COMMONWEALTH OF VIRGINIA
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GEOLOGY OF THE GROTTOES QUADRANGLE, VIRGINIA

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EXPLANATION

UNIT CHARACTERISTICS / GEOLOGIC AND ECONOMIC FACTORS AFFECTING LAND MODIFICATION

QUATERNARY

al — Alluvium: *Flood-plain deposits of stratified, unconsolidated clay, silt, and sand with quartzite gravel at base. Chert gravel at base and localized calcareous tufa (marl) deposits along streams draining carbonate rock terrane. Thickness: 0-20 feet (0-6 m).*

al — Alluvium: *Upland stream deposits of unconsolidated sand and gravel with cobbles and boulders of quartzite, sandstone, and metabasalt. Thickness: 0-15 feet (0-5 m).*

ta — Talus: *Slope deposits of angular quartzite boulders and cobbles. Thickness: 0-10 feet (0-3 m).*

ts — Terrace deposits: *Dissected remnants of unconsolidated, stratified alluvial deposits of clay, silt, and sand with quartzite gravels at base. Chert gravel at base near streams draining carbonate-rock terrane. Thickness: 0-20 feet (0-6 m).*

af — Alluvial fans: *Unconsolidated, locally dissected, poorly stratified, overlapping stream deposits of clay, silt, and sand with poorly sorted quartzite cobbles and boulders. Thickness: 0-200 feet (0-61 m).*

sc — Sandy clay: *Residual sand and clay deposits formed on the Shady Formation; includes some weathered phyllite and quartzite debris in creek bottom only). Thickness: undetermined.*

TRIASSIC

d — Diabase dikes: *Dark greenish-gray to black diabase. Thickness: 0-15 feet (0-5 m).*

ORDOVICIAN

Omb, Ombs, Ombp — Martinsburg Formation (Omb): *s, dark-green, fine- to medium-grained, medium- to thick-bedded lithic sandstone with graded bedding, flute casts, groove casts, load casts, and rare chert and black-slate pebbles interbedded with gray-green, laminated, thin-bedded calcareous argillite and black slate. Thickness: undetermined. s, dark-gray to black, laminated thin-bedded calcareous argillite with graded bedding and convolute folds interbedded with black calcareous slate. Thickness: 500-1,000 feet (152-305 m). s, black, very fine grained, graptolitic calcareous slate with a few beds of argillite. Thickness: 100-200 feet (30-61 m).*

Oelh — Lincolnshire Formation and New Market Limestone: *Lincolnshire—dark-gray, medium- to coarse-grained, bioclastic, fossiliferous, black chert bearing limestone with pink, argillite partings. New Market—dove gray, thick-bedded, massive, ultrafine-grained limestone. Thickness: 45-215 feet (14-66 m).*

Obul, Obulc, Obulp — Beekmantown Group: *Obul (upper limestone and dolomite unit), dove-gray, thin-bedded, ultrafine-grained limestone interbedded with light-gray, fine- to medium-grained, thick beds of laminated dolomite and a few thin beds of gray to tan shale and pink, calcareous mudrock. Thickness: 290 feet (88 m). Obul (upper dolomite unit), light- to dark-gray, fine- to medium-grained, thick-bedded, laminated siliceous dolomite interbedded with coarse-grained, locally brecciated, siliceous dolomite with beds and nodules of black to tan chert. Thickness: 250 feet (76 m). Obml (middle limestone and dolomite unit), dark-gray, medium- to coarse-grained, fossiliferous, bioclastic limestone with algal structures, oolites, cross-lamination and flat-pebble conglomerate interbedded with limestone, and dolomitic limestone with burrow structures silty calcarenite, and laminated dolomite. Thickness: 915 feet (279 m). Obld (lower dolomite unit), massive, dark-gray, coarse-grained, locally brecciated, siliceous dolomite with thin, dark-gray chert beds, chert nodules, quartz veins and quartz crystal-lined vugs; interbedded with light- to dark-gray, fine- to medium-grained, massive to laminated siliceous dolomite. Thickness: 1,240 feet (378 m). Obl (lower limestone unit), dark-gray, fine-grained, thick-bedded limestone interbedded with light-gray, fine-grained, laminated dolomite in upper part; dark-gray, ultrafine-grained, limestone with black chert nodules, undulose laminations, burrow structures and flat-pebble conglomerate in lower part. Thickness: 400 feet (122 m).*

