Triassic-Jurassic Stratigraphy of the Culpeper and Barboursville Basins, Virginia and Maryland

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By K.Y. LEE *and* A.J. FROELICH

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A clarification of the Triassic–Jurassic stratigraphic sequences, sedimentation, and depositional environments

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By K.Y. LEE and A.J. FROELICH

ABSTRACT

The Culpeper basin of northern Virginia and adjacent Maryland is an elongate, north-northeast-trending, fault-bounded trough containing a thick sequence of Upper Triassic to Lower Jurassic nonmarine sedimentary rocks. The similar but much smaller Barboursville basin, a few kilometers to the south, contains only Upper Triassic clastic sedimentary rocks. The Lower Jurassic strata of the Culpeper basin are interbedded with a series of basalt flows, and both Upper Triassic and Jurassic rocks are intruded by Early Jurassic tholeiitic diabase; the Barboursville basin contains no known igneous rocks.

The Culpeper Group of the Newark Supergroup is herein used for the entire sequence of lower Mesozoic strata in both basins. The term "lower part of the Culpeper Group" is used informally for the mainly Upper Triassic sequence of continental sedimentary rocks occupying the entire Barboursville basin and the southern quarter and eastern half of the Culpeper basin; the "upper part of the Culpeper Group" includes the Lower Jurassic sedimentary rocks and intercalated tholeiitic basalt flows restricted to the west-central Culpeper basin.

The lower part of the Culpeper Group, mostly of Late Triassic age, is subdivided into four formations: the Manassas Sandstone, the Balls Bluff Siltstone, the Tibbstown Formation, and the Catharpin Creek Formation. The Manassas Sandstone contains three distinctive lenticular cobble and boulder conglomerate members that lie at the base of the Culpeper Group in different areas along the eastern margin of the basins. These are the Reston Member, the Rapidan Member, and the Tuscarora Creek Member. The conglomerates each grade upward and laterally into the widespread Poolesville Member, the main arkosic red sandstone unit of the Manassas.

The Balls Bluff Siltstone conformably overlies, grades into, and intertongues with sandstone of the Manassas and occupies the medial part of both basins. The Balls Bluff is predominantly red-brown calcareous siltstone and fine-grained sandstone intercalated with greenish-gray to dark-gray fossiliferous mudstone; it intertongues with the Leesburg Member, which is predominantly limestone conglomerate, in the northwestern Culpeper basin. The Balls Bluff Siltstone is conformably overlain by the Tibbstown Formation in the Barboursville basin and the southern Culpeper basin, and by the Catharpin Creek Formation in the central Culpeper basin.

The Tibbstown Formation, predominantly arkosic sandstone at the base, contains the Mountain Run Member, mainly greenstone cobble conglomerate, and the Haudricks Mountain Member, primarily quartz, phyllite, and schist pebble conglomerate. These conglomerates are present at the top of the formation on the west side of the basin, and this upward-coarsening sequence constitutes the youngest sedimentary rocks of the Culpeper Group in the Barboursville and southern Culpeper basins. Similarly, the Catharpin Creek Formation in the central Culpeper basin, mainly arkosic sandstone at the base and containing rocks of both Late Triassic and Early Jurassic age, grades laterally and upward into the Goose Creek Member, a coarse conglomerate.

The upper part of the Culpeper Group of Early Jurassic age consists of the Mount Zion Church Basalt at the base, locally containing lenses of sandstones and siltstones that separate two basalt flows. The upper basalt flow is overlain by the Midland Formation, mainly reddish-brown sandstone and siltstone with gray, fossiliferous, calcareous shale zones near the base, succeeded by the Hickory Grove Basalt. The Hickory Grove contains lenticular sandstone and siltstone bodies that separate three or more basalt flows. It is overlain by the Turkey Run Formation, predominantly sandstone interbedded with red-brown and gray-green siltstone, capped by the Sander Basalt. The Sander Basalt comprises the greatest number and thickest series of flows, and contains the thickest and most extensive lenticular sandstone and siltstone intercalations. The overlying Waterfall Formation consists of interbedded sandstone, siltstone, conglomerate, and several fossiliferous, calcareous shale zones. The Waterfall displays several local and at least one regional unconformity near Thoroughfare Gap, where it is overlain by the Millbrook Quarry Member, a coarse boulder and cobble conglomerate that is the youngest Jurassic sedimentary unit of the Culpeper Group.

Fossil flora and fauna are present but generally sparse in the "red beds" of the Culpeper and Barboursville basins. Phytosaur bones of Late Triassic age have been identified from the Balls Bluff Siltstone; dinosaur tracks are well preserved in the same formation and in the Manassas Sandstone. Dinosaur tracks of Early Jurassic age occur in the Turkey Run and Waterfall Formations. More important, shales of the Midland and Waterfall Formations have yielded well-preserved freshwater fish. Conchostracans, ostracodes, fish scales, insect parts, and diagnostic spores and pollen are also present in the Manassas Sandstone, the Balls Bluff Siltstone, and the Tibbstown, Catharpin Creek, Midland, Turkey Run, and Waterfall Formations. The presence of Late Triassic and Early Jurassic spores and pollen throughout the exposed stratigraphic section has enabled the systematic palynofloral zonation of the entire Culpeper Group, supported in places by characteristic fish zones. Strata of the Culpeper Group range in age from the Late Triassic (at least late Carnian, about 225 Ma) to the Early Jurassic (late Sinemurian or early Pliensbachian, about 193 Ma), with the Triassic-Jurassic boundary (about 208 Ma) a short distance below the base of the Mount Zion Church Basalt in the upper part of the Catharpin Creek Formation.

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The distribution of strata in the Culpeper Group is explained by accumulation of clastic sediments in a closed basin flanked by fault-block mountains that were episodically uplifted and eroded. Deposition within the basin was controlled by subsidence accompanying extensional tectonics during a dominantly semiarid climate punctuated by periods of abundant precipitation. The Manassas, Tibbstown, Catharpin Creek, and Waterfall Formations and the Leesburg and Goose Creek Members of the Balls Bluff Siltstone reflect deposition near basin margins by braided streams and debris flows of alluvial fan complexes. The principal part of the Balls Bluff Siltstone, on the other hand, contains primary structures that suggest deposition in playa lakes, on subaerial silty fluvial mudflats, or at the distal parts of alluvial fans. The siltstone and shale cycles of the Balls Bluff, Midland, and Waterfall indicate deposition in lakes. Some of the lakes of the Balls Bluff were playas; others in the Midland and Waterfall Formations were probably perennial. Turbidite deposition in the lakes was locally important. Numerous local unconformities, commonly overlain by conglomerate, attest to the tectonic instability of the mountainous source areas flanking the Early Jurassic lakes. Tectonic instability in the Early Jurassic, indicated by upward-coarsening sequences in the Catharpin Creek Formation, was accompanied by fissure flows of basalt.

During the late stages of Jurassic deposition of the Culpeper Group, tholeiitic diabase stocks, sills, and dikes (about 195 Ma) extensively intruded the sedimentary rocks and basalt flows and thermally metamorphosed them. The strata in the Culpeper and Barboursville basins were regionally tilted to the west, particularly along the western border faults, which produced steep dips, drag folds, gravity slumping, and slippage along bedding planes; broad, gently southwest plunging folds, and en echelon and strike-slip faults along the western basin margin; and folds and transverse faults within the basins.

INTRODUCTION

The original stratigraphic nomenclature of the Culpeper basin was introduced by Roberts (1922, 1923, 1928) in Virginia. Jonas and Stose (1938) later introduced nomenclature from the Gettysburg basin into the Maryland part of the Culpeper basin; these units did not match those of Roberts. For about half a century there were no significant advances in the stratigraphy of any of the early Mesozoic basins of Eastern North America. The systematic palynological studies of Cornet (1977) provided precise new temporal data in previously undatable rocks that proved the presence of Early Jurassic as well as Late Triassic strata in the northern early Mesozoic basins of Eastern North America. Widespread stratigraphic revisions have followed. In the Culpeper basin, four systems of stratigraphic nomenclature have recently been proposed (Cornet, 1977; Lee, 1977, 1979, 1980; Lindholm, 1979). Objections have been raised to each, and no single scheme is in common use. Plate 1 (*A*) summarizes the evolution of stratigraphic nomenclature in the Culpeper basin. None of these systems, which describe the same sequence of rocks, is without shortcomings, whether based on recent geologic mapping (Lindholm, 1977, 1978, 1979; Lee, 1979, 1980; Gore, 1983), recent studies of fossil fish and dinosaur tracks and bones (Olsen, 1978, 1984; Olsen and others, 1982), or studies of spores and pollen (Cornet, 1977). Furthermore, none of these systems is compatible with recent revisions of the Newark Supergroup in Eastern North America (Froelich and Olsen, 1984), with usage in the Hartford basin as shown on the State geologic maps of Massachusetts (1983) and Connecticut (1983), or with the most recent revisions in the Newark basin of New Jersey and Pennsylvania (Olsen and others, 1982; Olsen, 1984).

A reexamination of the Late Triassic and Early Jurassic stratigraphy of the Culpeper basin indicates that it can be correlated with the newly revised stratigraphy of the Hartford and Newark basins to the north. In each of these major basins, two clastic sedimentary successions of Early Jurassic age occur between three major basalt flow sequences. The strata between the flows are now considered formations: the Shuttle Meadow and East Berlin Formations in Connecticut and Massachusetts and the Feltville and Towaco Formations in New Jersey. This pattern of nomenclature is herein extended to the southernmost exposed Jurassic strata in Eastern North America by defining and naming the Midland and Turkey Run Formations in the Culpeper basin. All of the remaining stratigraphic revisions stem logically from (1) considering the sedimentary sequences that are separated by basalt flows to be formations, (2) elevating the Newark Group of Eastern North America to a supergroup, and (3) establishing the entire section of Triassic and Jurassic strata in the Culpeper and Barboursville basins as a group.

REGIONAL SETTING

The Culpeper and Barboursville basins are centrally situated in a belt of Late Triassic to Early Jurassic fault-bounded troughs exposed in Eastern North America from Nova Scotia to the Carolinas. These troughs, containing nonmarine Newark Supergroup strata, are generally in alignment with the structural grain of enclosing upper Precambrian and lower Paleozoic crystalline and sedimentary rocks, and are located mostly within the Piedmont province of the Appalachian orogenic belt (Rodgers, 1970, p. 203-207; fig. 1, this paper). The Culpeper and Barboursville basins originated and evolved during the early Mesozoic, a time of continental rifting that preceded Coastal Plain deposition and the development of the modern Atlantic continental margin (Dickinson, 1974; Van Houten, 1977b, p. 83, 89-96). The Culpeper basin occupies about 2,750 km^2, most of which is in northern Virginia. At the southern end of the Culpeper basin, Conley and Johnson (1975) delineated a small, isolated

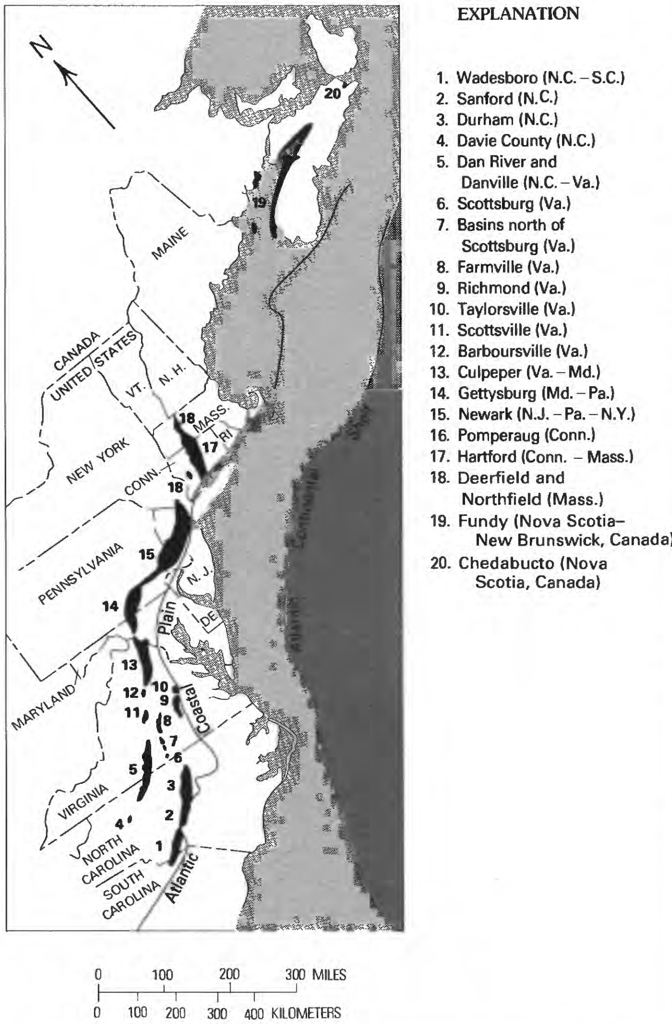


FIGURE 1.—Principal Triassic-Jurassic basins containing the Newark Supergroup strata exposed in Eastern North America.

trough, separated from the main basin to the northeast by about 2.5 km of Precambrian metamorphic rocks. This smaller trough, occupying about 51 km^2, was named the "Barboursville basin" (Lee, 1980) after the town of Barboursville, Orange County, Va.

The Culpeper and Barboursville basins contain fluvial and lacustrine clastic sedimentary rocks, chiefly "red beds" and conglomerates. A large number of Lower Jurassic fissure basalt flows are present throughout the west-central part of the Culpeper basin. These basalt flows are generally conformable with bedding and, in places, are intercalated with lenses of unaltered, fine-grained red beds and conglomerates, but neither the enclosed strata nor the overlying and underlying beds apparently contain volcanic ash. Locally, fresh basalt cobbles and boulders in polymict conglomerate are intercalated with Hickory Grove or Sander Basalt flows, and in places basalt forms the matrix of marble, basalt, and quartzite cobble conglomerate. These characteristics indicate that fissure eruption and flows were syndepositional with continental clastic sedimentation. Toward the end of basin filling, the sedimentary rocks and basalt flows in the basin were tilted toward the west and northwest. The tilting may be related to subsidence flanking the uplift of the central axis of the Appalachian deformed belt to the east (McKee and others, 1959, p. 24, pl. 9). This uplift may have been caused by crustal thinning and mafic magmatic intrusion at depth (Ballard and Uchupi, 1975), accompanied by extensive intrusion of tholeiitic diabase dikes and sheets in the Culpeper basin. The tilting was accompanied by large-scale movement along the normal western border fault, as contrasted with faults along the eastern border which locally show minor amounts of displacement, and by the development of broad, gentle, southwesterly plunging folds, strike-slip faults, and high-angle normal faults within the basins.

The Culpeper Group thus retains a partial record spanning some 30 million years of Late Triassic to Early Jurassic continental sedimentation, climatic change, basaltic volcanism, and mafic intrusion accompanying the incipient rifting of the North American and African plates, an event that culminated farther to the east with the opening of the Atlantic Ocean.

PREVIOUS INVESTIGATIONS

Studies related to the stratigraphy of the Culpeper basin began when W.B. Rogers' (1854) "New Red Sandstone of the Atlantic Slope" was designated the "Newark Group" in Virginia by Redfield (1856, p. 357). Roberts (1922, 1923, 1928) carried out the first systematic study of early Mesozoic geology in Virginia. He divided the rocks of the Culpeper basin into the Border Conglomerate, the Manassas Sandstone, and the Bull Run Shales and described the diabase and adjacent thermally metamorphosed red beds in the basin. He did not clearly define the stratigraphic units, identify the basalt flows, realize that conglomerates of many ages were present, or recognize the Jurassic age of part of the stratigraphic sequence. He also did not fully understand the importance of the regional structure or the significance of sedimentary facies changes in relation to depositional environments.

In Maryland, Dorsey (1918) made a regional study of the stratigraphy and structure of the Triassic rocks. Later, Jonas (1928) and Jonas and Stose (1938), during geologic mapping in Frederick and Carroll Counties, Md., adopted the name "New Oxford Formation," named by Stose and Bascom (1929) for the exposures at New Oxford, Adams County, Pa. The New Oxford Formation represents the lowest stratigraphic unit of the Triassic rocks in the Gettysburg basin of Pennsylvania and Maryland, and it was equated with all of the preserved Triassic section in the adjacent Culpeper basin of Maryland. Jonas and Stose (1938) mapped the early Mesozoic geology of the north end of the Culpeper basin adjacent to the Frederick Valley and separated limestone conglomerate from the adjacent sandstone, siltstone, and silty shale of the New Oxford Formation.

Since the late 1940's the geology of the Culpeper basin has been studied in greater stratigraphic detail, in part because of discoveries and studies of fossil fish and spores in other basins, and in part because of the discovery of fossil fish in the west-central and western parts of the basin by Baer and Martin (1949, fig. 2) and subsequent detailed studies of other fossil remains in the strata of the Culpeper basin. Schaeffer and others (1975) and Schaeffer and McDonald (1978) identified *Ptycholepis marshi* Newberry and *Redfieldius gracilis* recovered from a site in Licking Run northwest of Midland (fig. 2), Fauquier County, Va., and at the bridge abutment of U.S. Route 15 over Catharpin Creek (fig. 2) northwest of Haymarket, Prince William County, Va. Nicholas Hotten III (unpub. data, 1959) and Robert E. Weems (1979) identified Late Triassic phytosaur bones found by R.E. Eggleton at what is now the Dulles International Airport during his mapping of the Herndon quadrangle in the late 1950's (Eggleton, 1975).

Cornet (1977) made a detailed palynostratigraphic study in the northern part of the basin and first recognized and proved that Lower Jurassic as well as Upper Triassic sedimentary rocks are present in the basin. He placed the Triassic-Jurassic boundary just below the lowest basalt flow (Cornet, 1977, Palynoflorule 8/K2, p. 124, 175-183).

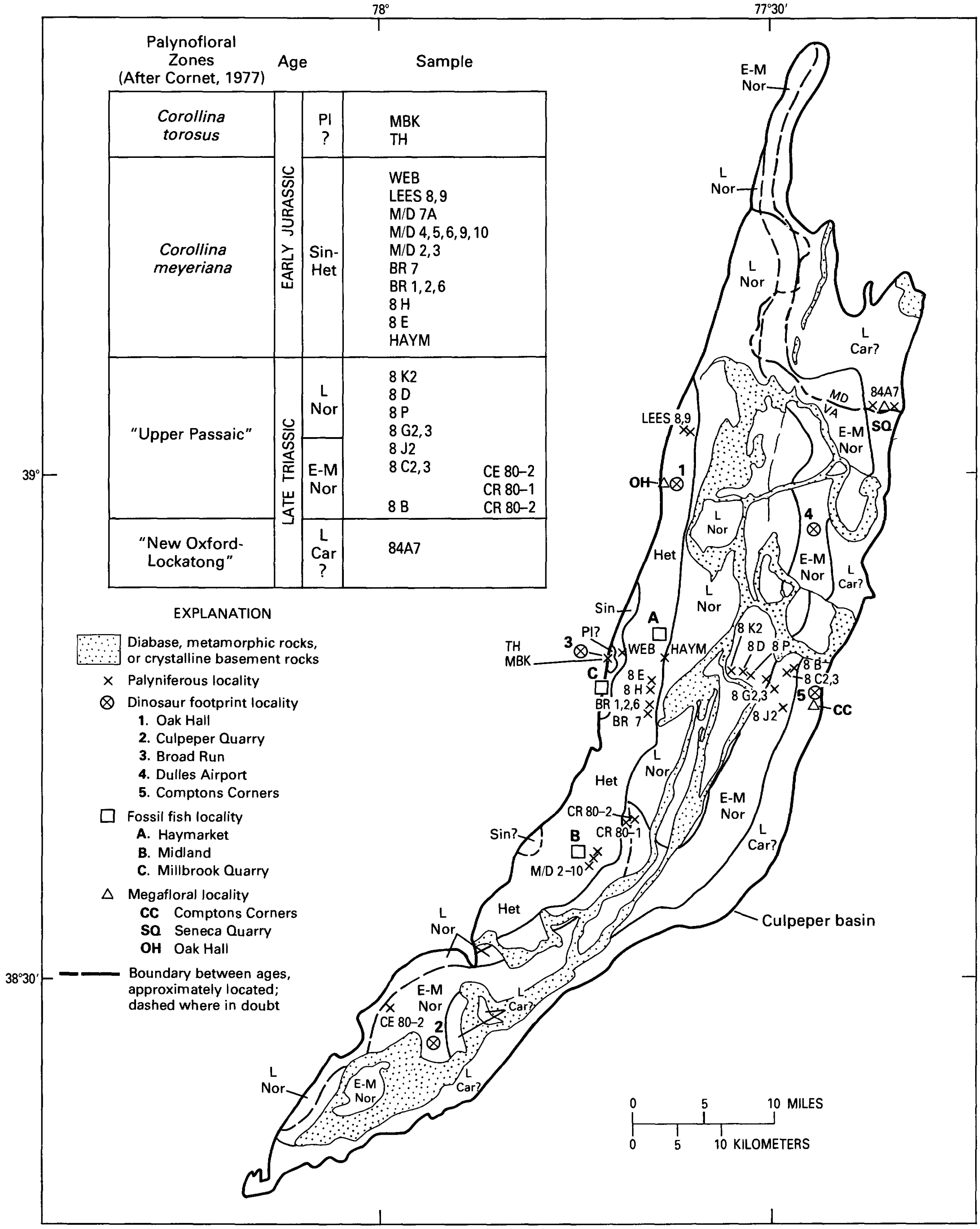
From 1951 to 1978, studies of the areal geology of small parts of the basin by several geologists of the U.S. Geological Survey (USGS) contributed unpublished and open-filed geologic data and maps (Bennison and Milton, 1954). Bain (1959) provided new petrographic data about the diabase in the Nokesville 7.5-min Quadrangle, and Lindskold (1961) studied the geology of the Gainesville 7.5-min Quadrangle and described the occurrence and petrography of the diabase there. Fisher (1964) provided detailed information on petrography and chemistry of the Triassic rocks in Montgomery County, Md. Toewe's (1966) geologic map of the Leesburg 7.5-min Quadrangle, Loudoun County, Va., delineated and described the stratigraphically lowest basalt flow in the basin and contributed detailed analyses of sedimentary facies in the area. However, Toewe interpreted thermally metamorphosed red beds as a sequence of pyroclastic rocks and mapped a second, in part porphyritic, basalt flow sequence as intrusive diabase in the southwestern part of the quadrangle. McCollum (1971) recognized and briefly described the basalt flows in the west-central part of the Culpeper basin. Froelich published data on the physical properties (1975a) and mineral resources (1975b) of the Triassic rocks in Montgomery County, Md. Hazlett (1978) made a field and petrographic study of the limestone conglomerate in the vicinity of Leesburg, Loudoun County, Va.

Nutter (1975) studied and documented regional hydrogeologic relations in the Maryland part of the Culpeper basin and provided a description of drill cuttings in Montgomery County (Nutter, 1975, table 10, p. 32, 33). Otton (1981, table 12, p. 46-52; fig. 3, this paper) continued hydrogeologic studies in Montgomery County and described two new drill holes.

Lindholm (1977, 1978, 1979) studied the Triassic-Jurassic geology of the Culpeper basin in Virginia by using soil maps, proposed a revised stratigraphy, and made a comprehensive interpretation of the geologic history of the basin. He described the basalt flows and intercalated strata exposed along the road cuts of U.S. Route 29-211, Prince William and Fauquier Counties, Va. Lindholm and others (1979) published a comprehensive summary and petrologic study of the diverse conglomerates in the basins, with an interpretation of their significance and origin.

Lee (1977) carried out detailed geologic mapping of the Triassic and Jurassic rocks of 7.5-min quadrangles in Fairfax and Loudoun Counties, Va., and reconnaissance geologic mapping in Montgomery and Frederick Counties, Md. He provided eight new measured sections in the northern part of the Culpeper basin (Lee, 1977; table 1, this paper). Lee found that the complex stratigraphic relations in northern Virginia could not be adequately portrayed by the existing formation names of Roberts (1928) and proposed changes in the nomenclature of the sedimentary rocks in the basin. These rocks were redefined on the basis of lithostratigraphic sequence and his interpretation of the depositional environments. A geologic map of the Arcola 7.5-min Quadrangle, Va., was published by Lee (1978), followed by two USGS open-file reports that contained 34 geologic maps of the remaining quadrangles of the Culpeper and Barboursville basins (Lee, 1979, 1980).

Hentz (1981, 1982, 1985) studied the structure and stratigraphy of the Jurassic Waterfall strata near Thoroughfare Gap in great detail, subdividing the lacustrine beds into eight subunits and showing that turbidites and unconformities are important in this area. He provided three new measured sections and two core hole descriptions (Hentz, 1981; tables 1 and 2, this paper). Upon completion of Lee's quadrangle



Palynofloral Zones (After Cornet, 1977)	Age		Sample	
Corollina torosus	EARLY JURASSIC	Pl ?	MBK TH	
Corollina meyeriana	EARLY JURASSIC	Sin-Het	WEB LEES 8, 9 M/D 7A M/D 4, 5, 6, 9, 10 M/D 2, 3 BR 7 BR 1, 2, 6 8 H 8 E HAYM	
"Upper Passaic"	LATE TRIASSIC	L Nor	8 K2 8 D 8 P 8 G2, 3 8 J2	
"Upper Passaic"	LATE TRIASSIC	E-M Nor	8 C2, 3 8 B	CE 80–2 CR 80–1 CR 80–2
"New Oxford-Lockatong"	LATE TRIASSIC	L Car ?	84A7	

FIGURE 2.—Sketch map of the age of strata, Culpeper Group, Culpeper basin, Virginia and Maryland, showing the location of diagnostic palynologic samples and palynofloral zones and paleontologic localities. Pl, Pliensbachian; Sin-Het, Sinemurian-Hettangian; L Nor, Late Norian; E-M Nor, Early to Middle Norian; L Car, Late Carnian; ?, age in doubt.

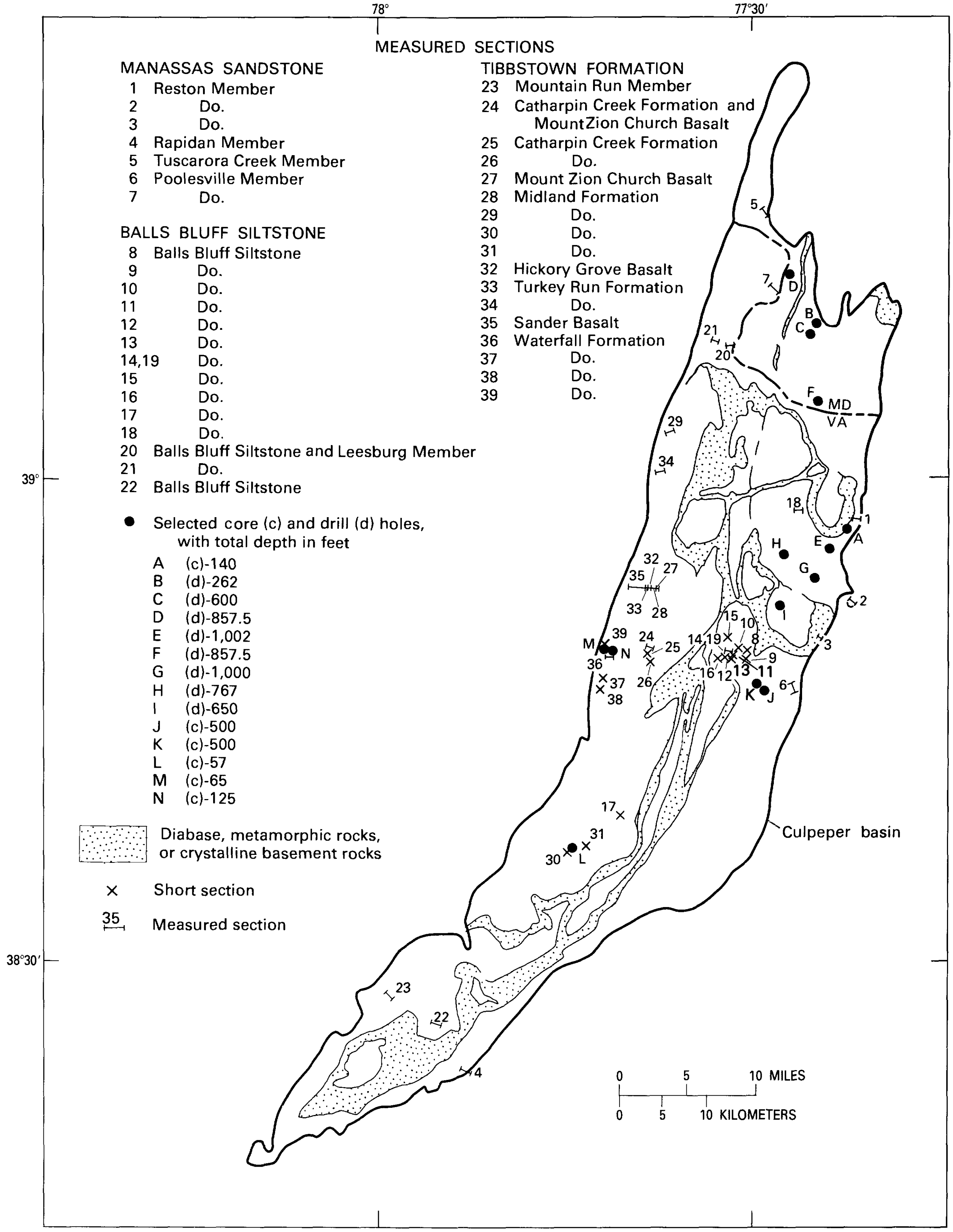


FIGURE 3.—Sketch map of the Culpeper basin, Virginia and Maryland, showing the location of measured sections and selected drill holes.

