VIRGINIA DIVISION OF MINERAL RESOURCES
PUBLICATION 126

REINTERPRETATION OF ROCKLANDIAN (UPPER ORDOVICIAN) K-BENTONITE STRATIGRAPHY IN SOUTHWEST VIRGINIA, SOUTHEAST WEST VIRGINIA, AND NORTHEAST TENNESSEE

With A Discussion of the Conglomeratic Sandstones in the Bays and Moccasin Formations

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FRONT COVER: The Walker Mountain Sandstone with its distinctive basal conglomeratic sandstone (lower left) and the structurally disrupted Deicke K-bentonite (at man's hand) in the upper Moccasin formation near Goodwins Ferry, Giles County, Virginia. Throughout its area of occurrence in Virginia, West Virginia, and Tennessee the Walker Mountain Sandstone is closely associated with the Deike and Millbrig K-bentonites. In the New River Valley and the western anticlines of Virginia and West Virginia the Deicke occurs just above the white conglomeratic sandstone, as shown here, or the equivalent finer-grained beds, and the Millbrig is several meters farther upsection. Elsewhere the Deicke is absent and the Millbrig is the first K-bentonite above the Walker Mountain Sandstone.

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John T. Haynes
University of Cincinnati[1]

ABSTRACT

The Rocklandian stratigraphic sequence in the Valley and Ridge province of southwest Virginia, southeast West Virginia, and northeast Tennessee is reinterpreted on the basis of field and laboratory work. The older two of the three thick K-bentonite beds that previous authors have reported from exposures throughout much of this area are identified as the Deicke and Millbrig K-bentonite Beds of the Upper Mississippi Valley, the two most widespread and thick (persistently greater than 30 centimeters) Ordovician K-bentonites in the southeastern U.S. Identification is based on differences in phenocryst mineralogy. Primary plagioclases in the Deicke are labradorites, whereas they are andesines in the Millbrig. Other common phenocrysts in the Deicke are Fe-Ti minerals such as ilmenite and magnetite; in the Millbrig other common phenocrysts are biotite and quartz. Various authigenic feldspars occur in both beds. The Deicke, the oldest of the three thick beds, is equivalent to K-bentonite V-3 in the central Valley and Ridge province, K-bentonite R-7 in the Powell Valley, and K-bentonite T-3 of the Cincinnati Arch, also known as the Pencil Cave bentonite. The Millbrig, the middle bed, is equivalent to K-bentonite V-4 in the central Valley and Ridge, K-bentonite R-10 in the Powell Valley, and K-bentonite T-4 of the Cincinnati Arch, also known as the Mud Cave bentonite. The youngest of the three thick K-bentonites has not been correlated with a K-bentonite in the Upper Mississippi Valley sequence; it is known most widely as bed V-7. In the shales, siltstones, and sandstones of the Bays Formation in the eastern belt only the younger two K-bentonites, the Millbrig and V-7, are present, with both beds being reported for the first time in the Bays. Bed V-3, the Deicke, was reported from exposures of the Bays near Roanoke in two earlier studies, but because deposition of the Deicke ashfall in this area occurred close in time to the deposition of a thin but widespread sequence of conglomeratic sandstones, the Walker Mountain Sandstone Member, the ash evidently was completely reworked and thus the Deicke does not persist as a discrete K-bentonite bed eastward into the Bays Formation.

Using the K-bentonites as time lines it is evident that the bases of the Eggleston Formation, the Bays Formation, and the Trenton ("Martinsburg")Formation become younger to the northeast. The Walker Mountain Sandstone also becomes younger to the northeast. In addition, it is now evident that the Walker Mountain Sandstone, which occurs throughout much of the eastern part of the basin, rests unconformably on the underlying sediments and is the basal unit of a regional transgressive sequence. The transgression is recorded vertically by the upper Moccasin Formation/Eggleston Formation/Trenton ("Martinsburg") Formation sequence in the central Valley and Ridge province and by the Bays Formation/Trenton ("Martinsburg") Formation sequence in the eastern Valley and Ridge.

"Deicke" and "Millbrig" are names that satisfy the requirements of the North American Stratigraphic Code, whereas alpha-numeric names such as "V-3" are not. Therefore, use of the name "Deicke" for the K-bentonite known as V-3, R-7, or T-3, and the name "Millbrig" for the K-bentonite known as V-4, R-10, or T-4, is herein recommended for formal usage in southwest Virginia, southeast West Virginia, and northeast Tennessee. Although V-7, the upper thick K-bentonite, occurs throughout this area, correlation with a K-bentonite bed farther west or south cannot be conclusively shown at this time so no recommendation for a change in nomenclatural usage can be made.

INTRODUCTION

Several potassium bentonite beds (clay-rich altered volcanic ash beds in which the clay, mixed-layer illite/smectite, has an illite:smectite ratio greater than about 1:1 or 1.5:1) occur in Rocklandian (Upper Ordovician) strata in eastern North America. These beds, known more commonly as K-bentonite beds, have been studied in many locations by various geologists over the past 70 years since they were first noted and described in the eastern United States by Nelson (1921, 1922, 1926), and the purpose of this paper is to synthesize past and present research on two of the three thickest and most stratigraphically useful Rocklandian K-bentonites in the Valley and Ridge province of southwest Virginia, southeast West Virginia, and northeast Tennessee.

Although many of the present findings are based on analyses using the petrographic microscope, the X-ray diffractometer, and the electron microprobe, the successful correlation of K-bentonite beds in this region requires more than just geochemical data. The biostratigraphy and lithostratigraphy has to be *very* well understood or else there is no foundation for the geochemical data. For example, before instrumental neutron activation analysis (INAA) was successfully used to identify chemical fingerprints for the several Rocklandian K-bentonites of the Upper Mississippi Valley (Kolata and others, 1986), a very detailed biostrati-

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graphic and lithostratigraphic framework based on many detailed studies was already in place (see Willman and Kolata, 1978, Sloan and others, 1987, and Sloan and Kolata, 1987, for a summary). In southwest Virginia and nearby areas of adjacent states, various authors have discussed the Rocklandian stratigraphy in great detail (Rosenkrans, 1936; Huffman, 1945; Woodward, 1951; Rodgers, 1953; Miller and Brosgé, 1954; Hergenroder, 1966; and Kreisa, 1980) and it is now broadly understood, but a bed-by-bed lithologic and paleontologic analysis of the sort that has been done in Rocklandian strata of the Upper Mississippi Valley has not yet been done in Virginia and nearby states. Because the lithostratigraphic framework is now very well understood based on the results of the present study, it is hoped that the impetus for additional detailed research of Rocklandian strata in the region has been provided.

Ordovician strata crop out extensively in southwest Virginia and adjacent areas of West Virginia and Tennessee. In the first volume of "Contributions to Virginia Geology" (1936), the Virginia Geological Survey published a paper by R. R. Rosenkrans that described the results of a detailed investigation of Ordovician K-bentonites (he referred to them simply as bentonites) in southwest Virginia and northeast Tennessee. In the intervening years more papers have been published in which additional information about the K-bentonites was reported. These include the papers by Bates (1939), Fox and Grant (1944), Huffman (1945), Woodward (1951), Rodgers (1953), Miller and Fuller (1954), Miller and Brosgé (1954), Webb (1965), Hergenroder (1966), and Kreisa (1980), but the study by Rosenkrans has remained the standard for the region.

As part of a regional study of the Deicke and Millbrig K-bentonites in the eastern midcontinent, many exposures of Rocklandian strata in the Central and Southern Appalachians that contain K-bentonites, including most described in previous studies, were examined, and samples of the K-bentonites were collected for laboratory analyses (Haynes, 1989). The present paper discusses the findings from this comprehensive study of these K-bentonite beds in the Valley and Ridge province of southwest Virginia and adjacent areas of West Virginia and Tennessee. Figure 1 shows the location of the sections that were studied in Virginia, West Virginia, and Tennessee . Sections along the Cincinnati Arch in Kentucky that were studied are also shown, because correlation of K-bentonites between that region and the Powell Valley in the western Valley and Ridge province is discussed.

The potential of the Rocklandian K-bentonite beds as stratigraphic markers on which to base correlations has long been recognized. Although several previous studies showed that precise correlations were possible locally, difficulties in correlating most beds over longer distances (150 km and greater) prevented a regional synthesis of the K-bentonite sequence. This is because of the structural and stratigraphic complexities in the Valley and Ridge province that make correlations difficult along strike and correlations across strike even more difficult. As a result, most previous detailed studies were of the K-bentonites in the central and western outcrop belts, on the thrust sheets between the Saltville fault and the Appalachian Plateaus. In several of these studies the authors presented evidence to support

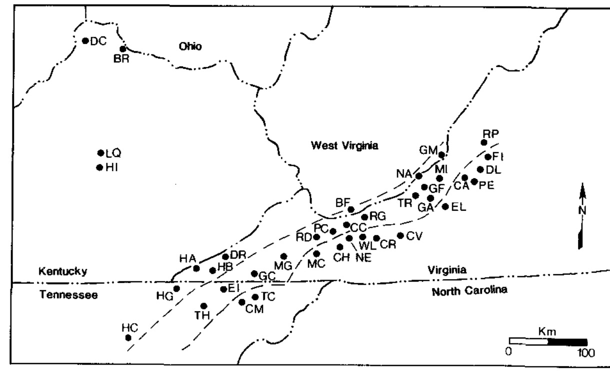

Figure 1. Location of outcrops that were studied in Virginia, West Virginia, Kentucky, and Tennessee. The dashed lines represent the approximate boundaries between the western, central, and eastern belts shown in Figure 2.
DC, Dravo Corp. (core); BR, Black River Mine; LQ, Lexington Limestone Quarry; HI, High Bridge; HC, Hinds Creek Quarry; HG, Harrogate; HA, Hagan; HB, Hurricane Bridge; DR, Dryden; TH, Thorn Hill; EI, Eidson; GC, Gate City; MG, Little Moccasin Gap; RD, Rosedale; PC, Plum Creek; CC, Cove Creek; BF, Bluefield; RG, Rocky Gap; TR, Trigg; GA, Gap Mountain; GF, Goodwins Ferry; NA, The Narrows; ML, Mountain Lake Turnoff; GM, Gap Mills; RP, Rich Patch Valley; CM, Charles Mountain; TC, Terrill Creek; MC, McCall Gap; CH, Chatham Hill; NE, Nebo; WL, Big Walker Lookout; CR, Crockett Cove; CV, Connor Valley; EL, Ellett/Den Creek; PE, Peters Creek; CA, Catawba; DL, Daleville (includes nearby Cloverdale section of Hergenroder (1966)); FI, Fincastle.

suggested correlations along strike in the central and western Valley and Ridge province. By contrast, comparatively little research has been done on the K-bentonites in the eastern belt, on the Pulaski, Cove Mountain, and Saltville thrust sheets.

Figure 2 shows the Valley and Ridge province in the study area divided into an eastern, central, and western outcrop belt. Those belts are made up of one or more thrust sheets, and the major thrust faults are shown. The stippled lines are the boundaries between the central and western belts, and between the central and eastern belts. The western boundary of the western belt is not a fault, but the eastern edge of the Appalachian Plateaus, indicated on Figure 2 by the dashed line. The eastern boundary of the eastern belt is the Blue Ridge thrust fault.

The three belts shown in Figure 2 are separated on the basis of major facies changes across the boundary faults. These differences probably were the major factor in the lack of suggested correlations across strike, but the studies by Rosenkrans (1936) and Hergenroder (1966, 1973) were exceptions. Not only did both geologists propose regional correlations of K-bentonites along strike from southwest Virginia to Georgia and Alabama, they also proposed regional correlations of the K-bentonites that occur in the siltstones and shales of the Bays Formation in the eastern belt with those that are present in the limestones to the northwest, across strike, in the central and western belts. Rosenkrans's conclusions concerning K-bentonite correlations in southwestern Virginia and surrounding areas have been widely accepted by almost all subsequent workers including Hergenroder.

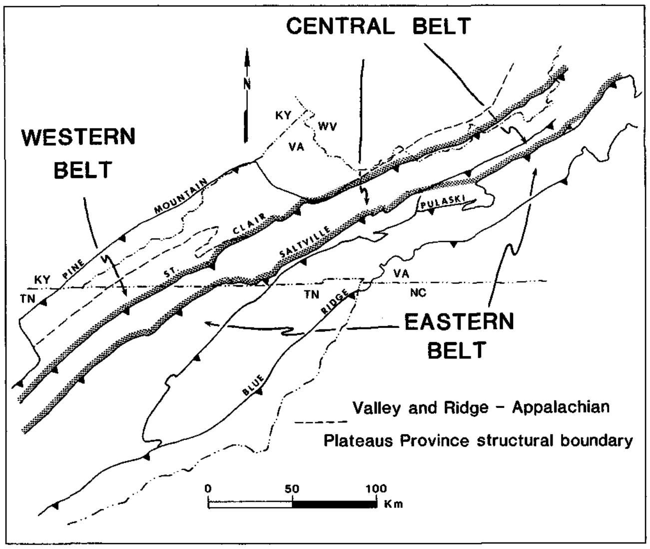

Figure 2. Western, central, and eastern belts in the Valley and Ridge province of southwest Virginia, southeast West Virginia, and northeast Tennessee. The base structure map is primarily from Kulander and Dean (1986). The boundary locations of the three belts are based on Kreisa (1980) and Rader (1982).

MINERALOGY OF THE DEICKE AND MILLBRIG K-BENTONITE BEDS

The Deicke and Millbrig K-bentonite Beds are the two thickest and most widespread Rocklandian K-bentonites in eastern North America (Huff and others, 1986; Huff and Kolata, 1990). Study of their coarse-grained zones from exposures along the Cincinnati Arch has shown that they can be distinguished by their different phenocryst compositions (Haynes and others, 1987), and Haynes (1989) has shown that the Deicke and Millbrig can be recognized on this basis throughout the southern Valley and Ridge province from Roanoke, Virginia, to Birmingham, Alabama. Table 1 summarizes the mineralogic differences between the phenocrysts in the coarse zones of the two beds. These differences obviously reflect variations between the composition of the original ash that is now the Deicke and Millbrig K-bentonites. Figure 3 shows several examples of the various minerals that are found in the K-bentonites, as well as the unusual occurrence of pseudomorphed glass shards in the Millbrig at the Catawba section that is discussed in more detail below. The coarse zones were studied in the most detail because it is those zones of the K-bentonites that reveal the most information petrographically given the abundance of coarse-grained non-clay minerals in them, including both primary phenocrysts and various authigenic phenoclasts. The finer-grained zones, which are the upper parts of both beds, are clay rich, and although the distinct non-clay mineralogies appear to persist upward, those zones are more difficult to study because of the finer grain size. Sampling locations and sample numbers are given in Appendix 1, and a description of the analytical methods that were used to study the K-bentonite samples is given in Appendix 2.

The surest way to distinguish the Deicke and the Millbrig K-bentonites is by comparing the composition of the primary plagioclases. Table 2 presents chemical analyses of two primary plagioclases in Deicke and Millbrig samples from a quarry in the Powell Valley. These compositions were determined with an electron microprobe. Throughout the Cincinnati Arch and the southern Valley and Ridge province, the primary plagioclases, although rarely present in abundance in any sample of the two beds (Table 1), are consistently andesines in the Millbrig and labradorites in the Deicke (Haynes, 1989). Figure 3A shows a zoned euhedral labradorite phenocryst in the Deicke and Table 3 presents the feldspar mineralogy as determined using both the electron microprobe and the petrographic microscope for several samples from the study area. Many samples from the central and eastern belt are quite weathered and therefore unsuitable for the polishing required for microprobe analysis. Nevertheless, adequate thin sections could usually be made, thus allowing for an accurate interpretation of the sample's mineralogy. The feldspars in V-7 have not been studied in sufficient detail to determine whether or not the bed can be distinguished from the Deicke or the Millbrig by its primary plagioclase mineralogy, but in the central belt V-7 can be readily identified by its stratigraphic position. It is five to eight meters above the Millbrig, one to three meters below the base of the "cuneiform" beds of the Eggleston Formation, where present (Rosenkrans, 1936), and two to nine meters below the base of the Trenton("Martinsburg") Formation. Using this information from the central belt V-7 can be identified at three sections in the eastern belt, principally by its occurrence as the first persistently thick K-bentonite above the biotite-rich Millbrig. At sections in the eastern belt where the Millbrig is covered, V-7 is not as readily identified because the K-bentonites in the Bays Formation above the Millbrig tend to be very similar in texture. Although these younger K-bentonites have not been studied in detail since the work by Rosenkrans (1936), they are almost certainly correlative with some or all of the K-bentonite beds in the central belt sections that he named beds V-8 through V-14.

The other distinguishing compositional feature of the two beds is the variation in the abundance of biotite, quartz, and Fe-Ti oxides, the other pricipal non-clay minerals present (Table 1). Biotite and quartz are very rare in the Deicke (Figure 3B), and at most outcrops that bed looks less like a bed of altered volcanic ash than like a crumbly, weathered arkosic sandstone, or, throughout most of the central belt, a weathered red shale. The Millbrig, by comparison, always contains abundant euhedral to subhedral biotite up to 1.5 millimeters across (Figure 3C); this biotite can be readily seen and identified in the field, usually without magnification. Even in very weathered samples where the biotite is a gold or bronze color rather than dark brown or black, it can be readily identified. This is true even in exposures of the Bays Formation along Big Walker Mountain where the biotite grains have been partly chloritized or kaolinized (Figure 3D).

Because analytical equipment cannot be brought to the field, quick identification has to be made based on the

Table 1. Framework grains in the Deicke and Millbrig K-bentonites.

Millbrig	Deicke
Primary Phenocrysts	
Andesine (1 - 15 %)	Labradorite (1 - 15 %)
Quartz (20 - 45 %)	Ilmenite (< 1 - 5 %)
Biotite (15 - 50 %)	Magnetite (< 1 %)
Apatite (< 1 %)	Quartz (< 1 %)
Zircon (< 1 %)	Biotite (< 1 %)
--	Apatite (< 1 %)
--	Zircon (< 1 %)
Authigenic Minerals	
K-feldspar - Or_{90-100} (5 - 60 %)	K-feldspar - Or_{90-100} (5 - 80 %)
Albite - Ab_{90-100} (0 - 20 %)	Albite - Ab_{90-100} (0 - 20 %)
Pyrite (< 1 %)	Leucoxene (0 - 10 %)
Hematite (< 1 %)	Anatase (0 - 10 %)
Chlorite (< 1 %)	Rutile (0 - 10 %)
Calcite (< 1 %)	Hematite (< 1 - 5 %)
--	Pyrite (< 1 - 5 %)
--	Calcite (< 1 - 5 %)
--	Gypsum (< 1 %)

Note: Albite is present in samples from the Valley and Ridge only. Abundances are expressed as a percentage of the total volume of non-clay minerals in the K-bentonites as determined from study of 81 thin sections.

Table 2. Chemical analyses of two primary plagioclase feldspars in the Deicke and Millbrig from the Hinds Creek quarry section.

	Major oxides (weight %) Millbrig	Deicke
Sample no.	TN 11-1	TN 10
SiO_2	57.41	54.85
Al_2O_3	26.43	28.78
CaO	9.32	12.13
Na_2O	5.98	3.97
K_2O	0.38	0.30
Total	99.52	100.03
Ab	52.5	36.6
Or	2.3	1.9
An	45.2	61.5
Grain type	Andesine	Labradorite

Note: Sample locality is given in Appendix I.

presence of very abundant biotite grains in the Millbrig, and this is the single most useful mineralogic difference with respect to identification of the two beds *in the field*. It is a difference noted decades ago in several early studies of the K-bentonites in the southeastern United States, including Bay and Munyan (1935), Rosenkrans (1936), and Bates (1939). When laboratory analysis can be performed on suitable samples, it of course should be undertaken to confirm the field observations.

The presence or absence of quartz and Fe-Ti oxides is more difficult to discern in the field. The quartz and feldspar phenocrysts are of similar size, and the quartz can have a milky color similar to the feldspars. The Fe-Ti oxide minerals of the Deicke are very small and difficult to see in the field with a hand lens, and are therefore best studied in thin section. Where the Deicke occurs in or just above the redbeds of the Moccasin Formation, it has a distinct red and yellow color and is very recognizable on this basis alone.

Iron oxide pseudomorphs of glass shards occur in a K-bentonite bed at the Catawba section (Figure 3E), and shard pseudomorphs also occur in the Millbrig at the Big Walker Lookout section (Haynes, 1989). The bed in which these unusual grains occur at Catawba is bed number eight of Hergenroder's Catawba section; the Millbrig is bed number four of that section (Hergenroder, 1966, p. 156). Attempts to isolate these pseudomorphs for analysis were unsuccessful because the grains disintegrate when wetted and they are

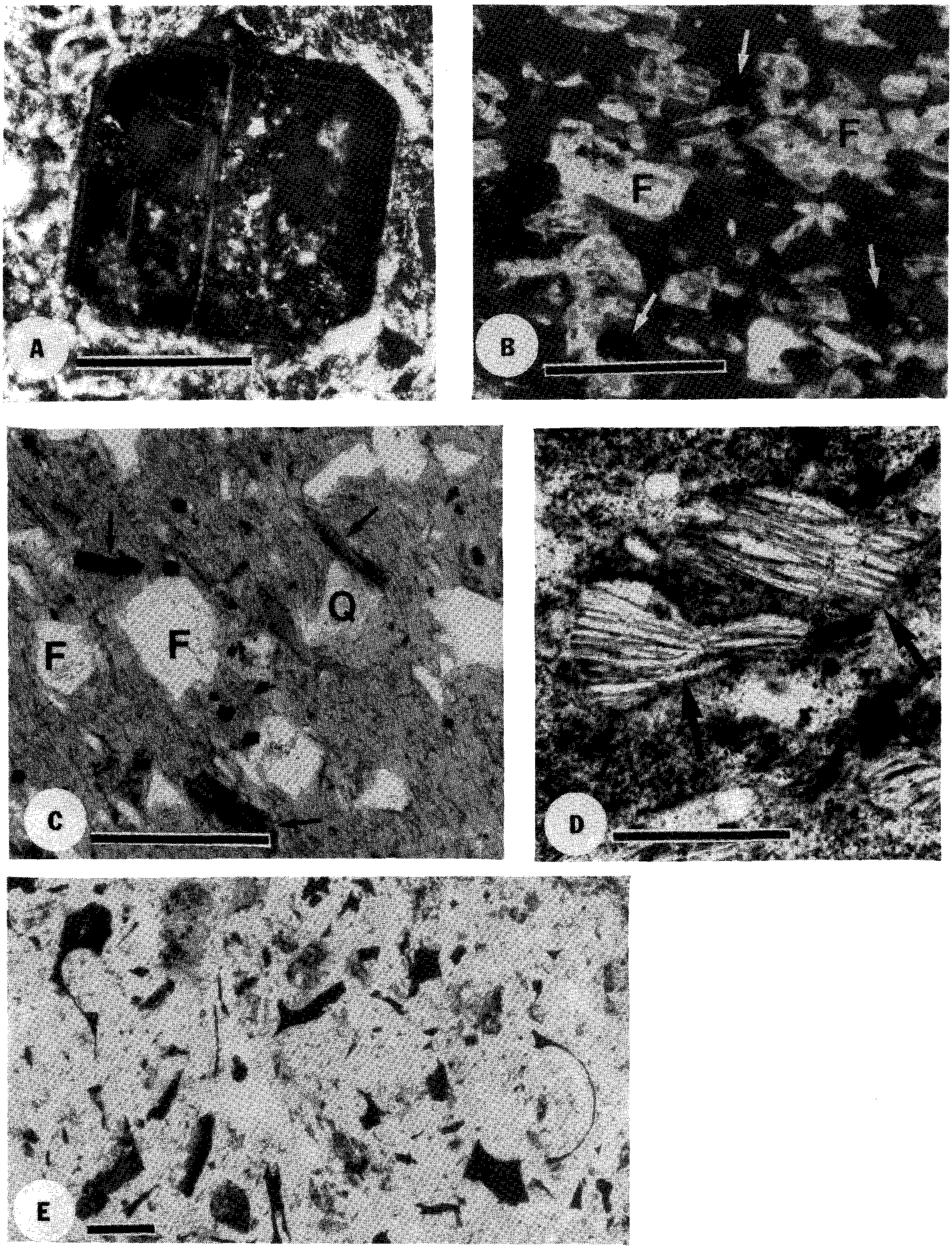

Figure 3. Photomicrographs of phenocrysts in the K-bentonites of the study area. Matrix is mixed-layer illite/smectite in all samples. Scale bar is 1.0 mm in length except in E, where it is 0.1 mm in length. **A.** Zoned euhedral labradorite. Sample from the coarse-grained zone in the Deicke at the Hinds Creek Quarry section, Tennessee. Cross-polarized light. **B.** Euhedral to subhedral feldspars (F), primarily K-feldspars, and Fe-Ti oxides (arrows). Note the lack of biotite and quartz. Sample from the coarse-grained zone in the Deicke at the Hagan section, Virginia. Plane-polarized light. **C.** Biotite (arrows), quartz (Q), and feldspars (F). Small opaque grains are pyrite. Sample from the coarse-grained zone of the Millbrig at the Gate City section, Virginia. Plane-polarized light. **D.** Chloritized biotites (arrows) showing a distinct expanded, almost vermicular texture, which indicates that some kaolinite is probably present. Sample from the coarse-grained zone of the Millbrig at the Chatham Hill section, Virginia. Plane-polarized light. **E.** Subopaque pseudomorphs of glass shards composed of or coated with iron oxide. Sample from the red K-bentonite at the Catawba section, Virginia, which is interpreted as the upper part of the Millbrig. Plane-polarized light.

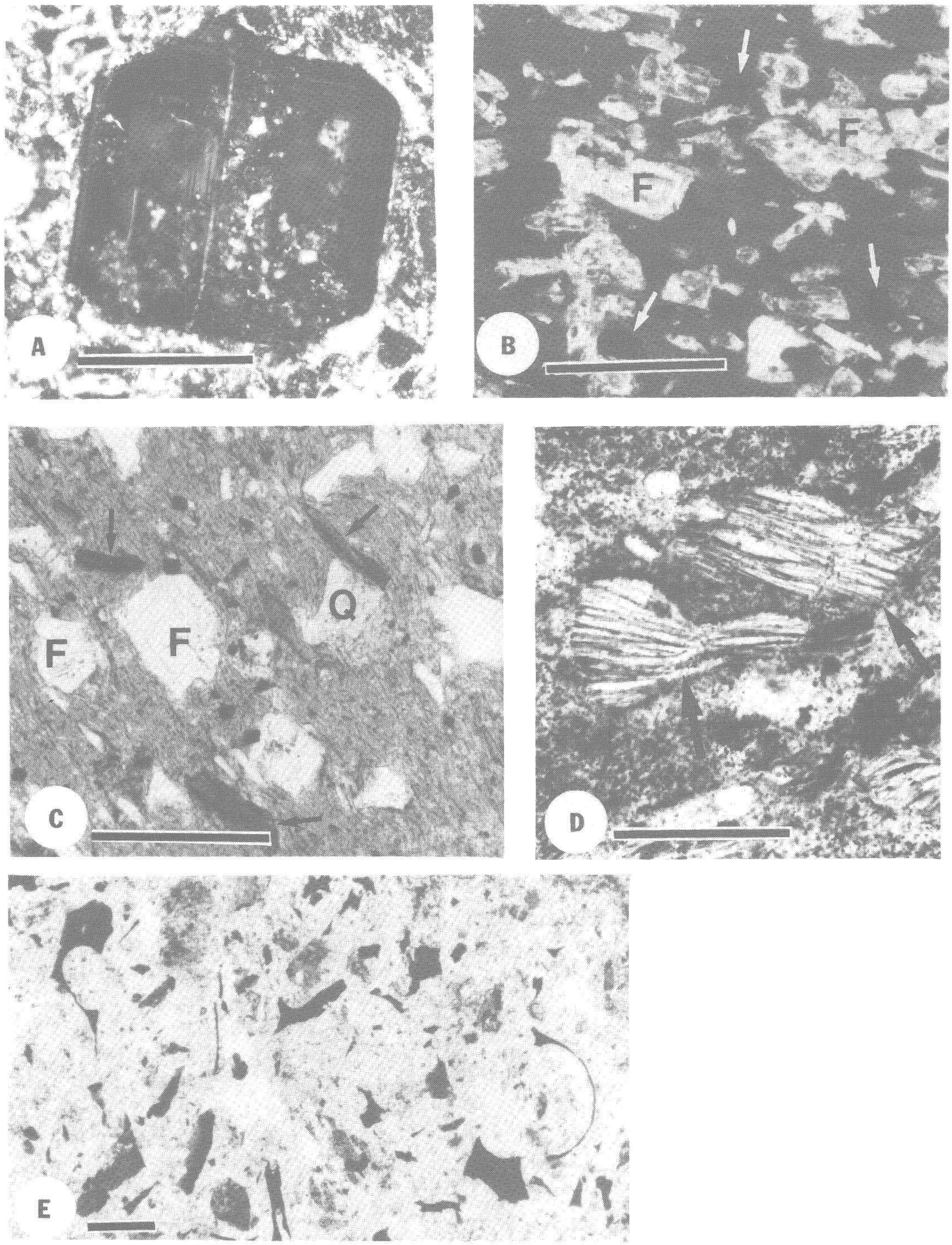

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Table 3. Feldspar mineralogy of selected Deicke and Millbrig samples.

Sample number	Formation	Authigenic feldspars	Intermediate plagioclases
Deicke: Cincinnati Arch section			
BRM T-3	Tyrone	K-feldspar	Labradorite
Deicke: Valley and Ridge sections			
TN 10	Chickamauga (Eggleston)	K-feldspar and albite	Labradorite
TN:CL 1-1	Eggleston	K-feldspar	Indeterminable
TN:HK 3-1	Moccasin	K-feldspar	Indeterminable
VA 2-1	Eggleston	K-feldspar and albite	Labradorite
VA:SC 1-1	Moccasin	K-feldspar and albite	Labradorite
VA:TZ 1-7	Moccasin	K-feldspar	Indeterminable
Millbrig: Cincinnati Arch sections			
BRM T-4	Tyrone	K-feldspar	Andesine
KRI 5-0	Tyrone/Lexington contact	K-feldspar	Andesine
Millbrig: Valley and Ridge sections			
TN 11-1	Chickamauga (Eggleston)	K-feldspar and albite	Andesine
VA 4-1	Eggleston	K-feldspar and albite	Andesine
VA:SC 1-2	Eggleston	K-feldspar and albite	Andesine
VA:GI 1-1	Eggleston	Indeterminable	Indeterminable
TN:HK 2-1	Bays	Indeterminable	Indeterminable
VA:SM 1-4	Bays	Indeterminable	Indeterminable
VA:WY 2-1	Bays	K-feldspar	Indeterminable
VA:WY 1-1	Bays	Indeterminable	Indeterminable
VA:RO 1-3	Bays	Indeterminable	Indeterminable
VA:BT 2-1	Bays	K-feldspar	Indeterminable

Note: Sample localities are given in Appendix I

much too small to pick by hand from a crushed sample. Because the Millbrig is thin but still recognizable at the Catawba section, and because the bentonitic sandstones between the Millbrig and this bed with the shard pseudomorphs contain much biotite, the upper K-bentonite bed is interpreted to be an ashfall that elsewhere is represented by the finer-grained upper zone of the Millbrig. If this interpretation is correct, it indicates that sedimentation rates were relatively high in this area, and the Millbrig was split into at least two distinct beds, with the intervening sandstones containing an abundance of reworked volcanic ash. The Bays in the Salem synclinorium was deposited more rapidly than the Bays elsewhere (Hergenroder, 1966), so this explanation seems plausible. In addition, three distinct fining upward zones are clearly evident at an exposure of the Millbrig in the Central Basin of Tennessee (Haynes, 1989). This is further evidence that although the Millbrig is usually a single thick bed, it does consist of more than one ashfall.

X-ray diffraction tracings of the ethylene glycol-solvated less than 2.0 micron clay mineral fraction were

Table 4. Peak positions, percent illite, and ordering of the I/S based on analyses of selected ethylene glycol-solvated Deicke, Millbrig, and V-7 samples.

Sample number	Peak positions (°2θCuKα)						Average % illite	Ordering
Deicke: Valley and Ridge sections (Moccasin or Eggleston Formation)								
TN:CL 1-1	--	8.769	17.386	26.689	45.285	--	92	R3
VA:SC 1-1	--	8.666	17.480	26.514	44.998	--	92	R3
VA:RL 2-1	6.990	9.036	17.009	26.573	44.896	--	83	R1/R3
VA:TZ 1-7	--	8.744	17.261	26.549	45.059	--	90	R3
VA:BL 1-1	--	8.768	17.426	26.634	45.202	--	92	R3
VA:GI 4-0	--	8.815	17.404	26.654	45.245	--	93	R3
Millbrig: Cincinnati Arch section (Tyrone Limestone)								
KRI 5-0	6.784	9.183	16.897	26.606	44.330	46.595	76	R1
Millbrig: Valley and Ridge sections (Eggleston Formation)								
TN:CL 1-2	7.224	8.817	17.201	26.614	45.223	--	88	R1/R3
VA 4-1	7.027	9.050	17.138	26.597	44.966	--	86	R1/R3
VA:LE 1-2	--	8.543	17.284	26.673	44.663	--	87	R3
VA:SC 1-2	--	8.785	17.287	26.662	45.115	--	90	R3
VA:GI 1-1	--	8.741	17.450	26.551	45.198	--	94	R3
Millbrig: Valley and Ridge sections (Bays Formation)								
VA:SM 1-4	7.536	9.022	17.212	26.610	44.897	--	88	R3
VA:WY 2-1	7.646	8.920	17.224	26.646	45.054	--	88	R3
VA:WY 1-1	--	8.740	17.588	26.607	45.267	--	97	R3
VA:RO 1-3	7.600	9.032	17.118	26.662	44.810	--	84	R1/R3
VA:BT 2-1	7.710	8.715	17.131	26.663	45.289	--	89	R3
V-7: Valley and Ridge section (Eggleston Formation)								
VA:TZ 2-3	--	8.702	17.160	26.531	44.717	--	86	R3
V-7: Valley and Ridge sections (Bays Formation)								
VA:RO 1-2	7.671	8.960	17.176	26.615	44.883	--	86	R3
VA:BT 2-2	7.600	8.849	17.536	26.662	45.420	--	94	R3

Note: The average percent illite and the ordering were calculated using the techniques of Środoń (1980, 1984), which are summarized by Środoń and Eberl (1984). These methods use the peak positions obtained from X-ray diffraction tracings of the clay mineral fraction of the samples.

Sample localities are given in Appendix I.

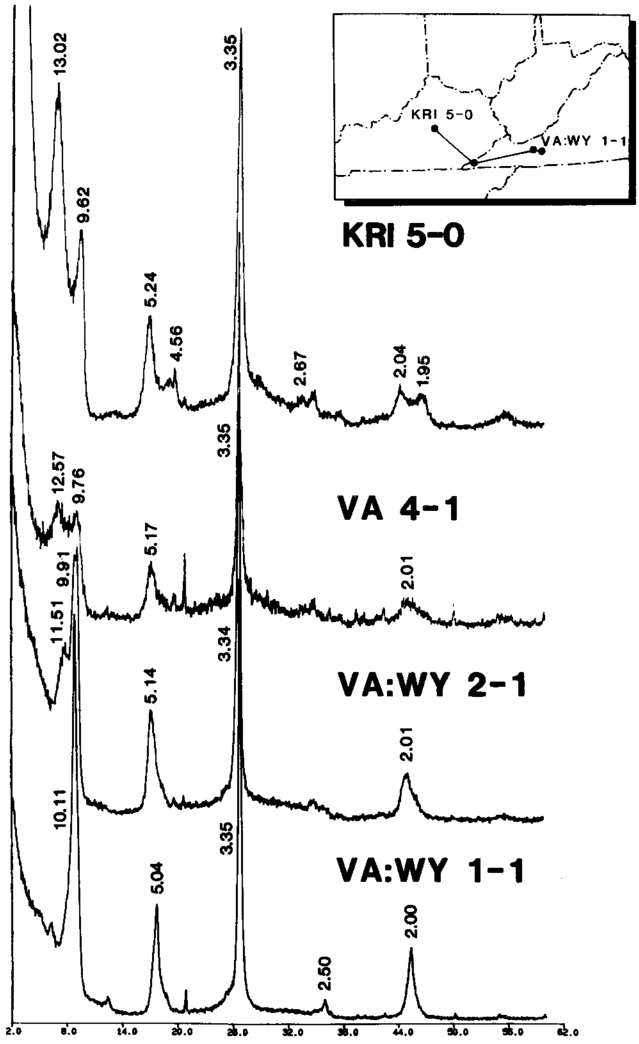


Figure 4. X-ray diffraction tracings of the less than two micron clay fraction of ethylene glycol solvated Millbrig samples, with d-spacings for the peaks shown. Actual peak positions are given in Table 4.

obtained for most of the samples collected. Analysis of these tracings using the methods of Środoń (1980, 1984) as summarized by Środoń and Eberl (1984), indicates that the predominant clay is mixed-layer illite/smectite (I/S), the diagnostic clay mineral in Paleozoic K-bentonites worldwide (Huff and others, 1988). Table 4 lists the peak positions, the average percent illite, and the ordering of the I/S as determined from these analyses and Figure 4 shows how the peak positions of the I/S change from the Cincinnati Arch into the Valley and Ridge province, and from west to east across the thrust sheets of that region. These data show that the beds are in fact potassium bentonites (K-bentonites) rather than true bentonites, which are geologically much younger clay-rich beds of altered volcanic ash in which the principal clay mineral is smectite, rather than I/S. The regional change in the low-angle reflections in Figure 4 also shows that the illite:smectite ratio increases from west to east. This trend reflects the increase in maximum burial temperatures in the basin toward the southeast and is an independent confirmation of the thermal gradients derived by Harris and others (1978) using conodont color alteration isograds.