Ccoc, Ccou, Ccol — Conococheague Formation: *Ccou (upper member), dark-gray, fine-grained, algal limestone alternating with flat-pebble limestone conglomerate, thin-bedded limestone with siliceous partings, laminated limestone, and laminated to thick-bedded, fine-grained, light-gray dolomite. Thickness: 1,100 to 1,800 feet (335 to 549 m). Ccol (lower member), medium-gray, fine- to medium-grained, massive to laminated dolomite. Thickness: 1,400 feet (427 m). Ccc, interbedded limestone and dolomite. Thickness: 1,800 feet (549 m). s, thin (0-10 foot or 0-3 m) beds of tan to brown, medium- to coarse-grained, cross-laminated quartz sandstone.*

Cel — Elbrook Formation: *Ceu (upper member), medium- to dark-gray (orangish-yellow on weathered surface), fine- to medium-grained, medium- to thick-bedded, massive or laminated dolomite interbedded with thin, dark-gray, algal limestone, flat-pebble limestone conglomerate, platy dolomitic siltstone, and a few thin sandstone beds. Thickness: 1,800 feet (549 m) maximum. Cel (lower member), pale-green, laminated to thin-bedded, platy dolomite; light- to dark-gray (buff where weathered), fine-grained, laminated dolomite and laminated maroon phyllite near base (in cross section only). Thickness: 1,100 feet (335 m) maximum.*

Ꞓwb — Waynesboro Formation: *Maroon, tan, and yellow phyllite and argillite, interbedded with limestone, dolomite, and thin sandstone (in cross section only). Thickness: 1,100 feet (335 m) maximum.*

Ꞓs — Shady Formation: *Dolomite and limestone (in cross section only). Thickness: 1,200 feet (366 m) maximum.*

Ꞓh — Harpers Formation: *Dark-green, quartz-chlorite-sericite phyllite and fine-grained, even-bedded sandstone with interbedded bluish-gray to white, medium-grained, cross-laminated quartzite. A few thin beds of purple to black, coarse-grained, metamorphosed ferruginous sandstone. Skolithos and worm borings, bioturbated beds, tracks and trails common in most sandstone and quartzite. Thickness: 1,600 feet (488 m).*

Ꞓa — Antietam Formation: *Massive, ledge-forming, white to light-gray, medium- to fine-grained, siliceous, Skolithos-bearing quartzite with minor amounts of interbedded phyllite in upper portion. Thickness: 800 feet (244 m).*

CAMBRIAN

Level land adjacent to streams, which may be readily tilled or excavated, is subject to periodic flooding that limits its use to farm or recreational activities. Excavations are subject to sliding and sloughing. In areas where alluvial and gravel deposits overlie cavernous limestone or dolomite, rapid ground-water withdrawals may induce surface subsidence or collapse. Marl deposits have been used locally as a source of agricultural lime.

Wet, boulder-strewn land with very thin soil along mountain streams is subject to periodic flooding. This land is most suitable as a woodland or grazing area.

Steep, boulder-covered slopes are unsuited for construction or any form of development because of creep, slide or rockfall hazard.

Level benches or flats near streams are generally above flood levels. Artificial cuts and excavations are subject to sloughing and creep, and land is subject to subsidence or collapse where terrace deposits overlie cavernous limestone or dolomite.

Gently sloping, rocky land is characterized by water-filled depressions, braided, sinking, or incised streams, and nobbly, sandy, droughty soil. Evidence of subsidence is common, where underlain by limestone and dolomite. Artificial cuts and excavations are subject to sloughing and collapse.

Thick, impermeable sandy clay is covered by alluvial fan and talus deposits along the western foothills of the Blue Ridge. Iron and manganese nodules are mined from these deposits. Clay deposits having economic potential may also be present locally. The sandy clay is subject to severe erosion where the overlying fan and talus deposits have been removed.

Dikes weather to large boulders and red clay near ground surface and may be difficult to excavate.

a— gently rolling to hilly upland has steep, V-shaped valleys along larger streams and rivers. Relatively shallow, well-drained, sandy and shaly soils are common. Rock outcrops are present. Erosion may be severe on slopes cut and filled during construction and rapid and rapid run-off of storm water. Artificial cuts and excavations may be unstable where bedding is undercut. Building sites are good on gentle slopes. Construction restrictions are imposed on the type and location of waste-disposal facilities in areas of shallow soil and rapid run-off of storm water. Ground water for domestic and farm use is generally available form wells less than 200 feet (61 m) deep.

a and c—gently rolling open land has shallow soil and moderate slopes. Severe soil erosion can be expected where deep denuded slopes, particularly where slate is predominant. Construction restrictions are imposed on the type and location of waste-disposal facilities in areas of shallow soil, rapid run-off of storm water, clayey subsoil and solution channels in calcareous rock. Shallow excavations may require some blasting to remove resistant ledges. Artificial cuts and excavations may be unstable where bedding or cleavage are undercut. This land is well suited for agriculture, particularly pasture. Water wells generally provide small yields from depths less than 150 feet (46 m). Ground water is moderately hard and may be slightly acidic or contain iron.

h low, gently rolling land surface with low, discontinuous ridges has developed on limestone. The soil is shallow, locally cobbly, and subject to severe erosion as evidenced by areas of exposed limestone ledges. Construction restrictions are imposed on type and location of waste-disposal facilities in areas of thin soil and solution channels and caves in the bedrock. Occurrence of bedrock pinnacles restricts all but very shallow excavations. The thick, high-calcium limestone is economically important. Ground-water availability is fair to poor, and the water may be very hard.