TABLE 1.—*Summary of measured sections in the Culpeper basin, Virginia and Maryland*

[Keyed to pl. 1. Do., ditto]

Map No.[1]	Field No.	Formation and Member	Thickness Meters	Thickness Feet	Reference
1	KYL-77-1	Manassas Sandstone, Reston Member (Partial)	5.5	18	Lee, 1977, p. C-9, sec. 1.
2	KYL-77-2	Do.	4.2	14	Lee, 1977, p. C-10, sec. 2.
3	KYL-77-3	Do.	3.6	12	Lee, 1977, p. C-10, 11, sec. 3.
4	KYL-84-1	Manassas Sandstone, Rapidan Member (Partial)	75.4	249	This paper, app. A, sec. 1.
5	KYL-84-2	Manassas Sandstone, Tuscarora Creek Member (Partial)	6.0	20	This paper, app. A, sec. 2.
6	KYL-77-4	Manassas Sandstone, Poolesville Member (Partial)	20	66	Lee, 1977, p. C-11, sec. 4.
7	KYL-77-5	Do.	37	122	Lee, 1977, p. C-12, sec. 5.
[2]8	PG-8/B	Balls Bluff Siltstone (Partial)	39.15	129.2	Gore, 1983, app. A, B, p. 297-343.
[2]9	PG 8/G	Do.	3.6	11.9	Do.
10	PG G-3	Do.	24.4	80.5	Do.
11	PG G-7	Do.	5.32	17.5	Do.
12	PG G-8	Do.	10	33	Do.
[2]13	PG 8/D	Do.	12	39.6	Do.
[3]14	PG G-1	Do.	6.82	22.5	Do.
15	PG G-5	Do.	4.15	13.7	Do.
[2]16	PG 8/K	Do.	47.3	156	Do.
17	PG C-1	Do.	11	36.3	Do.
18	AJF-82-1	Do.	5.5	18	Froelich and others, 1982, stop 1, p. 59-62.
[3]19	AJF-82-8	Do.	7.6	25	Froelich and others, 1982, stop 1, p. 59-62.
20	KYL-77-6	Balls Bluff Siltstone (Partial)	40	131	Lee, 1977, p. C-13, 14, sec. 6.
21	KYL-77-7	Leesburg Member (Partial)	76	251	Lee, 1977.p. C-15, sec. 7
22	JPS-84-1	Balls Bluff Siltstone (Partial)	65.6	215	This paper, app. A, sec. 5.
23	KYL-84-3	Tibbstown Formation, Mountain Run Member (Partial)	215.8	712	This paper, app. A, sec. 3.
24	AJF-82-7	Catharpin Creek Formation and Mount Zion Church Basalt (Partial)	18.2	60	Froelich, and others, 1982, stop 7, p. 75-76.
25	PG-T-3	Catharpin Creek Formation (Partial)	17.5	57.8	Gore, 1983, app. A, B. p. 297-343.
26	PG-T-1	Do.	10.45	34.5	Do.
27	KYL-84-4A	Mount Zion Church Basalt (Partial)	9.1	30	This paper, app. A, sec. 4A.
28	KYL-84-4B	Midland Formation (Complete)	378.8	1,250	This paper, app. A, sec. 4B.
29	ECT-66-1	Do. (Partial)	180	591	Toewe, 1966, app. I, p. 32-35.
30	PG-MID-1	Do.	9.9	32.7	Gore, 1983, app. A, B, p. 297-343.
31	PG-MID-2	Do.	10.43	34.4	Do.
32	KYL-84-4C	Hickory Grove Basalt (Complete)	211.1	695	This paper, app. A, sec. 4C.
33	KYL-84-4D	Turkey Run Formation (Complete)	216.6	715	This paper, app. A, sec. 4D.
34	KYL-77-8	Do. (Partial)	37	122	Lee, 1977, p. C-15, 16, sec. 8.
35	KYL-84-4E	Sander Basalt and sandstone and siltstone members (Partial)	805.7	2,659	This paper, app. A, sec. 4E.
36	TH-82-TC	Waterfall Formation (Partial)	141	465	Hentz, 1981, app. B.
37	TH-82-DB	Do.	10	33	Do.
38	TH-82-BR	Do.	34.5	114	Do.
39	AJF-82-6	Do.	14	46	Froelich, A.J. and others 1982, stop 6, p. 73-75.

[1]Map numbers correspond to numbers in figure 3.
[2]Cornet (1977) section measured and described by Gore (1983).
[3]Same section measured and described.

TABLE 2.—*Summary of core holes and selected drill holes in the Culpeper basin, Virginia and Maryland*

[Keyed to pl. 1. Do., ditto]

Map I.D.[1]	Well No. (WRD-ID)	Formation member interval (ft)	Cored (c) or Drilled (d)	Total depth Meters	Total depth Feet	Reference
A	F-52V-1D	(Partial) Manassas Sandstone, Poolesville Member, 0-75 ft. (Complete) Manassas Sandstone, Reston Member, 75-125 ft. Peters Creek Schlist, 125-140 ft.	c	42.5	140	Larson, 1978, app., p. 31-35.
B	Mo-DC-59	(Partial) Manassas Sandstone, Poolesville Member, 0-50 ft. (Complete) Manassas Sandstone, Reston Member, 50-105 ft. Peters Creek Schist, 105-262 ft.	d	79.4	262	Otton, 1981, table 12, p. 50-52.
C	Mo-Do-47	(Partial) Manassas Sandstone, Poolesville Member, 0-600 ft. (Partial)	d	181.8	600	Otton, 1981, table 12, p. 46-49.
D	Mo-Cb-26	(Partial) Manassas Sandstone, Poolesville Member, 0-770 ft. Manassas Sandstone, Tuscarora Creek Member, 770-808 ft. (Complete) Frederick Limestone (Cambrian), 808-857.5 ft.	d	260	857.5	Nutter, 1975, table 10, p.32, 33.
E	F-51V-14F	(Partial) Manassas Sandstone, Poolesville Member, 0-545 ft. Manassas Sandstone, Reston Member, 545-610 ft. (Complete) Peters Creek Schist, 610-1,002 ft.	d	301	1,002	This paper, app. B.
F	EC-10 Mo-EG10	(Partial) Balls Bluff Siltstone, 0-857.5 ft.	d	260	857.5	Otton, 1981.
G	51V-23H	(Partial) Manassas Sandstone, Poolesville, Member, 0-1,000 ft.	d	305	1,000	This paper, app. B.
H	51V-24H	(Partial) Balls Bluff Siltstone, 0-767 ft.	d	233.8	767	Do.
I	51V-13A	(Partial) Balls Bluff Siltstone, 0-280 ft. Hornfels (thermally metamorphosed siltstone), 280-650 ft.	d	198	650	Do.
J	Man-1	(Partial) Balls Bluff Siltstone, 0-550 ft.	c	165	550	Sobhan, 1985.
K	Man-2	(Partial) Balls Bluff Siltstone, 0-550 ft.	c	150	500	Do.
L	Mid-1	(Partial) Midland Formation, 0-56.4 ft.	c	17	56.4	Smoot, this paper, app. B.
M	TGC-1	(Partial) Waterfall Formation, 0-65 ft.	c	19.7	65	Hentz, 1981, app. 2.
N	TGC-2	(Partial) Waterfall Formation, 0-125 ft.	c	37.8	125	. Do.

[1]Map identification letters correspond to letters in figure 3.

mapping, Froelich and others integrated the geologic map coverage with newly acquired hydrologic and geophysical data and prepared a series of topical reports and regional maps at a scale of 1:125,000 (Leavy, 1980, 1984; Wise and Johnson, 1980; Froelich and Leavy, 1982; Johnson and Froelich, 1982; Leavy and others 1982, 1983; Posner and Zenone, 1983; Froelich, 1985; Zenone and Laczniak, 1985). Some of the newly acquired chemical and isotopic data on the igneous rocks had a significant bearing on the age and stratigraphic interpretation (Sutter and Arth, 1983; Lee and others, 1984), and this paper incorporates much of the data acquired by many workers in the Culpeper and Barboursville basins over the past decade.

SCOPE, PURPOSE, AND METHOD OF STUDY

Systematic mapping for this investigation was undertaken by Lee from the fall of 1973 to the spring of 1977. The purposes of that study were to define and map the stratigraphic units and to determine the geologic factors controlling the origin of the sedimentary and igneous rocks and the thermal metamorphism of country rocks adjacent to intrusive diabase in the Culpeper and Barboursville basins.

Geologic mapping at a scale of 1:24,000 was completed throughout most of the two basins (Lee, 1979, 1980). Individual lithologic units were identified on the basis of mineralogic composition, texture, structure, and other physical characteristics. Geologic contacts between stratigraphic units were located only approximately, because in most areas outcrops are very sparse and critical stratigraphic contacts are commonly covered. A sand/shale ratio of two to one was arbitrarily used to delineate the gradational contacts between deposits of shale and (or) siltstone and deposits of sandstone and (or) conglomerate.

Fresh rock exposures were sampled for laboratory investigation on the basis of lithostratigraphic facies changes, areal distribution, and variation of texture and mineralogy of rock types. Twelve typical sections across the basins were examined in detail to determine regional structure, lithostratigraphic facies, and contact relations between intrusive diabase and country rock with thermal metamorphism. Four sections were measured in the field, and thicknesses in the remaining eight sections were calculated as composite sections from the geologic quadrangle maps. In addition, thickness of individual stratigraphic units was measured at selected localities in the field (app. A, table 1) to supplement those measured previously and reported elsewhere (Toewe, 1966; Lee, 1977; Froelich and others, 1982; Hentz, 1982).

Measurements of crossbeds and other primary sedimentary structures were made in siltstones and sandstones to determine directions of paleocurrents. Pebble counts were made in conglomerates to ascertain the sediment provenance, and the rock fabric was studied to determine conditions of transportation and deposition. Such determinations enable an understanding of the physical characteristics of fluvial and debris-flow deposits; the areal distribution of fluvial fan-segments, which consist of the fanhead, midfan, fan base, and distal facies; and the nature of coalescence among the fans distributed throughout the basins.

Subsequently, we have gathered new age and correlation data and have assessed and compiled selected lithologic logs of deep water wells and core holes (tables 1 and 2, this paper; Sobhan, 1985).

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We are grateful to the residents in the Culpeper and Barboursville basins for their courtesy and hospitality. We are deeply indebted to many colleagues at the USGS with whom we have discussed various problems. Sincere thanks are due the following persons for their help during the course of this study: G.V. Cohee thoughtfully provided information on fossil fish in the Culpeper basin; E.C.T. Chao provided his unpublished data on Triassic and Jurassic geology in Fairfax and Loudoun Counties, Va.; N.F. Sohl and John Pojeta, Jr., identified freshwater crustacean fauna from limestone in Prince William County, Va.; S.H. Mamay identified plant remains from sandstones southwest of Frederick, Md.; Frank C. Whitmore, Jr., and Robert E. Weems identified the dinosaur tracks at the Culpeper Crushed Stone quarry in Culpeper County, Va.; E.I. Robbins made a palynologic study of siltstone in Culpeper County, Va.; Dr. Nicholas Hotten III, U.S. National Museum of Natural History, Smithsonian Institution, Washington, D.C., discussed the age of phytosaur remains in siltstone at Dulles Airport; D. Chaney of the Smithsonian Institution provided access to the Midland fish bed locality; Melody Hess determined clay minerals in siltstone and sandstone collected from U.S. Route 50 by X-ray diffraction methods; R.H. Johnston, J.D. Larson, Chester Zenone, and Alex Posner carried out ground-water quality and quantity appraisals, and Randall Laczniak prepared computer models of the ground-water flow system throughout the Culpeper basin. Brooks Ellwood, Carol Raymond, and others completed paleomagnetic studies of selected outcrops of basalt and diabase; John Sutter and Joseph Arth of the USGS determined isotope ratios and $^{40}Ar/^{39}Ar$ age spectrum dates of the same basalts and diabases; and John Puffer and Brian Leavy completed chemical and isotopic analyses of the basalts. David Gottfried contributed stimulating discussions, guidance, and chemical analyses of diabase and basalt. Joseph P.

Smoot measured and described sedimentologic aspects of the Midland core hole and the thick cyclic succession of Balls Bluff Siltstone at the Culpeper Crushed Stone quarry and provided many helpful suggestions in discussions of stratigraphic models.

STRATIGRAPHY

NEWARK SUPERGROUP

CULPEPER GROUP

General statement.—Upon completion of geologic mapping in the Culpeper and Barboursville basins it became apparent that the complex stratigraphic relations in the basins could not be adequately portrayed by existing stratigraphic nomenclature (pl. 1*A*). Consequently, a change in the nomenclature of both the sedimentary and basaltic rocks has been made to depict the stratigraphic relations on the basis of our understanding of the lithostratigraphic sequence, age relations determined on fossil content, depositional environment, provenance, areal structural relations, and isotopic age dating of igneous rocks. The name "Culpeper Group" (Lee, 1979, 1980) is adopted herein for the distinctive complete lithostratigraphic sequence of Upper Triassic and Lower Jurassic rocks in the basins (pl. 1*A*). This name was proposed informally by Cornet (1977, p. 119) and was used by Olsen (1978) and Lindholm (1979). It supersedes the term "Newark Group" (Lee, 1977, p. C2, C3), which was recently raised to Supergroup (Froelich and Olsen, 1984).

The term "lower part of the Culpeper Group" is used informally for the mainly Upper Triassic sequence of continental sedimentary rocks occupying the entire Barboursville basin and the southern quarter and eastern half of the Culpeper basin; the "upper part of the Culpeper Group" includes the Lower Jurassic series of tholeiitic basalt flows restricted to the west-central Culpeper basin and the intercalated sedimentary rocks. Correspondingly, for correlations between the Culpeper, Newark, and Hartford basins, as in plate 1*B*, the term "lower part of the Newark Supergroup" is used for the mainly Upper Triassic sequences of sedimentary rocks and the term "upper part of the Newark Supergroup" includes the Lower Jurassic basalts and intercalated sedimentary rocks in all three basins.

The Border Conglomerate of Roberts (1928) occurs on both flanks as well as in the interior of the Culpeper basin and spans the entire Triassic-Jurassic section. Most of the conglomerates are lenticular, isolated, and not coeval. They are separable into geographically and lithologically distinct members of several different formations of several ages. Therefore, the term "Border Conglomerate" is hereby abandoned (see pl. 1*A*). The name "New Oxford Formation," extended by Jonas and Stose (1938) into the Maryland portion of the Culpeper basin from the Gettysburg basin, is replaced by the Manassas Sandstone and is no longer recognized in the Culpeper basin (see pl. 1*A*). The Manassas Sandstone (Roberts, 1928) is retained, but several newly named conglomerate members are included within it (see pl. 1*A*). The type Bull Run Shales of Roberts (1928) is mainly siltstone, and the area he mapped within this unit in the Culpeper basin includes lithologies as diverse as conglomerate, sandstone, and basalt. The term "Bull Run Formation" has been used by Lindholm (1979) for a medial unit of mainly Upper Triassic calcareous siltstone; Lee (1977, 1979, 1980) expanded the unit to include Triassic and Jurassic strata and basalt flows. In all previous definitions, this heterogeneous unit lacks distinctive boundaries and is hereby abandoned. Cornet's informal usage of formations "A" through "K" (pl. 1*A*) is hereby abandoned, although the palynofloral zones that he established are incorporated and adapted to the appropriate named formations. Some of Lee's earlier informal proposals and nomenclature are adopted as presented, such as Mount Zion Church Basalt, Hickory Grove Basalt, Sander Basalt, and Poolesville, Reston, Tuscarora Creek, and Rapidan Members; some are redefined and retained, such as Catharpin Creek Formation, Balls Bluff Siltstone, Leesburg Member, and Mountain Run Member (see pl. 1*A*). Some of Lindholm's (1979) terminology is adopted as proposed or redefined and incorporated herein, such as Goose Creek Member and Waterfall Formation, whereas some stratigraphic names are abandoned, such as Buckland Formation, Cedar Mountain Conglomerate Member, and Barboursville Conglomerate Member (see pl. 1*A*). Thus the redefined stratigraphy of the Culpeper basin is an amalgam of previous usage and modified informal names, adapted to reflect our present understanding of age and complex lithofacies relationships. Some of the names in the Barboursville basin are carried over from the Culpeper basin, and some in the Barboursville basin carried over to the southern Culpeper basin.

Stratigraphic units and correlation.—The lower part of the Culpeper Group, mainly of Late Triassic age, is subdivided, in ascending order, into the Manassas Sandstone, the Balls Bluff Siltstone, the Tibbstown Formation, and the Catharpin Creek Formation. The Manassas Sandstone consists of the Reston Member, the Rapidan Member, and the Tuscarora Creek Member at the base, all chiefly conglomerates, overlain by and intertonguing laterally with arkosic sandstone of the Poolesville Member. The Balls Bluff Siltstone intertongues with its Leesburg Member, predominantly limestone conglomerate and with arkosic sandstones of the Manassas, Tibbstown, and Catharpin Creek Formations. The Tibbstown Formation, mainly arkosic sandstone, includes the Mountain Run and the Haudricks Mountain Members at the top, both conglomerates. The Catharpin Creek Formation, mainly arkosic sandstone, contains two fan-shaped lobes of the Goose Creek Member, a conglomerate that may contain lowermost Jurassic beds at the top. The upper part of the Culpeper Group of Early Jurassic age consists of the Mount Zion Church Basalt and associated sandstone and siltstone members; the Midland Formation; the Hickory Grove Basalt and associated sandstone and siltstone members; the Turkey Run Formation; the Sander Basalt and associated sandstone and siltstone members; and the Waterfall Formation, mainly sandstone, siltstone, and calcareous fossiliferous shale, with conglomerate of the Millbrook Quarry Member at the top.

The bulk composition of the conglomerates of the Culpeper Group shows considerable diversity of provenance (Lindholm and others, 1979). Their distinctive lithologic characteristics and restricted areal and stratigraphic distribution permit their differentiation into individual members and their correlation with specific source areas.

The Lower Jurassic basalts are thought to be synsedimentary surface flows, as no pillow structures are evident and the flows are interbedded with relatively unweathered sandstone, siltstone, and conglomerate; they are believed to be fissure flows because of their great areal extent and because pyroclastic debris is absent from overlying, underlying, and intercalated sedimentary rocks.

Stratigraphic correlation of the formations has been established throughout the basins by (1) detailed field investigations of the sedimentary succession and of the contained fossil flora and fauna, (2) interpretation of the conditions of transportation and deposition of individual stratigraphic units, and (3) lithostratigraphic analysis of the sedimentary rocks, particularly in relation to the stratigraphic position of the locally fossiliferous Balls Bluff Siltstone, the Midland and Turkey Run Formations, and the enclosing basalt flows (fig. 2 and pl. 1.)

Thickness.—The thickness of the Culpeper Group varies widely throughout the basins, in part because of highly variable rates of subsidence and continental sedimentation and in part because of erosion. In the northern Culpeper basin of Frederick County, Md., the measured or calculated thickness of this group is about 405 m (1,330 ft) about 2.3 km (1.4 mi) west of the intersection of Market and Patrick Streets, Frederick, Md., westward to east of Fuller, Md., and 627 m (2,057 ft) about 1.3 km (0.8 mi) N. 66° W. of Tuscarora, Md., westward to Point of Rocks, Md. It increases to 2,962 m (9,718 ft) across the basin from west of Dickerson, Montgomery County, Md., to the western border about 1.3 km (0.8 mi) west of Lucketts, Loudoun County, Va., and to 4,965 m (16,290 ft) in the area from north of Pender to north of Aldie, Va., and reaches a maximum of 7,900 m (25,920 ft) in the area south of Centreville to south of Antioch, Va., then decreases to 2,180 m (7,153 ft) in the area southeast of Mountain Run at Culpeper, Va., to the extreme southeastern corner of the Culpeper East 7.5-min Quadrangle, Orange County, Va. The thickness of the Culpeper Group in the Barboursville basin varies from 330 m (1,083 ft) to 576 m (1,890 ft). The preserved thickness at any point in the basins is indeterminate because of rapid lateral facies changes, widespread diabase intrusives, and poor exposures that may conceal major faults and unconformities.

Age.—Fossil fauna and flora, though generally sparse throughout the Culpeper basin, represent a diverse assemblage of continental varieties ranging from dinosaurs and well-preserved fish to microscopic spores and pollen. Important and diagnostic fossils and their localities and stratigraphic position are given in figure 2. Applegate (1956) indicated that further study was needed to determine the specific age of fossil fish found in the Culpeper basin. The paleontologic affinity of the Midland Formation with the Feltville Formation of the Newark basin, New Jersey, and the Shuttle Meadow Formation of the Hartford basin, Connecticut (pl. 1*B*), first established on the occurrence of *Ptycholepis marshi* Newberry (Schaeffer and others, 1975, p. 207, 208), was independently supported by palynologic studies of Cornet (1977, p. 134, 183) and by restudy of fossil fish by Olsen (1984) and Olsen and others (1982). These fossil fish were recovered from carbonaceous shale at Licking Run (fig. 2), about 2 km (1.25 mi) northwest of Midland, Fauquier County, Va. (Baer and Martin, 1949, p. 685; Schaeffer and others, 1975, p. 226-230), and at Catharpin Creek (fig. 2), at the bridge of U.S. Route 15 about 4.2 km (2.6 mi) north-northwest of Haymarket, Prince William, Va., by Schaeffer and others (1975, p. 229), who assigned a Late Triassic to Early Jurassic(?) age to the fish beds. Olsen and others' (1982) restudy of the fish fauna of the Culpeper basin confirmed the Early Jurassic (Hettangian) age of the Midland beds at the Licking Run and Catharpin Creek localities and supported the Sinemurian and possibly Pliensbachian age of the younger Waterfall sequence in the vicinity of Millbrook quarry in the Thoroughfare Gap quadrangle.

Palynological studies by Cornet (1977) identified a *Lower Passaic-Heidlersburg* palynoflora of Late Triassic age (early and middle Norian) in the lower part of his formation K, now the Manassas Sandstone, and a *Manassas-Upper Passaic* palynoflora (middle and late Norian) in the upper part of his formation K, now the Manassas Sandstone and Balls Bluff Siltstone. Cornet (1977, p. 134, 183; fossil location Mid-3-6, pl. 1*B*, this paper) indicated an Early Jurassic (Hettangian to early Sinemurian) age for the *Corollina meyeriana* palynoflora in the dark-gray, fish-bearing Midland beds (his formation I) at Licking Run. He placed the boundary between the Upper Triassic and Lower Jurassic above the stratigraphic level of his palynofloral 8-K2 (Cornet, 1977, p. 124; pl. 1*B*, this paper) that occurs in his formation K near Interstate Route 66 in about the center of the Gainesville 7.5-min Quadrangle. This locality is stratigraphically in the uppermost part of the Balls Bluff Siltstone; thus the Triassic-Jurassic boundary apparently is above the Balls Bluff and below the Mount Zion Church Basalt, and probably lies within the barren sandstones and conglomerates of the Catharpin Creek Formation.

Raymond and others (1982) determined the magnetization of core from representative sites within the intrusive and extrusive rocks of the Culpeper basin (pl. 1*C*). Measurements of six diabase sills, four diabase dikes, and three basalt flows yield a remanent magnetization after alternating field demagnetization that exhibits good within-site and between-site directional consistency. Paleopoles calculated from the remanent magnetization directions of these units correspond to the apparent polar wander path for North America at 200 Ma. Sutter and Arth (1983) determined the $^{40}Ar/^{39}Ar$ age spectrum dates and strontium isotope geochemistry from the same six diabase sill localities sampled by Raymond and others (1982). Whole-rock samples yield total gas $^{40}Ar/^{39}Ar$ apparent ages that range from 187 to 206 Ma. $^{40}Ar/^{39}Ar$ age spectra from the same six samples define plateau ages that range from 192 to 200 Ma and yield a mean age of 197±4 Ma, which they interpret as the best estimate of the age of intrusion and crystallization of the sills. Whole-rock samples from four of these sills have initial $^{87}Sr/^{86}Sr$ ratios ranging from 0.7060 to 0.7066 and a rather constant rubidium/strontium ratio of 0.10 to 0.13, values consistent with published values for Mesozoic diabase dikes and sills of Eastern North America. The strontium isotopic signature of these sills is clearly more characteristic of continental tholeiite than of normal midocean ridge basalts.

Cornet's (1977) palynologic study, Olsen and others' (1982) restudy and reevaluation of the fish fauna, the paleomagnetic pole positions of the basalts established by Raymond and others (1982), and finally the $^{40}Ar/^{39}Ar$ ages of the diabase sills and dikes by Sutter and Arth (1983) clearly establish the Early Jurassic age of the intercalated sedimentary and igneous rocks in the Culpeper basin. We, therefore, propose a Late Triassic age for the Manassas, Balls Bluff, and Tibbstown Formations, a Late Triassic and Early Jurassic age for the Catharpin Creek Formation, and an Early Jurassic age for the Mount Zion Church Basalt and all overlying formations and the intrusive diabase (pl. 1*A*).

MANASSAS SANDSTONE

The Manassas Sandstone was named for rocks exposed in the vicinity of Manassas, Prince William County, Va. (Roberts, 1923, 1928). This formation was revised by Lee (1977, p. C3-C5, C11, C12; 1979, 1980). As revised in this report (pl. 1*A*, 1*C*), the Manassas generally contains three discrete and separate lenticular lower conglomerate sequences, formerly part of the Border Conglomerate of Roberts (1928), each with pebbles and cobbles of distinctive lithologic types, such as schist and quartzite, greenstone, or limestone. These conglomerates are the Reston Member, which occurs in the east-central part of the Culpeper basin (Lee, 1977, p. C3, C4 C9-C11), the Rapidan Member (new name), which is exposed in the southeastern parts of the Culpeper and Barboursville basins, and the Tuscarora Creek Member (new name), which is located in the extreme northern part of the Culpeper basin. Each member unconformably overlies or is locally in fault contact with pre-Triassic crystalline rocks, and each grades into or interfingers with the overlying sandstone of the Poolesville Member (new name). These conglomerate members were probably more or less contemporaneous during the Late Triassic; the conditions of fluvial and debris-flow sedimentation were rapid and very similar, but the provenance was strikingly different for each. At the northern and southern extremities of the Culpeper and Barboursville basins, the basal outcrops are poor, conglomerate is absent, and the units consist of fine-grained sandstones and red-brown siltstones not typical of the Poolesville Member; at these localities the Manassas Sandstone is not divided (pl. 1*C*). The thickness of this restricted unit was not measured, but it probably does not exceed 250 m (820 ft).