AGE OF THE ROCKLANDIAN

Rocklandian strata have traditionally been considered Middle Ordovician in age. Recently, however, revisions in the correlation of the standard North American stratigraphic sequence with the standard British sequence have been made (Ross, Adler, and others, 1982) showing that the Rocklandian is correlative with part of the Caradocian in the British type section. Because the accepted age of the Caradocian is Late Ordovician, the Rocklandian is also Late Ordovician in age. Therefore the Rocklandian K-bentonites of the eastern United States are in Upper Ordovician strata. The correlation chart by Rader (1982) shows this chronostratigraphic relationship, as discussed by Ross, Adler, and others (1982), for the Virginia Valley and Ridge province.

Based on $^{40}Ar/^{39}Ar$ dating of biotites from samples of T-3 and T-4 collected in Kentucky, Tennessee, and Alabama (Kunk and Sutter, 1984), the mean isotopic age of the Deicke and Millbrig is 454.1 ± 2.1 Ma, and using fission track dating of zircons Ross, Naeser, and others (1982) obtained a mean age of 453 ± 3 Ma for the stratigraphic interval in which these two K-bentonites occur.

Using the conodont-based graphic correlation method of Sweet (1984), it has been determined by Huff and Kolata (1990) that the Deicke and Millbrig K-bentonites occur in the upper half of the *Phragmodus undatus* chronozone in the eastern midcontinental region.

K-BENTONITE NOMENCLATURE

Many workers have examined Rocklandian K-bentonites in several localities throughout the eastern midcontinent, and several different nomenclatural systems that attempted to organize the K-bentonites systematically have been introduced to the literature. Four are shown in Figure 8, adapted from Miller and Fuller (1954, Plate 26), which is a summary of their work in Lee County, Virginia as well as correlations suggested in other studies. The "T", "B", "R", and "V" nomenclatural systems shown in Figure 8 have been used in parts of Virginia, West Virginia, and Tennessee. The "N" system of Kay (1956), and the "S" system of Perry (1964) for K-bentonites farther north in Virginia and West Virginia are not discussed.

The North American Commission on Stratigraphic Nomenclature (1983) accepts only the names of geographic localities as suitable for formal stratigraphic names. The alpha-numeric terms that have been previously used to designate the K-bentonite beds, as shown for example in Figure 8, are inappropriate if formal usage according to the North American Stratigraphic Code is desired, although they can be useful informally in much the same way that, for example, "Number 9 Coal" is a useful stratigraphic term. Using geophysical logs of wells, Kolata and others (1984) and Huff and Kolata (1990) have correlated the Deicke and

Millbrig K-bentonite Beds of the Upper Mississippi Valley with the T-3 and T-4 K-bentonites, respectively, of the Cincinnati Arch and the western Valley and Ridge of Virginia and Alabama. "Deicke" and "Millbrig" are terms that meet the conditions of the stratigraphic code, with type localities for these K-bentonites having been described by Willman and Kolata (1978) and Kolata and others (1986). The results of the present study show that known K-bentonites at sections throughout the Virginia Valley and Ridge province correlate with T-3 and T-4, and thus with the Deicke and Millbrig. The names "Deicke" and "Millbrig" are preferable, but the informal alpha-numeric terms can still be useful, and therefore, the "V" series, "T" series etc., are referred to in parts of the following discussion, with particular reference to beds V-3, V-4, and V-7 and their equivalents. As study of the K-bentonites in this area progresses, it is possible that additional formal stratigraphic names will be proposed for K-bentonites in addition to the Deicke and the Millbrig, particularly bed V-7.

STRATIGRAPHIC SETTING OF THE DEICKE AND MILLBRIG K-BENTONITE BEDS

TYPE SECTIONS

The type sections of the Deicke and Millbrig K-bentonite Beds are in the Upper Mississippi Valley (Willman and Kolata, 1978; Kolata and others, 1986). In that region the base of the Rocklandian is placed at the base of the Deicke, and this designation is used in the present study. Those two beds have been correlated to the southeast with the T-3 and T-4 K-bentonites along the Cincinnati Arch in Kentucky and Tennessee and in the western Valley and Ridge province of Virginia and Alabama (Kolata and others, 1984; Huff and Kolata, 1990). In the present study, which is based on and is an expansion of previous work by Haynes (1989), the older two of the three thick Rocklandian K-bentonites that occur in southwest Virginia, southeast West Virginia, and northeast Tennessee are identified as T-3 and T-4. Thus the known extent of the Deicke and Millbrig K-bentonites is further expanded beyond the Upper Mississippi Valley.

STRATIGRAPHIC VARIATION BETWEEN MAJOR THRUST SHEETS

Although detailed stratigraphic work in this area is complicated by structural disruptions, the Valley and Ridge can nevertheless be conveniently divided into three strike belts based on stratigraphic similarities in each (Figure 2). This division of the Valley and Ridge province of this area into the three facies-related outcrop belts follows Hergenroder (1966), Kreisa (1980), and Rader (1982).

The facies of the western belt extend continuously from Alabama, Georgia, and Tennessee as far north as Lee County, Virginia, where strata of the Powell Valley anticline plunge under younger rocks of the Appalachian Plateaus province. Although a narrow belt of rocks that is part of the western belt occurs west of the St. Clair fault in the area around Bluefield, West Virginia, rocks younger than Devonian are are poorly exposed in that belt, and their limited outcrop along Gap Mountain near Gap Mills, West Virginia, was not studied.

The facies of the central belt extend intermittently from Alabama to Virginia; for the present study the area of interest was from the southern terminus of Clinch Mountain near Knoxville to the New River Valley of Virginia.

The facies of the eastern belt also extend intermittently from Alabama to Virginia, but only exposures in northeast Tennessee and southwest Virginia as far north as Roanoke are discussed.

As shown in Figure 2, the belts are bordered by thrust faults except for the western belt, which is bordered on the west by the Cumberland Escarpment, the structural boundary between the Appalachian Plateaus and the Valley and Ridge provinces. The western and central belts are separated by the St. Clair and Hunter Valley faults. The central and eastern belts are separated by the Saltville fault throughout the study area except in the New River Valley. There, the stratigraphic sequence in sections east of the Saltville fault is very similar to sections west of the fault, and it is the Pulaski fault that separates the central and eastern belts. The eastern belt also includes sections on the Cove Mountain thrust sheet (Kulander and Dean, 1986) and on the Salem synclinorium and Green Ridge plates, which are component plates of the Pulaski fault system and its various thrust sheets in the vicinity of Roanoke (Bartholomew, 1987). The eastern belt is bounded to the east by the Blue Ridge and Great Smoky faults, which place older sedimentary or crystalline rocks of the Blue Ridge province above the younger sedimentary rocks of the Valley and Ridge province.

Interestingly, although the Cove Mountain sheet is inferred by Kulander and Dean (1986) to be a detachment from the Saltville sheet, the Crockett Cove and Connor Valley sections on that sheet are stratigraphically and sedimentologically much more similar to the Ellett, Catawba, Peters Creek, Daleville, and Cloverdale sections in the Salem synclinorium on the Pulaski sheet just to the northeast than they are to the Big Walker Lookout, Nebo, Chatham Hill, and McCall Gap sections along Big Walker Mountain on the Saltville sheet to the west and southwest. This suggests that the sediments preserved on the Cove Mountain sheet were deposited between the two areas and that the Cove Mountain sheet is instead a detachment of the Pulaski fault. The Bays Formation sandstones in the sections on the Cove Mountain sheet include thick sequences of greenish gray lithic arenites (sandstone terminology used herein is that of Pettijohn and others, 1972), like the sandstones in the Salem synclinorium sections, whereas the sediments in the Bays Formation exposures on Big Walker Mountain are shallow shelf peritidal carbonates that grade upward into red tidal flat sandstones, siltstones, and shales, all of which were deposited in a restricted nearshore setting. This is discussed further in the following section on the relative age of the Bays and related formations.

Figures 5 and 6 summarize the nomenclature of the strata in which the Deicke and Millbrig K-bentonites occur in this region. Because most of the major facies changes occur across the Saltville fault, Figure 5 shows the stratigraphic sequences northwest of that fault, while Figure 6

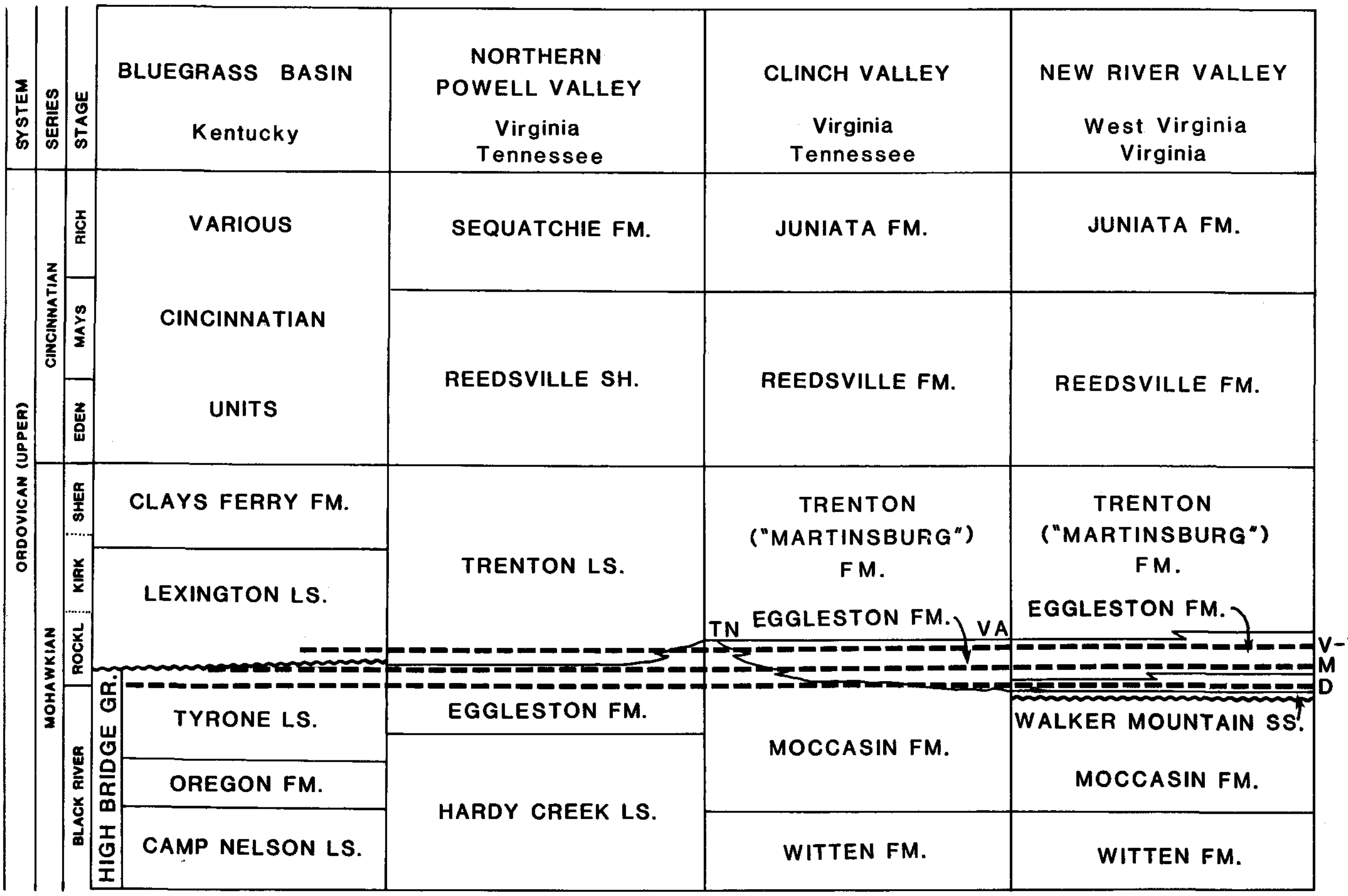


Figure 5. Correlation chart for the K-bentonites in the northwestern Valley and Ridge and the northern Cincinnati Arch. Following Kolata and others (1986), the base of the Rocklandian is placed at the base of the Deicke K-bentonite Bed. Other stratigraphic information is adapted from Rader (1982) and Diecchio (1985). Dotted lines separate the Rocklandian, Kirkfieldian, and Shermanian stages because those boundaries are not well established in this region.

shows various sequences southeast of it. Figure 5 includes the generalized sections for both the western belt (northern Powell Valley sequence) and the central belt (Clinch Valley and New River Valley sequences), as well as for the Cincinnati Arch in Kentucky. Limestones and shales of the Moccasin, Eggleston, and Trenton ("Martinsburg") Formations bracket the K-bentonites in the central and western belts, whereas shales, siltstones, and sandstones of the Bays Formation bracket them in the eastern belt. Distinctive grainstones and packstones of the Trenton ("Martinsburg") Formation overlie the Eggleston and the Bays, although the lower boundary of the Trenton becomes progressively lower in the section to the northwest, and the lowermost beds are quite possibly Rocklandian in age in the western belt. In the Fincastle synclinorium to the north of the Salem synclinorium, the lower Martinsburg Formation contains the Fincastle Conglomerate Member, a unit that is partly equivalent to the Bays Formation (Rader and Gathright, 1986). I failed to locate any K-bentonite beds in the well-exposed outcrops of that unit.

"Martinsburg" is used parenthetically in most instances throughout the text. The name *Martinsburg* was originally given to strata exposed in the Massanutten synclinorium near Martinsburg, West Virginia (Geiger and Keith, 1890), where the unit is a flysch sequence of basinal calcareous and argillaceous turbidites. Many geologists working in southwest Virginia and the nearby areas of adjacent states have used that name to refer to the thin bedded fossiliferous strata that occur between the Eggleston or Bays Formation and the Reedsville Formation, but in Virginia use of the name *Martinsburg* should properly be restricted to the turbidites and related flysch sediments in the Massanutten synclinorium and adjacent areas (Rader, 1984) such as the Fincastle synclinorium to the southwest, where the Martinsburg Formation has been identified by Rader and Gathright (1986). Rader (1982) shows this restricted usage of the name *Martinsburg*, referring to the post-Eggleston/Bays and pre-Reedsville strata as the Trenton ("Martinsburg") Formation. Use of the name *Martinsburg* is unfortunately very common in the central and western belts of the Valley and Ridge province, however, even though Diecchio (1985) notes that there is a significant difference between the graded beds that characterize the unit in southwest Virginia and have been interpreted by Kreisa (1980) to be storm deposits, and the graded beds that that characterize the unit in northern Virginia and have been interpreted by many authors to be turbidites and related flysch deposits. Although used herein, given its history of usage in Virginia beginning with Woodward (1932) and Butts (1933,1940), *Trenton* is hardly a better name for the lower part of this sequence in southwest

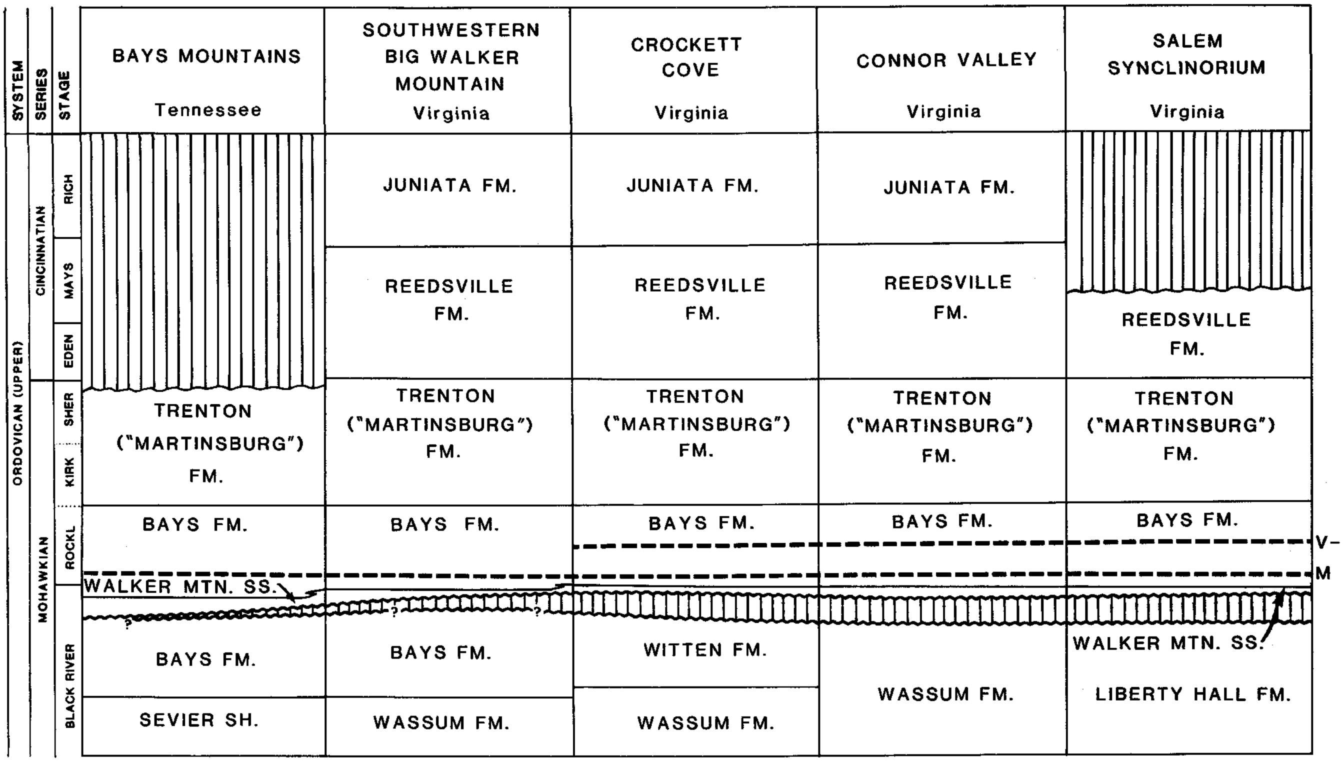


Figure 6. Correlation chart for the K-bentonites in the southeastern Valley and Ridge, where clastic strata of the Blount Group predominate. An erosional unconformity first noted at several outcrops by Hergenroder (1966) exists beneath the Walker Mountain Sandstone throughout the study area. The same stratigraphic notes given for Figure 5 apply, except that because the Deicke is absent in these sections the base of the Rocklandian is placed at approximately the position of the Walker Mountain Sandstone in the Crockett Cove, Connor Valley, and Salem synclinorium sections.

Virginia because *Trenton* is more appropriately a group name in this region (Perry, 1972). A better alternative would be to substitute instead a more regionally appropriate and suitable name such as *Dolly Ridge Formation* (Perry, 1972) for the pre-Reedsville strata now called Trenton, thus eliminating the confusing and awkward usage of *Trenton* and *Trenton ("Martinsburg")* from southwest Virginia and adjacent areas.

DESCRIPTION OF THE MOCCASIN, EGGLESTON, BAYS, AND TRENTON ("MARTINSBURG") FORMATIONS

The following discussion of stratigraphic units pertinent to the study of the K-bentonites is from a combination of my own field observations and the various references cited.

Moccasin Formation -- This 15 to 250 meter thick sequence of mostly red lime mudstones and calcareous shales named by Campbell (1894) is a transitional unit between the fluvial-deltaic clastics that predominate in the eastern outcrop belts and the marine carbonates that occur in the western belts (Butts, 1940; Woodward, 1951; Hergenroder, 1966; Kreisa, 1980; Read, 1980; Simonson, 1985). Red unfossiliferous lime mudstones are the dominant lithology, and there is a significant argillaceous component to some beds. Thin gray lime mudstone to packstone beds with sparse marine fossils also occur. The Walker Mountain Sandstone occurs in the uppermost Moccasin in the eastern New River Valley (Hergenroder, 1966; Kreisa, 1980).

Eggleston Formation -- This is a 0 to 60 meter thick sequence of green and olive-colored strata named by Mathews (1934) that is lithologically very similar to the Moccasin except for a lack of redbeds (Butts, 1940; Woodward, 1951; Miller and Fuller, 1954; Hergenroder, 1966; Kreisa, 1980; Read, 1980). Although faunal abundance and diversity is greatest in the Eggleston of the Powell Valley (cf. Huffman, 1945), bioclastic grainstones containing gastropods, brachiopods, bryozoans, and crinoids occur regionally throughout the Eggleston. Those relatively thin beds are similar to the abundant grainstone beds in the overlying Trenton ("Martinsburg") Formation, with which the Eggleston is conformable. The Eggleston overlies the Moccasin in the central belt, but a thicker Eggleston is partly equivalent to the Moccasin in the western belt. Along the southern end of Clinch Mountain in Tennessee the Eggleston thins rapidly, and the entire interval between the Witten Formation and the Trenton ("Martinsburg") Formation in the central belt is assigned to the Moccasin, as shown in Figure 5.

Bays Formation -- This is a 25 to 300 meter thick sequence of red and greenish gray to olive-colored fluvial-deltaic clastics named by Keith (1895) that is an upper unit of the Blount Group, a thick clastic sequence that extends from

Virginia to Alabama (Rodgers, 1953; Hergenroder, 1966; Kreisa, 1980; Read, 1980; Handwerk, 1981). Those sediments record an early episode of the Taconic Orogeny in the southern Appalachians known as the Blountian phase (Rodgers, 1971). The Bays is present on parts of the Saltville, Cove Mountain, and Pulaski thrust sheets, extending as far northeast as Daleville in the northeastern part of the Salem synclinorium. Here, a facies change occurs and the Bays grades into the slope and basin sediments of the Martinsburg Formation (Rader and Gathright, 1986). The Bays of the Cove Mountain and Pulaski thrust sheets is equivalent to the upper Moccasin and Eggleston Formations of the northwestern belts, whereas the Bays as it is defined on the Saltville thrust sheet is equivalent to the entire Moccasin and Eggleston of the central belt, and to part or all of the Bowen and Witten Formations in that belt as well (Hergenroder, 1966; Kreisa, 1980). Fossil diversity and abundance are very low in the Bays. Lingulid brachiopods occur infrequently throughout the Bays, and ostracodes and conodonts occur sporadically in some of the thin interbedded limestones.

A very distinctive unit in the Bays Formation throughout the study area, and in the Moccasin Formation in the New River Valley, is the little-studied Walker Mountain Sandstone Member (Butts and Edmundson, 1943). This is a sequence of yellow to gray to white sandstones with lesser siltstones and shales 0.3 to 15 meters thick that is easily spotted because of its distinct texture and composition. In the Bays Mountains and along Big Walker Mountain these are the only sandstones in the Bays that are not fine- to very fine-grained redbeds (Hergenroder, 1966). The Walker Mountain Sandstone is instead a sequence that consists mostly of moderately well-sorted to moderately poorly-sorted, fine- to coarse-grained to conglomeratic quartz arenites that contain moderately rounded to well-rounded quartz grains up to two millimeters in diameter with less than five percent chert grains, quartzite rock fragments, and accessory minerals like zircon, apatite, and tourmaline. The less well-sorted zones are actually bimodal, with each mode being well-sorted, a difference noted previously by Hergenroder (1966). In the lowest few centimeters, quartz and chert granules and pebbles comprise from ten to thirty percent of the bed, with the varicolored chert grains being particularly noticeable in the otherwise white rock.

In the exposures of the Bays on the Cove Mountain and Pulaski thrust sheets, the Walker Mountain Sandstone is identified for the first time on the basis of its distinct texture and composition and its stratigraphic position relative to the Millbrig K-bentonite. The Bays in those exposures contains no conglomeratic sandstones except in the Walker Mountain Sandstone Member. Redbeds are much less abundant as well, and instead the predominant sediments in the Bays are greenish gray to olive lithic arenites, sublitharenites, and lithic wackes. In the Bays Mountains of Tennessee the texture and composition of the sands in the Walker Mountain are quite uniform. It is a sequence of well-sorted medium- to fine-grained mature quartz arenites, with extremely few conglomeratic zones. Crossbedding in the sands indicates that the sediment transport direction was from the south or southwest (Hergenroder, 1966).

In Moccasin sections and those Bays sections where redbeds predominate, some beds in the Walker Mountain Sandstone are red because of iron oxide that is dispersed as hematite throughout the matrix and as coatings on the framework grains. In the Bays sections where greenish gray sandstones and siltstones predominate and the underlying unit is the Liberty Hall Limestone, the lowermost Walker Mountain sands contain pyrite that is dispersed throughout the rock as a coating. Where the rock is weathered the pyrite has been oxidized to an iron oxide, probably limonite (Hergenroder, 1966), and it is visible as discrete orange to brown blebs or "starbursts" on broken surfaces of the sandstone. In some exposures this oxidized material has formed patches of a brilliant orange ocherous material that forms a thin coating on the rock. An unusual bed occurs right at the contact of the Walker Mountain Sandstone and the Liberty Hall Formation at the Peters Creek section. There the lower one to three centimeters of the Walker Mountain consist of coarse quartz sand grains, granules, and pebbles that are loosely cemented by a gray, abundantly pyritiferous matrix. At this and other sections where it is the basal unit of the Bays, the Walker Mountain consists of at least two distinct medium-grained to conglomeratic quartz arenite beds, with interbedded finer-grained sandstones.

Rip-up clasts are common in the lowest few centimeters of some sections (Webb, 1965; Hergenroder, 1966), including the Connor Valley section. There, the Walker Mountain Sandstone overlies the Wassum Formation, and the lowest bed of the sandstone contains abundant angular to rounded clasts of the underlying shaly limestone as well as some rounded grains of chert. At that exposure the Walker Mountain Sandstone is also lacking significant amounts of pyrite.

On unweathered surfaces the conglomeratic sandstone is typically white to pale yellow, but on weathered surfaces it is a reddish brown color in the Bays exposures along Big Walker Mountain and in the Bays Mountains, and in the Moccasin exposures in the New River Valley. It is a yellow to yellowish-brown color on weathered surfaces in Bays exposures on the Cove Mountain and Pulaski thrust sheets.

In the exposures along Big Walker Mountain the conglomeratic sandstone occurs in the middle or upper Bays, whereas in the several sections on the Cove Mountain and Pulaski thrust sheets it occurs at the base of the Bays. In the New River Valley it occurs in the uppermost few meters of the Moccasin Formation and is a useful marker horizon.

Although Butts and Edmundson (1943) believed that the Walker Mountain Sandstone was equivalent to the "middle sandstone" of the Bays in the Bays Mountains of Tennessee, they were unable to demonstrate that correlation conclusively. Hergenroder (1966) showed the correlation in his Plate 3 but in his text (p. 39) he admitted that the correlation had not been proven. The findings of the present research, however, support this correlation (shown in Figure 6 of the present paper) based on the position of the sandstone relative to the Millbrig K-bentonite and therefore the term Walker Mountain Sandstone can properly be applied to that unit in the Bays Mountains, as shown herein in the various cross-sections.

<u>Trenton ("Martinsburg") Formation</u> -- In the Roanoke area and southward, this is a 250 to at least 500 meter thick

sequence of interbedded grainstones, packstones, wackestones, and calcareous siltstones and shales having an abundant and diverse assemblage of fossils (Kreisa, 1980). As noted above, the nomenclatural history of this part of the stratigraphic section is complex. The name *Trenton* was first used by Butts (1933) for the richly fossiliferous sequence of carbonates and shales in the Powell Valley of southwest Virginia, whereas Woodward (1932) had applied the name in the Roanoke area. The formation was deposited across the entire width of the Valley and Ridge in the study area, as it overlies the Bays and the Eggleston, and the contact of those units, where the relatively sudden occurrence of abundant bioclastic grainstones and packstones is in sharp contrast to the faunal paucity of the underlying strata, is a widely recognized marker throughout the region (Butts, 1940; Woodward, 1951; Kreisa, 1980).

Vertical sequences -- The vertical sequences represented by (1) the Tyrone-to-Lexington (exposures in the northern Cincinnati Arch; (2) the Eggleston-to-Trenton (exposures in the Powell Valley in the western belt); (3) the Walker Mountain Sandstone (where present)-to-upper Moccasin-to-Eggleston-to-lower Trenton (exposures on all thrust sheets in the Central belt; (4) the Walker Mountain Sandstone-to-upper Bays-to-lower Trenton (exposures along Big Walker Mountain on the Saltville thrust sheet in the eastern belt); and (5) the Walker Mountain Sandstone-to-Bays-to-Trenton (exposures on the Cove Mountain and Pulaski thrust sheets) each record a basinwide deepening of the water column that follows the period of basinwide shallowing described in southwest Virginia by Read (1980). The K-bentonites were deposited just below, at, or just above the top of this regressive sequence, and both the K-bentonites and this deepening upward sequence can be traced throughout the southeastern United States (Haynes, 1989).

In the Valley and Ridge province of the study area, the contacts between the Moccasin and Eggleston, the Eggleston and Trenton ("Martinsburg"), and the Bays and Trenton ("Martinsburg") are conformable and gradational over a few meters. This sequence records the appearance of successively more normal marine conditions (Kreisa, 1980). In the western belt the Eggleston Formation contains a diverse but still fairly restricted marine fauna (Huffman, 1945) in contrast to the overlying Trenton Limestone, which contains an abundant and diverse open marine fauna (Kreisa, 1980). In the central belt, the upper Moccasin and Eggleston are generally fossil-poor lime mudstones, but rare thin grainstone and packstone beds of bioclastic debris occur. These sediments and the equivalent red siltstones and shales in the upper Bays Formation along Big Walker Mountain were deposited in restricted tidal flat environments, with the few thin Trenton-like fossiliferous beds probably representing storm-derived sheets of reworked shelf sediments. The fossil-rich grainstones, packstones, siltstones, and shales of the Trenton were deposited in a storm dominated open-marine shelf environment of varying depths across the region (Kreisa, 1980). Hergenroder (1966) and Kreisa (1980) suggested that the green and gray sandstones, siltstones, and shales of the Bays in the eastern belt were deposited in a delta front setting. Based on detailed examination of the eastern belt sections, I would also infer that at least the upper sandstones in the Bays at the Ellett section (below the uppermost redbeds) were deposited in a storm-influenced shelf setting that was probably similar in many ways to the one inferred for the sediments in the overlying Trenton. Many of the sandstones in that part of the section fine upward, they contain horizontal plane lamination, hummocky cross-stratification, and other sedimentary structures associated with storm deposition in shelf sequences, they are submature to immature lithic arenites and quartz and lithic wackes (indicating a significant amount of mud in the sediment), and they contain reduced iron in the matrix (probably indicative of relatively rapid deposition and burial). The upper few meters of the Bays at the Crockett Cove, Connor Valley, Catawba, and Ellett sections contain some redbeds, suggesting that a minor shallowing upward sequence preceded deposition of the deeper water Trenton sediments.

SUMMARY OF PREVIOUS WORK

Many geologists have studied this stratigraphic interval in the Valley and Ridge of Virginia, West Virginia, and Tennessee, and a summary of several papers is given below. Also included are summaries of relevant papers by Young (1940) on K-bentonites in central Kentucky, Fox and Grant (1944) on K-bentonites near Chattanooga, Tennessee, and Wilson (1949) on the stratigraphic sequence of the Nashville Dome in central Tennessee. Figure 7, which gives an indication of the number of K-bentonites that occur in Upper Ordovician strata in this region, is a summary chart of correlations suggested by previous workers, and Figure 22 is the revised correlation chart based on the findings of the present study.

Rosenkrans (1936). In this study of exposures mostly in the central belt, Rosenkrans introduced the "V" system of K-bentonite nomenclature ("V" for Virginia), and his suggested correlations were based on detailed study of many exposures. Thirteen K-bentonites were identified in the Moccasin, Eggleston, and Trenton Formations; three in particular were relatively thick and laterally persistent. His work is still very accurate and useful when studying exposures in the field, particularly with regard to identification of the individual K-bentonites that occur in the sequence of the central belt.

The bed designated as V-3 is readily recognizable not only because of its thickness (0.1 to 1.0 m; usually greater than 0.3 m), but also because of its distinct coloration; it typically consists of interbedded red to maroon and greenish-gray or yellowish clay-rich layers. That pattern is present only where the bed occurs in the Moccasin Formation; evidently the iron oxide that imparts a red color to the Moccasin has done the same to the K-bentonite.

The bed Rosenkrans termed V-4 is recognizable because of its thickness (0.4 to 1.4 m) and abundant biotite. It occurs in the lower Eggleston Formation, about ten meters upsection from V-3, and is usually underlain by a blocky, brittle layer of dark chert. Bed V-7, the third thick bed (0.4 to 1.2 m), is recognizable by its occurrence just below the base of the "cuneiform" beds of the Eggleston, which are discussed below. V-7 occurs five to eight meters upsection

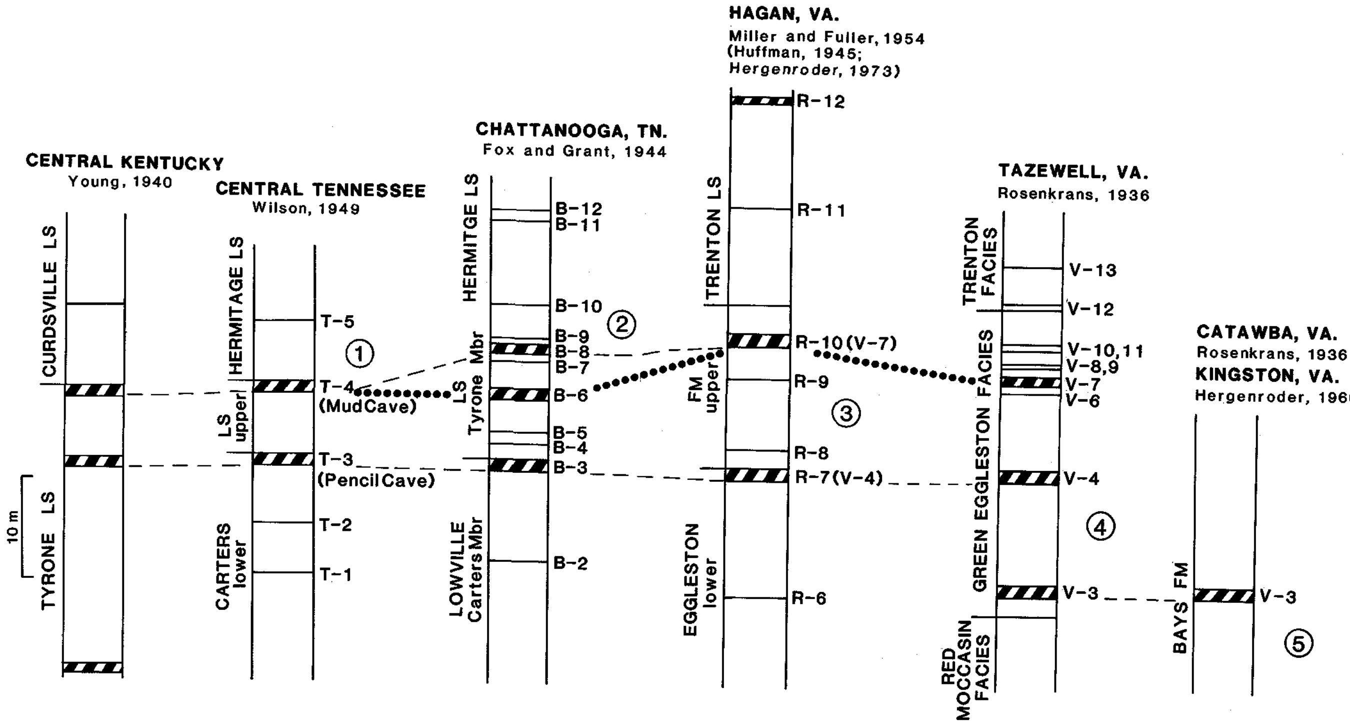


Figure 7. K-bentonite correlation chart presented by Miller and Fuller (1954), with additions from more recent studies on the K-bentonites of this area. The encircled numbers highlight correlations that are discussed in the text. Some of these have been reinterpreted, as a comparison with Figure 22, the revised correlation chart for this area, will show.

from V-4, and usually it is also underlain by a layer of dark chert. Most importantly, this bed also contains abundant biotite, but not the amounts seen in bed V-4.

Except for beds V-3, V-4, and V-7, Rosenkrans found that it was difficult to recognize the various K-bentonites consistently from outcrop to outcrop because none of them was nearly as thick as those three, nor did each K-bentonite appear to be present at every outcrop. In addition, color variations caused by weathering, similarities in texture between different beds, and variations in thickness within a single bed occurred all too commonly. Nevertheless, Rosenkrans was able to identify several additional K-bentonites above the thick bed V-7; he named these V-8 through V-14. Neither those beds nor the ones he named V-1, V-2, V-5, and V-6 were found at all sections by Rosenkrans.

The presence of chert layers directly beneath the thicker K-bentonites in carbonate sequences was one major criteria that Rosenkrans relied on to support his correlations. He also found that certain markers other than individual K-bentonites were also useful for correlation. The three that were most useful are

1) the interval in which the Moccasin redbeds grade upward into the olive and tan rocks of the Eggleston;
2) the interval in the Eggleston where several thin K-bentonites occur in a group of highly jointed thin lime mudstones that Rosenkrans named the "cuneiform beds" because of their supposed resemblance to ancient cunei form writings; and
3) the contact between the poorly fossiliferous Eggleston and the abundantly fossiliferous Trenton ("Martinsburg") Formation.

Because five K-bentonites were consistently associated with the "cuneiform" beds of the Eggleston, Rosenkrans named that particular interval of strata the "cuneiform group" of K-bentonites. The "cuneiform group" was correlated among several outcrops of the Eggleston, from the New River south to Tazewell County, a distance of more than 100 kilometers (Rosenkrans, 1936, Plate 13).