Gently rolling land surface with a few low, round hills and linear ridges has formed over limestone and dolomite generally covered with deep, well-drained soil. Appreciable soil creep and severe erosion may occur in modified land areas on steep slopes, whereas on gentle slopes, the soil is generally stable. There is a great variation in thickness of the soil over short distances; clay subsoil has a moderately high shrink-swell potential. Common sinkhole and cave development, particularly in the limestone units, necessitates restriction of choice in the determination of the type and location of waste-disposal facilities and other construction. Ground-water availability is good to fair, and the water is generally hard. The ground-water in these carbonate rocks is susceptible to contamination from surface sources where sinkholes are present or where the soil is thin; contaminants induced into the sinkholes may be transmitted for considerable distances through solution channels and fractures in the rock. Obul, Obml, Obll, and Ceu—rock ledges are exposed in most areas and rockland (areas where ledges are less than 10 feet or 3 m apart) occurs locally on thick sequences of alternating limestone and dolomite.

Obud and Obld—residual chert debris covers the rounded hills and lowlands underlain by siliceous dolomite.

s, in Ccu and Ccol—deep, residual sandy soil formed from thin, calcareous sandstone beds that commonly occur on linear ridge crests and slopes.

The limestone and dolomite, which underlie the alluvial fan deposits in a 1- to 2-mile (2 to 3 km) wide belt west of the foot of the Blue Ridge, have been penetrated by several drill holes. These rock units appear to comprise a major, relatively untapped aquifer system that is recharged by the percolation of surface water run-off from the Blue Ridge. The potential for large yields from deep wells is good but well construction may be difficult and the cost for all wells, particularly for municipal or industrial use, is relatively high because of the unstable, deeply weathered bedrock and the thick unconsolidated deposits overlying it. The ground water is generally hard but otherwise of good quality; the aquifer is susceptible to contamination by unsanitary surface sources.

The western slope of the Blue Ridge is underlain by metamorphosed clastic sedimentary rocks of the Harpers and Antietam formations that are well exposed along Madison Run in Shenandoah National Park. Phyllite, metamorphosed, impure sandstone and quartzite of the Harpers can be seen at REFERENCE LOCALITY 1, and massive ledges of Antietam quartzites are exposed at REFERENCE LOCALITY 2.

The *Harpers Formation* contains burrowed beds that are the earliest evidence of marine life preserved on the rocks of the Blue Ridge. The Harpers was formed from fine sand and mud that accumulated in coastal mud flats and lagoons at the continental edge during Cambrian time. While the mud flats along the shelf were subsiding, coarser sandstones were being deposited as local sand-shoal areas and barrier beaches. The clean, well-sorted quartzite of the *Antietam Formation* is indicative of the most extensive development of beach and off-shore barrier-bar environments during early Cambrian time. The quartzite contains a profusion of worm borings (Skolithos) that are preserved as straight, tube-like fossil forms 3 to 5 mm. in diameter and up to 1 meter (3.3 feet) in length which were oriented perpendicular to the original bedding surfaces.

Limestone and Dolomite

Carbonate rocks form the floor of the valley northwest of the Blue Ridge mountains. The oldest Cambrian carbonate units (*Shady* and *Waynesboro formations*) are covered by coarse colluvial deposits at the foot of the Blue Ridge. Solution features, such as sink holes in the alluvial cover, and sandy clay residuum in samples from deep wells indicate that the limestones and dolomites of these formations were dissolved near the surface by ground water.

The east to west change in lithofacies from the metamorphosed clastic sedimentary rocks of the Blue Ridge to limestone and dolomite in the valley to the northwest indicates a transition from a coastal environment that received abundant terrigenous sediment from the continental highlands to a very low-relief continental shelf environment. Through a combination of the shelf configuration, a warm climate and abundant organisms, a shallow-water carbonate platform (Figure 1) was established in early Cambrian time.