Reston Member

The Reston Member is the lower stratigraphic unit of the Manassas Sandstone in the drainage areas of the Potomac and Rappahannock Rivers, including Bull Run and the Goose Creek-Seneca Creek areas (pl. 1*C*). Lee (1977, p. C3, C4; measured sections 1, 2, and 3, p. C9-C11) defined this member for the typically weathered road-cut exposures of loose to semicompact sand and pebble and cobble gravel east of the junction of the south ramp of the Dulles Airport Access Road to Reston Avenue in the northwestern part of the Vienna

FIGURE 4.—Outcrop of the Reston Member of the Manassas Sandstone on a runway of the Old Dominion Speedway about 300 m (1,000 ft) southeast of Grant Avenue, town of Manassas, in the northwestern part of the Independent Hill 7.5-min Quadrangle. A lens of tightly packed imbricate quartzite-cobble conglomerate with a sandstone matrix is intercalated with planar-bedded conglomeratic sandstone. Outcrop is a nearly horizontal cross section of strata dipping gently away from the field of view (northwest). Lens cover is 5 cm (2 in) in diameter.

7.5-min Quadrangle (Lee, 1979, 1980). Drilled sections of this basal unit are documented in appendix B and table 2 of this paper and by Larson (1978), Nutter (1975), and Otton (1981).

Distribution.—The Reston Member is exposed along the eastern border of the Culpeper basin in Fairfax, Prince William, and Fauquier Counties, Va., and in Montgomery County, Md. Excellent exposures are along the road and creek cuts, but most are deeply weathered and disaggregated. Where penetrated in several wells along the eastern margin of the Culpeper basin, the Reston Member is firmly cemented by iron oxide and clays.

Lithology.—The Reston Member is composed of dusky-red, very dark red, and light-gray intermixtures of micaceous quartz and feldspar sand and angular to subangular boulders, cobbles, and pebbles of crystalline rock fragments in an interstitial clay-silt matrix (fig. 4). Generally, throughout this poorly sorted unit, the sand and silt are more abundant in the upper part of the unit than in the lower part. Clay minerals of two samples from Pender, Va., consist chiefly of illite, with subordinate amounts of kaolinite and halloysite. Quartz and feldspar contents in the sand fraction vary considerably; feldspar is dominant locally. The sand grains are predominantly subangular and, where sandstone is dominant, form beds that are thick to very thick. Cut-and-fill structures and gently inclined crossbeds are locally present in these sand beds. Rock fragments in the conglomerate beds are chiefly angular to subangular phyllite, schist, quartzite, and vein quartz, similar to bedrock exposed in the adjacent Piedmont to the east. The size and composition of these fragments differ from place to place. Rock fragments are as large as 0.5 m (1.6 ft) in length at the type locality and along U.S. Route 50 at Pender, Fairfax County, Va. Conglomerate beds within this unit show imbricate pebble structures along road cuts near Reston, Fairfax County, Va.

The Reston Member locally contains cross-laminated and compact lenses of micaceous, feldspathic siltstone and fine-to medium-grained arkosic sandstone, in addition to the main conglomeratic sandstone and conglomerate with schist, phyllite, quartzite, vein quartz, pebbles, and cobbles. Fining upward cycles of cobbles, pebbles, and granules occur locally.

Thickness.—The Reston Member ranges from less than 3 m (10 ft) to an estimated maximum thickness of about 100 m (330 ft). It is 5.5 m (18 ft) thick at the type section and 3 m (10 ft) thick along the south cut of Compton Road, Fairfax County, Va. Based on widely separated outcrops in Prince William County, Va., the composite thickness is calculated to be 85 m (280 ft). It ranges from 16.5 to 19.5 m (54-65 ft) thick in drill holes in Montgomery County, Md., and Fairfax County, Va. (table 2, app. B).

Relation to adjacent stratigraphic units.—The Reston Member unconformably overlies pre-Triassic Piedmont crystalline rocks and locally is truncated by steep faults exposed along the eastern border in Fairfax and Prince William Counties, Va. (pl. 1*C*, this paper; Leavy, 1980). The contact of the Reston with the Poolesville Member is laterally and vertically gradational and locally interfingering. A gradational contact is well displayed 1.3 km (.75 mi) southeast of Centreville, in Fairfax County, Va.

Deposition.—The Reston Member consists mainly of coarse clastic materials derived from adjacent eastern highlands. The sediments were apparently transported and deposited by means of high-gradient streams and debris flows along the base of highlands. The present outcrops are the remnants of coalescing fluvial fan deposits in which the lithofacies vary from part of the fanhead to midfan facies. These coarse clastic deposits grade into arkosic sandstone of the Poolesville Member, which locally contains fine gravel lenses. The imbricate pebble structure of conglomerates and cross-lamination and crossbedding of sandstones generally indicate eastern and southeastern source areas.

RAPIDAN MEMBER

The Rapidan Member is the lowest stratigraphic unit of the Manassas Sandstone in the drainage area of the Rapidan River and Mountain Run (pl. 1*C*, and measured section 1, app. A, this paper; table 1, Lee, 1980). It is herein named from typical exposures of greenstone conglomerate along the southern bank of the Rapidan River near Raccoon Ford, Unionville 7.5-min Quadrangle, in Orange County, Va.

Distribution.—The Rapidan Member is well exposed on the western slope of "The Ridge" in the east-central part of the Culpeper East 7.5-min Quadrangle, Culpeper County, Va., and the type section is along the southern side of the Rapidan River in the extreme southeastern corner of the Culpeper East 7.5-min Quadrangle and the northern part of the Unionville 7.5-min Quadrangle (measured section 1, app. A). It is widespread but poorly exposed in the northern and southeastern parts of the Barboursville basin.

Lithology.—The Rapidan Member is characterized by indurated conglomerates containing rock fragments of grayish-green and grayish-olive-green to dusky-green, Late Proterozoic metabasalt (Catoctin Formation) and minor amounts of rock fragments consisting of light-gray and bluish-gray, metamorphosed, feldspathic sandstone, quartzite, vein quartz, and schist (probably Lower Cambrian Chilhowee Group rocks). These rock fragments are intermixed with greenstone granules and greenish-gray clay sand and silt, which are cemented firmly by clay and silica and locally by secondary calcite. The rock fragments are angular to subangular or rounded; they show imbricate structure and, locally, cut-and-fill features. The average length of these fragments is 10 cm (4 in); some are as large as 30 cm (12 in) in the lowest part of this unit along cuts on the southern bank of the Rapidan River.

Thickness.—The thickness of this member ranges from 70 m (230 ft) to 140 m (460 ft) on the southern bank of the Rapidan River in Orange County, Va. It pinches out to the northeast along the eastern margin of the basin between the Rapidan and Rapahannock Rivers. No accurate thickness could be determined in the Barboursville basin.

Relation to adjacent stratigraphic units.—The Rapidan Member rests unconformably on and is locally in fault contact with pre-Triassic crystalline rocks (pl. 1*C*). It is laterally and vertically gradational and interfingers with sandstones of the Poolesville Member. These relationships are well shown along the southern bank of the Rapidan River in the extreme southeastern corner of the Culpeper East 7.5-min Quadrangle, Orange County, Va., where conglomerates of the upper part of the Rapidan Member are interbedded with sandstone of the lower part of the Poolesville Member.

Deposition.—The outcrop patterns, primary structures, and size distribution of clasts in the Rapidan Member suggest that this is a part of fanhead and midfan deposits and indicate that the sequence represents deposition of an isolated fluvial fan deposited along the northwestern front of Clark Mountain which spread to the Rapidan River and extended to "The Ridge" in Orange and Culpeper Counties, Va. (pl. 1*C*).

TUSCARORA CREEK MEMBER

Limestone and dolomite clast conglomerate, exposed on the southeastern bank of Tuscarora Creek in Frederick County, Md., is herein named the "Tuscarora Creek Member" of the Manassas Sandstone (Lee, 1979). The type section is exposed about 0.8 km (0.5 mi) S. 35° E. of the bridge over Tuscarora Creek on Maryland State Road 28. This member is the lowest stratigraphic unit of the Manassas Sandstone in the Frederick Valley of Maryland (pl. 1*A*; measured section 2 in app. A, table 2, this paper; Nutter, 1975, table 20, p. 32, 33).

Distribution.—The Tuscarora Creek Member underlies much of the northeastern border area of the Culpeper basin north of the Potomac River, Frederick County, Md. It is well exposed in road cuts along Maryland State Road 28, 1.5 km (0.9 mi) N. 55° W. of Tuscarora and about 0.6 km (0.4 mi) S. 55° E. of the type section near the lower reach of Tuscarora Creek, along the banks of Tuscarora Creek about 0.25 km (0.15 mi) N. 30° E. of Churchill, and along the road cuts 0.8 km (0.5 mi) due west of the State Police barracks west of Frederick, Md.

Lithology.—The Tuscarora Creek Member is well-to poorly sorted, thick-bedded to massive conglomerate composed of angular to subangular and subrounded pebbles and cobbles of light to dark gray and pinkish-red limestone, dolomite, and dolomitic limestone. The clasts were probably derived mainly from the Frederick and Grove Limestones (Upper Cambrian and Lower Ordovicion) that crop out nearby. The limestone in the clasts is very fine grained to very coarse grained, argillaceous and (or) quartzose; some clasts are flaggy and planar-laminated. The clasts are embedded in a calcite-cemented matrix chiefly composed of limestone and dolomitic limestone granules and dusky-red to grayish-red clayey sand and silt.

Thickness.—This member ranges in thickness from 21 m (70 ft) at the type section near the lower reaches of Tuscarora Creek to 67 m (220 ft) west of Frederick, Md., and thins and pinches out to the south. It is 12 m (39 ft) thick where penetrated in a water well drill hole south of Dickerson, Montgomery County, Md. (Nutter, 1975, table 10, p. 32, 33).

Relation to adjacent stratigraphic units.—The Tuscarora Creek Member unconformably overlies the Frederick Limestone. The contact is well exposed in a field north of Maryland State Road 28, about 1.8 km

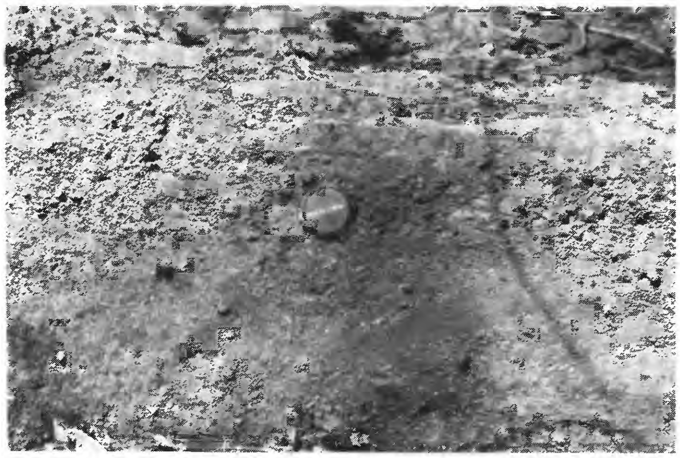

FIGURE 5.—Outcrop of the Poolesville Member of the Manassas Sandstone in the western part of the Independent Hill 7.5-min Quadrangle. Exposure is on the northwestern side of Cedar Run about 200 m (656 ft) southwest of the Virginia State Route 619 bridge. Poorly stratified, very coarse to coarse-grained sandstone is interbedded with pebble conglomerate lenses. Lens cover is 5 cm (2 in) in diameter.

FIGURE 6.—Upper surface of the Poolesville Member of the Manassas Sandstone showing carbonate nodules and cement. Outcrop is in the northern part of the Independent Hill 7.5-min Quadrangle along a road cut on Liberia Avenue about 250 m (820 ft) north of the junction with Virginia State Route 663. The light-gray irregular patches of cement and the abundant granule-size spherules of carbonate intermixed in the muddy sandstone are interpreted as paleosol caliche. Lens cover is 5cm (2 in) in diameter.

(1.1 mi) N. 55° W. of Tuscarora, Frederick County, Md., and along Tuscarora Creek a short distance northeast of Churchill. The Tuscarora Creek Member is laterally and vertically gradational to and interfingers with the Poolesville Member. These relationships are well shown in road cuts west of Frederick, Md.

Deposition.—Outcrops of the Tuscarora Creek Member in the Frederick Valley represent the remaining portion of coalesced fan deposits ranging from part of the fanhead to midfan facies. As indicated by preserved imbricate pebble structures, these fans were formed from fluvial debris of streams that emerged from the adjacent uplands on the east and northeast that were underlain by Upper Cambrian carbonate rocks (pl. 1*C*).

POOLESVILLE MEMBER

The Poolesville Member of the Manassas Sandstone is herein named for the exposures of arkosic sandstone interbedded with minor siltstone and mudstone near Poolesville, Md. (Lee, 1979). Lee (1977, p. C4, C5) previously called this unit the sandstone member and designated it as the uppermost stratigraphic unit of his Manassas Sandstone. The type section of this member is well exposed along the road cuts north and northeast of the city of Poolesville, Montgomery County, Md. A reference section for the Poolesville Member is along the northern bluffs of the Potomac River extending westward for 2 km (1.25 mi) from the mouth of Seneca Creek, west-central Seneca 7.5-min Quadrangle, Montgomery County, Md. Additional excellent outcrops are along the valley sides of Bull Run near the towns of Manassas and Yorkshire, Prince William County, Va., and along the banks of the Potomac River in Loudoun County, Va. (Lee, 1977, measured sections 4 and 5, p. C11, C12). This unit constitutes the bulk of the Manassas Sandstone (pl. 1*B*, 1*C*; table 2; app. B; figs. 5, 6).

Distribution.—The Poolesville Member is extensive throughout the eastern part of the Culpeper basin and the southeastern part of the Barboursville basin. It is well exposed along the valleys of major streams in the Culpeper basin and along the valley of Blue Run in the Barboursville basin.

Lithology.—The Poolesville Member is composed mostly of pinkish-gray, very fine grained to very coarse grained feldspar and quartz sand in a very dark red to dusky-red-purple clayey silt matrix, cemented mainly by silica and locally by calcite. It is micaceous and, in part, highly feldspathic. Clay-sized minerals from a sample collected at a road cut on U.S. Route 50, Fairfax County, Va., are chiefly illite and minor kaolinite. The unit is generally thick bedded to massive and planar-to cross-laminated, and locally contains large-scale "festooned" or trough cross-stratification (fig. 7). At places, pebble pavement showing imbrication of the larger fragments is a common feature. Red silty shale

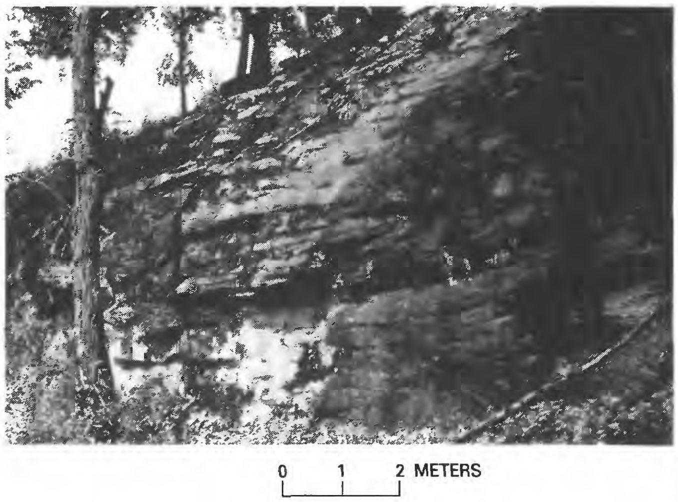

FIGURE 7.—Outcrop of the Poolesville Member of the Manassas Sandstone exposed on the west bank of the Potomac River near the end of Virginia State Route 656, Loudoun County, Va. Broad trough cross-stratification is shown with paleocurrent flow direction toward the viewer.

chips forming thin to thick intraformational conglomeratic sandstone lenses commonly occur in the upper part of this sequence in the Culpeper basin. An exposure of light-gray paleosol caliche is present in road cuts along Liberia Avenue southeast of Manassas (fig. 6). The caliche occurs as masses of spherules and irregular patches with sand grains in the lower part of this unit.

The Poolesville Member is generally intercalated with lenticular bodies of light-gray to gray, highly feldspathic sandstone and quartzite-pebble conglomerate. Calcareous sequences are commonly found in the transitional zones between the fluvial sandstone deposits and the overbank flood plain, mudflat, or playa lacustrine siltstone and shale of the Balls Bluff Siltstone.

Thickness.—The total thickness of the Poolesville Member ranges from about 200 m (656 ft) at the northern and southern limits of outcrop to more than 1,000 m (3,280 ft) in the east-central parts of the Culpeper basin.

Fossils and age.—Cornet (1977) included the rare palyniferous zones in the Poolesville Member in his *Manassas-Passaic* (shown as "lower Passaic" on fig. 2) palynofloral zone of Late Triassic (middle Norian) age. Rare plant fossils discovered in carbonaceous gray to green shale and siltstone east of Comptons Corner in the Manassas 7.5-min Quadrangle may be early Norian in age (Cornet, 1982, oral commun.). The fossil footprint *Cheirotherium* was recently discovered by P. Kimmil in red sandy siltstone a few hundred meters east of the plant fossil locality near Comptons Corner (R.E. Weems, 1984, oral commun.). Recently, spores collected from dark-gray carbonaceous siltstone in the prominent bluffs along the Potomac River have been tentatively identified as indicating a late Carnian age (Hugh Houghton, oral commun., 1984).

Relation to adjacent stratigraphic units.—The contact of the Poolesville Member with the underlying conglomerates (pl. 1*B*, 1*C*) is everywhere gradational and intertonguing. The Poolesville is laterally and vertically gradational with the lower part of the Balls Bluff Siltstone, indicating that these units are, in part, contemporaneous sedimentary facies.

Deposition.—The arkosic sandstones and pebbly sandstones of the Poolesville Member are the consolidated detritus that was derived from adjacent highlands and was deposited mainly by braided streams. The preserved primary structures in some outcrops indicate sand deposition to be chiefly confined to the areas of midfan and fan base (pl. 1*C*). The dip of cross-lamination in sandstone, the imbrication of quartzite pebbles, and the depositional patterns of quartzite-pebble conglomerate lenses indicate eastern and southeastern source areas along the eastern basin border. Evidence for a southeastern source is well displayed west of Adamstown and north of Tuscarora Creek in Frederick County, Md. Eastern and northeastern sources are indicated along the railroad cuts east of Dickerson and road cuts of Maryland State Road 28 in the vicinity of Poolesville, Md., and along road cuts of Maryland State Roads 107 and 28 in the vicinity of Dawsonville, Md.

In the Barboursville basin, paleocurrent directions indicate that the Poolesville Member was derived from southeastern highlands and was deposited by a northwesterly flowing drainage system.

BALLS BLUFF SILTSTONE

The Balls Bluff Siltstone was named for the rocks exposed near Balls Bluff National Cemetery on the west bank of the Potomac River, Loudoun County, Va. (Lee, 1977, p. C5 and measured sections, p. C13, C14; Lee, 1979, 1980; Froelich and others, 1982, p. 59-62, 76-78; pl. 1*B* and 1*C*, tables 1 and 2, figs. 2 and 3, and section 5 in app. A, this paper). This unit constitutes the bulk of the Upper Triassic deposits in both the Culpeper and Barboursville basins, and many of its rocks were previously mapped as the Bull Run Formation. In the northwestern part of the Culpeper basin, it includes the Leesburg Member, a lenticular limestone conglomerate that intertongues with calcareous sandstones and siltstones of the upper Balls Bluff.

Distribution.—The Balls Bluff Siltstone occurs throughout the central portions of the Culpeper and Barboursville basins. In the Culpeper basin, it crops out extensively along the west and south banks of the

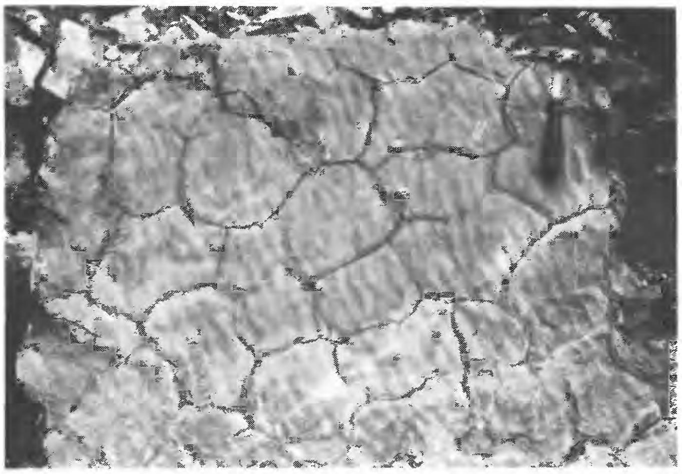

FIGURE 8.—Bedding plane exposure of ripple marks and mud cracks in the Balls Bluff Siltstone on a quarried slab at the Culpeper Crushed Stone quarry, Stevensburg, Culpeper County, Va. Symmetrical ripple marks were probably produced by gentle waves, and the polygonal cracks are interpreted as subsequent desiccation features. Hammer is 30 cm (12 in) long.

FIGURE 9.—Balls Bluff Siltstone exposed in north quarry face at the Culpeper Crushed Stone quarry near Stevensburg, Culpeper East 7.5-min Quadrangle. Cyclic lacustrine sequences are 3 to 4 m (10-14 ft) thick, dip gently westward, and consist of laminated siltstone and shale overlain by massive, bioturbated, mud-cracked mudstones with dinosaur tracks.

Potomac River in Loudoun County, Va., along the valley of Bull Run in Prince William and Fairfax Counties, Va., and along the south side of Mountain Run; it is well exposed at the Culpeper Crushed Stone quarry in Culpeper County, Va., and along road cuts of U.S. Routes 15, 29-211, and 66. In the Barboursville basin, excellent exposures of this unit are in the Webster Brick Company quarry in the Gordonsville 7.5-min Quadrangle and along the valley of Blue Run in Orange County, Va.

Lithology.—This unit is composed mostly of grayish-red and dusky-red, very fine grained to very coarse grained calcareous, clayey, micaceous, and feldspathic siltstone. Clay-sized minerals determined from three typical samples from road cuts of U.S. Route 50 in Fairfax County, Va., are mostly illite, with subordinate amounts of kaolinite and halloysite and a minor amount of montmorillonite and chlorite. The Balls Bluff is thin bedded to massive and extensively bioturbated, with irregular or convolute bedding, ripple marks (fig. 8), and planar or climbing-ripple cross-laminations. Mud cracks (fig. 8), rip-ups, animal and insect burrow casts, and plant rootlets are common. Siltstone is locally intercalated with thin lenses (1.0 to 20 cm; 0.25 to 8 m) of gray to bluish-gray, argillaceous, locally oölitic limestone and gray dolomite. Brownish-gray carbonate concretions, as well as lenses of oöids that contain minute caliche clasts and pellets, are also present in the middle part of the Balls Bluff Siltstone. Sobhan (1985) has described two 500-ft-deep core holes in the lower part of the Balls Bluff southwest of Manassas, Prince William County, Va. (table 2). Gray to light-gray and dark-red, calcareous, feldspathic, micaceous, fine-to medium-grained, thin-to thick-bedded, lenticular fluvial sandstone and dusky-red, calcareous, silty, micromicaceous shale are interbedded in the lower and upper parts of the unit. In the south-central part of the Culpeper basin, the Balls Bluff commonly contains two principal varieties of related lithology in addition to the typical dusky-red siltstone: (1) medium- to dark-gray, carbonaceous, fossiliferous, thin- to thick-bedded, massive clayey siltstone, silty shale, fissile to microlaminated shale and minor fine- to medium-grained sandstones, and (2) light-greenish-gray, very fine to medium-grained, thin- to thick-bedded, massive siltstone, silty shale, and fossiliferous shale. The latter unit represents either preserved remnants of marginal lacustrine or shallow playa lake deposits, whereas the former may be deep, less oxidized, possibly euxinic lacustrine sediments.

The dark-gray carbonaceous sedimentary sequence locally contains lenses of argillaceous and dolomitic limestone and lenses of reworked öids (Carozzi, 1964). Euhedral grains and aggregates of authigenic pyrite are scattered throughout the rocks. J.P. Smoot (table 2, app. B) has measured and described a thick cyclic succession of lake sediments and marginal deposits exposed at the Culpeper Crushed Stone quarry near Stevensburg, Culpeper County, Va. (fig. 9).

Fossils and age.—The Balls Bluff Siltstone locally contains fossil evidence of freshwater animals, such as tracks, trails, bones, and shells, mainly conchostracans,

FIGURE 10.—Bedding plane exposure of dinosaur tracks (light patches) in mud-cracked Balls Bluff Siltstone at the Culpeper Crushed Stone quarry, Stevensburg, Culpeper County, Va. Poorly defined tracks show movement across waterlogged mud from the lower left to the upper right. A 1-m (3.3-ft) tape is in the right-central part of the photo. Calcite veinlets fill intersecting joints in foreground.

notostracans, ostracodes, and rare stromatolites and fish teeth and scales. Froelich and others (1982, p. 77) described such a fossiliferous Late Triassic lacustrine sequence exposed on U.S. Route 29 in the Gainesville 7.5-min Quadrangle near Manassas Battlefield. E.I. Robbins (oral commun., 1977) made a preliminary study of filamentous algae and plant spores from samples collected from siltstone along the south side of Mountain Run due east of Culpeper City, Culpeper County, Va., and gave a Late Triassic age for the siltstone. Amphibious phytosaur remains were recovered at a site in the southeastern part of the Dulles International Airport property in Fairfax County, Va. (Nicholas Hotten III, unpub. data, 1959; Eggleton, 1975; Weems, 1979). Frank C. Whitmore, Jr., and Robert E. Weems (unpub. data, 1979) identified Upper Triassic dinosaur footprints exposed at the Culpeper Crushed Stone quarry near Stevensburg in the east-central part of the Culpeper East 7.5-min Quadrangle, Culpeper County, Va. (figs. 2, 10). Cornet (1977) identified freshwater crustaceans, ostracods, mollusks, fish scales, and plant spores (*Carnisporites granulatus* Schulz, 1967, and *Conbaculatisporites mesogoicus* Klaus, 1960) (fig. 3), in the east-central part of the Gainesville 7.5-min Quadrangle, Prince William County, Va. Cornet included all palyniferous zones in the Balls Bluff in his *Manassas-Passaic* palynofloral zone (shown as "lower Passaic" in fig. 2) of Late Triassic (middle to late Norian) age, but recent restudy of the lowest palyniferous gray-green silty shale zones indicate a late Carnian age (Hugh Houghton, written commun., 1984).

Thickness.—The total thickness of Balls Bluff Siltstone is estimated to range from 80 m (262 ft) near the northern border of the basin west of Frederick, Md., to 1,690 m (5,545 ft) in the central portion of the Culpeper basin. Within this unit, the dark-gray or greenish-gray sequences in the southern part of the Culpeper basin generally average 3 m (10 ft) thick, but locally as much as 45 m (148 ft) of rhythmic cyclic deposits are continuously exposed at the Culpeper Crushed Stone quarry near Stevensburg, with neither base nor top of the lacustrine sequence present (table 2, fig. 9, app. A; J.P. Smoot, oral commun., 1984).

In the Barboursville basin the maximum thickness of the Balls Bluff is estimated to be 120 m (394 ft) in the area surrounding the town of Somerset in the Gordonsville 7.5-min Quadrangle, Orange County, Va.

Relation to adjacent stratigraphic units.—The Balls Bluff Siltstone is gradational with the underlying Manassas Sandstone on the northeastern, eastern, and southeastern sides of the Culpeper basin and on the southeastern side of the Barboursville basin; with the overlying Catharpin Creek Formation on the southwestern, western, and northwestern sides of the Culpeper basin; and with the Tibbstown Formation in most of the Barboursville basin. The contacts of the Balls Bluff with adjacent stratigraphic units generally are vertically gradational and laterally intertonguing throughout both basins (pl. 1*C*). In the Culpeper basin, tongues of the Balls Bluff Siltstone in the Rapidan and Poolesville Members of the Manassas Sandstone are well exposed on the southern side of the Rapidan River in the northern part of the Unionville 7.5-min Quadrangle, Culpeper and Orange Counties, Va. Similar tongues in the Poolesville Member are well exposed on the western side of the Potomac River in Loudoun County, Va. In the Barboursville basin, the gradational stratigraphic relationship of this unit with underlying sandstone of the Poolesville Member is well exposed along Blue Run southeast of Barboursville. A similar relationship with the overlying sandstone of the Tibbstown Formation is well shown elsewhere in the tributary drainage areas of Blue Run.

Deposition.—The Balls Bluff Siltstone was deposited chiefly in the medial parts of the closed basins. When the rates of deposition and basin subsidence were approaching balance, the deposits consisted of alternating layers of siltstone and shale that grade into impure pelleted limestone and dolomitic limestone. This depositional environment is similar to that reported by Hooke (1968, p. 614) for modern alluvial fans and in playa lakes.