Rosenkrans suggested that although sections in the Ordovician of the Powell Valley in Lee County, Virginia, contain several K-bentonites, beds V-1 to V-6 as observed in the central belt were absent in the Lee County sections because of an erosional unconformity, and he did not suggest any correlations based on his field evidence. He did note, however, that the Lee County sections showed some similarity to sections near Chattanooga, Tennessee, which in turn were similar to sections along the Cincinnati Arch, and that further study might make correlations possible between all those sections. Bed V-3 was considered to be limited in its occurrence, restricted to southwest Virginia and northeast Tennessee as shown in Figure 7 (encircled number 4). This conclusion may have been reached because V-3 is not underlain by chert as are V-4 and V-7, whereas the two K-bentonites that are commonly present elsewhere in the southern Appalachians are usually underlain by chert. If this in fact was Rosenkrans's conclusion, it was probably reinforced by the sequence of K-bentonites in the section at the Narrows of the New River in Giles County, Virginia (cf. Rosenkrans, 1936). Rosenkrans relied on that section for much information; there, beds V-4 and V-7 occur in the Eggleston and are of normal thickness compared with most other sections in the region, but bed V-3, in the Moccasin, is only 15 to 20 centimeters thick, which is markedly thinner than in most sections to the southeast and southwest. Although the exposure at the Narrows is in the westernmost continuous outcrop of Ordovician strata in the Valley and

Ridge at this latitude, it is in the central belt, not the western belt (Figure 1). Rosenkrans perhaps reasoned that if the K-bentonite beds were traced from the Narrows through the subsurface west to exposures along the Cincinnati Arch, the two thick K-bentonites of that region would logically be equivalent to V-4 and V-7, the two thickest beds at the Narrows.

The thickness of V-3 at the Narrows cannot presently be checked because the exposure there is greatly weathered, but at the Bluefield section in the same outcrop belt 40 kilometers to the southwest (Figure 1), V-3 is exposed in the upper redbeds of the Moccasin and is about 25 centimeters thick. And, at the Goodwins Ferry section along the New River 20 km to the east of the Narrows, V-3 is 20 to 25 centimeters thick, whereas to the south at the Rocky Gap, Cove Creek, Plum Creek, and other sections it is nearly one meter thick. These observations suggest that Rosenkrans's conclusions concerning the thickness of V-3 at the Narrows are accurate.

As noted above, Rosenkrans only briefly mentioned sections in the Powell Valley, and he did not mention the section at Hagan, in Lee County, Virginia, which is a very important section as discussed in the following text.

A K-bentonite in the Bays Formation section at Catawba (Figure 7, encircled number 5) was mentioned by Rosenkrans. Several K-bentonites are actually present at the Catawba section, and the two thickest ones are red colored (Hergenroder, 1966). Presumably it was on the basis of thickness and color that one of those beds at Catawba was identified by Rosenkrans as V-3, but the description of that bed, one of the four detailed descriptions he gave of the internal stratigraphy of V-3 (Rosenkrans, 1936, p. 93-94), which were taken from Ross (1928), includes 5.5 inches of "yellow micaceous bentonite" in the middle of the bed. This identification is refuted in the present study. As shown in Table 1, V-3, the Deicke, contains little or no biotite, in contrast to bed V-4, the Millbrig, and as the Millbrig occurs in this section as a very thin bed, the description presented by Rosenkrans has to have been of a bed higher in the section than V-4, quite possibly V-7.

The important work by Rosenkrans established excellent stratigraphic control for the central belt of the Valley and Ridge in Virginia and Tennessee, and re-examination of the many outcrops in this area confirmed the accuracy and detail of his work in the area.

Bates (1939). In this study of several Ordovician sections in the north end of the Powell Valley, two thick K-bentonites were described in the Lowville Limestone, which underlies the Trenton Limestone (the Lowville is the Eggleston of current usage). In the upper bed, 17 feet (6 m) below the Lowville-Trenton contact, the presence of a micaceous zone was noted. Based on the results of the present study this bed is most likely the Millbrig.

Young (1940). This study described four K-bentonites in the Highbridge and Lexington Groups of the Jessamine Dome in central Kentucky. Three of the K-bentonites occur in the Tyrone Limestone, the upper unit of the Highbridge, and one occurs in the Curdsville Limestone, the lowest unit of the Lexington. The two thickest K-bentonites are in the Tyrone with the upper bed occurring right at the contact of the Tyrone and the Curdsville, and the lower bed occurring about 20 feet (6.5 m) below the upper bed. The lower bed is 2.0 feet (0.6 m) thick; the upper bed is 2.5 to 3.0 feet (0.75 to 1.0 m) thick. These are the T-3 and T-4 K-bentonites of Wilson (1949), and they are also known as the Pencil Cave and Mud Cave beds, respectively, of drillers' terminology.

Fox and Grant (1944). In a study of strata in the Chattanooga, Tennessee, region, Fox and Grant described 14 K-bentonites, 12 of which occur in the Lowville and Hermitage Limestones (Carters Limestone and Hermitage Formation of current usage). The "B" nomenclatural system was introduced by Fox and Grant ("B" for bentonite), and the beds they termed B-3, B-6, and B-8 are the thickest and most widespread in this region. Of primary interest to the present study are their descriptions of these beds and their Figure 2, which is partly summarized in the present Figure 7. Thicknesses were given as 2.75 feet (0.8 m) for bed B-3, 2.25 to 4.0 feet (0.7 to 1.2 m) for B-6, and 0.3 to 2.5 feet (0.1 to 0.75 m) for bed B-8.

As reported to Fox and Grant by C.S. Ross of the U.S. Geological Survey, samples of bed B-3 contained abundant feldspars but little quartz and almost no biotite, whereas samples of bed B-6 contained biotite as the most abundant mineral, with quartz and feldspars present in abundance as well.

Fox and Grant correlated beds B-3 and B-6 with the two thick K-bentonites in the Powell Valley reported by Bates (1939). The nearby Hagan section is very similar to the section described by Bates, and these correlations are shown below encircled number 2 in Figure 7 as a dashed line between B-3 and R-7 and as a dotted line between B-6 and R-10. Fox and Grant also correlated their B-3 and B-6 with the two thick K-bentonites of the Nashville Dome. Those beds were later named T-3 and T-4 by Wilson (1949), and that correlation is shown below encircled number 1 in Figure 7 as a dashed line between B-3 and T-3 and a dotted line between B-6 and T-4.

The work by Fox and Grant provided additional details about K-bentonite mineralogy and stratigraphy in the southern Valley and Ridge province, and their measurements were found to be accurate during examination of exposures in the Chattanooga region.

Huffman (1945). This study described the Middle Ordovician limestones (Upper Ordovician of current usage) in Powell Valley at several sections in Lee County, Virginia, and one section at Harrogate, just south of the Virginia-Tennessee state boundary in Claiborne County, Tennessee. Those rocks were then correlated with equivalent strata exposed in the Jessamine Dome of central Kentucky. At the Hagan and Harrogate sections Huffman recognized two thick K-bentonites in the Eggleston formation, both approximately three feet (1 m) thick. The younger K-bentonite bed occurs at the base of the Curdsville Formation (Trenton Limestone of current usage) and contains abundant biotite. Huffman believed that these two K-bentonites were equivalent to beds V-4 and V-7 of Rosenkrans's (1936) central belt sequence. That correlation is shown at encircled number 3 in Figure 7. Huffman's designation of the beds at Hagan are in parentheses. A thin K-bentonite at Hagan that separates the Eggleston from the underlying Moccasin (Hardy Creek Limestone of current usage) was considered by Huffman to be V-3; this K-bentonite is not shown on Figure 7. Evidently Huffman felt that his correlations were justified by the occurrence of three to five meters of "cuneiform" beds that overlie the upper thick K-bentonite he identified as V-7. Those beds are in turn overlain by the readily identifiable fossiliferous rocks of the Curdsville. As that is a similar sequence to the one above bed V-7 as described in detail by Rosenkrans (1936) in the central belt, Huffman believed the correlation of the younger bed at Hagan and Harrogate with V-7 to be logical on that basis. He also considered the thicknesses of the K-bentonites and the occurrence of chert layers beneath the two beds in both regions to be supporting criteria.

Huffman also suggested that the two thick K-bentonites at Hagan and Harrogate correlated with the two thick K-bentonites in the Tyrone Formation of the Highbridge Group in Kentucky, and with the Pencil Cave and Mud Cave (drillers' usage) of the Carters Limestone in central Tennessee. Following Rosenkrans (1936), Huffman suggested that bed V-3 did not persist from the Valley and Ridge to the Cincinnati Arch.

Huffman's correlation of V-4 and V-7 westward with the two thick K-bentonites along the Cincinnati Arch has been accepted and cited by many workers who have studied the Rocklandian sequence in either area (e.g., Huff, 1983). The present study refutes Huffman's correlation of the two thick K-bentonite beds at Hagan with V-4 and V-7 of Rosenkrans (1936), but Huffman was correct in assuming that the two beds at Hagan were the same as the two persistent ones along the Cincinnati Arch, so the spirit, if not the "letter", of his correlation with the Cincinnati Arch sections is supported by the present study.

Although mostly superceded by the study of Miller and Fuller (1954), Huffman's work is particularly important because it was the first to describe in detail the lithology and paleontology of the sections at Hagan and Harrogate, with their well-exposed K-bentonites.

Wilson (1949). Details of the Ordovician sequence in central Tennessee were presented in this study, and the "T" system of K-bentonite nomenclature was introduced ("T" for Tennessee). Wilson described five K-bentonites, and correlated the two thick beds of this region, which he labeled T-3 and T-4, between many outcrops of the Nashville Dome. Those beds were 1.0 to 2.0 feet (0.3 to 0.6 m) and 2.5 feet (0.75 m) thick respectively. He suggested that beds T-3 and T-4 were equivalent to the Pencil Cave and Mud Cave, respectively, of drillers' usage in the Cumberland Saddle between the Nashville and Jessamine Domes. He also correlated beds T-3 and T-4 with beds B-3 and B-6, respectively, of Fox and Grant (1944) as shown below encircled number 1 in Figure 7 as a dashed line between B-3 and T-3 and a dotted line between B-6 and T-4.

The stratigraphic divisions introduced in Wilson's study for the interval in which the K-bentonites occur are the ones currently used for central Tennessee. As such, bed T-3 separates the Lower Carters Limestone from the Upper Carters Limestone, and bed T-4 separates the Upper Carters Limestone from the overlying Hermitage Formation. That sequence persists throughout the Nashville Dome, although bed T-4 and part of the Upper Carters are absent in places on the west side of the Dome, and an erosional unconformity separates the Upper Carters and the Hermitage.

For the present study, petrographic examination of the Deicke and Millbrig K-bentonites began with samples collected from exposures along the Cincinnati Arch, and so the work by Wilson was very important, as it provides the stratigraphic framework to use when attempting to correlate strata from the west towards the east, between the Cincinnati Arch and the western Valley and Ridge province. This was shown by Milici (1969) and Milici and Smith (1969), who introduced parts of Wilson's stratigraphic sequence from the Nashville Dome to the Sequatchie Valley farther east in Tennessee and to the tri-state area around Chattanooga.

Miller and Brosgé (1954) and Miller and Fuller (1954). In these companion volumes reporting on detailed studies of the stratigraphy in and around Lee County, Virginia, yet another nomenclatural system for the K-bentonites was introduced, the "R" system ("R" for Rose Hill district). Thirteen K-bentonites were described from this area, with the thickest ones being R-7 (2.0 ft; 0.6 m), R-10 (3.3 ft; 1.1 m), and R-12 (1.0 ft; 0.3 m). These are shown in the Hagan section of Figure 7; like Huffman (1945), Miller and Brosgé and Miller and Fuller described the exposure at Hagan in detail, and they placed their beds R-7 and R-10 in the upper member of the Eggleston Formation, and bed R-12 in the lower part of the Trenton Limestone. Beds R-7 and R-10, both underlain by dark chert layers, are the same beds that were designated by Huffman as V-4 and V-7. Bed R-10 was reported to contain abundant biotite, and bed R-12 was said to contain some biotite.

In an attempt to unify the various nomenclatural systems then in use, Miller and Fuller included an illustration (Plate 26) showing suggested correlations between Hagan and various other well-described sections. They were the Tazewell section of Rosenkrans (1936) (the Plum Creek section of the present study), the eastern Tennessee section of Fox and Grant (1944), the central Kentucky section of Young (1940), and the central Tennessee section of Wilson (1949). This illustration was the first attempt at correlating widely separated sections in the Cincinnati Arch and the southern Valley and Ridge since Rosenkrans had done it in 1936, and the suggested correlations of Miller and Fuller are summarized in Figure 7, which as noted previously is adapted in large part from their Plate 26.

Although Miller and Fuller's Plate 26 shows bed R-10 correlating with bed B-8 of Fox and Grant (1944), their accompanying discussion indicates that bed R-10 is correlative with bed B-6 of Fox and Grant. These two differing correlations are shown below encircled number 2 on Figure 7 as a dashed line from R-10 to B-8 and a dotted line from R-10 to B-6. Based on the findings of the present research, it is beds R-10 and B-6 that are equivalent to each other and to bed T-4, the Millbrig, of the Cincinnati Arch. Therefore, the text of Miller and Fuller, rather than their Plate 26, is considered to explain the correlations correctly. Also in Figure 7, the dashed line below encircled number 1 shows the incorrect correlation of B-8 with T-4, as that is how Miller and Fuller's Plate 26 is drawn. The correlation of B-6 with

T-4 (dotted line) is also shown, as that is the correct correlation which is described in their text. The findings of the present research also support that correlation. This unfortunate misunderstanding between text and illustration is very confusing at first, but the revised correlation chart in the present paper (Figure 22) will supercede all previous such charts, and the confusion caused by Plate 26 of Miller and Fuller has been recognized and the proper corrections have been stated.

The works by Miller and Brosgé and Miller and Fuller are very important because they added to the work by Huffman on the stratigraphy of the important Hagan section, and the K-bentonite sequence of the Powell Valley was measured and described in detail for the first time.

Coker (1962). This primarily mineralogical study was of a K-bentonite exposed in the quarry along Hinds Creek near Clinton, Tennessee. That quarry is the Hinds Creek Quarry section of the present study, where both the Deicke and Millbrig are present, although at the time Coker was working there , quarrying had just recently begun , as evidently only one thick K-bentonite was exposed on the quarry face. Coker described the 35.5 inch (90 cm) thick zone of chert, K-bentonite, and cherty limestone in detail, noting its greenish color and vertical variations in texture. Using various separatory techniques in the laboratory he was able to identify and describe the clay and non-clay minerals in the bed, which are albite, anatase and leucoxene, apatite, biotite, calcite, quartz and chert/ chalcedony, zircon, various opaque iron oxides including goethite, hematite, and limonite, relict volcanic glass shards, and mixed-layer illite/montmorillonite and illite/ montmorillonite/chlorite. Albite, anatase and leucoxene, calcite, opaque iron oxide minerals, and volcanic glass shards were observed in samples from all zones of the K-bentonite. The occurrence of biotite was described as "[a] few flakes and books of light, pinkish-brown biotite...in all zones." The relative abundances of apatite, quartz, and zircon were not given.

Coker indicated that this bed correlated with the lower altered volcanic ash bed of Rodgers (1953). A comparison of Coker's findings on the non-clay minerals in the bed with the findings of the present study given in Table 1 indicates that the K-bentonite he studied was the Deicke, which is also presumed to be the lower ash bed of Rodgers (1953), who did not describe the two beds in any detail. Occasional biotite grains do occur throughout the Deicke, and the presence of abundant anatase or leucoxene is a good mineralogic indicator of the Deicke. I have studied both the Deicke and the Millbrig at the Hinds Creek Quarry section, and the Millbrig contains abundant biotite and quartz, and few opaque minerals, and given the thoroughness of Coker's descriptions I have no doubt that he was looking at the Deicke. As noted by Coker the quarry, now inactive, is in fact an excellent collecting locality for K-bentonite samples that are suitable for petrographic analysis. The data in Table 2 were collected from microprobe analyses of thin-sections made from very unweathered Deicke and Millbrig samples that were collected at the Hinds Creek Quarry.

Based on his interpretation of several X-ray diffraction tracings of the clay mineral fraction of the K-bentonite, Coker suggested that the predominant clay mineral was a randomly interstratified (ordered) mixed-layer illite/montmorillonite (illite/smectite of current usage). His conclusions were based on interpretations of primarily the 00*l* low-angle diffraction peaks that indicate d-spacings of between 10Å and 27Å. Clay mineralogists have for years had difficulty in interpreting these low-angle peaks when mixed-layer clays are the focus of study, but Środoń (1980, 1984) shows how the higher-angle diffraction peaks can be used to identify and distinguish mixed-layer I/S reliably. As a result, the findings of the present study differ greatly from those of Coker with respect to the clay mineralogy of the Deicke. Rather than being comprised primarily of randomly-interstratified mixed-layer I/S, as suggested by Coker, my interpretation of the clay mineralogy is that the predominant clay mineral in samples from the Valley and Ridge province is a highly illitic I/S characterized by long-range ordering (R3 ordering of Reynolds, 1980), as shown in Table 4. Elliott and Aronson (1987), who studied the clay minerals in samples of the Deicke and Millbrig from southwest Virginia and northeast Tennessee, also found that a long-range ordered mixed-layer I/S was the dominant clay mineral.

The work by Coker, although limited in scope to a single K-bentonite at one exposure, showed that a wealth of petrologic information could be obtained through the laboratory analysis of samples, and his study was important because it described in great detail the techniques used to identify the samples as clearly having been derived through the alteration of volcanic ash.

Hergenroder (1966). Hergenroder's study of the Bays Formation over its entire area of outcrop is particularly important because of the accuracy and detail of its measured sections; for the present study they were invaluable during field work. Although Hergenroder's research was on the stratigraphy of the Bays, the importance of the various K-bentonites was discussed in some detail, and he suggested that two thick K-bentonites occurring in some outcrops of the Bays in southeast Tennessee and northwest Georgia were the same as the two thick beds at Hagan, R-7 and R-10 (Hergenroder, 1966, Plate 12). Following the correlations of Huffman (1945) and Miller and Fuller (1954), he believed that R-10 correlated with bed V-7 of the central belt as shown at encircled number 3 in Figure 7. He also noted that the silicified zones which commonly occur at the base of the K-bentonites are more difficult to spot in the clastic sediments of the Bays, but as shown in Figure 20 those zones can be located at some exposures of the Bays.

Like Rosenkrans (1936), Hergenroder reported an occurrence of bed V-3 in the Bays near Roanoke. Hergenroder's Kingston section is shown schematically in Figure 7 (encircled number 5) and his suggested correlation with the Plum Creek section of Rosenkrans (1936) is shown below encircled number 4. The exposure described by Hergenroder was made during highway construction; it is now very poorly exposed and no K-bentonites were found there during the present study, but in Hergenroder's description of the Kingston section (p. 161) he notes that this K-bentonite contains two distinctly micaceous zones. Both the Millbrig (V-4) and V-7 contain biotite that is noticeable at outcrops in hand samples, but the Deicke (V-3) does not, so it is clear that this bed at Kingston is not V-3. The results of the present research in fact indicate that the Deicke is absent from the eastern belt in the study area.

Hergenroder included a relatively lengthy discussion of his findings concerning the petrography of the K-bentonites based on study of thin sections and X-ray diffraction tracings. He found abundant brown to black biotite at only three exposures in his study area: at Rocky Face and Ringgold, Georgia, and Hagan, Virginia, although he observed weathered biotite in many other samples. Hergenroder also noted that V-7 contains abundant biotite at several sections. The clay minerals in several samples were analyzed using X-ray diffraction. Like Coker (1962) Hergenroder relied mainly on the 00*l* low-angle diffraction peaks to determine the principal clay mineral(s) present in the samples, and on this basis the predominant clay minerals were identified as a randomly interstratified illite/montmorillonite (I/S of current usage) and dioctahedral illite. As discussed above, the findings of the present study indicate that the principal clay mineral in samples from the Valley and Ridge province is usually a long-range R3 ordered mixed-layer illite/smectite, not a randomly ordered illite/smectite. The finding of discrete dioctahedral illite separate from the I/S is also refuted, as the methods of Środoń (1980, 1984) used to interpret X-ray diffraction tracings will indicate whether or not discrete illite is present in the clay mineral fraction, and based on my observations of numerous tracings such as those shown in Figure 4 there is no discrete illite in the less than two micron size fraction of the samples I examined. It is also possible that some of the discrete illite observed by Hergenroder was sample contamination that came from the surrounding siltstones and shales, which contain abundant illite. Because all the samples Hergenroder analyzed contained discrete illite, however, it seems more likely that the techniques used to interpret the X-ray diffraction tracings did not allow for the precise identification of the clay minerals that is now possible using the higher-angle diffraction peaks on a given tracing (Środoń , 1980, 1984).

Plate 12 of Hergenroder (1966) is a correlation chart that, like Plate 26 of Miller and Fuller (1954) shows the correlation of K-bentonites along and across strike in the Valley and Ridge province from north Georgia to western Virginia. Hergenroder, like Huffman (1945) and Miller and Fuller (1954) before him, suggested that "...the upper thick bentonite at Hagan...is very likely equivalent to V-7 of Rosenkrans (1936)...", and Plate 12 of Hergenroder shows beds V-4 and V-7 in the Plum Creek (Tazewell) section of Rosenkrans (1936) correlating with the two prominent and thick K-bentonites at Hagan, beds R-7 and R-10 of Miller and Fuller. Nevertheless, in his 1973 paper, which was based in large part on this Plate 12, Hergenroder suggested that ...

> the upper thick bentonite (probably V-7) at Hagen [*sic*], Lee County, Virginia, can be correlated with the thick bentonite containing abundant biotite (T-4) near Gadsden, Alabama, 240 miles southwest. This bentonite has been tentatively identified at Birmingham, Alabama, and at Narrows, Virginia, 435 miles northeast.

Except that the upper bed at Hagan is equivalent to V-4 of Rosenkrans (1936), not V-7, as discussed above under the section on Huffman (1945), this definitive correlation by Hergenroder of the K-bentonites along strike in the southern Valley and Ridge province is in agreement with Haynes (1989) and the present study.

REINTERPRETATION OF REGIONAL CORRELATIONS IN ROCKLANDIAN STRATA

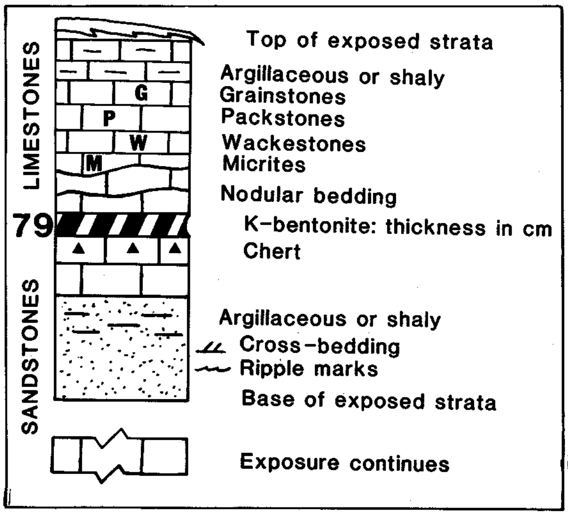
Five of the measured sections in southwest Virginia that were examined for the present research contain all three thick K-bentonites reported in previous studies of Rocklandian strata in the region. They are the Gate City, Rosedale, Plum Creek, Cove Creek, and Goodwins Ferry sections, and all five are in the central belt (Figure 1). Although the three thick K-bentonite beds were also described at the Hagan section in the western belt by Miller and Brosgé (1954) and Miller and Fuller (1954), the upper bed is now covered there. As a result no samples were collected and suitable measurements of the bed's thickness could not be made. Detailed study of these five key sections as well as of the many other less complete sections in the region provided the framework for the correlation of the K-bentonite sequence in the western belt with those in the central and eastern belts.

These correlations are based on the Deicke and Millbrig K-bentonites, which have been identified using the mineralogic criteria described in the preceding section. Because bed V-7 is a readily recognized K-bentonite at many exposures in the study area, particularly in the central belt where the stratigraphy is transitional between the eastern and western belts, it is also a very useful marker in several sections. Supplementing the K-bentonites as marker beds also are the three physical stratigraphic markers originally noted by Rosenkrans (1936) and listed above. The conglomeratic beds of the Walker Mountain Sandstone are also readily recognizable where present. Figure 8 shows the lines of the cross-sections that are discussed in the following sections.

K-BENTONITE STRATIGRAPHY OF THE WESTERN BELT

Figure 9 shows the correlation of K-bentonites between four sections along strike in the Powell Valley. Much of the stratigraphic information on the sections shown is from Huffman (1945), Miller and Brosgé (1954), Miller and Fuller (1954), and Kreisa (1980). The correlations are relatively straightforward, and they are supported by the mineralogical differences of the two thick K-bentonites, the Deicke and Millbrig. The Eggleston/ Trenton contact and the Millbrig K-bentonite can also be seen at the structurally disrupted section at Dryden.

At Hagan, three thick K-bentonites are present. The youngest and uppermost of the three is in the Trenton Limestone about 24 meters upsection from the middle bed. It is bed R-12 of Miller and Fuller (1954), and at present it is in a very poorly exposed part of the outcrop and no samples could be obtained during the present study. It is not shown in Figure 9. The two older beds, which are well exposed, are in the Eggleston Formation about eight meters apart and they are beds R-7 and R-10 of Miller and Fuller (1954). The upper



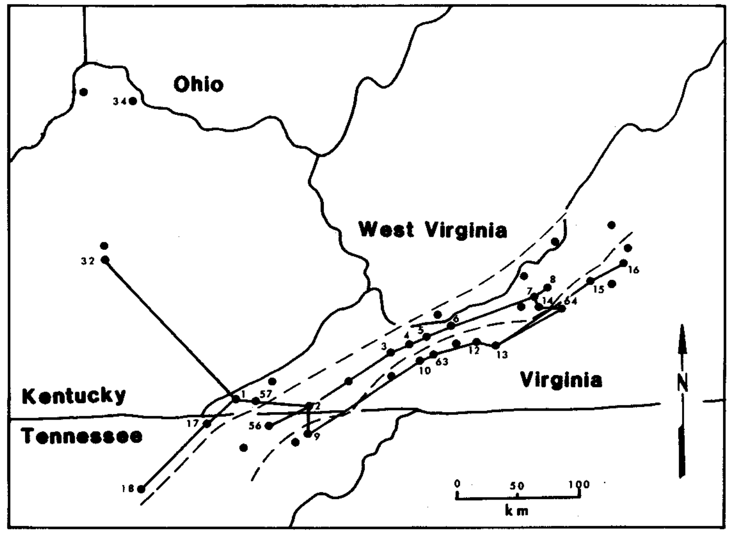


Figure 8. Legend and cross-section lines for Figures 9, 10, 13, 14, 19, and 21, with numbers of the measured sections. Section 34 is the location of the Black River Mine section in Figure 18. Dashed lines show the western, central, and eastern belts of Figure 2.

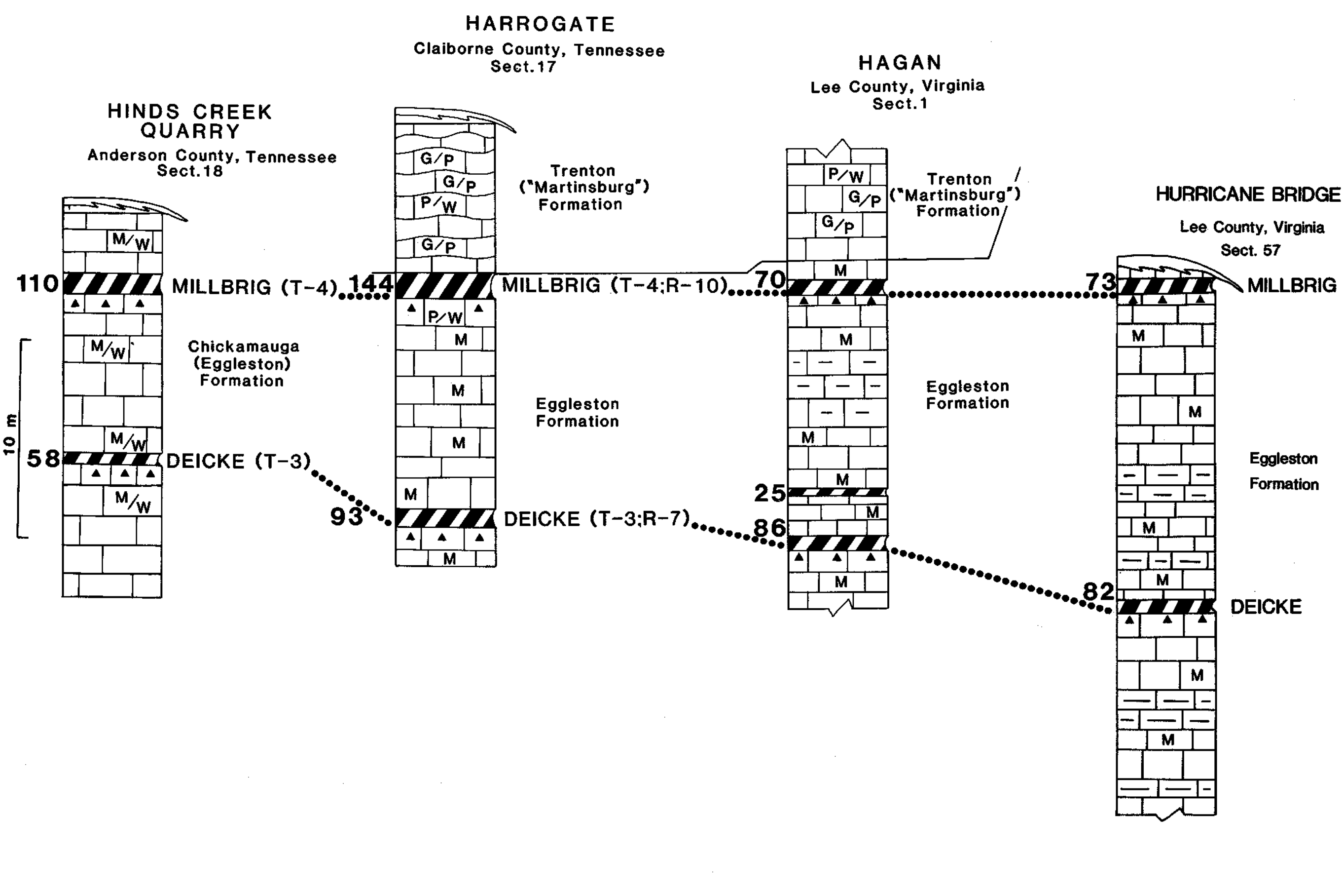


Figure 9. Correlation of the K-bentonite sequence along strike in the western belt between the Hinds Creek Quarry and Hurricane Bridge sections.

of these two K-bentonite beds is in the uppermost Eggleston Formation about three meters downsection from the base of the Trenton Limestone. The lower bed is in the middle of the Eggleston Formation. Petrographic examination shows that this lower bed, R-7, is equivalent to bed T-3 of the Cincinnati Arch, which Huff and Kolata (1990) have correlated with the Deicke K-bentonite Bed (Willman and Kolata, 1978) of the Upper Mississippi Valley. As a percent of the total phenocryst population, the coarse-grained part of this bed, the lowest 15 to 20 centimeters, contains less than one percent biotite or quartz, one to five percent Fe-Ti oxides, and the original plagioclases are labradorite. The upper of the two well-exposed beds, R-10, is correlated with bed T-3 of the Cincinnati Arch, which is equivalent to the Millbrig K-bentonite Bed (Willman and Kolata, 1978) of the Upper Mississippi Valley (Huff and Kolata, 1990). At Hagan, the coarsest part of this bed, which is the interval 10 to 25 centimeters above the chert layer at the base, contains 15 to 25 percent each euhedral biotite and subhedral to anhedral quartz, less than one percent opaque minerals, and the original plagioclases are andesine. The upper bed, R-12, was reported to contain some biotite by Miller and Fuller (1954), suggesting that it is equivalent to bed V-7 of Rosenkrans (1936), as that bed also contains biotite in noticeable amounts.

CORRELATION OF THE WESTERN BELT SEQUENCE WITH THE CINCINNATI ARCH SEQUENCE

Figure 10 shows the correlation of the K-bentonites at the Hagan section with the Deicke and Millbrig K-bentonites at the High Bridge section in the Bluegrass Basin of central Kentucky along the Cincinnati Arch. The section at Hagan is used for that correlation because it is typical of the western belt and it is very well exposed, as are several sections near High Bridge. Figure 11 shows the Deicke and Millbrig in the exposure at Hagan, and Figure 12 shows the Deicke at a quarry not far from High Bridge. The recessive weathering typical of the K-bentonites is apparent even in this relatively unweathered exposure along the adit to the underground workings of the quarry.

The most westerly exposures of Rocklandian strata in the Valley and Ridge province are in the Powell Valley. Sections there are lithologically and faunally transitional between those farther east in the Valley and Ridge province and those to the west along the Cincinnati Arch. For example, the K-bentonites at Hagan are texturally much more similar to those along the Cincinnati Arch even though the central belt sections with their K-bentonites that were described by Rosenkrans (1936) are geographically much closer to the Powell Valley. In the present study, this discovery proved to be the key in unifying the many different nomenclatural schemes shown in Figure 7. Thus, the section at Hagan, because of its geographic position between the more easterly outcrop belts in the Valley and Ridge and the outcrops along the Cincinnati Arch, is extremely important in the reinterpretation of the regional Rocklandian stratigraphic framework. The strata at Hagan are also very well exposed, and there is no doubt as to where in the section each K-bentonite is located, as demonstrated by the agreement of measured sections reported in several previous studies (Huffman, 1945; Miller and Brosgé, 1954; Miller and Fuller, 1954; Kreisa, 1980).

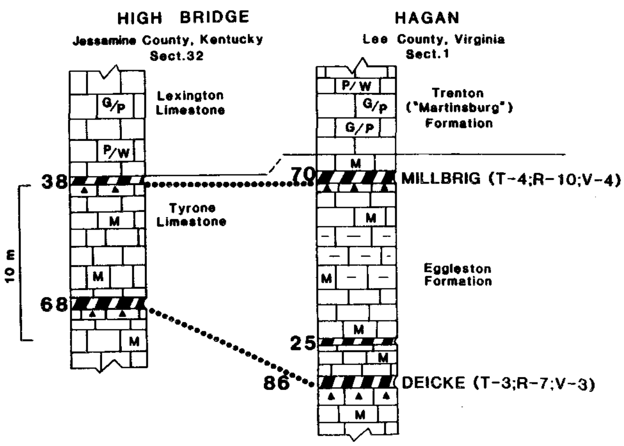
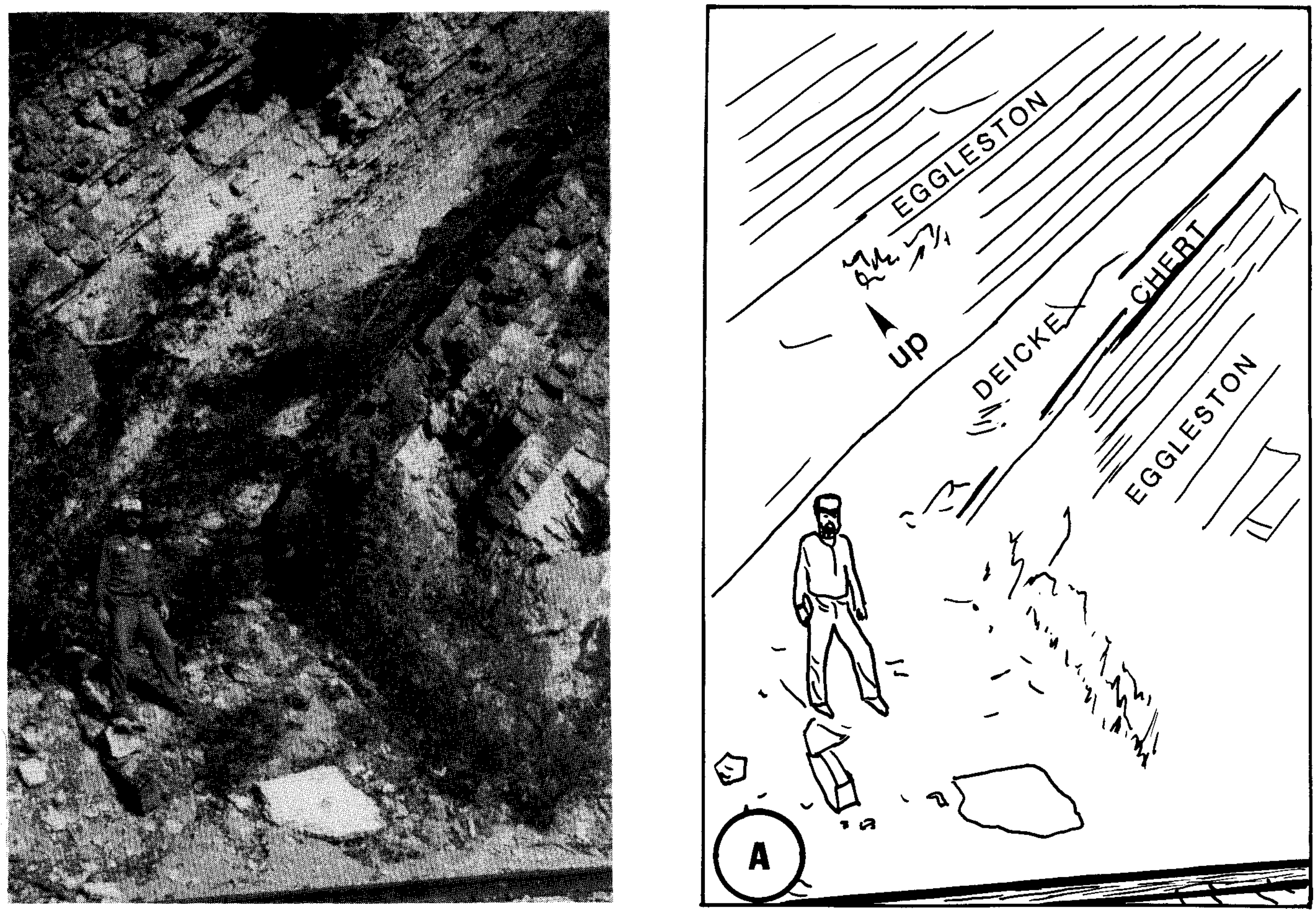


Figure 10. Correlation of the K-bentonite sequence between the High Bridge section in Kentucky and the Hagan section in Virginia.