Alternating limestone and dolomite beds in the Elbrook and Conococheague formations and the Beekmantown Group exposed northwest of the South Fork of the Shenandoah River have characteristics similar to cyclic sedimentation described in recent platform carbonate rocks. Their lithofacies and the inferred depositional environments are generally similar to the subfacies and related subenvironments described in detail by Ginsburg (1968) and Reinhardt and Hardie (1976) in Pennsylvania and Maryland. It is through analysis of the differences in successive cyclic sediments, and the inference of the differences in depositional environments, that the Cambro-Ordovician carbonate sequence has been divided for mapping as groups, formations, members and units. It must be emphasized that these are strictly lithostratigraphic units that may be time transgressive.

The *lower member of the Elbrook Formation* is not exposed within the quadrangle, but the uppermost dolomite beds of the *upper member* can be seen in an abandoned quarry across North River from Port Republic (REFERENCE LOCALITY 3). Characteristic lithofacies of the upper member are exposed in fields north of the gaging station on the South Fork of Shenandoah River at REFERENCE LOCALITY 4. Cyclic deposition is delineated by alternating limestone units and thin, platy dolomite interbeds. The cycles are comparatively short (7 to 10 feet or two to three meters thick) and consist of thin algal limestone (lower intertidal to upper subtidal) overlain by interlaminated, wavy-bedded limestone and dolomite (high intertidal algal flat) that are gradational upwards into thin, laminated (supratidal) dolomite beds (Figure 1).

The succession of subenvironments that can be inferred from Elbrook sedimentation shows a strong affinity towards and supratidal condition and is notably deplete in the lower intertidal and subtidal carbonate sand and algal limestone facies that characterize the overlying Conococheague limestones. The contact between the Elbrook and Conococheague formations is placed at the break in depositional environments between the supratidal facies from the cratonic side and the more marine cycles above. At the quarry (REFERENCE LOCALITY 3) the contact occurs between thick-bedded dolomite at the top of the Elbrook and the basal limestone in the Conococheague cycle above; northwest of REFERENCE LOCALITY 4 the contact is placed above the uppermost thin laminated dolomite that can be related to the last Elbrook cyclic deplete in coarse calcarenite and intraclast conglomerate but rich in thin, laminated to platy dolomite interbeds.

Massive dolomite and interbedded sandstone comprise the *lower member* of the *Conococheague Formation* northwest of Cross Keys (REFERENCE LOCALITY 5) and is similar to the lower part of the Conococheague in Frederick County, Virginia, and in Pennsylvania where it was mapped as the Spring Station Member (Wilson, 1952). These rocks form low, discontinuous ridges that are subordinate to the ridges formed by the upper member in this quadrangle. The lower member seems to be present only on the northwestern limb of the Massanutten synclinorium and may be time equivalent to the upper portion of the Elbrook Formation on the southeastern limb. The contact between the lower and upper members is placed at the bottom of the lowest limestone above the dolomite-sandstone sequence.

Exposures of limestone, dolomite and thin sandstone beds typical of the *upper member* of the *Conococheague Formation* occur on a stream southeast of *Montevideo* at REFERENCE LOCALITY 6. Lithofacies of this member are predominantly interbedded limestone and dolomite strata that range from decimeter (centimeters) to several feet (meters) in thickness. Repetition of a distinctive subfacies succession (subtidal to intertidal to supratidal) occurs in cycles 12- to 15-feet (4 to 5 meters) thick and is a dominant characteristic of the upper member. *The individual cycles, deposited by a* regressive sea, are bounded by erosional breaks that may represent an intermittently transgressive sea. Erosion of rock cycles responsible for elimination of certain subfacies of the previous cycle, and make the cycle record inconsistent, might not be observable as the underlying lagoon. A composite succession of subfacies begins with a 0- to 1.5-foot (0-5 m) interval of medium- to coarse-grained, cross-bedded, commonly oolitic calcarenite (subtidal) succeeded by 1 to 3 feet (.3 to 1 meter) of algal stromatolite-limestone (lower intertidal to upper subtidal). The algal limestone has irregular boundaries with coarse carbonate sand, and flat-pebble conglomerate layers above that form part of a thick interval (6 to 7 feet, 2 meters) of thin-interbedded "ribbon" limestone and dolomite (lower intertidal). The thin, interbedded subfacies commonly becomes more dolomitic towards the top and grades upwards through an interval of wavy interlaminated ultra fine-grained limestone and dolomite (upper intertidal) into laminated, mud-cracked dolomite (supratidal) at the top of the cycle (Figure 1).

Thin dolomitic beds that contain highly rounded and sorted quartz sand and cross-bedded sandstone strata may be indicative of aeolian transport during deposition of the Conococheague Formation. As there is no obvious source of such sediment within the carbonate platform, it may have been brought in by strong westerly winds that swept across the Cambrian carbonate shelf from dunal areas on the craton to the west.

