite, and chlorite. This unit is overlain by tan to purplish-gray, locally conglomeratic quartzite with thin interbeds of olive-gray sandy phyllite. The upper part of the group is composed of fine- to coarse-grained, silica-cemented, vitreous quartzite and subarkose; phyllite partings are common. Thin quartz-granule and -pebble conglomerate beds are present. The maximum thickness is approximately 3,500 feet (1,067 m).

ORDOVICIAN AND CAMBRIAN CARBONATE ROCKS

Dominant rock types between the sandstone of the upper Chilhowee Group and the slate of the Martinsburg Formation are limestone and dolomite that are assigned to the Shady, Waynesboro,

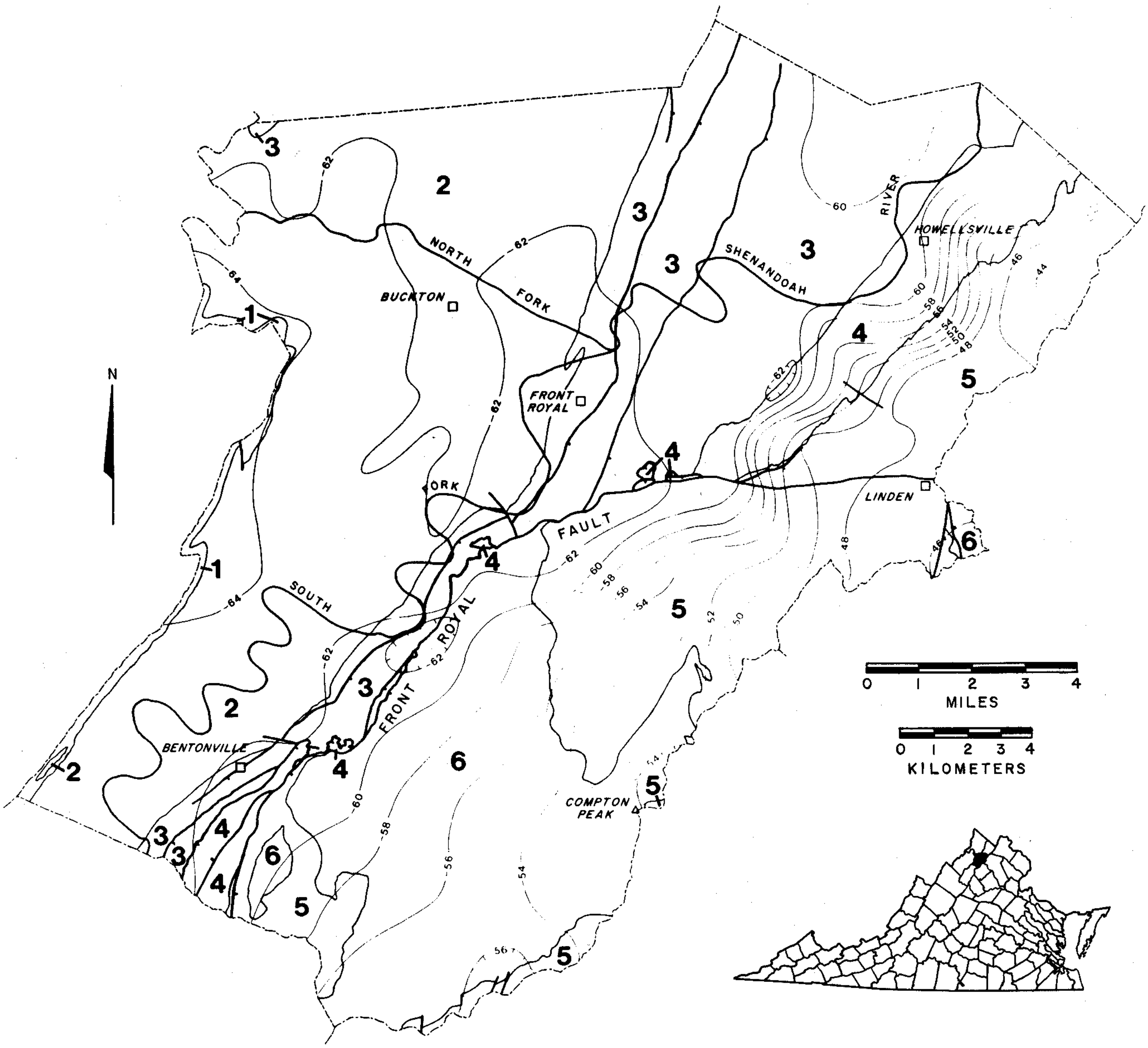

Figure 1. Generalized geologic and magnetic contour map of Warren County, Virginia: 1, Massanutten Sandstone; 2, Martinsburg and Oranda formations; 3, Ordovician and Cambrian rocks; 4, Chilhowee Group; 5, Catoctin and Swift Run formations; 6, Pedlar Formation. Contour interval, 20 and 100 gammas.

Elbrook, Conococheague, Stonehenge, Rockdale Run, New Market, Lincolnshire, and Edinburg formations. Only the Waynesboro and Edinburg contain appreciable quantities of noncarbonate rocks. Limestones are fine- to medium-grained, light- to dark-gray, thick- to thin-bedded, frequently fossiliferous. Dolomites are fine- to coarse-grained, light- to medium-gray, generally thick-bedded, and rarely fossilferous. The New Market contains high-calcium limestone. Thin dolomitic sandstones are present in the Conococheague. Chert nodules and masses are common in the Lincolnshire and Rockdale Run. Red and green shale and rusty brown sandstone are common in the upper and lower parts of the Waynesboro. Limestone of the Edinburg is black and argillaceous and interbedded with black shale. The maximum thickness of the unit is approximately 9,200 feet (2,804 m). See Rader and Biggs (1975, 1976) for a detailed description of these formations.

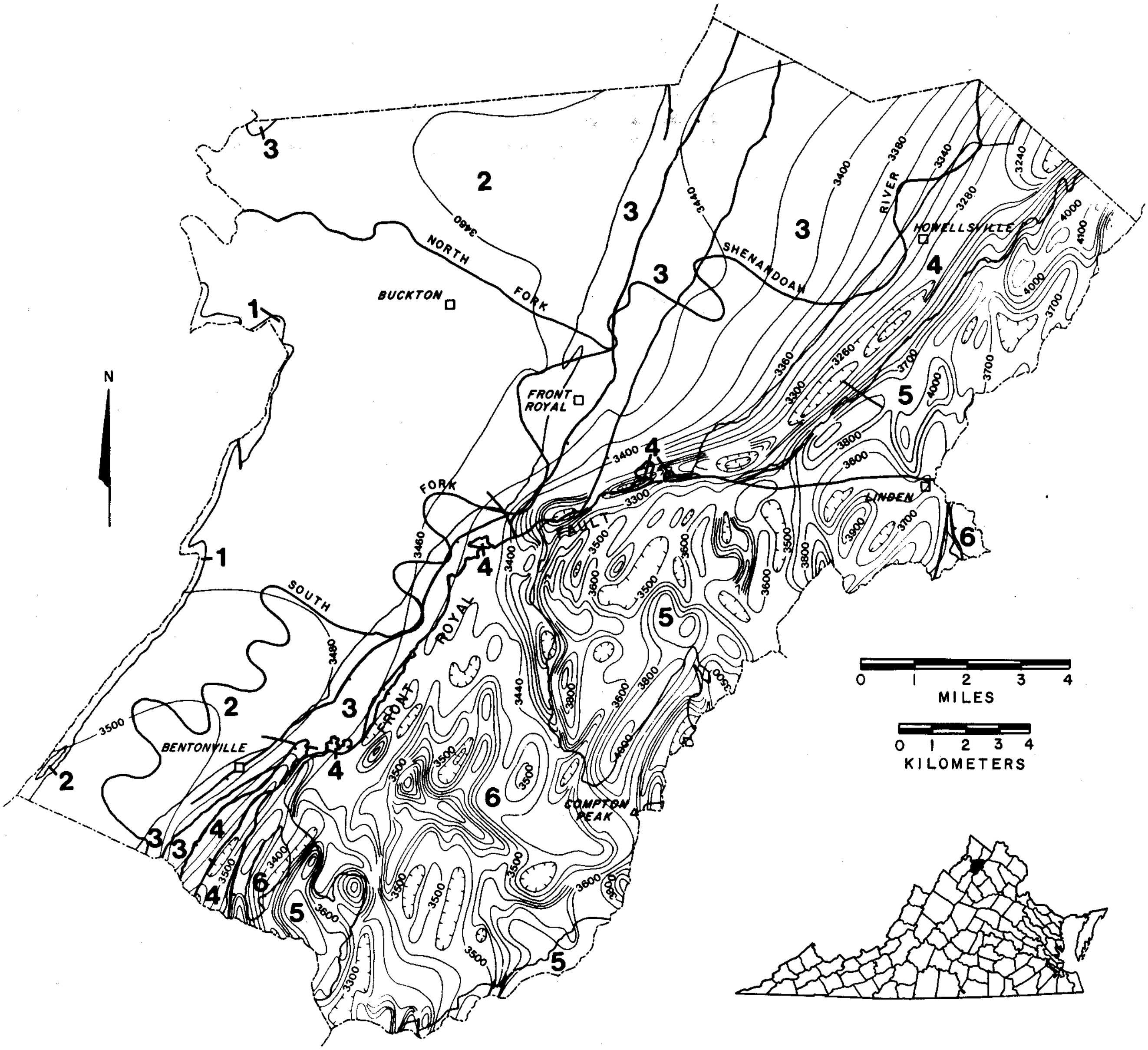

Figure 2. Generalized geologic and bouguer gravity map of Warren County, Virginia: 1, Massanutten Sandstone; 2, Martinsburg and Oranda formations; 3, Ordovician and Cambrian rocks; 4, Chilhowee Group; 5, Catoctin and Swift Run formations; 6, Pedlar Formation. Contour interval, 2 milligals.

Ordovician Clastic Rocks

Ordovician clastic rocks include the Martinsburg Formation and the relatively thin Oranda Formation at the base. The Oranda is a gray, calcareous siltstone with thin interbedded dark gray, argillaceous limestone and tan metabentonites. The Martinsburg proper may be divided into three lithologic units (in ascending order: black slate and limestone, sandstone and shale, and sandstone). The lower unit consists of 200 to 250 feet (61 to 76 m) of black, aphanic, argillaceous limestone; black calcareous slate; and thin, tan metabentonites. The bulk of the formation is a typical flysch sequence of alternating olive-green, brown, and greenish-gray, silty shale and olive-green to gray, fine- to medium-grained lithic sandstone. Overlying the flysch sequence is a brown, medium-grained lithic sandstone about 170 feet (51 m) thick. The lower 100 feet (30 m) contains marine fossils whereas the upper 70 feet (21 m) is devoid of fossils. The total thickness of the Oranda and Martinsburg is estimated to be 3,200 feet (975 m).

SILURIAN CLASTIC ROCKS

Massanutten Sandstone

The Massanutten Sandstone forms the northeastward-trending Massanutten Mountain along the western boundary of Warren county. The basal contact with the Martinsburg is unconformable. The upper contact is not exposed in the county. White, locally conglomeratic quartz sandstones and quartzites are the major rock types. Crossbeds are intermediate to high angle. Subangular to angular framework grains range from 0.5 to 1 mm. Quartz cement comprises less than 10 percent of the rock. The interlocking grain boundaries show that the grains have been pressure welded. Thin, black, organic-appearing, sandy shales are present at the top of many of the fining-upward sequences. Nematophytes (plants) from 13 horizons along Passage Creek (Shenandoah County) have been reported (Pratt, Phillips, and Dennison, 1975). Only the lower 200 feet (61 m) of the Massanutten Sandstone occurs in Warren County.

DIKES

Igneous intrusives with dike-like form of three distinct compositions occur in Warren County: amphibolite; metabasalt; and mica peridotite.

Amphibolite dikes intrude Precambrian gneiss south of Linden. The amphibolite is composed of actinolite with or without plagioclase and accessory chlorite, epidote, and sphene. Lukert and Nuckols (1976, p. 26) report that the enclosing rock has not been altered by dike intrusion.

Metabasalt dikes intrude the gneiss south of Linden and the Pedlar Formation east of Bentonville. These dark grayish green aphanitic dikes are composed of lath-shaped plagioclase with chlorite and magnetite. Phenocrysts of plagioclase are common in some of the dikes. Zonal alteration of the enclosing rock was observed at Boyds Mill 2.2 miles (3.5 km) east of Bentonville. The dike at this locality is a porphyritic metabasalt. Zone 1 (closest to the dike) is a light gray to white, coarse-grained, pegmatitic-appearing rock composed of microcline, quartz, plagioclase, garnet, and graphite. Zone 2 is a gray, medium- to coarse-grained rock composed of plagioclase, quartz, titanium-rich biotite, garnet, and magnetite. Zone 3 is a greenish-gray, coarse-grained rock composed of plagioclase, microcline, quartz, titanium-rich biotite, and magnetite. Beyond Zone 3 the enclosing rock is the typical quartz monzonite of the Pedlar.

Mica peridotite intrudes the Martinsburg Formation 1.2 miles (1.9 km) southwest of Buckton. The following minerals were reported by Young and Bailey (1955) and Rader and Biggs (1976): chlorite, phlogopite, hydrobiotite pseudomorphs after-olivine and pyroxene, pyrite, perovskite, leucoxene, apatite, dolomite, ankerite, ilmenite, magnetite, epidote, quartz, serpentine(?), garnet, rutile, talc, and calcite. Soil samples collected over the highly magnetitic portion of the dike contain zinc, lead, copper, chromium, nickel, calcium, and magnesium (Rader and Biggs, 1976).

STRUCTURE

Warren County may be divided into three structural units: the Front Royal thrust sheet, the overturned folds east of Front Royal and the Shenandoah River that is here in referred to as the Howellsville unit, and the Massanutten synclinorium. The Front Royal sheet is bounded on the west and north by the Front Royal Fault. The maximum displacement along the fault is between Bentonville and Front Royal where the Precambrian Pedlar is faulted over the overturned Lower Ordovician Rockdale Run Formation (stratigraphic throw more than 12,000 feet, 3,655 m). South of Bentonville the fault appears to split into three branches and die out to the south in overturned fold limbs north of Luray, Page County. Southwest of Front Royal the northeast trend of the fault changes abruptly to an east-west trend. Along this segment of the fault those rocks on the south side are less deformed than those to the north. Broad, open folds characterize the southern rock while folds to the north are overturned.

The Howellsville unit is characterized by overturned folds. The western margin of the unit is marked by an iron oxide cemented sandstone breccia. This zone of brecciation has been interpreted in previous studies as a thrust fault (Wickham, 1971; Edmundson and Nunan, 1973; Rader and Biggs, 1975; Lukert and Nuckols, 1976). The breccia zone probably developed as an aftereffect of solution by ground water and is not the result of tectonic faulting. Partial solution of carbonate rocks of the Shady Formation beneath overturned quartzite beds of the Antietam lead to differential subsidence and gradual collapse forming a linear unit of quartzite rubble (personal communication, Gathright, Henika, and Sullivan, 1978)

This material was later cemented by iron oxides from meteoric solutions.

The eastern portion of the Massanutten synclinorium is characterized by overturned folds and high angle reverse faults. The Martinsburg Formation contains overturned isoclinal folds with a later open-fold imprint. Small-scale faulting is visible in almost every exposure. These faults range from horizontal to vertical. Small asymmetric to overturned folds in the Massanutten Sandstone have a later broad, open-fold system imprint.

GEOPHYSICS

Aeromagnetic surveys were flown over Warren County at 500 feet above terrain at one-half mile intervals in an east-west flight-line pattern. The aeromagnetic data has excellent correlation with the regional and local geology. In comparing the magnetic field with known rock types, several correlations become readily apparent. In reviewing the magnetic data for the county (Figure 1) a change in the magnetic pattern between the northwestern and the southeastern parts of the county can be seen. The predominant rock in the southeastern half are the Chilhowee Group, and the Catoctin and Pedlar formations. In the northwestern half, the units are Cambro-Ordovician shale, sandstone, and carbonate rocks.

The Catoctin Formation displays a typical pattern of random highs and lows with no specific trend displayed within its formational boundaries. This "character" is probably due to weathering, formational thickness, lithology, and percentage of magnetic minerals that vary throughout the formation. The Pedlar Formation displays an overall lower magnetic field than the Catoctin Formation. This lower field is due to lithology (quartz monzonite and granulite). The linear highs in the southeastern portion of the county in the Pedlar Formation are related to greenstone dikes (not shown on Figure 1).

The formational contact between the Catoctin and Pedlar formations is shown quite well by magnetics south of Front Royal where there is a strong north-south anomaly; the northeast-southwest high, just southeast of the north-northwestward-trending anomaly; and the high at the southern county line.

The magnetic gradient changes very quickly from a steep to a more gradual one to almost no gradient westward from the Chilhowee Group-Catoctin Formation contact. This sequence of rock units from the contact to the western county line is composed of shale, sandstone, and carbonates as indicated by the lack of any magnetic signature. The magnetic field over this sequence of rock is probably a reflection of granitic basement.

Elongate lows east and south of Front Royal, at the Catoctin contact and over the Chilhowee Group in the southwestern part of the county are due to faulting. Northeast of Front Royal the magnetic lows are over the collapse-breccia zone.

Warren County was included in a regional gravity survey (Johnson, 1971). So that a more definitive map could be contoured, additional data points were occupied in the early part of 1976. With the acquisition of this control a two-milligal-contour-interval map was prepared (Figure 2). The gravity data has excellent correlation with the aeromagnetic data. The change between the southwestern and northeastern areas of the county is readily noted. In the Cambro-Ordovician section the gravity data denotes a six milligal change to the west. The southern part of the county shows a slowly decreasing gravity field to the west, a reflection of a deepening basement. In the northeastern part of the county, the gravity gradient increases over the Harpers-Catoctin formational contact.

This difference in gravity gradient is bounded by a north-northwestward-south-southeastward linear and the abrupt change in the strike of the Front Royal fault. This linear can be seen on high altitude aerial photographs, LANDSAT images, and the "Aeromagnetic Map of Virginia" (Zietz and others in press). Where the Front Royal fault crosses the linear the strike changes from northeast-southwest to east-west (Figures 1, 2). To the east in Fauquier County the fault again abruptly changes from an east-west trend to the more normal northeast-southwest trend.

The abrupt change in strike of the fault appears to be related to movement along the linear. Ordovician units on both flanks of the Massanutten synclinorium show an abrupt strike change that coincides with the strike change of the Front Royal fault. Based on the length of the east-west segments, the movement appears to have been greatest to the southeast. On Compton Peak bedding has a dip to the north. South of the east-west segment of the fault, older rocks are exposed at the surface at the same or higher elevations than to the north. Considering the above observations, movement on the linear was up on the southwest and/or down on the northeast. The linear appears to be the result of movement on a vertical to southwestward-dipping basement fault after the implacement of the Front Royal thrust sheet. Fault displacement of the cover rocks did not occur. The north dips along Compton Peak appear to be remnants of a northeastward-facing monocline that developed above the basement fault. Thus the sinuous nature of the Front Royal fault may be explained by late basement movement along a northwest-southeast linear that warped the fault as part of a northeastward-facing monocline. Warping of the cover rocks decreased the dip of the fault south of the linear and increased the dip north of the linear. The Fauquier County segment of the fault is east of the Warren County segment due to dip differential and later erosion. The east-west segment is the fault trace across the eroded monocline.

It is interesting to note that along the linear native copper has been mined. Several copper prospects have been located along this trend (Luttrell, 1966; Rader and Biggs, 1975). Silver, gold, malachite, azurite, chrysocolla, bornite, and cuprite have been reported from these mines and prospects.

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CORRELATION OF STREAM-SEDIMENT MINERALOGY WITH GEOLOGY, CENTRAL PIEDMONT OF VIRGINIA[1]

By
Richard S. Good

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ILLUSTRATIONS

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ABSTRACT

Semiquantitative analysis of minerals in stream sediments from the fine sand (-80+230 mesh) fraction of low-order streams in Fluvanna and western Goochland counties accurately reflects nearby bedrock geology in much of the area and is useful as an aid or supplement to geologic mapping.

Rapid analysis by X-ray diffraction and binocular microscope was made on samples already collected for regional trace-element studies. Most of the samples were examined without heavy-liquid separation. Comparisons were made in selected cases with tetrabromoethane concentration of stream-sediment and soil mineralogy and the results were indicative of a much greater abundance and freshness of unstable minerals in stream sediments compared to soils. Distance of transport was found to be generally less than a mile from the source with marked changes in less than 1,000 feet (305 m) from the geologic contact.

Microcline and plagioclase feldspar commonly compose 15 to 25 percent by weight of sediment

[1] Portions of this contribution may be quoted if credit is given to the Virginia Division of Mineral Resources. It is recommended that reference be made in the following form:

Good, R. S., 1978, Correlation of stream-sediment mineralogy with geology, central Piedmont of Virginia, *in* Contributions to Virginia geology—III: Virginia Division of Mineral Resources Publication 7, p. 99-113.

samples close to known source areas. Microcline in large amounts (5 to 25 percent) was found to be associated with sediments derived from migmatite of the Hatcher complex, particularly in areas of younger plutons within the Hatcher and in areas of pegmatite. Microcline is strikingly absent (less than 2 percent) in the Columbia syncline. Amphibole (hornblende) comprises 3 to 15 percent of samples taken from streams draining Chopawamsic metavolcanic rocks and actinolite from some diorite intrusives. Epidote in amounts of 3 to 15 percent is characteristic of sediments derived from the Hatcher complex and is strikingly absent from the Arvonia and Columbia synclines and thus outlines them. The garnet-staurolite mica schist belt of the Columbia syncline is shown by both garnet and staurolite, and rocks of the Candler Formation are reflected in a broad zone of high mica stream sediments with statistically high lithium content.

INTRODUCTION

Various techniques for assisting geologic mapping include the use of soil maps (Overstreet and Bell, 1965), panning for heavy minerals from saprolite (Overstreet and others, 1963), concentration of heavy minerals from stream sediments regionally (Carpenter, 1970) and in restricted areas (Ellison, 1973), and the use of aeroradiometric and aeromagnetic maps (Neuschel, 1970; Conley and Johnson, 1975). To the writer's knowledge, however, no semiquantitive results have been published on the use of unconcentrated stream sediment as an aid in geologic mapping in Virginia.

More than 3,000 stream-sediment and soil samples were collected for geochemical studies of gold (Good, Fordham, and Halladay, 1973, 1974, 1977) in the Caledonia and Pendleton quadrangles of Fluvanna, Goochland, and Louisa counties and in regional trace metal studies by the writer and O. M. Fordham covering all of Fluvanna and Goochland counties. Most of these samples were sediments taken in smaller streams relatively close to the source. The original purpose of sample collection was primarily for chemical analysis. However, due to difficulties in geologic mapping in many parts of the Piedmont because of deep weathering and thick soil and saprolite cover, an effort was made to see what additional information could be obtained from sediment samples. Heavy-liquid concentration was used for comparison of mineralogy along a few traverses because of different rates of weathering between soils and sediments in streams.

GEOLOGIC SETTING

Workers who have contributed to the geology of the study area include Watson and Powell (1911), Taber (1913), Brown (1937), Stose and Stose (1948). Smith, Milici, and Greenberg (1964), Brown (1969), Fullager (1971), Harper, Russell, and Sherrer (1973), Good, Fordham, and Halladay (1973, 1974, 1977), Conley and Johnson (1975), and Bourland (1976). Discussions of dating and correlation of rocks in surrounding areas with portions of the study area are given by Brown (1970), Brown and Griswold (1970), Higgins (1973), Pavlides, Daniels, and Bates (1974), Seiders and others (1975), Wright and others (1975), and Pavlides (1976). However, serious problems of interpretation of stratigraphy remain and uncertainties connected with rock dating have not been entirely eliminated with newer dates.

A generalized geologic map (Figure 1) of Fluvanna and western Goochland counties shows the bedrock of the area is mostly metamorphosed volcanic, volcaniclastic, and sedimentary rocks of late Precambrian and Ordovician age with the remainder being primarily Cambrian migmatite and younger felsic to intermediate intrusives of probable Devonian to Carboniferous age.

EXPLANATION FOR FIGURE 1

5 Ordovician—Bremo Formation: micaceous, chloritic, and feldspathic quartzite. Arvonia Formation: slates containing muscovite, quartz, minor plagioclase, biotite, siderite, pyrite, and magnetite with minor amounts of chlorite schist, amphibole schist, and garnet-amphibole-quartz schist; basal conglomerate schist.

4 Cambrian and Ordovician(?)—Garnet-staurolite-kyanite-muscovite-biotite schist and phyllite locally with graphite and chlorite; kyanite, kyanite-garnet quartzite and biotite quartzo-feldspathic gneiss; kyanite-sillimanite quartzite (Q) ridge.

3 Late Precambrian and Cambrian—Hatcher complex: Migmatite includes Columbia granite with younger plutons (P). Intrudes, interfingers with, and grades into Chopawamsic Formation. Altered epidote-bearing microcline-biotite granite, granodiorite, and quartz diorite with lenses, pods, and small bodies of amphibolite and hornblende gneiss retaining regional trend. Rarely xenolithic, generally shows gradational relationships into biotite gneiss, biotite schist, hornblende-biotite gneiss; nebulitic in places; pegmatitic southeast of Columbia syncline; intruded with porphyritic Ellisville biotite granodiorite (P), which is probably Ordovician or younger in age; unfolded metadiorite (D); both P and D may be related to middle to late Paleozoic intrusions.