This interesting relationship, where the stratigraphic sequence at Hagan is more similar to a sequence 200 kilometers away than to one that is only 50 kilometers away, holds for not only the K-bentonites and the other Ordovician strata but also for much of the Silurian, Devonian, and Mississippian strata in the Powell Valley (Butts, 1940; Miller and Brosgé, 1954; Rader, 1982). The rapid facies changes to the east made it very difficult for many previous workers to demonstrate correlation of strata in Powell Valley sections, such as at Hagan, with strata from well-studied localities farther east, such as at Tazewell, Virginia, where the Ordovician sequence has been described in detail (Cooper and Prouty, 1943). The paper by Miller and Brosgé (1954) resolved this problem by recommending many revisions of the Powell Valley stratigraphic nomenclature, and the names they introduced are now currently used in that area (cf. Rader, 1982), and those names are generally suitable for use throughout the Powell Valley farther south in Tennessee as well.

K-BENTONITE STRATIGRAPHY OF THE CENTRAL BELT

Throughout the central belt, the oldestr of the three thick K-bentonite beds is the readily recognized V-3 described by Rosenkrans (1936). It generally occurs within or one to three meters above the uppermost redbeds of the Moccasin Formation, and the K-bentonite itself consists of interbedded red and green/yellow-gray clay, with the coarser zones near the base containing many feldspar phenocrysts or weathered ghosts of those grains (up to 90 percent of the total phenocryst population) and opaque iron oxides (five to 15 percent) but no appreciable biotite or quartz (less than one percent). The next thick bed, V-4, is in the Eggleston Formation, five to eight meters above V-3. It contains abundant coarse biotite (15 to 25 percent), feldspar (30 to 50



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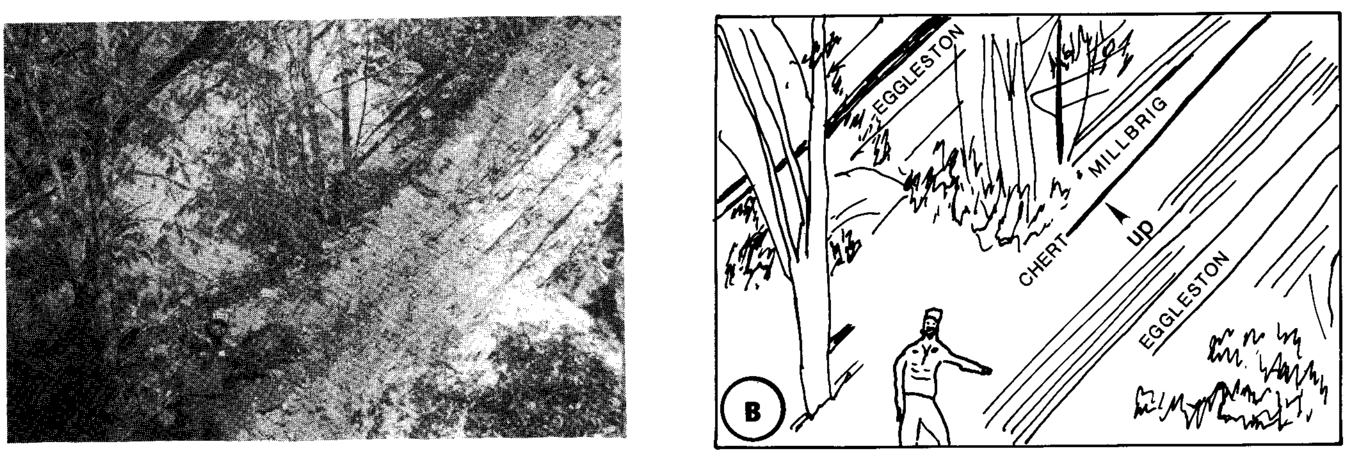

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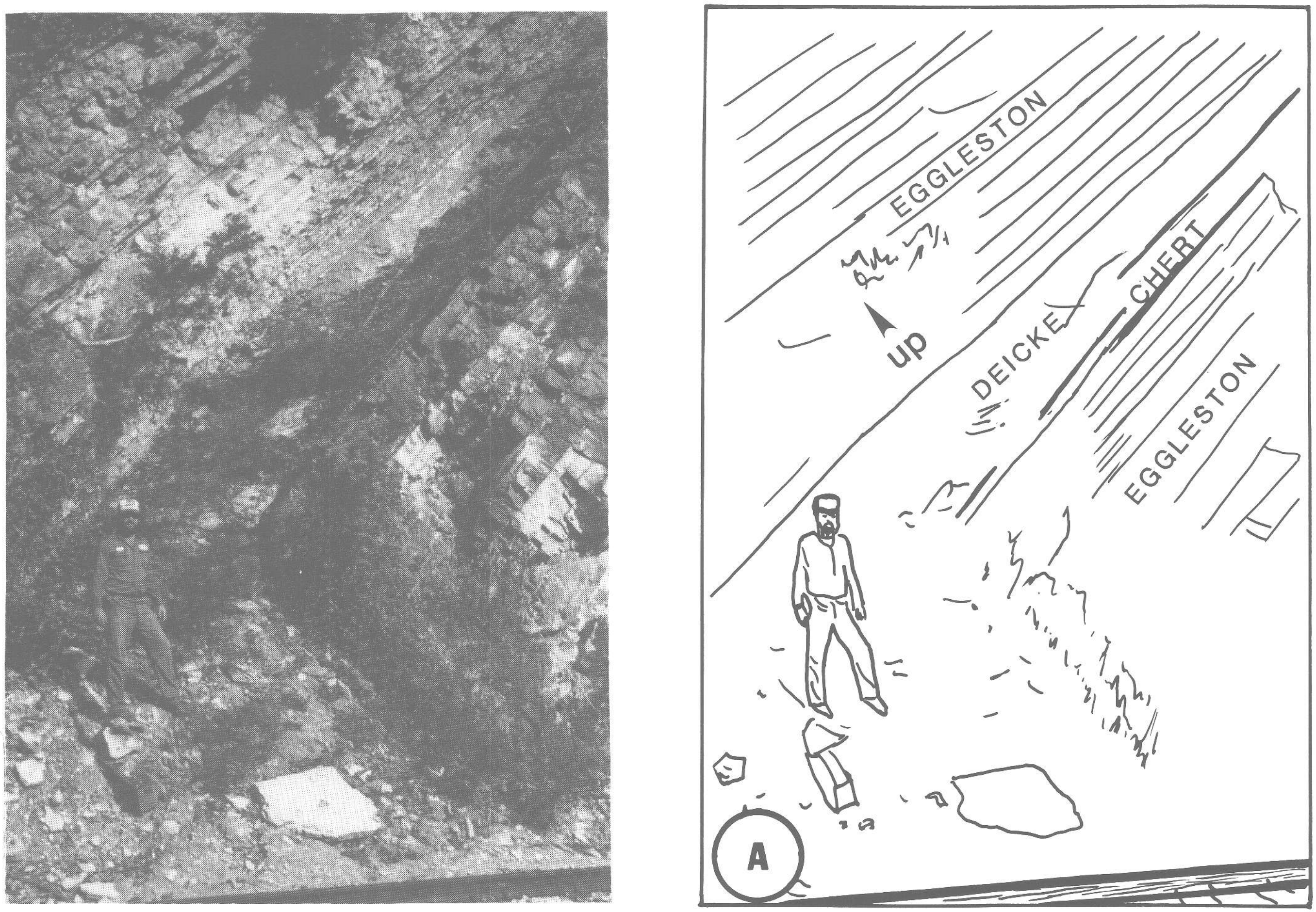
Figure 11. The Deicke and Millbrig K-bentonites at Hagan, Virginia. This excellent and important exposure is little changed from the time that the photographs and sketches in Miller and Fuller (1954) and Miller and Brosgé (1954) were made; nonetheless, fresh samples were obtained only after extensive excavation of both beds. Both beds are a greenish gray to gray color at this exposure. **A.** The Deicke. This bed is in the more prominent of the two recessed intervals along the railroad. **B.** The Millbrig. This bed occurs in the recessed interval that is overgrown with vegetation.



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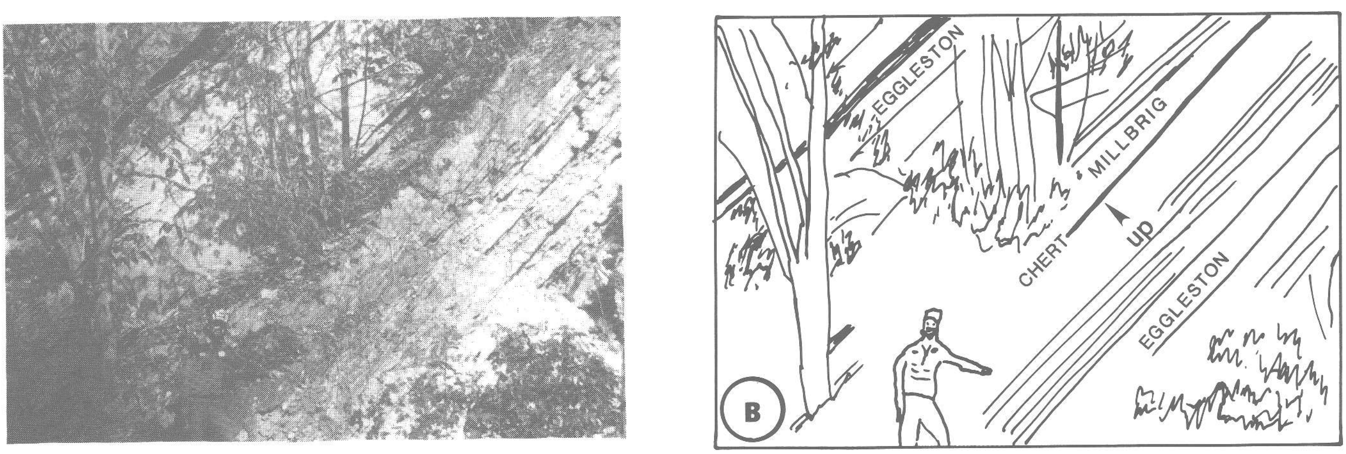

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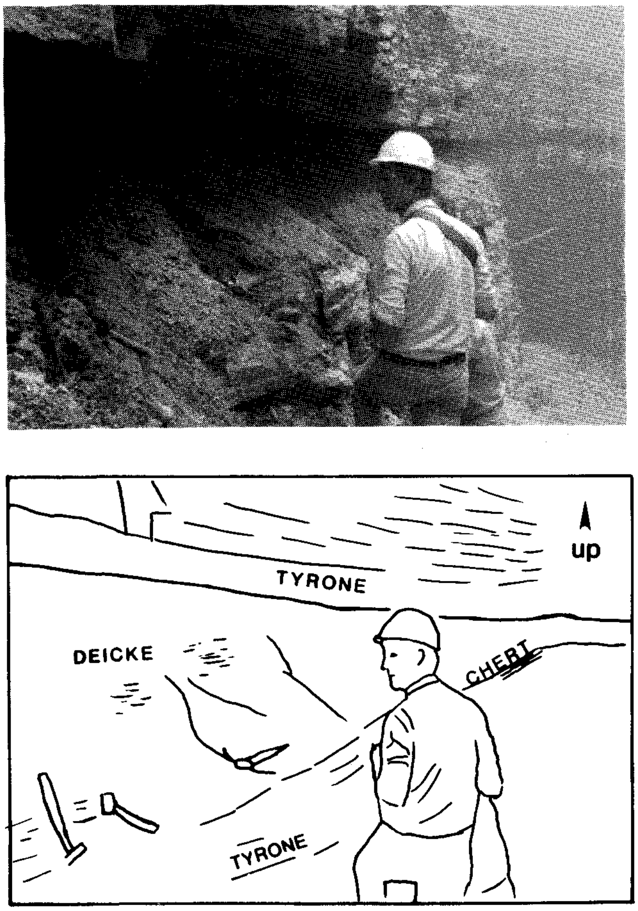


Figure 12. Exposure of the Deicke in the adit to the underground workings at the Lexington Limestone Quarry, Nicholasville, Kentucky. There are no significant changes in the texture or composition, and little change in thickness, of the K-bentonite between here and the exposure at Hagan (Figure 11A).

percent), and quartz (30 to 50 percent) phenocrysts. The abundant euhedral biotite in the coarse-grained zone that is the interval from 10 to 25 centimeters above the base is the distinguishing textural feature of this bed because the biotite grains are readily visible in hand samples of unweathered samples. Bed V-7 is five to eight meters upsection from V-4 and it is one to three meters below the "cuneiform beds" of the Eggleston, which are a distinct stratigraphic unit in the upper Eggleston Formation. The cuneiform beds are three to four meters of medium bedded micrites that are cut by numerous joints, giving the beds a resemblence to ancient cuneiform markings (Rosenkrans, 1936). V-7 contains biotite and quartz but in lesser amounts than in V-4. The lowest bioclastic grainstone bed of the Trenton ("Martinsburg") Formation occurs two to nine meters upsection of V-7.

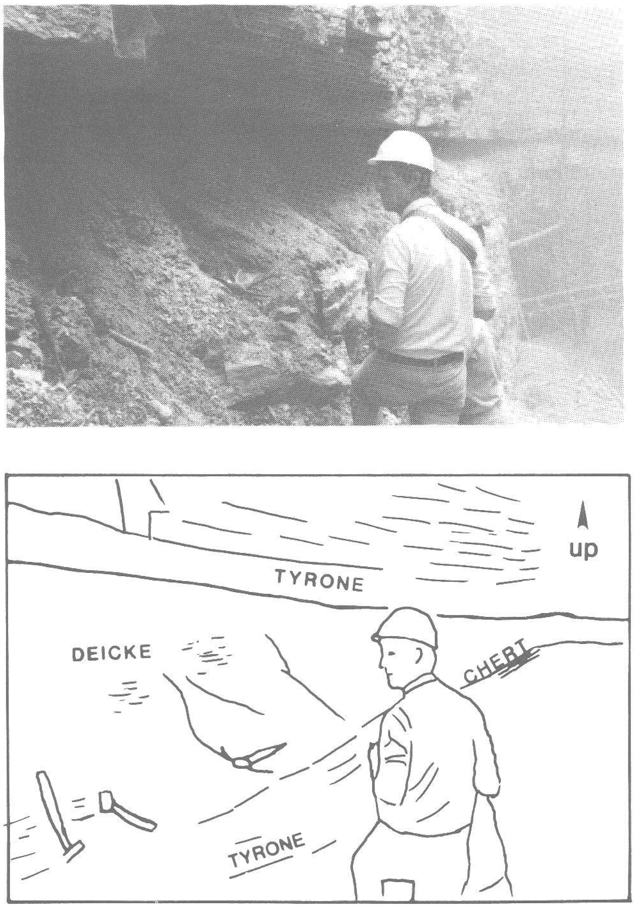
Figure 13 shows the correlation of the K-bentonite sequence in the central belt. Much of the stratigraphic information on the sections shown is from Rosenkrans (1936), Hergenroder (1966), and Kreisa (1980). Correlation of these sections along strike as shown is relatively straightforward as shown by Rosenkrans (1936), and as with the along strike correlations in the western belt (Figure 9) they are supported by the mineralogical differences of the Deicke and Millbrig K-bentonite beds. Parts of the central belt sequence can also be seen at the Thorn Hill, Little Moccasin Gap, Bluefield, Narrows, Trigg, Gap Mountain, and Mountain Lake Turnoff sections as well. The thinner K-bentonites that occur above bed V-7 at the Plum Creek and Goodwins Ferry sections were collected but not studied in detail. They are some of the K-bentonites that Rosenkrans labelled beds V-8 to V-14.

CORRELATION OF THE WESTERN BELT SEQUENCE WITH THE CENTRAL BELT SEQUENCE

Figure 14 shows the correlation of the Hagan section of the western belt with the Gate City section of the eastern belt based on the K-bentonites. The evidence that supports the correlation of each of the K-bentonites is discussed separately for each bed. Correlation with the Terrill Creek section is discussed later in the text.

Beds R-7 and V-3 How the sequence of K-bentonites at Hagan correlates with the standard section described by Rosenkrans (1936) at Plum Creek in Tazewell County, and with other sections in the central belt, is not at first readily apparent to the casual observer. Assuming that bed R-7 at Hagan is equivalent to bed V-3 at the Gate City section simply because each is the oldest thick K-bentonite in the section, it is obvious that the characteristic red color of V-3 is absent in bed R-7, which is greenish gray. That is because the Moccasin Formation, with its redbeds, is replaced in the Powell Valley by the gray carbonates of the Hardy Creek Limestone and a thicker Eggleston Formation (Miller and Brosgé, 1954; Le Van and Rader, 1983). Thus there are no surrounding red sediments that can impart a reddish tint to the bed, as with V-3 in the central belt, and in color bed R-7 at Hagan more closely resembles the Deicke (T-3) K-bentonite of the Cincinnati Arch, as discussed above. The sections that Rosenkrans (1936) chose for his descriptions of V-3 were all from exposures where V-3 occurs in what he considered to be either the Moccasin or Bays. Those units contain much reddish strata, and once the redbeds pinch out along or across strike, the distinct red color of bed V-3 disappears as well. A field comparison of the Hagan and Gate City sections shows that this is the case.

Petrographic study of samples from the coarser-grained lower zone of bed V-3 from the Thorn Hill, Eidson, Gate City, Plum Creek, and Cove Creek sections shows that less than one percent of either biotite or quartz phenocrysts are present. Feldspars are abundant, however, comprising up to ninety percent of the total phenocryst population. Samples from the Thorn Hill and Eidson sections, where the phenocrysts are noticeably coarser-grained than in the sections farther north, are greatly weathered and the feldspars highly altered, precluding precise quantitative analysis. Nonetheless, ghosts of numerous feldspar grains indicate that the K-bentonite was originally feldspar-rich. Although biotite and quartz are virtually absent, reddish-brown grains of hematite are present (1 to 10 percent). This hematite probably formed



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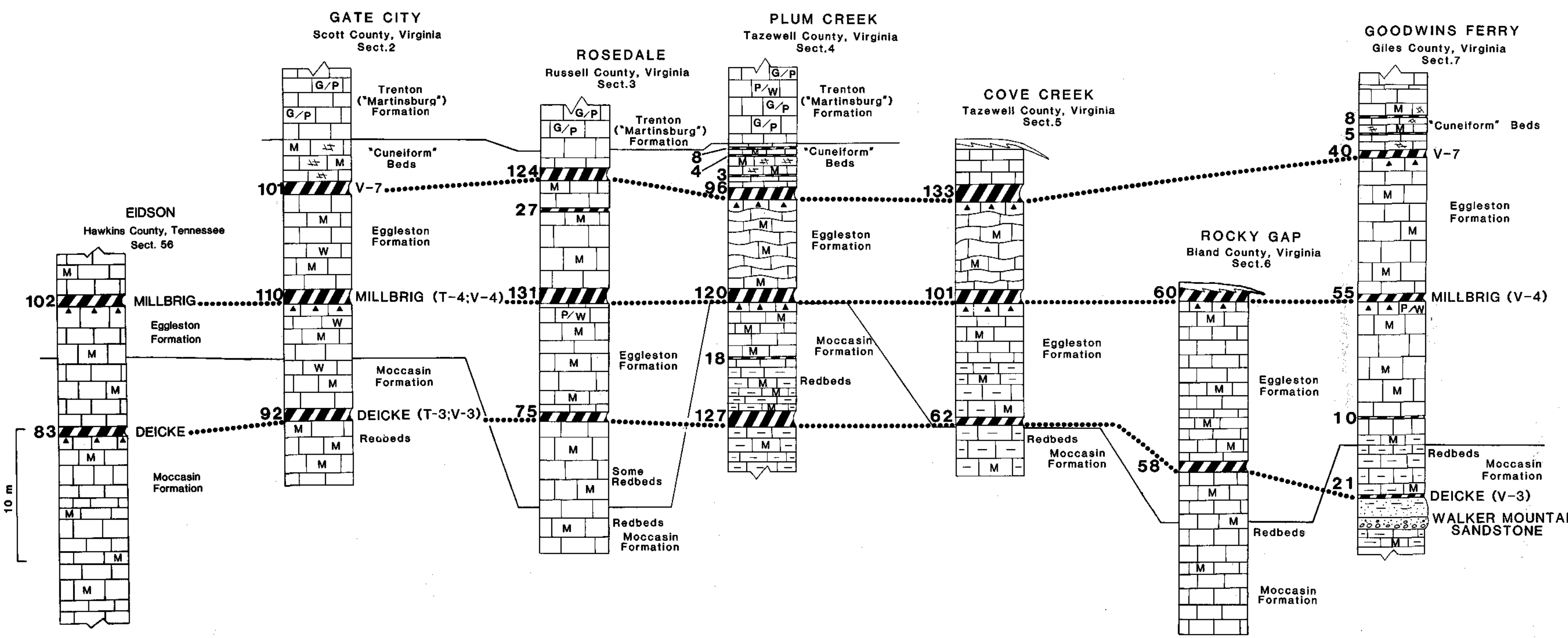


Figure 13. Correlation of the K-bentonite sequence along strike in the central belt between the Eidson and Goodwins Ferry sections. This is the area studied in detail by Rosenkrans (1936), whose "V" system of K-bentonite nomenclature is widely used in the region.

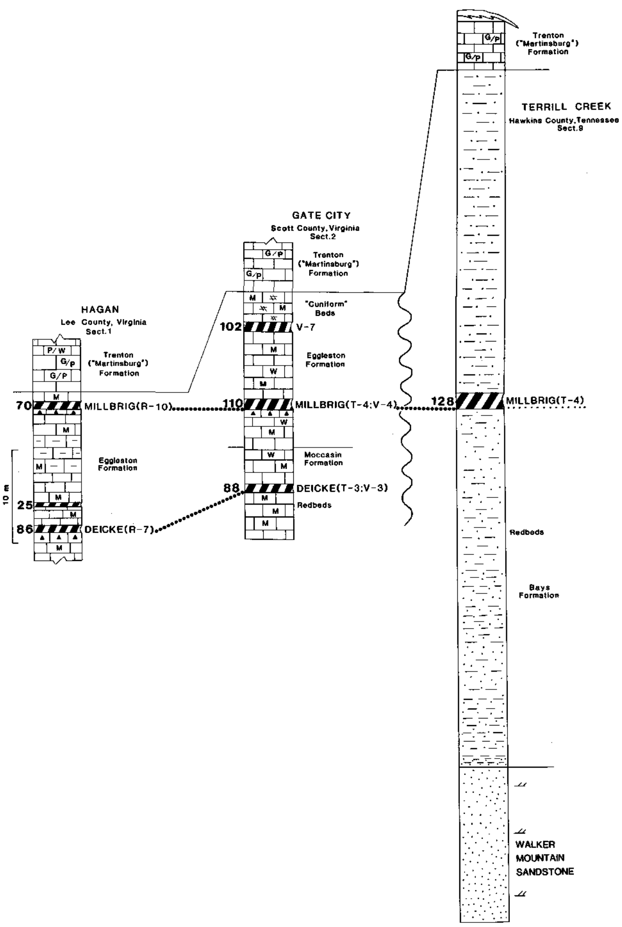


Figure 14. Correlation of the K-bentonite sequence between the western, central, and eastern belts in the southwestern part of the study area. Note the disappearance of the Deicke towards the southeast into the Bays and the persistence of the Trenton ("Martinsburg") Formation across the three belts.

from the oxidation of pyrite, which is abundant in samples of the Deicke along the Cincinnati Arch and in the western belt and is an older authigenic mineral (Haynes, 1989). The pyrite evidently formed during an early diagenetic phase as the ilmenite in the Deicke ash altered to rutile or anatase. Iron in the Moccasin Formation sediments has been thoroughly oxidized, imparting the distinct red color to that unit. This contrasts with the green and gray limestones of the Eggleston Formation, which contain reduced iron. Alteration of the pyrite to hematite presumably occurred after early diagenesis of the ash, when the original ilmenite was altered. Because ilmenite is stable under oxidizing conditions, the evidence suggests that locally reducing conditions within the ash occurred subsequent to deposition but prior to the pervasive oxidation that later affected the iron in both the Moccasin and the Deicke ash.

From this evidence it is most logical to correlate bed V-3 in the central belt with bed R-7 at Hagan, even though the diagnostic minerals listed in Table 1 could not be conclusively identified because of the diagenetic alteration of the ash. Because the petrographic evidence indicates that bed R-7 of Miller and Fuller (1954) correlates with bed T-3 along the Cincinnati Arch, which correlates with the Deicke K-bentonite Bed of the Upper Mississippi Valley (Huff and Kolata, 1990), then by association bed V-3 of Rosenkrans (1936) is also the Deicke.

Examination of the physical stratigraphic position of bed V-3 furnishes additional evidence to support this correlation. In the sections where beds V-3 and V-4 are exposed, V-4 is the next thick K-bentonite upsection from bed V-3 and it contains the diagnostic mineralogy of the Millbrig (Table 1). The interval between those two K-bentonites can be measured most precisely at the Rosedale, Plum Creek, Cove Creek, and Rocky Gap sections (Figure 13), where it changes very little.

Although the thicknesses of the K-bentonites do not change significantly between these sections, the relative stratigraphic position of the Deicke changes noticeably. In the Rosedale and Rocky Gap sections, which are along the western edge of the central belt, the Deicke occurs several meters above the Moccasin/Eggleston contact, whereas elsewhere in the central belt the Deicke is within the redbeds at the very top of the Moccasin. This is additional evidence that the base of the Eggleston Formation, like the base of the Trenton ("Martinsburg") Formation, becomes younger to the north and east in the study area. Figure 15A shows the Deicke at the Rocky Gap section in the westernmost outcrop belt of Rocklandian strata in the central belt, where the uppermost redbeds of the Moccasin Formation are a few meters downsection and the Deicke occurs in the lower Eggleston Formation. Figure 15B shows the Deicke in the redbeds of the upper Moccasin Formation in the excellent exposure at Gate City. At the Gate City section, the Moccasin/Eggleston contact, the Millbrig K-bentonite, K-bentonite V-7, and the Eggleston/ Trenton ("Martinsburg") contact are all very well exposed.

North of the Cove Creek section, V-3 becomes finer grained and thus thin-section study reveals little about the phenocryst mineralogy. The bed does retain its distinctive red color and its stratigraphic position near the top of the Moccasin north to the New River Valley, although it does become thinner. North of Giles County, the red color rapidly disappears as the redbeds of the Moccasin are eventually replaced by the gray limestones of the Nealmont Formation (Woodward, 1951; Kay, 1956).

Note in the Goodwins Ferry section in Figure 13 that the Deicke is associated with the Walker Mountain Sandstone and its strikingly distinct white conglomeratic quartz arenite that stands out the in redbeds of the Moccasin. This stratigraphic association is shown in Figure 24 and it can also be seen at the Mountain Lake Turnoff section (Figure 21) and at the Trigg section (Hergenroder, 1966, p. 307).

<u>Beds R-10 and V-4</u> The coarse-grained zone of bed V-4 from the Gate City, Rosedale, Plum Creek, Cove Creek, Rocky Gap, and Gap Mountain sections contains abundant coarse-grained biotite and quartz (30 to 50 percent of the total phenocryst population), with the biotite being recognizable even in some of the more deeply weathered samples. V-4 is the only thick K-bentonite bed (greater than 10 cm) in the region that contains abundant bronze, gold, dark

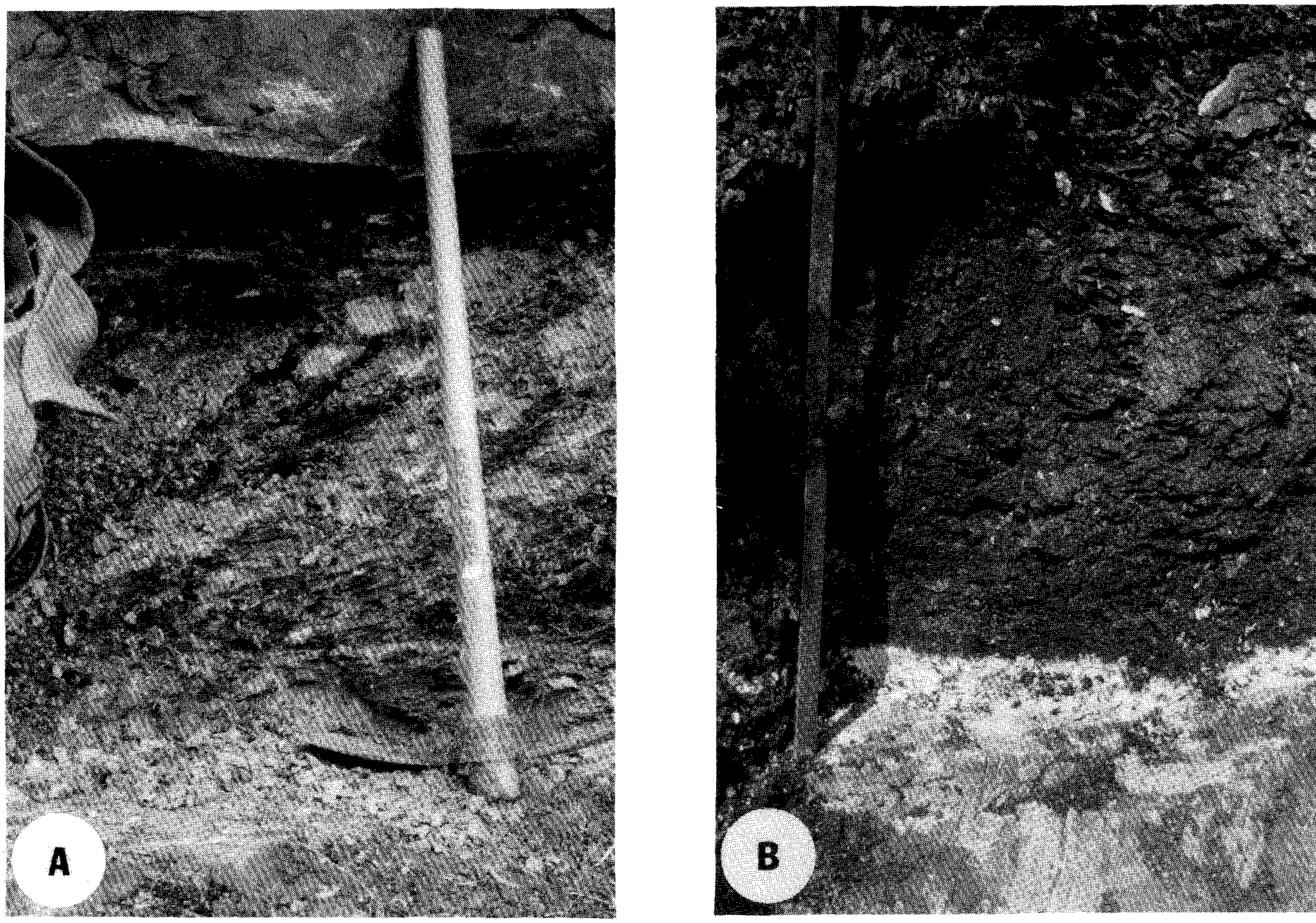


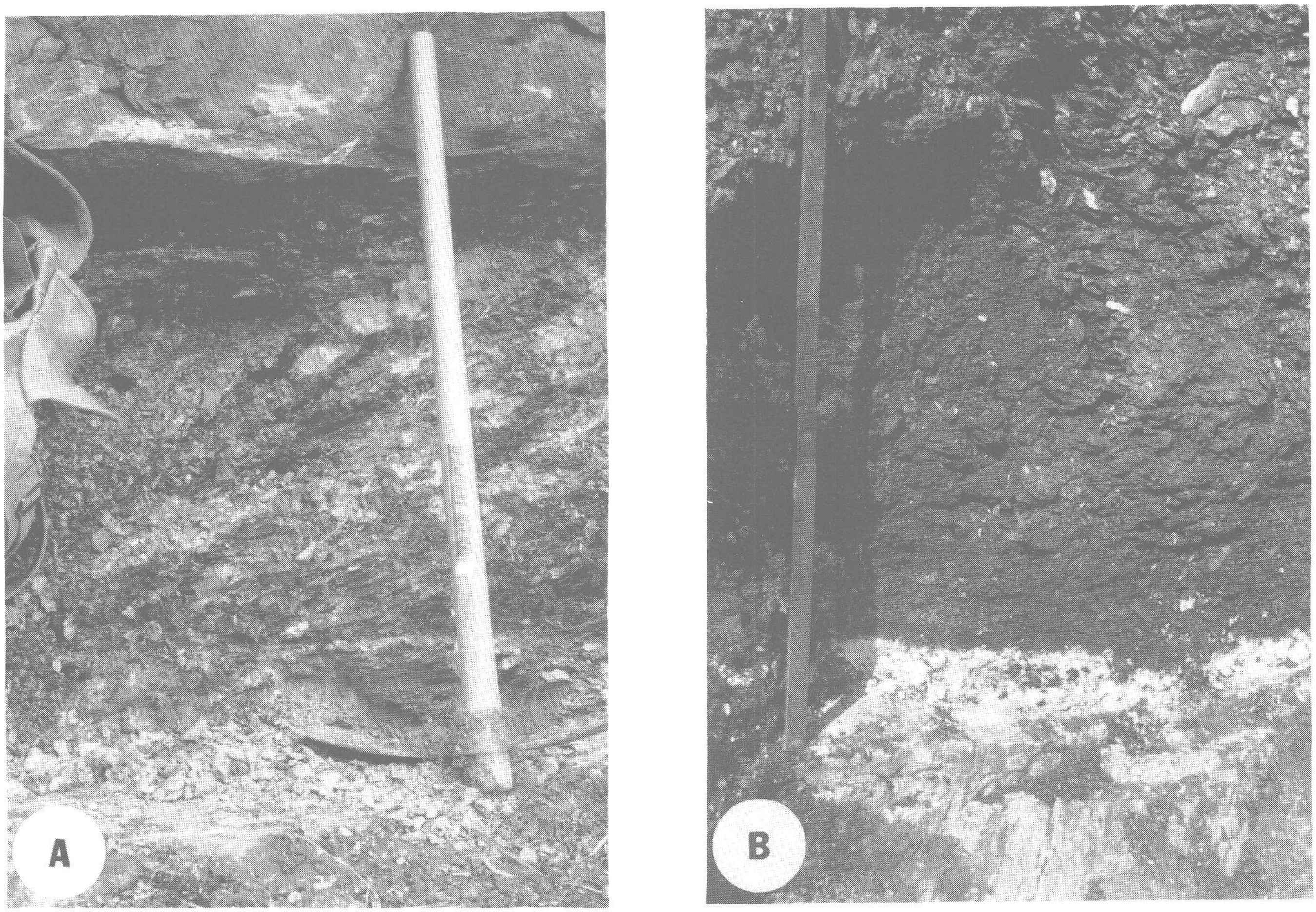
Figure 15. Exposures of the Deicke K-bentonite Bed. The relative stratigraphic location of this K-bentonite changes noticeably across strike in the study area. **A.** The Deicke in the Eggleston Formation at Rocky Gap, Virginia, along Frontage Road. The uppermost redbeds of the Moccasin are several meters downsection, yet the red and yellow coloration that is characteristic of this bed in the central belt is still evident. The mattock rests on the top of the underlying limestone and leans against the overlying limestone, and the handle is 75 centimeters long. **B.** The Deicke in the redbeds of the upper Moccasin Formation at Gate City, Virginia. Here it is nearly completely red except for the plastic whitish gray clay at the base. The measuring rule rests on the top of the underlying limestone and leans against the overlying bed and the scale is in centimeters .

brown, or black euhedral to subhedral biotite grains up to 1.5 millimeters in length. The biotite is readily noticed in the field when samples from the coarser parts of the bed are examined, and even samples from the finer-grained upper part usually contain visible biotite. The bed can thus be consistently recognized in the field *in unweathered or well-excavated exposures* on this basis much as bed V-3 in the central belt is recognizable on the basis of red color. Figure 16 shows the Millbrig in the Eggleston Formation at the Gap Mountain section.

Unlike the marked textural differences between bed V-3 at Plum Creek and bed R-7 at Hagan, beds V-4 and R-10 are texturally very similar. Because the texture is regionally consistent it is this bed that most readily establishes the correlation between the western and central belt K-bentonite sequences, and between the Cincinnati Arch and Valley and Ridge sequences, as there is little visible difference compositionally in samples from the two belts.

The petrographic evidence thus indicates that bed V-4 in the central belt as described by Rosenkrans (1936) is equivalent to bed R-10 at Hagan as described by Miller and Fuller (1954). Because bed R-10 of Miller and Fuller (1954) correlates with bed T-4 along the Cincinnati Arch, which correlates with the Millbrig K-bentonite Bed of the Upper Mississippi Valley (Huff and Kolata, 1990), then by association bed V-4 of Rosenkrans (1936) is also the Millbrig.