The contact between the Conococheague Formation and the overlying Beekmantown Group is placed at the top of the uppermost thinly laminated, supratidal dolomite that can be related to the last Conococheague cycle. Where the contact is poorly exposed it has generally been placed at the break in slope adjacent to massive limestones in the base of the Beekmantown Group.

The *Beekmantown Group* has been subdivided into five unnamed formations that are well exposed along North River northwest of Fort Republic (REFERENCE LOCALITY 7). The *lower limestone unit* includes limestone and some dolomite beds previously mapped as the Chepultepec Formation (Brent, 1960). Beds in the base of the unit are generally thick-bedded calcarenite or algal limestone and seem to represent a lower intertidal to lower subtidal environment similar to one in the Conococheague cycle. In comparison with the Conococheague beds the limestone strata in the base of the Beekmantown Group are much thicker, indicating a longer period of intertidal or subtidal deposition or a more rapid subsidence of the carbonate shelf. Interlaminated limestone and dolomite beds similar to the upper intertidal subfacies of the Conococheague occur sporadically within the lower limestone unit, but there are few complete cycles in the Beekmantown Group. Alternating limestone and dolomite beds in the upper part of the unit are similar to cyclic beds described in the middle limestone and dolomite unit. The contact between the lower limestone and the lower dolomite units is placed at the top of the uppermost limestone that occurs stratigraphically below a very thick section composed entirely of siliceous and vuggy dolomite.

The *lower dolomite unit* is resistant to erosion and forms Lungo Hill as well as the linear chert-covered ridge northeastward to Pineville. The unit contains mud cracks, algal lamination, and thin dolomite intraclast layers and is considered to be largely supratidal to intertidal in origin, having been deposited on an algal flat similar to an environment of the Elbrook Formation. Frosted-quartz sand grains and the relatively high silica content (bedded and nodular chert) suggest recurrent wind transportation of fine silica across the supratidal flats from the craton to the west.

The contact between the lower dolomite and the middle limestone and dolomite units is placed at the base of the lowest limestone bed. Cyclicly bedded limestone typical of the *middle limestone and dolomite unit* is well exposed on Stonehouse Farm (REFERENCE LOCALITY 8). An idealized middle Beekmantown limestone cycle contains calcarenite beds with thin flat-pebble conglomerate zones near the base that may be channeled down into the underlying dolomite. Cross-bedded, oolitic carbonate sands (lower intertidal to upper subtidal) have also been observed in the lower part of the cycle. Molded, partly dolomitized limestone with burrow structures and thin-bedded to laminated, silty calcarenite beds may alternate in the upper part. At the top of the cycle partly dolomitized limestone with burrow structures grades upwards into mottled, then thin laminated dolomite. The calcarenite beds are generally fossiliferous and in addition to algal biostromes, contain cephalopods, gastropods, fragments of crinoids, brachiopods and trilobites. The sediments were deposited on a relatively high-energy, subtidal, wave-swept platform that graded upwards into a supratidal zone. The frequency of environmental changes may indicate a more tectonically active shelf during Beekmantown time.

The contact between the middle limestone and dolomite and the upper dolomite units is placed at the top of the uppermost limestone in the middle limestone and dolomite unit, underlying a thick section composed entirely of siliceous dolomite. *The upper dolomite unit* is generally similar to the lower dolomite unit, but is not as thick. Each contains evidence (mud cracks, algal lamination, thin dolomite intraclast layers) of an algal flat inundated irregularly during major storms. Vuggy, mottled and internally disrupted beds may indicate crystal growth under evaporative conditions, and the high silica content suggests input by an external (aeolian) depositional system operative during dust storms.

The contact between the upper dolomite and the upper limestone and dolomite units is placed at the base of the lowest limestone interbed above the massive dolomite section. The *upper limestone and dolomite unit* contains incomplete, eroded cycles of massive micritic limestone, micritic limestone with abundant burrow structures, a few thin layers of shale and minor calcareous mudrock overlain by thin, laminated dolomite. Characteristic structures are bird's-eye texture, mud cracks, lamination, intraformational conglomerates and burrows. Environmental conditions seem to have fluctuated between intertidal and supratidal zones with the culmination being a prolonged period of erosion.