2 Late Precambrian and Cambrian—Chopawamsic Formation: lower member, clastic metasedimentary rocks gradational with underlying Candler Formation; upper unit dominantly volcanics, interlayered metamorphosed andesite, andesitic basalt tuff, flows, volcaniclastics, mixed volcanic sediments, soda rhyolite flows, and pyroclastics; at greenschist grade in

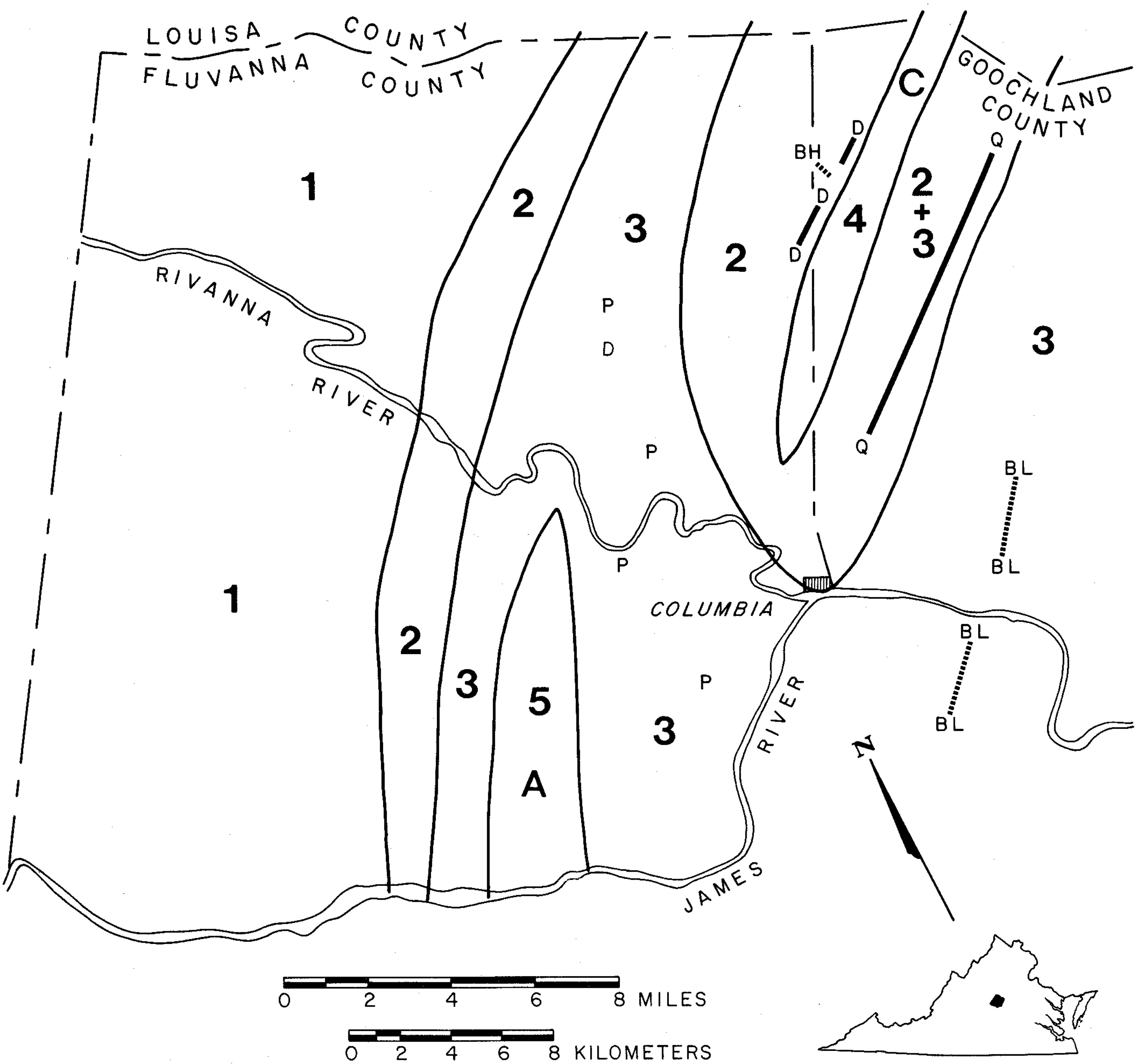


Figure 1. Generalized geologic map of Fluvanna and western Goochland counties.

central Fluvanna County. Partly greenschist grade in western limb of Columbia syncline and amphibolite grade on eastern limb of Columbia syncline. Greenstone with albitic plagioclase, amphibolite, hornblende gneiss with oligoclasic and andesitic plagioclase; felsite and felsite porphyry. Includes thin amygdaloidal andesitic basalt and near top of formation thin ferruginous quartzite (banded magnetite-quartz and magnetite-hematite-quartz iron formations) on both limbs of Columbia syncline. Contains zones of ovoidal epidosite; small felsic and mafic dikes, sills, and plugs.

1 Late Precambrian—Candler Formation: Muscovite, chlorite and paragonite-bearing phyllite, feldspathic schist, quartzite, and greywacke metamorphosed at greenschist grade. Contact with Chopawamsic gradational from more sedimentary character in west to volcanic in east.

BL Silicified mylonite breccia with zeolite fault zone (from Conley and Johnson, 1975; Bourland, 1976).

BH Silicified mylonite breccia with barite fault zone (from Good, Fordham, and Halladay, 1977).

Q Garnet kyanite sillimanite quartzite (line represents trend of quartzite).

D Nonfoliated metadiorite; may be associated with younger plutons (line represents trend of metadiorite).

P Younger plutons including Ellisville biotite granodiorite.

A Arvonia syncline.

C Columbia syncline.

Note: Mesozoic diabase dikes and small areas of metapyroxenite, hornblendite, and talc-chlorite-actinolite schist are not shown.

The area is a maturely dissected, rolling upland largely between 300 and 500 feet (91 and 152 m) above sea level; however, elevations near the James River are less than 200 feet (61 m). Local relief in the uplands is about 50 feet (15 m) and rarely 100 feet (30 m) near larger rivers. Almost the entire area drains into the James River, largely in dendritic patterns, but with a few trellis ones. Many of the smaller streams follow joint directions.

The stream systems may be considered as a collection of small, self-contained, drainage basins with areas of between 2 and 20 square miles (8 and 83 sq. km). A thin veneer of colluvium or alluvium is present in some areas; the larger stream valleys, however, contain thick alluvium. Terrace deposits are generally developed in upland areas adjacent to the James and Rivanna river valleys.

Deep saprolite has formed over almost all the uplands. According to Smith, Milici, and Greenberg (1964) depth to bedrock averages about 50 feet (15 m) with a maximum of 98 feet (30 m) recorded. Much of the area is covered by mature residual soil with a light yellowish brown silt loam A-horizon and a dark-red, yellowish-red, or yellowish-brown, clay-rich B-horizon ranging from 5 to 16 inches (13 to 41 cm) below the surface. Bottom lands, steep upland slopes, and forest swamps lack this development. About 75 percent of the area is forested and the rest is agricultural land. The large amount of forest has a bearing on the amount and distance of transport of that portion of stream sediments derived from soils.

SAMPLING AND LABORATORY PROCEDURE

Stream-sediment samples were collected at an average density of 0.64 sample per square mile (1.66 per sq km) in the lower order streams close to their source area. Most of the streams that were sampled were first, second, or third order with only a few fourth-order tributaries.

Sample sites were in running water about 100 feet (30 m) from stream junctions. Approximately 9 pounds (4 kg) of wet sieved sediment were collected and passed through 2 mm stainless steel mesh. During this step much of the clay and silt fraction was removed. After oven drying in the laboratory the sample was further sieved into −10+80 mesh (coarse and medium sand), -80+230 (fine sand), and -230 mesh (silt and clay) fractions. One gram of the fine sand fraction was heated for 1 hour with 1:1 HCl on an oscillating hot plate and analysed by atomic absorption spectroscopy. Acid-washed residues from these samples were retained for binocular microscope examination. A separate split of the fine sand fraction, not acid treated, was analysed by standard powder diffraction analysis using an acetone-Duco cement mix on glass slides and a copper X-ray target.

Stream-sediment samples include fines that have come from nearby (0.5 mile or 0.8 km) to far away (about 5 miles or 8 km). Most detrital material in the fine-sand fraction, however, comes from much closer than 5 miles (8 km), generally a mile or less. Figure 2 illustrates an abrupt mineralogical change in samples concentrated by heavy-liquid separation. A marked change related to known bedrock outcrop is shown in less than 1,000 feet (305 m). The heavy-liquid separation accentuates the relative amount of garnet-staurolite residue washed downstream beyond the geologic contact. This traverse was taken in the Caledonia quadrangle and the stream has a gradient of 63 to 100 feet per mile in a drainage area of 1 square mile (3 sq km). Total stream length within this drainage is about 2 miles (3 km) and 4 miles (6.7 km) counting large gullies with intermittent streams. Stream gradients elsewhere within the study area range from 11 to 237 feet per mile (2 to 45 m/km), most commonly in the 53 to 158 feet per mile (10 to 30 m/km) range.

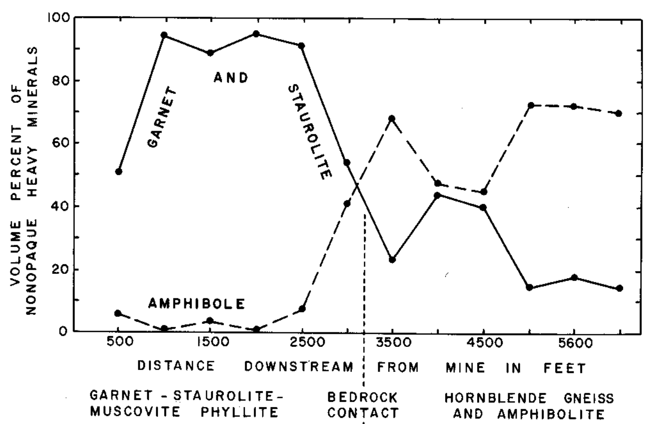


Figure 2. Change in abundance of garnet, staurolite, and amphibole in relation to distance downstream from a geologic contact. Heavy-liquid separation of -10+200-mesh sediment from samples in stream draining Payne mine, Caledonia 7.5-minute quadrangle, Goochland County.

Further evidence of nearness of source and short exposures to weathering of much or most of the detrital fine-sand fraction is indicated by the overall mineralogy of the sediment samples collected in Fluvanna and western Goochland counties. Minerals identified in stream sediment include quartz, plagioclase (albite, oligoclase, andesine) microcline (twinned and untwinned), muscovite, vermiculite, chlorite, hornblende, actinolite, tremolite, epidote, zoisite, clinozoisite, staurolite, kyanite, sillimanite, rutile, anatase, zircon, tourmaline, magnetite, ilmenite, hematite, limonite, spinel (pleonaste), gahnite, (zinc spinel), allanite, sphene, pyrite, barite, and gold.

Most of the grains are at least partially coated with an iron oxide film. The fine sand fraction, largely angular to subangular, ranges in quartz content from less than 50 percent to about 95 percent with most samples falling closer to the 50 percent level. The abundance of both K-feldspar (microcline) and plagioclase, each in the amounts commonly up to 25 percent by weight near or on granitic source areas, is surprisingly high compared to the small amounts of fresh feldspar not converted to clay in soil and saprolite. The common occurrence of relatively unstable minerals, such as epidote and amphibole, in amounts up to 20 percent by weight with concentration in areas of clearly identifiable source rock is an additional indication of fluvial immaturity of the sediment. Biotite is one of the least stable minerals, and is quickly converted to hydrobiotite or vermiculite; however, muscovite and chlorite are locally abundant in amounts up to 20 percent. Over or close to source areas garnet, staurolite, or kyanite may constitute 1 to 5 percent of the sediment without concentration.

A more precise quantitative index of the amount of movement of fine sand-size detrital grains is shown by pyrite in stream sediment from a known restricted source (Figure 3). Although physically weak under stream attrition, it is chemically protected by a hematitic or limonitic husk from short-term weathering. Pyrite as single grains is common locally in very small amounts in Fluvanna County sediment samples. However, its movement and stability is better shown by a small stream, Gold Mine Branch, which drains a massive sulfide zone near Dillwyn, Buckingham County (Figure 3). Detrital pyrite was found in this stream in large enough amounts to allow quantitative estimates after acid treatment without heavy liquid separation. The stream passes through outcrops containing weathering massive sulfides, and the drainage is favorable to collect sediment from the massive sulfide zone. Pyrite can be readily observed in acid-washed sediment up to about 1 mile (1.6 km) downstream from the source. An unnamed stream to the west with unfavorable drainage on the other side of a low ridge showed no pyrite in the sediment. Barite was also found up to about 0.5 mile (0.8 km) downstream along Gold Mine Run (Figure 4), but it was also absent from the stream that did not contain pyrite.

Three stable soil minerals in particular, zircon, rutile, or tourmaline are known for their long distance of transport and long term stability. They may also be formed authigenically in soils. Based on average percentages of nonopaque heavy mineral

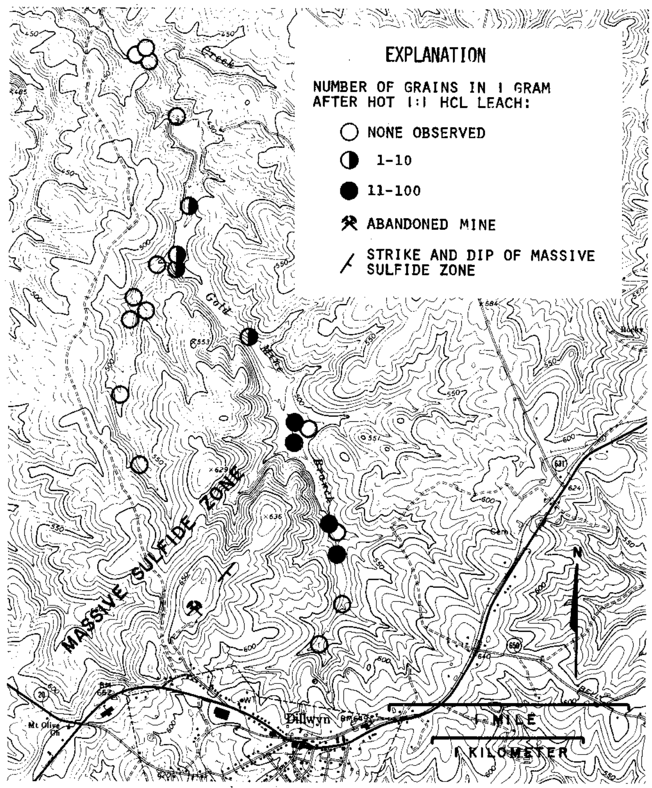


Figure 3. Distance of transport of detrital pyrite in -80 + 230-mesh stream sediment downstream from massive sulfide restricted source, Gold Mine Branch near Dillwyn, Buckingham County.

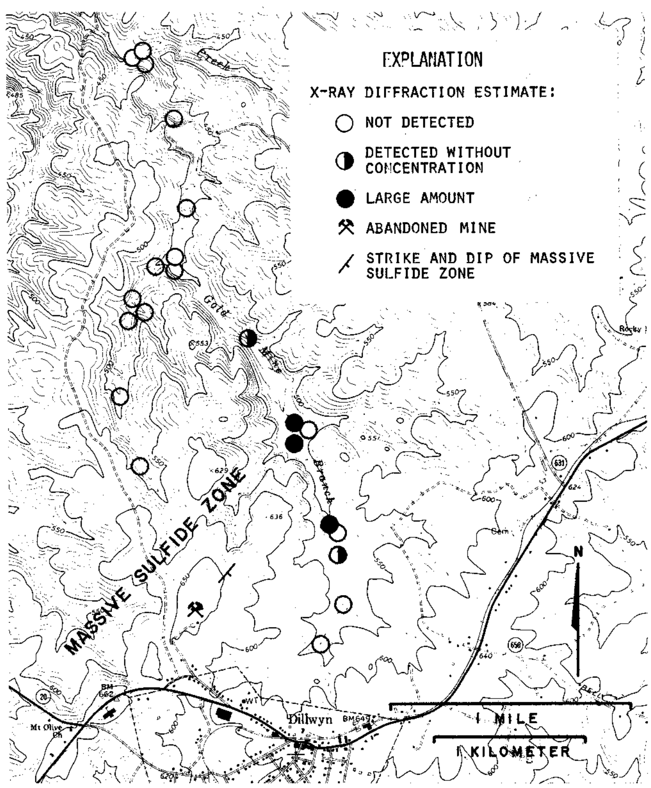


Figure 4. Distance of transport of detrital barite in -80 + 230-mesh stream sediment downstream from massive sulfide restricted source, Gold Mine Branch near Dillwyn, Buckingham County.

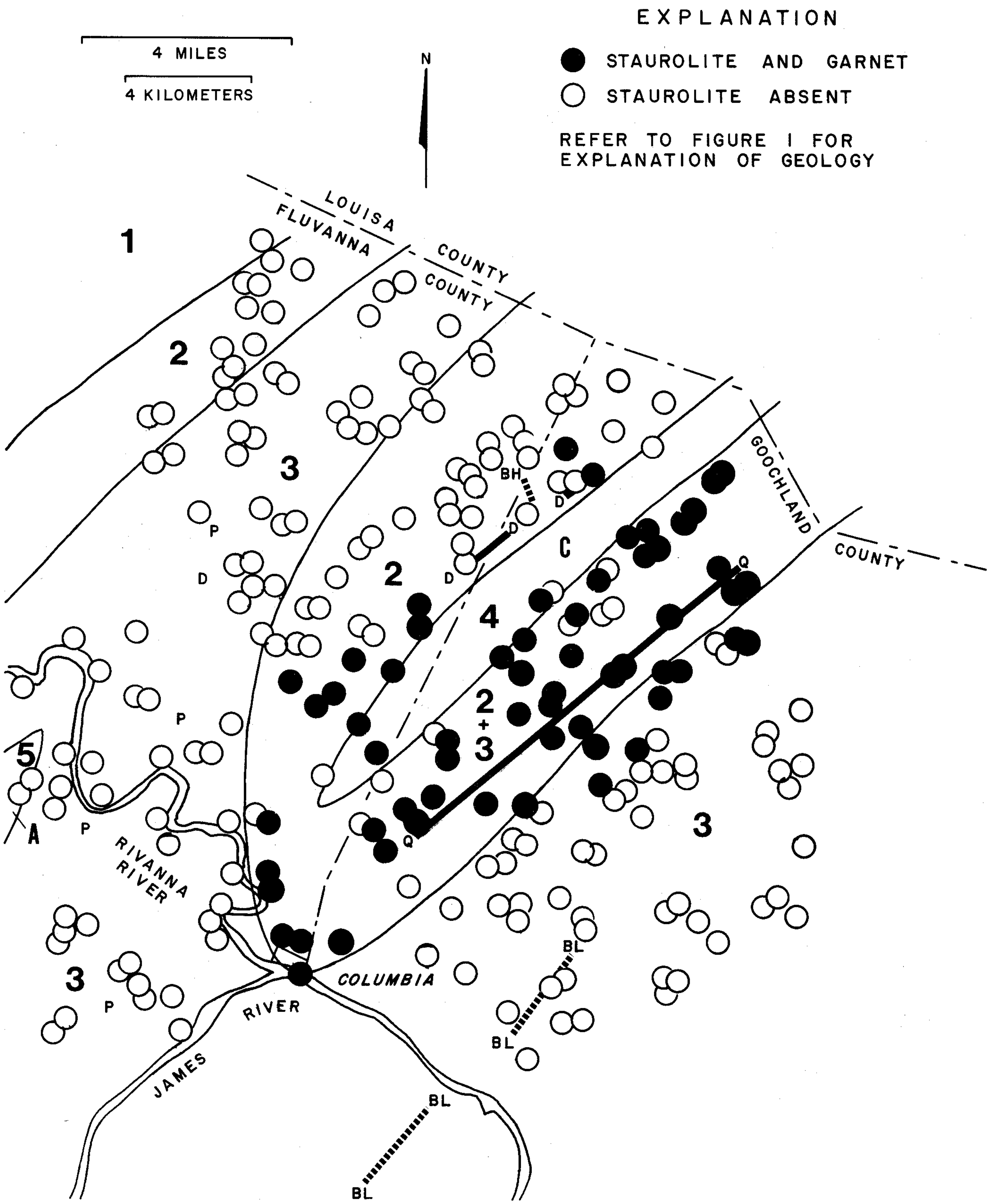


Figure 5. Occurrence of staurolite and garnet in -80 + 230-mesh stream sediment from binocular microscope examination of unconcentrated samples.

separations from six stream and four soil traverses, it was found that these three minerals had much higher (10-100 times) values in soils than in stream sediments from areas of similar rocks. Conversely, garnet was 10-20 times more abundant in stream sediments compared to soils nearby. This observation is further confirmation of the known poor stability of garnet (Dryden and Dryden, 1946; Dietz, 1973; Grimm, 1973; Nickel, 1973). The fine fractions of stream sediment contain a greater percentage of minerals derived from soil by runoff during unusually heavy rainfall. It would appear, however, that relatively unstable minerals, such as the feldspars, amphiboles, and epidote, do not occur in large amounts in coarser fractions, in sediments of low order streams more than a mile from their source, and frequently considerably less than a mile. This is also true for large amounts of garnet, staurolite, and kyanite. All these minerals persist, however, in the fine fractions and can be identified after heavy liquid separation, many tens of miles from their source in high-order streams and rivers.

RESULTS OF STREAM-SEDIMENT STUDY

For mapping purposes the effectiveness of stream-sediment mineralogy depends on the lack of significant sediment cover younger than the rocks being mapped, nearness to sample source, and low to moderate stream gradient. The Piedmont of Virginia lies south of any known glacial deposits, but remnants of Cretaceous and post-Cretaceous sediments lie west of the Coastal Plain as scattered patches. None of the Coastal Plain sediment outliers have been mapped as far west as western Goochland and Fluvanna counties.

During previous work (Good, Fordham, and Halladay, 1977) the writer noted poorly consolidated, hematitic quartz-breccia conglomerate containing staurolite and zoisite[2] in a stream bed in the southwestern part of the Pendleton quadrangle, which adjoins the Caledonia quadrangle to the north. In the present study plots of staurolite in the fine sand (-80 + 230 mesh) fraction of sediments of the Columbia syncline show the distribution throughout the whole supposed area of the Columbia syncline, not just close to the known extent of the garnet-staurolite-mica schist (Figure 5). The mica schist zone as shown in Figure 1 corresponds very closely to LANDSAT (ERTS) lineament photography (BAND 7 in winter). It is not clear whether this garnet-staurolite distribution is due just to stability in transport or to a more widespread distribution of staurolite-bearing rock or staurolite-bearing soil. It is possible that there were small patches of Triassic or post-Triassic rocks and sediments overlying the Columbia syncline, which now would be eroded away. The nearest Triassic basins lie about 23 and 24 miles (35 and 37 km) away both to the east and west respectively, and 42 miles (68 km) away on strike to the southwest. All other evidence, however, supports the view that younger sediments do not contribute a significant portion of heavy or light minerals in stream sediments, and that major changes in mineral abundances of coarser fractions are due to lithologic changes short distances upstream.

Figure 6 shows the relative amount of microcline in fine sand fractions of stream sediment. A marked break in concentrations is shown along a line east of and parallel to the Fluvanna-Goochland county line. To the west of the line within the Columbia syncline there is no microcline above the detection limit of X-ray (1 to 2 percent). To the east of the line sediments contain abundant microcline (5 to 25 percent). This line corresponds to the contact between pegmatite bearing-migmatite and interbanded mafic gneiss, felsic gneiss, quartz-feldspathic gneiss, and quartzite as previously mapped by the writer (Good, Fordham, and Halladay, 1977). It also marks a change in magnetic intensity with low values over the pegmatite zone. A central Piedmont lineament described by Neuschel (1970) and referred to by Bourland (1976) lies farther to the east beyond a silicified mylonite zone described by Conley and Johnson (1975) and Bourland (1976). Some microcline is found in sediments derived from granitic rocks to the west and northwest of Columbia in areas around porphyritic Ellisville biotite granodiorite, but the contrast is not so sharp. The simplest explanation for the lack of microcline in the Columbia syncline is that there is no sizable amount of metamorphosed microcline granite or gneiss exposed in the area. Rocks in the Columbia syncline may or may not lie partly unconformably over older migmatitic rocks containing microcline. Orthoclase perthite is known in Ellisville granodiorites, but felsic volcanic rocks of the Columbia syncline are apparently deficient in potassium as shown by analysis of soda rhyolite (Table 1). It is not certain whether this lack of potassium is due to metamorphism or whether sodic felsite represents an extrusive equivalent of a plagiogranite magma. Unfoliated metadiorite and small dikes and plugs are the only definitely in-

[2] Virginia Division of Mineral Resources repository number R-4570, 0.2 mile (0.3 km) west of the South Anna River, unnamed creek northeast of Route 640, 1.3 miles (2.1 km) N. 16° E. from Bridge 269 on Route 640, UTM coordinates 239,300 m East; 4,199,750 m North.