Bed V-7 As previously noted, K-bentonite bed V-7 of Rosenkrans (1936) occurs in a distinct stratigraphic position in the central belt, only one to three meters below the base of the "cuneiform" beds of the Eggleston Formation and just a few meters below the fossiliferous grainstones and packstones that mark the base of the Trenton ("Martinsburg") Formation. Petrographic study of V-7 was undertaken initially with the first petrographic investigation of bed V-4 because V-7 had been considered by Rosenkrans (1936), Huffman (1945), and Miller and Fuller (1954) to be equivalent to the younger of the two thick K-bentonites that occurs in Rocklandian strata along the Cincinnati Arch and elsewhere in the southern Valley and Ridge province. Although that K-bentonite, bed T-4 of Wilson (1949), has now been identified as the Millbrig, that correlation was not clear at the



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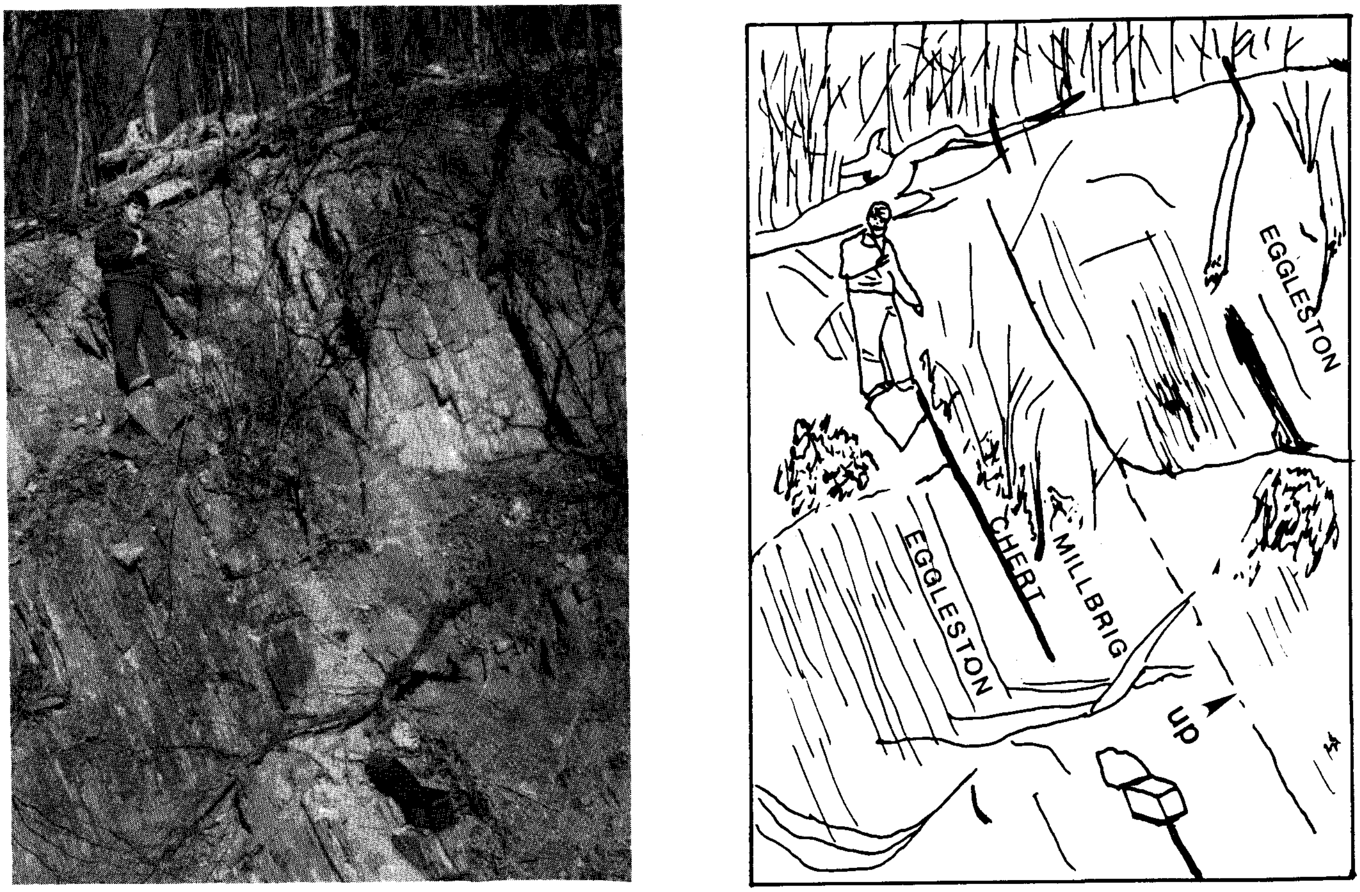


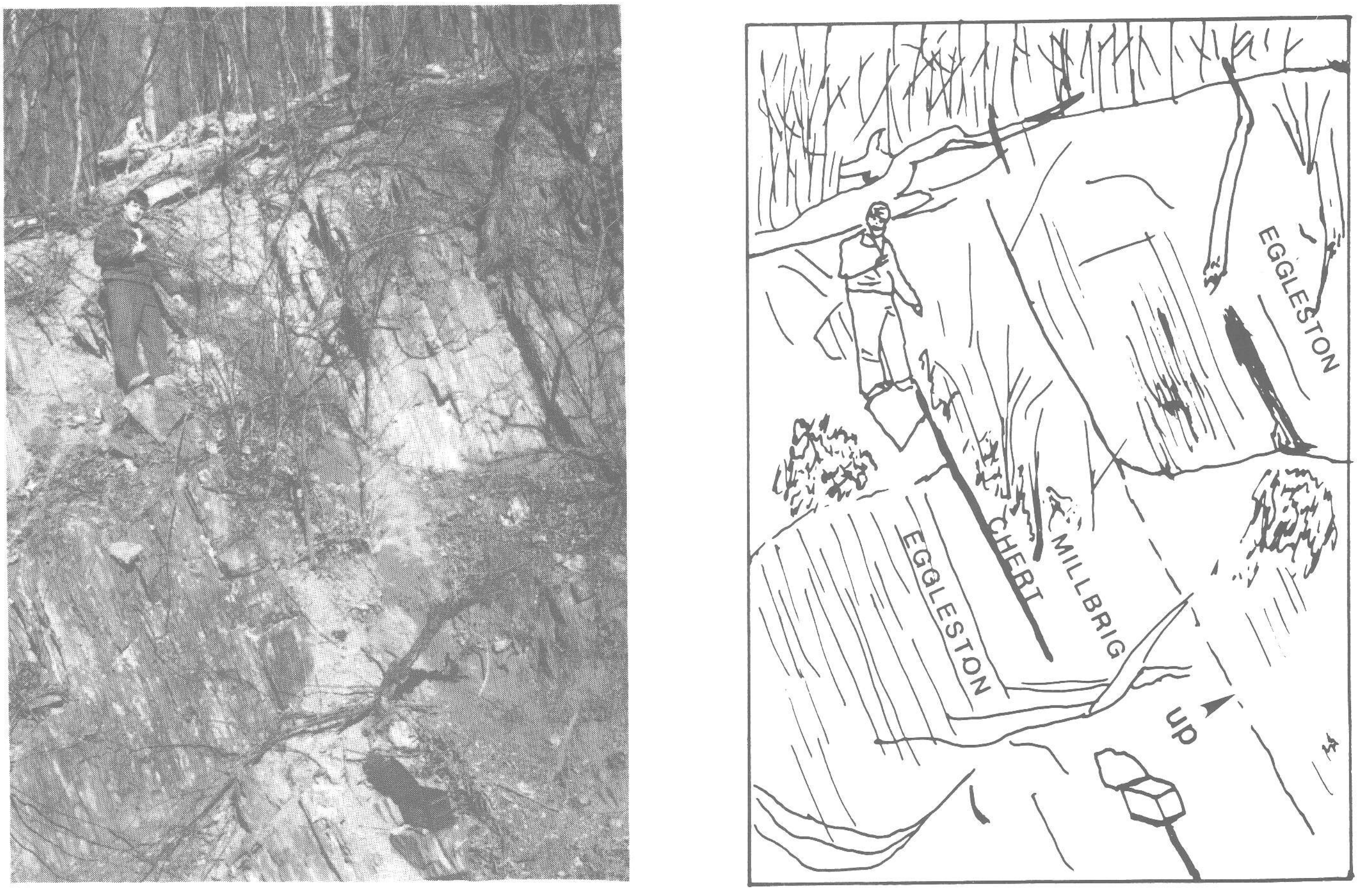
Figure 16. The Millbrig in the Eggleston Formation at the Gap Mountain section, just downstream of the Upper Narrows of the New River in Virginia.

beginning of the present study. Bed V-7 contains visible biotite, which was expected assuming that it was equivalent to bed T-4, samples of which were being studied from exposures along the Cincinnati Arch. It was soon discovered, however, that samples of beds V-4 and V-7 from the central belt both contain more than just a few scattered grains of biotite, unlike bed V-3 from the same belt. The biotite in bed V-4 is more abundant and the grains are consistently larger, however, suggesting that bed V-7 should be correlated not with T-4 but with one of the K-bentonites that occurs upsection from T-4 in the Cincinnati Arch (cf. Huff, 1983). Examination of samples from several of these K-bentonites from exposures along the Cincinnati Arch shows that they contain varying amounts of biotite: none contains biotite in the size or abundance that is seen in bed T-4, but they all contain more biotite than is present in bed T-3. Also, as previously noted, Miller and Fuller (1954) had observed some biotite in the upper of the three beds at the Hagan section in the Powell Valley, further supporting the conclusion that bed V-7 of Rosenkrans (1936) is not equivalent to bed T-4, the Millbrig K-bentonite, in the exposures along the Cincinnati Arch. Because the focus of the present study was on the Deicke and Millbrig, no further petrographic study of bed V-7 was undertaken. Figure 17 shows bed V-7 in the Eggleston at the Gap Mountain section.

If V-7 is in fact correlative with one of the K-bentonites above the Millbrig in the exposures along the Cincinnati Arch, it appears that it thins rapidly in that direction. This is because the K-bentonites above the Millbrig in exposures along the Cincinnati Arch tend to be consistently less than 30 centimeters thick. The section at the Black River Mine along the eastern edge of the Cincinnati Arch in Carntown, Kentucky (Figure 18) does, however, contain a thick K-bentonite that is above the Millbrig. That 0.7 meter thick bed may be equivalent to bed V-7 as it is the only thick K-bentonite above the Millbrig. Both the Millbrig and an unusually thin Deicke have been identified there petrographically using the criteria in Table 1 (Haynes, 1989).

K-BENTONITE STRATIGRAPHY OF THE EASTERN BELT

K-bentonites in the eastern belt are exposed in several outcrops of the Bays Formation. At first appearance the K-bentonite sequence in the Bays is quite unlike the sequence in the Moccasin and Eggleston Formations to the west. Only one or two thick K-bentonites occur in the Bays at the Terrill Creek, Chatham Hill, Crockett Cove, Connor Valley, and Daleville sections, all of which are quite well exposed. As with the K-bentonites elsewhere in the study area, these beds are identified conclusively as K-bentonites by their distinct clay mineralogy. The older bed everywhere contains abundant biotite grains (up to 60 percent of the total phenocryst



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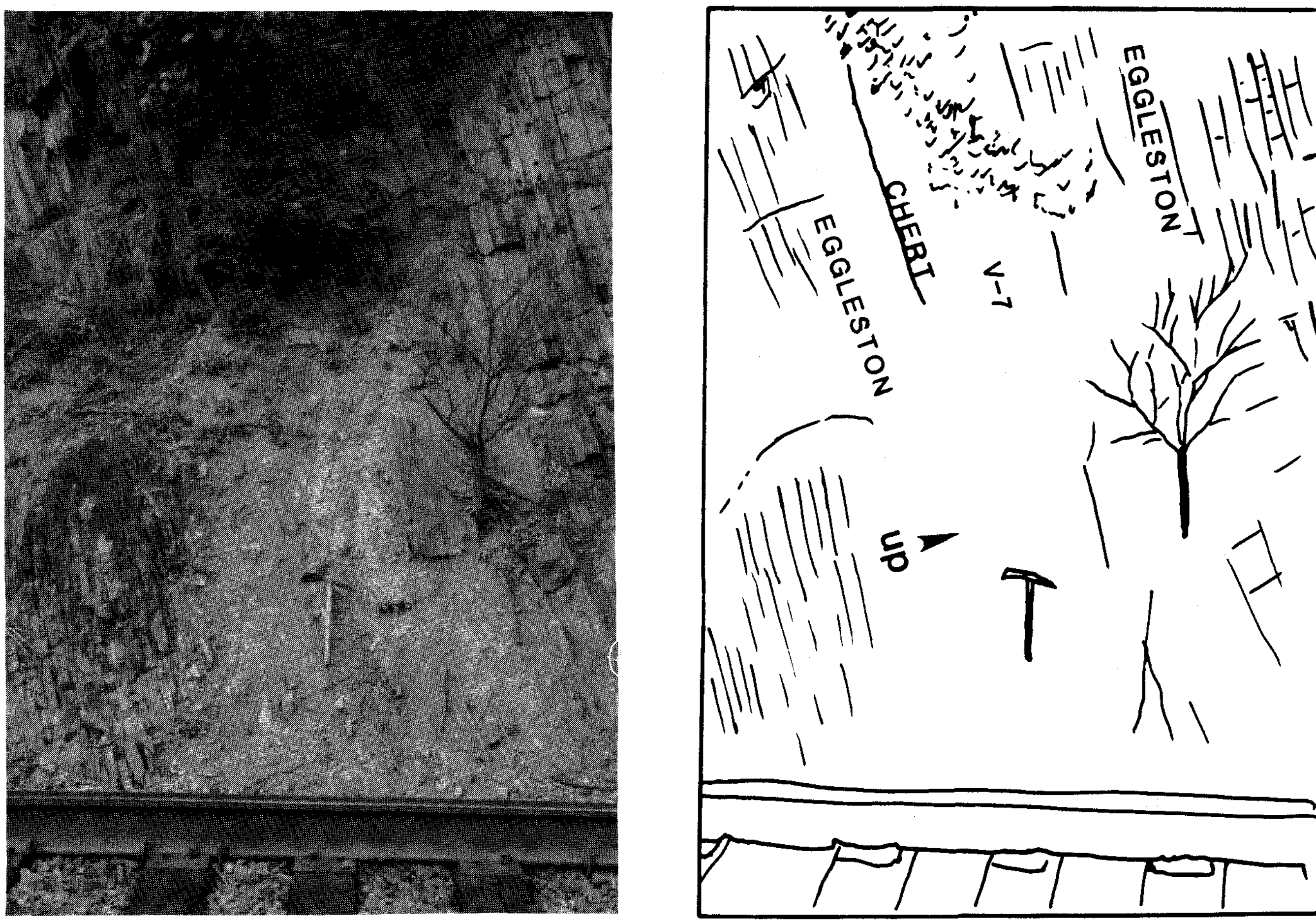
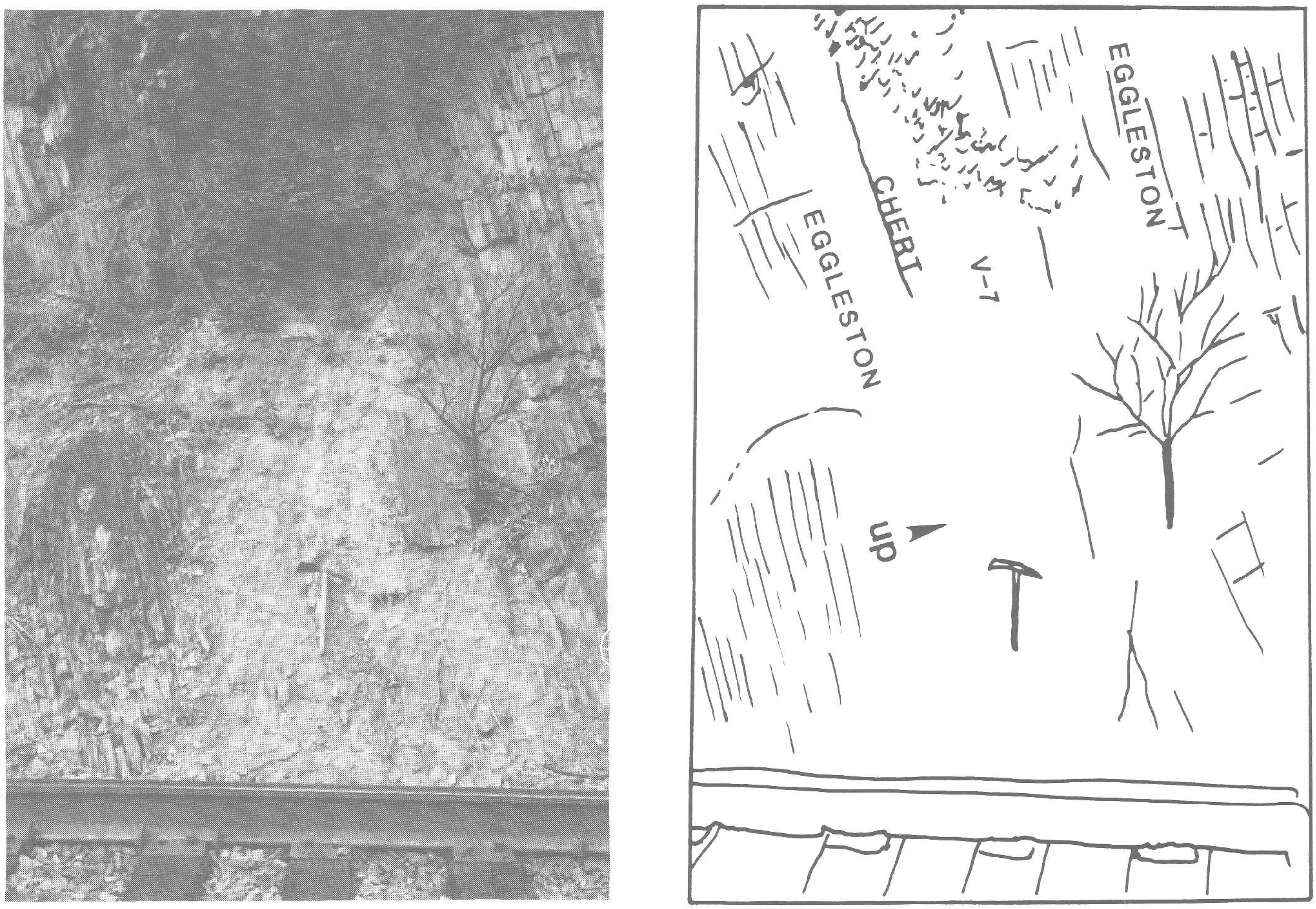


Figure 17. Bed V-7 in the Eggleston at the Gap Mountain section just upsection from the Millbrig, shown in Figure 16. This section is southeast of the Saltville fault, yet the stratigraphic sequence is nearly the same as at the nearby Goodwins Ferry section across the fault to the northwest although the Moccasin Formation is thinner at the Gap Mountain section.

population) that in the exposure at Chatham Hill are partly chloritized and kaolinized but still recognizable as biotite (Figure 3D). Although this K-bentonite is grayish red at Chatham Hill, like the surrounding Bays sediments, it is grayish white with red mottles at the Terrill Creek section, grayish white and pale orange at the Connor Valley section, and greenish gray at the Crockett Cove and Daleville sections. Biotite in samples from those exposures is golden bronze to black rather than blue-green like the abundant but highly chloritized biotites that occur at the Chatham Hill section. Quartz and feldspar phenocrysts are common (50 to 70 percent) in samples of the bed from the Crockett Cove and Daleville sections, although the feldspars are highly altered, precluding identification with the electron microprobe or petrographic microscope. Also, the sandstones in the two to three meters immediately overlying this K-bentonite at the Crockett Cove section contain abundant coarse biotite both along bedding planes and throughout the rock, indicating that a significant amount of reworked ash is present. This lower K-bentonite is identified as the Millbrig principally because of its thickness and abundant biotite and quartz grains, and overall lack of abundant Fe-Ti oxide minerals. Almost equally as significant, however, is that the Deicke, which in the Moccasin Formation at the Goodwins Ferry section to the northeast immediately overlies the Walker Mountain Sandstone (Figure 13), is clearly absent from this same stratigraphic interval in the Bays at the well-exposed Chatham Hill and Nebo sections (Figure 19), where local structural disruption is negligible. From study of the McCall Gap and Terrill Creek sections, which are less well exposed, it appears that the Deicke is again absent from that stratigraphic interval. Because the Millbrig is the next thick K-bentonite upsection from the Deicke in the normal Rocklandian K-bentonite sequence, this is also very compelling evidence for identifying the thick K-bentonite, which is clearly the first one in the Bays above the Walker Mountain Sandstone at those exposures, as the Millbrig. In an exposure on the Saltville thrust sheet near Marion, Virginia, Hergenroder (1966, Mitchell Valley section, p. 268, unit 5) describes a coarse-grained sandstone 140 feet above the base of the Bays that fits the description of the Walker Mountain Sandstone. According to his description the next 180 feet of the Bays is completely exposed, and the first K-bentonite he notes is a four foot thick bed that is about 71 feet (21 meters) above this coarse sandstone. This interval is comparable to the interval between the Walker Mountain Sandstone and the Millbrig at the Chatham Hill section a few kilometers to the west on the same thrust sheet. Therefore, although I was



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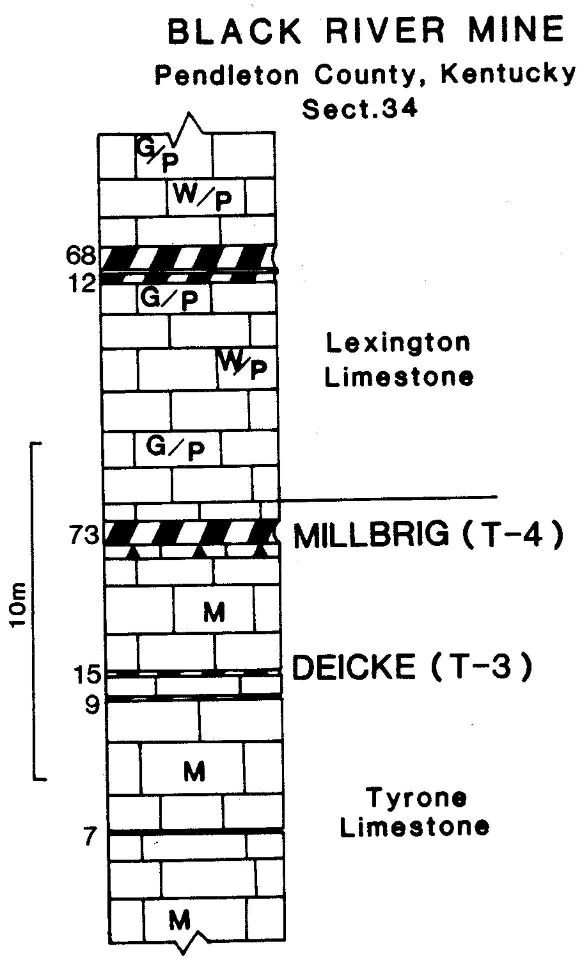


Figure 18. Measured section in the entrance shaft to the Black River Mine in Carntown, Kentucky. See Figure 8 for symbols key. The Deicke is quite thin at this locality, only 15 centimeters thick, which is comparable to its thickness at the Goodwins Ferry (Figure 13) and Narrows (Rosenkrans, 1936, Plate 10, bed V-3) sections in the New River Valley.

unable to locate this exposure, the stratigraphy of the Mitchell Valley section also supports the conclusion that the Deicke is absent from the Bays.

It is likely that the Deicke ash almost certainly was deposited across the basin but because of reworking or removal by erosion it was not preserved as a separate, discrete bed of bentonitic material in the Bays. The lack of biotite and quartz in the Deicke means that the reworked ash would not be as noticeable in the surrounding strata as is the case with the biotite of the Millbrig in the overlying sandstones at the Crockett Cove and Catawba sections. The phenocrysts of the Deicke are more labile in sedimentary environments than those of the Millbrig, and because the Bays contains significant amounts of feldspar throughout (Hergenroder, 1966), there is little chance that any reworked Deicke ash would be recognizable in the rocks immediately overlying the Walker Mountain Sandstone.

The exposure of the Millbrig in the Bays Formation at the Crockett Cove section is shown in Figure 20. Additional evidence that this first thick K-bentonite above the base of the Bays is the Millbrig is found at the Daleville section, where again almost the entire Bays and its upper and lower contacts are completely exposed. At that section the strata, although nearly vertical, are also little disrupted structurally on an outcrop scale and there are two biotite-bearing K-bentonites several meters upsection from the base of the Bays. The older K-bentonite, which is about 18 meters above the base, is coarser grained, whereas the younger K-bentonite, although quite similar in appearance, is slightly finer grained. This sequence clearly suggests that the older bed is correlative with the Millbrig and the younger bed is correlative with bed V-7 of the central belt.

An unusual sequence is seen at the Catawba section (Figure 19). At that section a 0.1 meter thick K-bentonite (bed number 4 of Hergenroder, 1966, p. 156) occurs near the base of the exposure. Closer examination shows that the overlying 0.5 meter thick sandstone sequence contains abundant coarse biotite both along bedding planes and throughout the rock. These observations suggest that this K-bentonite is the Millbrig and that the biotite-rich zone of the ash was extensively reworked and dispersed in the overlying sands. Although the K-bentonite bed itself is very thin, it is texturally very similar to the biotite-poor lower 10 to 15 centimeters of the Millbrig at the Crockett Cove, Connor Valley, and Daleville sections. And, the sandstones overlying the Millbrig at the Crockett Cove section also contain abundant coarse grained biotite, but there the Millbrig is of more normal thickness, as shown in Figures 20 and 21.

K-bentonite bed V-7 has been identified at the Connor Valley, Catawba, and Daleville sections. It is a predominantly maroon red bed at the Connor Valley and Catawba sections, whereas at the Daleville section it is greenish gray. It contains biotite but not of the size or amount seen in the Millbrig where that bed is exposed and can be studied downsection.

The thin K-bentonite above bed V-7 at Catawba and Daleville is most likely equivalent to either bed V-8, V-9, or V-10 of Rosenkrans (1936). The five K-bentonites in the Bays redbeds in the upper part of the Ellett section were also sampled. One of them is over 60 centimeters thick (bed 97 of Hergenroder, 1966, p. 276) and it seemed likely that that bed would be either the Millbrig or V-7. On closer examination, however, it appears that the bed has been structurally thickened from shearing and crumpling along one of the many faults visible in this exposure (Hergenroder noted 18 faulted contacts and two probable covered fault zones in the upper 300 feet of the Bays at Ellett, which is a well-exposed part of the section). In addition, that bed and the thinner beds just below it contain some biotite, but not in the amounts normally seen in the Millbrig or V-7. Assuming that this thicker K-bentonite bed has been structurally disrupted and thickened, then these five K-bentonites are a good match for beds V-10 through V-14 of Rosenkrans (1936). Rosenkrans described those beds as ranging in thickness from one to 14 inches (2.5 to 35.5 cm), and such thicknesses compare favorably with the thicknesses of the five beds at Ellett. Also, Rosenkrans noted that the fossiliferous beds at the base of the Trenton ("Martinsburg") Formation usually appear between beds V-11 and V-12. Because the base of the Trenton is younger to the northeast it is logical to expect that in the Salem synclinorium, where the Ellett section is located, these upper K-bentonites, if present, would be at or

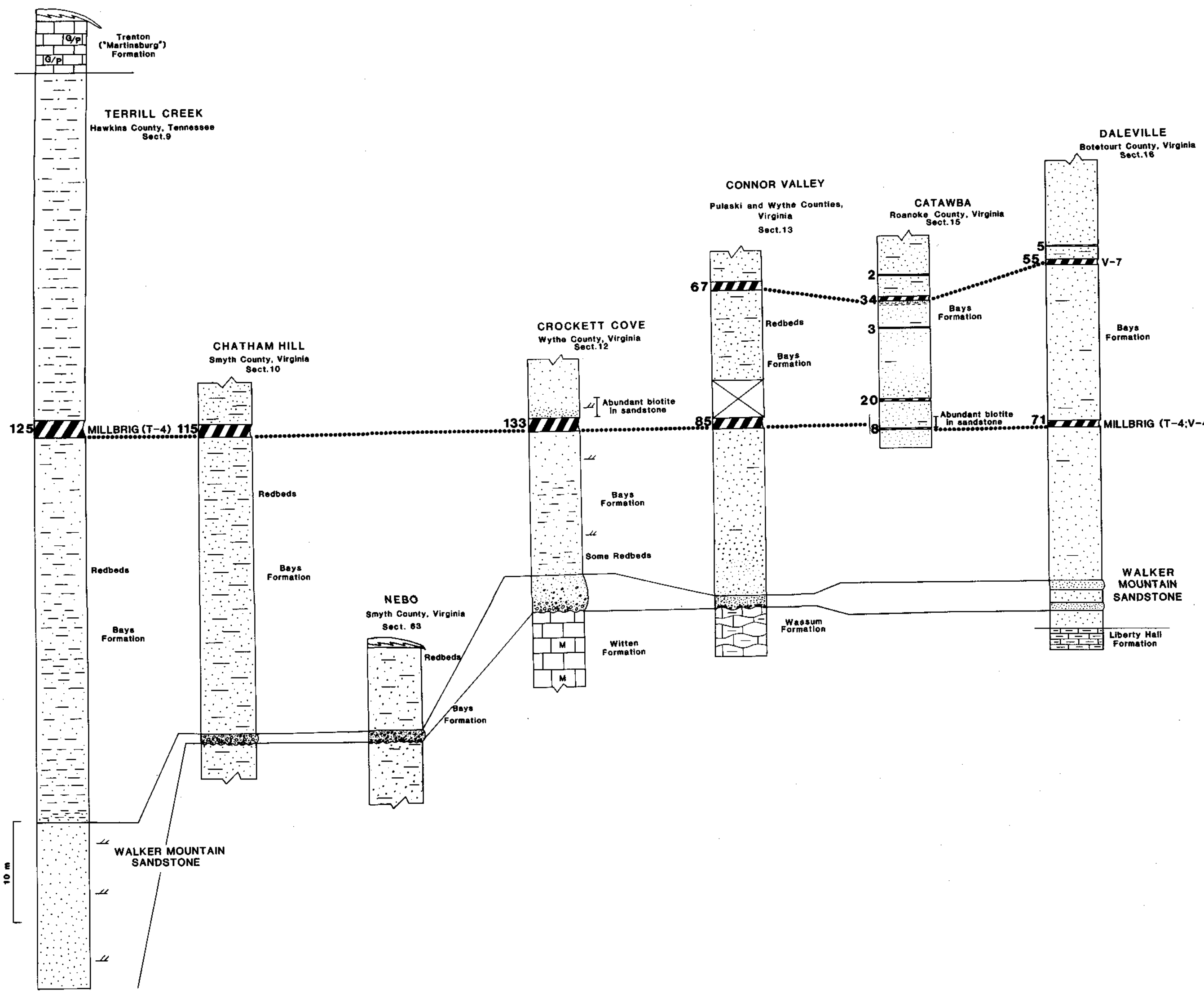


Figure 19. Correlation of the K-bentonites along strike in the eastern belt between the Terrill Creek and Daleville sections. The Trenton Formation, shown only on the Terrill Creek column, occurs above the Bays at each of these sections.

just below the base of the Trenton. This is what is seen at the Ellett section, even though the Bays/Trenton contact is faulted. Because of the unusually great thickness of the Bays reported there (cf. Hergenroder, 1966), the Ellett section is discussed in detail in the section on the conglomeratic sandstones in the Bays.

CORRELATION OF THE CENTRAL BELT SEQUENCE WITH THE EASTERN BELT SEQUENCE

Previous studies have shown that there are no readily apparent criteria on which to base any correlations of the K-bentonites that occur in the Bays Formation with those that occur in the Moccasin, Eggleston, and Trenton Formations farther west, even using the criteria on which correlations in the central and western belts are based. Both Rosenkrans (1936) and Hergenroder (1966) reported that V-3 occurred in the Bays near Roanoke, as shown in Figure 7. Rosenkrans, whose description of V-3 came from the Catawba section, based his correlation on thickness and color only (1936, p. 93), whereas Hergenroder gave no definitive criteria for his identification of the K-bentonite at Kingston as V-3 (1966, pp. 69 and 161). Identification of these beds as V-3 is refuted in the present study by noting, among other things, that in the measured sections given by both authors cited above, one (Catawba) or two (Kingston) micaceous zones are described; using the criteria for identification of the principal Rocklandian K-bentonites set forth in the present study it is evident that neither of those beds can be V-3. At the Kingston section this bed is either the Millbrig, V-7, or one of the thicker beds of Rosenkrans such as V-12 or V-13. Although samples of the bed are needed to say with certainty which K-bentonite it is, clearly it is *not* the Deicke (bed V-3), and, based on the interval between it and the basal sandstone (over 250 feet; Hergenroder, 1966, p. 161-162) as discussed above, it is probably not the Millbrig either. At the Catawba section, which was examined for the present study, the bed described by Rosenkrans as being 21 inches (53 cm) thick partly matches the description of the bed there that I indemtify as V-7. This is bed number 16 of Hergenroder, which is 34 centimeters thick. Immediately beneath this K-

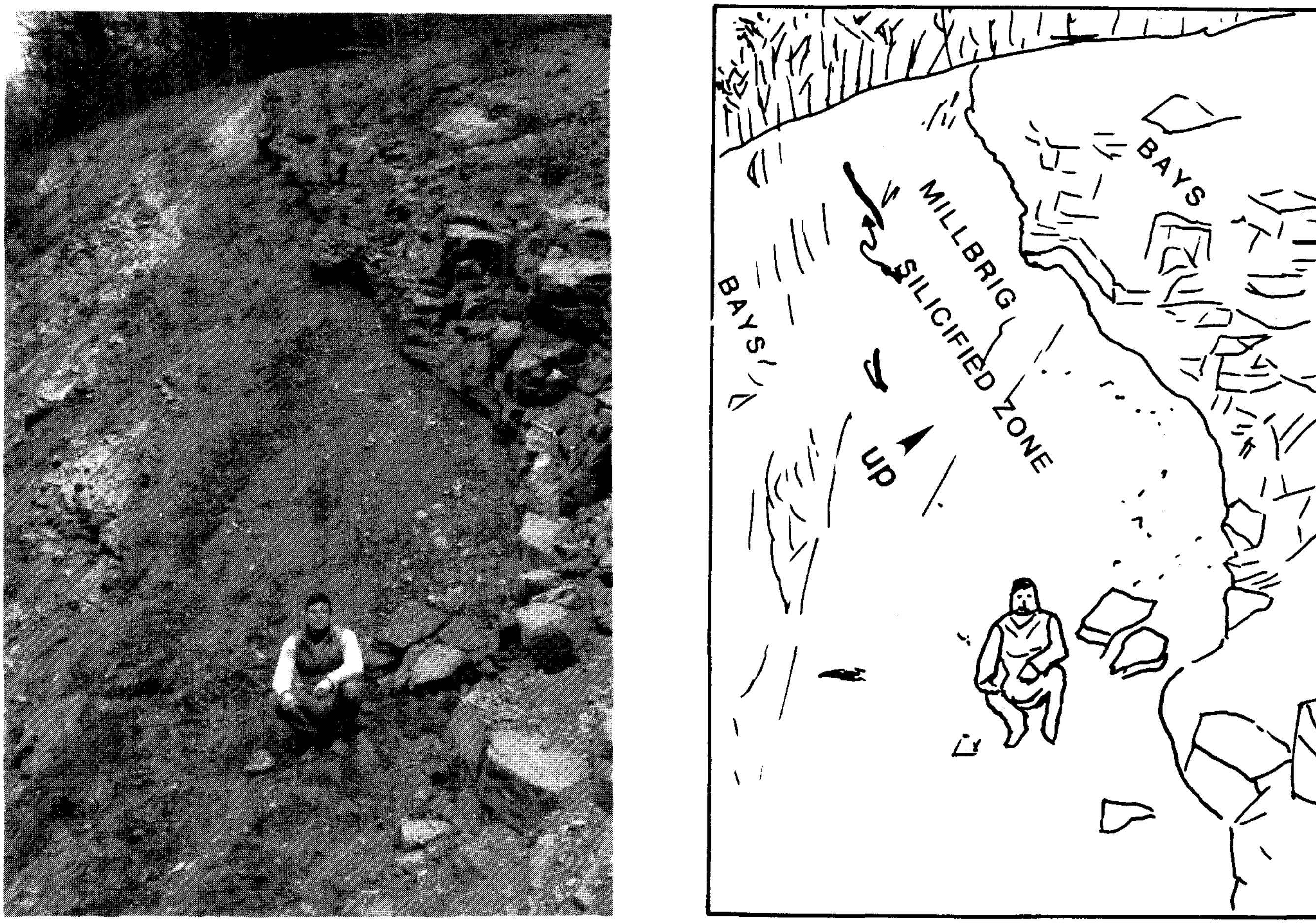


Figure 20. Exposure of the Millbrig along the westbound lane of I-77 at the Crockett Cove section west of Wytheville, Virginia. The lower part of the Bays Formation is completely exposed here, and the Walker Mountain Sandstone occurs downsection to the left, out of the picture.

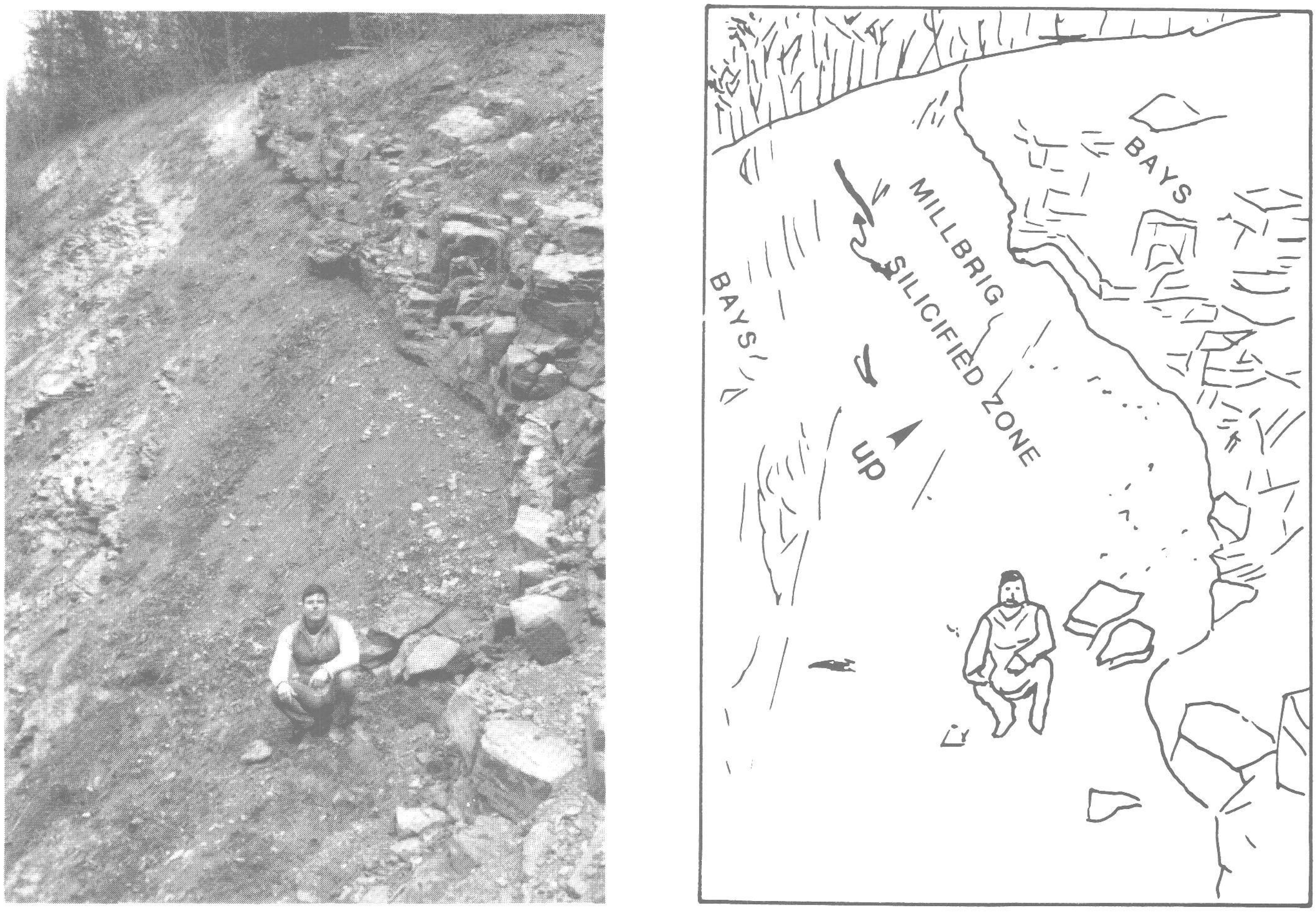
bentonite bed is a fine grained sandstone about ten centimeters thick (bed number 15 of Hergenroder), and beneath that is a bed of hackly red shale about 33 centimeters thick that weathers recessively and might be mistaken for a K-bentonite (bed number 14 of Hergenroder). It is possible that Rosenkrans's description of V-3 was for a composite of these three beds, only one of which is a K-bentonite based on examination of the clay mineralogy.