Most of the sediment deposition of this sequence may have occurred within or immediately adjacent to playa lakes where most of the distal facies of fluvial fans are localized. Sedimentary features indicate that during the lifespan of lakes in the Culpeper basin, little significant erosion of the lake sediments occurred, except possibly during periods of drought, when desiccation took place, or when caliche accumulated, or when fluvial channels scoured and reworked soil zones.

The oölitic layers of the dark-gray carbonate rocks found locally in the Culpeper basin consist of reworked oöids (Carozzi, 1964, p. 231-241). These oöids consist of simple or compound nuclei enveloped by several sets of concentric or nonconcentric rings with intercalations of argillaceous limestone and were formed in a shallow lake environment, probably near the margins.

LEESBURG MEMBER

The Leesburg Member of the Balls Bluff Siltstone is here redefined. It was previously called the Leesburg Limestone Conglomerate Member of the Bull Run Formation by Lee (1977, p. C6) and the Leesburg Conglomerate Member of the Bull Run Formation by Lindholm (1979, p. 1718) and Lindholm and others (1979, p. 1249). It is named for the exposures near the town of Leesburg, Loudoun County, Va. This unit forms the lenticular upper member of the Balls Bluff Siltstone in the northwestern part of the Culpeper basin. The type section is exposed in road cuts southeast of the junction of U.S. Route 15 bypass and the entrance road to Balls Bluff National Cemetery in Loudoun County, Va. (pl. 1*C*).

Distribution.—The Leesburg Member underlies the northwestern part of the Culpeper basin in Virginia and Maryland. It is well exposed north of Leesburg along U.S Route 15 (Toewe, 1966, p. 5; Hazlett, 1978) and along the valley of the Potomac River in Loudoun County, Va., and Frederick County, Md.

Lithology.—The Leesburg Member is composed chiefly of angular to subangular and subrounded to rounded cobbles of lower Paleozoic (probably mostly Cambrian) light-gray to grayish-black and pinkish-red limestone and dolomitic limestone and contains minor clasts of dolomite, quartzite, vein quartz, schist, slate, and greenstone embedded in a matrix of carbonate-rock granules, red sand, and clayey silt that is firmly cemented by calcite (fig. 11). Pebble counts of conglomerate from 29 selected locations within this unit show 94 percent limestone and dolomitic limestone, 2 percent dolomite, 1 percent greenstone, 2 percent quartzite and metamorphosed feldspathic sandstone, and 1 percent slate, schist, chert, and siltstone. Each count represents a conglomerate area of 1 m^2. Generally, dolomite fragments increase in abundance northwesterly from the northeast suburbs of Leesburg. The Leesburg Member contains both matrix-supported

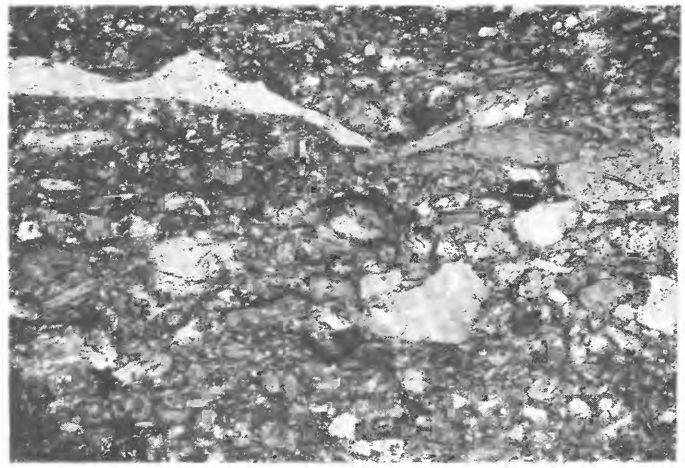

FIGURE 11.—Exposure of a limestone conglomerate in the Leesburg Member of the Balls Bluff Siltstone in a road cut of U.S. Route 15, north of Leesburg, Va. Very poorly sorted subangular limestone and dolomitic limestone clasts, ranging in size from granules to small boulders, are randomly distributed in a red muddy matrix. The conglomerate is firmly cemented by calcite. Lens cover is 5 cm (2 in) in diameter.

and clast-supported conglomerates, as well as interbedded pebbly red sandstone and massive red mudstone (Lindholm, 1979, p. 1722; Lindholm and others, p. 1254, 1255).

Limestone clasts in the Leesburg Member are very fine to medium grained and holocrystalline. Some of these rock fragments are argillaceous, quartzose, flaggy, and planar laminated. Rock fragments generally increase in size westerly and northwesterly from about 6.35 cm (2.5 in) in the vicinity of Leesburg to as large as 1.2 m (4 ft) near Limestone Branch, north of Leesburg, Loudoun County, Va.

The limestone conglomerate is metamorphosed into a light-gray marble in contact with intrusive diabase in the southeastern part of Leesburg. Shannon (1926) called this rock Potomac marble, a name popularly used for the unmetamorphosed limestone conglomerate exposed near Point of Rocks, Frederick County, Md., and formerly used as dimension stone.

Thickness.—The Leesburg Member ranges in thickness from 40 m (131 ft) in the northwestern part of the Culpeper basin, Frederick County, Md., to 1,070 m (3,510 ft) west of the Potomac River in Loudoun County, Va. The deposits are thickest at the base of Catoctin Mountain, and the prism of conglomerate pinches out abruptly to the southeast into calcareous siltstone of the Balls Bluff and lower sandstones of the Catharpin Creek Formation in the vicinity of Leesburg, Loudoun County, Va.

Relation to adjacent stratigraphic units.—The Leesburg Member interfingers with the upper part of the

Balls Bluff Siltstone in the northwestern part of the Culpeper basin. The gradational and interfingering contact with the lower part of the Catharpin Creek Formation is well exposed along the road cuts southeast and south of Leesburg, Loudoun County, Va. (pl. 1*C*).

Deposition.—The sediments of the Leesburg Member were derived by erosion from adjacent highlands to the west and northwest, as indicated by crossbeds and imbricate pebble structures. The lower Paleozoic carbonate rock fragments were transported and deposited by means of swift streams and debris flows that accumulated along a scarp at the base of the highlands. The present outcrops are the remnants of debris flows and coalescing fluvial fan deposits in which lithofacies vary from fanhead to midfan facies. These coarse clastic deposits contain scattered streamflow channel sandstone lenses in the eastern part of Leesburg. Lindholm and others (1979, p. 1254, 1255) indicate that debris flow, mudflow, and sheet flood deposits are also important environments of deposition represented in the Leesburg Member.

TIBBSTOWN FORMATION

The Tibbstown Formation is herein named for the sequence of predominantly arkosic sandstone and conglomerate that crops out in Tibbstown at the southern foothills of Haudricks Mountain less than 1 km (0.6 mi) northeast of the town of Barboursville, Orange County, Va., which is designated the type section. The unit overlies the Balls Bluff Siltstone in the Barboursville basin and in the southwestern Culpeper basin. This formation is equivalent to the lower part of the informal basaltic-flow bearing clastics member of the Bull Run Formation of Lee (1977, p. C7, C8). It locally includes two conglomerate members, the Mountain Run and Haudricks Mountain Members, which occur at the top of the formation in different localities.

Distribution.—The Tibbstown Formation crops out extensively in the Barboursville basin and in a narrow arcuate belt between Culpeper and Brandy Station in the southwestern Culpeper basin. It is present discontinuously south of Culpeper, where most of the unit is incorporated in the thermal metamorphic aureole adjacent to intrusive diabase.

Lithology.—The Tibbstown Formation is predominantly reddish-brown, fine- to medium-grained, feldspathic, micaceous sandstone interbedded with red-brown, medium- to coarse-grained pebbly arkose conglomerate, and dark-red siltstone and minor beds of gray, fine-grained sandstone, siltstone, and shale.

Thickness.—The thickness of the sandstone part of this formation (exclusive of the conglomerate members) is estimated to average 450 m (1,475 ft) in the Barboursville basin and about 300 m (1,000 ft) in the southwestern part of the Culpeper basin.

Fossils and age.—Although almost all of this formation is believed to be barren of diagnostic fossils, samples from a gray carbonaceous shale interbedded with fine-grained sandstone and siltstone east of the town of Culpeper contained sporomorphs characteristic of Late Triassic, early Norian age (Cornet, oral commun., 1982).

Relation to adjacent stratigraphic units.—The arkosic sandstone of the Tibbstown Formation overlies the siltstone of the Balls Bluff Formation in apparent conformity, and intertongues with and is overlain conformably by the conglomerate members.

MOUNTAIN RUN MEMBER

The Mountain Run Member of the Tibbstown Formation, named herein, was defined informally by Lee (1980) for greenstone conglomerate exposed along the eastern and southeastern sides of Mountain Run at the city of Culpeper, Culpeper County, Va. The type section is south of the filtration plant and on the eastern bank of Mountain Run in road cuts of Virginia State Road 3, south and southeast of Culpeper, and in the vicinity of the Culpeper water tower (pl. 1*C*; app. A, measured section 3). This unit was called the trap conglomerate by Roberts (1928, p. 20), who included it in his Border Conglomerate, and the Cedar Mountain Conglomerate Member of the Bull Run Formation by Lindholm and others (1979, p. 1249-1251).

Distribution.—The Mountain Run Member underlies much of the southwestern parts of the Culpeper basin, occupying a north-northeast-trending belt about 28 km (17.5-mi) long and about 3 km (1.9 mi) wide along the western basin margin between Locust Dale and Brandy Station. Excellent exposures of this unit are along Mountain Run at Culpeper, at Cedar Mountain, and in the area north of Brandy Station, Culpeper County, Va.

Lithology.—The Mountain Run Member consists of two principal sequences of greenstone conglomerate. The lower sequence is composed of conglomerate with angular to subangular fragments of dusky-yellowish-green to dark-yellowish-green greenstone in a dusky-red to pale-green clayey sand and silt matrix (fig. 12). The upper sequence consists generally of conglomerate with more than 60 percent angular to subangular greenstone fragments, a subordinate amount of angular to subangular quartzite and feldspathic sandstone clasts, and minor vein quartz fragments. Cut-and-fill features and pebble imbrication within this member are well shown in Culpeper and at Cedar Mountain.

FIGURE 12.—Outcrop of indurated greenstone conglomerate of the Mountain Run Member of the Tibbstown Formation exposed at the west end of Chandler Street, Culpeper, Va. Angular to subangular greenstone cobbles and boulders with scattered vein quartz, quartzite, and schist pebbles are randomly intermixed with a predominantly greenstone granule, sand, and silt matrix, firmly cemented by clay and silica. Typical closely packed, matrix-rich, poorly sorted texture of this member near the source area. Lens cover is 5 cm (2 in) in diameter.

Thickness.—The Mountain Run Member ranges in thickness from a featheredge to 640 m (2,099 ft) near Culpeper, Culpeper County, Va.

Relation to adjacent stratigraphic units.—The conglomerates of the Mountain Run Member occur at the top of the formation, and lower and lateral contacts of the conglomerate with sandstones of the Tibbstown Formation are gradational or intertonguing, as shown along Mountain Run and in railroad cuts in the southeastern part of Culpeper. The upper contact relations are unknown as erosion has removed all overlying units.

Deposition.—The Mountain Run Member is a series of fluvial fan deposits derived from erosion of the adjacent Precambrian terrane on the west, northwest, and southwest (pl. 1*C*). The apexes of fans were located near the present basin border, and the detrital materials were transported and deposited by streams heading in the adjacent highlands. Outcrops show that debris-flow deposits of the lower sequence of this member are less extensive than those of the upper sequence. In the southern part of the Culpeper basin, the upper sequence of this member at Cedar Mountain coalesced with the lower sequence in the vicinity of Cedar Run. The distribution and lithology of this member indicate an increased rate of uplift of the adjacent highlands in the later stages of the deposition of conglomerates of the Tibbstown Formation.

HAUDRICKS MOUNTAIN MEMBER

The Haudricks Mountain Member of the Tibbstown Formation is herein named for the pebble and cobble conglomerate interbedded with arkosic sandstone that conformably overlies and intertongues with the sandstone of the Tibbstown Formation in Haudricks Mountain north of the town of Barboursville, Orange County, Va. The type locality of the Haudricks Mountain Member is along the secondary road across the crest of Haudricks Mountain 2 km (1.25 mi) north-northwest of the town of Barboursville in the Barboursville 7.5-min Quadrangle. These rocks were included by Roberts (1928, p. 17, 18) in his "schist conglomerate" of the Border Conglomerate. Lee (1980) informally included the Haudricks Mountain Member in the Mountain Run Member while recognizing the regional lithologic difference in clast components.

Distribution and provenance.—The Haudricks Mountain Member crops out only in the Barboursville basin, where good outcrops are sparse and commonly deeply weathered to saprolite. The main source of the clasts in the conglomerate is the Fauquier and Catoctin Formations exposed in the adjacent Blue Ridge province.

Lithology.—Sandstone, quartzite, and fine-grained metasiltstone clasts are the chief components of the conglomerate interbedded with fine-to coarse-grained arkosic sandstone at Haudricks Mountain. The weathered sandstone clasts are mainly light to dark gray and rounded to subrounded, and consist of medium to coarse quartz and feldspar grains. Minor clast components include vein quartz, phyllite, gneissic granite, and greenstone, and the matrix is generally loose, dark-grayish-maroon clayey sand and silt.

Thickness.—It is difficult to estimate an accurate minimum thickness, but at least 500 m (1,640 ft) are calculated to be preserved on the flanks and crests of Haudricks Mountain.

Relation to adjacent stratigraphic units.—The basal and lateral contacts of the Haudricks Mountain Member with the upward-coarsening sequence of sandstones of the Tibbstown Formation appear to be gradational, but exposed contacts are rare and deeply weathered. The upper relations are unknown as erosion has removed all overlying units.

Deposition.—The lower part of the conglomerate at Haudricks Mountain was deposited by streams having headwaters in the adjacent northwestern highlands, as indicated by clast lithology, imbrication, and crossbeds; the upper part of the conglomerate in the southwestern part of the Barboursville basin suggests deposition from an east-northeasterly flowing stream.

CATHARPIN CREEK FORMATION

The Catharpin Creek Formation is herein formally named for the well-exposed sequence of clastic sedimentary rocks that overlie the Balls Bluff Siltstone and underlie the Mount Zion Church Basalt along Catharpin Creek north and northwest of Haymarket, Prince William County, Va., which is designated the type section. In the west-central part of the Culpeper basin, it includes the Goose Creek Member (Goose Creek Conglomerate Member of the Bull Run Formation of Lindholm and others, 1979, p. 1249). The rocks of the Catharpin Creek Formation were originally included as the lower units of the informal basaltic-flow-bearing clastics member of the Bull Run Formation (Lee, 1977, p. C7), and later as the informal Catharpin Creek Member of the Bull Run Formation (Lee, 1979, 1980).

Distribution.—The Catharpin Creek Formation underlies a belt along the western part of the Culpeper basin, but it is not recognized in the Barboursville basin. Excellent exposures are along Bull Run, Broad Run, the Rappahannock River, Mountain Run, and road cuts of U.S. Routes 15, 29-211, and 50 in the Culpeper basin.

Lithology.—The lower part of this formation consists of very dark red to dusky-red, micaceous, feldspathic fine-to coarse-grained sandstone and clayey siltstone, locally containing conglomerate lenses (fig. 13). These rocks grade upward into a sequence of dark-red to gray, micaceous, feldspathic sandstone; thin-bedded clayey siltstone; and laminated, fissile, silty shale.

Thickness.—Because of poor exposures and extreme thickness variation, it is difficult to estimate the thickness, but the unit may be as much as 500 m (1,640 ft) thick excluding the conglomerate member.

Relation to adjacent stratigraphic units.—The contact of the Catharpin Creek Formation with the Balls Bluff is gradational and intertonguing. This relationship is well shown along Bull Run and in road cuts in Loudoun, Prince William, and Fauquier Counties, Va. The contact of this formation with the Leesburg Member of the Balls Bluff in the northwestern part of the Culpeper basin is gradational or intertonguing south, east, and southeast of Leesburg, Loudoun County, Va. The upper contact with the Mount Zion Church Basalt is a sharp disconformity.

Deposition.—Deposition of the Catharpin Creek Formation was contemporaneous with adjacent stratigraphic units. The detritus is thought to have been derived from the rocks of the adjacent western highlands, and was deposited by braided streams and debris flows on fans. The outcrops indicate deposition to be chiefly confined to the area of midfan and fan base. The fanheads are deeply buried downdip to the west or were partly located outside the present basin border. On the basis of the trends of gravel trains and imbrication of pebbles, this unit was deposited by streams draining the northwestern, western, and southwestern highlands. During the processes of fan development, the areas of fan base and distal facies probably formed as a series of deltaic and overbank stream deposits which graded into finer materials in the lowland areas. The presence of conglomerate lenses and layers throughout this unit indicates that fluvial fans were active and that tectonic movements played a major role during deposition.

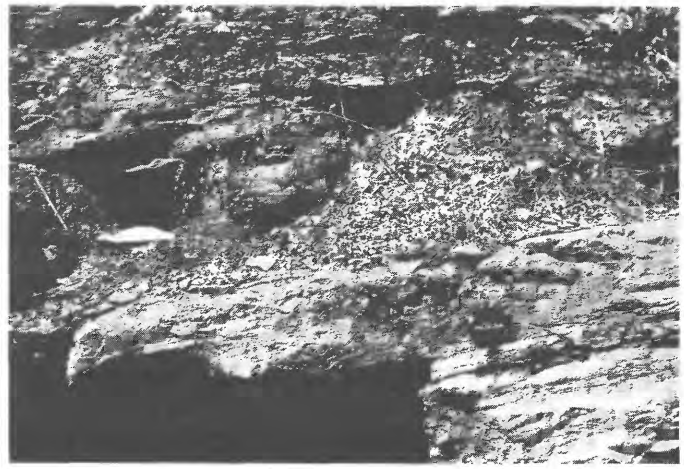

FIGURE 13.—Outcrop of interbedded sandstone and siltstone of the Catharpin Creek Formation in the east-central part of the Thoroughfare Gap 7.5-min Quadrangle. Exposure is along a road cut of U.S. Route 15, about 0.7 km (0.4 mi) northeast of the intersection with Virginia State Route 55. Sandstone beds are 5-15 cm (2-6 in) thick and lenticular, while siltstone beds are thinner but more continuous; both show faint internal planar-lamination. Lens cover is 5 cm (2 in) in diameter.

GOOSE CREEK MEMBER

The Goose Creek Member of the Catharpin Creek Formation is redefined and adopted herein. It was named the "Goose Creek Conglomerate Member of the Bull Run Formation" by Lindholm (1979, p. 1721), who identified this unit from "outcrops on the south side of Goose Creek 2 km (1.2 mi) east of the confluence of Goose Creek and Little River in Loudoun County."

Distribution.—The outcrop belt of the Goose Creek Member, which is less than 3 km (1.9 mi) wide, strikes northerly for about 28 km (17.5-mi) from Catharpin Creek north of Haymarket, Prince William County, Va., to Sycolin Creek south of Leesburg, Loudoun County, Va. The lenticular conglomerate bodies that characterize the member are discontinuous and irregular, separated from one another laterally by sandstones and siltstones. Lindholm states (1979, p.

1722), "This pattern may reflect the presence of several different alluvial fans at the time of deposition."

Lithology and provenance.—The predominant lithology consists of lenses of grayish-green to red-brown cobble and pebble conglomerate that fill scoured channels and grade laterally and vertically to coarse- and fine-grained reddish-brown arkosic sandstone and sandy siltstone. Lenses of conglomerate within this sequence consist chiefly of rounded to subrounded and subangular cobbles and pebbles of greenish-gray, fine- to coarse-grained quartzite, metasiltstone, greenstone and metabasalt, vein quartz, limestone, and granitic pegmatite. According to Lindholm (1979, p. 1722), most of the clasts were derived from the Catoctin Formation and Chilhowee Group, metamorphic rocks now exposed in the Blue Ridge province just west of the Culpeper basin.

Thickness.—Lindholm stated (1979, p. 1722), "Although the paucity of outcrops precludes an accurate determination, the thickness exceeds 900 m" (2,952 ft). The lenticular unit tongues out abruptly, north and south along the strike.

Relation to adjacent stratigraphic units.—The Goose Creek Member grades laterally and vertically into arkosic sandstones of the Catharpin Creek Formation; where the Goose Creek Member forms the top of the formation, it is overlain by the Mount Zion Church Basalt at a locally irregular but regionally paraconformable contact.

MOUNT ZION CHURCH BASALT

The basalt exposed at Mount Zion Church, on U.S. Route 50 in the Arcola Quadrangle, Loudoun County, Va., is herein named the Mount Zion Church Basalt (Lee 1979, 1980). It is the lowest basalt flow and was first described in the Leesburg 7.5-min Quadrangle by Toewe (1966). It is equivalent to Lindholm's basalt flow unit I, the lowermost unit of his Buckland Formation (Lindholm, 1979, p. 1724, 1725, and fig. 8, p. 1729), and to formation J of Cornet (1977).

Distribution.—The Mount Zion Church Basalt extends discontinuously for more than 55 km (34.4 mi) in the west-central part of the Culpeper basin (pl. 1*C*). The basalt apparently pinches out southwest of Haymarket in the northeastern part of the Catlett 7.5-min Quadrangle, Prince William County, Va., and is truncated by the western border fault southwest of Leesburg in the western part of the Leesburg 7.5-min Quadrangle, Loudoun County, Va. It occurs as two separate thin flowsheets separated by a sequence of red sandstone and siltstone to the west of the town of Catlett, and to the northeast and north of the city of Remington, Fauquier County, Va., but individual lentils are too thin to show

FIGURE 14.—Mount Zion Church Basalt exposed on the north cuts of the Southern Railroad about 50 m (165 ft) northwest of the intersection with U.S. Route 15, in the east-central part of the Thoroughfare Gap 7.5-min Quadrangle. Prismatic jointed weathered flow surface is shown. Lens cover is 5 cm (2 in) in diameter.

at this scale (pl. 1*C*). In places the basalt flows crop out as discontinuous strike ridges, the gaps resulting from Early Jurassic erosion or nondeposition over paleotopographic highs (Lindholm, 1979, p. 1725). A shallow USGS exploratory core hole located to intercept the lowest basalt flow horizon downdip of its surface occurrence recovered less than 10 m (33 ft) of basalt cobble conglomerate sandwiched between red arkosic sandstone, and no intact basalt, suggesting that Early Jurassic erosion accounts for the absence of basalt at this locality.

Description of rock.—The Mount Zion Church Basalt is medium to dark gray, very fine to medium crystalline, porphyritic in part, mostly equigranular, and holocrystalline (fig. 14). Augite and plagioclase (chiefly labradorite and andesine) display ophitic or subophitic texture (fig. 15). Vesicles are scattered but are mostly concentrated in the lower and upper parts of the sequence. Columnar joints are well developed in places. The basalt locally encloses poorly exposed, irregular lenses of dusky-to grayish-red, very fine to medium-grained, feldspathic and micaceous sandstone and siltstone, an example of which is exposed at a road cut along U.S. Route 15 about 100 m (328 ft) S. 50° W. of the intersection of U.S. Route 15 and the Southern Railroad southwest of Haymarket in the east-central part of the Thoroughfare Gap 7.5-min Quadrangle, Prince William County, Va.

Geochemistry.—Based on chemical analyses of several samples of unweathered but altered basalt (Puffer and others, 1981; Leavy and Puffer, 1983; Lee and others, 1984), the Mount Zion Church Basalt is a high-TiO_2,

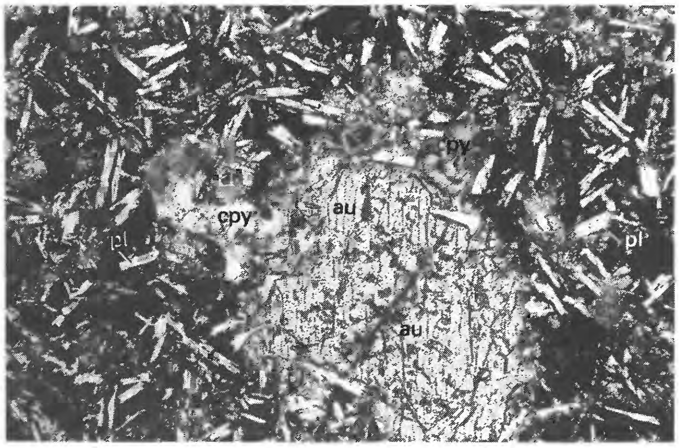

FIGURE 15.—Photomicrograph of the Mount Zion Church Basalt from an exposure in Virginia State Route 600 east of Bull Run. Augite (au), serpentinized clinopyroxene (cpy), and laths of plagioclase (pl) (chiefly labradorite) make up an ophitic intergrowth with accessory magnetite and ilmenite (black). The field of view is 2.2 mm (0.08 in) across (plane-polarized light).

quartz-normative tholeiite chemically similar to the Orange Mountain Basalt of the Newark basin in New Jersey and the Talcott Basalt of the Hartford basin in Connecticut (Puffer and Hurtubise, 1983).

Thickness.—The Mount Zion Church Basalt ranges in thickness from 3 m (10 ft) north and northeast of Remington, Fauquier County, to 85 m (279 ft) west of Haymarket, Prince William County, Va., and from 90 m (295 ft) to about 140 m (459 ft) southwest of Leesburg, Loudoun County, Va. Lindholm (1979, p. 1730) calculated thicknesses at 17 localities that ranged from 10 to 180 m (33 to 590 ft); he also showed that his basalt flow unit I, the Mount Zion Church Basalt, thickens to the north. Siltstone and sandstone lenses are poorly exposed and generally less than 10 m (33 ft) thick.

MIDLAND FORMATION

The Midland Formation is herein named for the locally well exposed succession of clastic sedimentary rocks that overlies the Mount Zion Church Basalt and is succeeded by the Hickory Grove Basalt along Licking Run about 2 km (1.25 mi) north of the town of Midland in the Midland 7.5-min Quadrangle, Fauquier County, Va. This section, which contains the Midland Fish Bed, is designated the type locality of the Midland Formation. This unit is equivalent to sedimentary unit I-II of the Buckland Formation of Lindholm (1979, p. 1724, 1725, and fig. 8, p. 1729), to the lower sedimentary unit of Lee's informal basaltic-flow-bearing clastics member of the Bull Run Formation (Lee, 1977, p. C7), and to formation I of Cornet (1977).

Distribution.—The Midland Formation occupies a well-defined north-trending arcuate belt averaging 1.0 km (0.625 mi) wide and slightly concave to the west between the Mount Zion Church and Hickory Grove Basalts. It extends for about 67 km (42 mi) from about 5 km (3 mi) north of Brandy Station to Sycolin Creek, about 6 km (4 mi) south-southwest of Leesburg, Loudoun County, Va.

Lithology.—The Midland Formation consists of dark-red to reddish-brown micaceous, feldspathic, cross-bedded, ripple-laminated, fine- to medium-grained sandstone interbedded with reddish-brown, ripple-laminated, micaceous siltstone, dark-red, greenish-gray, and dark-gray to nearly black calcareous, silty microlaminated fossiliferous shale, and thin-bedded argillaceous limestone. Some thin beds of dark-gray to black shale are carbonaceous and pyritic, and some display desiccation cracks. In places, lenses of conglomerate and conglomeratic, coarse-grained, red, brown, and gray arkosic sandstone are abundant, particularly near the northern limit of outcrop.

Thickness.—The thickness of the Midland Formation ranges from about 300 m (984 ft) along the north side of Goose Creek, where it contains many conglomerate layers, to about 150 m (500 ft) northwest of Remington, where the underlying Mount Zion Church Basalt is absent or replaced by diabase intrusive rocks (pl. 1*C*). A fossiliferous sequence containing the fish-bearing beds was recently cored at the type locality; it consists of approximately 10 m (33 ft) of fossiliferous gray shale overlain and underlain by reddish-brown siltstone and sandstone (app. B).

Relation to adjacent stratigraphic units.—Although both upper and lower contacts of this formation are poorly exposed, the contacts are either slight disconformities or paraconformities, based on local and regional structural relations. Along Goose Creek in Loudoun County where the upper contact with the Hickory Grove Basalt is well exposed, the contact is baked for about 10 cm (4 in) and is locally irregular with as much as 1 m (3 ft) of local relief. Conglomerates in the lower part of the Midland Formation contain no recognizable basalt cobbles or boulders; however, where the Mount Zion Church Basalt is discontinuous, the equivalent horizon in a USGS core hole near Midland is marked by a basalt cobble and boulder conglomerate, confirming that Early Jurassic erosion was locally important.