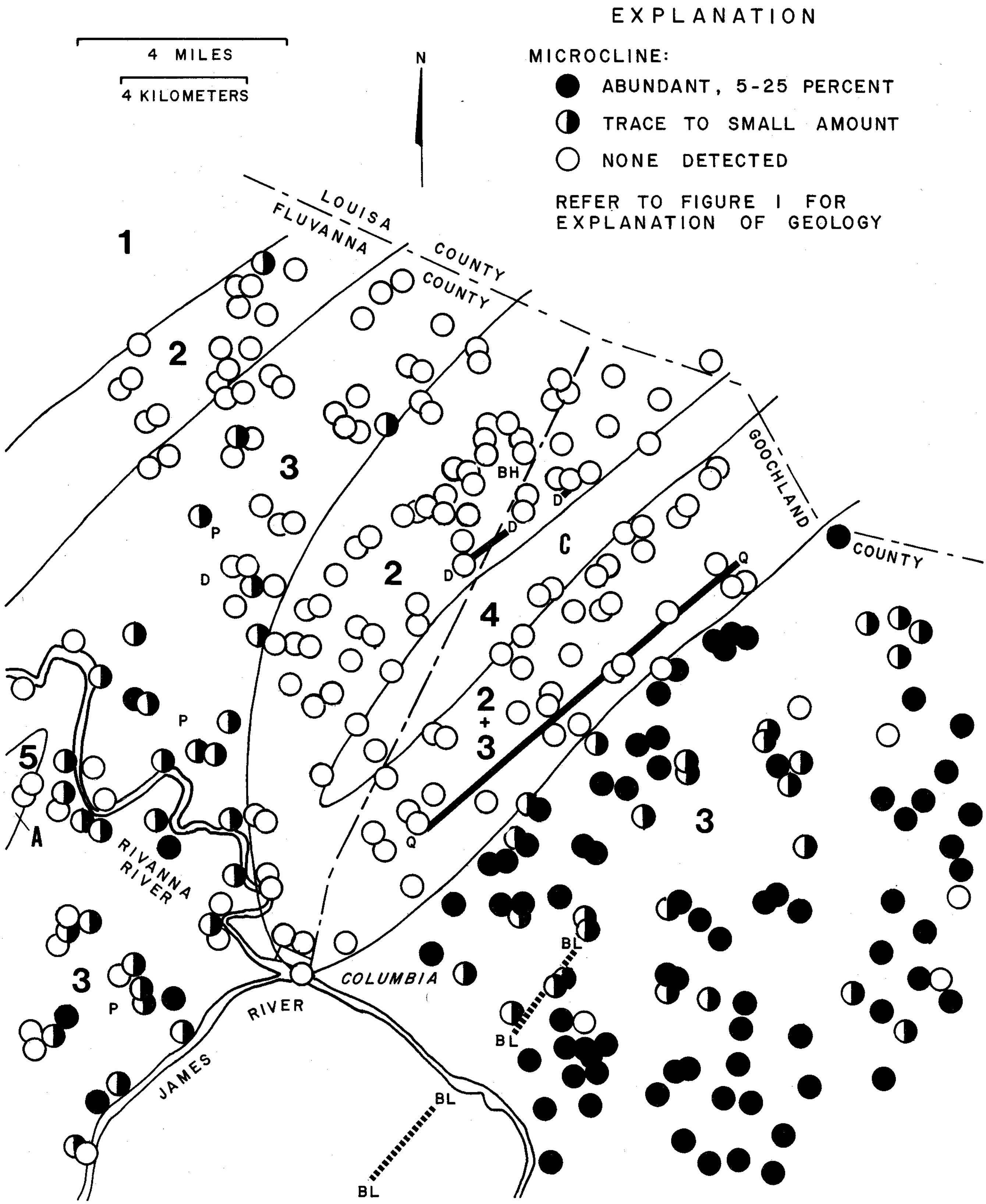


Figure 6. Relative amount of microcline in -80 + 230-mesh stream sediment from X-ray diffraction.

trusive rocks in the Columbia syncline, but some of the fine-grained felsite and felsic rocks may be granophyres, which were formed at or close to the surface.

A SYMAP plot of the epidote data from stream sediment (Figure 7) shows a clear association with granite and granodiorite known to be altered and characterized by their epidote content. Remarkably, there seems to be a "blank" area deficient in epidote outlining the Columbia syncline, even though small amounts of epidote are almost ubiquitous in the area and are known to be associated with some of the mafic metavolcanic rocks and locally abundant as epidosite masses within amphibolite. Epidote does show up in heavy mineral concentrates within the Columbia syncline, but the total volume is apparently much less than that derived from rocks of the migmatite complex, which averages 5-20 percent epidote. Note also the "shadow" of epidote-deficient sediments outlining the Arvonia syncline. The epidote data may be an indication that a migmatite complex as a whole may underlie both the Arvonia and Columbia synclines. Chemical analyses of slate from the Arvonia Slate, garnet-mica schist from a unit in the Columbia syncline, and garnet-mica schist from the Quantico syncline are similar in all major elements (Table 2). This similarity is further evidence for suggesting correlation of these units.

A SYMAP plot of the amphibole content of sediments primarily outlines the Chopawamsic Formation in the Columbia syncline (I) and one amphibole-rich area to the west of the Columbia syncline that seems to be part of the migmatite complex, based on plots of the epidote data (Figures 7, 8). However, Smith, Milici, and Greenberg show an area of diorite that coincides with the amphibole-rich (II) rocks. Amphibole-rich sediments are shown (III) near the James River on the west limb of the Arvonia syncline, which is also an area of high trace metals in iron-oxide detrital coatings and is considered geochemically anomalous for base metals. The amphibole plots show only areas with sufficient hornblende or actinolite to give an X-ray response of

Table 1.—Whole-rock analyses of Chopawamsic metavolcanic unit, Columbia syncline, Caledonia 7.5-minute quadrangle.

	A	B	C
SiO_2	76.13	53.25	55.93
Al_2O_3	12.26	15.47	12.74
Fe_2O_3	3.61	13.74	13.36
MgO	0.51	5.32	2.99
CaO	0.67	4.75	8.95
Na_2O	6.09	5.52	2.72
K_2O	0.06	0.08	0.10
TiO_2	0.20	1.16	1.23
MnO	0.03	0.20	0.19
P_2O_5	0.01	0.11	0.09
H_2O	0.43	0.40	1.70

A— Felsite member of interbanded metavolcanic unit; Byrd Creek, East branch, southeast part of, Caledonia quadrangle; UTM coordinates, 754,580 m East, 4,194,290 m North; Virginia Division of Mineral Resources repository number R-4317.

B— Slaty greenstone, west limb of Columbia syncline, Caledonia quadrangle; UTM coordinates, 753,730 m East, 4,191,550 m North; Virginia Division of Mineral Resources repository number R-4275.

C— Zoisite-epidote, amygdaloidal amphibolite; Peters Creek, east limb of Columbia syncline, Caledonia quadrangle; UTM coordinates; 759,860 m East, 4,193,920 m North; Virginia Division of Mineral Resources repository number R-4331.

Analyst, O. M., Fordham, Jr.; by X-ray fluorescence employing a lithium tetraborate fusion and computer correction for matrix interferences and recalculated to 100 percent.

Table 2.—Analyses of garnet-mica schist from the Quantico Slate, a garnet-mica schist from a unit in the Columbia syncline, and slate from the Arvonia Slate.

	A	B	C
SiO_2	63.75	66.44	62.53
Al_2O_3	17.59	16.78	16.02
Fe_2O_3	6.93	6.77	7.69
MgO	1.45	1.45	2.17
CaO	0.26	0.18	0.67
Na_2O	1.25	1.10	1.37
K_2O	4.10	3.29	3.52
TiO_2	0.98	0.99	0.97
MnO	0.05	0.04	0.14
P_2O_5	0.13	0.10	0.18
H_2O	3.51	2.86	4.74

A— Quantico garnet-mica schist; Quantico syncline; Virginia Division of Mineral Resources repository number R-6130.

B— Garnet muscovite-biotite schist; Columbia syncline; UTM coordinates 237,020 m East, 4,199,240 m North; North Branch of Fork Creek, Pendleton 7.5-minute quadrangle; Virginia Division of Mineral Resources repository number R-4496.

C— Arvonia slate; from Buckingham quarry, Dillwyn, Buckingham County; Virginia Division of Mineral Resources repository number R-6129.

Analyst, O. M. Fordham, Jr.; by X-ray fluorescence employing a lithium tetraborate fusion and computer correction for matrix interferences and recalculated to 100 percent.

EXPLANATION

GEOCHEMICAL RECONNAISANCE OF FLUVANNA COUNTY, VIRGINIA

EPIDOTE IN STREAM SEDIMENTS, 80 TO 230 MESH, 50% HCL EXTRACTION

CONTOUR INTERVALS ARE 0.0 TO 0.5, 0.5 TO 1.5, AND 1.5 TO 2.0

REFER TO FIGURE 1 FOR EXPLANATION OF GEOLOGY

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	X	Y	Z
SYMBOLS	....X....	000000000 000000000 0000Y0000 000000000 000000000	■■■■■■■■■ ■■■■■■■■■ ■■■■Z■■■■ ■■■■■■■■■ ■■■■■■■■■
FREQ.	269	72	104

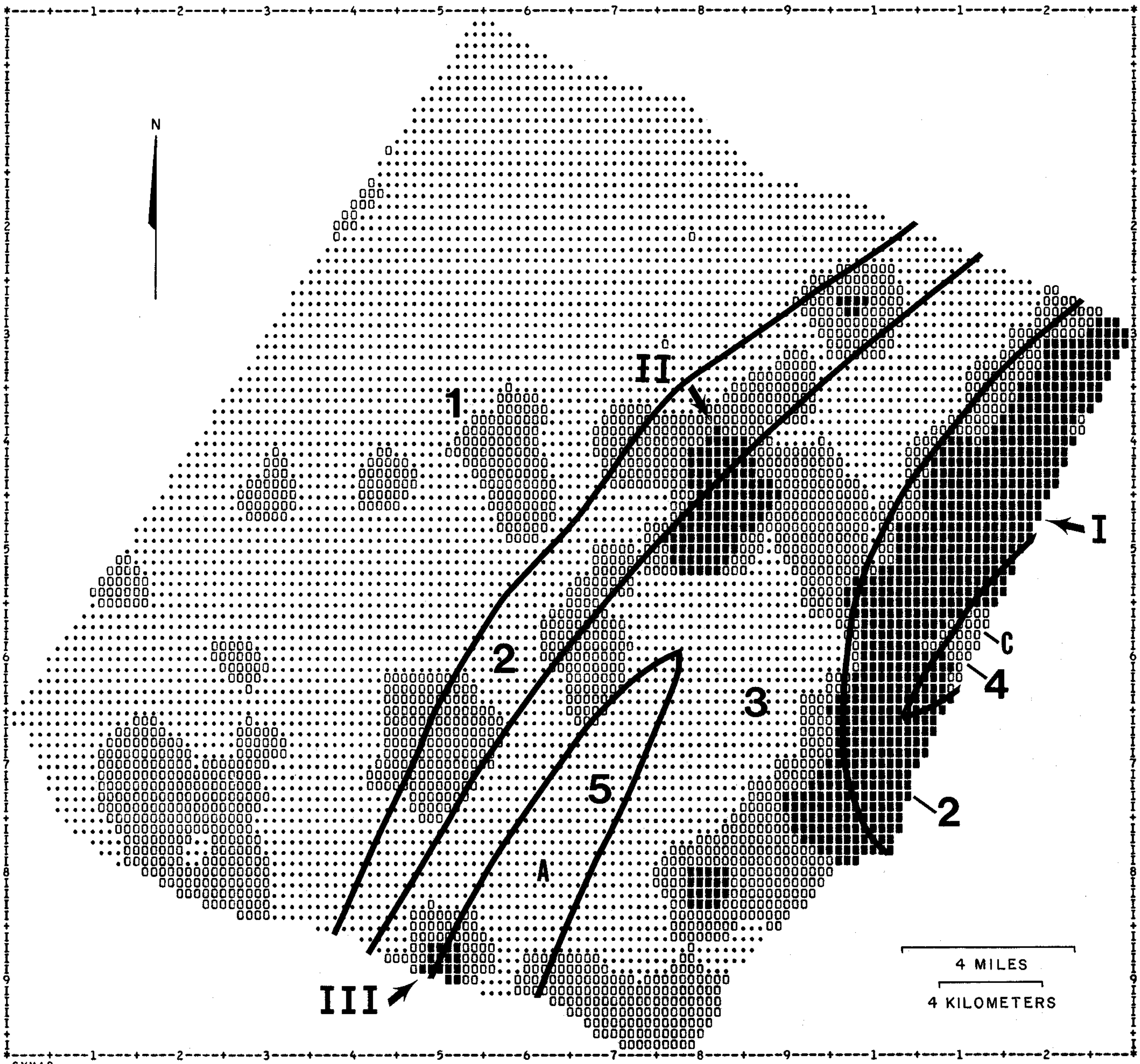
EPIDOTE:

X TRACE OR NONE, APPROXIMATELY 0-1 PERCENT

Y PRESENT, APPROXIMATELY 1-3 PERCENT

Z ABUNDANT, APPROXIMATELY 3-15 PERCENT

Figure 7. Relative amount of epidote in unconcentrated -80 + 230-mesh stream sediment from binocular microscope examination.



SYMAP

EXPLANATION

GEOCHEMICAL RECONNAISANCE OF FLUVANNA COUNTY, VIRGINIA

AMPHIBOLE IN STREAM SEDIMENTS, 80 TO 230 MESH, 50% HCL EXTRACTION

CONTOUR INTERVALS ARE 0.0 TO 0.5, 0.5 TO 5.0, AND GREATER THAN 5.0

REFER TO FIGURE 1 FOR EXPLANATION OF GEOLOGY

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	X	Y	Z
SYMBOLS	....X....	0000Y0000	■■■■Z■■■■
FREQ.	344	35	66

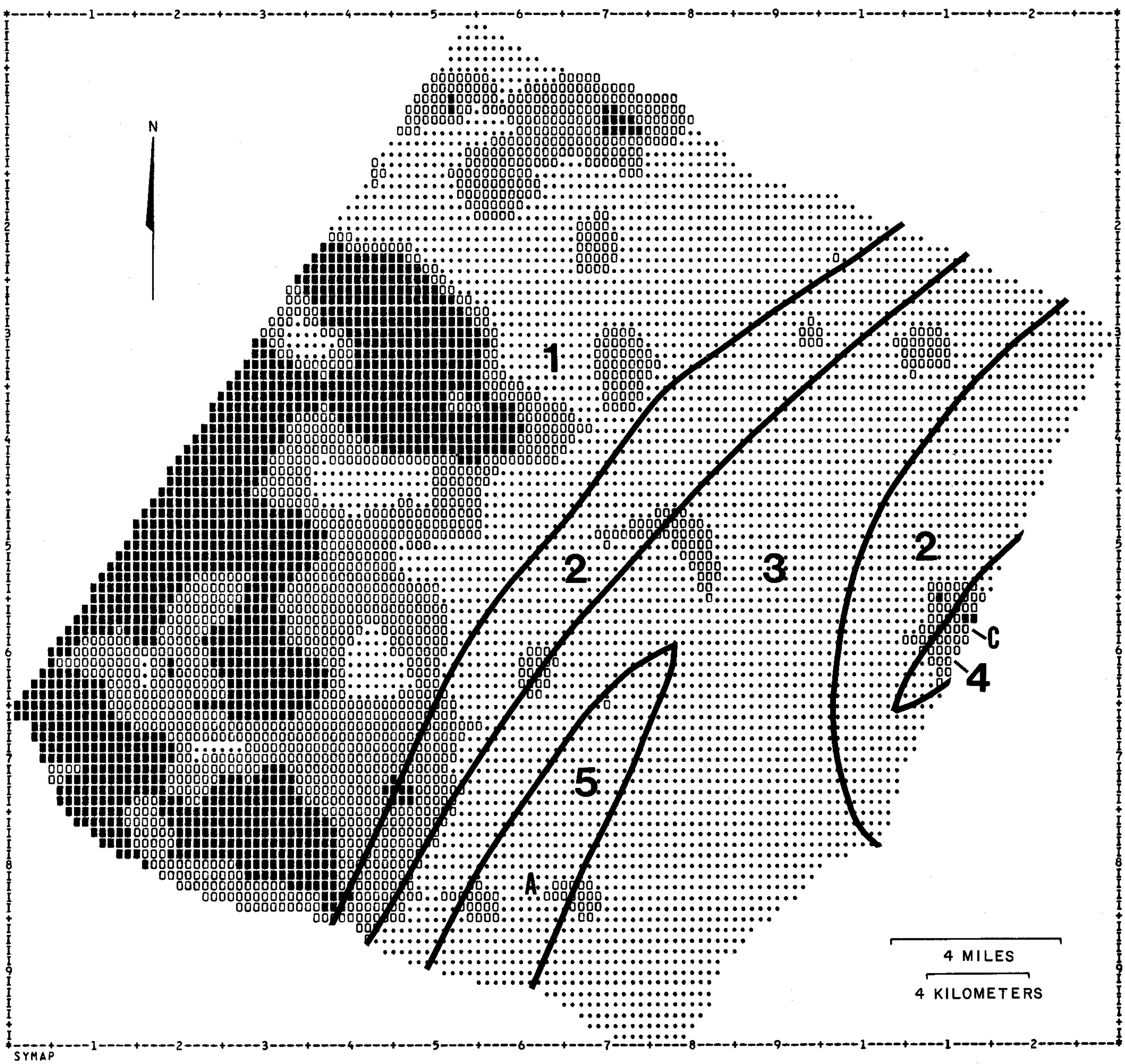
AMPHIBOLE:

X TRACE OR NONE, APPROXIMATELY 0-3 PERCENT

Y PRESENT, APPROXIMATELY 3-5 PERCENT

Z ABUNDANT, APPROXIMATELY 6-20 PERCENT

Figure 8. Relative amount of amphibole in unconcentrated -80 + 230-mesh stream sediment from X-ray diffraction and binocular microscope estimates.



EXPLANATION

GEOCHEMICAL RECONNAISANCE OF FLUVANNA COUNTY, VIRGINIA

MICA IN STREAM SEDIMENTS, 80 TO 230 MESH, 50% HCL EXTRACTION

CONTOUR INTERVALS ARE SELECTED BY THE PROGRAM AS ONE-THIRD OF THE RANGE

REFER TO FIGURE 1 FOR EXPLANATION OF GEOLOGY

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	X	Y	Z
SYMBOLS	....X....	0000Y0000	■■■■Z■■■■
FREQ.	279	86	80

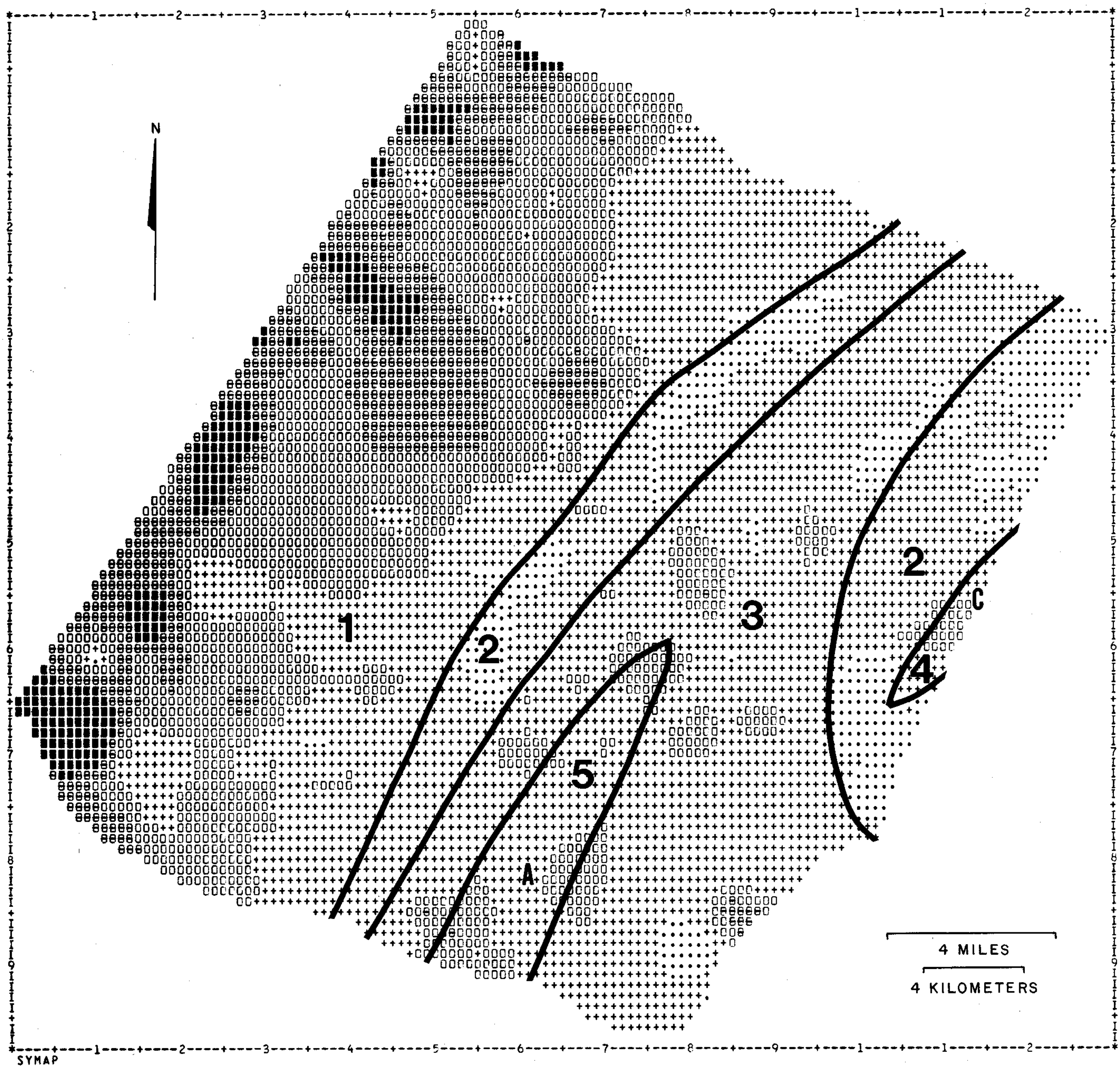
MICA:

X TRACE OR NONE

Y PRESENT, APPROXIMATELY 2-10 PERCENT

Z ABUNDANT, APPROXIMATELY 10-25 PERCENT

Figure 9. Relative amount of mica content from -80 + 230-mesh stream sediment from X-ray diffraction and binocular microscope examination.



EXPLANATION

GEOCHEMICAL RECONNAISANCE OF FLUVANNA COUNTY, VIRGINIA

LITHIUM IN STREAM SEDIMENTS, 80 TO 230 MESH, 50% HCL EXTRACTION

CONTOUR INTERVALS BASED ON ARITHMETIC STANDARD DEVIATION UNITS

REFER TO FIGURE 1 FOR EXPLANATION OF GEOLOGY

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	X	Y	Z	XX	YY
SYMBOLS	....X....	++++Y++++	0000Z0000	888XX8888	■■■YY■■■■
FREQ.	47	238	127	57	18

LITHIUM (PPM)

X	<0.8
Y	0.8-3.4
Z	3.4-6
XX	6-8
YY	>8.6

Figure 10. Computer contours of lithium content of -80 + 230-mesh stream sediment from atomic absorption analysis by hot HCl leach.

about 3 percent by weight in unconcentrated sediment. Maximum amounts are in the 10-20 percent range. Darker hornblende can easily be noted in binocular examination compared to the much lighter actinolite, and plots based on this difference might prove useful. As in plots of other minerals, heavy-liquid separation would show some amphibole occurring outside of the "blank" areas.

Plots (not shown) on SYMAP computer printouts were also made on plagioclase, chlorite, and mica. In Fluvanna County high plagioclase amounts in sediments is generally associated with granite and granodiorite, and quartz diorite. These rocks, including later potash-rich intrusives, are grouped as a "migmatitic complex," corresponding in part to Brown's (1969) Hatcher complex. There is also a large area of abundant plagioclase in the SW part of Fluvanna County that does not correspond with any obvious lithology as mapped by Smith, Millici, and Greenberg (1964).

Plots based on chlorite in sediment show larger concentrations associated with the Candler Formation mostly in the western half of Fluvanna County. Chlorite showed a "blank area" where underlain by granitic rocks. Tourmaline was also plotted from binocular microscope examination of unconcentrated sediment and shows a very close correlation with the Candler Formation in the western half of Fluvanna County.

In many parts of the western half of Fluvanna County highly micaceous stream sediments are closely related to the Candler rocks (Figure 9). A small area of such sediment in the eastern border of the county can also be noted and is related to the garnet-mica schist belt of the Columbia syncline. The mica content is presumed to be largely muscovite since biotite is very rapidly altered to hydrobiotite, vermiculite, or chlorite. Illitic clay is largely removed in the washing and sieving process. It is not known what portion, if any, of the mica recorded is due to paragonite (sodium muscovite) which occurs in important amounts in the western half of Fluvanna County (Smith, Milici, and Greenburg, 1964).

Atomic absorption analyses of the sediment samples were originally made for iron, manganese, zinc, copper, lead, chromium, nickel, cobalt, lithium, strontium, barium, rubidium, and silver as part of a previous investigation. Many of these elements show relationships statistically related to their original abundances in various types of bedrock. For example, lithium can be clearly related to the abundance of micaceous rocks in the Candler Formation and the larger amount of mica in the sediment analysed (Figures 9, 10). However, for mapping purposes a total chemical attack technique of the sediment would be more appropriate than the HCl leach, which primarily dissolves only the iron oxide coatings of the detrital grains, magnetite, hematite, chlorite, clays (partially) and muscovite (partially). Most other silicates are dissolved little or not at all.