The contact between the upper limestone and dolomite unit and the overlying New Market or Lincolnshire limestones is placed above the uppermost thick-bedded dolomite. The *New Market Limestone* is mapped in combination with the Lincolnshire Formation as it is thin and probably discontinuous. The New Market is deposited on the Beekmantown Group and may be separated from it by an unconformity, although no evidence of angularity has been found in exposures. The high-calcium limestone in Lincolnshire beds thin from 55 feet (16.7 m) near Stowville (REFERENCE LOCALITY 9) southwestward to 4 feet (1.2 m) northeast of Mount Meridian (REFERENCE LOCALITY 10). In the removed section at REFERENCE LOCALITY 9 dolomitic partings in the lower 20 feet (6 m) of the New Market suggests a transitional boundary with the rocks of the Beekmantown Group; a shallow, intertidal micritic limestones similar to those in the New Market are interspersed with thin, supratidal dolomitic beds in the upper Beekmantown.

The *Lincolnshire Formation* is a dark, coarse-grained, cherty, fossiliferous, eurfodial limestone that appears to be continuous along both limbs of the Massanutten synclinorium in this quadrangle (Figure 2), but varies from a few feet (meters) on the southeastern limb to more than 200 feet (61 m) on the northwestern limb. Along the southeastern limb of the synclinorium the shape and distribution of this reef facies suggest that, locally, *reef* life temporarily survived the rapid subsidence of the carbonate shelf edge (Figure 1) to build mounds of carbonate debris around patch reefs before being inundated during the deposition of pelagic muds that marked the beginning of Martinsburg deposition.

The black, micritic *Liberty Hall* limestone of the *Edinburg Formation* characterized by even, flysh-like, rhythmic bedding with convolute intraformational folds at some horizons, overlies the Lincolnshire Formation along the west limb of the Massanutten synclinorium. A few feet of black slate is commonly present at the base of the unit, and the lower black slate member of the Martinsburg Formation overlies it along a transitional boundary. The association of the Liberty Hall limestone with the pelagic facies of the Martinsburg, its flysh-like character, and the presence of convolute, soft-sediment folds suggest that the Liberty Hall was deposited in deep water on the foreslope (Figure 1) of a carbonate shelf (Thomson and Thomasson, 1969, p. 75). The presence of black, pelagic slates above and below the limestone unit indicates the deposit formed contemporaneously with the basal black slate member of the Martinsburg Formation.

Sandstone, Argillite, and Slate

The *Martinsburg Formation* has been subdivided into three rock units, and is the basinal facies (Figure 1 and Figure 2) of the Ordovician System in Shenandoah Valley. *The lower member*, a black, graptolitic, *calcareous slate**, was derived from pelagic sediments deposited on the sediments of the Lincolnshire or Edinburg formations after they had subsided into relatively deep water. The black slates are very poorly exposed in the Grottoes quadrangle, but their presence is expressed by a belt of thin, shaly soil and small exposures of slate adjacent to the rocks of the Lincolnshire (REFERENCE LOCALITY 10).

The pelagic slates are transitional upward into the middle member, a turbiditic facies distinguished by the appearance of a rhythmic succession of silty, *calcareous argillite*, black, fine-grained limestone and slate that have the same rhythmic bedding as the Liberty Hall limestone of the Edinburg Formation (REFERENCE LOCALITY 11). The mixture of calcareous and terrigenous sediment in this member indicates it was derived from two source areas, carbonate mud transported by turbidity flow from the shelf west of the basin, and terrigenous mud transported down the basin by turbidity flow from tectonic lands to the southwest (McBride, 1962). The middle member is transitional upwards into the upper turbidite, *sandstone-bearing member*. The contact is placed at the base of the lowest lithic sandstone bed, a less distal turbidite unit distinguished by characteristic sole markings at the base of the sandstone beds. A few black-chert cobbles and metamorphic rock fragments have been found in the lower sandstone beds suggesting a source area of metamorphic rocks undergoing vulcanism (REFERENCE LOCALITY 12). The sandstone beds thin and decrease in number westward across the basin so that along the west flank of the synclinorium the upper member is dominated by the interbedded slates and argillites that persist throughout the upper Martinsburg.

Igneous Rocks

A swarm of north-northwest trending, near vertical *diabase dikes* were intruded into the Paleozoic rocks during the Mesozoic Era. The dikes are composed of fine-grained, greenish-black to black olivine diabase that weathers to distinctive, large boulders and orange-red soil.

Surficial Deposits

Thin *lowland alluvial deposits* are present in the flood plains of most streams and rivers. They are composed of sediment derived from weathering and erosion of siliceous rocks in the Blue Ridge and, to a lesser degree, the chert- and sandstone-bearing rocks of the valley. The alluvial deposits include fine-sand-and-silt at the top to coarse quartzite cobbles and pebbles in a sand matrix at the base along rivers and smaller streams that originate in the mountainous areas. Silty clay deposits with chert gravel at the base are common in the flood plains of streams draining areas of cherty carbonate rocks.