Fossils and age.—The Early Jurassic fossil fish *Ptycholepis marshi* Newberry was identified from the dark-gray, microlaminated shale and impure limestone sequence along Licking Run (Schaeffer and others, 1975; Schaeffer and McDonald, 1978). Olsen and others (1982, p. 36) subsequently identified *Redfieldius sp,* *Semionotis micropterus*, and *Diplurus longicaudatus* and assigned them to his *Semionotis micropterus* zone. Cornet (1977) identified diagnostic plant spores *Alisporites grandis* (Cookson), *Verrucosisporites cheneyi*, and *Convolutispora klukiforma* (Wilson) from these beds. Cornet (1977) assigned the spores to his *Corollina meyeriana* palynofloral zone of Early Jurassic (Hettangian to Sinemurian) age.

Deposition.—Although the bulk of the Midland Formation is reddish-brown siltstone, fine-grained, ripple laminated sandstone, and medium- to coarse-grained, crossbedded sandstone and lenticular conglomerates, indicating deposition by streams, the most distinctive unit is the widespread dark-gray to black, fish-bearing, fossiliferous, calcareous shale and impure limestone sequence which is of lacustrine origin. Although these beds cannot be traced continuously along the depositional strike because of sparse outcrops, they mark widespread, possibly recurrent, lacustrine conditions in the Early Jurassic of the Culpeper basin. Another ostracod-bearing greenish-gray shale zone was exposed during recent excavations at the type locality about 10 m (33 ft) above the Mount Zion Church Basalt; however, the exposure was deeply weathered and has not been found elsewhere.

HICKORY GROVE BASALT

The middle sequence of basalt flows in the upper part of the Culpeper Group is herein named the "Hickory Grove Basalt" for the exposures at the type locality along Virginia State Road 701, about 180 m (590 ft) N. 82° W. of the intersection of U.S Route 15 and Virginia State Road 701, near Hickory Grove in the southeastern part of the Middleburg 7.5-min Quadrangle, Prince William County, Va. (Lee, 1979, 1980; measured section 4C, app. A, this paper). It is equivalent to basalt flow unit II of the Buckland Formation of Lindholm (1979, p. 1724, 1725, and fig. 8, p. 1729) and formation H of Cornet (1977).

Distribution.—The Hickory Grove Basalt extends more than 62 km (50 mi) in the western parts of the Culpeper basin (pl. 1*C*). This basalt occurs as two separate flows separated by dark-red, fine-grained sandstone and siltstone north of Casanova Junction and pinches out near the southwestern border of the basin in Culpeper County, Va. To the north it occurs as at least three flows separated by fine-to coarse-grained sandstone and conglomerate beds southwest of Leesburg, Loudoun County, Va., where it is truncated by the western border fault.

Description of rock.—This basalt is medium to dark gray, very fine to coarse crystalline, mostly equigranular and holocrystalline (fig. 16). Euhedral or subhedral crystals of plagioclase, chiefly labradorite and andesine, are embedded in a ground mass of augite crystals, forming ophitic or subophitic textures. Accessory minerals are chiefly magnetite and ilmenite. Vesicles are present mainly in the upper part of the sequence. Compared with the Mount Zion Church and the Sander Basalts, the Hickory Grove is the least intensely altered and mineralized. The upper part of this basalt is interbedded with a polymict marble and basalt-cobble-bearing conglomerate at an abandoned quarry on the southern side of Goose Creek in Loudoun County, Va. This indicates that the basalt eruption was contemporaneous with fluvial deposition of the conglomerate, as the basalt occurs both as matrix to and as subrounded cobbles within the conglomerate.

FIGURE 16.—Exposure of the Hickory Grove Basalt on the south bank of Broad Run in the southern part of the Thoroughfare Gap 7.5-min Quadrangle. Polygonally jointed flow surface contains numerous vesicles and amygdules. Lens cover is 5 cm (2 in) in diameter.

Geochemistry.—Based on chemical analyses of several samples of unweathered but altered basalts (Puffer and others, 1981; Leavy and Puffer, 1983; Lee and others, 1984), the Hickory Grove Basalt is a high-Fe_2O_3, high-TiO_2, quartz-normative tholeiite chemically similar to the Preakness Basalt of the Newark basin in New Jersey and the Holyoke Basalt of the Hartford basin in Connecticut (Puffer and Hurtubise, 1983).

Sandstone and siltstone members.—The sandstone and siltstone members consist of two or three poorly exposed lenticular units sandwiched between three or more separate basalt flows. The sandstone is dark red to red brown, arkosic, micaceous, fine to coarse grained, conglomeratic, and poorly sorted. It is interbedded with dusky-red siltstone, which is argillaceous, micaceous, and sandy.

Thickness.—The Hickory Grove Basalt ranges in thickness from 80 m (262 ft) near the southwestern basin border, Culpeper County, Va., to 212 m (695 ft) (measured section 4C, app. A) in the west-central part of the basin, Prince William County, Va. Lindholm (1979, p. 1730) calculated thicknesses for his basalt flow unit II, the Hickory Grove Basalt, at 17 sites, where it ranged from about 50 to 380 m (165 to 1,246 ft), and he showed that the flows thicken to the north. The thickness of the sandstone and siltstone members is estimated to be less than 120 m (394 ft) collectively, but individual lentils are less than 50 m (165 ft) thick.

TURKEY RUN FORMATION

The Turkey Run Formation is herein named for the predominantly sandstone, siltstone, and shale sequence that overlies the Hickory Grove Basalt and is overlain by the Sander Basalt at the type locality along Turkey Run northwest of Casanova Junction in the southwest part of the Catlett 7.5-min Quadrangle, Fauquier County, Va. This unit is equivalent to sedimentary unit II-III of the Buckland Formation of Lindholm (1979, p. 1724, 1725, and fig. 8, p. 1729), to the middle sedimentary unit of Lee's informal basaltic-flow-bearing clastics member of the Bull Run Formation (Lee, 1977, p. C8, and measured section 8, p. C15, C16; measured section 4D, app. A, this paper), and to formation G of Cornet (1977).

Distribution.—The Turkey Run Formation occupies a sinuous north-trending swale from 0.5 to 1.5 km (0.3 to 0.9 mi) wide, generally concave to the west between subdued strike ridges formed by the Sander and Hickory Grove Basalts. It extends for about 63 km (39.5 mi), from about 5 km (3 mi) north of Brandy Station, Culpeper County, to Goose Creek, about 11 km (7 mi) south-southwest of Leesburg, Loudoun County, Va. It crops out extensively in the west part of the Catlett 7.5-min Quadrangle and is especially well exposed in the vicinity of the community of Balls Mill along Licking Run, along Turkey Run 1 km (0.6 mi) northwest of Casanova, and 0.7 km (0.4 mi) northwest of Auburn, Fauquier County, Va.

Lithology.—The Turkey Run Formation at its type locality consists largely of dark-red to medium-dark-greyish green, micaceous, feldspathic, laminated, ripple-laminated, and crossbedded, thin- to thick-bedded to massive, very fine to coarse-grained sandstone, siltstone, and silty shale. Near the south end of its outcrop belt, along the Rappahannock River, the Turkey Run consists of upward-fining and upward-coarsening cyclic sequences of red-brown to greenish-gray, very fine to medium-grained sandstone, siltstone, and shale 5 to 10 m (16.5 to 33 ft) thick.

Fossils.—Dinosaur tracks have been found at a quarry in this unit on the northern bank of the Little River about 0.7 km (0.4 mi) S. 30° W. of U.S. Route 15 in the extreme southwestern part of the Leesburg 7.5-min Quadrangle, Loudoun County, Va. Fine-grained, greenish-gray sandstone, siltstone, and carbonaceous shale along the Rappahannock River contain scattered plant fragments. Dark-gray to black, laminated, lacustrine shale and siltstone beds are present near the base of the formation east of Broad Run on U.S. Route 15-29-211 in Prince William County and at Cedar Run near Auburn in Fauquier County, where it contains black, phosphatic fish scales.

Thickness.—The thickness of the Turkey Run Formation ranges from less than 150 m (492 ft) near the south end of the outcrop belt north of Culpeper to 218 m (715 ft) at State Route 701 (measured section 4D, app. A); it increases to as much as 330 m (1,082 ft) near Sander quarry and the village of Casanova; from there to the north end of the outcrop belt south of Leesburg, it averages about 300 m (1,000 ft). According to Lindholm (1979, fig. 8, p. 1729), this unit averages about 250 m (820 ft) in the vicinity of Buckland along U.S. Route 15-29-211 in Prince William County.

Relation to adjacent stratigraphic units.—Both upper and lower contacts of this formation are poorly exposed; however, based on local and regional structural relations, the contacts with both overlying and underlying basalts are either slight disconformities or paraconformities.

Deposition.—The abundant crossbedded arkosic sandstone suggests deposition under fluvial conditions; however, the climbing-ripple-laminated siltstone and silty shales, although predominantly red brown in color, locally contain some gray and green fissile shales similar to fossiliferous lacustrine strata of the Midland Formation. The Turkey Run Formation is everywhere overlain and underlain by subaerial fissure basalt flows, suggesting that the continental sediments are predominantly fluvial in origin; the sands were

FIGURE 17.—Sander Basalt exposed in the northwestern part of the Sander quarry, 7 km (4.3 mi) southeast of Warrenton, Fauquier County, Va. View looking south at west-dipping sequence of several basalt flows with amygdaloidal tops and well-developed columnar joints.

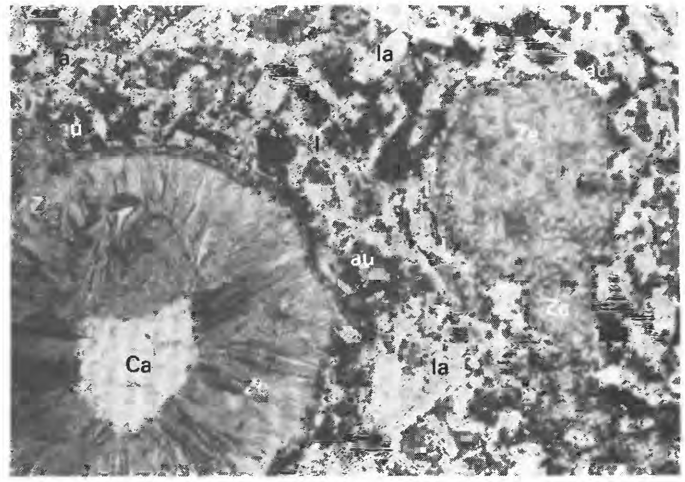

FIGURE 18.—Photomicrograph of zeolitic amygdules in the upper sequence of the Sander Basalt at the Sander quarry, Fauquier County, Va. Zeolite-filled amygdules (ze) in a holocrystalline ground mass showing primary ophitic intergrowth of augite (au) and labradorite (la) with accessory magnetite and ilmenite (black euhedra). Late-stage calcite (ca) occurs in center of the larger zeolite amygdule. The field of view is 2.2 mm (0.08 in) across (plane-polarized light).

deposited by mainly east-flowing streams, based on crossbed vector means (Lindholm, 1979, fig. 5, p. 1717). The alternating upward-coarsening and upward-fining cycles suggest at least a local deltaic origin, and the basal beds between Cedar Run and Broad Run clearly indicate deposition under lacustrine conditions.

SANDER BASALT

The basalt exposed at the Sander quarry, Fauquier County, Va., is herein named the "Sander Basalt" (Lee, 1979, 1980; measured section 4E, app. A, this paper). It is the uppermost sequence of basalt flows (fig. 17) and is equivalent to basalt flow units III, IV, and V of the Buckland Formation of Lindholm (1979, p. 1724, 1725, and fig. 8, p. 1729) and to formations B, D, and F of Cornet (1977). The Sander quarry is located about 7.2 km (4.6 mi) S. 35° E. of Warrenton, on the northeastern side of Virginia State Road 643 in the western part of the Catlett 7.5-min Quadrangle, Fauquier County, Va. The type section, in the northwestern part of the Sander quarry, consists of a lower sequence of mostly medium-grained, but partly coarse-grained, basalt and an upper sequence of aphanitic to medium-grained and in part porphyritic basalt, characterized by zeolite-filled almond-or pea-shaped vesicles (fig. 18).

Distribution.—The basalt flows extend for more than 60 km (37.5-mi) in the western part of the Culpeper basin and are separated by intercalated sandstones and siltstones into several flowsheets in Loudoun, Prince William, and Fauquier Counties, Va. (pl. 1*C*). The Sander Basalt terminates near the southwestern border of the basin in the extreme southeastern part of the Brandy Station 7.5-min Quadrangle, Culpeper County, Va. It is truncated by the western border fault along the western basin margin in the Remington, Warrenton, Catlett, Middleburg, and Lincoln 7.5-min Quadrangles, Va. An isolated, shattered, altered, and steeply tilted basalt flow extends in a narrow belt for more than 4 km (2.5 mi) south-southwesterly from near Millbook quarry and is truncated by the normal western border fault; it is probably a fault sliver or horse of the Sander Basalt. A similar basalt is interposed with steeply dipping limestone, pebble-bearing conglomerate, and shattered sandstone at the abandoned Millbook quarry near the western border of the basin in the west-central part of the Thoroughfare Gap 7.5-min Quadrangle, Prince William and Fauquier Counties, Va.

Description of the rock.—The Sander Basalt is dark to bluish and grayish black and mostly holocrystalline and equigranular, but in part microcrystalline and porphyritic. Crystals of augite and plagioclase (chiefly andesine and labradorite) exhibit ophitic or subophitic texture. The coarsest zone of the lower sequence of this basalt flow contains patchy streaks of micropegmatite, as much as 152 mm (6 in) thick. These coarse-grained streaks consist of blades of plagioclase and clinopyroxene with minor vermicular quartz. Vesicles and amygdules are commonly present in the upper part of the flows (fig. 18). In places the Sander Basalt is intensely hydrothermally altered and locally mineralized with copper and iron sulfides, as well as zeolites.

Geochemistry.—Based on chemical analyses of several samples of unweathered but altered basalts (Puffer and others, 1981; Leavy and Puffer, 1983; Lee and others, 1984), the several Sander Basalt flows are diverse and very complex. Some flows are high-Fe_2O_3, high-TiO_2, quartz-normative tholeiites, while others are high-Fe_2O_3, low-TiO_2, quartz-normative tholeiites. They are generally chemically different from the Hook Mountain Basalt of the Newark basin in New Jersey and the Hampden Basalt of the Hartford basin in Connecticut (Puffer and Hurtubise, 1938).

Sandstone and siltstone members.—The poorly exposed sandstone and siltstone members of the Sander Basalt are composed of three or more lenticular units sandwiched between separate flows (pl. 1*C*), as well as several minor lentils too thin to portray at map scale. They consist of predominantly very dark red to grayish-red, greenish-gray to olive-gray, feldspathic, micaceous, fine-to coarse-grained and pebbly sandstone, thin to thick bedded, and in places interbedded with silty dark-red shale and locally with dark-gray calcareous shale and silty shale. The sandstones are crossbedded in places and fine upward to climbing-ripple-laminated siltstone. The siltstone is red brown, micromicaceous, and interbedded with dark-red silty shale and locally with dark-gray calcareous shale.

Thickness.—The thickness of the Sander Basalt is 242 m (794 ft) southeast of Warrenton and northwest of Catlett, Fauquier County, Va., and ranges from 140 m (459 ft) to more than 600 m (1,970 ft) west of U.S. Route 15, Prince William County, Va. (measured section 4E, units 1, 3, 5, and 7, app. A). Lindholm (1979, p. 1730) calculated thicknesses for his basalt flow units III, IV, and V, the Sander Basalt, at 25 sites. It is difficult to estimate the collective thickness at any given site because some flows are absent owing to structural truncation along the border fault and some flows contain thick lenses of sedimentary rocks; however, a partial minimum thickness of the lower flow is about 150 m (500 ft), and a maximum composite thickness of the three combined flows of Lindholm is 690 m (2,264 ft). Collectively and individually, the three major flow sequences and the numerous individual flows constituting the Sander Basalt apparently thicken to the north. The three Sander sandstone and siltstone members west of U.S. Route 15 are about 205 m (674 ft) thick collectively (measured section 4E, units 2, 4, 6, with 55 m (181 ft) covered; app. A).

WATERFALL FORMATION

The Waterfall Formation, named by Lindholm (1979, p. 1725, 1726) for outcrops "in the vicinity of the community of Waterfall (Prince William County) especially in the fields north of Route 630, 0.3 km (0.2 mi) northwest of Waterfall" is here adopted. As revised herein, the upper conglomerate unit of the Waterfall Formation is named the "Millbrook Quarry Member." The Waterfall Formation overlies the youngest flow of the Sander Basalt and is the uppermost formation of the Culpeper Group.

Distribution.—Lindholm (1979, p. 1731) stated: "The Waterfall Formation lies adjacent to the western border fault and extends northward from just south of the community of Broken Hill in Fauquier County to the Bull Run Estates in Prince William County. This area is 18 km (11 mi) long and has a maximum width of 2.3 km (1.4 mi)."

Lithology.—The Waterfall Formation consists mainly of interbedded sandstone, siltstone, mudstone, shale, and conglomerate. Sandstone ranges from fine- to coarse-grained and pebbly, reddish-brown arkose to fine-to coarse-grained light- to dark-gray and bluish-gray calcareous graywacke; in places the light-gray sandstone is well sorted, crossbedded, quartzose, and slightly to moderately porous (less than 5 to 25 percent) and permeable (as much as 260.0 millidarcies). The siltstone and shale interbedded with the reddish-brown arkose are also red brown, in places mottled with grayish-green patches, commonly micromicaceous and slightly calcareous; siltstone, shale, and mudstone intercalated with the graywacke are light to dark gray, greenish and bluish gray, calcareous, fossiliferous, and phosphatic in places; six or more fish-bearing, gray to black, calcareous lacustrine shale beds (described by Baer and Martin 1949; Hentz, 1981, p. 20; 1985, p. 95-98, fig. 4; Olsen and others, 1982, p. 36) are present in the Waterfall Formation. According to Lindholm (1979, p. 1731), the conglomerate beds "are dominantly composed of clasts of fine-grained silicates and quartzite...." Greenstone metavolcanic and weathered basalt clasts are locally abundant, indicating that nearby Jurassic basalt flows were eroded and incorporated into the Waterfall Formation. The conglomerates are usually soft and deeply weathered, with clasts and matrix commonly altered to saprolite. Hentz (1981, p. 16, 17) has presented strong evidence indicating that many of the gray shales, siltstones, sandstones, and conglomerates are part of a complex lacustrine turbidite sequence. He also recognized at least four major angular unconformities in the Waterfall succession (Hentz, 1981, p. 13; 1985, p. 106).

Fossils.—A small assemblage of probable freshwater biota from calcareous mudstones of the Waterfall Formation in the Middleburg 7.5-min Quadrangle is reported in an unpublished (1976) study of fossils by John Pojeta, Jr., and by Hentz (1981, p. 20; 1985, p. 95). At least two taxa of conchostracan arthropods are present, one identified as belonging to the family *Vertexiidae*; ostracodes and a single phytosaur tooth were also recovered. At Thoroughfare Gap, conchostracans, ostracodes, gastropods, and a variety of vertebrate remains were also found (Hentz, 1981, p. 20, and 1985, p. 95; Olsen and others, 1982, p. 36), including nonmarine fish fauna consisting of *Semionotus elegans*, *Redfieldius* cf. *G. gracilis*, *Diplurus* cf. *D.longicaudatus*, and *Ptycholepis* sp. (Schaeffer and others 1975; Schaeffer and McDonald, 1978). Dinosaur tracks were reported from recent road cuts of U.S. Route 66 about 2 km (1.25 mi) N. 80° W. in Prince William County, Va. (R.E. Weems and T.F. Hentz, pers. commun., 1979); Hentz (1981, p. 20; 1985, p. 95) documented two other sets of tracks, one identified as *Eubrontes*(?) by R.E. Weems (oral commun., 1981), on steeply dipping sandstones along Broad Run about 2 km (1.25 mi) south of Route 66. Abundant carbonized plant remains, including cycadophyte and lignite fragments, have been found in the area around Millbrook quarry. Cornet (1977) assigned the abundant palyniferous gray beds in his formation A, the Waterfall Formation, to the *Corollina torosus* palynofloral zone of Early Jurassic (Sinemurian to Pliensbachian) age.

Thickness.—According to Lindholm (1979, p. 1732), "The maximum thickness of the Waterfall Formation (including the Millbrook Quarry Member) is calculated to be 1,500 m (5,000 ft) in the vicinity of Waterfall." Lee (1977, pl. 1b) calculated a thickness of 1,718.5 m (5,638 ft) in the Antioch area north of Thoroughfare Gap. Along Interstate Route 66 and elsewhere in the vicinity of Thoroughfare Gap, Hentz (1981, p. 13) measured and calculated a composite section of 1,150 m (3,773 ft).

Relation to adjacent stratigraphic units.—Although the contacts are generally covered, the Waterfall Formation apparently overlies the Sander Basalt either conformably or in a paraconformity. The predominantly sandstone, siltstone, and calcareous shale of the Waterfall Formation is overlain by conglomerates of the Millbrook Quarry Member, locally disconformably and elsewhere in a gentle, locally obscure, angular unconformity apparently no more profound than other angular unconformities within the Waterfall Formation.

Millbrook Quarry Member

The Millbrook Quarry Member of the Waterfall Formation is herein named for the uppermost conglomerate and sandstone unit of the Waterfall Formation exposed at and near the type locality, Millbrook quarry, south of Virginia Route 55, 1.2 km (0.7 mi) east of Thoroughfare Gap, in the Thoroughfare Gap 7.5-min Quadrangle, Prince William County. The Millbrook Quarry Member is a conglomerate unit that includes what Roberts (1928, p. 15, 16) called the arkose conglomerate of his Border Conglomerate, and is the uppermost part of Lee's (1977) informal basaltic-flow-bearing clastics member of the Bull Run Formation. Both Lindholm (1979, p. 1731) and Hentz (1981, p. 13) included strata assigned to the the Millbrook Quarry Member in the Waterfall Formation, while Lee (1980) included this unit in his informal Mountain Run member of the Bull Run Formation. Detailed mapping by Hentz in the Thoroughfare Gap area revealed a profoundly "unconformable relationship between the thick conglomerate on the western side of the field area and the underlying finer grained deposits to the east" (Hentz, 1981, p. 116); this conglomerate is the Millbrook Quarry Member, and the underlying deposits are the balance of the Waterfall Formation. Both matrix-supported and clast-supported pebble and cobble conglomerates are present, the latter type filling large channel forms (Hentz, 1981, p. 79).

Lithology.—The conglomerate of this member contains abundant cobbles of weathered greenstone and lesser amounts of quartzite, gneiss, marble, limestone, basalt, and vein quartz in a clayey sand and silt matrix generally firmly cemented by calcite or silica. The clasts average 9 cm (4 in) in diameter but are locally as large as 1 m (3.3 ft). The conglomerate is intercalated with lenses of medium -to coarse-grained reddish-brown arkosic sandstone and sandy micaceous dusky-red-brown siltstone. In places, as at Bull Run Mountain Estates and near the village of Waterfall, the unit is deeply weathered to saprolite.

Distribution.—The Millbrook Quarry Member crops out in the foothills of Bull Run Mountain along the western margin of the central part of the Culpeper basin, with good exposures of the conglomerate at Millbrook quarry; along Broad Run and its western tributaries to the south of the quarry; in the vicinity of the village of Waterfall; in the stream valley 0.3 km (0.2 mi) southeast of Beulah Church in Fauquier County; and along road cuts west of Route 600 in Prince William County. These latter outcrops are deeply weathered to saprolite and are less than 50 m (164 ft) east of the border fault (Froelich and others, 1982, p. 71, 72).

Thickness.—It is extremely difficult to estimate an accurate thickness because of the discontinuous nature of outcrops and ill-defined lenticular bedding; however, Hentz (1981, p. 144) calculates an approximate thickness of 450 m (1,476 ft) in the area south of Millbrook quarry.

Relation to adjacent stratigraphic units.—Although outcrops are generally poor and the lower contact generally covered, the conglomerates of the Millbrook Quarry Member overlie the Waterfall beds in an apparent disconformity in most places; locally, as shown by detailed mapping along Broad Run, the contact is a gentle angular unconformity. The commonly steep and characteristically erratic dip of the crudely bedded conglomerates of the Millbrook Quarry Member compound the problem of deciphering local relations. The upper contact is obscure, as erosion has long since removed any overlying units.

Deposition.—The conglomerate deposits near Waterfall and scattered outcrops in the foothills of Bull Run Mountain suggest deposition as fluvial fan deposits; primary structures and clast lithologies indicate that the apex of the fan lay in the adjacent highlands to the west-northwest.

GENERAL DISCUSSION OF THE DEPOSITIONAL MODEL

The great thickness of discrete conglomerate lenses that are largely restricted to narrow zones along the basin margins is strongly suggestive of alluvial fans. This marginal distribution is well explained in the model of equilibrium between fan sedimentation and basin area (fig. 19). The generally poor sorting, coarseness, and paucity of well-defined sedimentary sequences suggest episodic sedimentation from areas of high relief, probably by debris flows, rock avalanches, and steep, shallow streams. The angularity of the clasts and the lack of weathering of boulders and cobbles despite labile mineralogies indicate either very rapid erosion and burial or arid conditions, or both. Bull (1964, p. 105) pointed out that some fans are segmented owing to repeated periods of uplift and erosion, and subsequent redeposition of gravels in lower segments at reduced gradients; commonly in intermontane basins, the lower fan segments coalesce with other fans, which may be the case along the eastern margin of the Culpeper basin. Conglomerates commonly intertongue with sandstone, a condition that might result from perturbations of Hooke's (1968) steady-state equilibrium model by fan segmentation or by changes of average discharge (Bull, 1964, p. 101-106, 128; 1972).

Arkosic sandstone and lithic graywacke are interpreted primarily as fluvial deposits because of unidirectional crossbedding, upward-fining sequences from pebbly sands to silts, and the presence of channel-like scours. Many of the grayish-red arkosic sandstones were probably deposited by small streams, because the basal scours are shallow, sandstones are relatively thin

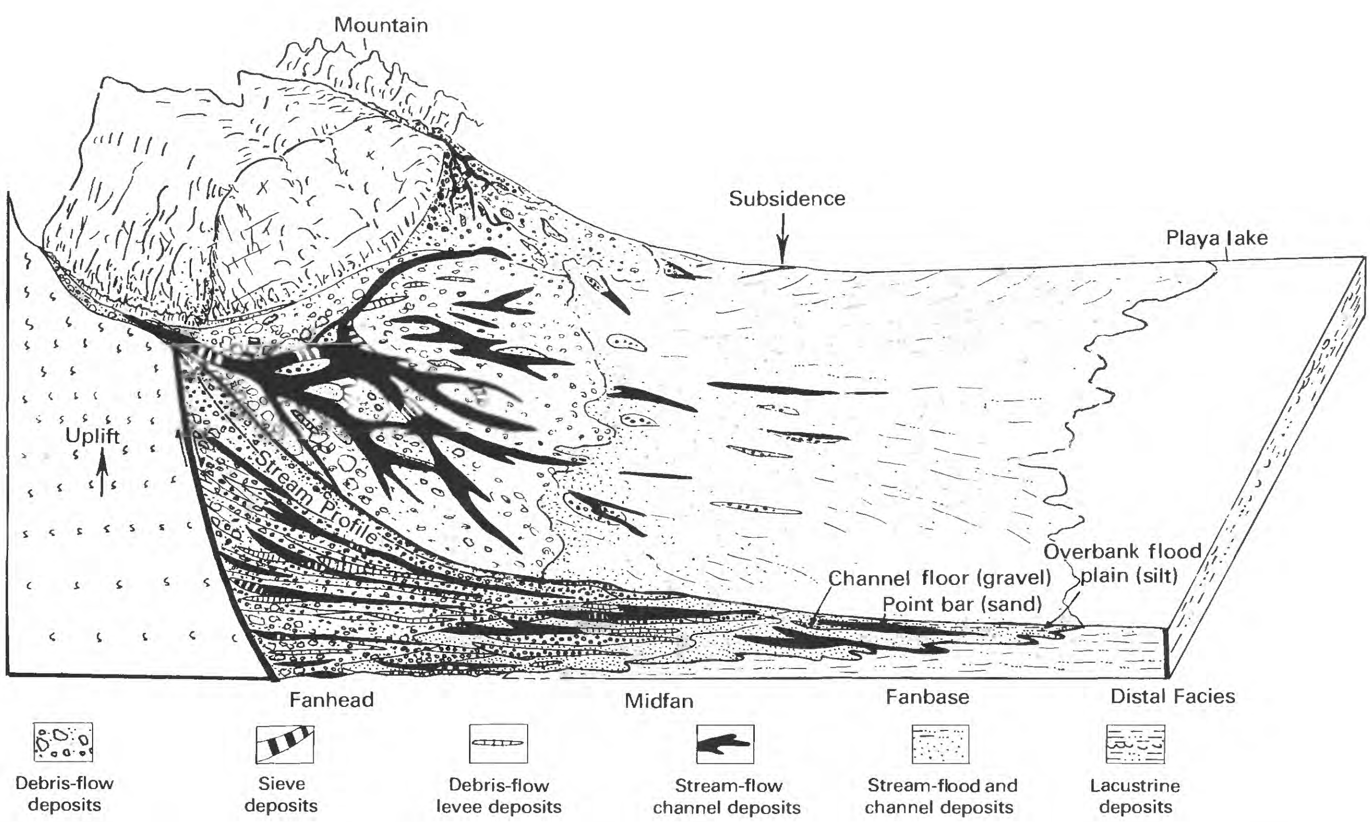

FIGURE 19.—Diagrammatic sketch showing stratigraphic relations of an alluvial fan to lacustrine deposits in a closed basin, the facies distribution, and the concave-upward radical fan profile (modified after Spearing, 1974, fig. 1; Bull, 1964, p. 105, 106; Denny, 1967; Hooke, 1967, 1968; Selley, 1978; and Blatt and others, 1980).

and medium- to fine-grained, and crossbeds are small in scale. Associated sandy micaceous siltstones containing abundant tubes (interpreted as root casts and burrows), mud cracks, dinosaur tracks, and carbonate nodules of reworked caliche are interpreted as subaerial, overbank, and flood-plain deposits, in places modified by soil-forming processes.