Quantification of stream sediment mineralogy is limited (at least in large numbers of samples) by inherent variability in X-ray diffraction analysis of powdered samples, by the size fraction examined, and by the relative crudity of binocular microscope examination compared to time-consuming heavy-liquid separations. It is further limited by variable geologic factors such as (1) relative rate of weathering of different types of bedrock, (2) vegetation, slope, and thickness of soil or saprolite cover within the drainage basin just upstream from the sample, (3) size of effective drainage basin upstream from sample site, (4) stream gradient, (5) position relative to source of stream drainage network (stream order), (6) stream density (ratio of total stream length within the drainage basin to area of basin), (7) amount of rainfall and occurrence of unusual storms or floods prior to sampling, and (8) occurrence of beaver dams and man-made ponds. The results of this study are an indication that while these factors may be important for a rigorous approach to mineral abundance, they appear to be relatively unimportant for rough assistance to geologic mapping.

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GEOLOGY OF THE PIEDMONT OF VIRGINIA—INTERPRETATIONS AND PROBLEMS[1]

by
James F. Conley

CONTENTS

[1]Portions of this contribution may be quoted if credit is given to the Virginia Division of Mineral Resources. It is recommended that reference be made in the following form:

Conley, J. F., 1978, Geology of the Piedmont of Virginia — Interpretations and problems, *in* Contributions to Virginia geology — III: Virginia Division of Mineral Resources Publication 7, p. 115 - 149.

ILLUSTRATION

ABSTRACT

Virginia contains three areas of exposed Grenville-age basement—the Sauratown Mountains anticlinorium, the Blue Ridge anticlinorium, and the gneiss dome in Goochland County. Rocks of the Blue Ridge anticlinorium are separated from rocks of the Sauratown Mountains anticlinorium by those of the Smith River allochthon in the southwestern Piedmont of Virginia. Rocks of the Lynchburg, Catoctin, Candler, and Chopawamsic formations overlie the basement on the southeastern limb of the Blue Ridge anticlinorium. The Chopawamsic Formation is correlated with metavolcanic rocks to the southwest at Danville. Rocks of the Carolina slate belt are suggested to conformably overlie these metavolcanic rocks. The Quantico and Arvonia synclines contain rocks that are tentatively correlated with each other and are believed to unconformably overlie the Chopawamsic Formation. The Quantico syncline is thought to be folded around the northwest limb and nose of the later-formed Columbia synform. With increasing metamorphic grade to the southeast, rocks of the Chopawamsic Formation grade into the Hatcher complex. The discovery of billion-year-old felsic gneiss in an antiformal structure in G ochland County is evidence that continental crust underlies this sequence of rocks and makes questionable a suture zone in the Piedmont of Virginia.

INTRODUCTION

The purpose of this paper is to describe rock units older than those of Triassic age thus far recognized in the Piedmont of Virginia and to discuss their stratigraphic relationships. A generalized geologic map of the region (Figure 1) is summarized to the extent that present knowledge of the geology will allow. Structure is not discussed in detail except where it affects stratigraphic relationships. It is shown how interpretations have changed as research continued and new data was obtained. Because of the lack of detailed maps over much of the Piedmont, each new map that is completed commonly produces radical changes in interpretations of regional geology. This paper is primarily a progress report on the geology of the Piedmont of Virginia and both new data and ideas not previously published are included.

The Piedmont is underlain by igneous and metamorphic rocks ranging in age from Precambrian to lower Paleozoic and by sedimentary rocks of the Triassic. Some of these rocks have been affected by as many as three and possibly four metamorphic events. Rocks of the region show multiple deformations ranging up to four superimposed fold systems. Interpretation of regional geologic structure has ranged from theories that folds were the dominant structures to those that the area is covered by vast thrust sheets. An early proponent of the fold theory was Keith (1923), who believed that the major structures in the southern Appalachians were generally asymeterical folds locally broken by thrust faults. In contrast Jonas (1932) proposed that thrust sheets were the predominant structures and recognized the Blue Ridge, Martic, and Appomattox sheets as major structural units in the Piedmont and Blue Ridge of Virginia. Bloomer (1950) and Bloomer and Werner (1955) did not recognize any faults along the Martic zone. Brown (1953, 1958) and Espenshade (1954), although recognizing imbricate thrusting in the James River synclinorium, did not believe that any of these faults represented the displacements envisioned by Jonas (1932). With the mapping of the Grandfather Mountain window in North Carolina by Bryant and Reed (1959, 1970) and the realization that the Blue Ridge thrust sheet had moved at least 35 miles (56 km) to the northwest, Jonas' concept of major thrust nappes in the southeastern Piedmont becomes more plausible. Additional support was provided by mapping the Smith River allochthon (Conley, Henika, and Algor, 1971; Conley and Henika, 1973; Espenshade and others, 1975). Major nappes are probably widespread in the southeastern Piedmont as based on (1) recognition that rocks of the Inner Piedmont in North Carolina are thrust northwestward along the Brevard zone and the discovery that the zone passes northeastward into broad folded nappe structures (Espenshade, 1969; Espenshade and others, 1975), (2) recognition of a major fold nappe in the central Virginia Piedmont (Tobisch and Glover, 1971), and (3) interpretation by Crowley, Reinhardt, and Cleves (Crowley, 1976, Plate 1) that the Baltimore gneiss domes are actually basement-cored fold nappes.

Major structural elements in the Piedmont of Virginia are the Sauratown Mountains anticlinorium, the Smith River allochthon, the Blue Ridge anticlinorium, the southeastern flank of the Blue Ridge anticlinorium, the Virgilina synclinorium of the Carolina slate belt, the Quantico-Columbia and Arvonia synclines, the James River synclinorium, and the Outer Piedmont. Triassic sedimentary rocks occur in half-grabens and grabens in the Piedmont east of the Blue Ridge anticlinorium, but are not discussed in this report.

C.R. Berquist, R.G. Piepul, and J.D. Marr aided in compiling a geologic map (Figure 1) from all available sources. From numerous discussions with T.M. Gathright a better understanding of the geologic relationships of the rocks of the Piedmont has emerged. Appreciation is expressed to Louis Pavlides who read selected parts of this report and made valuable comments. The writer was also able to benefit from examination and discussions in the field of his work in the Fredericksburg area, which gave insight into the complex geology of the northern Virginia Piedmont.

SAURATOWN MOUNTAINS ANTICLINORIUM

The anticlinal nature of the rocks of the Sauratown Mountains was recognized by Mundorff (1948) and the structure was named the Sauratown Mountains anticlinorium by Butler and Dunn (1968, p. 23). Rankin, Espenshade, and Shaw (1973, p. 29, 36) consider it a foliation arch of Paleozoic age. The possibility that the anticlinorium is contained within a window was suggested by Bryant and Reed (1961), based on stratigraphic evidence. This interpretation was rejected by Butler and Dunn (1968). However, the anticlinorium could be contained within a window surrounded by the sillimanite-grade rocks of the Smith River allochthon to the northwest and the Inner Piedmont belt to the south and southeast. It could be a window, based on mapping of the Smith River allochthon (Conley and Henika, 1973; Espenshade and others, 1975; Price, 1975) that bounds the anticlinorium to the northwest and the discovery of a thrust fault that separates rocks of the anticlinorium from rocks of the Inner Piedmont belt along the southeastern boundary (Espenshade and others, 1975).

The entire outcrop area of the Sauratown Mountains anticlinorium in Virginia has been mapped at a scale of 1:24,000 (Conley and Henika, 1973; Price, 1975). To the northwest rocks of the anticlinorium dip under rocks of the Smith River allochthon along the Ridgeway fault and to the northeast the structure is truncated by the border fault of the Danville basin, which contains rocks of Triassic age. The axial portion of the anticlinorium at the surface consists of granitic augen gneiss that is probably equivalent to granitic basement, which is dated by Rankin and others (1971, p. 343) at 1,192 million years old. This Grenville-age basement has been suggested by Thomas (1977, p. 1239) to be an isolated basement block, which was detached from

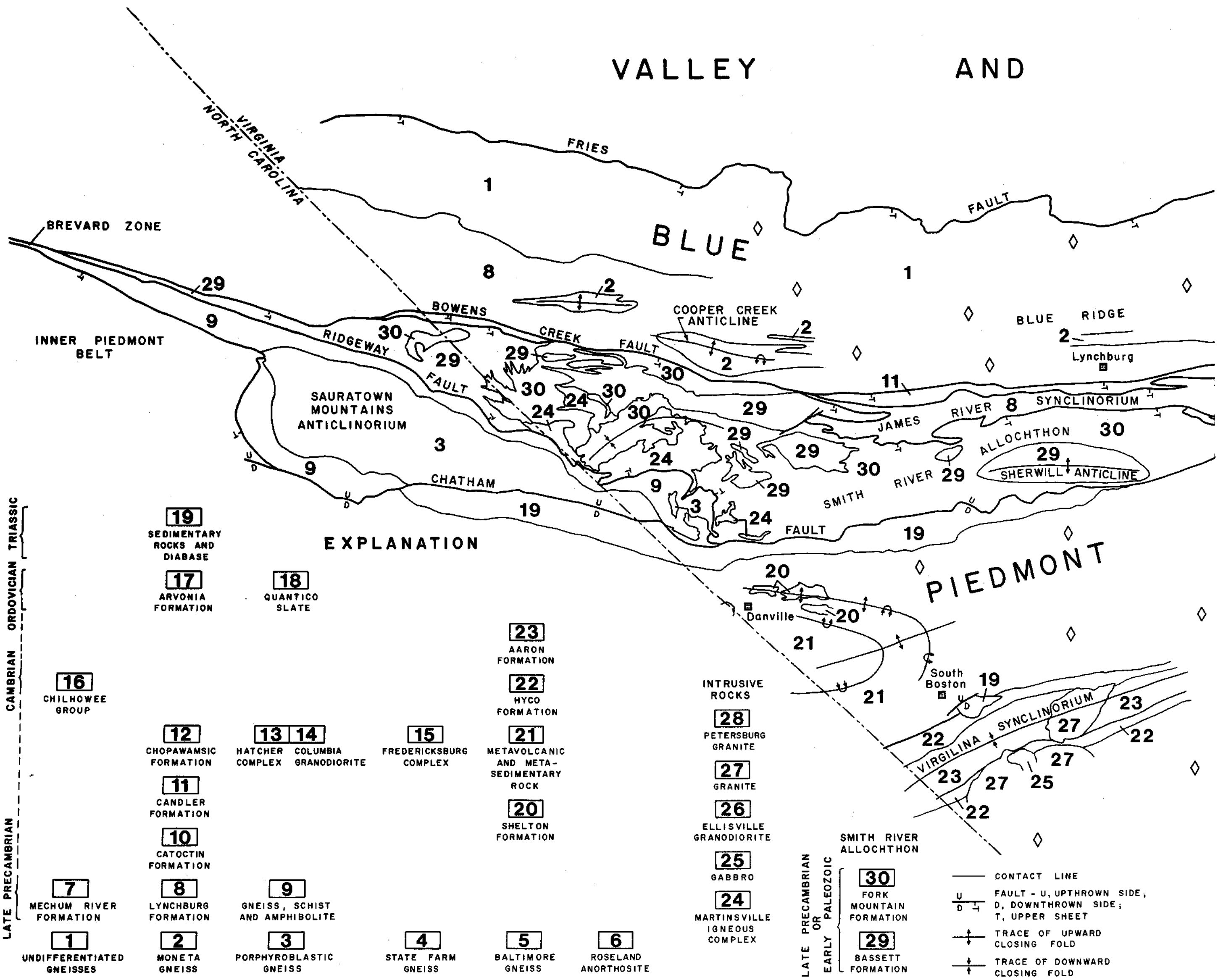
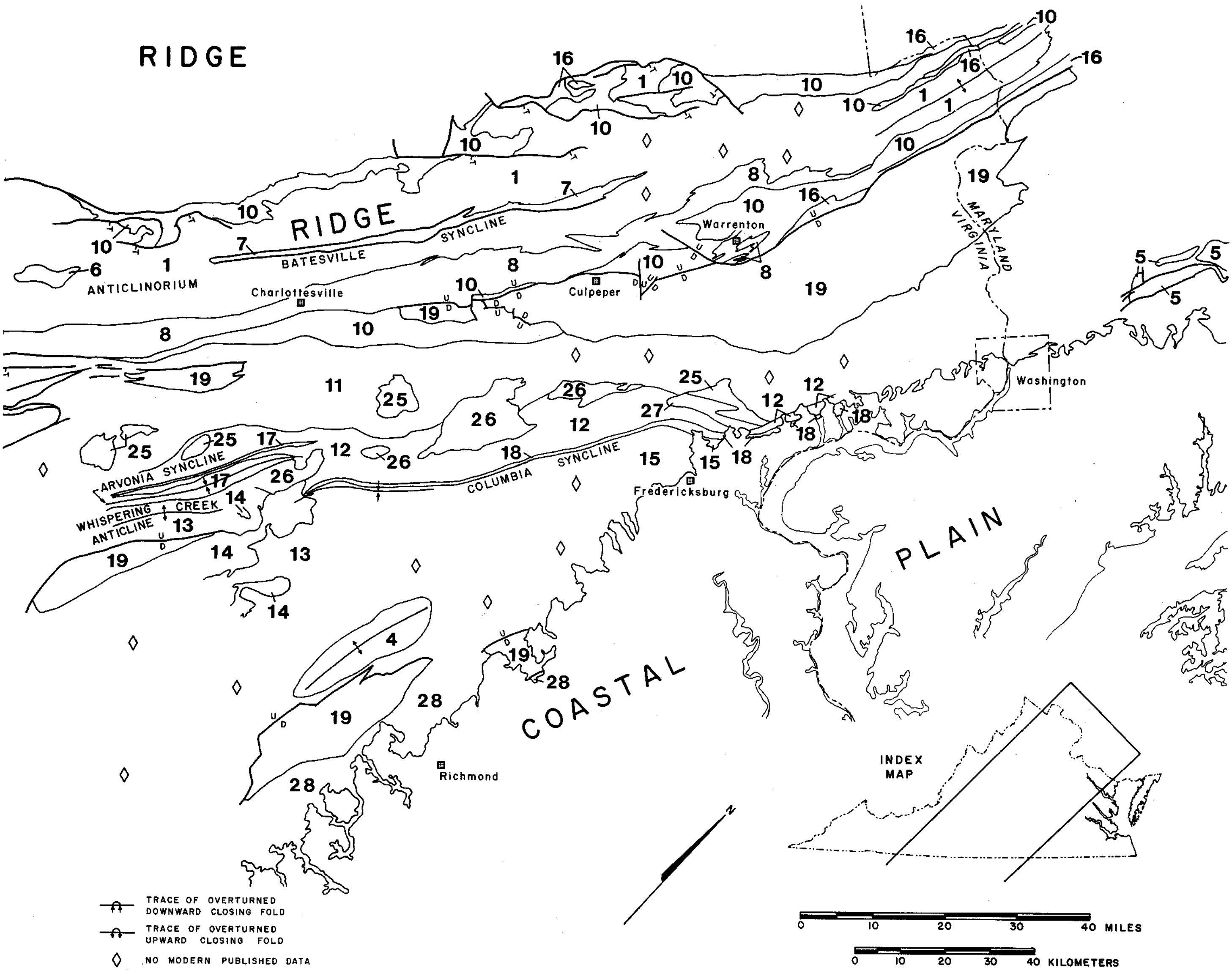


Figure 1. Generalized geologic map of the Piedmont of Virginia and adjacent areas showing major structural features.


RIDGE
RIDGE
BATESVILLE SYNCLINE
ANTICLINORIUM
Charlottesville
Culpeper
Warrenton
MARYLAND
VIRGINIA
Washington
ARVONIA SYNCLINE
WHISPERING CREEK ANTICLINE
COLUMBIA SYNCLINE
Fredericksburg
Richmond
COASTAL
PLAIN
INDEX MAP
N
TRACE OF OVERTURNED DOWNWARD CLOSING FOLD
TRACE OF OVERTURNED UPWARD CLOSING FOLD
NO MODERN PUBLISHED DATA
0 10 20 30 40 MILES
0 10 20 30 40 KILOMETERS

the continental margin during initial rifting in late Precambrian time. The basement rock is overlain by metasedimentary rock consisting of a lower mica gneiss and an upper garnetiferous mica schist. This metasedimentary rock probably correlates with the Lynchburg Formation (Conley and Henika, 1973, p. 30). It has been called the Ashe Formation, which is also correlated with the Lynchburg Formation (Rankin, Espenshade, and Shaw, 1973, p. 16).

The stratigraphic order of the metasedimentary rocks that overlie the basement as proposed by Conley and Henika (1973, p. 31) should be in reverse order and consists of a basement of granitic augen gneiss overlain by mica gneiss that in turn is overlain by garnet-mica schist. This reversal of stratigraphic order was determined by Van Price (personal communication) while mapping the geology of the adjoining Draper 7.5-minute quadrangle and surrounding area. From the Draper quadrangle Van Price and the writer were able to trace a thin, but consistent band of mica gneiss between the basement granitic augen gneiss and the garnet mica schist across the Spray quadrangle to the Virginia-North Carolina boundary.

GRANITIC AUGEN GNEISS

The granitic augen gneiss is exposed along the western edge of the Danville basin and in two smaller isolated fold cores surrounded by metasedimentary rock. The granitic augen gneiss is composed predominantly of porphyroblastic gneiss in which the porphyroblasts have been sheared into augen gneiss and locally into flaser gneiss. The unit contains foliated granite, biotite schist, and intrusive(?) amphibolite. In saprolite the extremely sheared gneiss has the appearance of being composed of alternating gneiss and schist layers. Closer examination reveals that these schist layers actually contain augen that have been reduced to paper thin lenticles.

MICA GNEISS

The mica gneiss overlies the granitic augen gneiss along a probable angular unconformity. This unconformity is inferred, as both rock types are polydeformed and have been transposed into a generally parallel relationship. The predominant lithology of the mica gneiss is a muscovite-biotite gneiss that contains interlayers of mica schist. Garnetiferous amphibolite is exposed both at the bottom and at the top of the mica gneiss unit. The basal part of the unit may contain micaceous quartzite and lenticular calcareous gneiss layers.

GARNET-MICA SCHIST

The garnet-mica schist is generally composed of biotite and subordinate muscovite and as much as 20 percent garnet. The rock is at lower amphibolite facies and may contain kyanite and large (2 cm) staurolite porphyroblasts. Retrograde chlorite is present near the Ridgeway fault. The unit may contain thin gneissic and graphite schist layers. Ultramafic rocks, generally altered to talc and amphibolite, are exposed in both the mica gneiss and the garnet-mica schist units.

SMITH RIVER ALLOCHTHON

The Smith River allochthon, which was named by Conley and Henika (1973, p. 42), is a synformal, rootless mass between the Blue Ridge anticlinorium to the northwest and the Sauratown Mountains anticlinorium to the southeast. It has been mapped from 37°00 N. southward to the Virginia-North Carolina boundary at a 1:24,000 scale (Conley and Toewe, 1968; Conley and Henika, 1970; Henika, 1971; Conley and Henika, 1973; Price, 1975; Henika 1977; unpublished recent mapping by the Division of Mineral Resources). The rocks of the allochthon have been traced northward and apparently terminate at about the Buckingham-Appomattox county boundary. Southward it has been traced (Rankin, Espenshade, and Neuman, 1972; Espenshade and others, 1975) as a narrowing wedge that finally terminates in the Brevard zone of North Carolina. The northwestern edge of the allochthon is bounded by the Bowens Creek fault and the southeastern edge by the Ridgeway fault (Conley and Henika, 1973). To the northeast the southeastern edge is bounded by the Chatham fault along the western border of the Danville basin, where it is marked by an extensive zone of cataclasis. The Chatham fault, however, extends to the northeast beyond the Danville basin. The Bowens Creek and Ridgeway fault planes were folded after emplacement as they show a sinuous trace with a number of embayments. A zone of cataclasis and retrograde metamorphism is present along the Bowens Creek fault ("cs" unit as mapped by Conley and Henika 1970; Henika, 1971; and Conley and Henika, 1973). Deformation and retrograde metamorphism is not as intense along the Ridgeway fault, although sheared rocks occur in a zone several hundred feet wide on either side of the fault and chlorite retrograded from biotite is abundant in intensely deformed schist adjacent to the fault (Conley and Henika, 1973, p. 33, 40, 46).

The Smith River allochthon is composed of two metasedimentary units, the Bassett Formation and the Fork Mountain Formation, named by Conley and Henika (1973, p. 10, 12). These metasedimentary rocks are intruded by a large pluton composed of felsic and mafic rocks, named the Martinsville igneous complex by Ragland (1974). This complex is composed of felsic rock, named the Leatherwood Granite by A. I. Jonas (Virginia Geological Survey, 1928) and a mafic sequence, named the Rich Acres Norite by Conley and Toewe (1968, p. 17) and renamed the Rich Acres Formation by Conley and Henika (1973, p. 25) so that it could include gabbro and diorite facies that were found during mapping of adjoining areas.

Bassett Formation

The lowest structural (and possibly oldest stratigraphic) unit in the allochthon is the Bassett Formation, which consists of a biotite gneiss overlain by amphibolite. The biotite gneiss is intruded by numerous altered mafic and ultramafic rock bodies ranging in composition from gabbro to metapyroxenite. The amphibolite probably represents mafic tuffs and basaltic lava flows. Textures resembling amygdules have been observed in the unit (Conley and Henika, 1970, p. 9). Gray, unfoliated granoblastic pyroxene granofels occurs as boudins and possibly dikes in the amphibolite.

Fork Mountain Formation

The Bassett Formation is overlain by the Fork Mountain Formation with a fairly sharp contact between them. The Fork Mountain is composed of two major lithotypes—garnet-mica schist and garnet-biotite gneiss. The garnet-mica schist was recognized by Jonas (1929, p. 508) who considered it to be Wissahickon Formation. She interpreted the polymetamorphism in this rock to be a product of extreme shearing and retrograde metamorphism along the Martic thrust fault.

The garnetiferous mica schist is subdivided into a staurolite schist that crops out adjacent to the Bowens Creek fault and a sillimanite schist that occurs farther to the southeast. Both units are partially to totally retrograded to sericite psuedomorphs after either staurolite or sillimanite. The contact between those two units is therefore a relict regional metamorphic isogradic boundary.

The garnet-biotite gneiss generally is in contact with rocks of the Martinsville igenous complex, and the theory was proposed that these rocks were produced as an aureole effect (Conley and Henika, 1973). In the vicinity of the igneous complex anatectic melting and feldspathization has occurred; however, the gneiss could be in part a stratigraphic unit with complex relationships with the garnet-mica schist. This is based on the widespread occurrence of garnet-biotite gneiss along the north-central and southeastern borders of the allochthon and sparsity of rocks of the igneous complex in this area. Discontinuous, thin quartzite and calc-silicate quartzite layers are common both in the gneiss and schist units.

Martinsville Igneous Complex

The Martinsville igneous complex underlies a large area along the southeastern border of the allochthon and occurs as a semiconcordant pluton. The mafic unit of this complex, the Rich Acres Formation, is composed predominantly of pyroxene gabbro but contains lesser amounts of norite and diorite. The Leatherwood Granite and associated pegmatites and alaskitic pegmatites generally occur as thin sheets at the top of the pluton. The two plutonic rock units, probably formed contemporaneously, as granite has been observed cutting gabbro as well as norite cutting granite. Retrograde metamorphism at greenschist facies and shearing were noted in the gabbro adjacent to the Ridgeway fault; thus the allochton was probably emplaced after intrusion of the complex.

Metamorphism

Three periods of metamorphism can be observed in the metasedimentary rocks of the Fork Mountain Formation. The first was regional metamorphism at amphibolite facies producing staurolite along the northwestern border of the formation and sillimanite to the southeast. The rocks were next retrograded to greenschist facies and sillimanite and staurolite were partially to totally altered to pseudomorphous sericite. This was followed by intrusion of the Martinsville igneous complex and development of a contact metamorphic aureole around the intrusion. Generally, anatactic melting occurred next to the pluton. Farther away, fine-grained sillimanite grew in sercite masses that are the sites of former regional sillimanite and staurolite. Still farther away from the pluton, sillimanite is replaced by kyanite and in turn is replaced by staurolite. Nonoriented chloritoid crystals that have grown in sites of retrograded sillimanite and staurolite are found beyond the staurolite zone, and an isograd delineating the first occurrence of chloritoid has been traced across the Bassett quadrangle by Henika (1971).

Correlation and Age

A fundamental question is, where and from what rocks did the Smith River allochthon originate? Rocks of the Smith River allochthon have been correlated with those of the Inner Piedmont belt of North Carolina (Conley and Toewe, 1968) where it is suggested that they originated (Conley and Henika, 1973). Rankin (1975, p. 320) agrees and he suggests that the bounding faults represent an ancient suture zone, which was transported westward. However, if the suggestion by Odom and Fullagar (1973) is correct that the Inner Piedmont belt is allochthonous, the important question might not be, did the Smith River allochthon root in the Inner Piedmont, but rather where does the Inner Piedmont root?