Upland alluvial deposits are generally present in stream valleys of the Blue Ridge mountains. They are composed of pebbles, cobbles, and boulders derived from the rock outcrops on adjacent slopes. The sediment in these deposits is coarser upstream, and the deposits grade into finer-grained lowland alluvium downstream.

Extensive *talus-like talus deposits* of angular quartzite boulders are present on the slopes and in the hollows below prominent quartzite ledges of the Antietam and Harpers formations. The deposits contain angular boulders that range up to 3 feet (1 m) in length and are relatively uniform in size within a single deposit. Generally, little matrix material is present between the boulders, and the talus slopes are mostly devoid of vegetation. Phyllite and sandstone bedrock beneath the talus deposits is more deeply weathered than in adjacent areas with no talus cover.

Between South River and the foot of the Blue Ridge a series of overlapping *alluvial fan deposits* form a broad, westward-sloping apron of unconsolidated clay, silt, sand, gravel and coarser quartzite debris. These materials, with the flood-plain alluvium and terrace deposits along South River, form an almost unbroken cover on the underlying rocks. The fan deposits are thinnest where they overlies phyllites and argillites of the Waynesboro Formation and are thickest where they overlie limestone and dolomite beds near the foothills of the Blue Ridge. The base of this unconsolidated material has been penetrated by only a few water wells and is difficult to recognize as it appears to grade into the residual clay derived from the deeply weathered carbonate bedrock. The residual clay deposits shown as sandy clay in the cross section may exceed 100 feet (30 m) in thickness above portions of the Shady or Waynesboro formations; such thicknesses have also been reported in areas having similar geologic conditions (King, 1950, Figure 16, Section S–S'; and Knechtel, 1943, p. 181-184). The alluvial fans are locally incised by streams flowing westward from the Blue Ridge. Some streams are debris-filled and braided, and some sink into the permeable alluvium before reaching South River. In places, large springs emerge from the alluvial fans to form streams, or to flow directly into South River.

The deeply weathered, dissected remnants of ancient flood plains form discontinuous *terrace deposits* above the flood plains of the rivers and some of the larger streams. These deposits, like the lowland alluvium, have silt and sand in the upper part and a layer of gravel at the base.

GEOLOGIC STRUCTURES AND METAMORPHISM

The quadrangle is located diagonally across the Massanutten synclinorium just south of the Massanutten mountains and includes a portion of the Blue Ridge mountains in its southeastern corner. The small fan of the synclinorium is comprised of a series of open-to-closed, asymmetric-to-overturned folds. The scale of the folding varies with the rock types involved: thin, incompetent interbeds of limestone, slate or sandstone of the Martinsburg Formation have been folded into closed, chevron-like folds with amplitudes and wave lengths of meters to more than 100 meters (several tens to more than 300 feet). Folds in the limestone and dolomite sequences are much broader and higher-amplitude structures with wave lengths and amplitudes ranging from several hundred to more than 1,000 meters (several hundred to more than 3,000 feet). The folds are warped upward along a northeast axis that diagonally crosses the quadrangle, and plunge northeast and southwest from this axis. This structural culmination has brought the resistant Cambrian clastics of the Blue Ridge to the surface farther northwest than in adjacent areas to form a topographic saddle. The limestones and the more argillaceous rocks have well-developed slaty, axial-plane cleavage along which metamorphic sericite and chlorite were formed. All of the Paleozoic rocks in the quadrangle are metamorphosed to lower greenschist facies, but the metamorphism seems to be less prominent on the northeastern, less-folded limb of the synclinorium. The rocks are also well jointed, and a major joint (Pulaski-Staunton) fault separates rocks of the Beekmantown Group from the overriding Elbrook Formation on the northwest corner of the quadrangle.

MINERAL RESOURCES

West Sand and Gravel, Inc. produces concrete sand, masonry sand, and sized gravel and is the only active mineral producer in the quadrangle. The gravel pits and crushing plant are located at the end of Dry Hill street extended, northwestward from Grottoes on the southeast side of South River (REFERENCE LOCALITY 13).

Grand Caverns, located within Cave Hill east of Grottoes, is the longest-operating commercial cave area in the state. The three caves in Cave Hill (Grand, Fountain, and Madison), are the result of solution of limestones in the hinge area of minor folds in the Conococheague Formation. Besides giving Grottoes its name, Grand Caverns has long been a major tourist attraction.