There is now adequate evidence to correlate K-bentonites in the Bays Formation with those in the Moccasin and Eggleston Formations of the central and western belts. Using the criteria in Table 1, the Millbrig has been identified as the thick K-bentonite in the several outcrops of the Bays Formation shown in Figure 19. Bed V-7 of Rosenkrans (1936) is also now recognized in the Bays Formation.

Correlation is most easily demonstrated from west to east. As shown in Figure 21, the Millbrig K-bentonite (V-4), V-7, the Walker Mountain Sandstone, and the Moccasin/Eggleston and Eggleston/Trenton contacts are all exposed at both the Goodwins Ferry and Gap Mountain sections of the central belt. At the Goodwins Ferry section the Deicke K-bentonite is exposed as well, occurring directly above the Walker Mountain Sandstone (Figure 24A). The interval from below the Walker Mountain Sandstone to the base of the Trenton ("Martinsburg") Formation is also well-exposed at the Mountain Lake Turnoff and Trigg sections, where again the Deicke is noticeably thinner than in sections farther south. This northeastward thinning of the bed was described by Rosenkrans (1936), as his Plate 10, specifically bed V-3, shows.

The Mountain Lake Turnoff, Goodwins Ferry, and Trigg sections are all on the Narrows thrust sheet. From those three outcrops, the Millbrig K-bentonite and K-bentonite bed V-7 can be traced across the Saltville fault to the Gap Mountain section on the Saltville thrust sheet. The Walker Mountain Sandstone can also be traced there, where it occurs in a ravine that is mostly covered at present. The Deicke is not presently exposed at the Gap Mountain section, although with some digging it is likely that it would be found. The Moccasin/Eggleston and Eggleston/Trenton contacts can also be traced from the Goodwins Ferry section to the Gap Mountain section, as shown in Figure 21.

From the Gap Mountain section, the Millbrig and V-7 can be traced to the Daleville and Catawba sections on the Pulaski thrust sheet to the north and to the Connor Valley section on the Cove Mountain thrust sheet to the south. The Millbrig can be traced to the Crockett Cove section, also on the Cove Mountain thrust sheet, as shown in Figure 21.



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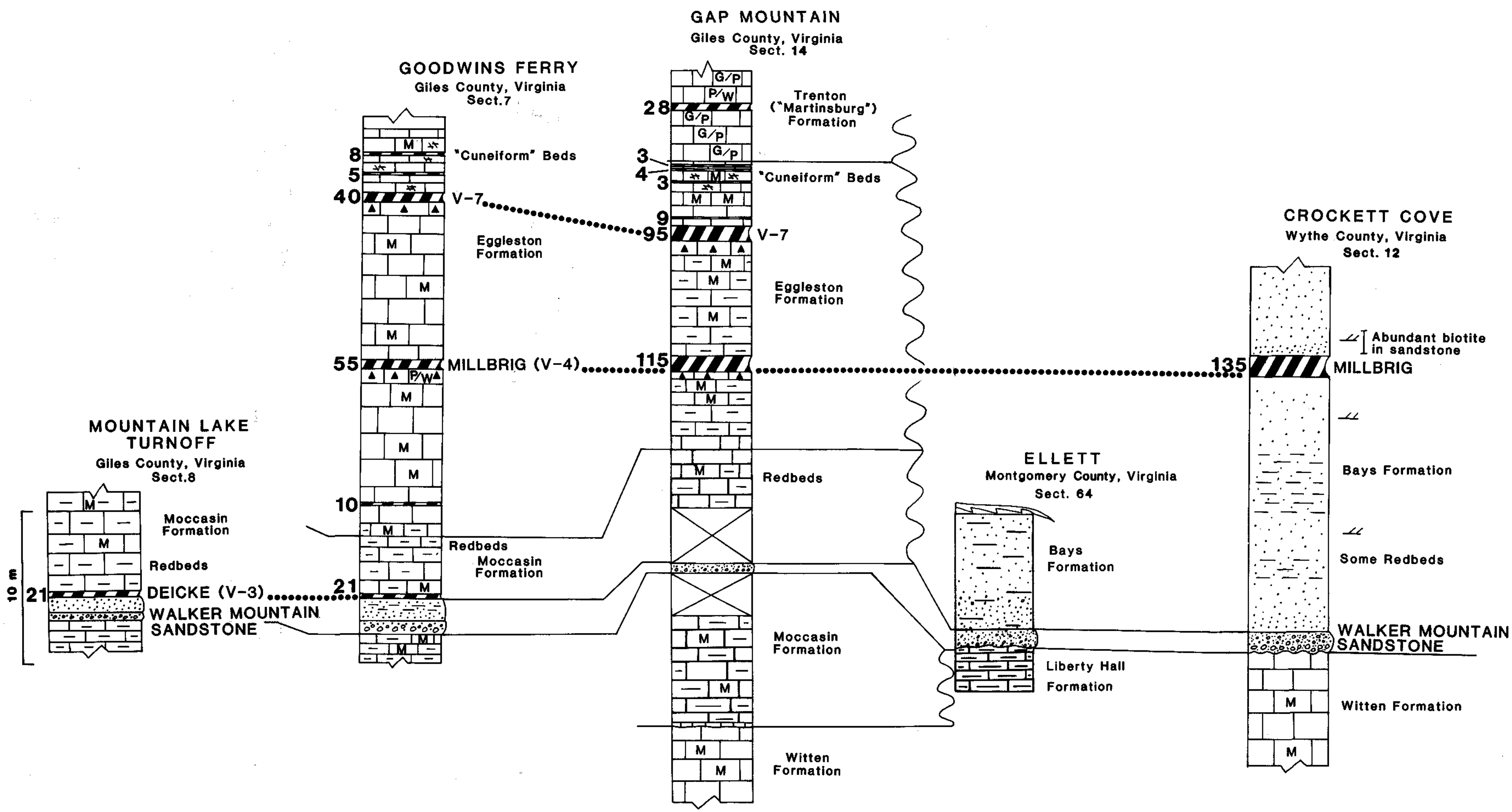


Figure 21. Correlation of the K-bentonites between the central and eastern belts in the northeastern part of the study area. The interval between the Millbrig and the Walker Mountain Sandstone is fairly consistent from the central belt eastward into the eastern belt. Only the lowermost exposure of the Ellett section is shown; refer to the text for further discussion of this section.

The base of the Trenton ("Martinsburg") Formation is another stratigraphic marker that can also be followed into the eastern belt. As shown in Figure 14, that contact is an even more important marker in southwesternmost Virginia and northeast Tennessee because in that area the Walker Mountain Sandstone is not present in the central belt. Thus there is less lithostratigraphic evidence to support the correlations across strike than there is farther north, although because the Millbrig can be identified at the Hagan, Gate City, and Terrill Creek sections based on its phenocryst mineralogy the lack of supporting evidence is not of concern. Nevertheless, the base of the Trenton is the only marker besides the Millbrig that can be traced from Hagan to Gate City and then to Terrill Creek, across all three belts in this part of the study area.

Correlation of the K-bentonites is thus demonstrated between the central and eastern belts, through the major facies changes that occur from east to west (Rader, 1982). The two K-bentonites that persist in the Bays are the Millbrig and bed V-7 of Rosenkrans (1936). This is the first time that this correlation has been demonstrated and it is also the first time that either bed has been recognized in the Bays.

SUMMARY OF CORRELATIONS

Figure 22 shows how the K-bentonite sequences at various sections in the region correlate with one another. Some of the correlations shown are reinterpretations of those suggested by previous workers, while others are in agreement with eaılier correlations. Figure 22 supercedes Figure 7, which as discussed above is actually based on Plate 26 of Miller and Fuller (1954).

CONGLOMERATIC SANDSTONES IN THE BAYS AND MOCCASIN FORMATIONS

PETROGRAPHY

At the Crockett Cove, Connor Valley, Ellett, Peters Creek, and Daleville sections the base of the Bays Formation is well-exposed. Figure 23 shows three of these sections, and compares them with the Chatham Hill and Goodwins Ferry sections. Except at Daleville the basal unit consists of one or two beds of yellow to white (on fresh surface) medium-grained to conglomeratic quartz arenite up to one meter in thicknes. Abundant clasts of the underlying fossiliferous to micritic limestone are present in the lowermost bed at some sections. Thin beds (generally less than 50 centimeters) of siltstone and finer grained sandstone separate the coarsest sandstone beds, but many of these interbedded units contain lenses and very thin beds of the coarse quartz sandstone that is petrographically very similar to the sands in the thicker beds. At Daleville, the basal unit is also a sandstone, but it is greenish gray rather than yellow to white and it does not contain conglomeratic zones.

Unlike sections to the west on the Saltville thrust sheet, in which the lowermost Bays is gradational with the underlying limestones of the Wassum Formation (Hergenroder, 1966), the basal unit of the Bays in these sections on the Cove Mountain and Pulaski thrust sheets rests with apparent disconformity on the underlying unit, which is the Witten Formation at Crockett Cove, the Wassum Formation at Connor Valley, and the Liberty Hall Limestone at Ellett, Peters Creek, and Daleville. This generally coarse-grained basal sandstone was also described by Webb (1965) at two exposures in the Crockett Cove area including the exposure near St. Lukes Fork measured during field work for the present study, and by Hergenroder (1966) in his Cloverdale, Salem, Hanging Rock, and Kingston sections. Hergenroder (1966) also described a similar unit at the base of the Moccasin Formation at his New Castle Fish Hatchery section.

Conglomeratic sandstones are also present farther west along Big Walker Mountain in the Walker Mountain Sandstone Member (Butts and Edmundson, 1943) is the only coarse-grained sandstone in the exposures of the Bays along Big Walker Mountain. Hergenroder described that bed as a generally well-sorted to moderately poorly-sorted conglomeratic quartz arenite that in places consists of up to 98 percent well-rounded quartz sand grains and granules. Accessory framework grains include rare shell fragments, rounded detrital chert grains, quartzite rock fragments, zircon, apatite, and tourmaline. These grains range in size from medium to coarse sand (up to two millimeters in length) with some larger granules in the lowest few centimeters of the bed. I would add that the bed is usually cemented by sparry calcite, but some zones in which silica and hematite may be a cement are present.

In the New River Valley, the Walker Mountain Sandstone is present in the Moccasin Formation (Kreisa, 1980). At the Mountain Lake Turnoff, Goodwins Ferry, and Trigg sections on the Narrows thrust sheet, and also at the nearby Gap Mountain section on the Saltville thrust sheet, the Walker Mountain, with its readily recognized conglomeratic sandstone, is a thin tongue of Bays-like sandstone that includes up to 4 meters of greenish gray lithic arenites and wackes that are in stark contrast to the surrounding redbeds of the Moccasin. The basal bed, the white to gray to pale yellow conglomeratic quartz arenite, is evident in Figure 24A, which shows the Walker Mountain Sandstone and the Deicke K-bentonite at the Goodwins Ferry section.

It is important to note just how lithologically distinctive the Walker Mountain Sandstone and its conglomeratic sandstones really are, and how much they contrast with the adjacent sediments upsection and downsection. The Walker Mountain Sandstone contains the only conglomeratic sandstone in the exposures of the Bays Formation along Big Walker Mountain, and after careful examination of the Bays in the Crockett Cove, Connor Valley, Peters Creek, Ellett, and Daleville sections I found that the only conglomeratic quartz arenites in the Bays are in the lowest few meters of the Bays. The descriptions by Hergenroder (1966) of several sections of the Bays in the study area support these observations as well.

These findings contradict those of Webb (1965), who indicated that polymictic conglomerates are present in the Bays about 100 feet above the base of the Bays in Crockett Cove along St. Lukes Fork. This is near an exposure that has since been markedly improved by the construction of Interstate 77 and is the Crockett Cove section of the present study.

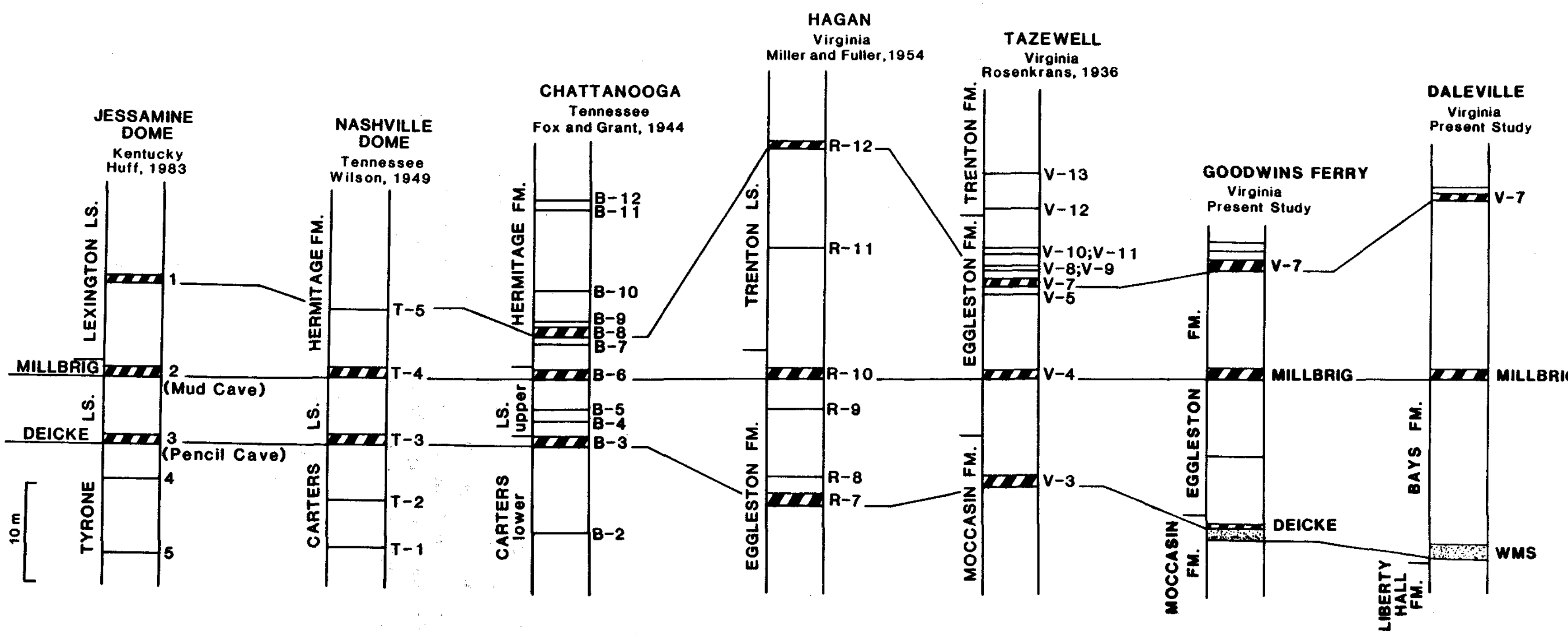


Figure 22. Revised correlation chart for several well-known exposures in which Rocklandian K-bentonites occur in the southeastern U.S., with reference to the authors in which the most detailed descriptions of measured sections can be found. This chart is based on the results of the present study and it is intended to replace all previous such correlation charts such as the one shown in Figure 7, which is adapted from Plate 26 of Miller and Fuller (1954). WMS = Walker Mountain Sandstone.

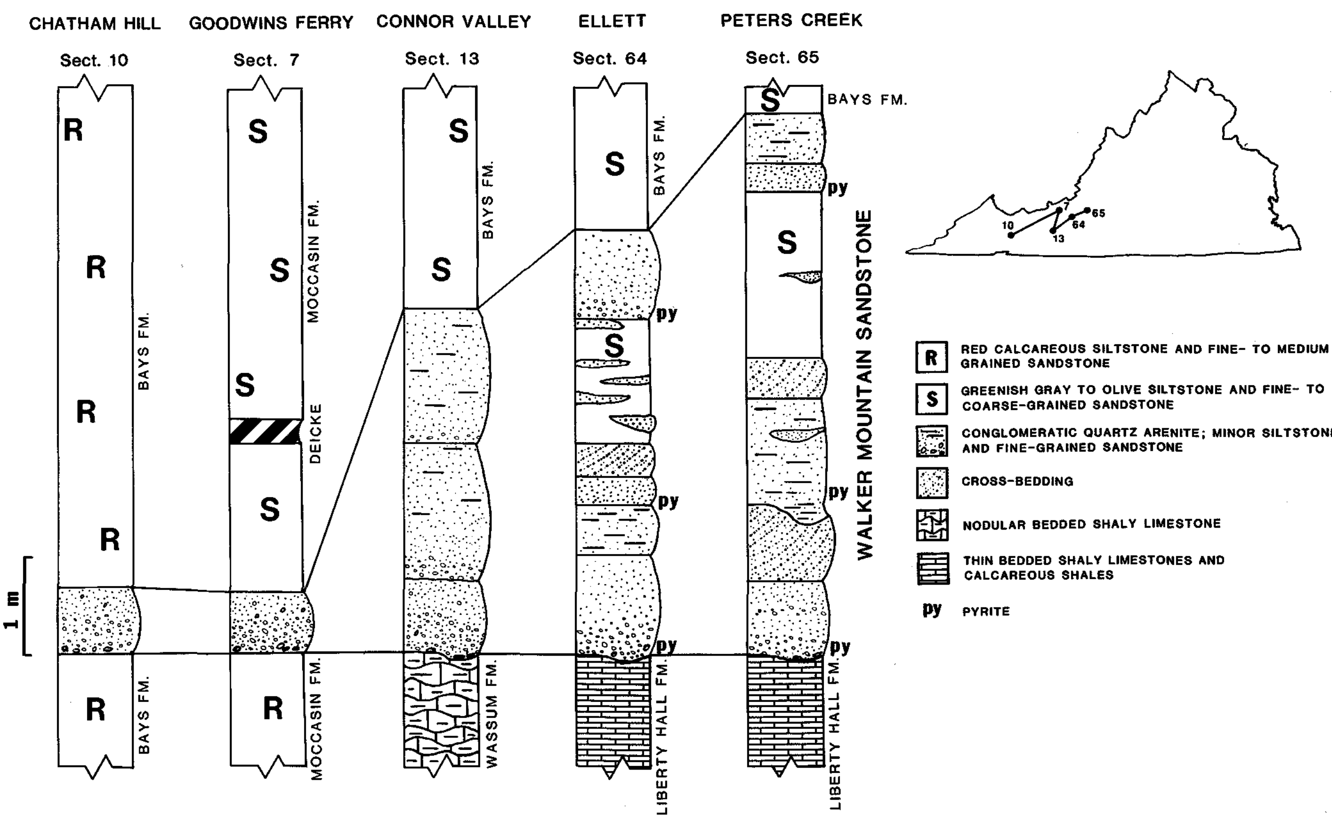


Figure 23. Stratigraphic details of the conglomerate zone of the Walker Mountain Sandstone in five sections. Compare with Figures 19 and 21 to see the stratigraphic association of the Walker Mountain Sandstone with the Millbrig (V-4) K-bentonite upsection.

Tuffaceous sandstones do occur at that section immediately above the Millbrig and they are the coarsest sandstones in the exposure except for the basal sandstone overlying the Witten Formation, but they are not conglomeratic nor are they quartz arenites; they are greenish-gray lithic arenites and wackes that contain abundant biotite from reworked Millbrig ash, as noted above. Thus petrographically they are very unlike the basal sandstones.

Another section where coarse sandstones in the Bays Formation have been noted is the Ellett section. Although Hergenroder (1966, p. 39) stated that Butts (1940) implied that the thick sequence of sandstones in the upper well-exposed part of the Ellett section were equivalent to the conglomeratic sandstone in exposures farther west along Big Walker Mountain (the unit that in 1943 Butts and R.S. Edmundson named the Walker Mountain Sandstone Member of the Bays), the text in Butts (1940) is actually somewhat ambiguous and it is not explicitly stated that Butts was indeed referring to the upper sandstones at Ellett. My interpretation of this discussion by Butts (1940) is that he was more likely referring to the coarse sands in the Ellett section at the base of the Bays (which he called the Moccasin), rather than the prominent sandstone sequence in the upper part of that section. The upper sandstones at Ellett are indeed medium to coarse grained but they are not conglomeratic, and they are greenish-gray lithic arenites and wackes with lesser quartz wackes and sublitharenites (Hergenroder, 1966) that bear little resemblence petrographically to the compositionally mature quartz arenites and conglomeratic quartzose sands at the base of the Bays in the same section.

Based on the petrographic comparison of the conglomeratic sandstones at the base of the Bays Formation on the Cove Mountain and Pulaski thrust sheets with the Walker Mountain Sandstone at the several sections along Big Walker Mountain and at the Trigg, Goodwins Ferry, and Mountain Lake Turnoff sections in the New River Valley, I believe that they are one and the same unit. Both the Walker Mountain Sandstone along Big Walker Mountain and along Spruce Run Mountain in the New River Valley (areas where its identification is well established), and the one or more meter-thick beds of conglomeratic quartz arenites that occur at the base of the Bays in the exposures on the eastern thrust sheets, contain primarily moderately to well-sorted and well-rounded quartz grains up to two millimeters in diam-

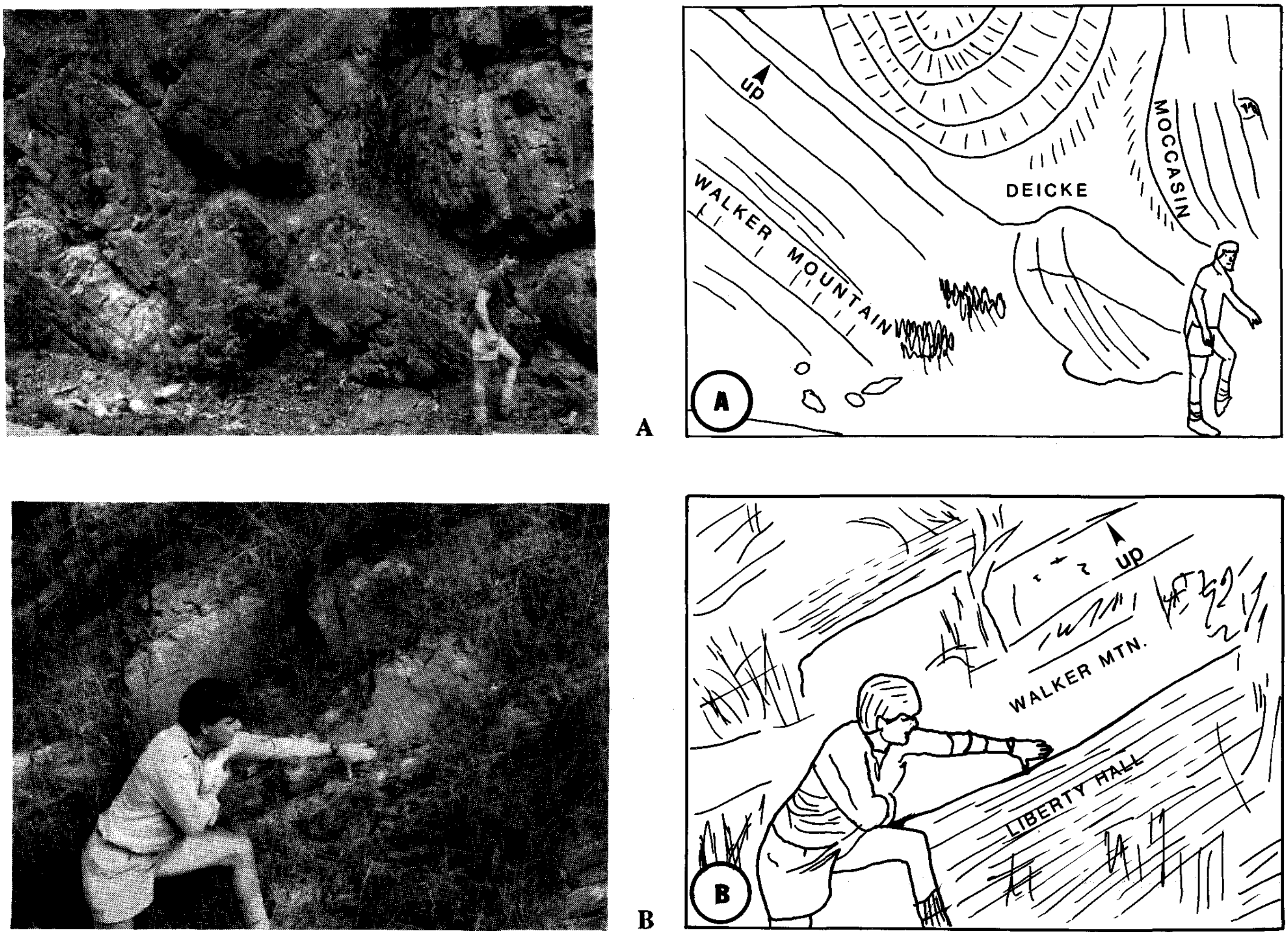
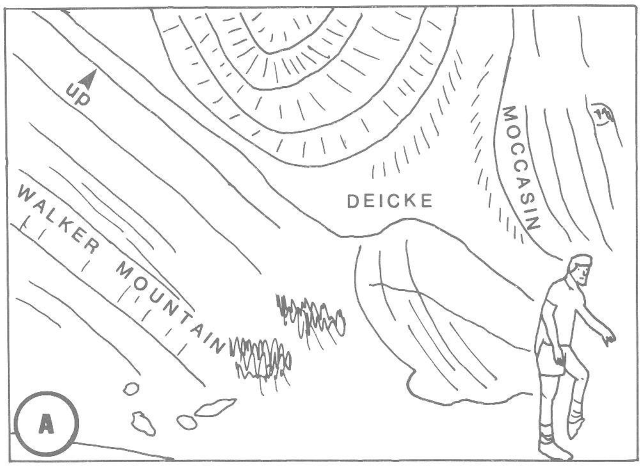


Figure 24. The Walker Mountain Sandstone in Virginia. **A.** At the Goodwins Ferry section, it is the distinctive white conglomeratic quartz arenite in the upper Moccasin Formation and the succeeding four to five-meter thick sequence of greenish gray lithic arenites. Those rocks represent a tongue of the Bays from sections on the Pulaski thrust sheet farther east (cf. Figure 26, A-A'). The Deicke (V-3) K-bentonite, which here has been squeezed and deformed along a localized zone of detachment, occurs in this region in or immediately above this sandstone tongue. **B.** The two lowermost conglomeratic quartz arenite beds in the Walker Mountain Sandstone at the base of the Bays Formation near Ellett. At this and other exposures on the Cove Mountain and Pulaski thrust sheets, where it is the basal unit of the Bays, the Walker Mountain is several meters thicker than it is in the exposures on the Narrows and Saltville thrust sheets farther west. The Deicke is absent at this and all other exposures of the Bays Formation.

eter, with some samples being noticeably bimodal, as noted by Hergenroder (1966). Accessory framework grains (less than 5 percent) are black, green, gray, and red rounded chert, with one to five percent rock fragments, primarily polycrystalline quartzite grains, and less than one percent heavy minerals such as zircon. Texturally there is a wide range of sizes in the framework grains. I measured the size of several of the quartz and black chert pebbles in the lower few centimeters of the bed in various sections, with the largest being 22 millimeters in length at the Ellett section; Hergenroder (1966) describes pebbles from this basal sandstone at Ellett that are greater than 25 millimeters in length. The smallest grains in these sandstones occur in the zones having a distinct bimodal texture. These fine-grained quartz grains range in length from less than 0.1 to 0.5 millimeters. Thus these conglomeratic sands are correlated with the Walker Mountain Sandstone.

The sandstone at the base of the Daleville section is considered to be the edge of this conglomeratic facies. The outcrop belt in which the Daleville section is located is as far north as the Bays Formation occurs. To the north the equivalent strata are basin margin and basinal flysch deposits of the lower Martinsburg Formation (Rader and Gathright, 1986). Evidently the environment in which the conglomeratic sands were reworked and deposited did not extend to the Daleville section, although at the nearby Cloverdale section Hergenroder (1966, p. 160) reported that the lowermost bed in the Bays is a conglomeratic sandstone.



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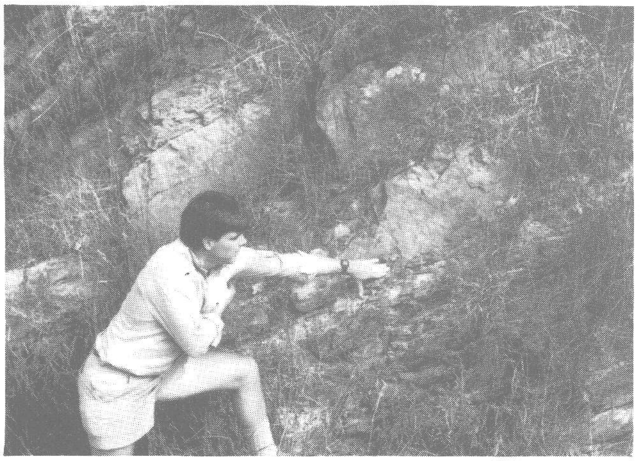

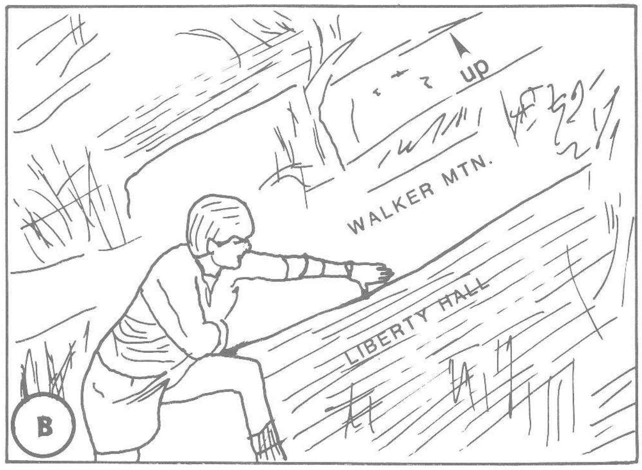

B

Figure 24. The Walker Mountain Sandstone in Virginia. **A.** At the Goodwins Ferry section, it is the distinctive white conglomeratic quartz arenite in the upper Moccasin Formation and the succeeding four to five-meter thick sequence of greenish gray lithic arenites. Those rocks represent a tongue of the Bays from sections on the Pulaski thrust sheet farther east (cf. Figure 26, A-A'). The Deicke (V-3) K-bentonite, which here has been squeezed and deformed along a localized zone of detachment, occurs in this region in or immediately above this sandstone tongue. **B.** The two lowermost conglomeratic quartz arenite beds in the Walker Mountain Sandstone at the base of the Bays Formation near Ellett. At this and other exposures on the Cove Mountain and Pulaski thrust sheets, where it is the basal unit of the Bays, the Walker Mountain is several meters thicker than it is in the exposures on the Narrows and Saltville thrust sheets farther west. The Deicke is absent at this and all other exposures of the Bays Formation.

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GEOMETRY

Study of the distribution and thickness of the Walker Mountain Sandstone and the basal conglomeratic sandstones at the base of the Bays also suggests that they are equivalent. Both units are clearly thin sheet sandstones consisting of less than one to about four meters of compositionally mature, quartzose, conglomeratic sandstone. By contrast the sandstones overlying and underlying the Walker Mountain Sandstone in the Bays on the Saltville sheet are a repetitive sequence of fine-grained redbeds with a significant calcareous content. Likewise, the sandstones higher in the section in the Bays on the Cove Mountain and Pulaski sheets are much different from the sandstones at the base of the Bays. These higher units, well exposed at the Daleville, Ellett, Connor Valley, and Crockett Cove sections, are locally thick but areally restricted sequences of predominantly greenish gray medium to coarse-grained lithic arenites, sublitharenites, and wackes with thinner interbedded greenish gray to red siltstones and shales.

CORRELATION

Although petrographic analysis and consideration of the geometry of certain beds indicates that the basal sandstone unit in the Bays Formation on the Cove Mountain and Pulaski thrust sheets is equivalent to the Walker Mountain Sandstone in the Bays on the Saltville thrust sheet, there is an even better tool that can be used to support this correlation, and that is a comparison of the stratigraphic interval between the Walker Mountain Sandstone and the Millbrig K-bentonite upsection. Figure 19 shows this interval as measured at the Chatham Hill, Crockett Cove, Connor Valley, and Daleville sections; in addition, the interval between a bed that is most likely the Walker Mountain Sandstone and a K-bentonite that is most likely the Millbrig can also be measured at the Mitchell Valley section of Hergenroder (1966) as discussed previously. Also, the interval between the Walker Mountain Sandstone and the Millbrig K-bentonite can be measured at the Gap Mountain and Trigg sections in the central belt, although the accuracy of the measurements is not as good because of local structural disruption. At Chatham Hill, the base of the Millbrig is about 28 meters above the top of the Walker Mountain Sandstone. At the Mitchell Valley section this interval is about 21 meters. At Crockett Cove and Connor Valley the interval between the basal sandstone and the Millbrig is about 18 meters, and at Daleville this same interval is about 19 meters. This approximately ten meter difference in the interval as measured at the Chatham Hill section and those to the east might be significant except that as noted above there are no other conglomeratic sandstones elsewhere in that interval, which is completely exposed at these four outcrops. At the Chatham Hill section and the nearby Nebo section, there are no conglomeratic sandstones in the Bays below the Walker Mountain Sandstone, and at the Mitchell Valley section Hergenroder (1966, p. 268-269) does not describe any coarse-grained sandstones in the Bays beneath his bed number five, which I believe to be the Walker Mountain Sandstone. At the Crockett Cove, Connor Valley, and Daleville sections, by comparison, there is simply no Bays beneath the coarse basal sandstone, which instead rests disconformably on carbonates of the Witten, Wassum, or Liberty Hall Formations. At the Gap Mountain and Trigg sections, the interval between the Walker Mountain Sandstone and the Millbrig is about 12 meters. Because the Millbrig is of course an ideal time line, as it is a bed of altered volcanic ash, the cumulative evidence suggesting that these conglomeratic sandstones at the base of the Bays are correlative with the Walker Mountain Sandstone of Big Walker Mountain is compelling.

From its type area along the southwestern end of Big Walker Mountain (Butts and Edmundson, 1943) the Walker Mountain Sandstone can be traced northeastward along strike to the Gap Mountain section. As shown in Figure 21, it can then be traced westward across the Saltville fault to the Goodwins Ferry and Mountain Lake Turnoff sections on the Narrows thrust sheet. From those sections it can be traced to the nearby Trigg section, also on the Narrows thrust sheet. The Millbrig K-bentonite and K-bentonite bed V-7 can also be traced to those three sections westward across the Saltville fault.

From the Gap Mountain section the Walker Mountain Sandstone can be traced eastward into the Bays Formation on the Pulaski and Cove Mountain thrust sheets, where it occurs at the base of the Bays in the Daleville section about 55 kilometers east northeast of the Gap Mountain section, the Peters Creek section about 38 kilometers east, the Ellett section about 23 kilometers southeast, the Connor Valley section about 35 kilometers southwest, and the Crockett Cove section about 52 kilometers west southwest. The strata immediately above the Walker Mountain are well-exposed at those sections and as discussed above there are no K-bentonite beds in the Bays in that interval of strata, suggesting that the Deicke is absent. Correlation between the Gap Mountain, Ellett, and Crockett Cove sections is shown in Figure 21. Figure 24A shows the Walker Mountain Sandstone and the Deicke at the Goodwins Ferry section in the New River Valley. The most recognizable bed of the Walker Mountain Sandstone is the 60 centimeter thick white bed at the left of the picture. Thisconglomeratic quartz arenite contains quartz and chert pebbles up to 1 cm in length. Between that bed and the Deicke, and for one to two meters above the Deicke, are fine- to coarse-grained greenish gray sandstones that are very similar in appearance to the lithic arenites of the Bays Formation on the Pulaski thrust sheet farther east. Figure 24B shows the lowermost thick conglomeratic quartz arenite beds of the Walker Mountain Sandstone in the lower part of the Ellett section. These two sandstone beds are pale yellowish white, and at the very base of the lowest sandstone are quartz and chert pebbles over 2 cm in length. At this exposure, the lowest eight to ten meters of the Bays and the upper one to two meters of the underlying Liberty Hall Formation are exposed below a long covered interval. This exposure at Ellett is discussed in more detail below.

DEPOSITIONAL SETTING OF THE CONGLOMERATIC SANDS, WITH DISCUSSION OF THE BAYS FORMATION NEAR ELLETT, VIRGINIA

Possible depositional settings for the conglomeratic sands in the Moccasin and the Bays Formations have been suggested in earlier studies. In his discussion on sedimentation in the Crockett Cove area, especially the southern end of the Cove where the Crockett Cove section of the present study was measured, Cooper (1964) suggested that the conglomeratic sands at the base of the Bays might be turbidites:

> The Bays Formation in the Queens Knob syncline is well over 200 feet thick and exhibits the greatest known thickness of the coarsest conglomerates. The conglomerates, some of which are markedly polymictic, are nestled right down in the deepest part of the synclinal trough. In that portion, coarse grits and conglomerates directly overlie shell limestones and calcarenites [of the Witten Formation that are] essentially free of quartz sand. The sands may have been flushed in as a sudden precipitous slug of sediment, possibly as a turbidity slide.