Regional metamorphism to sillimanite-grade and retrograde metamorphism to greenschist facies occurred prior to intrusion of the Martinsville igneous complex and associated contact metamorphism. Time of intrusion of the complex is suggested by the age of the Leatherwood Granite which has been dated at 450 million years old (Rankin 1975). Previous determination of a Precambrian age of 1,020 million years for the Leatherwood from Pb-U analyses by Isotopes Incorporated (Conley and Henika, 1973, p. 22 and Figure 14) is probably inaccurate; the raw data from those analyses was examined by Leroy Odom (written communication) who felt that there was too much dispersion in the analyses to produce a meaningful date. A logical interpretation from available data is that the allochthon was emplaced after intrusion of the Martinsville igneous complex. As Rankin, Espenshade, and Neuman (1972) and Espenshade and others (1975) show that the allochthon terminates in the Brevard zone, it is plausible that both of these structures developed during the same event. Odom and Fullagar (1973) by use of the Sr-Rb method have dated blastomylonites from the Brevard zone along strike to the southwest at 356 million years old. Additionally, Deuser and Herzog (1962) have made Rb-Sr age determinations from pegmatite micas emplaced in rocks along the Ridgeway fault, and found that they are 321 million years old. Potassium-argon dates from the Brevard zone in Alabama obtained by Wampler, Neathery, and Bentley (1971) are 300 million years old. It is concluded from this data that development of the Brevard zone and emplacement of the Smith River allochthon probably occurred between 300 and 356 million years ago. Rankin (1975, p. 321) feels that retrograde metamorphism of staurolite occurred after thrusting. Conley and Henika (1973) place retrograde metamorphism before emplacement of the Martinsville igneous complex and the regional growth of chloritoid during or after the intrusion. This would place regional retrograde metamorphism definitely before thrusting of the Smith River allochthon.

BLUE RIDGE ANTICLINORIUM

The Catoctin-Blue Ridge anticlinorium named by Jonas (1927, p. 840) is here shortened to the Blue Ridge anticlinorium. It includes rocks of the Blue Ridge and westernmost part of the Piedmont of Virginia and is a throughgoing structure exposed entirely across the State in a northeasterly-southwesterly direction. The anticlinorium is overturned to the northwest and the foliations have dips generally to the southeast (Whitaker, 1955). Exceptions are late cleavage folds such as the Cooper Creek anticline (Conley and Henika, 1970; Henika, 1971; Conley and Henika, 1973) that in places is upright.

Virginia Blue Ridge Complex

The core of the Blue Ridge anticlinorium is composed of pre-Grenville- and Grenville-age basement rocks intruded by upper Precambrian igneous rocks that were called the injection complex by Jonas and Stose (1939, p. 580) and were later renamed the Virginia Blue Ridge complex by Brown (1958, p. 7) and are shown as such on the "Geologic Map of Virginia" (Virginia Division of Mineral Resources, 1963). However, it must be recognized that there are many separately mappable units within this complex. In the widest place this core is over 20 miles (32 km) wide. It can be traced from south-central Maryland, where it plunges gently under a cover of upper Precambrian metavolcanic and metasedimentary rocks (Maryland Geological Survey, 1968) southwestward through Virginia into North Carolina. In Carroll County, southwestern Virginia, the basement is almost entirely overridden and cut out by the Fries thrust fault, the bounding front of one of several thrust sheets that make up the Blue Ridge of southwestern Virginia (Jonas and Stose, 1939; Rankin, Espenshade, and Neuman, 1972). However, to the southwest, toward the Virginia-North Carolina boundary, rocks of the complex are exposed in a wide band primarily in the Stone Mountain thrust sheet which underlies the Fries fault; these rocks are also exposed to the northwest of the Fries fault. The Fries fault has not been traced northeastward; however, a major refolded nappe that has been thrust to the northwest was reported in the central part of the core of the Blue Ridge anticlinorium by Gathright, Henika, and Sullivan (1977).

In general, augen gneiss and layered gneiss are the predominant lithologic units along the southeast limb of the anticlinorium whereas charnockitic rocks are more common toward the central and western limbs in the central part of the State. A number of formation names have been proposed for rocks of the Virginia Blue Ridge complex. These rocks have been correlated over wide areas, based on lithologic similarity by A. I. Jonas (Virginia Geological Survey, 1928), but the validity of some units over extensive areas is questionable and will remain so until detailed mapping is completed.

From reconnaissance mapping A. I. Jonas (Virginia Geological Survey, 1928) recognized several units in the Virginia Blue Ridge complex which she named and showed their areal extent. She (Virginia Geological Survey, 1928) named the Lovingston granite gneiss, which in part is an augen gneiss. It is shown in an area from Culpeper County southwestward to Franklin County along the southeast limb of the Blue Ridge anticlinorium. This unit was later renamed the Lovingston Formation and is shown as such by the Virginia Division of Mineral Resources (1963). Bloomer and Werner (1955, p. 582) and Batholomew (1971) find that the Lovingston is made up of a porphyroblastic to augen gneiss and granitic rock. Davis (1974) dated two size fractions of zircons from the Lovingston augen gneiss at 913 and 1,870 million years old. His interpretation of these two dates is that the augen gneiss is a metamorphosed clastic sediment containing zircons from a source that is 1,870 million years old and was metamorphosed at 913 million years ago. Quartz monzonite and pegmatite facies of the Lovingston were dated at 1,080-1,330 and 1,080-1,180 million years respectively (Davis, 1974).

A. I. Jonas (Virginia Geological Survey, 1928) also named the younger Marshall granite which is in the central part of the Blue Ridge anticlinorium from the Maryland boundary to Nelson County. She (Virginia Geological Survey, 1928) shows hypersthene granodiorite occurring discontinuously along the northwest limb of the anticlinorium from Fauquier County to northern Floyd County. This unit was originally called hypersthene syenite by Watson and Cline (1916) and was later named the Pedlar Formation by Bloomer and Werner (1955). It is considered by Herz (1968) to be charnockite, which is partly an intrusive and partly a granulite facies metamorphic rock. Zircons from a gneissic phase of the unit have been radiometrically dated at between 1,070 and 1,150 million years old by Davis and others (1958).

A number of igneous plutons intruded the central and northern parts of the Virginia Blue Ridge complex. The Roseland Anorthosite was named by Ross (1941). It is exposed in an area about 9 miles (14 km) long and 2.5 miles (4.0 km) wide that has intruded country rock, which is composed of charnockite, augen and granitic gneiss, and cataclastic rock (Hillhouse, 1960; Herz, 1968).

The Old Rag Granite, which was named by Furcron (1934), is probably older than the Pedlar Formation because a Pedlar-like intrusive cuts the granite on the crest of Old Rag Mountain, Madison County (Gathright, 1976). Lukert (1977), however, has obtained a discordant U-Pb age date of about 1,138 million years on the Old Rag Granite, suggesting that the Pedlar and Old Rag are about the same age. Rocks mapped as banded biotite gneiss by Conley and Johnson (1975) and layered gneiss by Lukert and Nuckols (1976) in the north-central part of the Virginia Blue Ridge complex were informally named the Flint Hill gneiss by Espenshade and Clarke (1976) and formally named the Flint Hill Gneiss by Lukert, Nuckols, and Clarke (1977) for exposures in a quarry 0.5 mile (0.8 km) east of the Flint Hill community. The Flint Hill Gneiss is considered to be a metamorphosed igneous rock because of its homogeneity. Zircon ages date it at 1,081 million years old; but it is cut by intrusive rocks of the Old Rag Granite dated at 1,140 million years. The suggestion is made that either both formed during the Grenville orogeny or the Flint Hill is older and has had its radiometric clocks reset (Lukert, Nuckols, and Clarke, 1977, p. 26).

The Robertson River Formation, which was named by Allen (1963), is composed of hornblende granite and syenite. Based on zircon U-Pb dates this formation was emplaced between 730 and 750 million years ago and is one of the youngest Precambrian plutons in the Virginia Blue Ridge complex (Lukert and Banks, 1969).

Nelson (1962) named the Crozet porphyritic granite, which has only been recognized in Albemarle County. The Rockfish granodiorite, which is an intrusive into granitoid rocks of the Lovingston Formation, has been dated by Davis (1974) to be 820 million years old.

In the southwestern part of the Virginia Blue Ridge complex, Dietrich (1959) gave the name Little River gneiss to gneiss and augen gneiss in Floyd County. He concluded that the Little River gneiss was of sedimentary origin and correlated it with Lovingston gneiss. Espenshade and others (1975) place this unit and the Cranberry Gneiss in the Elk Park Group, named by Rankin (1970) for Elk Park, North Carolina. The Cranberry granite, named by

Keith (1903) and renamed Cranberry Gneiss by Bryant (1962), has been mapped in reconnaissance northeastward into southwestern Virginia by Rankin, Espenshade, and Neuman (1972) and Espenshade and others (1975). It occurs primarily in the Blue Ridge thrust sheet. In Virginia the Cranberry was called the Grayson granite gneiss by A. I. Jonas (Virginia Geological Survey 1928); however, the name Cranberry has precedence. Additionally, Espenshade and others (1975) consider the Saddle gneiss, Cattron diorite, Beaverdam Creek augen gneiss, Comers granite, and Shoal gneiss (cataclastic), all named by Stose and Stose (1957), as part of the Cranberry Gneiss. Fullagar and Odom (1973) obtained a Rb-Sr whole-rock date of 1,252 ± 45 million years from the Cranberry Gneiss of central Ashe County, North Carolina. They note that these and other dates from the Elk Park Group are older than the Grenville orogeny and are some of the oldest dates reported from the Blue Ridge. They consider them to be coeval with and genetically related to buried basement of the interior platform (Fullagar and Odom, 1973, p. 3077).

The Striped Rock granite and Carsonsville granite named by Stose and Stose (1957) are included by Espenshade and others (1975) in the Crossnore plutonic-volcanic group, which is a sequence of upper Precambrian felsic and mafic rocks named by Rankin (1970, p. 231).

LYNCHBURG FORMATION

The Lynchburg Formation was named by Jonas (1927, p. 845) for the City of Lynchburg, where it is typically exposed. The formation, as mapped by the Virginia Division of Mineral Resources (1963), constitutes much of the rock considered to be Loudoun Formation by the Virginia Geological Survey (1928) and by Furcron (1935, Plate 1), which is shown to underlie the Catoctin greenstone from northern Virginia almost to Amherst.

The Lynchburg Formation occurs along the southeast flank of the Blue Ridge anticlinorium from northern Virginia to the North Carolina boundary (Virginia Division of Mineral Resources, 1963). In northern Virginia, Parker (1968) mapped Precambrian metasedimentary rocks under the Catoctin Formation on both limbs of the Blue Ridge anticlinorium which he called the Swift Run Formation. Espenshade and Clarke (1976) questioned whether these rocks on the southeast limb of the fold should be called the Swift Run because they do not contain tuffaceous rocks and comprise a considerably thicker deposit than the normal Swift Run. Additionally, boulder conglomerate in this metasedimentary unit on the southeast limb of the anticlinorium is similar to the Rockfish conglomerate of Nelson (1932) which is at the base of the Lynchburg Formation in Albemarle County.

Lower Contact

Jonas (1927, p. 845) originally thought that the Lynchburg was the oldest unit in the Blue Ridge anticlinorium and that it had been intruded by the granitic rocks of the Virginia Blue Ridge complex. Jonas and Stose (1939) were convinced that the Lynchburg unconformably overlies the granitic rocks in the core of the anticlinorium after discovery by Nelson (1932, p. 456) of the Rockfish conglomerate at the base of the Lynchburg, which contains lithic cobbles derived from the Virginia Blue Ridge complex.

Dietrich (1955, p. 284) questions the Rockfish being a basal conglomerate. He indicates that the Rockfish-type deposits are lenticular masses that occur at several stratigraphic horizons. Later mapping (Conley and Henika, 1970; Henika, 1971; Conley and Johnson, 1975) supports this conclusion. Additionally, the Rockfish at its type locality is a graywacke conglomerate that shows graded bedding indicative of a normally lenticular turbidite deposit.

During field mapping in central Virginia Conley and Johnson (1975) observed the contact in several places between the Lynchburg and rocks of the Virginia Blue Ridge complex (which consist of either augen gneiss or Robertson River Formation). In each instance this contact was a thin biotite schist zone that does not exceed a meter in thickness. Foliation is generally parallel in both the rocks of the Virginia Blue Ridge complex and the Lynchburg due to later deformation, thus erasing primary evidence for an unconformity. In central Virginia Bloomer and Werner (1955) found a gradational contact zone between the Lynchburg and the core rocks ranging from a few to several tens of feet across. They suggest that this zone is a saprolite developed on the rocks of the complex on which the Lynchburg was deposited.

From Lynchburg southwestward, the Marshall and Lovingston gneisses in the core of the Blue Ridge anticlinorium are separated from the Lynchburg Formation by the Moneta gneiss. In the Moneta-Bells area southwest of Lynchburg Pegau (1932) recognized the Moneta gneiss as being a unit composed of biotite gneiss and interlayered amphibolite gneiss that is different from the Lynchburg Formation. Diggs (1955) in the Otter River area recognized that the Moneta gneiss underlies the Lynchburg with a sharp to gradational contact between the two units. He found that the contact between the Moneta and the underlying Lovingston gneiss was gradational. Brown (1951, 1953, 1958) named a hornblende gneiss, which was injected with leucogneiss, the Reusens migmatite facies of the Moneta gneiss because this unit was obviously in part equivalent to the Moneta gneiss of Pegau (1932) and Diggs (1955). He considered the new name was justified because the Moneta gneiss of Pegau (1932) and Diggs (1955) does not contain migmatite and probably contains some rocks of the Lynchburg Formation.

Farther to the southwest in the area north of Bassett, Henika (1971) found that an amphibolite layer separated the layered biotite gneiss of the Moneta and the recognizable metasedimentary rocks of the Lynchburg Formation. Recent mapping by the Virginia Division of Mineral Resources in four adjacent quadrangles shows that this amphibolite persists to the northeast on both limbs of the Cooper Creek anticline. The Lynchburg probably is tightly infolded into the Moneta, based on geologic mapping by M. B. McCollum in parts of the Redwood and Moneta Southwest quadrangles. He has mapped elongate, parallel folds with wavelengths of about 0.6 mile (1.0 km) or less. They produce a repetitive sequence consisting of Moneta-amphibolite-Lynchburg-amphibolite-Moneta. Infolding of Lynchburg Formation with the Moneta was not recognized by Pegau (1932) and therefore Brown (1958) was probably correct in his observation that the Moneta in the type area probably contains some Lynchburg Formation. The question can also be asked as to whether or not the amphibolite is interlayered with the biotite gneiss of the Moneta gneiss as suggested by Pegau (1932) or is stratigraphically on top of the Moneta.

Rankin, Espenshade, and Shaw (1973, p. 35) consider the Moneta as mapped by Conley and Henika (1970) to be equivalent to the Ashe Formation of Rankin (1970), which they correlated with the Lynchburg Formation.

Possible interpretations of the origin of the Moneta gneiss could be (1) sheared and recrystallized augen gneiss of the Grenville basement based on the striking resemblance to Grenville-age sheared augen gneiss in the Sauratown Mountains anticlinorium (Conley and Henkia, 1970), (2) a sequence of rocks between the Lynchburg Formation and Grenville basement, or (3) Lynchburg metasedimentary rocks of higher metamorphic grade in which all metasedimentary textures have been miraculously erased across a thin amphibolite zone. To discover the origin of the Moneta will require further research. Regardless of its origin, the Moneta is a homogeneous mappable gneiss unit below a heterogeneous sequence of recognizable clastic metasedimentary rocks of the Lynchburg Formation. The Moneta is generally separated from the recognizable metasedimentary rocks of the Lynchburg by a persistent amphibolite layer, which the writer would interpret as a basal metabasalt of the Lynchburg Formation with possible associated intrusive dikes and sills.

Stratigraphy

Disseminated pyrite and graphite as well as pyritic graphite schist are ubiquitous to the Lynchburg Formation from west of Culpeper to northwest of Martinsville. The Lynchburg is marked by rapid facies changes both laterally and vertically. It is generally made up of a lower sequence of interlayered metamorphosed graywacke, graywacke conglomerate, and mica schist. Toward the top of the section in the central and southwestern parts of Virginia, mica schist and graphite schist are more common and metagraywacke is less abundant. Quartzite may occur locally in the upper part of the formation and marble lenses have been found from northern Virginia to Rocky Mount. The lower and middle parts of the formation are intruded by gabbro sills and generally concordant ultramafic rocks. The Lynchburg may locally contain considerable amounts of fine-grained, generally massive, schistose intrusive and/or extrusive metabasalt that contains little or no recognizable volcanic textures.

On U. S. Highway 522 between New Salem Church and Griffinsburg northwest of Culpeper meta-arkose occurs at the base of the Lynchburg. This arkose, except for rounded quartz pebbles, is generally hard to distinguish from underlying quartzo-feldspathic gneiss in the core of the Blue Ridge anticlinorium. Upward in the stratigraphic section to the southeast the arkose is superceded by metagraywacke and interlayered mica schist. Meta-arkose is more common to the northeast along strike in rocks that are the stratigraphic equivalent of the Lynchburg Formation (Bloomer and Werner, 1955, p. 583; Furcron, 1969). These rocks were named the Fauquier formation by Furcron (1939, p. 36) for a sequence of slate, schist, biotite gneiss, and marble that he mapped in the Warrenton 15-minute quadrangle. The Fauquier formation differs from the Lynchburg in that it contains cross-bedded meta-arkose rather than the normal graded metagraywacke characteristic of fluvial rather than turbidite deposits (Espenshade and Clarke, 1976). Theismeyer (1939) has described bluish slate with graded bedding from the Fauquier formation, which he suggests might represent glacial varves. An alternate explanation might be that they are distal turbidite deposits.

Several researchers have attempted to subdivide the Lynchburg into separate formations. Furcron (1969, p. 72-76) revised the Fauquier formation and called it the Lynchburg Group. Furcron divided it into a lower, Bunker Hill formation, composed of meta-arkose and gray slate and retained the name Fauquier formation for the upper unit composed of gneiss, schist, slate, and marble. Espenshade and Clarke (1976, p. 7) can find no evidence for Furcron's two-fold division of the stratigraphic unit. They agree that these rocks are an on-strike equivalent of the Lynchburg, but would prefer to retain the name Fauquier formation because of variations in lithology with the Lynchburg at its type locality.

Nelson (1962) subdivided the Lynchburg Formation in Albemarle County into the Rockfish conglomerate formation, the Lynchburg gneiss (containing varve-like layers of graphite and sericite schist) formation (restricted), the Johnson Mill graphite slate formation, and Charlottesville (quartz-biotite gneiss and calcareous gneiss) formation. The Charlottesville formation is intruded by soapstone dikes (sills?) Nelson, 1962, p. 22).

Although units within the Lynchburg were not given formal names in the Philpott Reservoir quadrangle, Conley and Henika (1970) recognized a lower sequence of metagraywacke and mica schist, a middle unit of metagraywacke and metabasalt, and an upper unit of graphite schist with minor interbeds of quartzite, metagraywacke, and calcareous gneiss. Additional mapping to the northeast (Henika, 1971; M. B. McCollum, personal communication, 1977) shows that these units are lenticular and subject to rapid facies changes.

In North Carolina Rankin (1970) named the Ashe Formation for a fine-grained mica gneiss with interlayered amphibolite that nonconformably overlies the Cranberry Gneiss of pre-Grenville age. The Ashe is correlated with the Lynchburg and possibly also the Swift Run and Catoctin formations in Virginia (Rankin, 1970, p. 235). Later, Rankin, Espenshade, and Shaw (1973, p. 17) retained the name Ashe Formation for the lower part of the unit, but they proposed the name Alligator Back Formation for the gneiss, pelite, amphibolite, and minor quartzite and marble at the top of the unit. They recognize a gradational contact between the Ashe Formation and Alligator Back Formation and correlate the Alligator Back with rocks of the Evington Group.

Upper Contact

The Lynchburg Formation, including the Fauquier formation of the Warrenton area, is directly overlain by the Swift Run Formation. The Swift Run occurs as lens-shaped masses at the base of the Catoctin and may or may not be present. In its absence the overlying Catoctin Formation is in contact with the Lynchburg. This relationship is found on the southeastern limb of the Blue Ridge anticlinorium from northern Virginia southwestward to a point approximately two-thirds of the way between Charlottesville and Lynchburg. From this point southwestward to south of Smith Mountain Lake the Lynchburg Formation is in fault contact with the Candler Formation. Espenshade (1954, p. 34-35) states that faulting has occurred along the contact between the Lynchburg and overlying Candler Formation throughout the 60-mile extent of his mapped area. He does not consider this fault to have any great amount of displacement. If Espenshade is correct that the Lynchburg is overthrust by the Candler, then the top of the Lynchburg is not exposed at its type area. This would explain why the Lynchburg Formation at Lynchburg contains the relatively uniform sequence of metagraywackes generally found near the base of the unit and does not contain abundant pelites near the top of the section as is found in the Philpott Reservoir quadrangle to the southwest (Conley and Henika, 1970) and in Albemarle County to the northeast (Nelson, 1962). The obvious reason is that those upper units are cut out by faulting at Lynchburg, the type locality. From south of Smith Mountain Lake to Philpott Reservoir the Lynchburg is in fault contact with rocks of the Smith River allochthon.

Environment of Deposition

Brown (1973, p. 381-382) proposes a model for the environment of deposition of the Lynchburg Formation during separation of North America and Africa and the formation of a proto-Atlantic Ocean in late Precambrian time. He notes that as separation began subsidence occurred along the North American plate, and pebbly graywacke and boulder conglomerate were deposited. This was followed by continued separation of plates, and the eastward deposition of turbidite deposits. This model is similar to models of development of initial rift systems described by Dewey and Bird (1970, p. 2629) and Dewey and others (1973, p. 3150). It seems to explain the presence of fluvial-deltaic arkoses and cross-bedded arkoses of the Fauquier formation in the Warrenton area, which were deposited in the initial stages of rifting as fluvial-deltaic deposits built outward in a narrow graben-like basin. These deposits are replaced to the southwest by turbidite deposits and turbidite deposits with interlayered basalts, as the basin deepened and widened in that direction. With time the basin continued to widen and was filled with sediments. Pyrite and graphite throughout the Lynchburg indicates that it was deposited in a restricted anaerobic basin. The clastic turbidite deposits were gradually replaced by muds and organic-rich muds and limestones. If the Lynchburg was deposited in a widening rift basin as suggested by Brown (1973) the questions could be asked: is this the reason that the Lynchburg is confined to the southeast limb of the Blue Ridge anticlinorium (except possibly in the northern part of the area where it is mapped as occurring on both limbs of the structure by Parker, 1968) and is the morthwestern contact between the Lynchburg and rocks in the core of the anticlinorium a fault surface which marks the western boundary of the rift basin?

Age

The Lynchburg Formation is in contact with, but not intruded by, the igneous rocks of the Robertson River Formation. Therefore the Lynchburg is younger than the Robertson River dated by Lukert and Banks (1969) at between 730 and 750 million years old. Earliest identifiable Cambrian fossils occur considerably higher in the stratigraphic section, at the top of the overlying Chilhowee Group (Walcott, 1892, p. 52-57 and King, 1950, p. 24). For these reasons the Lynchburg is here considered of late Precambrian age.

Mechum River Formation

Gooch (1954, 1958) mapped a sequence of low-rank metasedimentary rocks in a narrow band from less than 0.6 mile (1 km) to over 1.5 miles (2 km) wide and about 60 miles (96 km) long that is exposed from near Amissville in Rappahannock County to southwest of Crozet in Albemarle County. This unit is contained totally within the Virginia Blue Ridge complex. Gooch (1958, p. 571) considered the unit that he called the Mechum River metasedimentary rocks to be in a structural feature that he named the Batesville syncline. Allen (1963) named the unit the Mechum River Formation and Schwab (1974a) also used the name Mechum River Formation.

The unit is composed of metamorphosed conglomerate, sandstone, and phyllite (Gooch, 1958, p. 572) that ranges from 1,500 to 3,000 feet (457 to 914 m) thick (Schwab, 1974b). Gooch (1954) notes graywacke and rocks that show graded bedding in the unit and concludes that it is a geosynclinal deposit. Allen (1963, p. 32) also reports graywacke in the Mechum River Formation. Schwab (1974a, b) suggests that the formation is of fluvial origin because of channel deposits, cross bedding, and the fining upward of the metasediments as well as absence of graded bedding and detrital matrix in the clastic metasediments.

Gooch (1958) concludes that the structure is a synclinal infold that may be faulted in places along the contact with basement rocks. Conley and Johnson (1975) suggest that in the area west of Culpeper, that the Mechum River Formation unconformably overlies augen gneiss in the core of the Blue Ridge anticlinorium and is in fault contact with the Robertson River Formation to the southeast. Nelson (1962, p. 24) considers the Batesville syncline to be a graben structure. Brown (1973) proposes that the Batesville syncline containing the Mechum River Formation is a partly faulted infold of Lynchburg Formation that developed because of fragmentation during separation of North America from Africa in late Precambrian time. He notes that development of the Batesville syncline is similar to development of Triassic basins in the Piedmont.

Gooch (1958) correlates the Mechum River Formation with the Lynchburg Formation and with the Swift Run Formation, which he considers to be a western facies of the Lynchburg. Nelson (1962, p. 24) thinks that the Mechum River contains the basal Rockfish conglomerate of the Lynchburg, which is overlain by the Swift Run Formation. Allen (1963, p. 32) notes that the Mechum River is lithologically similar to the Lynchburg but considers it to be a separate Precambrian unit. As previously noted, Brown (1973) considers the Mechum River to be a faulted infold of Lynchburg Formation. Espenshade and Clarke (1976, p. 7) note the similarity between the Mechum River and the Fauquier formations.