Limestones, dolomite and quartzite have been quarried for use as building stone and road metal, and limestone for the production of lime since the early days of settlement in the Shenandoah Valley. Several abandoned quarries are shown on the map. High-calcium limestone, which has many industrial and chemical uses, occurs interbedded with dolomite in the upper limestone and dolomite unit of the Beekmantown Group, and generally comprises the entire thickness of the New Market Limestone. Edmundson (1945) in his survey of industrial limestones and dolomites, gives the following analysis of New Market Limestone near Cross Keys: SiO_2, 0.86; Fe_2O_3, 0.08; Al_2O_3, 0.74; CaCO$_3$, 97.74; MgCO$_3$, 1.23; total 100.15. It should be noted, however, that in both the southeastern and northwestern belts of New Market the limestone thins from north to south, and that this thinning may preclude economic development in the Grottoes quadrangle.

A slate sample from the sandstone-bearing unit of the Martinsburg Formation was tested in regard to blasting and fining characteristics, and good expansion occurred at temperatures between 1150°-1200° C. Other samples (Calver, et al, 1961) from the sandstone-bearing unit of the Martinsburg showed potential for common brick, tile or possibly light-weight aggregate. However, the coarse sandstones interbedded with the slate would make separation difficult for brick or light-weight aggregate production.

Of historical economic interest is the iron furnace located on Madison Run (REFERENCE LOCALITY 14), which is the old "Mount Vernon Furnace" mentioned by Watson (1907, p. 434). An old iron-manganese pit located in residual sand and clay approximately 2.5 miles (4 km) northeast of the furnace may have been one source of limonite for smelting.

GEOLOGIC FACTORS THAT AFFECT LAND MODIFICATION

Areas underlain by similar rock types, or having similar surficial deposits, form land units that have been evaluated on the basis of lithology, slope stability, erodability, and response to excavation and ground-water withdrawals. The locations of major sinkholes and modified-land areas are shown on the geologic map and described in the legend as special units involving land modification. Rock units are guides to land units with similar environmental and physical properties. However, as some of the rock units vary internally in lithology and structure, a detailed evaluation of individual sites is recommended. Data on forestry, regional planning, soils and water may be obtained from the following agencies: (1) Virginia Division of Forestry, P. O. Box 2758, Charlottesville, VA 22903; (2) Central Shenandoah Planning District Commission, P. O. Box 1337, 119 West Frederick Street, Staunton, VA 24401 (3) Soil Conservation Service, U. S. Department of Agriculture, P. O. Box 10026, Richmond, VA 23240; (4) State Water Control Board, P. O. Box 268, Bridgewater, VA 22812.

KEY

CONTACTS
Exposed or approximate

FOLDS
Syncline—trace
Direction and angle of plunge of minor anticline
Direction and angle of plunge of minor fold showing strike and dip of axial plane
Direction and angle of plunge of minor fold showing strike and dip of axial plane and symmetry of fold

FAULTS
Black line where exposed or approximate; gray line where covered or inferred; T, upper sheet

ATTITUDE OF ROCKS
Strike and dip of beds
Strike and dip of overturned beds
Strike of vertical beds
Horizontal beds

FOLIATION
Strike and dip of schistosity

LINEATION
Direction, angle of plunge, and symmetry of crenulation

MINE AND QUARRIES
Abandoned mine or quarry
fm—mine (iron and manganese)
Crushed stone quarry (limestone, limestone and dolomite, or quartzite)
g—sand and gravel quarry

SAMPLE LOCATIONS
R-7082 R, repository number of rock sample on file at Virginia Division of Mineral Resources
F-7091 Sample of raw material having potential for commercial use; R, repository number
F-939 F, repository number of fossil sample on file at Virginia Division of Mineral Resources
Reference locality described in discussion

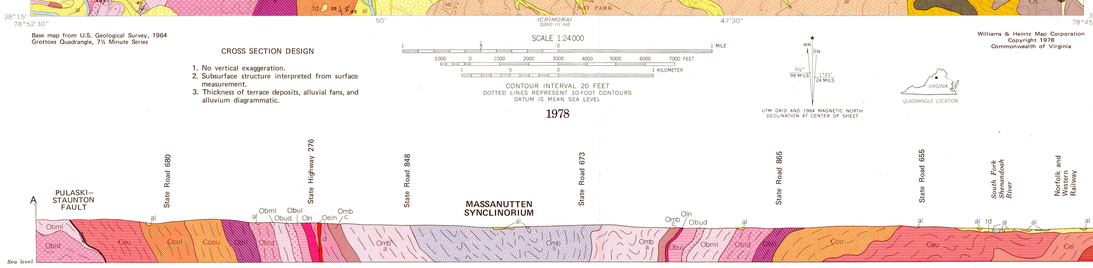

Figure 1. Generalized cross section showing morphology of the Cambro-Ordovician carbonate shelf environment—central Shenandoah Val