Dusky-red mudstone and silty mudstone containing abundant mud cracks, dinosaur footprints, and carbonate pellets are interpreted as the deposits of subaerially exposed playa mudflats. Light-gray and ripple-laminated greenish-gray silty mudstone, sparsely fossiliferous gray calcareous shale, and carbonaceous shale are interpreted as probable shallow lake deposits, while dark-gray, silty, calcareous, varved, or laminated, phosphatic fish-bearing carbonaceous shales are interpreted as relatively deep lakebeds. The cyclic alternations of these fine-grained lithologies are believed to reflect expansions and contractions of perennial lakes, primarily in response to climatic fluctuations. The presence of graded beds from coarse to fine, flute casts and sole marks, slumped and convolute bedding, and lenticular pebble conglomerates within laminated dark-gray shale sequences has been interpretated as evidence of turbidites in the Jurassic strata near the western basin margin (Hentz, 1982, 1985, p. 102).

Evidence of climatic cyclicity in the deposits of the Late Triassic to Early Jurassic basins of eastern North America has been repeatedly documented (Reinemund, 1955; Hubert and others, 1976; Cornet, 1977; Hubert, 1977; Van Houten, 1977a 1977b; Wheeler and Textoris, 1978; Olsen and others, 1982; Olsen, 1984). Hubert (1977) convincingly documented the origin of carbonate nodules in the New Haven Arkose of the Connecticut Valley as caliche, produced under semiarid conditions, and the abundant carbonate nodules in the Culpeper basin were probably formed under similar conditions. Conversely, the presence of rich and diverse palynofloral remains in the gray silty mudstones and carbonaceous shales intercalated in the red bed sequences of the Culpeper basin are believed to reflect intermittent humid conditions.

The cumulative depositional thicknesses, the intertonguing relationships of extremely diverse lithologies, the presence of turbidites in lake strata, the distribution of conglomerates, and the presence of local unconformities all support the interpretation of an episodically subsiding, intermontane, fault-bounded continental basin flanked by periodically uplifted mountains. The cyclicity of some of the sedimentary packages, the diversity of flora and fauna, and the primary structures and mineralogy of the conglomeratic and red bed strata all indicate a fluctuating but prevailing semiarid climate punctuated by episodic humid conditions in the Late Triassic and Early Jurassic of the Culpeper and Barboursville basins. In the Early Jurassic, the Culpeper basin erosional and depositional enivironment was punctuated by extensive fissure eruptions and subaerial basalt flows fed by deep-seated intrusions.

DIABASE

DISTRIBUTION AND MODE OF OCCURRENCE

Diabase is confined to the Culpeper basin and apparently intruded the Triassic-Jurassic sedimentary rocks shortly before or concurrent with westerly tilting of the basin during the latest stages of sedimentation. Outcrops of diabase extend from Boyds, Montgomery County, Md., to south of the Robinson River, Madison County, Va. Diabase occurs chiefly as stocks, sills, saucer-shaped sheets, and dikes in the northern basin, and as sills, sheets, and dikes in the south. Small dikes with north, northwest, and northeast trends are scattered throughout the basin and locally cut through both Mount Zion Church and Hickory Grove Basalt flows in Prince William County, Va. (pl. 1*C*), although they may also be exposed feeders to some of the flows.

DESCRIPTION OF ROCK

The diabase is medium and medium-dark gray, chiefly equigranular and locally coarse to very coarse crystalline, but aphanitic at chilled intrusive margins. It consists of dark-grayish-green to black discrete crystals of pyroxene, mostly augite with lesser amounts of pigeonite, which, with scattered granules or aggregates of magnetite and ilmenite, fill the interstices between light-gray plagioclase laths, chiefly labradorite (figs. 20, 21). The more quickly cooled dikes and other small intrusions and the borders of large bodies are generally darker in color, finer grained, and more dense than diabase in the interior of the large bodies. Some narrow dikes and small pluglike features in the central part of the basin are olivine-bearing. The diabase locally shows a textural change from normal diabase to granophyre associated with syenite, ferrogabbro, and a pegmatitic facies of the diabase (fig. 22). Generally, the diabasic pegmatite facies evolved because of slower cooling and an increase in volatiles within the central portion of the magma, and occurs as irregular bodies, bands, and lenses in the diabase masses. The pegmatite is composed of light-gray to pinkish-gray plagioclase feldspar, minor potassium feldspar, and sparse grains of quartz occurring in the interstices of bladelike pyroxene associated with minute

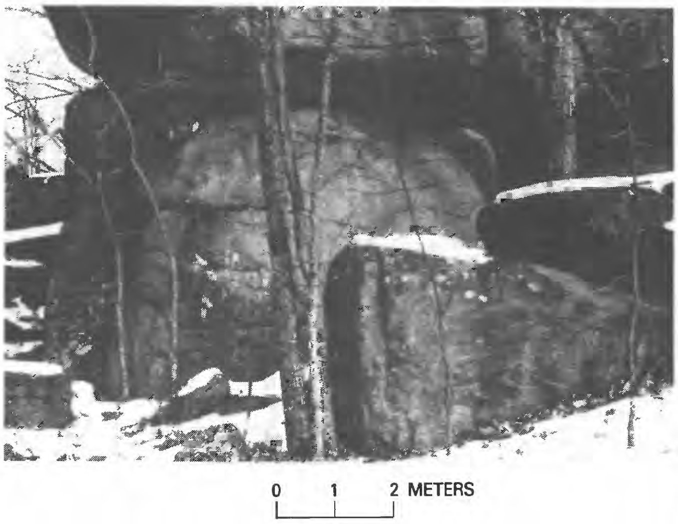

FIGURE 20.—Diabase at Mount Pony, Culpeper County, Va. Equigranular and medium-grained orthopyroxene-bearing diabase shows well-developed, widely spaced joints and subhorizontal sheets.

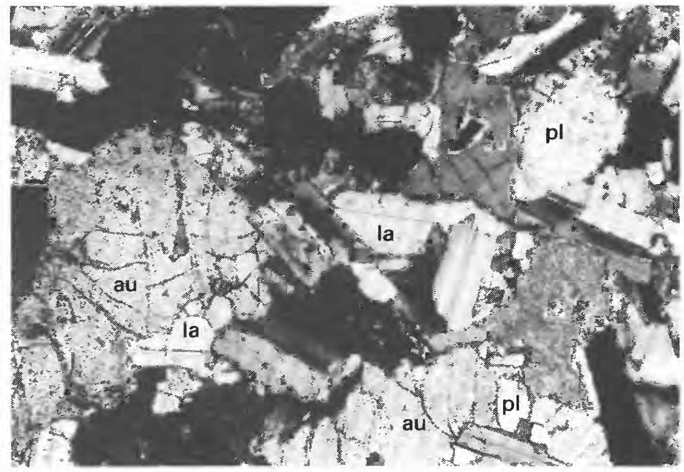

FIGURE 21.—Photomicrograph of the Mount Pony diabase, Culpeper County, Va. Augite (au) and labradorite (la) in subophitic intergrowth with scattered sericitized plagioclase (pl), magnetite, and ilmenite. The field of view is 2.2 mm (0.08 in) across (plane-polarized light).

crystals of ilmenite and magnetite. The sheets at Boyds, Md., and north of Rapidan, Va., also carry abundant orthopyroxene phenocrysts, mainly hypersthene and bronzite, concentrated in thick layers or zones of gabbro and norite.

During late stages of magmatic differentiation, and partly as a result of assimilation of wall rock and contamination, the composition of the magma had changed sufficiently to permit the crystallization of granophyre (fig. 23). The granophyre is pale pink to pink, medium to coarse grained, and in part porphyritic. It consists of sodic plagioclase, potassium feldspar, and sparse micropegmatitic quartz, associated with discrete crystals of hornblende and clinopyroxene, and minor biotite, actinolite, magnetite, ilmenite, chlorite, and apatite. A large body of granophyre covers about 3 km^2 (1 mi^2) on the south side of Mountain Run in Culpeper County, Va., and smaller differentiated bodies of granophyre, syenite, ferrogabbro, and pegmatite extend in a linear belt of podlike segregations almost to the town of Nokesville.

GEOCHEMISTRY

Chemically, most of the Early Jurassic diabase sheets of this basin are high-TiO_2, quartz-normative tholeiites, similar to the York Haven diabase of Pennsylvania (Smith and others, 1975). Some of the dikes and the sheets at Gainesville, Nokesville, and Catlett, however, are low-TiO_2, quartz-normative tholeiites chemically similar to the Rossville diabase of Pennsylvania (Smith and others, 1975). Some thin dikes and small pluglike intrusives are olivine-bearing and rich in MgO. The quartz-normative basaltic magma that supplied the principal sheets and dikes is probably genetically related to that which was extruded in the west-central portion of the basin as surface flows during the Early Jurassic. The orthopyroxene-rich sheets at Boyds, Md., and Rapidan, Va., are considerably higher in MgO than the sheets and sills in the central part of the basin.

THERMALLY METAMORPHOSED ROCKS

The contacts of diabase with Triassic and Jurassic country rocks are generally sharp, but in some areas of wholesale assimilation and magmatic contamination around large sills and stocks, contacts are transitional across tens of meters; nevertheless, thermal metamorphism of country rocks is extensive throughout the basin, and the thermal aureole surrounding the larger bodies is on the order of one-fourth to one-third the thickness of the intrusive. Metamorphic rock types are gray to dark-gray, medium-bluish-gray, and olive-black hornfels and light-gray granulite (granofels), metaconglomerates, and quartzite. These rocks were chiefly derived from feldspathic, micaceous, argil-

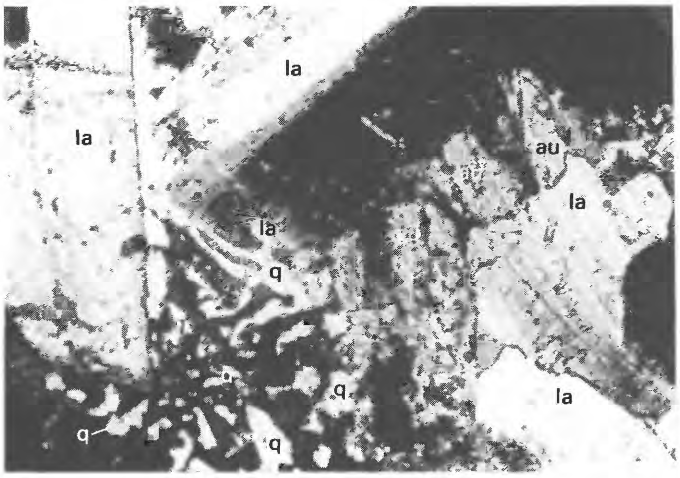

FIGURE 22.—Photomicrograph of the pegmatitic phase of a diabase exposed in the Luck quarry, Loudoun County, Va. Elongated labradorite (la) and augite (au) form an intergrowth with vermicular quartz (q) grains. The field of view is 2.2 mm (0.08 in) across (plane-polarized light).

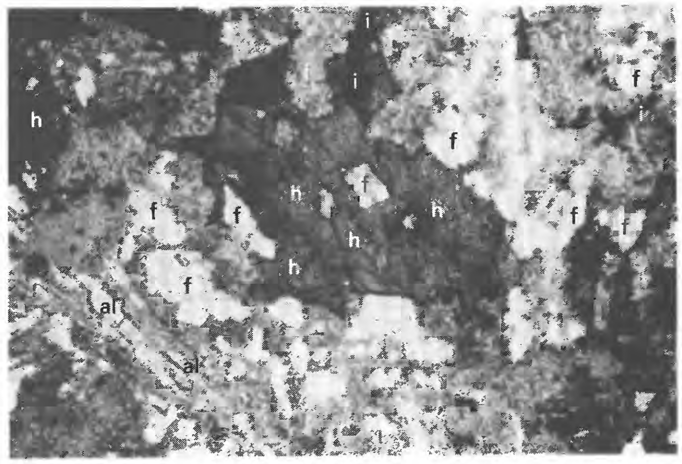

FIGURE 23.—Photomicrograph of the granophyric phase of diabase along the south side of Mountain Run, 2 km (1.25 mi) east of The Ridge, Germanna Bridge 7.5-min Quadrangle, Culpeper County, Va. Holocrystalline intergrowth of hornblende (h) and turbid potash feldspar (f) with albite (al) laths, minor quartz grains, and scattered ilmenite (i) and magnetite. The field of view is 2.2 mm (0.08 in) across (plane-polarized light).

laceous, arenaceous, ferruginous, and (or) calcareous sandstone and siltstone and minor conglomerate and shale of the Culpeper Group. Light-gray to gray marble was derived from contact metamorphism of limestone conglomerate of the Leesburg Member, and the Mount Zion Church, Hickory Grove, and Sander Basalts were slightly thermally altered by diabase dikes, some of which may be part of a near-surface feeder system.

Hornfels is the dominant type of metamorphosed argillaceous rock (fig. 24, this paper; Lee and Froelich, 1985). In contact aureoles, an inner zone, generally characterized locally by cordierite, biotite, quartz, and plagioclase, is succeeded by a middle zone of cordierite, andalusite, plagioclase, and quartz, which is followed by an outer zone of chlorite, epidote, and quartz (Lee, 1982). Granulite and quartzite form fused lenses, bands, and irregular masses (fig. 25). The inner zone in these rocks is characterized either by a zone of decussate biotite, plagioclase, and fused quartz, or by a zone of hornblende, sodic plagioclase, titanite, and myrmekite-quartz. This zone is succeeded outward either by a zone of cordierite, andalusite, plagioclase, and fused quartz, or by a zone of fine black tourmaline, plagioclase, and quartz, which is generally followed by an outer zone of chlorite, epidote, and locally spotted aggregates of recrystallized feldspar (Lee, 1982). Marble derived from metamorphosed limestone conglomerate consists of calcite, lime-garnet, diopside, and serpentine, associated with minor amounts of vesuvianite, magnetite, fluorite, and wollastonite.

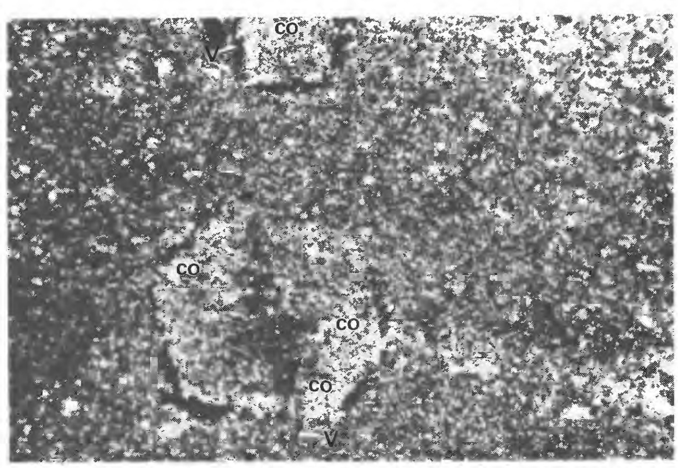

FIGURE 24.—Photomicrograph of a cordierite-hornfels from the Chantilly Crushed Stone quarry, in the eastern part of the Arcola 7.5-min Quadrangle, Loudoun County, Va. It is probably a metamorphosed argillaceous, calcareous, and ferruginous siltstone of the Balls Bluff Siltstone. Cordierite (co) shows a well-developed hexagonal outline, cut by a sericite-quartz veinlet (v). Cordierite crystals are mostly altered to sericite, chlorite, biotite, and an isotropic substance (shimmer aggregate) with inclusions of quartz, magnetite, specularite, and ilmenite. The crystals are also partially rimmed by opaque iron and titanium oxides. The field of view is 2.2 mm (0.08 in) across (plane-polarized light).

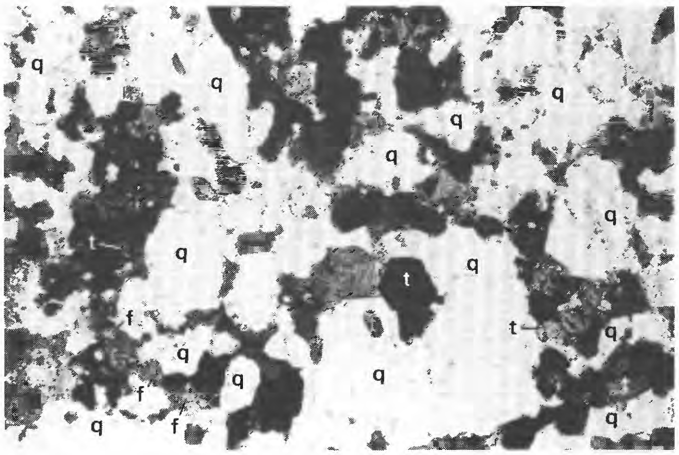

FIGURE 25.—Photomicrograph of a granulite (granofels) from the east bank of Little Rocky Run, Fairfax County, Va. This is probably a metamorphosed feldspathic, ferruginous sandstone of the Poolesville Member of the Manassas Sandstone. Recrystallized mosaic of quartz (q) and turbid potash feldspar (f) contains euhedral to anhedral tourmaline (t). The field of view is 2.2 mm (0.08 in) across (plane-polarized light).

SUMMARY

The Triassic-Jurassic Culpeper and Barboursville basins were initiated and evolved during the early Mesozoic period of continental fragmentation and rifting that preceded continental drifting in the development of the modern Atlantic continental margin. Detrital sedimentary rocks of the Culpeper Group were derived by erosion from adjacent steep highlands and were deposited as alluvial fans along the base of adjacent highlands by streams and debris flows that in some cases bordered playa lakes. This sedimentation was controlled by extensional tectonics and fluctuating, generally semiarid conditions.

The composition of the red beds of the Culpeper Group suggests that relief in the source areas was great and that rapid erosion and deposition resulted. The red color of the detritus is most likely allogenic, prediagenetic, and in places diagenetic. It is estimated that red beds make up 90 percent of the Manassas Sandstone and Balls Bluff Siltstone and at least 30 percent of the overlying formations. A dry climate of long duration is indicated by the development of extensive paleosol caliche, abundant desiccation cracks, bioturbation, and the scarcity of bone remains. A wet climate cycle is marked by plant remains and the cyclic accumulation of laminated fossiliferous shales in lakebeds, but semiaridity probably was dominant, as even the dark-gray lake sediments show mud cracks and fossil soils.

At the beginning of basin fill, the adjustments of the Earth's crust caused by intrusion at depth (Ballard and Uchupi, 1975) accelerated the rate of uplift of the adjacent highlands, accompanied by initiation of uplift along border faults. In early Manassas time, the rate of deposition was greater than the rate of basin subsidence and coarse fans and debris flows accumulated along the base of fault-block highlands. Fragments of Piedmont schist, gneiss, and quartz of the Reston Member accumulated in the east-central part of the basin, and at about the same time deposition of the limestone detritus of the Tuscarora Creek Member in the northeast and greenstone fragments of the Rapidan Member in the southeast accumulated. Fluvial sands of the Poolesville Member gradually accumulated as source areas were worn down. Toward the middle of deposition of the Balls Bluff Siltstone, the movement along border faults reached a steady-state relation with deposition of fine-grained fluvial and lacustrine clastic sediments in the basin. During late Balls Bluff time, uplift of the western highlands was renewed by movement at the west border normal fault, resulting in deposition of the limestone clasts of the Leesburg Member in the northwestern Culpeper basin. This episode of coarse clastic deposition continued intermittently throughout Catharpin Creek time, with large aprons of Goose Creek gravels carried far out into the basin in latest Triassic and earliest Jurassic time. Tectonism along the western margin in Early Jurassic time was apparently more intense and somewhat more extensive than that along the eastern margin in the Late Triassic. The different style and the magnitude of the Early Jurassic episode is indicated by the widespread and repeated eruption of basalt flows, by the presence of turbidites, by local unconformities, and also by the size of the preserved Early Jurassic fans, which are apparently larger in the western portion of the basins than fans of the Late Triassic in the east and southeast. Perhaps relief in the western source area was greater than that in the Piedmont on the east, and it is possible that the western border faults of the basin migrated progressively westward with time, in part accounting for the asymmetry of lithofacies preserved in the present basins. Basin subsidence was accompanied by widespread episodic outpouring of basalt flows in the Early Jurassic, punctuated by long periods of fluvial and lacustrine deposition. Mesozoic deposition essentially ceased after regional basin tilting adjacent to the western border fault commenced. Toward the end of basin filling, large-scale westward monoclinal tilting of the rocks in the basin occurred, with the Jurassic rocks in the western part of the basin tilted steeply toward the border faults, accompanied by extensive intrusion of tholeiitic diabase sills, stocks, and dikes. A long period of uplift and erosion followed, causing deep denudation and exposure of the interior of both the Culpeper and the Barboursville basins.

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APPENDIX A: MEASURED SECTIONS

SECTION 1.—RAPIDAN RIVER, VIRGINIA

[Type section of the Rapidan Member of the Manassas Sandstone. Measured by K.Y. Lee using hand level and tape, 1976, along the south side of the Rapidan River in the southern part of the Culpeper East 7.5-min Quadrangle; about 720 m (2,362 ft) due north of a spot (elevation 339 ft), on Virginia State Road 681, in the northeast Unionville 7.5-min Quadrangle, Orange County, Va.]

	Thickness	
	Meters	*Feet*
Upper Triassic and Lower Jurassic:		
Culpeper Group (in part):		
Upper Triassic:		
Manassas Sandstone (in part):		
Rapidan Member:		
2. Conglomerate, grayish green[1] (5G 5/2), dusky-green (5G 3/2), and grayish-olive-green (5GY 3/2), subangular to angular greenstone pebbles and cobbles averaging 100 mm (4 in) in diameter; scattered gray quartzite and vein quartz fragments within a matrix of greenstone granules and grayish-red sand and silt; firmly cemented by clay and silica. Contains grayish-red and dark-red, fine- to coarse-grained, feldspathic and micaceous sandstone lenses	33	108
1. Conglomerate, dusky-green (5G 3/2) and grayish-olive-green (5GY 3/2), subangular to angular greenstone pebbles and cobbles averaging 128 mm (5 in) in diameter, as large as 300 mm (12 in); scattered gray quartzite and vein quartz fragments in matrix of greenstone granules, dusky-red sand and silt; cemented firmly by clay and silica	43	141
Total thickness of Rapidan Member	76	249
Angular unconformity. Pre-Triassic gray to grayish-black mica-talc-shist (not measured).		

SECTION 2.—TUSCARORA CREEK, MARYLAND

[Type section of the Tuscarora Creek Member of the Manassas Sandstone. Measured by K.Y. Lee using hand level and tape, 1976, along Maryland State Road 28; about 800 m (2,624 ft) southeast of the bridge of Maryland State Road 28 over Tuscarora Creek in the Buckeystown 7.5-min Quadrangle, Frederick County, Md.]

	Thickness	
	Meters	*Feet*
Upper Triassic and Lower Jurassic:		
Culpeper Group (in part):		
Upper Triassic:		
Manassas Sandstone (in part):		
Tuscarora Creek Member (incomplete):		
2. Conglomerate, light-gray (N7) to medium-gray (N5), grayish-red (5R 4/2) subangular limestone cobbles and pebbles averaging 26 mm (1 in) in diameter; limestone fragments are lithographic to medium-grained; scattered vein quartz, quartzite, and chert fragments in matrix of limestone granules and dusky-red silt; firmly cemented by calcite. Grades into or intertongues with dusky-red and grayish-red feldspathic sandstone	4	13
1. Conglomerate, medium-gray (N5), light-gray (N7), subangular to rounded limestone pebbles and cobbles, averaging 28 mm (1 in) in diameter, as large as 200 mm (8 in); limestone fragments are lithographic to medium-grained; some clasts are vein quartz, quartzite, and chert within matrix of limestone granules and dusky-red clayey silt; firmly cemented by calcite	2	7
Total thickness of Tuscarora Creek Member	6	20
Angular unconformity. Upper Cambrian gray to blackish-gray lithographic to fine-grained Frederick Limestone (not measured).		

SECTION 3.—CULPEPER, VIRGINIA

[Type section of the Mountain Run Member of the Tibbstown Formation. Measured by K.Y. Lee using hand level and tape, 1976, about 640 m (2,099 ft) southeast of the overpass bridge of Virginia State Route 3 over the Southern Railroad in the northwestern part of the Culpeper East 7.5-min Quadrangle, Culpeper County, Va.]

	Thickness	
	Meters	*Feet*
Upper Triassic and Lower Jurassic:		
Culpeper Group (in part):		
Upper Triassic:		
Tibbstown Formation (in part):		
Mountain Run Member (incomplete):		
4. Conglomerate, dusky-yellow-green (5GY 5/2), grayish-olive-green (5GY 3/2), and grayish-green (10G 4/2), subangular to angular greenstone pebbles and cobbles averaging 128 mm (5 in) in diameter, as large as 600 mm (24 in); scattered vein quartz, gray quartzite, and schist fragments in matrix of greenstone granules, dusky-red and dark-red sand and silt; firmly cemented by clay and silica. Commonly intercalated with dark-red, feldspathic, micaceous, clayey sandstone and siltstone. Scattered epidotization of feldspar	6	20
3. Conglomerate and sandstone, interlensed; greenstone conglomerate, same as unit 4. Sandstone, very dark red (5R 2/6), grayish-red (10R 4/2); very fine to very coarse grained, and in		

[1] Color description are based on the "Rock-Color Chart" of the Geological Society of America (Goodard and others, 1948).

	Thickness Meters	Thickness Feet
part, conglomeratic; feldspathic, clayey, micaceous, and slightly calcareous; thick-bedded to massive; clayey, silty matrix; firmly cemented by clay, silica and locally minor calcite	7	26
2. Covered	52	171
1. Conglomerate, grayish-olive-green (5GY 3/2), grayish-green (10G 4/2), angular to subangular greenstone pebbles and cobbles averaging 210 mm (8.5 in) in diameter, as large as 900 mm (36 in); scattered vein quartz, quartzite, and schist fragments in matrix of greenstone granules, grayish-olive-green and grayish-red sand and silt; firmly cemented by clay and silica	151	495
Total thickness of Mountain Run Member	217	712

SECTION 4.—HICKORY GROVE, VIRGINIA

[Section of the Mount Zion Church Basalt (4A), Midland Formation (4B), Hickory Grove Basalt (4C), Turkey Run Formation (4D), and Sander Basalt (4E). Measured by K.Y. Lee using hand level and tape, 1975; about 576 m (1,889 ft) east of the intersection of Virginia State Route 701 and U.S. Route 15 at Hickory Grove, Va.; and from the base of the Mount Zion Church Basalt in the southwest Arcola 7.5-min Quadrangle and southeast Middleburg 7.5-min Quadrangle, Prince William County, Va.]