Cross-bedded conglomerate and arkosic sandstone (Conley and Johnson, 1975, stops 5 and 6, p. 32) are similar to arkosic rock found in the basal Lynchburg west of Culpeper and in the Fauquier formation, an on-strike equivalent of the Lynchburg in the Warrenton area. Phyllite having graded bedding (Conley and Johnson, 1975, Stop 6, p. 32) is similar to varved slate described by Thiesmeyer (1939) in the Fauquier formation. It is probably not a stratigraphic equivalent of the Swift Run Formation, based on the absence of felsic volcanic tuff beds and tuffaceous sedimentary rocks. The most plausible correlation is with the Lynchburg and its on-strike equivalent, the Fauquier formation. It was probably deposited in a fluvial environment as suggested by Schwab (1974a, b) and in a Triassic-like half-graben that developed as a flanking structure to the main graben in which the Lynchburg Formation was being deposited during the beginning of separation of North America from Africa (Dewey and Bird, 1970, p. 2629; Brown, 1973). The presence of graywacke (Gooch 1954 and Allen 1963) and phyllite with graded bedding lead to the interpretation that the fluvial deposits were possibly replaced by turbidites as the basin widened and deepened, which is similar to the proposed evolution of the Lynchburg-Fauquier basin.

SWIFT RUN FORMATION

The Swift Run tuff was recognized by Jonas and Stose (1939) and named by Stose and Stose (1946) for exposures on U. S. Highway 33 just east of Swift Run Gap. Bloomer and Bloomer (1947, p. 95) named the Oronoco formation from Oronoco Post Office, Amherst County. Bloomer (1950) considers the Oronoco and Swift Run as the same unit and suggests the abandonment of the name Oronoco formation. King (1950, p. 9) changed the name of the unit to Swift Run Formation because of the subordinate tuffaceous element to clastic metasedimentary rocks in the Elkton area.

Bloomer and Bloomer (1947) recognized that considerable relief had developed on the rocks of the Virginia Blue Ridge complex prior to deposition of the Swift Run Formation (Oronoco formation). Reed (1955, p. 887) estimates that as much as 1,000 feet (305 m) of relief was developed on the pre-Swift Run-Catoctin surface and Gathright (1976, p. 87) estimates more than 2,000 feet (610 m) of relief on this surface. The rather discontinuous occurrence of the Swift Run is therefore attributed to the fact that it is in part fluvial meta-arkose and clastic sedimentary rock, and thus would only have been deposited in valleys in streams flowing on this ancient erosion surface (Reed, 1955, Figure 3; King, 1950, Figure 4). The Swift Run Formation is varied in composition and may contain arkosic quartzite; arkosic metaconglomerate; brown, gray, and purple tuffaceous slate; felsic metatuff; thin metabasalt; and volcano-clastic rock (King, 1950, p. 10; Gathright, 1976, p. 18). The meta-arkose probably was derived from the Virginia Blue Ridge complex as King (1950) notes that many of the quartz grains and pebbles in the clastic metasedimentary rocks are blue in color and speculates that they were derived from blue quartz-bearing rocks of the complex. The contact between the Swift Run Formation and the overlying Catoctin Formation is indefinite; King (1950) chooses the contact to be at the base of the lowest massive greenstone.

Stose and Stose (1946, p. 28) propose that the Lynchburg Formation on the southeast limb of the Blue Ridge anticlinorium is equivalent to the Swift Run on the northwest limb. This correlation was accepted by Bloomer (1950) who thinks that the Swift Run is the thinned western edge of the Lynchburg and further proposes that all rocks from the Lynchburg through the Chilhowee Group are conformable. Although the Lynchburg contains metabasalts, the felsic metavolcanic rocks in the Swift Run are totally absent from the Lynchburg. Also, the Swift Run occurs on top of the Lynchburg on the southeast limb of the Blue Ridge anticlinorium (Nelson, 1962, Plate 1). During field mapping for geophysical studies (Conley and Johnson, 1975) thin discontinuous lenses of Swift Run meta-arkose and felsic metatuff were observed on top of the Lynchburg in at least three places between Culpeper and Charlottesville. This is an indication that the Swift Run is not a continuous band overlying the Lynchburg as shown by Nelson (1962), but that it occurs as thin lenses of valley fill at the base of the Catoctin similar to its occurrences on the northwest limb of the Blue Ridge anticlinorium. The Swift Run lenses on top of the Lynchburg could be indicative of an erosion surface with considerable relief, not only developed on rocks of the Virginia Blue Ridge complex on the northwest limb of the Blue Ridge anticlinorium, but also on the Lynchburg Formation on the southeast limb. Furthermore, the arkose on the southeast limb of the structure is an indication that the rocks of the Virginia Blue Ridge complex, or similar granitic rocks, were the source of the meta-arkose on both limbs of the anticlinorium.

One of the best exposures of Swift Run Formation on the southeast limb of the Blue Ridge anticlinorium is located just northwest of Priddy Creek Church, approximately 1.4 miles (2.2 km) northwest of Stony Point, Albemarle County. The stratigraphic section consists of Lynchburg metagraywacke and interlayered schist overlain by the Swift Run Formation composed of a basal coarse (1 to 2 cm) quartz-feldspar-arkoses showing little or no metamorphic textures, and an upper felsic metavolcanic sequence. A thin section (R-3221) of drill core composed of felsic metavolcanic rock from a borehole (W-1719, at 95 feet or 29 m) in the vicinity of the Stony Point copper mine (Nelson, 1962, p. 66) was examined by R S. Good who reports that the rock is a lapilli tuff, containing what seems to be collapsed pumice fragments and resembles a welded tuff. If this rock is a welded tuff, then at least part of the Swift Run Formation was probably subaerially deposited.

CATOCTIN FORMATION

The Catoctin schist was named by Geiger and Keith (1891, Plate 4) in the legend of a map and was described by Keith (1894). Furcron (1935, p. 405) called the unit Catoctin basalts, which he later changed to Catoctin series (Furcron, 1939). Stose and Stose (1946, p. 20) referred to the unit as Catoctin metabasalt and Bloomer and Bloomer (1947) were the first to name it the Catoctin Formation.

The Catoctin Formation occurs on both the northwest and southeast limbs of the Blue Ridge anticlinorium from the Maryland boundary southward to an area between Charlottesville and Lynchburg, where it thins and dies out on both limbs of the structure.

Lower Contact

Keith (1894) thought that the Catoctin was intruded by granitic rock of the Virginia Blue Ridge complex. Furcron (1934, p. 405) suggested that the Catoctin metabasalt flowed out on an eroded surface developed on granodiorite, but was intruded by the Old Rag Granite. Later, Furcron and Woodward (1936, p. 47) stated that they believe the hypersthene granodiorite (Pedlar Formation) of the Virginia Blue Ridge complex is also intrusive into the Catoctin. Stose and Stose (1946) recognized that Catoctin-like dikes (feeder dikes for Catoctin metabasalt) cut rocks of the complex, and they refute the idea that rocks of the complex intrude the Catoctin.

Where valley-fill rock of the Swift Run Formation is present, the Catoctin Formation conformably overlies this unit. In areas on the northwest flank of the Blue Ridge anticlinorium, where the Swift Run Formation is absent (presumably on topographic highs developed on rocks of the Virginia Blue Ridge complex in pre-Swift Run time) the Catoctin metabasalt nonconformably overlies rocks of the Virginia Blue Ridge complex. Such an area is located on the south side of U. S. Highway 33 at Swift Run Gap. Because the Swift Run is frequently absent on the southeast limb of the Blue Ridge anticlinorium, the Catoctin in most places overlies the Lynchburg Formation. As previously noted the Lynchburg-Swift Run contact is an erosional surface and it can be logically suggested that in the absence of the Swift Run, the Lynchburg-Catoctin contact is also an erosional unconformity.

Stratigraphy

The Catoctin Formation is from 2,000 feet (610 m) (Gathright, 1976) to 2,200 feet (671 m) thick (Lukert and Nuckols, 1976) and thins to the northeast where it ranges from 0 to 50 feet (15 m) at the Potomac River (Nickelsen, 1956, p. 245). It is composed primarily of metabasalt flows ranging from 75 to 150 feet (23 to 46 m) in thickness (Lukert and Nuckols, 1976, p. 31). It also contains metamorphosed sandstone, conglomerate, volcanic breccia, and tuff interlayered between the metabasalt flows (Gathright, 1976, p. 19). Rhyolitic metatuffs are found in the lower part of the Catoctin in the Linden quadrangle (Lukert and Nuckols, 1976, p. 29) and rhyolite in the Ashby Gap (Gathright and Nystrom, 1974) and Lincoln quadrangles (Espenshade and Clarke, 1976, p. 8). Metavolcanic agglomerate of basaltic composition, named the Warrenton agglomerate member of the Catoctin series by Furcron (1939, p. 20), occurs in the lower part of the Catoctin from north of The Plains to southwest of Warrenton in Fauquier County (Espenshade and Clarke, 1976, p. 9).

The metabasalt in the Catoctin contains an abundance of primary textures including flow lines; amygdules filled with either, or combinations of, epidote, calcite, quartz, and jasper; volcanic breccias (collapsed flow tops); and columnar joints (Gathright, 1976, p. 21-23). Reed (1955, p. 884) notes that amygdules can be found in almost every outcrop of metabasalt.

Some of the metabasalt is purple in color but does not show a difference in chemical composition from normal Catoctin metabasalt (personal communication, J. C. Reed, Jr., 1967). This purple color undoubtedly represents a higher oxidation state. Purple phyllite occurs as interlayers between some of the metabasalt flows. Keith (1894, p. 324 and Keith *in* Williams and Clark, 1893, p. 68) recognized a sequence of purple phyllite, metaconglomerate, feldspathic meta-sandstone, and marble between the Catoctin and Weverton formations, which he named the Loudoun formation. On the older edition of the "Geologic Map of Virginia" (Virginia Geological Survey, 1928) the Loudoun formation is shown as both underlying and overlying the Catoctin greenstone. Stose and Stose (1946, p. 34) place the Loudoun on top of the Catoctin but state that in Loudoun County, the Loudoun overlaps the Catoctin and Swift Run and rests directly on rocks of the Virginia Blue Ridge complex. In the Elkton area King (1950, p. 16) considers the Loudoun to be a dull purple spotted slate of pyroclastic origin, averaging about 100 feet (30 m) thick, that probably unconformably overlies the Catoctin.

Furcron and Woodward (1936) report a purplish-red slaty lava flow in the Stony Man quadrangle, Page County, that overlies the Catoctin and is overlain by the Loudoun. King (1950) believes that much of this flow is of pyroclastic origin and is equivalent to his Loudoun Formation and that the overlying Loudoun Formation of Furcron and Woodward (1936) is not Loudoun but Weverton Formation.

Reed (1955, p. 892-893) essentially agrees with Furcron and Woodward (1936) that the oval-shaped spots are amygdules, although they could be altered phenocrysts. Reed (1955, p. 873) further suggests that the purple slate in which they occur is a metamorphosed saprolite developed on the Catoctin prior to deposition of the Chilhowee Group. The writer has examined thin sections of these supposed amygdules from the west side of Rockfish Gap, Augusta County. They have a dark dense nucleus and a lighter rim; faint concentric banding may be developed in some individual samples. These masses resemble accretionary lapilli more than amygdules. They seem to be of the same composition as the surrounding matrix, whereas amygdules would be expected to be different, as they would be filled with a mineral or minerals from an external source. Toewe (1966, p. 4), Gathright and Nystrom (1974, p. 11), Rader and Biggs (1975, p. 9), Lukert and Nuckols (1976, p. 35), and Gathright (1976, p. 25) have recognized this purple slate at the top of the Catoctin, but consider it part of the Catoctin and not a separate formation.

Upper Contact

The Catoctin is overlain by the Weverton Formation along the northwest limb of the Blue Ridge anticlinorium and the contact of these two units is shown around the nose of the structure (Maryland Geological Survey, 1968) to the southeastern corner of the Lincoln quadrangle (Parker, 1968, Plate 1). To the southeast it is covered by Triassic sedimentary rock of the Culpeper basin. Where the top of the Catoctin has again been mapped in the Rapidan quadrangle southeast of the Culpeper basin (Conley and Johnson, 1975, p. 34), it is not overlain by the Weverton, but by the Candler Formation. Nelson (1962, p. 30) calls the purple phyllite of the Candler Formation the Loudoun Formation in Albemarle County. It seems doubtful but not impossible that the thin zone of purple tuff at the top of the Catoctin Formation could become the wide outcrop belt of Candler Formation in the central Piedmont of Virginia. This problem can not be resolved at present because of lack of data and will have to wait until geologic maps are available for the intervening area to the northeast.

There is little agreement in the literature as to whether an unconformity exists between the Catoctin Formation and the overlying Chilhowee Group on the northwest limb of the Blue Ridge anticlinorium. Bloomer and Bloomer (1947, p. 106), Cloos (1951, p. 25-28), Whitaker (1955, p. 44), Nickelsen (1956, p. 246), and Werner (1966, p. 21) working in different areas, all consider the contact between the Catoctin and Chilhowee to be gradational and do not recognize an unconformity between the two units. Furcron and Woodward (1936, p. 51), however, note that the purple lava flow (purple Loudoun phyllite at the top of the Catoctin Formation of present usage) was eroded before deposition of the Cambrian sediments (Chilhowee Group). Later workers (Toewe, 1966, p. 4; Gathright and Nystrom, 1974, p. 10; Rader and Biggs, 1975, p. 11; and Lukert and Nuckols, 1976, p. 35) are in agreement that there is an erosional unconformity between the Catoctin Formation and the Chilhowee Group and Gathright (1976, p. 26) proposes that up to 100 feet (30 m) of relief had developed on the eroded Catoctin surface before the deposition of the basal Chilhowee. T. M. Gathright II (personal communication, 1978) also found subrounded pebbles of greenstone and purple phyllite derived from the Catoctin in the basal Chilhowee.

Environment of Deposition

Bloomer (1950, p. 773) thinks that the Catoctin metabasalts are lavas deposited in a geosynclinal environment. Brown (1958, p. 24) agrees with Bloomer that the Catoctin is "analgous to spilitic lavas which characterize euogeosynclinal environments about the world." Brown (1973, p. 381) later proposed that the Catoctin was deposited partly on land and partly at sea. Bloomer and Werner (1955, p. 592) determined that Catoctin feeder dikes are of the same composition as the basaltic lava flows. As the feeder dikes could not have been exposed to sea water, they propose that spilitization was caused by deuteric alteration.

Reed (1955, p. 893-894) proposes that the Catoctin is a subaerial tholeiitic plateau flood basalt as shown by columnar jointing, absence of pillow structures, and wide areal extent of individual flows. Albite as the feldspar in these flows is produced by low-grade metamorphism of more calcium-rich feldspars and not by reaction with sea water. Analyses of rare-earth and trace elements of Catoctin samples from Virginia, Maryland, and Pennsylvania show that they are very similar in composition to average continental plateau basalt (Davis, Blackburn, and Brown, 1978, p. 166). The presence of flow-top breccias, ash-flow tuffs (Gathright, 1976, p. 23-24), volcanic agglomerates (Furcron, 1939, p. 20-22; Espenshade and Clarke, 1976, p. 8), fluvial metasedimentary layers in the Catoctin containing volcanic material eroded from the metabasalts (Conley and Johnson, 1975, p. 30), and possible lapilli tuffs all are indicative of a subaerial-fluvial origin of the lava flows, tuff, and metasedimentary rocks which compose the Catoctin Formation. As pointed out by Reed (1955, p. 884) amygdules are present in almost every Catoctin flow. These amygdules are generally of large size and could not have formed in water of any great depth because as water depth increases water pressure increases and the size of amygdules decrease. With increasing water depth, water pressure would eventually equal gas pressure of the magma, thus preventing vesiculation (Jones, 1966). The Catoctin is a subaerial deposit similar to other flood basalt provinces, which Dewey and others (1973, p. 3151) propose are deposited during initial oceanic opening. Brown (1958, Plate 1) shows the Catoctin metabasalt interlayered with euogeosynclinal metasedimentary rocks near the top of the Lynchburg Formation at Lynchburg. This metabasalt does not contain the obvious amygdules typical of the Catoctin, but is more like metabasalt thought to be deep-water flows mapped in abundance in the Lynchburg Formation farther to the southwest (Conley and Henika, 1970; M. B. McCollum, personal communication, 1977). This rock interlayered with the Lynchburg Formation could well be a spilitic basalt deposited in a euogeosynclinal environment as suggested by Brown (1958, p. 24), but it should not be confused with subaerial Catoctin metabasalt.

Age

Catoctin metabasalt dikes of the same composition as the Catoctin metabasalt flows cut the intrusive rocks of the Robertson River Formation (Conley and Johnson, 1975, p. 31). Therefore, the Catoctin must be younger than the Robertson River Formation dated at between 730 and 750 million years old (Lukert and Banks, 1969). Rankin and others (1969, p. 741-744) have obtained a discordant date of 820 million years old by plotting Pb-U ratios of rhyolite from the Grandfather Mountain Formation in the Blue Ridge of North Carolina, the Mount Rogers Formation in the Blue Ridge of southwestern Virginia, and the Catoctin Formation in southern Pennsylvania. These three widely separated formations were apparently thought to be the same age because they were underlain by a billion year-old basement and overlain by rocks of the Chilhowee Group. Since publication of this 820 million years date, Bartlett and Kopp (1971, p. 293-294) report the discovery of a well-preserved linguloid brachiopod in a float cobble from the Mount Rogers Formation. The fossil was not found in place but field research, textural features, and mineralogic composition of the enclosing matrix are indicative of rock that could be derived from the site in which it was found. Williams and Stevens (1974, p. 785) point out that the date of 820 million years of Rankin and others is considerably old and note that "... Ar^{40}/Ar^{38} studies of basement gneisses in the Central Blue Ridge indicate a long cooling history before the deposition of unconformable cover sequences, so that a more favorable age for the Catoctin Formation is 650-700 million years (personal communication, R. Dallmeyer, 1974) . . .". Thus, the Catoctin is considered to be late Precambrian age based on present data. It is no older than the 720 to 730 million-year-old Robertson River Formation and could range, in age from 600 to 700 million years old.

SOUTHEASTERN FLANK OF THE BLUE RIDGE ANTICLINORIUM

Candler Formation

The Candler phyllite and schist was named by Brown (1951, p. 1547) who later changed the name to Candler formation (Brown, 1953, p. 93). Espenshade (1954, p. 15) formally named the Candler Formation for silvery green to gray phyllite and schist that occur on Candler Mountain (Bedford County). Previously the Candler had been considered part of the Wissahickon and Loudoun formations (Virginia Geological Survey, 1928). Nelson (1962, p. 29) considered it to be the Loudoun Formation on the southeast limb of the Blue Ridge anticlinorium.

The Candler has been traced as a continuous band from its terminous in the Penhook 7.5-minute quadrangle northeast of Martinsville in the southwestern Piedmont of Virginia, northeastward to the southeastern corner of the Rapidan 7.5-minute quadrangle north of Orange (Espenshade, 1954; Brown, 1958; Nelson, 1962; Redden, 1963; Smith, Milici, and Greenberg, 1964; Ern, 1968; Conley and Johnson 1975). The formation has not been traced northeastward from the Rapidan quadrangle, but Candler-like phyllite occurs in the northwestern part of the Storck quadrangle (personal communication, Louis Pavlides). Pavlides (1976, p. 9) notes that this unit in the northwest part of the Storck quadrangle is on strike to the northeast with rocks assigned by Southwick, Reed, and Mixon (1971) and Mixon, Southwick, and Reed (1972) to the Wissahickon Formation. Between this schist and slate and the overlying Chopwamsic Formation, Southwick, Reed, and Mixon (1971) and Pavlides and others (1974, Figure 3, p. 571) show a boulder gneiss (diamictite) unit, which was previously mapped as Sykesville Granite in Maryland. Mixon and others (1972) considered this boulder gneiss (diamictite) to grade laterally into the phyllitic schist of the Wissahickon and to be either interlayered with, or conformably overlain by, the Chopawamsic Formation. Pavlides (1976, p. 11) states that the diamictite is the only unit common to the Piedmont of Maryland and Virginia and points out that the Wissahickon of Southwick, Reed, and Mixon (1971) and Mixon, Southwick, and Reed (1972) has not been traced into the Wissahickon of Maryland. Pavlides (1976, p. 11) points out that it is inadvisable to extend the Wissahickon into Virginia.

Lower Contact

The base of the Candler Formation is exposed in excavations just south of an abandoned quarry at Madison Run, Orange County (Conley and Johnson, 1975, Stop 14, p. 36); Candler phyllite is separated from Catoctin metabasalt by a thin quartzite layer indistinguishable from quartzite interlayers between metabasalts of the underlying Catoctin Formation. The contact at this exposure seems to be conformable between the phyllite and the quartzite. A second exposure of the Catoctin-Candler contact was observed during straightening of State Road 640 northwest of Cash Corner, Albemarle County, Keswick 7.5-minute quadrangle. At this exposure the contact seems to be gradational over several feet and consists of alternating thin interbeds of mafic metavolcanic rock and phyllite. The basal Candler phyllite contains rounded pebbles of metabasalt, which were probably eroded from the Catoctin during deposition of basal Candler.

Espenshade (1954, Plate 1) has mapped a southeastward-dipping thrust fault at the base of the Candler from southern Albemarle County to just southwest of the Bedford-Campbell county boundary, but states (Espenshade, 1954, p. 29) that "... displacement along this fault might be relatively slight." This fault zone was recently exposed during excavation for construction of a shopping center at the intersection of Campbell Avenue (U.S. Highway 501) and Florida Avenue in the Fairview Heights section in the southwestern part of the City of Lynchburg. The Candler Formation is separated from the Lynchburg Formation by a milled zone up to 7 feet (2 m) wide. A fault, probably a continuation of this fault, is recognized by C.R. Berquist (personal communication) at the base of the Candler Formation in the Sandy Level 7.5-minute quadrangle, Pittsylvania County, which he has been able to trace to the southwest into the adjoining Penhook 7.5-minute quadrangle where the Candler is terminated by being overridden by a later (or higher) thrust sheet. This fault could explain the rapid thinning and eventual disappearance of the Catoctin Formation southwest of Charlottesville in the Piedmont of central Virginia. The Catoctin is progressively cut out to the southwest by being overriden by the Candler, until the Candler is finally overriding the Lynchburg in the area halfway between Charlottesville and Lynchburg. The writer is concerned about this interpretation of younger rocks being thrust over older rocks, unless a major erosional surface had developed to the west on the Candler-Lynchburg surface prior to this thrusting. Catoctin pebbles in the basal part of the Candler Formation, near Cash Corner, Albemarle County, might be evidence for such an erosional surface. Similarly, MacLachlan (1967, p. 97) has suggested folding and considerable erosion of the plunging nose of the South Mountain anticlinorium of Pennsylvania prior to emplacement of the Yellow Breeches thrust sheet.

In the Lynchburg quadrangle Brown (1958, Plate 1) recognizes this fault at the base of the Candler for only a short distance on either side of the James River. Elsewhere in the quadrangle Brown (1958, p. 31) considers the Candler to stratigraphically overlie the Lynchburg with either a gradational or a sharp contact.

Stratigraphy

The Candler Formation is predominantly metamorphosed reddish purple to pink-weathering, gray, reddish-gray, and grayish-green quartz-chlorite-sericite phyllite, and schist that may show relict bedding and graded bedding composed of alternating thin (1-2 mm) quartzite layers overlain by thicker (1-2 cm) phyllite layers. Rocks of intermediate to felsic composition that resemble tuff occur at the base of the Candler on U.S. Highway 15, halfway between Gordonsville and Madison Run in Orange County. These rocks underlie a well-defined aeroradiometric high (open-file map, Virginia Division of Mineral Resources, 1975).

The lower part of the Candler contains discontinuous marble lenses. One of these is a fine-grained white marble that crops out several tens of feet from the base of the formation in the bed of Howards Creek (shown on Boswells Tavern 7.5-minute quadrangle as Happy Creek), Albemarle County, where State Highway 231 crosses the creek

(Conley and Johnson, 1975, Stop 17, p. 36). A pink, medium- to coarse-grained marble occurs several tens of feet above the base of the Candler in an abandoned quarry on the southeast side of State Road 647 at Madison Run, Orange County (Conley and Johnson, 1975, Stop 14, p. 36). At least three fine-grained, gray marble layers, which are stratigraphically above the white and pink marble beds, have been traced discontinuously across the Orange, Gordonsville, and Boswells Tavern 7.5-minute quadrangles in central Virginia (Conley and Johnson, 1975, p. 34). These three marble bands could be the same layer repeated by folding. The three separate gray marble layers had not been previously recognized; however a single gray marble, which was named the Everona limestone (Jonas, 1927, p. 842), was mapped in this area (Virginia Geological Survey, 1928; Mack, 1965). Although segmented by cross faults, Nelson (1962, Plate 1) also shows a continuous band of Everona Formation across southern Albemarle County to where it is covered by Triassic sedimentary rocks in the Scottsville basin. Jonas (1927, p. 842) reports that she collected poorly preserved fragments of trilobites from sandy beds near the contact with this limestone in an area south of Orange, but these fragments were unrecognizable even to genus by E. O. Ulrich.

Brown (1958, p. 45) notes that rocks of ultramafic association in the Lynchburg quadrangle are generally localized near the top of the Lynchburg in close association with Catoctin greenstone and are apparently absent in rock younger than Lynchburg and Catoctin. In contrast, in central Virginia the Candler and overlying Chopawamsic formations have been intruded by semiconcordant mafic plutons composed of metagabbro, metadiorite, and associated ultramafic rocks (Ern, 1968, p. 201; Brown, 1969, p. 7, 19-20; Henika, 1969; and Conley and Johnson, 1975, p. 34-35). Brown (1976, p. 242) states that gravity measurements show that the Diana Mills pluton, Buckingham County, is rootless and may constitute exotic blocks folded into a tectonic melange. However, contact metamorphism of country rock and structure around the Green Springs pluton, Louisa County, is the basis for the interpretation that it is probably a concordant intrusive body.