This interpretation can be refuted because the sedimentologic evidence suggests deposition on a shallow shelf rather than on a submarine fan or other basinal environment. Because turbidite sandstones are in fact deposited as a "sudden precipitous slug of sediment" they are universally almost always poorly sorted immature lithic wackes exhibiting one or more units in the Bouma sequence (Bouma, 1962), whereas shallow shelf sheet sands tend to be mature to supermature, moderately- to well-sorted quartz arenites. In particular, many sheet sand deposits are composed of multicycle sands that contain little else besides rounded grains of quartz, quartzite rock fragments, chert, zircon, apatite, and tourmaline (Pettijohn and others, 1972). This accurately describes the petrography of the Walker Mountain Sandstone, the basal sandstone in particular (it should also be noted that in addition to the ubiquitous chert and monocrystalline quartz grains, Hergenroder (1966, p. 93) counted 105 tourmaline grains in a thin section of the basal sandstone at Ellett, and he observed that some of the conglomeratic sands in the Bays contained five percent or more quartzite rock fragments), so it is unlikely that these sandstones are turbidites.

The conglomeratic sandstones at the base of the Bays in Crockett Cove were further described by Webb (1965) as

> ...45 feet of polymict granule conglomerate which is cross-bedded with the foreset beds dipping to the northwest. The conglomerates are generally light brownish-gray to tan and, in a few instances, almost white. The conglomerates contain rounded to subrounded quartz granules, rounded ellipsoidal chert granules, angular blocky shale pebbles, and granules and pebbles of medium to dark-gray fine-grained limestone...In the northeastern end of the Cove on the Charles King farm, the Bays consists mainly of a basal light-gray to white, relatively clean, slightly conglomeratic quartz sandstone at the base. The basal sandstone is approximately 30 feet thick.

Polymictic conglomerates similar to these mentioned by Cooper (1964) and described by Webb (1965) also occur in the Bays at the Connor Valley section in the lowermost bed of the basal sandstone that immediately overlies the Wassum Formation. That bed contains abundant rounded clasts that texturally resemble the underlying fossiliferous wackestones of the Wassum. Petrographically, the sand around these clasts is texturally identical to the sand of the other mature quartz arenites in this basal sandstone unit, suggesting that the clasts were derived locally from scouring and erosion of the lime muds of the underlying Wassum, which were evidently lithified. At the Peters Creek and Ellett sections also (Figure 23), the lowermost bed of the basal sandstone unit contains flat rip-up clasts that texturally are like the shaly limestones of the Liberty Hall Formation immediately underlying the Bays. In these sections the chert grains and granules that are ubiquitous in the conglomeratic sands are present in both the lowermost bed and in the quartz arenites immediately above it that do not contain calcareous rip-up clasts.

My interpretation is that the Walker Mountain Sandstone is a transgressive sheet sand deposited on a shallow shelf, and that the lowermost bed in that unit was deposited disconformably on the underlying sediments across the basin. Final deposition was probably in a shore face to beach environment along the fringe of an older clastic delta, one perhaps associated with the submarine fan deposits of the Knobs and Sevier Formations, coarser sandy equivalents of the Liberty Hall Formation to the southwest (Read, 1980). The bimodal texture of many samples suggests eolian reworking (Pettijohn and others, 1972). Sand from the underlying deposits was reworked during some period of time when the influx of sediments into the basin had decreased, and when there was some subaerial exposure, allowing for reworking by eolian processes. Although waves and currents are able to wash fine-grained sediments out into a quieter part of a basin and to mechanically break down labile minerals and rock fragments, wind is an evenmore effective winnowing agent, especially when the sand has already been sorted in water by waves and currents. The remaining sand is a collection of grains resistant to abrasion and dissolution; this is why quartz, chert, zircon, tourmaline, etc., are the most common grains in sands such as the quartz arenites of the Wlaker Mountain Sandstone.

Reworking of the conglomeratic sands in the Bays was probably a continuous process that occurred as the conglomeratic lithofacies moved generally northward across the now shallow basin, transgressing in succession and with increasing disconformity to the north and east the lower redbeds of the Bays and Moccasin Formations (sections in the Bays Mountains and along Big Walker Mountain and in the New River Valley on the Narrows and Saltville thrust sheets), the peritidal carbonates of the Witten Formation (Crockett Cove section on the Cove Mountain thrust sheet), the ramp carbonates of the Wassum Formation (Connor Valley section on the Cove Mountain thrust sheet), and finally the basin margin shaly limestones of the Liberty Hall Formation (sections on the Pulaski thrust sheet). At most exposures studied the contact between the conglomeratic sandstones of the Walker Mountain and the underlying carbonates is clearly disconformable. The contrast is particularly striking where the Walker Mountain Sandstone overlies the basin margin shaly limestones of the Liberty Hall Formation. At the Ellett and Peters Creek sections (Figure 23) the uppermost few meters of the Liberty Hall are no different texturally than beds several meters to tens of meters downsection. This suggests that uplift and erosion occurred subsequent to their deposition, and that the conglomeratic shallow marine sheet sands at the base of the Bays were deposited disconformably on these limestones. The presence of rip-up clasts in the lowest sandstone bed supports this conclusion, but it is more significant that the uppermost beds of the Liberty Hall show no indication of deposition in a shallow marine environment. Evidently the magnitude of the unconformity at the base of the Bays in the sections on the Cove Mountain and Pulaski thrust sheets could be greater than Hergenroder (1966) had suggested and shown in his Plate 13.

At the Daleville section there is evidence that the contact between the conglomeratic sandstones of the Walker Mountain and the underlying carbonates is gradational. There, the Walker Mountain Sandstone is less conglomeratic and it has the greenish gray color of the overlying sandstones, suggesting that it was deposited near the shelf edge in a deeper water setting where reworking was not as thorough. Bays-like greenish-gray lithic arenites persist to the north of Daleville, occurring in several beds immediately above the Fincastle Conglomerate (Rader and Gathright, 1986; Zhenzhong and Eriksson, 1991) and as a one to two meter-thick bed in the shelf carbonate sequence of the western anticlines (Kay, 1956). In Rich Patch Valley this bed is recognizable as the upper Walker Mountain Sandstone by its lithology and stratigraphic position in the Eggleston Formation immediately beneath the Deicke K-bentonite. Given the lateral persistence of only the more fine-grained sands northward from Daleville, it is likely that the Bays in the Daleville area was deposited in a slightly deeper part of the shelf. In such a setting the sands of the Walker Mountain would not have been thoroughly reworked and washed of the clay matrix and pelitic rock fragments that impart the distinct greenish gray color to the Bays sandstones in the exposures throughout the Salem synclinorium.

It is apparent that the development of the conglomeratic Walker Mountain lithofacies, which is present over much of the eastern part of the study area, occurred during a hiatus in sedimentation along the eastern margin of the depositional basin. This hiatus began when deposition of the shelf, ramp, and basin margin carbonate sediments of the underlying Witten, Wassum, and Liberty Hall Formations ceased, probably as a response to uplift to the southeast of the basin. Following uplift the upper Liberty Hall Formation was evidently eroded, resulting in a beveling that placed the ramp and basin margin sediments of the Liberty Hall and Wassum Formations at nearly the same topographic level as the peritidal carbonates of the Witten Formation, which were originally deposited in a shallow shelf environment. Following this uplift and erosion but before sedimentation rates again increased along the northeastern margin of the basin, a region-wide transgression spread across much of the region and deposited thin but compositionally mature sands of the conglomeratic lithofacies that had been reworked by both littoral and eolian processes.

At some point uplift either resumed or the existing rate of uplift was accelerated, a process that led to increased rates of sedimentation along the basin margin. This increase in sediment influx resulted in the rapid burial of the conglomeratic quartz arenites that had transgressed over the Witten, Wassum, and Liberty Hall Formations by the thick but areally restricted sequence of lithic arenites and wackes of the Bays Formation that prograded out across the shelf. This uplift along the southeastern basin margin changed the configuration of the basin most dramatically in the areas now exposed on the Salem synclinorium and Green Ridge plates of the Pulaski thrust sheet. There, the lithic arenites and wackes of the Baysburied the older, shallow marine conglomeratic sandstones, which had previously prograded across the Liberty Hall following uplift and erosion of the basin margin shaly limestones that characterize that unit.

Regardless of whether or not the apparently great thickness of the Bays Formation near Ellett (discussed below) results from local variations in the geometry of the sedimentary basin or from post-depositional tectonic processes, the increase in sedimentation that caused the compositionally conglomeratic sandstones at the base of the Bays to be buried by more lithic-rich sands of the younger Bays was clearly localized spatially and temporally. As shown in Figure 26 there are several meters of redbeds in the uppermost Bays at the Catawba, Ellett, Connor Valley, and Crockett Cove sections, indicating not only that sedimentation rates were decreasing, but that this part of the basin had again become relatively shallow and oxidation of the iron in the sediments was occurring. Of the various sections on the Cove Mountain and Pulaski thrust sheets, the Crockett Cove section actually contains the fewest beds of greenish gray lithic arenites, as there are several meters of redbeds between the conglomeratic sandstones at the base of the Bays and the Millbrig K-bentonite upsection. This is an interval of the Bays where no redbeds have been observed at the other sections on those thrust sheets, including the Connor Valley section between the Crockett Cove section and those on the Pulaski thrust sheet. There are also redbeds in the Bays at Crockett Cove above the Millbrig, suggesting that the several meters of greenish gray lithic arenites directly overlying the Millbrig there are merely a tongue of the greenish gray sandstones that make up most of the Bays in the sections to the northeast. Another older, tongue of these same distinctive sediments is present at the Mountain Lake Turnoff section, where about four meters of greenish gray Bays-like sandstones occur in the Moccasin Formation as the upper beds of the Walker Mountain Sandstone; this is the same tongue that persists into the western anticlines. Farther southwest, at the McCall Gap, Chatham Hill, and Nebo sections along Big Walker Mountain, the Walker Mountain Sandstone is immediately underlain as well as overlain by fine-grained redbeds of the Bays, and there are none of the greenish gray medium- to coarse-grained unoxidized sands and silts that characterize the Bays to the northeast. As in the sections farther east, a disconformity is presumably present at the base of the Walker Mountain Sandstone, but it is not as striking because the contrast between the underlying and overlying sediments is minimal.

Hergenroder (1966) first suggested that the relatively clean quartzose sandstones in the Bays probably were deposited in a beach environment, and as discussed above it is likely that the conglomeratic units in the Walker Mountain

Sandstone include sediments that were extensively reworked and eventually deposited in a littoral zone along a beach or barrier island. By contrast, the fine-grained redbeds were deposited in tidal mudflats (Kreisa, 1980), apparently on a shallow part of the shelf perhaps caused by uplift related to the Tazewell arch (Read, 1980), and the greenish gray lithic arenites and wackes are delta front sands deposited in a deeper part of the shelf or shelf margin in an area below normal wave base but that may have been affected episodically by storms. Parts of the sequence at the Ellett and Crockett Cove sections include interbedded coarse sandstones and finer grained siltstones and shales that contain sedimentary structures such as hummocky cross-stratification and horizontal plane-lamination, structures that can be indicative of storm action on the sediments at the base of the water column (Kreisa, 1980).

The Walker Mountain Sandstone in the Bays Mountains appears to be a transitional sequence. At the Terrill Creek section (Figure 19) and at several other sections the Walker Mountain occurs in the middle of the Bays, where it was called the Middle Sandstone member by Hergenroder (1966). It is overlain by a significant thickness of typical Bays redbeds, suggesting burial by prograding tidal flat sediments as in the Virginia sections along Big Walker Mountain. With its 15 to 30 meters of well-sorted mature quartz arenites, however, it more closely resembles the Colvin Mountain Sandstone farther south in Alabama and Georgia (Jenkins, 1984) than the thin conglomeratic sands that characterize the Walker Mountain Sandstone in Virginia. It thus appears that the sands in the Bays Mountains were more intensely reworked by waves and currents in a nearshore marine environment, and that perhaps there was more sediment entering the basin but that overall it was finer-grained than farther north. Subsequently the sands of the Walker Mountain were buried beneath the thick sequence of redbeds that occurs in the upper part of the Bays in northeastern Tennessee, as in Virginia.

The Bays Formation near Ellett, Virginia. A markedly increased thickness of the Bays Formation at the exposure along the North Fork of the Roanoke River near Ellett has been noted in many studies. There, the upper few meters of the underlying Liberty Hall Limestone and lower several meters of the Bays are well exposed (Figure 24); above that interval the strata are mostly covered and the exposure is generally very poor until the upper 100 or so meters of the section are encountered. In that interval the strata are very well exposed and they are comprised of thick bedded medium- to coarse-grained greenish gray lithic arenites and wackes and interbedded thinner siltstones and shales. Several small-scale(?) apparently normal faults cut many of the beds in this interval.

As noted by Cooper (1964),

> The great thickness of the Bays Formation at the west end of the Catawba syncline is most peculiar. No such thickness is known anywhere farther southwest in Virginia, and there is no Bays Sandstone known northeast of the Catawba syncline...Evidently in Bays time the Catawba syncline attract[ed] a maxiumum thickness of Bays sediments...

Eubank (1967) mapped the Ellett area in detail, although his measurements of the Bays at the Ellett section are actually those of Hergenroder (1966). Eubank's interpretation of this apparently great thickness of the Bays near Ellett indicates that he favored deposition in a narrow trough:

> The unusual thickness of the Ellett section appears to represent deposition in a relatively narrow (about 3,700 feet in width), locally subsiding sediment "trap." The [Bays] formation thins rapidly on both sides of the thick section, and no erosional trough appears to exist in the Liberty Hall below the thick section...1,450 feet of [the overlying] Martinsburg [are present] 17 miles northeast...on Catawba Mountain...1,300 feet of Martinsburg [are present] on the western slopes of Paris Mountain east of Lusters Gate, and about 1,500 feet [are present] on Hightop Mountain northwest of Fagg.

The Hightop Mountain section of the Martinsburg (Trenton of current usage) is the closest to Ellett of the three, and it is evident that there the Trenton is only 200 feet (61 meters) thicker than in the sections farther north, suggesting that sedimentation patterns in the Trenton, like those in the underlying Liberty Hall, were little affected by the supposed accumulation of a great thickness of the Bays at Ellett.

Figure 25 shows two sketch maps of the outcrop pattern of the Bays Formation in the Ellett area. The pattern as mapped by Eubank (1967, Plate 1) is shown without changes in Figure 25A. Figure 25B is a reinterpretation of the outcrop pattern based on mapping done by the present author. Shown at (1) in Figure 25B is the location of an exposure of the Bays not mapped or noted by Eubank, and shown at (2) are locations where the Walker Mountain Sandstone is exposed at the Liberty Hall/Bays contact. Shown at (3) is an exposure of travertine that may be fault related; the trace of this possible fault is also shown. Strikes and dips are shown as well.

As measured by Eubank (1967), the thickness of the Bays at nearby sections ranges from 65 to 100 meters. These measurements are from an exposure along Slate Lick Run about 4 kilometers to the northeast, where the Bays is approximately 100 meters thick, an exposure along Den Creek just 1 km south, where the Bays is approximately 65 meters thick, and an exposure east of the settlement of Lusters Gate about 7 kilometers to the northeast, where the Bays is approximately 75 meters thick. At Ellett, by contrast, the Bays has been reported to be over 250 meters thick: Butts (1940) measured 830 feet (250 meters) of Bays (he called it Moccasin) at Ellett, Cooper (1964) reported that the Bays was 1,050 feet (320 meters) thick there, Hergenroder (1966) gives a total thickness of 892 feet (270 meters). Using the positions of the upper and lower contacts along Routes 603 and 641, and an average strike of N30E and an average dip of 35 degrees SE, which are parameters based on my mapping, the calculated thickness of the Bays would be over 320 meters, *assuming that there is no duplication of strata.* This is similar to the thickness reported by Cooper (1964). My measurements, which are based on the strikes and dips shown in Figure 25B, clearly show how earlier workers could easily have assumed a great thickness of Bays at Ellett.

Examination of the well-exposed upper 100 meters of the Bays, along State Roads 603 and 641 shows that there are no coarse polymictic pebble conglomerates or turbidites in like those that occur in the Fincastle Conglomerate to the

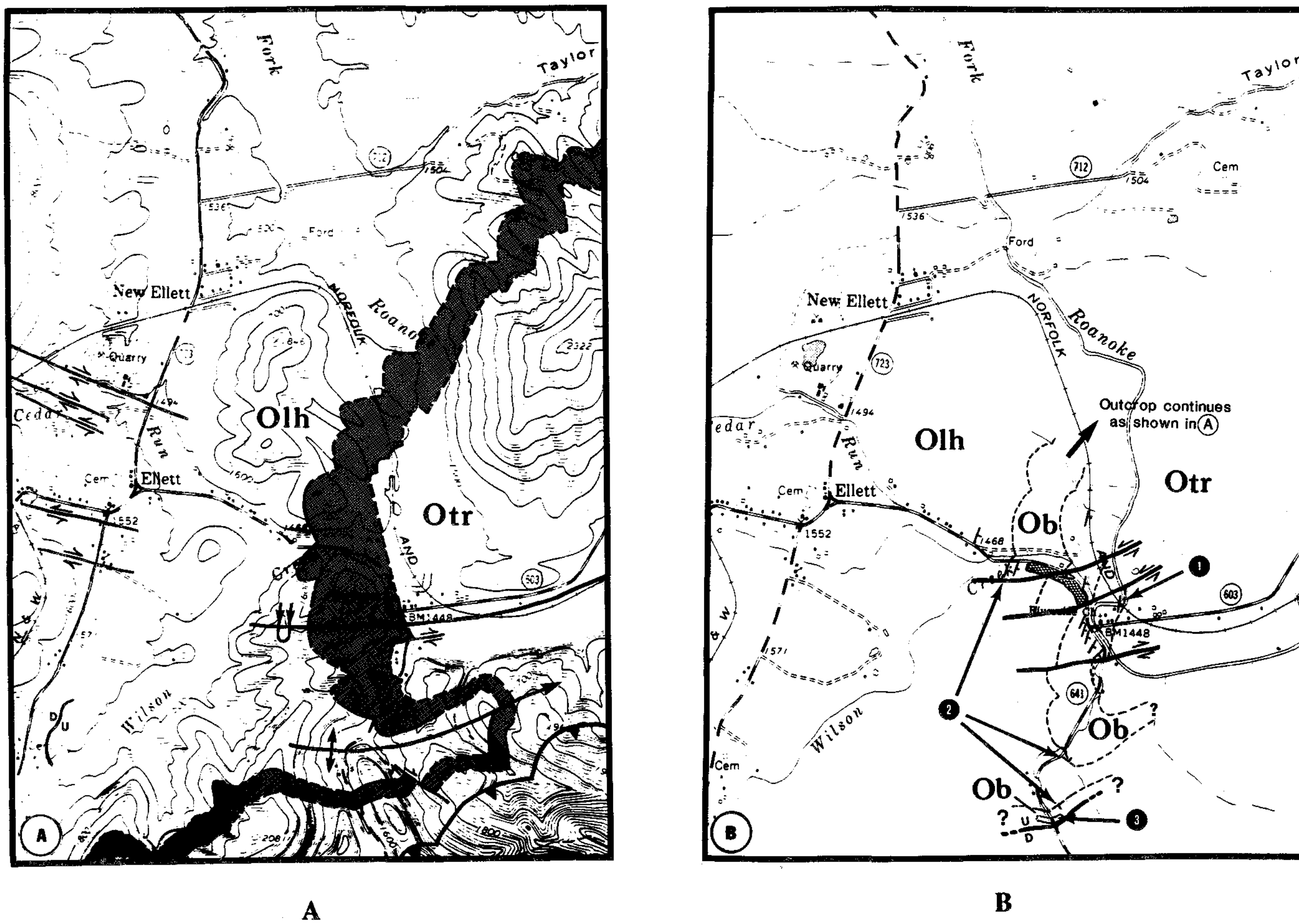

Figure 25. Geologic sketch maps of the Bays Formation outcrop near Ellett, Virginia. **A.** Outcrop (shaded area) mapped by Eubank (1967, Plate 1). **B.** Outcrop as inferred from mapping of the well-exposed section along Routes 603 and 641 by the present author. Shown are measured strikes and dips; the measured dips range from 26 to 72 degrees with the mode being between 35 and 45 degrees. The patterened area is the approximate extent of a mostly covered interval where float samples are moderately fractured. (1) Isolated exposure of Bays beneath the railroad trestle. (2) Exposures of the Bays - Liberty Hall contact. (3) Approximate area of a travertine exposure along Den Creek. Otr = Trenton Formation, Ob = Bays Formation, Olh = Liberty Hall Formation. Units younger than the Trenton and older than the Liberty Hall are not shown; refer to Eubank (1967, Plate 1) for details.

north. The Fincastle Conglomerate is a very localized sequence of polymictic conglomerates and turbidites. Most of this unit was deposited on a submarine fan (Rader and Gathright, 1986; Zhenzhong and Eriksson, 1991). If the sort of narrow and necessarily rapidly subsiding trough as envisioned by Eubank (1967) existed, sediments similar to those in the Fincastle Conglomerate might logically be expected to occur in the Bays at Ellett, particularly if subsidence outpaced sedimentation, even for a relatively short period of time. Conversely, if sedimentation merely kept pace with subsidence of such a narrow trough, allowing the supposedly great thickness of Bays sediments to accumulate at Ellett in a shelf setting that remained shallow, why is there no apparent sedimentologic evidence of this localized subsidence in either the underlying Liberty Hall or overlying Trenton ("Martinsburg") Formations? As noted above, depositional patterns in both of these units were evidently unaffected by the supposed accumulation of a very thick sequence of Bays sandstones, and during mapping of the area no new evidence was found to suggest otherwise.

In the Ellett area the only reported localized thickening of Ordovician sediments is in the sequence directly above the post-Knox unconformity (Mussman and Read, 1986, Figure 5). Those sediments (the Blackford Formation) were deposited unconformably on the paleokarst surface of the Knox Group, an erosional surface on which relief is locally over 140 meters in southwest Virginia (Mussman and Read, 1986). Localized thickening of the sediments directly overlying the unconformity near Ellett is a function of these abrupt topographic changes in the surface of the underlying Knox Group, and although the topography of the unconformity did influence sedimentation patterns in younger strata, including the Middle Ordovician buildups (Read, 1980; Mussman and Read, 1986), it is unlikely that they could have caused a localized thickening of the Bays Formation much farther upsection. This is because a great thickness (several hundred meters) of shaly basin margin limestones of the Liberty Hall Formation separates the two stratigraphic intervals of concern. I believe that this thick Liberty Hall sequence would have effectively "smoothed out" the noticeable topographic variations on the upper surface of the Knox Group and as a result such variations would have had no effect on Bays sedimentation patterns in the Upper Ordovician.

A localized thickening of lithologically similar greenish gray lithic arenites occurs in the Upper Ordovician Oswego Sandstone in Rockingham County, Virginia (Diecchio, 1985). This thickened sequence, however, can be traced along strike for at least 20 kilometers (Diecchio, 1985, Cooper Mountain and Brocks Gap sections) and the lateral distribution of this thickened Oswego reflects a sedimentation pattern that, unlike the allegedly thick Bays at Ellett, is understandable in the context of modern fluvial-deltaic depositional systems. Therefore this localized thickening of the Oswego does not provide a suitable depositional analog for explaining the reported *apparent* thickness of the Bays at Ellett, although it is in fact a useful analog for understanding the distribution pattern of the Bays based on what I believe to be its *true* thickness at the Ellett section, as discussed below.

The area around the Ellett section is structurally complex (Bartholomew, 1987), and as noted previously the exposed part of the outcrop is cut by many small-scale(?) normal faults. In addition to these faults, there are several faults near Ellett that Eubank (1967) mapped that also have a strike-slip component; these are shown in Figure 25A. Normal faults having a similar WNW-ESE structural orientation were mapped in an adjacent area of the Blacksburg quadrangle by Bartholomew and Lowry (1979).

After studying the Bays Formation in the Ellett area it is my conclusion that at least part of the reason for the supposedly localized thickening of the Bays there is that one or more faults in the long covered interval are offsetting the section. Such a fault was shown by Cooper (1964), and Bartholomew (1987, Figure 12) also shows a large fault in the vicinity of the section. In addition, as shown at (1) in Figure 25 there is an isolated exposure of probable Bays sandstones outcropping along the river directly beneath the railroad trestle about 400 meters east of the bluff above the road where the main Ellett section is exposed. These sandstones are in an area where Eubank mapped the Martinsburg, but lithologically they are very similar in appearance to the greenish gray lithic arenites and wackes of the Bays. This apparent "outlier" of Bays may be best explained by faulting, as shown in Figure 25B; perhaps one or more of the several faults that are shown on the maps by Eubank (1967) and Bartholomew and Lowry (1979) just to the west of the Ellett section actually continue to the east across the Bays Formation and into the Trenton Formation, where they may die out. Furthermore, the presence of travertine along Den Creek just upstream from the southernmost exposure of the Walker Mountain Sandstone in the area suggests that a fault unrecognized by Eubank may cut that exposure as well; this could be the reason that Eubank measured an anomalously thin section of Bays, only 65 meters thick, along Den Creek. Also, the strike and dip measurements of the beds in the Bays along the bluff are difficult to reconcile with the strike of the Bays - Trenton ("Martinsburg") contact as mapped by Eubank, whereas the outcrop pattern of the Bays shown in Figure 25B, specifically the Bays - Trenton ("Martinsburg") contact, agrees more closely with the measured strikes as shown.

Examination of float and of the sparse outcrops in the long covered interval at the Ellett section revealed that some samples are characterized by a sometimes extensive network of quartz-filled fractures, and that some probable drag folds are present as well. The fracturing appears to be much more pervasive and extensive than any of the fractures seen in the well-exposed part of the Bays farther upsection. This is taken as further evidence that one or more faults offset the Bays in this covered interval at the Ellett section.

If the apparent thickness of the Bays near Ellett as previously reported is in fact the result of offset and duplication of section along one or more faults, then the cumulative thickness of the approximately 100 meters of Bays exposed at Ellett beneath the base of the Trenton ("Martinsburg") Formation (units 21 to 110 of Hergenroder, 1966, p. 275-281) combined with the 10 to 12 meters exposed above the top of the Liberty Hall Formation (units 2 to 9 of Hergenroder) makes a reasonably good match with the thickness of the Bays as measured by Eubank (1967) along Slate Lick Run and near Lusters Gate. When these other measured thicknesses are considered the abrupt thickening of the Bays at the Ellett section is indeed, as Cooper (1964) stated, "most peculiar." In fact, the pattern of the Bays outcrop belt in this area as mapped by Eubank (Figure 25A) can be best described as looking like a long snake that has just swallowed a very large rat, with the Bays at the Ellett section being the bulge caused by the rat. Clearly this is an unusual map pattern which is all that more unusual because it is apparently not mirrored sedimentologically by either a thinning or thickening of either the overlying or underlying formations, nor are the sediments in the Bays at this location indicative of deposition over a scarp and along or into a narrow trough.

My interpretation therefore is that the true thickness of the Bays at Ellett is probably somewhere between 100 and 200 meters, and that the apparent thickness of over 300 meters results from offset of the beds along faults that are mostly covered. No sedimentologic evidence that clearly supports a greatly thickened Bays sequence was found. Localized thickening or symmetrical thinning in either the overlying or underlying formations has not been observed. Possible effects on sedimentation patterns in the Bays by localized topographic variations in the surface of the Knox Group downsection can be discounted because the influence of these variations on subsequent sedimentation patterns most likely ended when the thick Liberty Hall Formation was deposited, and the base of the Liberty Hall is several hundred meters downsection from the base of the Bays. A thickness of 100 to 200 meters still represents a noticeable increase over some of the nearby exposures, particularly along Den Creek, but such a thickness is more in line with the sections along Paris Mountain to the northeast as measured by Eubank (1967). The abrupt southward thinning of the Bays towards Den Creek is mirrored sedimentologically upsection in this part of the Salem synclinorium by a similar trend in the rest of the Upper Ordovician (the entire Juniata Formation is missing), the Silurian, and even the Devonian (Eubank, 1967; Diecchio, 1985), although as discussed above and as shown on Figure 25B the presence of travertine suggests that the upper part of the Bays is probably faulted out along Den Creek.

Deposition of 100 to 200 meters instead of 300 meters or more of predominantly lithic arenites and wackes of the Bays Formation at Ellett can be more readily explained using the Oswego Sandstone analogy from Rockingham County discussed above. This implies that the southwest end of the Salem synclinorium (the area where the Bays Formation is thickest) was an area of rapid subsidence. This subsidence was to a great extent syndepositional, with the axis of subsidence passing through the Ellett area; the subsidence possibly caused deposition of a thicker Bays Formation on the Green Ridge plate as well (Bartholomew, 1987), where the Peters Creek section is located. As noted above, however, nowhere in the Salem synclinorium or nearby areas was this subsidence apparently great enough to cause deposition of polymictic conglomerates in the Bays like those that occur to the north in the Fincastle Conglomerate, and even in isolated parts of the thick Oswego Sandstone in Rockingham County (Rader and Perry, 1976). Nor were any turbidites like those in the Fincastle Conglomerate deposited in the Bays. Lithologically the Bays Formation at the Ellett section, particularly the sandstones, bears a striking resemblence to the Oswego Sandstone at the Brocks Gap section (Diecchio, 1985), as would be expected given what I interpret to be the apparently similar depositional environments of each.

RELATIVE AGE OF THE BAYS AND EQUIVALENT STRATA

RELATION OF THE UPPER AND LOWER CONTACTS TO THE K-BENTONITES

Several authors, from Rosenkrans in 1936 to Kreisa in 1980, have noted that the base of the Trenton ("Martinsburg") Formation, which represents similar paleoenvironmental conditions everywhere it is observed across the basin, becomes younger to the north and east, and that the base of the Eggleston also is younger in that direction. Based on the findings of the present research it is clear that the base of the Trenton (which is the top of both the Eggleston and the Bays) crosses K-bentonite bed V-7 to the north and east. At the Hagan section it is the Millbrig K-bentonite that is about three meters below the base of the Trenton whereas at sections to the east it is bed V-7 that is just a few meters beneath the base of the Trenton (Figures 13 and 14). And, between Hagan and the central belt sections it is clear that the base of the Eggleston crosses the Deicke, because at Hagan the Deicke is in the Eggleston but in the central belt sections it is in the uppermost redbeds of the underlying Moccasin Formation except at the Rosedale and Rocky Gap sections. At those two sections, which are in the westernmost belt of Rocklandian strata in the central belt not far from the St. Clair fault, the boundary between the central and western belts, the Deicke is several meters above the uppermost redbeds of the Moccasin. Evidently the sequence at these two sections is transitional to some extent between the central belt sections farther east where the base of the Eggleston is above the Deicke, such as the Plum Creek section (Figure 13), and the sections in the western belt such as Hagan, where the base of the Eggleston is about 30 meters below the Deicke. Kreisa (1980, p. 334) noted that the lower beds of the Trenton ("Martinsburg") Formation exposed in the Rosedale section are transitional between his central and western belts, the boundaries of which are essentially the same as those used in the present paper.

Based on these findings it is logical to assume that the base of the Bays Formation would also become younger to the north and east as well. Hergenroder (1966) discussed the difficulties in constraining the age of the base of the Bays in southwest Virginia, noting that

> ...the best stratigraphic control between southeastern (Bays) belts and middle (Moccasin) belts at the base of the sequence is in the southwestern part of the Walker Mountain belt. In this area the Bowen and Witten equivalents can be recognized easily in the lower part of the Bays...The lowest red beds in the Bays Formation at the southwest end of the Walker Mountain belt (Bowen equivalent) are older than the lowest red [bed] at [the] New River (lower Moccasin). The age of the lower Bays in the Salem-Catawba syncline is uncertain, but may be equal to that of the Bowen Formation...The presence of a thin bentonite near the base of the Bays in the Bonsack section [a few kilometers northeast of Roanoke] indicates that the basal Bays strata at that locality are probably much younger than in belts to the southwest.

I am in general agreement with these statements except that based on the findings of the present research the age of the lower Bays in the Salem-Catawba syncline (the Salem synclinorium) can now be better constrained. For the reasons set forth in preceding sections I believe that the conglomeratic sandstone unit at the base of the Bays Formation in the Roanoke area is correlative with the Walker Mountain Sandstone in exposures in its type area farther west. With that correlation it is now evident that the lower Bays in the exposures referred to by Hergenroder above, which are along the southwestern part of Big Walker Mountain and include the several tens of meters of redbeds below the Walker Mountain Sandstone, are clearly older than the lowest Bays at the sections in the Salem synclinorium and at the nearby Connor Valley and Crockett Cove sections. At none of those sections is there any Bays Formation beneath the conglomeratic basal sandstones. I would therefore suggest that the Bays at the Salem synclinorium sections and the nearby Connor Valley and Crockett Cove sections is not correlative with the Bowen Formation but instead is everywhere younger than the base of the Bays in the exposures along Big Walker Mountain. There, as noted in the quotation above, the lower Bays contains beds that are recognizable as being correlative with the Bowen and Witten Formations, downsection from the Walker Mountain Sandstone.

Figure 26 is a reinterpretation of the facies relationships of the Moccasin, Eggleston, Trenton ("Martinsburg"), and Bays Formations, and related units as shown. From study of the K-bentonites it is clear that the bases of the Eggleston, Bays, and Trenton ("Martinsburg") Formations become younger to the north and east. This illustration also gives an indication of the basin evolution during the time that these strata were deposited.

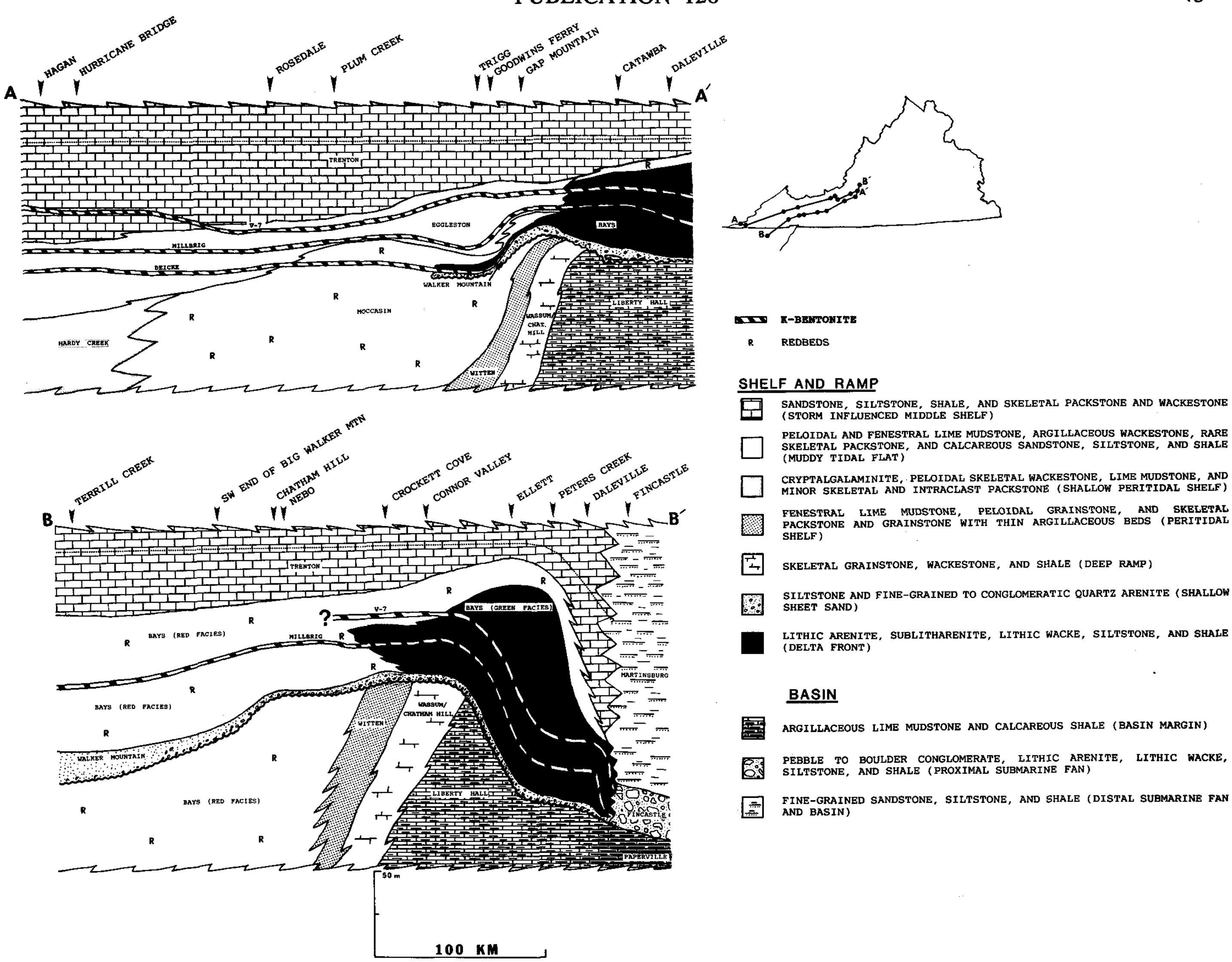

Figure 26. Interpretive cross-sections of Rocklandian and adjacent strata based on study of the K-bentonites. The dotted line in the lower Trenton is the datum, as discussed in the text. It is evident that the bases of the Eggleston, Trenton, and Bays Formations all become younger to the north and east, and that the Walker Mountain Sandstone was deposited as a sheet sand across much of the basin. The "green facies" of the Bays is clearly restricted in its distribution, suggesting that this localized delta system existed for only a relatively short time. Horizontal distances are pre-deformational (palinspastic) distances based on the maps of Dennison and Woodward (1963) and Pedlow (1976).