	Thickness Meters	Thickness Feet
Upper Triassic and Lower Jurassic:		
Culpeper Group (in part):		
Lower Jurassic:		
4A. Mount Zion Church Basalt (incomplete):		
1. Basalt, medium-dark-gray (N4); weathered light brown (5YR 5/6) to dark-yellowish-brown (10YR 4/2); fine- to medium-crystalline; chiefly equigranular and holocrystalline; porphyritic in part; plagioclase, chiefly labradorite, and augite show ophitic texture. Scattered aggregates of magnetite and ilmenite.		
Total thickness of Mount Zion Church Basalt (partial)	9	30
Covered.		
Upper Triassic and Lower Jurassic:		
Culpeper Group (in part):		
Lower Jurassic:		
4B. Midland Formation: (complete):		
1. Sandstone, dusky-red (5R 3/4) to grayish-red (5R 4/2); very fine to medium-grained; feldspathic, micaceous, and clayey; thin-bedded to very thick bedded and planar-laminated. Intercalated with layers of medium-dark-gray (N4) and dark-gray (N3) clayey siltstone and silty shale in the lower part. Locally intercalated with dark-gray, fissile, silty shale, such as at the intersection of Virginia State Route 701 and U.S. Route 15	93	305
Covered (This interval contains fish-bearing shale as at Licking Run)	288	945
Total thickness of Midland Formation (complete)	381	1,250
Upper Triassic and Lower Jurassic:		
Culpeper Group (in part):		
Lower Jurassic:		
4C. Hickory Grove Basalt (complete):		
1. Basalt, medium-dark-gray (N4); weathered light-brown (5YR 5/6); very fine to very coarse crystalline; equigranular and holocrystalline; euhedral to subhedral crystals of plagioclase, chiefly labradorite, embedded in an augite groundmass; scattered grains of magnetite and ilmenite. Zeolite-filled vesicles present mainly in the upper part.		
Total thickness of Hickory Grove Basalt (complete)	212	695
Upper Triassic and Lower Jurassic:		
Culpeper Group (in part):		
Lower Jurassic:		
4D. Turkey Run Formation (complete):		
1. Siltstone, dark-reddish-brown (10R 3/4), blackish-red (5R 2/2), and grayish-red (5R 4/2); weathered light-brown (5YR 6/4); very fine to very coarse grained; feldspathic, clayey, and micaceous; very thin to very thick bedded and planar-laminated. Intercalated with layers of sandstone and silty shale; feldspar epidotized near the contact with basalt.		
Total thickness of Turkey Run Formation (complete)	218	715
Upper Triassic and Lower Jurassic		
Culpeper Group (in part):		
Lower Jurassic:		
4E. Sander Basalt (incomplete)(Units 1, 3, 5, 7—basalts; units 2, 4, 6—intercalated sandstone and siltstone lentils):		
7. Basalt, medium-dark-gray (N4), dark-greenish-gray (5GY 4/1), and medium-bluish-gray (5B 5/1); weathered pale brown (5YR 5/2), dark-yellowish-brown (10 YR 4/2), and light-brown (5YR 5/6); aphanitic to medium crystalline; equigranular and in part porphyritic; plagioclase, chiefly labradorite, laths intergrown with augite; scattered grains of magnetite and ilmenite in a holocrystalline groundmass	112	367
Covered	55	181

6. Sandstone, greenish-gray (5GY 6/1) to olive-gray (5Y 4/1), and moderate-yellowish-brown (10YR 5/4); very fine to medium-grained; feldspathic and micaceous; thin- to thick-bedded and planar laminated. Contains subordinate amounts of clayey siltstone and silty shale	75	246
5. Basalt, same as unit 7, except porphyritic texture common; columnar jointing well developed	76	249
4. Sandstone, very dark red (5R 2/6) to grayish-red (10R 4/2); very fine to coarse-grained; feldspathic, micaceous, silty, and clayey; very thin bedded to very thick bedded, in part massive. Intercalated with subordinate amounts of siltstone and silty shale	55	181
3. Basalt, same as unit 7, except mostly medium-crystalline; contains scattered zeolite-filled vesicles. Porphyritic texture common	55	181
2. Siltstone, grayish-red (5R 4/2), very dusky red (10R 2/2) to medium-dark-gray (N4); very fine to very coarse grained; clayey, feldspathic, micaceous, and calcareous; bedding very thin to massive. Contains beds of silty shale and fine-grained sandstone. Epidotization of feldspar common	20	66
1. Basalt, medium-dark-gray (N4), dark-greenish-gray 5GY 4/1), and medium-bluish-gray (5B 5/1); weathered dark-yellowish-brown (10YR 4/2) and light brown (5YR 5/6); aphanitic to coarse-crystalline, in part pegmatitic in texture; equigranular to porphyritic; plagioclase, chiefly labradorite, laths intergrown with augite; scattered magnetite and ilmenite in holocrystalline groundmass. Zeolite-filled vesicles common in the upper part	303	994
Total thickness of Sander Basalt measured (partial)	751	2,465

SECTION 5.—STRATIGRAPHIC SECTION OF THE BALLS BLUFF SILTSTONE AT THE CULPEPER CRUSHED STONE QUARRY, STEVENSBURG, CULPEPER COUNTY, VIRGINIA

Joseph P. Smoot

The quarry exposure is primarily composed of about 65.5 m (215 ft) of slightly thermally altered mudstones and siltstones. These rocks are well indurated and have a slabby to blocky parting. The sandstone and coarse siltstone layers appear to be quartzose with a dolomitic cement, based on their weathering characteristics and examination under a hand lens. Carbonate minerals are apparently altered to epidote in a few zones. The carbonate minerals include a tan-weathering cement, which is interpreted as a ferroan dolomite, and a white calcite cement. The cements are intergranular in coarser layers and occur as tube- and crack-fillings and as nodules in mudstones.

Most of the mudstones and siltstones have been divided into eight lithologic types on the basis of their primary depositional features (fig. A-1). These lithologic types occur repeatedly throughout the section, defining cycles. Portions of the exposure were inaccesible for examination owing to the steepness of the quarry wall. These sections (from about 1 to 7 m (3.3 to 23 ft) and from 10 to 15.5 m (33 to 51 ft) below the uppermost layer) were measured by dropping a metric tape over the ledge and making observations with binoculars. The lithologic types are indistinguishable over significant portions of these sections and are labeled lithologic type 9. Five additional lithologic types were recognized, but each of these occur only once in the section. These are labeled a-d.

LITHOLOGIC TYPES

1 *Dark-gray to black, laminated shaly mudstone*: Laminae are defined by alternations of silt layers with silty clay layers. The fine silt layers are flat and continuous, and the coarse silt layers form thick laminae which are lenticular or which pinch and swell rhythmically. Sole markings resembling trails are common on bedding planes, as are sand-sized peloidal structures, which may be fecal pellets or internal molds of ostracode shells. Mud cracks are absent or rare.

2 *Dark-gray and purplish-red platy mudstone that is laminated to thin-bedded*: Layering is defined by alternations of muddy silt layers with silt to very fine sand layers. The coarser layers pinch and swell rhythmically or are lenticular, forming oscillatory ripple marks on bedding planes. The thin silt layers may have internal low-angle inclined lamination, and the thicker layers, particularly near the tops of this lithologic type, contain internal asymmetric, sinusoidal, cross-laminae indicating transport to the E.-SE. The sand layers may have scoured basal contacts and load casts. Polygonal mud cracks are common and more abundant toward the tops of these units. Cracks near the base are 15-20 cm (6-8 in) deep and 40-50 cm (16-25 in) apart, while cracks near the top are around 5 cm (2 in) deep and 10-15 cm (4-6 in) apart.

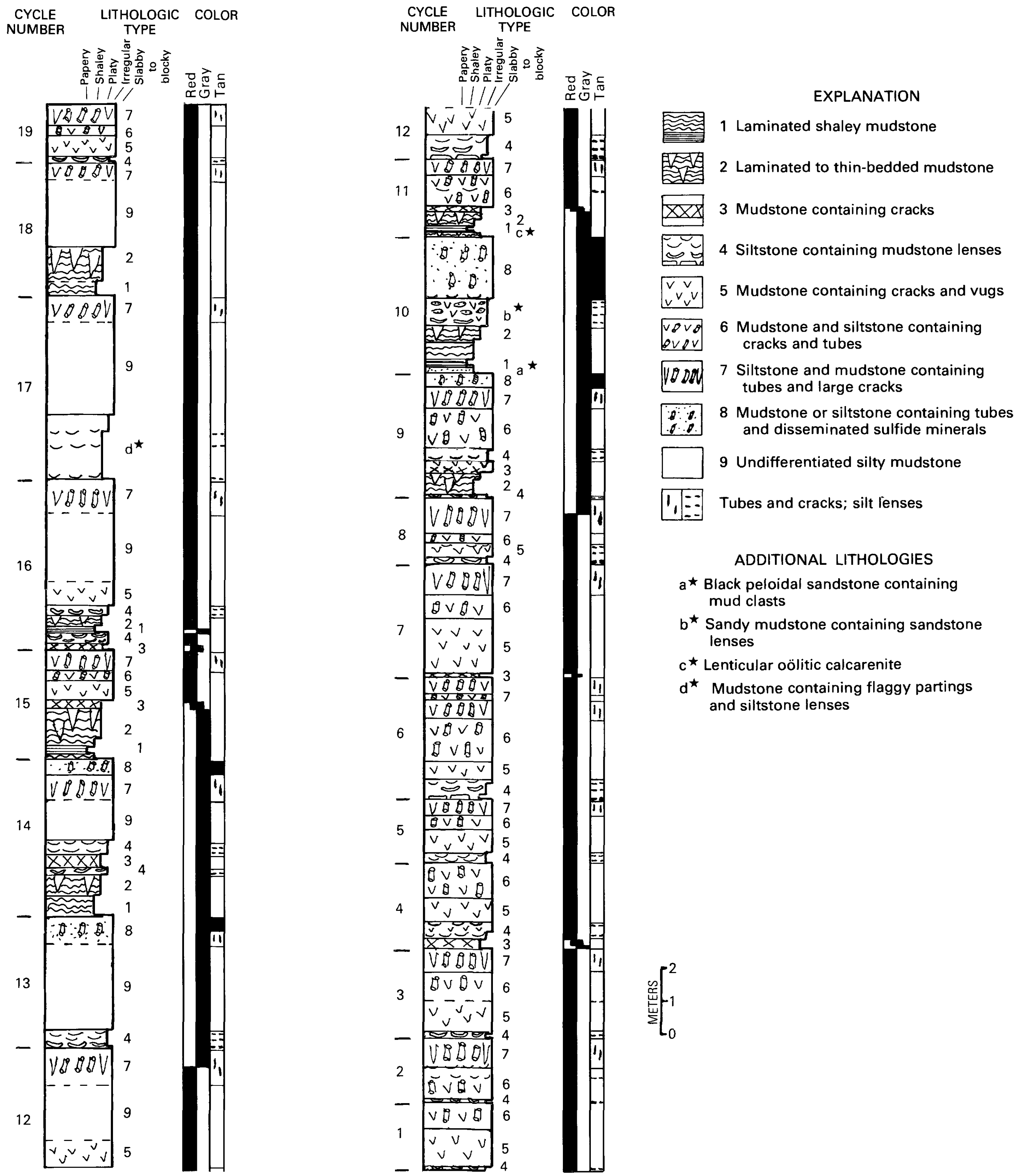

FIGURE A-1.—Stratigraphic section of the Balls Bluff Siltstone at the Culpepper Crushed Stone quarry, Stevensburg, Va.

3 *Gray and purplish-red mudstone disrupted into breccia-like blocks by abundant red or gray, silty mudstone-filled, polygonal cracks*: The cracks are typically narrow and jagged in cross section, forming crosscutting polygons, each 5-10 cm (2-4 in) in diameter, in plan view. The mudstone blocks may have internal lamination as in lithology 2, and the layering in adjacent blocks is parallel, showing no evidence of rotation.

4 *Tan-weathering, thin beds of siltstone occurring as layers of concave-upward, curling lenses in red and gray silty mudstone*: The siltstone beds are commonly disrupted by broad (to 20 cm (8 in)), flat-bottomed areas of silty mudstone which define polygonal cracks. The siltstone beds, have internal asymetric, sinusoidal, ripple cross lamination or horizontal planar-lamination and mud partings. Small scours and internal grading are common in the siltstone beds, and sole markings resembling small trails, dinosaur tracks, and prod marks are also common. The silty mudstone in the cracks contains abundant spherical to very flattened elliptical blobs of dolomite or calcite which are interpreted as cement-filled vugs. The silty mudstone between the siltstone beds contains narrow, jagged cracks, some filled with dolomite or calcite, and fewer of the "vugs." The siltstone lenses near the base of these units are closely spaced and show little curvature, while those near the top are widely spaced and strongly curled. The upper siltstone layers also contain numerous narrow, angular internal cracks.

5 *Massive, red and gray, silty mudstone to muddy siltstone with abundant narrow, jagged cracks and calcite- or dolomite-filled spheroidal to flattened elliptical "vugs"*: The cracks define irregular, crosscutting polygons 3-10 cm (0.6-4 in) in diameter and also occur as horizontal cracks connecting the "vugs." Small tubes (diameters less than 1 mm (.04)) may be present in the crack fillings.

6 *Massive, red and gray, silty mudstone to muddy siltstone with abundant narrow, jagged cracks and dolomite- or calcite-filled tubes*: The tubes are 0.2-2.0 mm (.008-0.8 in) diameter, sinous, and mostly oriented perpendicular to bedding and may bifurcate and taper. The cracks are similar to those of lithology 5 except in the upper parts of the units where the cracks are wider and the polygons have greater diameters (as much as 20 cm (8 in)). The tubes appear to preferentially occur within polygonal crack fillings near the bases of the units and are more randomly distributed near the tops.

7 *Massive, red and gray, muddy siltstone to silty mudstone with abundant dolomite-or mud-filled tubes and 10-20 cm (4-8 in) deep, narrow, sinuous cracks*: The tubes range in diameter from sub-mm-to cm-scale, commonly branch and taper, and are randomly distributed. Some of the smaller tubes are filled with calcite, and the larger tubes are commonly filled with coarse silt and nodular dolomite. The cracks are mostly filled with muddy silt containing dolomitic cement and define polygons 20-40 cm (8-16 in) in diameter.

8 *Massive, gray to black, sandy mudstone or siltstone with abundant dolomite- and calcite-filled tubes and disseminated sulfide minerals*: The tubes range in diameter from sub-mm- to cm-scale and may branch and taper or remain the same diameter for their exposed length. Dolomitic nodules are common in the larger tubes and are also randomly scattered (the largest reaching 15 cm (6 in) in diameter). Narrow, sinuous cracks 20-30 cm (8-12 in) long are common and define polygons 30-40 cm (12-16) in diameter. Small, irregular patches of sandstone are probably remnants of bedding disrupted by bioturbation. Low-amplitude, long-wavelength (30-40 cm (12-16 in)), symmetric ripple structures are present on some of the upper bedding planes.

9 *Undiffentiated, massive, red and gray, silty mudstone*: The sedimentary features are probably the same as either lithology 5 or lithology 6.

a *Black, peloidal sandstone with mud clasts to granule size*: The layer is 1-7 cm (0.4-2.8 in) thick lying on a sharp, erosional basal contact with as much as 4 cm (0.8 in) relief. Thin bedding is defined by changes in grain size and thin, shaly partings. The overall unit appears to be coarse-tail graded. Disseminated sulfide minerals are abundant.

b *Dark-gray, tan-weathering, sandy mudstone with sandstone lenses and pods*: Sandstone lenses are 1-5 cm (0.4-2.0 in) thick and 5-10 cm (2-4 in) long and have internal flat lamination to cross-lamination. The lamination is commonly deformed into concave-convex folds which appear to be coincident with dinosaur tracks on the bedding surface. Polygonal cracks 10-20 cm (4-8 in) in diameter are common, as are tubes filled with sand, mud, and dolomite. Sulfide minerals are abundant in the sandstone lenses.

c *A lenticular oölitic calcarenite overlying the irregularly humpy bedding surface of lithology 8*: The upper surface of lithology 8 is dominated by nodules of dolomite and epidote, large tubes, polygonal ridges, and trails of poorly defined dinosaur tracks. Some of the humpiness may be due to superimposed tracks. The humpiness appears to decrease downdip, and the polygons have larger diameters and are less ridgelike in that direction (west). The oölitic calcarenite varies in thickness from 0 to 20 cm (8 in). It contains flat-lying, pebble-sized clasts of mudstone and laminar micrite. The laminar micrite also occurs as humpy layers within the calcarenite. Disseminated sulfide minerals are abundant.

d *Mudstone with flaggy partings and beds of curled siltstone lenses, viewed through binoculars*: The siltstone lenses appear to be present at the basal contact and a few other horizons within this lithology. The lower meter appears to have thinner parting than the upper meter. The weathering style of this zone is similar to the lower meter of cycle 16.

e *Shaly to flaggy mudstone interval, viewed through binoculars*: Large mud cracks are visible in the upper portion, whereas none were seen in the lower part. Therefore, the basal part is assigned to lithology 1 and the top is assigned to lithology 2.

INTERPRETATION OF THE ENVIRONMENT OF DEPOSITION

Lithology 1 is interpreted as the bottom sediments of a perennial lake that may have been very deep at some times. Lithology 2 is interpreted as a shallower, wave-reworked lake deposit that was intermittently subaerially exposed and desiccated. Lithology 3 is interpreted as lake sediments that were subaerially exposed and intermittently rewetted. The brecciation is believed to be the result of repeated desiccation with very little sediment accumulation. Lithology 4 is interpreted as the deposits of a temporary lake which were disrupted by desiccation cracks during prolonged periods of subaerial exposure. Lithology 5 is interpreted as heavily desiccated deposits of an aggrading, playalike mudflat. The vugs are believed to be vesicles formed during flooding events over the dry flats. Lithologies 6 and 7 are interpreted as root-disrupted deposits of vegetated subaerial flats. Lithology 6 is believed to represent drier conditions than lithology 7 because the mud cracks are smaller and narrower and the proposed root structures preferentially occur in the cracks. Lithology 8 is interpreted as the deposits of a vegetated, intermittently desiccated, shallow lake margin.

The cycles are defined by the systematic vertical changes from rocks having well defined layers to rocks that are internally massive. The contacts between the cycles are abrupt, while the boundaries between lithologic types within the cycles are gradational. Two end-member types of cycles are proposed: 2-1-2-3-4-6-7-8 and 4-5-6-7. The cycles are interpreted as representing transgressions and regressions of a lake, probably due to climatic changes. Cycles of the longer type, which are predominately gray colored, are interpreted as representations of overall wetter conditions than the shorter cycles, which are predominately red. Transgressions are believed to be from the west-northwest toward the east-southeast. This interpretation is based on the cross-lamination in asymmetric oscillatory ripple structures in lithologies 2 and 4 and the observed lateral transitions within beds of lithology 4 from better layered on the western side of the quarry to more mud cracked on the eastern side. The shorter cycles appear to be more abundant at the base of the section. The cycles gradually change to the longer variety toward the middle portions of the section, and then start to change to the shorter variety toward the top. This may represent a longer term climatic cyclicity.

APPENDIX B: DRILL AND CORE HOLE DESCRIPTIONS AND COLUMNS

(Geologic logs of selected water wells and core holes, Culpepper basin, Va.)

WELL E.—U.S. GEOLOGICAL SURVEY TEST HOLE F-51V 14F

Fox Mill Subdivision, Fairfax County, Va.

Well no. 51V-14F
Elevation: 340 ft
Location: lat 38° 55′28″ N., long 77° 23′27″ W.
Formation: Triassic Manassas Sandstone: Poolesville Member, Reston Member; Peters Creek Schist

Quadrangle: Herndon 7.5-min
Total depth: 305.5 m (1,002 ft); -202 m (-662 ft)
Logged by J.D. Larson and A.J. Froelich, Oct. 20-26, 1978

Depth, in feet	Lithology	Remarks
0-3	Soil and alluvium	Sand and silt, yellow brown; loose quartz pebbles.
Culpeper Group, Manassas Sandstone (partial), Poolesville Member (partial)		
3-10	Siltstone and shale	Red-brown, soft, micromicaceous, fractured, noncalcareous.
10-60	Siltstone and shale	Red-brown to grayish-red[1](10R 4/2); in part very calcareous matrix and fracture filling; firm.
60-100	Sandstone and siltstone	Red-brown to purplish-brown; interbedded, micromicaceous, firm, platy, arkosic, in part calcareous; first water influx at 75 ft.
100-110	Sandstone	Fine- to medium-grained, reddish-brown and gray, with scattered coarse subangular quartz and feldspar grains to 2.0 mm.
110-130	Siltstone and shale	Reddish-brown (10R 3/4 to 10R 4/2); interbedded, firm, platy, noncalcareous.
130-180	Sandstone	Fine- to medium-grained, with medium, coarse, and very coarse grains of quartz and feldspar at 170-180 ft, reddish-brown (10R 4/2), in part with calcareous matrix; slight water influx.
180-200	Siltstone and sandstone	Very fine grained, grayish-red (10R 4/2), platy, micromicaceous, brittle.
200-240	Sandstone	Medium- to coarse-grained and conglomeratic, with abundant quartz and schist fragments, gray, arkosic, partly calcareous.
240-280	Siltstone and sandstone	Very fine grained, grayish-red (10 R 4/2), in part mottled green and gray at 280-290 ft, noncalcareous except for rare calcite veinlets.
280-290	Sandstone	Reddish-brown (10R 3/4) to gray, mottled; medium- to coarse-grained and conglomeratic, in part slightly calcareous.
290-320	Siltstone and sandstone	Grayish-red (10R 4/2), fine-grained, arkosic, micromicaceous, noncalcareous.
320-330	Sandstone	Gray, medium- to coarse-grained and conglomeratic, arkosic, in part with calcareous cement.
330-350	Sandstone	Reddish-brown (10R 3/4), very fine to fine-grained, micaceous, silty and clayey matrix, noncalcareous.
350-360	Sandstone	Gray, very coarse grained to conglomeratic, abundant quartz and schist fragments 1.0 to 2.5 cm.
360-390	Siltstone and sandstone	Dusky-red-brown (5R 3/4), very fine grained, micromicaceous, mostly noncalcareous.
390-400	Sandstone	Dusky-red-brown (5R 3/4) and gray, very coarse to medium-grained, scattered quartz pebbles, blocky.
400-450	Sandstone	Red brown (5R 3/4), very fine to medium-grained, arkosic, micromicaceous, platy.
450-545	Sandstone and siltstone	Grayish-red-brown (5R 4/2), in part mottled gray and green, interbedded, with calcite and quartz fragments; impure mottled silty limestone at 470-480 ft.
Top Reston Member (complete, 19.8 m (65 ft))		
545-590	Conglomerate	Red-brown (5R 4/2), abundant angular quartz and schist fragments to 2.5 cm; matrix is medium- to coarse-grained arkose; malachite stain at 580-590 ft.
590-610	Conglomerate	Brownish-gray (5YR 4/1), abundant quartz and schist pebbles and fragments to 2.5 cm; matrix is fine-grained sandstone and siltstone.
Base Reston Member, Unconformity, Peters Creek Schist		
610-620	Saprolite	Weathered schist, reddish-brown and greenish-gray, mottled, polyfoliated.
620-710	Schist	Greenish-gray, chloritic, slightly weathered at 620-630 ft; abundant vein quartz at 650-660, 700-710 ft, with traces of pyrite and magnetite.
710-840	Schist	Silvery-gray-green (5GY 4/1), chloritic, sericitic(?), polyfoliated; abundant vein quartz at 730-740, 790-840 ft, with traces of fresh pyrite and magnetite.
840-1002	Schist	Silvery-gray-green (5GY 4/1), chloritic, micaceous, in part quartzose, in part pelitic with

Depth, in feet	Lithology	Remarks
		fine-grained metagraywacke, polyfoliated; abundant vein quartz at 840-850, 880-900, 930-950 ft; with traces of pyrite, magnetite, and garnet(?), pyrite common from 930-1,002 ft; increase in water inflow to 50 gal/min between 840 and 900 ft.

NOTE.—The section of the Reston Member and partial Poolesville Member of the Manassas Sandstone penetrated apparently constitutes a stacked succession of eight upward-fining fluvial sequences, with the bases at 610, 400, 360, 330, 290, 240, 180, and 110 ft.

[1]Color descriptions are based on the "Rock-Color Chart" of the Geological Society of America (Goodard and others, 1948).

WELL G.—FAIRFAX COUNTY WATER AUTHORITY WELL NO. TW-1

Brookfield, Va., U.S. Route 50 and Flatlick Branch

USGS well no.: 51V-23H
Elevation: 280 ft
Location: lat 38°53'20" N., long 77°25'17" W.
Formation: Triassic Manassas Sandstone (partial); Poolesville Member (partial)

Quadrangle: Herndon 7.5-min
Total depth: 305 m (1,000 ft); -219.5 m (-720 ft)
Logged by J. Carey and S. Morsches, Aug. 10-24, 1979

Depth, in feet	Lithology	Remarks
0-3	Soil and alluvium	Clay, silt, sand, quartz pebbles; yellow-brown, micaceous, loose.
Culpeper Group, Manassas Sandstone (partial) Poolesville Member (partial)		
3-20	Sandstone and siltstone	Sandstone, very fine grained, light-blue-gray to light-olive-gray, very micaceous; interbedded with siltstone, moderate-brown, calcareous, micromicaceous, platy to fissile.
20-30	Siltstone and shale	Moderate-brown, calcareous, micromicaceous, platy- fissile, interbedded.
30-70	Siltstone and sandstone	Sandstone, fine- to medium-grained, scattered coarse grains and conglomeratic at 60-70 ft; green-gray to light-gray, abundant loose quartz grains, in part micaceous, calcareous; siltstone as above; scattered calcite crystals at 50-60 ft.
70-90	Sandstone and siltstone	Sandstone, fine grained, pale brown to brown-gray, calcareous, micaceous; siltstone, pale to moderate brown, calcareous, micaceous; scattered copper minerals: malachite, azurite, cuprite, chrysocolla at 85-92 ft (X-ray I.D.)
90-100	Siltstone and shale	Moderate-brown, calcareous, micaceous.
100-170	Sandstone and siltstone	Sandstone, fine- to medium-grained, moderate-gray brown, scattered coarse-grained sandstone and pebbles at 160-170 ft; calcareous, micaceous siltstone, as above; trace copper minerals—azurite, cuprite, malachite—at 150-160 ft, scattered calcite crystals at 130, 150, 160 ft.
170-200	Sandstone and siltstone	Sandstone, fine- to medium-grained, pale- to moderate-brown, scattered coarse-grained sandstone and pebbles at 190-200 ft, abundant loose sand; calcareous, micaceous; siltstone, as above.
200-280	Siltstone and sandstone	Siltstone, pale- to moderate-brown and gray-red, calcareous, micaceous, fissile; sandstone and loose sand, as above; copper at 230 ft, calcite crystals and veinlets at 240-270 ft.
280-390	Siltstone	Gray-red, micromicaceous, calcareous matrix and veinlets at 290, 320 ft; copper minerals (azurite, malachite) at 320, 350 ft.
390-450	Siltstone and sandstone	Siltstone, as above; sandstone and loose sand, fine- to medium-grained, as above; coarse-grained sand at 410-420 ft.
450-480	Siltstone	As above; in part, fine sandy at 460-470 ft.
480-520	Siltstone and sandstone	Siltstone, as above; sandstone, as above; medium-coarse-grained sandstone, friable, at 490-500 ft with calcite crystals. (Note: Casing run at 500 ft; flowing 15 gal/min at surface prior to installation of casing)
520-540	Siltstone and shale	Siltstone, as above; shale, moderate-brown, calcareous, micromicaceous, fissile, in part silty, scattered clacite crystals and veinlets at 520-530 ft.
540-670	Sandstone and siltstone	Siltstone, fine- to medium-grained, moderate-gray-brown, calcareous, micaceous; siltstone, as above; shale, moderate-brown, silty at 580-590 ft.
670-690	Sandstone	Medium- to fine-grained, moderate-brown, calcareous, micaceous, silty.
690-710	Sandstone and siltstone	As above.