Upper Contact

In central Virginia the Candler Formation grades vertically into the overlying Chopawamsic Formation (Conley and Johnson, 1975, p. 30). The Candler contains quartzite layers at the top and grades upward into pink- and purple-weathering metagraywacke siltstone of the Chopawamsic Formation containing minor Candler-like phyllite layers. The metasiltstone in turn is replaced upward by an increase of metavolcanic rock. The contact between the Chopawamsic and the Candler formations is drawn where metasiltstone and interlayered metavolcanic rocks predominate over phyllite. To the southeast the top of the Candler was overthrust by igneous and metamorphic rocks of the Smith River allochton or is in fault contact with Triassic sedimentary rocks in the Danville basin.

Environment of Deposition

The Candler Formation represents a change in environment of deposition from the subaerial plateau basalt and interlayered pyroclastic and fluvial sedimentary rock of the Catoctin Formation to probable shallow-water shale and limestone. The grading of the Candler upward into siltstone and into metavolcanic rock of the Chopawamsic Formation probably represents a change to deeper water and deposition of graywacke and volcanic rock from submarine eruptions and flows.

CHOPAWAMSIC FORMATION

The Chopawamsic Formation was named by Southwick, Reed, and Mixon (1971, p. D1-D7) for exposures along Chopawamsic Creek on the Quantico Marine Base in northeastern Virginia. The formation was called the Peters Creek quartzite on the "Geologic Map of Virginia" (1928 edition) and metamorphosed volcanic and sedimentary rocks on the "Geologic Map of Virginia" (1963 edition). It is possibly equivalent to volcanic rocks mapped by Smith, Milici, and Greenburg (1964) and Brown (1969) underlying the Arvonia Formation, volcanic rocks below the Carolina slate belt rocks in the Virgilina synclinorium of southern Virginia (Kreisa, personal communication), Charlotte belt rocks of Tobisch and Glover (1971), and the James Run Gneiss and the Cecil County volcanic complex of Maryland (Southwick, Reed, and Mixon, 1971, p. D-19).

The Chopawamsic is composed of metamorphosed felsic and mafic flows and volcanoclastic rocks with interlayered quartzite, quartzose graywacke, and phyllite (Southwick, Reed, and Mixon, 1971, p. D1-D2). In the type area there is no evidence for large-scale repetition of stratigraphic units by folding (typical of rocks on the southeast limb of the Blue Ridge anticlinorium in northern and central Virginia) and the thickness of the formation is estimated to be between 6,000 and 10,000 feet (1,829 and 3,048 m). As originally described, the Chopawamsic is conformably underlain by and locally interfingers with boulder gneiss of the Wissahickon Formation and grades upward into the overlying Quantico Slate. This graditional contact is questioned by Pavlides and others (1974, p. 572) who suggest that there is an unconformity at the top of the Chopawamsic Formation.

On the basis of a belt of positive magnetic anomalies Pavlides and others (1974, p. 576-577, Figure 8) propose that the outcrop belt of the Chopawamsic extends from the southern part of the Storck quadrangle southwestward into the northwest limb of the Columbia syncline. Louis Pavlides (personal communication, 1976) has subsequently traced this band of Chopawamsic southwestward to Lake Anna. Conley and Johnson (1975, Figure 2, p. 34-35) have mapped the Chopawamsic to the southwest of Lake Anna, along the western edge of the Columbia syncline. In this area the formation had previously been mapped as Evington Group(?) (Smith, Milici, and Greenberg, 1964; Brown, 1969). The Chopawamsic is divided by Conley and Johnson (1975) into a lower unit composed predominantly of metagraywacke siltstone and an upper unit composed predominantly of metavolcanic rocks. The diamictite facies is absent in central Virginia and the contact between the Chopawamsic and the underlaying Candler Formation is gradational.

Lower Unit

The lower unit of the Chopawamsic consists of pale pink to purple-weathering, light-green to gray micaceous metagraywacke siltstone and minor metagraywacke sandstone and granule conglomerate. Most of the metagraywacke shows relict bedding in form of 2.0 to 5.0 cm mica-quartz layers alternating with 0.2 to 1.2 cm schist layers. There is a gradational finer grain size upward in some beds, which may be indicative of graded bedding. The unit also contains interbeds of quartzite, garnetiferous quartzite, and felsic and mafic metavolcanic rocks. The metagraywacke siltstone has a pronounced rodding produced by intersection of bedding and cleavage; if the rock is broken normal to this rodding, it shows a characteristic hackly fracture.

Upper Unit

The upper unit of the Chopawamsic Formation is primarily an interlayered felsic and mafic metavolcanic sequence. Purple-weathering phyllite similar to Candler phyllite and metagraywacke similar to that in the lower unit of the Chopawamsic are also exposed in the upper unit. The metavolcanic rocks consist of felsic and mafic tuff, breccia, and basalt. The upper part of the upper unit contains impure quartzite and ferruginous quartzite associated with mica schist and mafic volcanic rocks. The quartzite could be in part metamorphosed volcanic chert (Espenshade and Potter, 1960, p. 40). Metamorphic grade increases to the southeast across the outcrop belt of the Chopawamsic Formation and in the Caledonia 7.5-minute quadrangle it has developed garnets and kyanite. Rocks of the upper unit occupy the central part of the Columbia syncline and occur between infolded younger rocks of the Quantico Slate on the northwest limb and the Hatcher complex to the southeast.

Hatcher Complex

The Hatcher complex was named by Brown (1969, p. 14) for granitic gneiss, hornblende gneiss, and migmatitic rock near Hatcher in western Cumberland County. He apparently intended for the Hatcher complex to replace the Columbia granite, which was named by A. I. Jonas (Virginia Geological Survey, 1928). Brown justified the change on the grounds that the name conflicted with the Columbia Group of Pleistocene age and that little of the material in the complex is of granite composition. Smith, Milici, and Greenburg (1964, p. 18) previously had objected to the name Columbia granite and had called it the granodiorite unit. The Hatcher complex as mapped by Conley and Johnson (1975, Figure 2, p. 30) is composed of biotite gneiss that is migmatitic in places with lesser amounts of amphibolite, amphibole gneiss, quartzite, kyanite-garnet quartzite, and minor amounts of mica schist and graphitic mica schist. Rocks on strike with the Hatcher complex to the northeast have been called a migmatite complex by Good, Fordham, and Halladay (1977, p. 15). Brown (1969, p. 14) notes that the Hatcher complex merges westward and southwestward into metasedimentary rocks (Chopawamsic Formation) and speculates that the complex is a product of granitization and migmatization. Rocks of the Chopawamsic Formation do seem to grade into rocks of the Hatcher complex with increasing metamorphic grade to the southeast (Conley, 1977, p. 28). The Hatcher is primarily composed of high-rank Chopawamsic rocks. This is based on the composition of the high-rank rocks and presence of relict quartzite and amphibolite units that are traceable into recognizable metabasalt at lower metamorphic grade to the west. The Hatcher also contains rocks that are probably infolds of the Arvonia and

Quantico slates. The absence of granitic rocks in the Chopawamsic (with exception of intrusive bodies of Ellisville Granodiorite) and the appearance of migmatites, pegmatites, alaskites, and granite in the Hatcher complex is attributed to increasing metamorphic grade to the southeast and formation of anatectic granitic melts.

The Hatcher complex has been intruded by granodiorite containing numerous inclusions of biotite gneiss (xenoliths of country rock?) as typically exposed at the abandoned Cowherd quarries at Columbia (type locality of the Columbia granite of Jonas, 1932, p. 19). Conley and Johnson (1975, p. 30) recognized that this unit named by Jonas is primarily a granodiorite. The contact between the granodiorite and the biotite gneiss country rock is generally indistinct, if not gradational, suggesting that the granodiorite could be an igneous body intruding its own volcanic pile (Chopawamsic volcanic rocks). Because of low Sr^{87}/Sr^{86} ratios Fullagar (1971a, p. 2860) concludes that rocks of the Piedmont physiographic province, including the granodiorite in the Cowherd quarry, were derived from the lower crust and anatexis of sialic metasedimentary rocks is insignificant.

Plutons of the porphyritic Ellisville Granodiorite, named by Hopkins (1960, 1961) are intrusive into the high-rank rocks of the Hatcher complex as well as the lower rank rocks of the Chopawamsic Formation and underlying Candler Formation, and therefore should not be considered exclusively intrusive into the complex. The Ellisville is only slightly foliated at Louisa in Louisa County, but it is considerably sheared and foliated to the southwest along the James River. Brown (1969, Figure 6, p. 17) does not separate the Ellisville as a mapping unit from the Hatcher complex, although he does show it in a photograph of rock from the complex. Stose and Stose (1948) note that an exposure of granite (Ellisville Granodiorite) near Carysbrook, Fluvanna County is different in texture and composition from the granodiorite at Columbia. They propose that the contact between these units is a fault, along which the granodiorite and associated metamorphosed volcanic and sedimentary rocks (Chopawamsic Formation) are thrust over the granite at Carysbrook. This relationship was not observed by the writer and Ellisville contacts generally seem to be subconcordant and of an intrusive nature. Other igneous rocks in the complex include pegmatites and alaskitic pegmatites.

Kyanite Belt

Jonas (1932, Plates 1, 2) mapped the geology of an area from Louisa County southwestward to the Roanoke River just northeast of Danville that she called the kyanite belt of central Virginia. The northwestern part was mapped as Wissahickon Formation composed of interlayered schist, kyanite quartzite, and hornblende gneiss. These rocks in the northern part of the belt are correlated with the Evington Group by Smith, Milici, and Greenburg (1964), with the Evington Group(?) by Brown (1969), and with the Chopawamsic Formation by Conley and Johnson (1975).

The southeastern two-thirds of the kyanite belt is underlain by rocks mapped by Jonas (1932) as Columbia granite. This unit is composed of gneiss, augen gneiss, granodiorite, granite, and hornblende gneiss. These rocks in the northeastern part of the kyanite belt were subsequently mapped as rocks of the Hatcher complex (Brown, 1969; Conley and Johnson, 1975).

The rocks of the kyanite belt were mapped in more detail in the Willis Mountain-Woods Mountain area, Buckingham County and in the Baker Mountain-Madisonville area, Prince Edward and Charlotte counties as part of a study of kyanite by Espenshade and Potter (1960, Plates 2 and 3). These rocks are on strike to the northeast with rocks of the Hatcher complex as mapped by Brown (1969) in a continuation of the Whispering Creek anticline, named by Espenshade and Potter (1960, p. 36). Espenshade and Potter (1960, p. 36-38) outlined a stratigraphic sequence composed of biotite gneiss, probably derived from graywacke, that is overlain by schist and quartzite which may contain kyanite and were probably derived from shale and impure sandstone. These rocks in turn are overlain by hornblende gneiss and schist, which were probably derived from mafic lava flows. Ferruginous quartz rock and garnet-quartz rock containing amphibole, which were probably derived from ferruginous chert and clayey and sandy dolomite, are interlayered with the hornblende gneiss and schist. This stratigraphic sequence has a striking similarity to the Chopawamsic Formation to the northeast as mapped by Conley and Johnson (1975) and described in this paper.

Southwestern Extension

Rocks on strike to the southwest with rocks of the kyanite belt of Jonas (1932) between the Danville basin, which contains Triassic sedimentary rocks, and the Virgilina synclinorium along the North Carolina boundary were mapped by Tobisch (1972), Henika (1977), and R. D. Kreisa (personal communication). They consist of felsic and mafic metavolcanic and interlayered metasedimentary rocks correlated by Glover (1974, p. 757) and Conley (1977, p. 28) with the Chopawamsic Formation on strike to the northeast. Metamorphic grade rises toward the center of this mapped zone, reaching sillimanite grade in the center and dropping to greenschist facies on either side (Tobisch and Glover, 1969, p. C-2 to C-5; Henika, 1975, p. 449). The result is that felsic and mafic gneiss occurs in the center of the zone and grades into recognizable metavolcanic and metasedimentary rocks at lower grade on the west side.

Tobisch and Glover (1969, p. C-1) have applied the name Charlotte belt to this sequence of rocks, although the Charlotte belt in North Carolina as originally defined by King (1955, p. 346-347) is composed of felsic and mafic plutonic igneous rocks. King (1955, p. 347) states that "Toward the northeast end of the belt, near Greensboro, North Carolina, the plutonic rocks finger out into gneisses and altered volcanic rocks." From this statement it is obvious that the igneous belt is ending and is replaced along strike to the northeast by volcanic rocks and gneiss; therefore, it is questionable as to whether or not the Charlotte belt should be extended into Virginia. Tobisch and Glover (1969, p. C-1) state that some of the gneiss is orthogneiss, although Henika (1977) and R. D. Kreisa (personal communication) considered it to be mostly metavolcanic and metasedimentary rock at high metamorphic grade.

Henika (1977) defined a stratigraphic sequence in these gneiss, schist, and metavolcanic and metasedimentary rocks in the Danville area. The oldest unit recognized in the sequence is a gray to pink quartz monzonite to granite gneiss originally named the Shelton granite gneiss by A. I. Jonas (Virginia Geological Survey, 1928) and renamed the Shelton Formation by Henika (1977, p. 2). The Shelton is overlain, possibly unconformably, by recognizable metamorphosed volcanic and sedimentary rocks subdivided into a lower unit composed of interlayered felsic and mafic metavolcanic rocks and metasedimentary rocks composed of metagraywacke, schist, and quartzite. The lower unit is overlain by an upper unit composed predominantly of felsic metavolcanic rocks.

In the South Boston area, R. D. Kreisa (personal communication) has subdivided these metavolcanic rocks into a lower unit composed of interlayered felsic and mafic gneiss overlain by biotite gneiss. The lower unit is similar to the lower unit of Henika (1977) in the Danville area, but the overlying biotite gneiss cannot be directly correlated with either high-rank or low-rank rocks of the Danville area; thus, this may be indicative of a facies change between Danville and South Boston.

Fredericksburg Complex

Rocks on strike with the Hatcher complex to the northeast were informally named the Fredericksburg complex by Pavlides and others (1974, p. 569), who note that it is a tectonic rather than a stratigraphic complex. The complex is composed of amphibolite gneiss, and schist that contains numerous granitic intrusions, primarily dikes and sills (Pavlides, 1976, p 1). The precise nature of the western contact of the complex is not clear; it could conformably overlie the Quantico Slate, which is younger than the Chopawamsic or it could be the Chopawamsic raised in metamorphic grade, thrust over these younger rocks, and both units later folded with each other (Pavlides, 1976, p. 12). A discordant Pb^{207}/Pb^{206} age of 594 million years was obtained from a hornblende-biotite paragneiss in the complex; however, because the rock is a paragneiss, the date is discordant and subject to error (Pavlides, 1976, p. 12). Although the Fredericksburg complex is similar to Chopawamsic rocks at higher metamorphic rank in the Hatcher complex, additional work in the intervening area is required to correlate these two units.

Environment of Deposition

The Chopawamsic Formation is recognized as a volcanic-sedimentary pile containing metamorphosed graywacke, shale, felsic and mafic volcanic tuff, basaltic flows, pillow lavas, chert, and ferruginous chert (quartzite). These rocks represent submarine sediments and volcanic eruptions. In contrast Brown (1976, p. 142) proposes that the metagraywacke at the base of the Chopwamsic may represent a melange scraped from the sea floor during subduction and that these rocks are unconformably overlain by the felsic and mafic metavolcanic rocks. This unconformity was not confirmed by the mapping of Conley and Johnson (1975) who found this contact to be gradational.

Pavlides (1976, p. 26) suggests that the Chopawamsic represents the deposits in an ensialic volcanic chain bordered to the east by a westward-dipping subduction zone. In such a model it would be expected that the rocks would be composed of both felsic and mafic volcanic material, which could be derived from both continental and oceanic crust. The graywacke and shale could be derived from a source on the bordering continental mass. The volcanic rocks include pillow lava and basalt containing sparse small amygdules that together are indicative of subaqueous flows that occurred at shallow to intermediate depths. Much of the felsic rocks could also be derived from subaqueous eruptions. The quartzite and ferruginous quartzite are probably chert deposited in association with these submarine volcanic rocks.

Age

The Chopawamsic Formation was originally suggested to include rocks of early Paleozoic and possibly late Precambrian age (Southwick and Fisher, 1967); however, Southwick, Reed, and Mixon (1971, p. D-5, D-9, D-10) do not rule out the possiblity that it could be as young as Ordovician age. It overlies late Precambrian rocks and could overlie Cambrian rocks, depending on the credence placed in the supposed trilobite fragments near the base of the Candler Formation reported by Jonas (1927, p. 842). Glover, Sinha, and Higgins (1971, p. 313) report Pb/Pb age dates from the gneiss west of Virgilina as being much older and ranging from 620 to 740 million years with the oldest rocks in this area ranging from 685 to 740 million years. Glover (1974, p. 757) later reports an age of 530 to 570 million years for the Chopawamsic. Fullager (1971b, p. 2852) reports a Sr/Rb whole-rock date on the granodiorite at Columbia as 595 ± 80 million years. If the granodiorite is an intrusive into its own volcanic pile, as previously suggested in this paper, it could represent a date for deposition of part of the volcanic rocks. Higgins and others (1971, p. 320) also report Cambrian dates (Pb-Pb and Pb-U) from the James Run and Chopawamsic formations and for plutons that intrude the James Run. Based on these dates of Higgins and others (1971), Pavlides (1976, p. 9) tentatively considers the Chopawamsic to be of Early Cambrian age. The range in ages suggested by radiometric dates and the unreliability of fossil evidence indicate that the age of the Chopawamsic cannot be more closely defined than late Precambrian or early Paleozoic(?). The 620 to 740 million date reported by Glover Sinha, and Higgins (1971, p. 313) seems to be anomalously old and might be the product of contamination of younger rocks by older zircons. A similar situation was pointed out by Higgins and others (1977), where Chopawamsic and younger rocks are cut by plutonic rocks that have apparent ages, as determined by radiometric means, that are older than the age of the intruded rocks.

VIRGILINA SYNCLINORIUM

Greenschist facies rocks of the Carolina slate belt occur in Virginia in a southwestward-plunging trough, recognized as a synclinorium by Laney (1917, p. 43) and named the Virgilina synclinorium by Brown (1953, p. 97). This structure is located just east of South Boston in the south-central Piedmont of Virginia. It has a maximum width of slightly more than 10 miles (16 km) and has been mapped from the Virginia-North Carolina boundary north-northeastward to beyond Keysville (Laney, 1917, Plate 1), a distance of about 40 miles (64 km).

HYCO FORMATION

The Hyco quartz porphyry, which occurs on both limbs of the Virgilina synclinorium, was named by Laney (1917, p. 20) for the Hyco River. R.D. Kreisa (personal communication) renamed it the Hyco Formation because it contains a sequence of separately mappable units. The formation is a stratigraphic equivalent of the Uwharrie Formation of North Carolina named by Conley and Bain (1965, p. 121), which is the lower unit of the Carolina slate belt as defined by Emmons (1852).

Laney (1917) also named the Goshen schist, which occurs on the southeast limb of the synclinorium, but he admitted it was probably sheared Hyco. During field mapping in the area the writer had an opportunity to examine this unit. It is indistinguishable from the Hyco Formation and there seems to be no reason to perpetuate the name Goshen schist.

Lower Contact

The Hyco Formation is in contact with higher rank gneiss on the northwestern limb of the Virgilina synclinorium and with felsic and mafic intrusive rock along its southeastern limb (Laney, 1917, Plate 1; R. D. Kreisa, personal communication). The contact of the higher rank gneiss (Chopawamsic Formation; Glover, 1974, p. 757 and Conley, 1977, p. 28) with the overlying Hyco Formation marks the base of the Carolina slate belt. This base is generally not seen in North Carolina because the western contact of this group of rocks is separated from the igneous rocks of the Charlotte belt to the northwest by the Gold Hill fault zone. Thus, an opportunity is afforded in the Virgilina synclinorium in Virginia to discern the nature of this contact, which has a profound bearing on interpretations of stratigraphy and structure of the slate belt.

Laney (1917, p. 18) believed that the contact between the gneiss and the Hyco was an unconformity, based primarily on the fact that the rocks of the Carolina slate belt are at greenschist facies and the gneiss to the west is at amphibolite facies. Tobisch and Glover (1969) have found that metamorphic grade increases to the northwest, and they cannot find any metamorphic break at the base of the Hyco. Also, they have not found a break in structural style between rocks of the Carolina slate belt and the gneiss to the west. Further, Tobisch and Glover (1971, p. 2222) find that the steeply dipping slate-belt rocks "... change gradually and continuously to gently dipping or subhorizontal surfaces ..." of fold nappes proposed to occur in the gneiss to the west. In the South Boston area R.D. Kreisa (personal communication) found an increasing metamorphic gradient to the west across the Carolina slate belt-Chopawamsic boundary and a conformable relationship between the two units. If this is a conformable relationship, then the Carolina slate belt rocks stratigraphically overlie the Chopawamic Formation.

Stratigraphy

The Hyco Formation is composed predominantly of felsic volcanic rocks. In the Virgilina synclinorium it is estimated to be 15,000 feet (4,572 m) thick (R. D. Kreisa, personal communication) and is composed of crystal and lithic tuff. Welded flow tuff and flows are reported from North Carolina (Conley and Bain, 1965, p. 121). Metavolcanic sandstone and greenstone layers are exposed near the top of the unit (R. D. Kreisa, personal communication). The Hyco on both limbs of the synclinorium is intruded by concordant plutons of quartz monzonite-trondjemite composition. As this rock intrudes the Hyco exclusively and has not been observed intruding younger rocks, it is suggested to be contemporaneous with volcanism during Hyco time.

Environment of Deposition

The great thickness of felsic volcanic rocks of the Hyco Formation over a wide area in North Carolina and Virginia is sufficient reason to believe that it must have been derived from sialic crust. Such sialic crust is proposed to underlie the slate belt as a detached crustal block by Black (1978, p. 163) and by Hatcher (1978, p. 170). The presence of welded flow tuffs is adequate reason to interpret that the unit is in part a subaerial deposit. If the gneiss, which underlies the Virgilina synclinorium, is Chopawamsic Formation, the change from primarily submarine volcanism during Chopawamsic time to partly subaerial volcanism in Hyco time would be reason to believe that development of a true island arc system to the east was taking place by Hyco time. A compound arc system is suggested by Black (1978, p. 163).

Age

Hills and Butler (1969, p. 445) report a Sr/Rb age of 535 ± 50 million years and Wright and Seiders (1977, p. 197-198) report a discordant U/Pb date of 580 million years for the Uwharrie Formation in North Carolina. Glover, Sinha, and Higgins (1971) report an even older discordant Pb/Pb age of 620 million years for the equivalent Hyco Formation in Virginia. Recognizing the existence of earliest Cambrian to youngest Middle Cambrian trilobite fossils in the stratigraphic section above the Hyco (St. Jean, 1973), a tentative age of late Precambrian-Cambrian is suggested for the Hyco until further radiometric dates are available to resolve the discrepencies between Cambrian dates of Hills and Bulter (1969) and Wright and Seiders (1977) and the Precambrian date of Glover, Sinha, and Higgins (1971).

AARON FORMATION

Laney (1917, p. 24-25) named the Aaron slate for Aaron Creek which flows across the Virginia-North Carolina boundary east of Virgilina. Laney (1917, p. 27) also named the overlying Virgilina greenstone for the town of Virgilina. R. D. Kriesa (personal communication) found that rocks of almost identical composition and appearance as the Aaron slate overlie the Virgilina greenstone. These rocks above the Virgilina greenstone had also been mapped as the Aaron slate by Laney (1917, Plate 1). For this reason R. D. Kreisa (personal communication) dropped the name Virgilina greenstone and redefined the Aaron Formation, subdividing it into a lower slate member, a middle mafic metavolcanic member, and an upper slate member. The Aaron Formation as renamed by Kriesa is equivalent to the Efland Formation named by Conley and Bain (1965) in North Carolina.

Stratigraphy

The lower member of the Aaron Formation seems to conformably overlie the Hyco Formation. The unit is composed predominantly of green slate. A zone of metaconglomerate occurs toward the base of the unit and mafic metavolcanic rock occurs as interbeds in the member.

The middle member of the formation, the Virgilina greenstone of Laney (1917), is composed of mafic flows and tuffs with thin interbeds of metavolcanic sandstone and felsic and intermediate tuff.

The upper member of the formation is composed predominantly of light-gray to purple phyllite. Much of the phyllite is composed of lithic volcanic fragments. This member also contains green slate and thin mafic metavolcanic beds.

At the intersection of Wilmoth Branch and Difficult Creek, Clover quadrangle, the writer has observed phyllite showing graded bedding similar to those found in the overlying Tillery Formation. Units above the basal Tillery Formation have not been observed in the Virgilina synclinorium.

Age

Age dates have not been obtained from the Aaron Formation in Virginia. Glover, Sinha, and Higgins (1971, p. 313) propose that the Hyco and overlying Aaron formations were folded into a major synclinorium (Virgilina synclinorium?) and intruded by granodiorite at Roxboro, North Carolina prior to middle Paleozoic metamorphism. Age dates on the granodiorite range from 588 to 573 million years, although Glover, Sinha, and Higgins (1971, p. 363) believe that 573-million-year date is the younger age limit of the slate belt in the area. Considering the fact that only the Tillery Formation separates the Aaron Formation from the McManus Formation, which has produced earliest Cambrian to earliest Middle Cambrian trilobite fossils (St. Jean, 1973), and no unconformities have been demonstrated in the section between the Aaron and the McManus, it would seem logical to consider the Aaron to be from latest Precambrian to earliest Middle Cambrian age.

QUANTICO-COLUMBIA AND ARVONIA SYNCLINES

QUANTICO SLATE-ARVONIA FORMATION

Darton (1894) named the Quantico Slate for Quantico Creek in the northern Virginia Piedmont and Watson and Powell (1911) named the Arvonia slates of central Virginia. Higgins (1972, p. 129) has traced in reconnaissance rocks of the Quantico syncline into rocks of the Columbia syncline. Smith, Milici, and Greenberg (1964, p. 14) consider the slate of the Arvonia, Long Island, and Columbia synclines as correlative and rename the unit the Arvonia Formation. Brown (1969, p. 23) agrees that the Arvonia and Long Island synclines both contain rocks of the Arvonia Formation.

Lower Contact

Lonsdale (1927, p. 72) notes that at Dumfries, Prince William County and at Kelloggs Mill there is a sharp contact between the Quantico Slate and the older underlying rocks (Chopawamsic Formation) and suggests that it might be a fault contact. Southwick, Reed, and Mixon (1971, p. D3) state that the contact between the Quantico Slate and underlying Chopawamsic Formation is gradational. Pavlides (1973, p. 38), however, indicates that the Quantico is separated from the underlying Chopawamsic by an unconformity in the Stafford quadrangle. He finds a system of folds in the Chopawamsic that are absent from, and older than, the Quantico Slate. He recognizes a quartzite at the base of the Quantico that locally may be up to 500 feet (152 m) thick. During field mapping in the Columbia quadrangle Conley and Johnson (1975) found a garnetiferous quartzite locally containing kyanite at the base of the Quantico Slate in the Columbia syncline. Quartzite and conglomerate also occur at the base of the Arvonia Formation, especially along the southeast limb of the Arvonia syncline (Taber 1913, p. 40; Stose and Stose, 1948, p. 401; Smith, Melici, and Greenberg, 1964, p. 14; and Brown, 1969, p. 27).

The Arvonia Formation in the Arvonia syncline is thought by Smith, Milici, and Greenberg (1964, p. 14) to conformably overlie metamorphosed volcanic and sedimentary rocks (Chopawamsic Formation). Most other writers, however, have considered that the Arvonia unconformably overlies these rocks (Taber, 1913, p. 40; Stose and Stose, 1948, p. 408; Brown, 1953, p. 96, 1969, p. 31). Stose and Stose (1948, p. 406) recognize that the granite near Carysbrook is different in composition and texture from the Columbia granite of Jonas (1932). Conley and Johnson (1975, p. 34-35) map this unit as Ellisville Granodiorite, an igneous rock which has intruded the underlying Candler Formation, the Chopawamsic Formation and the Hatcher complex. The Ellisville is in contact with and underlies the Arvonia, but does not intrude the Arvonia Formation, further indicative of an unconformity at the base of the Arvonia Formation. If, as proposed in this paper, the rocks of the Carolina slate belt in the Virgilina synclinorium stratigraphically overlie the Chopawamsic Formation, then the unconformity between the Chopawamsic and the Quantico Slate-Arvonia Formation would represent a time span of the deposition and erosion of the Carolina slate belt.

Stratigraphy

In the northern part of the Stafford quadrangle the Quantico Slate is a carbonaceous slate containing considerable pyrite and a few clastic layers: however, to the southwest it becomes a graphite-muscovite-garnet-biotite schist that locally may contain kyanite, sillimanite, and thin layers of diopsidic calc-silicate rock (Pavlides and others, 1974, p. 372 and Pavlides, 1976, p. 4).

To the south along strike the Quantico Slate in the Columbia synform consists of graphitic schist containing garnet and staurolite and a minor amount of graphitic siltstone and granule conglomerate (metagraywacke); it seems to be the Quantico Slate at higher metamorphic grade as described by Pavlides and others (1974) to the northeast. Smith, Milici, and Greenberg (1964, Plate 1) mapped the western part of the Columbia syncline. They found rocks that they called the Arvonia Formation along the northwest limb of the structure, which they interpreted to be overlain by the Bremo Member in the core of the structure. During mapping in the Columbia quadrangle, however, Conley and Johnson (1975) (Conley, 1977, p. 28) found that the basal quartzite occurs on both sides of the narrow band of Quantico Slate as mapped by Smith, Milici, and Greenberg (1964, Plate 1) on the northwest limb of the Columbia syncline. This is an indication that this band of slate is in reality a synclinal infold, probably a continuation of the Quantico syncline on the northwest limb of the Columbia syncline (synform). Continued mapping to the east indicates that the synformal band of slate is wrapped around the nose of the Columbia synform and that it plunges out on the southeast limb of the structure. Rocks along the axis of the Columbia synform are not the Bremo Member, but a sequence of quartzite and interlayered felsic and mafic rocks thought to be in the upper part of the Chopawamsic Formation. Therefore the Columbia is a later open synform that has refolded earlier structures. Refolding of earlier folds is reported in the Arvonia syncline by Brown and Griswold (1970, p. 198) and Pavlides (1976, p. 25), thus strengthening this interpretation.

Metamorphic grade drops rapidly to the west and amphibolite-grade schists in the Columbia synform are at greenschist facies in the northwest limb of the Arvonia syncline. Brown (1969, Plate 1) maps slate on the northwest limb of the Arvonia syncline and the same slate unit at higher metamorphic rank on the southeast limb of the structure. The slate and schist on the southeast limb was recognized by Rogers (1884) who called them bird's-eye maple slate and by Taber (1913) who called them knotted schists. The Bremo quartzite, named by Stose and Stose (1948, p. 397) and renamed Bremo Member by Smith, Milici, and Greenberg (1964) is thought by Brown (1969, p. 31) to occur in the medial or lower part of the Arvonia Formation in the Arvonia syncline. Smith, Milici, and Greenberg (1964, Plate 1) show the Bremo overlying Arvonia slate in the Arvonia syncline as well as in the Columbia synform. Brown (1969, p. 32-33) named the Buffards Formation, which is metavolcanic conglomerate that he feels unconformably overlies the Arvonia Formation.

The Long Island syncline and the refolded syncline containing Quantico slate on the west flank and nose of the Columbia synform are both elongate, tightly compressed structures and contrast markedly with the open, almost symmetrical structure portrayed by Smith, Milici, and Greenberg (1964, Plate 1, cross sections B-B′, C-C′) and by Brown (1969, Plate 1, cross sections A-A′, B-B′, C-C′) for the Arvonia syncline. This is even more puzzling as polyphase deformation is recognized in the Arvonia syncline (Brown and Griswold, 1970, p. 198) and in the Quantico syncline (Pavlides 1976, p. 25). The Buffards Formation has a fishook-shaped outcrop pattern as mapped by Brown (1969, Plate 1) northeast of Dillwyn and is similar in shape to the refolded fold containing Quantico Slate on the northwest limb and nose of the Columbia synform. If this were the case, then stratigraphic relationships would have to be reexamined. The Buffards Formation of the Arvonia syncline (Brown, 1969), has not been identified in the Quantico syncline. With recognition of polyphase deformation in both of these structures the question must be asked could the Buffards Formation in the Arvonia syncline actually be the underlying Chopawamsic metavolcanic rock that has been caught up in an anticlinal fold which is flanked on either side by the Arvonia Formation in a syncline which has been refolded around the nose of a latter Arvonia syncline. In that case the unconformity that separates the Arvonia and Buffards formations would be the same one that separates the Chopawamsic and Arvonia formations in other areas; thus, the Buffards and Chopawamsic could be correlative. Stose and Stose (1948, p. 401) in part recognized the above described structure as they note that the Arvonia syncline is a double syncline.

Other Possible Infolds

Pavlides (1974, p. 569) notes that the Fredericksburg complex contains infolds of Quantico Slate. During field mapping the writer noted bands of graphitic and garnetiferous mica schist in the Hatcher complex. Good outcrops can be seen at the intersection of State Roads 605 and 690 northwest of Hamilton in the Lakeside Village quadrangle. A second band of schist has been traced discontinuously to the southwest from the intersection of State Highway 45 and State Road 611 at Bushy Park in the Lakeside Village quadrangle to the west bank of Bonbrook Creek on the west-central edge of the Whiteville quadrangle. Henika

(1977, p. 3) notes a graphite occurrence in a terrain of metamorphosed volcanic and sedimentary rocks in the Danville area, and R. D. Kreisa (personal communication) notes a graphite occurrence in similar rocks in the South Boston area.

One of the best exposures is on the right-hand bank of Wolf Island Creek due east of Bluestone Church in the Brosville quadrangle. The country rock at this locality is high-rank gneiss derived from felsic and mafic volcanic rock. Infolded into this rock is what seems to be a synform containing graphitic schist and graphitic metasiltstone. The schist is separated from the high-rank rocks by a quartzite layer from one to several meters thick. The country rock is at upper amphibolite facies and if the overlying graphite schist were metamorphosed at this grade it might be expected that the graphite would for the most part be dissipated as CO_2 and CH_4 in the presence of water (Winkler, 1976, p. 22). Infolds of Quantico-Arvonia rocks might be more common than previously realized, as based on occurrence of bands of graphite schist in high-rank metavolcanic rocks of the Fredericksburg complex, the Hatcher complex, and the rocks of the Danville-South Boston area.

Age

Darton (1892) collected fossils from rocks of the Arvonia Formation which were identified by Walcott as Cincinnatian age. Watson and Powell (1911) collected fossils from the Quantico Slate which were identified as Cincinnatian by Bassler. Later workers have also identified fossils of Middle to Upper Ordovician age from the Arvonia Formation (Dale, 1906; Tillman, 1970). Stose and Stose (1948, p. 412) suggested that these rocks might be Silurian or younger age based on stratigraphic evidence. Seiders and others (1975, p. 507) note that the locality where Watson and Powell (1911) collected fossils from the Quantico Slate is probably under fill dirt of U.S. Interstate 95 and the fossil collection from this locality has been lost. Material from a second locality described by Watson and Powell near Marumsco Creek was visited by Seiders and Mixon (Seiders and others 1975, p. 507-508) who found impressions identified by Yochelson and Pojeta as being probably inorganic in origin.

Zircons obtained from the Dale City Quartz Monzonite, which cuts the Quantico Slate, and the Occoquan Adamellite, which cuts the underlying Chopawamsic Formation, both give discordant radiometric ages of 585 million years (Seiders and others, 1975). Higgins and others (1977) suggest that this date is too old and feel that the zircons analyzed contain lead inherited from Precambrian parent rocks and were later affected by Paleozoic metamorphism. Pavlides (1976, p. 10-11) collected Quantico Slate along Powell Creek that contains forms resembling graptolites, which W. B. N. Berry agrees have the appearance of being graptolites and thus would be indicative of an age no older than Ordovician. Harper and others (1973, p. 402) have obtained a K-Ar date from the Arvonia Formation of 300 million years, which they interpret as the time of formation of slaty cleavage in the rock during metamorphism.

The Quantico Slate and the Arvonia Formation probably are correlative as there is a striking similarity between the slate and schist in both the Quantico and Arvonia synclines. Fossils from the Arvonia Formation are indicative of an Upper Ordovician age; however, fossil evidence from the Quantico Slate is less convincing.

JAMES RIVER SYNCLINORIUM

The James River synclinorium lies just east of Lynchburg and can be traced from just west of Wingina in a southwesterly direction to just south of Penhook. The interpretation of the structure and stratigraphy of this band of rocks has raised more controversy than any other geologic province in the Piedmont of Virginia.

Jonas (1929, p. 508) recognized the rocks of the Fork Mountain Formation of Conley and Henika (1973) along the western edge of the Smith River allochthon, but thought the regional retrograde metamorphism of staurolite to sericite and development of secondary chlorite in these rocks was a product of mylonitization and recrystallization (diaphthorisis) along her Martic thrust fault. She suggested that the fault probably continued northeastward into Maryland and Pennsylvania; however, the writer has been able to trace the rocks of the Smith River allochthon to only a few miles northeast of Appomattox. In order to trace the Martic fault through Virginia to the northeast Jonas (1932, p. 33-34) also included the metasedimentary rocks of the Candler Formation in her diapthoritic zone and incorrectly proposed that the Candler was a phyllonite.

Furcron (1935) was the first geologist to do regional mapping in the area from Lynchburg northeastward to Howardsville. He recognized the Lynchburg Formation and thought that it was separated from rocks of the Glenarm Series by the Catoctin Mountain border fault. He believed that the Lynchburg was intruded by rocks of the core of the Blue Ridge anticlinorium. Graphitic schist, conglomerate, and quartzite within the Lynchburg were mapped by him as the Loudoun Formation, which he thought unconformably overlay the Lynchburg. Furcron (1969, p. 72, 74) later refuted both these ideas and thought the Lynchburg unconformably overlay the core rocks and included rocks he had mapped as Loudoun in the Lynchburg Formation. Northeast of Lynchburg, Furcron (1935, Plate 1) shows a southwestward thinning wedge of Catoctin Formation overlying the Loudoun (Lynchburg Formation.

The basal unit of the Glenarm Series was named the Mount Athos Formation for Mount Athos in Campbell County by Furcron (1935). This formation is composed of quartzite and graphite schist with metabasalt flows at its base. He thought that the Mount Athos was overlain by the Cockeysville Marble and the Wissahickon Formation. The Wissahickon Formation of Furcron (probably the Fork Mountain Formation) is composed of a mica schist containing biotite and garnet retrograded to chlorite, staurolite retrograded to sericite, and a garnetiferous biotite gneiss. Furcron (1935) concluded that the structure of the James River synclinorium was controlled by northeastward- and northwestward-trending gravity faults which produced a series of horst and graben structures.

Espenshade (1954, Plate 1) described an area between the southern part of Albemarle County and the Roanoke River. He shows that the Lynchburg Formation contains greenstone interlayers and agrees with Furcron that it is separated from rocks to the east by a fault which he traced for 60 miles (97 km) along the western contact of the Candler Formation. East of this fault, he mapped the Evington Group, which was named by Brown (1953, p. 91). The basal unit of this group is the Candler Formation, which is composed of phyllite and locally, quartzite and marble beds. It is overlain by the Archer Creek Formation, which is composed of graphite schist and contains a marble member in its upper part. The Archer Creek is overlain by the Mount Athos Formation, consisting of interlayered micaceous quartzite, conglomerate, marble, and quartz-mica schist, which in turn is overlain by greenstone.

To the southeast the Evington Group is bordered by mica schist and staurolite-bearing biotite schist with interlayered greenstone and soapstone of unknown correlation (rocks of the Smith River allochthon) that Espenshade (1954) suggests might be equivalent to rocks of the Lynchburg Formation and the Evington Group. He states that the regional structure is probably synclinal, but is complicated by thrust faults and imbricate high-angle reverse faults. Espenshade (1954, p. 25) presents a preferred stratigraphic sequence that is the reverse of that proposed by Furcron, but recognized that this favored interpretation may be incorrect and that the Candler Formation may be the youngest unit in the Evington Group.

In the Lynchburg 15-minute quadrangle Brown (1953) mapped the Lynchburg Formation on the southeast limb of the Blue Ridge anticlinorium and considers metabasalt interlayers near the top of the formation to be Catoctin Formation. Brown (1951, 1953) recognized the Candler Formation as the basal unit in the Evington Group. He does not recognize the fault mapped by Furcron and Espenshade that separates the Candler from the underlying Lynchburg Formation, except for a short distance on either side of the James River southeast of Lynchburg. Elsewhere he considers the contact to be stratigraphic and ranging from sharp to gradational (Brown, 1953, p. 31). Brown (1953, p. 91) divides Espenshade's Archer Creek Formation into the Joshua schist and the Arch marble, and the Mount Athos into the Pelier schist and the Mount Athos Formation. The name Slippery Creek greenstone is applied to the metabasalt at the top of the Evington Group.

Brown (1953) proposes that the rocks of the Evington Group are contained within the James River synclinorium. He shows a band of high-rank staurolite-mica schist in the southeastern part of the Lynchburg quadrangle (Brown, 1958) that were previously called the Wissahickon Formation by Furcron and rocks of uncertain correlation by Espenshade (1954, Plate 1) and proposes that these rocks are the Candler Formation at higher metamorphic grade on the southeast limb of the James River synclinorium. He further correlates the amphibolite and underlying gneiss in the Sherwill anticline in the extreme southeastern corner of the quadrangle with the Catoctin and Lynchburg formations that occur on the northwest limb of the synclinorium (southeast limb of the Blue Ridge anticlinorium). A thrust fault is shown along the northwestern boundary of this supposed band of high-rank Candler, except in the extreme east-central part of the quadrangle, where he shows a stratigraphic contact between this unit and the Mount Athos Formation. To the southwest of this area, in the extreme east-central part of the quadrangle, this fault separates rocks called high-rank Candler by Brown (1958) from the rest of the Evington Group to the northwest. Brown (1958, Plate 1) apparently thought that this fault had very little displacement, as shown by his cross sections B-

B' through E-E'. The writer examined these units and finds the gneiss in the core of the Sherwill anticline is probably the lower gneiss member of the Bassett Formation, the overlying amphibolite is the upper amphibolite member of the Bassett, and the high-rank schist containing staurolite at the top of this section is Fork Mountain Formation—all units of the Smith River allochthon. The thrust fault mapped by Brown (1958) along the northwest boundary of the Fork Mountain Formation is probably a continuation of the Bowens Creek fault, a major displacement along the northwest boundary of the Smith River allochthon, which has been traced to the southwest into the Brevard fault zone (Espenshade and others, 1975). In the event that gneiss and overlying amphibolite of the Bassett Formation could be proven to be the Lynchburg and Catoctin formations and the Fork Mountain proven to be the Candler Formation as suggested by Glover (1976), the large amount of displacement on the Bowens Creek fault in transporting the allochthon westward over tens of miles would preclude the possibility that the polydeformed and retrograded rocks of the Fork Mountain would be part of the southeastern limb of a local fold. For this reason the writer seriously questions the existence of the James River synclinorium.

Along the strike belt of the Evington Group to the northeast Ern (1968, Plate 1) has mapped a thin band of quartzite and marble that he called Mount Athos Formation, and some thin discontinuous lenses of blue-gray marble and schist that he called Archer Creek Formation. These units occur in a vast area of Candler Formation, and it could be interpreted that they are interbeds in the Candler. Farther to the northeast Conley and Johnson (1975) did not recognize the Archer Creek Formation, the Mount Athos Formation, or the Slippery Creek greenstone, but found that the Candler graded upward into the Chopawamsic Formation.

From mapping in the Altavista 15-minute quadrangle southeast of Lynchburg, Redden (1963) proposed that the Candler was the youngest unit in the Evington Group and that the stratigraphic order was opposite of that proposed by Espenshade (1954) and Brown (1958). Redden (1963, p. 83) did not find a gradational contact between the Lynchburg and the Candler and proposes that either an unconformity or a fault separates the Candler from the Lynchburg. He notes that at no place in the central and southern parts of the quadrangle is the Candler preserved below the Mount Athos, as would be expected if the Mount Athos were younger than the Candler.

C. R. Berquist (personal communication, 1978), mapping for the Virginia Division of Mineral Resources in the Sandy Level and Penhook 7.5-minute quadrangles farther along strike to the southwest of the Altavista quadrangle, finds that the Candler is thrust over metabasalt, quartzite, marble, and graphite schist in the upper part of the Lynchburg Formation. The Candler in turn is overthrust by this same sequence of Lynchburg metasedimentary and metavolcanic rocks, which completely overrides and cuts out the Candler in the northern part of the Penhook quadrangle. These upper Lynchburg rocks, which are thrust over the Candler, have been traced northeastward into rocks mapped as Mount Athos and Archer Creek formations by Redden (1963). Based on this, Redden (1963) is probably correct in the interpretation that the Candler is younger than the Mount Athos and Archer Creek formations, which belong to the upper part of the underlying Lynchburg Formation. From this data it is suggested that the structure of the James River synclinorium and the stratigraphy of the Evington Group could be incorrect.

OUTER PIEDMONT

Gneiss, schist and amphibolite, which are intruded by the Petersburg granite, lie to the east of the Hatcher complex and Virgilina synclinorium and west of the unconsolidated sedimentary rocks of the Coastal Plain (Virginia Geological Survey, 1928). Little is known about the details of these rocks that underlie the Outer Piedmont because of the lack of adequate geologic maps.

STATE FARM GNEISS

The State Farm Gneiss was named by Brown (1937, p. 13) for exposures on the State Prison Farm, which is located between Maidens and Crozier in Goochland County. It is described as a light- to dark-gray, uniform, even-banded, medium-grained, well-foliated gneiss. The morphic character of zircons from the formation are indicative of a sedimentary origin (Bobyarchick and others, 1976). The State Farm Gneiss occupies the core of a northeastward-tending, doubly-plunging antiform, and Higgins and others (1973, p. 178) and Clement and others (1974, p. 12) have suggested that this structure is a gneiss dome cored by 1,100-million-years-old basement rocks. Glover and others (1978, p. 169) have dated a granite that intrudes the State Farm Gneiss at 1 billion years old using the Rb-Sr whole-rock method, thus confirming the speculations of Higgins and others (1973) and Clement and others (1974).

ROCKS OVERLYING THE STATE FARM GNEISS

The State Farm Gneiss is conformably(?) overlain by an amphibolite, the Sabot Formation of Glover and others (1978), and in turn it is overlain by a metagraywacke and quartz arenite formation, the Maidens Gneiss of Glover and others (1978). The Elk Hill complex of Brown (1937, p. 15) is composed of amphibolite and granite and probably is equal at least in part to the Sabot Formation and Maidens Gneiss. Brown (1937, p. 15) observes that this complex is separated from the Columbia granite of A.I. Jonas (Hatcher complex) by a pegmatite belt.

PETERSBURG GRANITE

The Petersburg granite, which was named by Jonas (Virginia Geological Survey, 1928), is shown on the latest edition of the Geologic Map of Virginia (Virginia Division of Mineral Resources, 1963) as a pluton of batholithic porportions along the edge of the Coastal Plain from just north of Richmond to the Virginia-North Carolina boundary. Bloomer (1939, p. 142-143) states that there are three facies of the Petersburg granite: gray to pink, medium-grained granite (the most common); blue, fine-grained granite; and porphyritic granite. Fullagar and Bottino (1970, p. 210-211) have dated the Petersburg at 580 million years old using the Rb-Sr whole-rock method. Wright, Sinha, and Glover (1975) report a zircon age for the Petersburg of 330 ± 8 million years. Clement and others (1974) report that the Petersburg granite intrudes the State Farm gneiss.

SUTURE ZONES AND THE AVALONIAN OROGENY

Rodgers (1972) proposed that a volcanic chain—The Avalonian belt—developed, primarily within the Appalachian geosyncline, during Precambrian and Early Cambrian(?) time. It is now incorporated into the Appalachians from Newfoundland southwestward through Virginia into Georgia. Rocks of the Carolina slate belt probably compose part of this volcanic chain. Conversely, Williams and Stevens (1974, p. 793) propose that the Avalonian zone is underlain by continental basement and probably was attached to North Africa in Precambrian time. They suggest that a suture zone is located between the Charlotte belt and Inner Piedmont belt in North Carolina. Furthermore, the rocks of the Carolina slate belt were metamorphosed in late Precambrian or early Cambrian time and were later sutured to North America.

Glover, Sinha, and Higgins (1971), Glover and Sinha (1973), and Glover (1974) suggested that the rocks of the Carolina slate belt in Virginia and North Carolina were metamorphosed during the Avalonian orogeny in late Precambrian or early Cambrian time. Glover and Sinha (1973) disagree with Rodgers that the island arc (represented by the rocks of the slate belt) developed in an area removed from continental crust, and they give evidence that these rocks developed on a continental margin with an eastward-dipping subduction zone on the African plate. A suture zone is predicted by Glover and Sinha (1973) to occur either in the Charlotte belt or between the Charlotte belt and the Inner Piedmont belt.

After discovery that the State Farm Gneiss is intruded by a billion-year-old granite, Glover and others (1978) revised the orogenic model for the Virginia Piedmont. They note that south of Richmond, rocks similar to the State Farm Gneiss underlie rocks of the Carolina slate belt, and they suggest that quartz aernite pebbles in the Aaron Formation (Efland Formation in North Carolina) might be derived from the Maidens Formation. Because of this new evidence, they reject orogenic models that require oceanic crust under the slate belt and major suture zones between continental plates in the Piedmont of Virginia. They propose that this suture must lie to the east of the Piedmont, possibly in the Coastal Plain. This revised model better fits the stratigraphic relationships as presently understood by the writer, who believes that there are probably no major stratigraphic breaks from the base of the Candler Formation to the top of the Carolina slate belt sequence in the Virgilina synclinorium. Furthermore, if the Shelton Formation underlying the Chopawamsic Formation is Grenville basement, an interpretation could be logically made for an eastward-facing prograding sequence that was being deposited on basement. During Middle or Late Ordovician time (Taconic orogeny) these rocks were folded and metamorphosed, and later they were eroded. The Arvonia and Quantico slates of Late Ordovician age were deposited on this erosion surface. The rocks of the Arvonia syncline were probably deformed by the Acadian orogeny and later Allegheny orogeny.

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