Depth, in feet	Lithology	Remarks
710-730	Sandstone	As above, fine- to medium-grained, with cuprite(?) and chrysocolla and malachite, scattered calcite crystals as above.
730-750	Sandstone and siltstone	As above.
750-760	Siltstone	As above.
760-790	Siltstone and sandstone	As above.
790-820	Sandstone	Medium- to fine-grained, moderate-brown, calcite crystals and veinlets.
820-840	Sandstone and siltstone	As above.
840-880	Missing	
880-970	Sandstone	Fine-grained, as above, calcite crystals at 880-900 ft.
970-990	Missing	
990-1,000	Sandstone	Fine-grained, as above.
1,000	Total depth	At total depth, well flowed at 25 gal/min prior to pump test; 11-hr pump test at 350 gal/min with 95-ft drawdown.

NOTE.—Geophysical logs available: Gamma ray to 656 ft; caliper to 654 ft; multipoint electric to 656 ft (16 in and 64 in normal resistivity).

WELL H.—FAIRFAX COUNTY WATER AUTHORITY WELL NO. TW-2

U.S. Route 50 1.5 mi west of Chantilly, Va. at Friendly Village (of Dulles) Trailer Park

USGS well no. 51V-24H
Elevation: 260 ft
Location: lat 38°53′50″ N., long 77°27′25″ W.
Formation: Triassic Balls Bluff Siltstone

Quadrangle: Herndon 7.5-min
Total depth: 233.8 m (767 ft); -154.6 m (-507 ft)
Logged by J. Carey and S. Morsches, Aug. 7-8. 1979

Depth, in feet	Lithology	Remarks
0-3	Soil	Clay, silt, and sand, yellow-brown, loose, scattered pebbles.
	Culpeper Group, Balls Bluff Siltstone (partial)	
3-40	Siltstone	Moderate-brown to gray-red, micaceous, calcareous, soft.
40-100	Siltstone	Gray-red, micromicaceous, in part with very calcareous matrix and calcite fracture filling.
100-150	Siltstone and shale	Gray-red, micromicaceous, calcareous matrix and calcite vein fillings.
150-170	Siltstone	As above.
170-180	Shale and siltstone	As above.
180-200	Shale	Gray-red, micaceous, calcareous matrix.
200-250	Siltstone and shale	Gray-red and moderate-brown, micaceous, calcareous matrix, sparse calcite fracture fillings.
250-290	Siltstone	Moderate-brown, micaceous, calcareous matrix and vein filling.
290-330	Siltstone and shale	As above.
330-470	Shale	Moderate-brown, argillaceous, gray-red, micaceous, calcareous, silty; with scattered calcite veinlets.
470-510	Siltstone	As above. (Note: Intermediate casing run at 500 ft)
510-700	Siltstone	Moderate-brown, micaceous, calcareous, argillaceous, fissile to platy; trace copper mineral malachite (at 560, 630, 660, 690 ft) calcite crystals and veinlets common.
700-767	Siltstone and shale	Moderate-brown, micaceous, fissile, calcareous.

NOTE.—Geophysical logs available: Gamma ray to 503 ft; caliper to 503 ft; multipoint electric to 503 ft (16 in and 64 in normal resistivity).

Well yield while drilling (air pumped with compressor on rig):

Depth (feet)	*Est. yield (gal/min)*
300	200
325	400 (picked up a lot of water between 310 and 320 ft)
500	425
680	150
(Cased to 500 ft)	

WELL I.—FAIRFAX COUNTY WATER AUTHORITY WELL NO. TW-3

Braddock Road and Flatlick Branch

USGS well no.:51V-13A
Elevation: 230 ft
Location: lat 38°52′05″ N., long 77°27′55″ W.
Formation: Triassic Balls Bluff Siltstone and hornfels—thermally metamorphosed siltstone

Quadrangle: Manassas 7.5-min
Total depth: 198 m (650 ft); -128 m (-420 ft)
Logged by J. Carey and S. Morsches, July 11-30, 1979

Depth, in feet	Lithology	Remarks
0-3	Soil and alluvium	Clay, silt, sand, gravel, yellow-brown; quartz and siltstone pebbles, loose.
	Culpeper Group, Balls Bluff Siltstone (partial)	
3-50	Siltstone	Gray-red, calcareous, micromicaceous, argillaceous,

Depth, in feet	Lithology	Remarks
		platy, fissile; scattered calcite crystals and veinlets.
50-110	Siltstone and shale	Siltstone, pale-red to gray-red, as above; shale, gray-red, calcareous, fissile, silty, scattered claystone.
110-190	Siltstone	As above, minor shale-claystone, gray-red, calcareous, micaceous; scattered calcite crystals and veinlets.
190-210	Siltstone, shale, and sandstone	Siltstone and shale; as above; sandstone, very fine grained.
210-220	Siltstone and shale	As above.
220-230	Siltstone, shale, and sandstone	Siltstone and shale; as above; sandstone, very fine grained, gray-red, calcareous.
230-250	Siltstone	Gray-red, calcareous, micromicaceous (Note: Flow gaged at 24 gal/min)
250-280	Siltstone and shale	As above.
HORNFELS—Thermally metamorphosed siltstone		
280-290	Siltstone, shale, and hornfels	Siltstone and shale, as above; hornfels, grayish-green, silicious, abundant epidote and calcite.
290-300	Siltstone	As above.
300-350	Siltstone and hornfels	Siltstone, gray-red to dusky-brown, gray-brown, argillaceous, micaceous, calcareous; hornfels, greenish-gray and red, hard, laminated with abundant (30 percent) epidote, calcite, quartz and feldspar crystals.
350-370	Siltstone	Gray-red, argillaceous, micaceous, calcareous; abundant epidote, copper mineral (malachite?).
370-530	Siltstone and hornfels	Siltstone, gray-red, laminated, calcareous, very hard; interbedded with hornfels, dark-gray, green, abundant epidote, feldspar. (Note: Flow gaged at 35 gal/min, installed casing to 500 ft)
530-600	Hornfels and siltstone	Hornfels, dark-gray, yellow-gray, olive-gray, with epidote, calcite, felspar, biotite; siltstone, gray-brown, slightly calcareous.
600-650	Siltstone and hornfels	Siltstone, brown to dusky-brown, hard, brittle, laminated, calcareous, micaceous; hornfels, dusky-brown to light-olive-gray; abundant epidote and feldspar; well flowed at 5 gal/min at total depth.

CORE L OF THE MIDLAND FORMATION AT LICKING RUN

Joseph P. Smoot

This core was taken through the Midland Fish Bed, a fossiliferous Lower Jurassic calcareous shale, formerly exposed at the Licking Run dam site in the Midland 7.5-min Quadrangle. It starts in a sandstone overlying the shale and ends in red mudstones beneath it. About 15 m (50 ft) of core was recovered and is illustrated in the measured section (fig. B-1). The thicknesses presented here and their relative depths were determined by direct measurement of the recovered material, which probably has resulted in some inaccuracies. The relationships presented here are a reconstruction made by matching the ends of broken core segments, by determining the orientation by sedimentary structures, and by matching similar sedimentary features or trends where necessary. Two important contacts, which were not well determined, are the red-to-gray color transition and the diabase-sandstone contact. The color transition appears to be very sharp, but the lower contact of the gray mudstone is a drilling spinout; however, a matching spinout was not observed on top of the underlying red siltstone. The base of the sandstone overlying the diabase appears to be thermally altered and, thus, is probably correctly oriented. However, the pieces do not fit, suggesting that there may be some material missing between the two lithologies.

The lowest portion of the core consists of silty mudstones that contain abundant mud cracks and bioturbation and thin sandstones that form sharp-based, graded units dominated by ripple cross-lamination. These are followed by silty mudstones that have larger, better defined burrows and deeper, wider cracks. Sandstones associated with these mudstones are dominated by ripple cross-lamination like the sandstones below,but they have load casts and foundered ripples at their bases and soft-sediment deformation is common. The red-to-gray transition occurs within this portion of the core. Above this is a fine-grained silty mudstone containing abundant carbon-filled tubes and zones of thin, flat silt laminae. A brownish, organic-matter-rich, calcareous shale containing fish fossils abruptly overlies an ostracodal sand that fills a scour contact in the underlying silty mudstone. The brownish shale grades back into the gray silty mudstone with an increase in bioturbation. The mudstone becomes coarser grained upward by a gradual increase in the thickness and number of silt laminae. This culminates in a medium-grained sandstone with dune-scale crossbeds fining upward into rippled siltstone. After the thin diabase intrusive, a thick sequence of flat-laminated, fine-grained sandstone marks the top of the core.

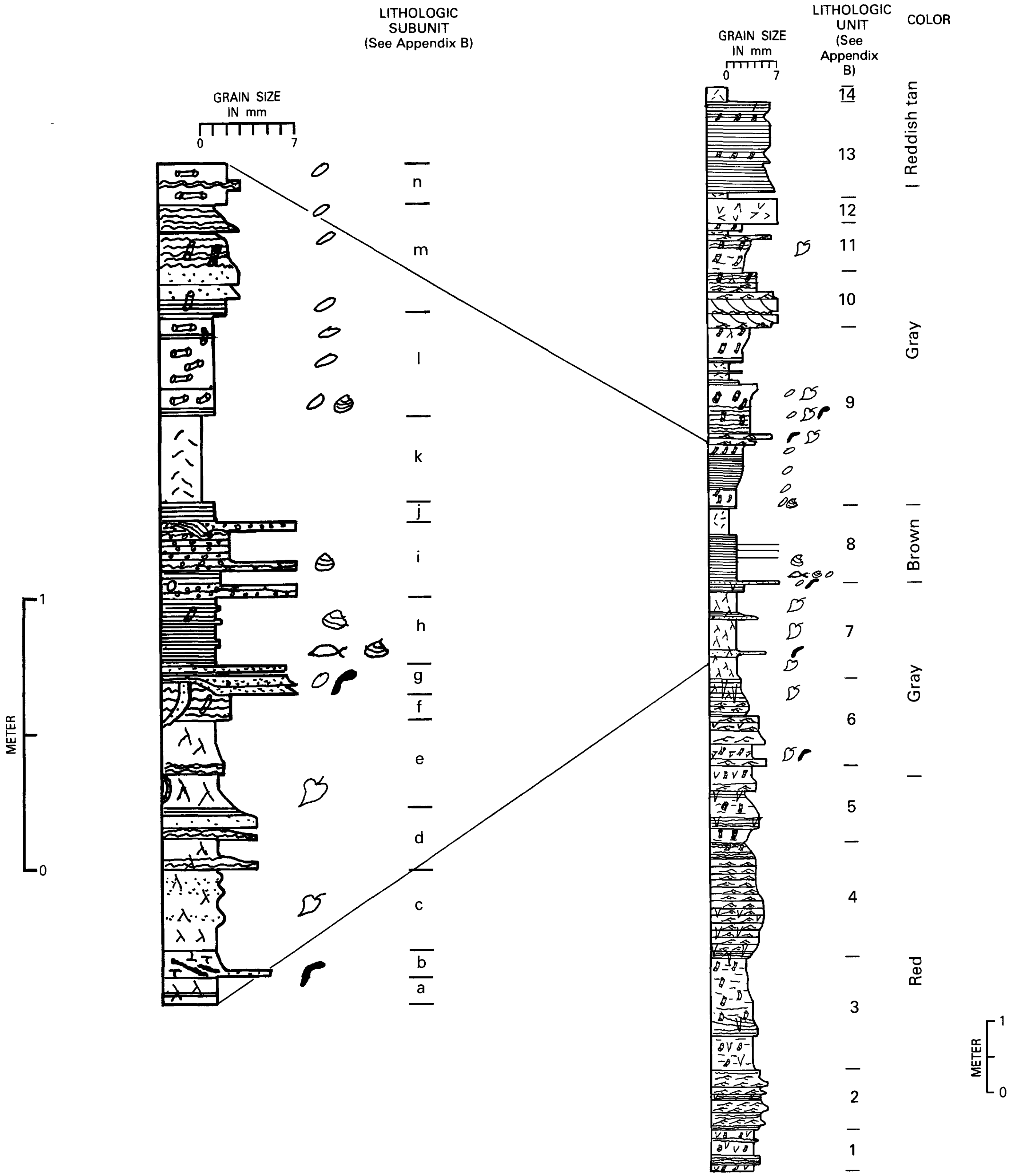

FIGURE B-1.—Core of the Midland Formation at Licking Run.

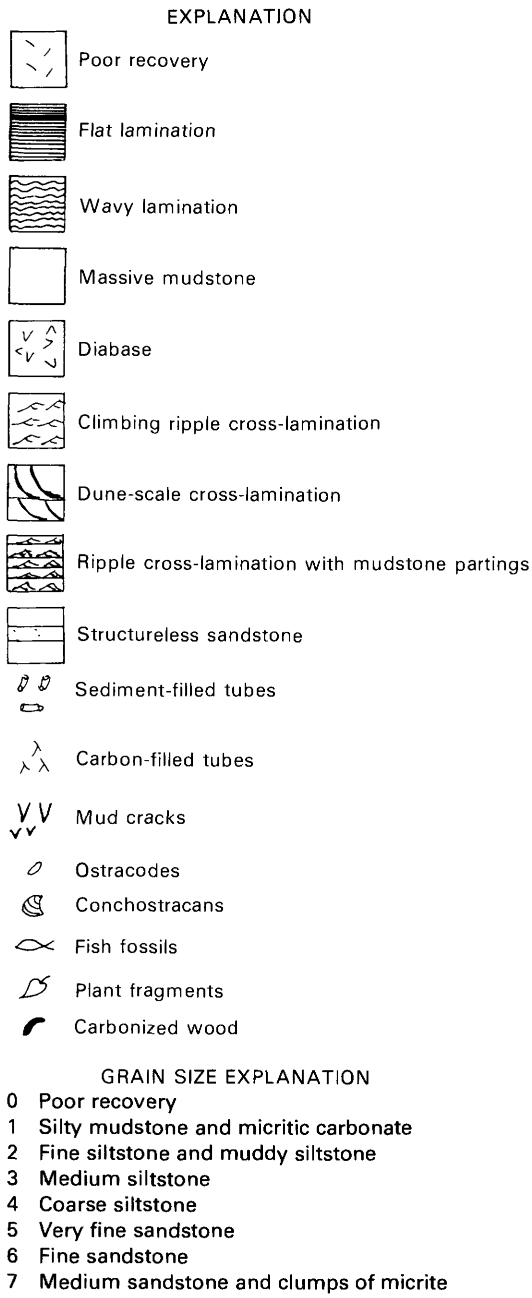

FIGURE B-1.—Continued.

LITHOLOGIC UNITS

1 *Muddy siltstone with interbeds of flat- to wavy-laminated coarse siltstone*: The coarse siltstone layers may have ripple cross-lamination and are commonly disrupted by tubes (burrows?). The muddy siltstones appear to be bioturbated (abundant tube cross sections), and narrow, jagged mud cracks are abundant. Scattered, anhedral to euhedral crystal molds are common and are usually filled to partially filled with calcite cement. These molds preferentially follow cracks and tubes in some cases. An irregularly shaped pod of coarse siltstone near the base may be a large track.

2 *Coarse siltstone to very fine sandstone forming graded beds 5-20 cm (2-8 in) thick*: Each graded bed consists of a basal, flat-laminated, mud intraclast-rich layer overlying a flat, erosional contact. It is capped by a deceleration-of-flow sequence of trough-shaped, ripple cross-laminae; wavy, draped ripple cross-laminae; and bioturbated flat laminae. Crystal molds similar to those in unit 1 are common near the tops of graded beds.

3 *Muddy siltstone with coarse siltstone interbeds*: The muddy siltstone appears to be bioturbated, including numerous mud- and silt-filled tubes, some with internal spreiten (Scoyenia?). The coarse siltstone layers have sharp basal contacts, many with load casts, and may be graded or have internal pinch-and-swell laminae. They are commonly disrupted by tubes. Mud cracks at the base and top of this unit are 10-15 cm (4-6 in) long and up to 3 cm (1.2 in) wide. Crystal molds similar to those in unit 1 are common, filling cracks and tubes. A graded bed 20 cm (8 in) thick, composed of coarse silt laminae with internal pinch-and-swell and ripple lamination alternating with muddy silt layers, appears to be dipping more steeply than the surrounding layers.

4 *Graded, very fine grained sandstone in thin beds with thin mudstone partings*: Sandstone beds in the lower 70 cm (28 in) are similar to those of unit 2, but the partings are a silty clay with mud cracks. Sandstones in the upper 70-80 cm (28-32 in) are generally thinner, 1-5 cm (0.4-2 in) thick, lack the trough-shaped ripples, and have soft sediment deformation, including oversteepened foresets, loadcasts, and foundered silt ripples. The clay layers are thinner and mud cracks are absent. Crystal molds similar to those in unit 1 are scattered and rare except for a large patch at the top of this unit.

5 *Muddy siltstone with some graded beds of coarse siltstone*: The muddy siltstone is heavily bioturbated except for a layer 5 cm (2 in) thick with flat lamination of muddy silt alternating with a grayish silty mud. Two zones of coarse siltstone are composed of several graded beds 2 to 5 cm (0.8-2 in) thick with wavy ripple cross-lamination at the base and bioturbated muddy silt at the top. The thin beds are commonly disrupted by tubes. Sinuous mud cracks begin at several levels in

this unit and are 10-15 cm (4-6 in) long and up to 2 cm (0.8 in) wide. The red-gray color change is sharp, but there is a spinout cone at the contact.

6 *Very fine grained sandstone to coarse siltstone beds alternating with bioturbated muddy siltstone*: The lowest sandstone bed, 10 cm (4 in) thick, has internal low-angle, climbing ripple cross-laminae. The upper contact was disrupted by drilling and is overlain by unoriented chips of bioturbated siltstone with wood fragments. The second sandstone bed is graded with a deceleration-of-flow sequence of trough-shaped, ripple cross-laminae grading to high-angle, climbing ripples capped by wavy laminated silt with bioturbation. The siltstone beds are graded and are progressively thinner upward. Wavy, ripple-scale cross-lamination occurs at the bases of the thicker siltstone beds,and pinch-and-swell laminae with low-angle, inclined lamination occur at the bases of the thinner siltstone beds. Small mud cracks occur in the muddy silt partings of the lower coarse siltstone beds, and mud cracks 20-30 cm (8-12 in) long occur in the upper portion of this unit. Carbon-filled, sub-mm tubes are also present in the upper portion of this unit. They appear to branch and taper and are interpreted as roots.

7 *Silty mudstone and fine muddy siltstone*: Most of this unit is massive, with abundant carbon-filled tubes interpreted as roots and possibly plant stems. Siltstone layers form vague to well-defined graded thin beds, and laminated zones with pinch-and-swell layering are present. Sulfide minerals are abundant, associated with the carbon-filled tubes. (See the subunits of the expanded section, fig. B-1, for more details.)

8 *Organic-matter-rich, calcareous shale*: The lower portion is finely laminated with alternations of brown organic material and micritic carbonate. The upper portion contains layers of sand- to granule-sized micritic clumps which are draped by the finer laminae. The basal contact is an ostracodal sandstone containing wood fragments. A zone of crumpled, flaky material 30 cm (12 in) thick is probably fault gouge. (See the subunits of the expanded section, fig. B-1, for details.)

9 *Silty mudstone and muddy siltstone*: The lower portion of this unit is mostly silty mudstone and is heavily bioturbated. Pinch-and-swell laminae of silt increase in number and thickness upward, and two graded sandstone beds with internal ripple cross-lamination complete a coarsening-upward sequence. Another coarsening-upward sequence is composed of graded thin beds with internal pinch-and-swell lamination. The base of each graded bed is massive and the top is bioturbated. Bioturbation increases toward the top of the sequence, mixing the coarse- and fine-grained sediments together. A third coarsening-upward sequence is present at the top of the unit, with a poorly recovered silty clay at the base and bioturbated muddy siltstone with carbon-filled tubes at the top.

10 *Medium-grained sandstone capped by coarse siltstone*: The basal sandstone forms two dune-scale crossbeds (15 and 20 cm (6 and 8 in) thick) with wavy-ripple cross-laminae at their bases. The crossbeds are capped by 8 cm (3.2 in) of slightly finer sandstone with low-angle, climbing-ripple cross-laminae. The climbing ripples are thinner upward and bioturbated at the top. The coarse siltstone is wavy laminated with some low-angle cross-laminae at the base and increased bioturbation toward the top. The basal contact with the sandstone is sharp. Carbon-filled tubes similar to roots occur throughout and increase in number toward the top.

11 *Muddy siltstone with a fine sandstone interbed*: The muddy siltstone is similar to the upper part of unit 9. A ripple cross-laminated, fine-grained sandstone 4 cm (1.6 in) thick overlies a coarse siltstone with wavy lamination. A discontinuity in the core separates the sandstone from a bioturbated muddy siltstone, which is indurated at its base and a hornfels in the upper 5 cm (2 in).

12 *Diabase*: The diabase is aphanitic and vesicular at the base and top. It is fine to medium crystalline in the center. The upper contact appears to be a spinout cone.

13 *Fine sandstone with flat, horizontal discontinuous lamination*: The lamination is formed by alternations of pinch-and-swell, quartzose laminae alternating with thinner, finer grained, more continuous, micaceous laminae. The layering thickens and thins with the relative dominance of the two lamina types. The lowest portion of the sandstone appears to be coarsest and is very indurated (metamorphosed). The micaceous layers show the most evidence of thermal alteration. Bioturbation occurs in two of the most thinly laminated zones.

14 *Loose chips of sandstone and basaltic fragments*: Some of the sandstone chips appear to be thermally altered.

LITHOLOGIC SUBUNITS

a *Massive silty mudstone with abundant sub-mm, carbon-filled tubes*: The laminated portion in the middle has very fine grained siltstone layers which pinch and swell slightly. The silty mudstone above the laminated portion contains carbonized wood fragments as much as 2 cm (0.8 in) long and mud-filled tubes. Sulfide minerals occur with the carbon-filled tubes and wood fragments.

b *Calcite-cemented, silty mudstone surrounding a piece of carbonized wood (concretion?)*: Both the wood and the mudstone have septarianlike cracks with calcite cement linings. The wood is lined by a layer of sulfide minerals which also form irregular blebs within it. Very fine grained sandstone occurs adjacent to the wood.

c *Silty mudstone with interbeds of muddy siltstone*: The muddy siltstone beds have indistinct contacts and contain mud-filled tubes. Carbon-filled tubes with abundant sulfide minerals are common in both mudstone and siltstone.

d *Silty mudstone with interbeds of coarse siltstone*: The two lower siltstone layers have graded, pinch-and-swell laminae separated by silty mudstone laminae. The layering is disrupted by carbon-filled tubes and larger silt-filled tubes. The upper siltstone layer is massive at the base with a sharp, irregular basal contact. It grades into a finer siltstone with pinch-and-swell laminae similar to the lower layers. Carbon-filled tubes with abundant sulfide minerals are common throughout.

e *Massive silty mudstone with carbon-filled tubes containing sulfide minerals*: The laminated portion has thin, fine-grained, siltstone laminae which pinch and swell slightly. The upper transition to massive silty mudstone is gradational. A crack filled with fine-grained silt is present below the laminated layer.

f *Laminated siltstone and silty mudstone*: Siltstone laminae pinch and swell or are lenticular with internal low-angle, inclined lamination. Silt-filled tubes disrupt lamination, and a crack filled with ostracodal sand extends down from the overlying layer. Carbon-filled tubes with sulfide minerals are present.

g *Ostracodal sandstone*: Three coarse-tail graded sandstone beds, composed of articulated and unarticulated ostracode shells, grade into brown, calcareous mudstone with scattered ostracode shells. The basal contacts of the two lower sandstone layers appear to cut into the underlying beds, while the third layer is flat bottomed. The two lower layers also appear to be soft-sediment deformed. A large piece of carbonized wood is present at the base of the first layer, and a small piece of carbonized wood is present in the second layer.

h *Laminated brown micritic carbonate and organic material*: Sub-mm lamination is defined by blebby carbonate laminae and thinner, more continuous organic laminae. The lamination appears to thicken toward the top of this unit and to become more irregular, and the carbonate laminae appear to be more sandy owing to larger blebs. Some micrite-filled tubes are present in this upper part. Fish fossils, fecal pellets, and conchostracans are present in some layers.

i *Laminated brown micritic carbonate and organic material with layers of coarse sand- to pebble-sized micrite clumps*: The lamination is similar to that of subunit h, but thick laminae of porous-looking micritic clumps are common. The largest clumps lie flat on underlying laminae and are draped by the overlying laminae. Synsedimentary faults are common, and a layer of lamination 3 cm (1.2 in) thick is tilted by a fault near the top of the subunit. Conchostracans are present in some layers.

j *Laminated brown micritic carbonate, organic material, and gray silty mudstone*: The gray mudstone laminae are thicker, flatter, and more continuous than the carbonate laminae. The mudstone laminae are more abundant toward the top.

k *Flakes of fine-grained, silty mudstone in a muddy matrix*: The mudstone flakes are similar to the mudstone in subunit j. The flakes are browner at the base and grayer toward the top. Slickensides are common on the larger flakes: a probable fault gouge.

l *Massive silty mudstone with abundant silt- and mud-filled tubes*: The laminated portion at the base is similar to subunit j. Numerous tubes oriented roughly parallel to bedding are present in the rest of the subunit. Several shaly, brown-colored layers 1-2 cm (0.4-0.8 in) thick have less obvious bioturbation except for tubes oriented perpendicular to layering. Ostracodes are abundant in some layers and are uncommon in the brown layers.

m *Laminated siltstone and silty mudstone*: Siltstone laminae have sharp basal contacts, and the thicker ones have load structures. The laminae near the base are thin and flat, grading into thicker laminae that pinch and swell. Fining-upward sequences with coarse siltstone laminae at their base are present in the upper portion of the subunit. Ostracodes are abundant in the finest grained layers of these sequences. Silt-filled tubes are common.

n *Massive muddy siltstone with abundant silt- and mud-filled tubes*: Tubes are mostly oriented roughly parallel to layering. The layered portion has pinch-and-swell laminae of coarse-grained siltstone with mud partings containing abundant ostracodes.

INTERPRETATION OF THE ENVIRONMENT OF DEPOSITION

The sequence of sediments in the core is interpreted as a transgression of a lake over a swampy fluvial deposit and its regression, followed by outbuilding of a thin deltaic channel system. The basal mudstones and sandstones (units 1-4) reflect mostly subaerial conditions with sporadic flooding events. The sandstones may be overbank deposits of a larger fluvial system or the distal portions of low-gradient streams. Channel scours about 30 cm (12 in) deep and 5 m (16.5 ft) wide were observed in laterally equivalent strata temporarily exposed during construction of a dam spillway. The channel scours were filled with fine-grained sandstone with ripple cross-lamination. The next layers of sandstones and mudstones in the core (units 4-6) were deposited during much wetter conditions and were probably only intermittently subaerially exposed. The gradational character of these sandstones to the underlying ones suggest the two are laterally equivalent. They may be part of a small deltalike deposit in a shallow lake or splays built into small ponds between fluvial channels. The fine-grained silty mudstones with abundant carbon-filled tubes, interpreted as roots (unit 7), represent either a vegetated, shallow lake margin or a pond in a swampy fluvial system. No fossils of lacustrine animals were observed in this unit. The laminated brownish shales (unit 8) are definitely lacustrine and were probably deposited in fairly deep water (at least several tens of meters). The upper portion of these shales have layers containing clumps of carbonate micrite which may be intraclasts or tufa fragments brought in by storms. The increase of bioturbation above the shales (unit 8) is interpreted as representing shallower lake conditions. This transition occurs in less than a meter of vertical section, suggesting that the lake was drying out rather than being filled in. The upward coarsening (units 9-10), however, is similar to a deltaic progradation, and the crossbedded, medium-grained sandstone layers reflect fluvial deposition without any evidence of subaerial exposure. The sequence is interpreted as a prograding distributary channel built as the lake level fell. The origin of the uppermost sandstone (unit 13) is unclear. The horizontal, discontinuous lamination suggests upper plane bed flow conditions, and the abundant mica is more consistent with fluvial rather than wave conditions. This sandstone seems to be equivalent to sandstone exposed on the dam spillway. These sandstones have dune-scale and ripple-scale cross-lamination and much soft-sediment deformation and are probably also distributary channel deposits.