Although these cross-sections are based on the stratigraphic positions of the Rocklandian K-bentonites, the datum is the dotted line in the lower Trenton ("Martinsburg") rather than one of the K-bentonites, even though the K-bentonites are of course ideal isochrons. The intent of Figure 26 is to show the restored paleogeographic setting of the basin as accurately as possible, and placing a time line in the lower Trenton allows this, because the base of the Trenton represents deposition in a relatively similar paleoenvironmental setting across the entire basin (Kreisa, 1980). The Trenton ("Martinsburg") Formation was deposited following a period of dissimilar settings across the basin: tectonic activity had caused deposition of the deltaic "green facies" of the Bays along the eastern margin of the basin, while at the same time carbonate sedimentation had continued uninterrupted along the basin's western edge. If one of the K-bentonites is used as the datum, therefore, the cross-section is not as informative, and can be misleading because of marked differences in thickness of various units. Even so, the actual base of the Trenton itself is not shown as a horizontal line because it clearly becomes younger towards the north and east. The chronostratigraphic relationships in the area between Daleville and Fincastle (Section B-B') are not as precisely known because none of the K-bentonites has been found at Fincastle. The time line is shown bending downward in Section B-B' to reflect the abrupt deepening of the shelf margin in the Fincastle region (Rader and Gathright, 1986).

From section B-B' in Figure 26 it is evident that the Walker Mountain Sandstone lithofacies transgressed across the basin from southwest to northeast. The thickness of the interval between it and the Millbrig decreases gradually in that direction, from 36 meters at the Terrill Creek section in the Bays Mountains to 28 meters at the Chatham Hill section on Big Walker Mountain to 18 meters at the Connor Valley section near Pulaski. This interval is again 18 meters at the Daleville section; farther north at Fincastle the Bays passes into the Fincastle Conglomerate, at the base of the flysch sequence that characterizes the true Martinsburg Formation in that area and to the north.

IMPLICATIONS FOR PALEOENVIRONMENTAL RECONSTRUCTION

The evidence thus suggests that both the upper and lower contacts of the Bays Formation in southwest Virginia become younger to the north and east, and that the oldest "red" Bays (Saltville thrust sheet) is older than the oldest "green" Bays (Cove Mountain and Pulaski thrust sheets). This implies that regional changes in sediment dispersal patterns also occurred. Figure 27 summarizes the changes in delta loci, which were responsible for shifts in deposition of the facies that is represented by the "green" Bays of the Salem synclinorium. The changes in sediment dispersal patterns reflect changes in the drainage patterns of the fluvial systems coming from highlands to the east. Sediment had previously been deposited farther south by big rivers emptying into the basin, the eastern edge of which may have been very steep, resulting in mostly deep-water submarine fan sedimentation rather than shallow-water deltaic sedimentation. When the shallow sheet sand represented by the Walker Mountain Sandstone was deposited, sedimentation rates had evidently slowed considerably across much of the basin, probably because uplift and the increased subsidence that had accompanied it had slowed or stopped, leading to a gradual decrease in erosion rates. This resulted in a slowing or halting of deposition of the lithic arenites and wackes that characterize the upper sections of both the Knobs and Sevier Formations (associated with delta (1) on Figure 27). Wind and wave related processes then became dominant over fluvial ones, and the Walker Mountain facies developed in a sequence of events that is sometimes referred to as the "destructional phase" of delta sedimentation. Removal of the fines produced the bimodal but compositionally mature quartz arenites of the Walker Mountain Sandstone. This winnowing could have occurred in just a few thousand years; the Chandeleur Islands in the Gulf of Mexico are barrier islands that are still forming and re-forming -- in a wind- and wave-dominated "destructional phase" environment -- from the reworking of the sands, silts, and muds of the Mississippi River's St. Bernard subdelta during just the past 5,000 years (Miall, 1979).

When uplift resumed it was farther northeast, so that what is now the Salem synclinorium and nearby areas became the area of most rapid subsidence along the eastern edge of the depositional basin. To the southwest where the earlier uplift had resulted in deposition of the Knobs and Sevier Formations, further uplift did not occur. Instead, a tidal flat environment had been prograding across the now-filled Sevier basin, resulting in deposition of the Bays redbeds and equivalent units that would eventually be covered by the open marine sediments of the Trenton

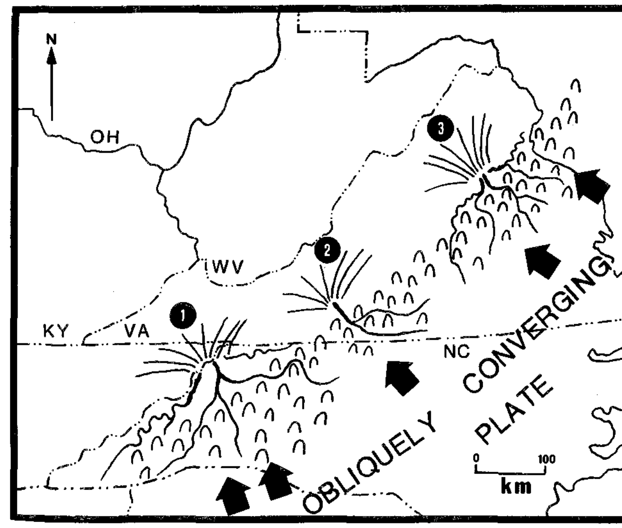

Figure 27. Changes in the loci of deltaic sedimentation in the Ordovician of the central and southern Appalachians. These deltas, which developed successively in time, occurred westward of uplifted areas to the east. Those areas presumably formed as the result of an oblique, scissors-like collision of the North American plate's eastern continental margin with another plate. Approximate distribution of the prodelta sediments of the Knobs Formation (1), the delta front facies of the Bays Formation (2), and the delta front facies of the Oswego Sandstone (3) are shown. The areal extent of the Knobs and Oswego are discussed in Read (1980) and Diecchio (1985), respectively.

("Martinsburg") during the next widespread marine transgression. In the Salem synclinorium and nearby areas, however, the increased rate of uplift eventually resulted in increased erosion, and this caused the delta front to change from a wave-dominated "destructional phase" environment to a fluvial-dominated "constructional phase" environment, *not* to a quiet tidal flat environment like that farther south. The quartzose sands of the Walker Mountain Sandstone, derived from the reworking of older sands on the eroded surface of the underlying carbonates (Figure 26), were buried beneath an influx of lithic sands and muds brought into the basin by rivers draining the newly uplifted highlands to the east (delta (2) in Figure 27). These sediments are the "green facies" of the Bays, shown in Figure 26, whereas the tidal flat deposits farther south and west are the "red facies" of the Bays. The volcanic ashes that are now the Deicke, Millbrig, and V-7 K-bentonites were deposited during this time. To the north the polymictic conglomerates of the Fincastle Conglomerate Member of the Martinsburg Formation were deposited during this time also, on a submarine fan below the edge of the delta platform.

As the uplifted area was eroded the influx of fluvial sediments onto the shelf waned; this occurred at about the time that bentonites V-8 through V-13 or V-14 of Rosenkrans (1936) were deposited in the upper Bays and lower Trenton ("Martinsburg") Formations. The first bioclastic grainstones and packstones of the Trenton ("Martinsburg") Formation appear in this interval across most of the basin, and the normal marine conditions they represent prevailed until the basin again shallowed later in the Ordovician, and the redbeds of the Juniata Formation were deposited above the Reedsville Formation.

Interestingly, deltaic sedimentation (represented by the "green facies" of the Bays) did not end, it simply shifted farther northeast again, where it is represented by the coarse greenish gray sands of the Oswego Sandstone, particularly along Little North Mountain northwest of Harrisonburg, in northern Virginia (Diecchio, 1985). This episode of deltaic sedimentation is represented by delta (3) on Figure 27. As discussed above, the Oswego sands are lithologically similar to the sands in the Bays Formation on the Pulaski and Cove Mountain thrust sheets; both are fluvial-deltaic "green facies," not tidal flat "red facies."

The "green" Bays and the Oswego are interpreted as representing deltaic sedimentation along the eastern edge of the basin, whereas the Knobs and Sevier Formations are basinal units associated partly with sedimentation on submarine fans (Read, 1980). Shallower delta front facies may or may not have later prograded over those basinal units; in any event there are apparently no delta front sands preserved in that region. Nevertheless, the petrographic description of the coarser sandstones in the upper Knobs and Sevier Formations (Read, 1980) indicates that they are similar to the greenish gray lithic arenites and wackes of the Bays in the Salem synclinorium.

The lateral shift of the delta loci shown in Figure 27 reflects the episodic northward shifting of uplifted areas along the eastern margin of the Appalachian basin, represented by arrows. This shifting most likely resulted from a collision of the North American plate with a smaller plate, probably the Inner Piedmont (Sinha and Zietz, 1982). Evidence suggests that the collision occurred in an oblique, scissors-like fashion along the continental margin. It started in the south, possibly as far south as Alabama or Georgia, causing uplift and associated downwarping that created a foreland basin in which the Athens Shale and its basinal equivalents were deposited. As the collision shifted northward, the uplift migrated as well, and deposition of the coarser sands of the upper Sevier Shale and the Knobs Formation in southwesternmost Virginia and Tennessee occurred. The next shift resulted in uplift in central Virginia, causing deposition of the "green facies" of the Bays Formation in the Salem synclinorium and nearby areas, and of the Fincastle Conglomerate in the Pine Hills syncline. This was followed by uplift farther north, which resulted in deposition of the thick Oswego Sandstone sections in northern Virginia.

This brief synopsis of how the deltaic sands of the Bays in the Rocklandian sequence fit in regionally with the paleoenvironmental setting as it is currently understood shows how the Rocklandian K-bentonites can be successfully used to constrain the relative age of the Bays Formation over a significantly larger area than has previously been possible using biostratigraphic criteria alone. A detailed comparison of the provenance of the upper Knobs Formation, the Bays Formation of the Salem synclinorium and adjacent areas where the greenish gray lithic sandstones predominate, and the Oswego Sandstone in Rockingham County is being planned as part of a study of the source terranes that provided sediment to the foreland basin throughout the Late Ordovician.

SUMMARY AND CONCLUSIONS

Examination of K-bentonites in Rocklandian strata in the Valley and Ridge of southwest Virginia and nearby areas of West Virginia and Tennessee has resulted in a significant reinterpretation and expansion of several previous correlations of those beds and the enclosing strata. The three thickest K-bentonites are correlated along and across strike throughout this region on the basis of petrographic and lithostratigraphic criteria, and for the first time a set of time lines has been shown to link the Rocklandian strata across the width of the Valley and Ridge province in this area. This provides a foundation on which future studies of these strata and of the other K-bentonites in the sequence can be attempted.

Several statements, conclusions, and reinterpretations concerning the stratigraphic relationships of the Rocklandian K-bentonite sequence and the surrounding Upper Ordovician strata are summarized as follows:

1) There are three thick K-bentonites that occur in Rocklandian strata of the Valley and Ridge province in southwest Virginia and nearby areas of adjacent states. They have been reported in many previous studies, and they have been known most widely in the central belt, in ascending order, as beds V-3, V-4, and V-7 (Rosenkrans, 1936), and in the western belt as beds R-7, R-10, and R-12 (Miller and Fuller, 1954).

2) Based on a study of the non-clay mineralogy, the K-bentonite bed known as T-3 in exposures along the Cincinnati Arch can be correlated with bed R-7, which can in turn be correlated with bed V-3. Because T-3 has been correlated with the Deicke K-bentonite Bed (Willman and Kolata, 1978) of the Upper Mississippi Valley using geophysical logs of wells by Huff and Kolata (1990), R-7 and V-3 are also the Deicke K-bentonite Bed.

3) Based on a study of the non-clay mineralogy, the K-bentonite bed known as T-4 in exposures along the Cincinnati Arch can be correlated with bed R-10, which can in turn be correlated with bed V-4. Because T-4 has been correlated with the Millbrig K-bentonite Bed (Willman and Kolata, 1978) of the Upper Mississippi Valley using geophysical logs of wells by Huff and Kolata (1990), R-10 and V-4 are also the Millbrig K-bentonite Bed.

4) K-bentonite bed V-7 of Rosenkrans (1936) was not studied in the detail that the two lower beds were, but its readily recognized stratigraphic position in the central belt (one to three meters below the base of the "cuneiform" beds and two to nine meters below the fossiliferous beds that mark the base of the Trenton ("Martinsburg") Formation throughout the region) and persistent thickness throughout the study area make it a useful marker bed in many sections. Its stratigraphic relationship with the K-bentonite sequence in the Rocklandian of the Cincinnati Arch and the Upper Mississippi Valley is not known, although it quite possibly is equivalent to either the Elkport or Dickeyville K-bentonite Bed of the Upper Mississippi Valley (Willman and Kolata, 1978).

5) These correlations represent a significant reinterpretation of those suggested by Huffman (1945), Miller and Fuller (1954), and Hergenroder (1966, 1973), who believed that V-4 of the central belt was correlative with

R-7 of the western belt. Although Huffman and Hergenroder indicated that V-7 was correlative with R-10, Miller and Fuller believed that R-10 did not correlate with V-7 but with a higher bed in the central belt sequence, although they did not suggest an alternate correlation. With the regional reinterpretation, R-7 is correlated with V-3, and R-10 is correlated with V-4, not with V-7 or any higher bed. In addition, Miller and Fuller (1954) incorrectly labeled bed T-4 as the Pencil Cave, and T-5 as the Mud Cave in their Plate 26 when in fact those names refer to beds T-3 and T-4, respectively. Also, I believe that the thicknesses for T-4 and T-5 shown in their Plate 26 were inadvertently reversed, as T-4 is reported as being only four inches thick, while T-5 is reported as 2.5 feet thick. Those two errors are not shown in the present Figure 7 but rather the correct sequence and thicknesses as originally described by Wilson (1949) are shown (encircled number 1).

6) Although all three of these thick K-bentonites can be located at exposures in the central and western belts, and in exposures along the northern and eastern edge of the Bluegrass Basin of Kentucky along the Cincinnati Arch, only beds V-4, the Millbrig, and V-7 persist eastward into the Bays Formation on the Saltville, Cove Mountain, and Pulaski thrust sheets of the eastern belt. It is the Millbrig that is the oldest K-bentonite bed in the Bays Formation, as the Deicke, bed V-3, is absent. Although Rosenkrans (1936) and Hergenroder (1966) indicated that a thick K-bentonite in the Bays Formation near Roanoke was correlative with bed V-3 in the central belt, it is evident that this thick K-bentonite is not V-3 based on a comprehensive petrographic and lithostratigraphic analysis of the sequence. The K-bentonite bed that those authors described from the Bays is evidently either the Millbrig or bed V-7, the only two relatively thick K-bentonites that occur in the Bays Formation.

7) Because bed V-3 is correlative with the Deicke, it is evident that that bed is more widespread than was originally thought by Rosenkrans (1936) and Hergenroder (1966). It can be traced to the south and west in the study area into the Eggleston Formation and the equivalent part of the Chickamauga Limestone in the Powell Valley of Tennessee, but it does not persist eastward, as it is absent from the Bays Formation. This bed also thins noticeably to the north and northwest, rather than to the south and west as indicated by those authors, but it is not missing in Lee County because of an unconformity, as postulated by Rosenkrans (1936). At the Goodwins Ferry section (Figure 13) the Deicke is around 25 centimeters thick, which is much thinner than in sections farther south, and at the Black River Mine section in Carntown, Kentucky (Figure 18), it is only 15 centimeters thick, indicating a thinning of the bed in this direction.

8) The conglomeratic sandstone that occurs at the base of the Bays Formation in exposures on the Cove Mountain and Pulaski thrust sheets is correlated with the Walker Mountain Sandstone Member (Butts and Edmundson, 1943) in the Bays Formation on the Saltville thrust sheet along Big Walker Mountain, and in the Moccasin Formation on the Saltville and Narrows thrust sheets in the upper New River Valley. This correlation is based on petrographic and lithostratigraphic study of these units and on a comparison of the stratigraphic interval between those sandstones and the Millbrig K-bentonite.

9) Based on the positions of the K-bentonite beds, it is evident that the base of the Bays Formation becomes younger to the north and east. The petrographic character of the Bays changes as well, from a sequence of fine-grained tidal flat redbeds ("red facies") in northeast Tennessee and along the southwest end of Big Walker Mountain to a sequence of coarser, greenish gray delta front sands composed of lithic arenites and wackes ("green facies") in the Salem synclinorium. This interpretation of the facies relationships between the "red" and "green" Bays has been noted previously by Hergenroder (1966), but with the time lines provided by the K-bentonites the nature of the lateral sedimentologic changes in the Bays is now better understood.

10) Deposition of the delta front sands clearly began later than deposition of the Bays redbeds farther south, and the lithologic character of these delta front sands reflects the successive northward shifting of uplifted areas along the eastern margin of the basin. This shifting caused the deposition of the lithic arenites and sublitharenites and wackes of the Bays Formation in the Salem synclinorium sections and the nearby Connor Valley and Crockett Cove sections.

11) It is recommended that the names "Deicke K-bentonite Bed" and "Millbrig K-bentonite Bed" be introduced and recognized in southwest Virginia, southeast West Virginia, and northeast Tennessee as the formal stratigraphic names for the lower two of the three thickest K-bentonites that have been described from the Rocklandian sequence. These are appropriate names for those two K-bentonites because they are correlative with the two thick beds that occur to the west in outcrops along the Cincinnati Arch. Those two beds have been correlated with the Deicke and Millbrig K-bentonite Beds of the Upper Mississippi Valley, where type localities for each have been measured and described (Willman and Kolata, 1978; Kolata et al., 1986). They are also more appropriate names than the alpha-numeric names now in widespread use because those names have never been formalized for usage, and as names for stratigraphic units they are unacceptable by the standards of the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983). In the Valley and Ridge province, therefore, use of the name Deicke thus formally replaces the name B-3 of Fox and Grant (1944) in the Chattanooga region, R-7 of Miller and Fuller (1954) in the Powell Valley sections of the western belt of the Valley and Ridge, and V-3 of Rosenkrans (1936) in the central belt of the Virginia and Tennessee Valley and Ridge. It also replaces the name T-3 of Wilson (1949) in the Cincinnati Arch. Use of the name Millbrig replaces the terms B-6, R-10, V-4, and T-4 in the above areas, respectively.

It should be noted that with the reinterpretations discussed herein the numbering systems used most widely in Virginia and Tennessee to distinguish the K-bentonites, the "V" series of Rosenkrans (1936), the "B" series of Fox and Grant (1944), and the "T" series of Wilson (1949), now match up by number with respect to the first thick bed, i.e., T-3 equals V-3 equals B-3. This indicates that the first thick K-bentonite in the Rocklandian is in much of the region the third K-bentonite upsection. In addition, T-4 equals V-4, the next thick K-bentonite upsection in the two regions where those systems have commonly been used.

These correlations, which are a reinterpretation and expansion of parts of earlier studies including those of Rosenkrans (1936), Huffman (1945), Miller and Fuller (1954), and Hergenroder (1966; 1973), integrate the Rocklandian sequence of this area. They provide a set of time lines that will greatly aid in furthering our knowledge and understanding of these strata, which are an important part of the Ordovician in this region.

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APPENDIX I

DESCRIPTION OF SAMPLE LOCALITIES AND NEW MEASURED SECTIONS

DESCRIPTION OF SAMPLE LOCALITIES

This appendix includes a description of sample localities by number, the appropriate USGS 7½ minute quadrangle showing the location of the exposure(s), and the citations of references in which detailed descriptions of the measured section are given. Only Deicke, Millbrig, and V-7 K-bentonite sample numbers are given, along with the sample number of Walker Mountain Sandstone samples. For purposes of cross-referencing, if a previously published measured section was used the appropriate bed number from that measured section is matched with the K-bentonite sample numbers. New sections measured by the author are at the end of this appendix.

1) Hagan, Lee County, Virginia
Rose Hill 7½ minute quadrangle

Hardy Creek Limestone and Eggleston and Trenton Formations in exposure on the east side of the rail switchback along the CSX (ex-L&N) right-of-way near State Road 621 about 0.8 kilometers north of the intersection with U.S. Highway 58 (Huffman, 1945; Miller and Fuller, 1954; Miller and Brosgé, 1954; Kreisa, 1980, p. 308-309).

Sample VA 4-1, Millbrig (bed 2, Kreisa)
Sample VA 2-1, Deicke (bed 8)

2) Gate City, Scott County, Virginia
Gate City 7½ minute quadrangle

Upper Moccasin, Eggleston, and lower Trenton ("Martinsburg") Formations in exposure at the west end of the Gateway Plaza, on south side of combined U.S. Highways 23, 58, and 421 immediately before the gap through Clinch Mountain used by the highway and the Norfolk Southern railroad.

Sample VA:SC 1-3, V-7
Sample VA:SC 1-2, Millbrig
Sample VA:SC 1-1, Deicke

3) Rosedale, Russell County, Virginia
Elk Garden 7½ minute quadrangle

Upper Moccasin, Eggleston, and lower Trenton ("Martinsburg") Formations in exposure along the northeast side of the old (i.e., up the embankment from new) Route 80, 2.3 kilometers northwest of the intersection with U.S. 19 at Rosedale.

Sample VA:RL 2-3, V-7
Sample VA:RL 2-2, Millbrig
Sample VA:RL 2-1, Deicke

4) Plum Creek, Tazewell County, Virginia
Tazewell South 7½ minute quadrangle

Upper Moccasin, Eggleston, and lower Trenton ("Martinsburg") Formations in exposures along the southeast side of Route 16 along Plum Creek between Frog Level and Thompson Valley (Hergenroder, 1966, p. 271-272).

Sample VA:TZ 1-1, V-7 (bed 53, Hergenroder)
Sample VA:TZ 1-8, Millbrig (bed 48)
Sample VA:TZ 1-7, Deicke (bed 43)

5) Cove Creek, Tazewell County, Virginia
Cove Creek 7½ minute quadrangle

Upper Moccasin and lower Eggleston Formations in exposure along State Road 614 at the first hairpin turn in the road below Crabtree Gap.

Sample VA:TZ 2-3, V-7
Sample VA:TZ 2-2, Millbrig
Sample VA:TZ 2-1, Deicke

6) Rocky Gap, Bland County, Virginia
Rocky Gap 7½ minute quadrangle

Upper Moccasin and lower Eggleston Formations in exposure along southwest side of U.S Highway 52 (Frontage Road for I-77) 1.5 kilometers south of Rocky Gap.

Sample VA:BL 1-2, Millbrig
Sample VA:BL 1-1, Deicke

7) Goodwins Ferry, Giles County, Virginia
Eggleston 7½ minute quadrangle

Upper Moccasin Formation, Walker Mountain Sandstone, and Eggleston and lower Trenton ("Martinsburg") Formations in exposure along the east side of State Road 625, on the east bank of the New River 500 meters north (uphill) from the railroad grade crossing (Hergenroder, 1966, p. 200-300; Kreisa, 1980).

Sample VA:GI 4-2, V-7 (bed 49, Hergenroder)
Sample VA:GI 4-1, Millbrig (bed 40)
Sample VA:GI 4-0, Deicke (bed 29)

8) Mountain Lake Turnoff, Giles County, Virginia
Eggleston 7½ minute quadrangle

The upper Moccasin Formation and the Walker Mountain Sandstone in exposure along the northeast side of westbound U.S. Highway 460 400 meters east of the intersection with State Road 700 to Mountain Lake (Hergenroder, 1966, p. 311).

Sample VA:GI 5-1, Deicke (bed 16, Hergenroder)
Sample WMS 2, Walker Mountain Sandstone

9) Terrill Creek, Hawkins County, Tennessee
Stony Point 7½ minute quadrangle

Walker Mountain Sandstone, upper Bays Formation, and lower Trenton ("Martinsburg") Formation in exposure along the northeast side of the road above Terrill Creek in the gap between Hennard and River Mountains (Hergenroder, 1966, p. 174).

Sample TN:HK 2-1, Millbrig (bed 21 of Hergenroder)

10) Chatham Hill, Smyth County, Virginia
Chatham Hill 7½ minute quadrangle

Walker Mountain Sandstone and upper Bays Formation in exposure along northeast side of Route 16 on northwest side of Big Walker Mountain 3.7 kilometers south of Chatham Hill (Hergenroder, 1966, p. 260-262; Kreisa, 1980).

Samples VA:SM 1-3 to 1-6, Millbrig (beds 58 and 59, Hergenroder)
Sample WMS 3, Walker Mountain Sandstone

12) Crockett Cove, Wythe County, Virginia
Wytheville 7½ minute quadrangle

Upper Witten Formation, Walker Mountain Sandstone, and lower Bays Formation in exposure along the northeast side of northbound I-77 about 2 kilometers northwest of the interchange with I-81.

Sample VA:WY 2-1, Millbrig

13) Connor Valley, Wythe and Pulaski Counties, Virginia
Fosters Falls 7½ minute quadrangle

Wassum Formation, Walker Mountain Sandstone, and Bays Formation in 2 exposures: A) in Wythe County along State Road 614 in Connor Valley in the cut through the low ridge (Hergenroder, 1966, p. 303); B) in Pulaski County along Frontage Road for I-81 just south of "T" intersection with Route 100.

Sample VA:WY 1-2, V-7 (bed 4, Hergenroder)
Sample VA:WY 1-1, Millbrig
Sample WMS 4, Walker Mountain Sandstone

14) Gap Mountain, Giles County, Virginia
Radford North 7½ minute quadrangle

Witten, Moccasin, Eggleston, and Trenton Formations, and the Walker Mountain Sandstone in exposure along the northeast side of the Norfolk Southern (ex-VGN) Railroad right-of-way along Route 625 on the east side of the New River about 500 meters north of Big Falls on the Clinch Sandstone (Hergenroder, 1966, p. 297-298; Kreisa, 1980).

Sample VA:GI 1-2, V-7 (bed 20, Hergenroder)
Sample VA:GI 1-1, Millbrig (bed 16)

15) Catawba, Roanoke County, Virginia
Catawba 7½ minute quadrangle

Upper Bays Formation in the exposure along the southwest side of Route 311 50 meters southeast of the bridge over Catawba Creek. (Hergenroder, 1966, p. 155-156; Kreisa, 1980).

Sample VA:RO 1-3, V-7 (bed 16, Hergenroder)
Sample VA:RO 1-1, Millbrig (bed 4) and sample VA:RO 1-2, Millbrig (bed 8; unit is split into 2 separate beds)

16) Daleville, Botetourt County, Virginia
Daleville 7½ minute quadrangle

Upper Liberty Hall Limestone, Walker Mountain Sandstone, Bays Formation, and lower Trenton ("Martinsburg") Formation in exposure along the east side of the Norfolk Southern Railroad Lone Star Spur, about 800 meters due west of Lord Botetourt High School (Hergenroder, 1966, p. 157).

Sample VA:BT 2-2, V-7 (bed 11, Hergenroder)
Sample VA:BT 2-1, Millbrig (bed 9)

17) Harrogate, Claiborne County, Tennessee
Middlesboro South 7½ minute quadrangle

Upper Eggleston and lower Trenton ("Martinsburg") Formations in exposure along the now dismantled CSX (ex-L&N) Railroad right-of-way about 500 meters southeast of the former grade crossing at Myers School (Huffman, 1945, p. 163).

Sample TN:CL 1-1, Millbrig (bed V-7, Huffman)
Sample TN:CL 1-2, Deicke (bed V-4)

18) Hinds Creek Quarry, Anderson County, Tennessee
Powell 7½ minute quadrangle

Upper Chickamauga Limestone exposed in the inactive quarry in the Lone Mountain Subdivision on Brushy Mountain Road 0.5 km northeast of the mouth of Hinds Creek near

Clinton (Coker, 1962, p. 4-8).

Sample TN 11, Millbrig
Sample TN 10, Deicke (this is the bed studied by Coker)

32) High Bridge, Mercer County, Kentucky
Wilmore 7½ minute quadrangle

Upper Tyrone and lower Lexington Limestones in exposures along the Norfolk Southern (CNO&TP) Railroad right-of-way and in the quarry at High Bridge.

Sample KRI 5-0, Millbrig
Sample KRI 5-1, Deicke

34) Black River Mine, Pendleton County, Kentucky
Moscow 7½ minute quadrangle

Upper Tyrone and lower Lexington Limestones exposed in the shaft to the underground workings at the Black River Mine, Carntown (Kunk and Sutter, 1984, p. 15).

Sample BRM T-4, Millbrig (2nd K-bentonite bed from top, Kunk and Sutter)
Sample BRM T-3, Deicke (3rd K-bentonite bed from top)

56) Eidson, Hawkins County, Tennessee
Kyles Ford 7½ minute quadrangle

Moccasin Formation and lower Eggleston Formation in exposure along the south side of Rt. 70 on northwest slope of Clinch Mountain between Eidson and Rogersville (Hergenroder, 1966, p. 191).

Sample TN:HK 3-2, Millbrig (bed 26 of Hergenroder)
Sample TN:HK 3-1, Deicke (bed 24)

57) Hurricane Bridge, Lee County, Virginia
Hubbard Springs 7½ minute quadrangle

Hardy Creek Limestone and lower Eggleston Formation in exposure along the north side of State Road 654 south of Hurricane Bridge over the Powell River (Miller and Brosgé, 1954, p. 110).

Sample VA:LE 1-2, Millbrig (bed 20, Miller and Brosgé)
Sample VA:LE 1-1, Deicke (bed 18)

63) Nebo, Smyth County, Virginia
Nebo 7½ minute quadrangle

Bays Formation and the Walker Mountain Sandstone in exposure on east side of State Road 622 on northwest side of Big Walker Mountain 2 kilometers south of Nebo (Handwerk, 1980).

Sample WMS 1, Walker Mountain Sandstone

64) Ellett, Montgomery County, Virginia
Ironto 7½ minute quadrangle

Upper Liberty Hall Limestone, Walker Mountain Sandstone, Bays Formation, and lower Trenton ("Martinsburg") Formation in exposure on the south side of State Road 603 beginning just east of the bridge over Wilson Creek (Butts, 1940; Hergenroder, 1966, p. 275).

Sample WMS 5, Walker Mountain Sandstone

65) Peters Creek, Roanoke County, Virginia
Salem 7½ minute quadrangle

Upper Liberty Hall Limestone, Walker Mountain Sandstone, and lower Bays Formation in bluff along State Road 629 at the headwaters of Peters Creek about 2.1 kilometers east of Hanging Rock.

Sample WMS 6, Walker Mountain Sandstone

NEW MEASURED SECTIONS

During the field work for this study the measurements for all but nine of the above sections were taken from the cited references, which were checked for accuracy. In particular I found the measurements by Hergenroder (1966) of the various sections to be extremely accurate. Measurements for the nine new sections are given below. The Gate City and Crockett Cove sections are near to the sections of those names that were measured by Hergenroder (1966), but because I collected the K-bentonites from newer exposures, measurements of those sections have been included. Butts (1940) included a measured section of the Rosedale exposure, which I measured. Those intervals of the Cove Creek and Rocky Gap, sections that contain K-bentonites are herein described for the first time. The Connor Valley section is actually a composite of two measured sections, as Hergenroder's (1966) Conner [*sic*] Valley section includes only the upper part of the Bays. The Hinds Creek Quarry section was partly measured by Coker (1962) but evidently the Deicke was not yet exposed at that time. The classic Ordovician section at High Bridge, Kentucky has been studied by many geologists, but I felt that it was appropriate to include my measurements of that section. The Peters Creek section is one of many that I studied where no K-bentonites were collected, but the measurements for it are included because it is shown in Figure 23.

Section 2. Gate City Thickness (meters)

The upper Moccasin, Eggleston, and lower Trenton ("Martinsburg") Formations in exposure at the west end of the Gateway Plaza, on south side of combined U.S. Highways 23, 58, and 421 immediately before the gap through Clinch Mountain used by the highway and the Norfolk Southern railroad.

Trenton ("Martinsburg") Formation

1. Covered.

2. Fossiliferous grainstones and packstones, thin to medium bedded with lesser amounts of siltstone and shale. Strata are warped and probably faulted. .... 20±

Eggleston Formation (14 meters ±)

3. Lime mudstones, greenish gray, thin to medium bedded with a variable argillaceous content. Some beds have a fenestral texture.Rare very thin beds of fossiliferous grainstones.Strata are warped and faulted. . 4±

4. K-bentonite bed V-7. Red, green, and gray bentonitic clay, with some biotite. Numerous calcite filled fractures. Bed is greatly thickened at base of exposure because of faulting 1

5. Lime mudstones as in unit 3, with some nodular, cobbly beds. Strata are warped and faulted.. 6±

6. Millbrig K-bentonite bed. Sharp basal contact with underlying chert. Gray fine- to medium-grained bentonitic clay in lowest 8 to 10 cm, coarse-grained gray tuffaceous material with abundant black biotite grains in next 15 to 20 cm, upper 80 cm is progressively finer grained bentonitic clay with visible biotite. Uppermost zone includes a noticeable argillaceous component and is transitional with the overlying shaly greenish gray limestones. Bed is thickened from faulting and the biotite rich zone appears to be repeated near the top of the bed........................... 1.1

7. Chert, black, with abundant joints perpendicular to bedding.................................. 0.03

8. Lime mudstones as in unit 3..................... 4

Moccasin Formation

9. Lime mudstones, thin bedded, grayish red, with a noticeable argillaceous component.. 4

10. Deicke K-bentonite bed. Lower 2 cm is a white plastic clay, very sticky. Remainder of bed is red bentonitic clay with minor lenses of yellow to brown slightly coarser bentonitic material...................... 0.88

11. Lime mudstones, as in unit 9................... 3.5

12. Covered.

Section 3. Rosedale Thickness (meters)

The upper Moccasin, Eggleston, and lower Trenton ("Martinsburg") Formations in exposure along the northeast side of the old (i.e., up the embankment from new) Rte. 80, 2.3 kilometers northwest of the intersection with U.S. 19 at Rosedale.

Trenton ("Martinsburg") Formation

1. Not measured.

2. Fossiliferous grainstones and packstones, thin to medium bedded, with lesser amounts of interbedded siltstone and shale.. 30

Eggleston Formation (26 meters)

3. Lime mudstones, greenish gray to light brown,thin to medium bedded with a variable argillaceous content. Rare very thin beds of fossiliferous grainstones...... 1.5

4. K-bentonite bed V-7. Yellow to brown bentonitic clay with some biotite. Bed is poorly exposed.................................... 1.24

5. Lime mudstones as in unit 3. A 27 cm thick K-bentonite bed occurs about 4 meters below the top of this unit............ 8.5

6. Millbrig K-bentonite bed. Yellow to brown bentonitic clay, very sheared. Abundant bleached biotite is visible on some chips. Apparent thickness is over 2.5 m, but true thickness of the bed is less because the bed has been thickened along the numerous shear zones................................ 2.5+

7. Lime mudstones as in unit 3. Upper bed is silicified in places.................................... 9.7

8. Deicke K-bentonite bed and thin limestone interbed. Maroon red and yellow bentonitic clay, with some shearing evident.... . 0.75

9. Lime mudstones as in unit 3...................... 3.5

Moccasin Formation

10. Lime mudstones, thin bedded, grayish red, with a noticeable argillaceous component.	5
11. Covered.	

Section 5. Cove Creek — Thickness (meters)

The upper Moccasin and lower Eggleston Formations in exposure along Rte. 614 at the first hairpin turn in the road below Crabtree Gap.

Eggleston Formation

1. Covered.	
2. Shaly lime mudstones, greenish gray, thin to medium bedded with a variable argillaceous content. Rare very thin beds of fossiliferous grainstones	2
3. K-bentonite bed V-7. Gray to brown bentonitic clay with some visible dark brown biotite.Very weathered and mostly covered..	1.3
4. Chert, dark brown to black..........................	0.02
5. Shaly lime mudstones as in unit 2..............	6.5
6. Millbrig K-bentonite bed. Yellowish brown to gray bentonitic clay in lowest 8 to 10 cm, sharp basal contact. Next 15 to 20 cm is yellowish brown tuffaaceous material with abundant dark brown biotite grains. Upper 70 cm is finer grained bentonitic clay with visible biotite throughout. Upper contact is gradational.............	1
7. Chert, black, with abundant fractures........	0.02
8. Lime mudstones, greenish gray, fenestral, nodular to cobbly, thin to medium bedded with a variable argillaceous content. Minor interbedded greenish gray shales. Rare very thin beds of fossiliferous grainstones..	9.4
9. Deicke K-bentonite bed. Lowest 3 cm is plastic to waxy green clay. Next 45 cm is red bentonitic clay followed by 15 cm of bentonitic green hackly shale, the transition interval between the K-bentonite and the overlying greenish gray lime mudstones.......................................	0.6

Moccasin Formation

10. Lime mudstones, thin bedded, grayish red, with a noticeable argillaceous component...	2.5
11. Covered.	

Section 6. Rocky Gap — Thickness (meters)

The upper Moccasin and lower Eggleston Formations in exposure along southwest side of U.S Highway 52 (Frontage Road for I-77) 1.5 kilometers south of Rocky Gap.

Eggleston Formation

1. Covered.	
2. Millbrig K-bentonite bed. Lowest 8 to 10 cm is fine-grained greenish gray bentonitic clay. Next 15 to 20 cm is greenish gray tuffaceous material with abundant dark brown to black coarse biotite grains. This grades into about 30 cm of successively finer grained material, but the true thickness is difficult to determine because the upper contact of the bed is covered...	0.6+
3. Lime mudstones, greenish gray, fenestral, nodular to cobbly, thin to medium bedded with a variable argillaceous content. Minor interbedded greenish gray shales. Thin chert layer at top. Rare very thin beds of fossiliferous grainstones...............	12.5
4. Deicke K-bentonite bed. Lowest 12 cm is green to yellow bentonitic clay with minor amounts of red bentonitic clay. The overlying 40 cm is mixed red and yellow bentonitic clay. This zone may have been sheared to some extent as the layering does not parallel the bedding. There are some calcareous nodules in the upper part of this zone. The uppermost 6 cm of the bed is gritty, hackly olive green shale with a minor bentonitic component..........	0.58
5. Lime mudstones as in unit 3.......................	4

Moccasin Formation

6. Lime mudstones, thin bedded, grayish red, with a noticeable argillaceous component. Some covered intervals............................	8±
7. Covered.	

Section 12. Crockett Cove Thickness (meters)

The upper Witten Formation, Walker Mountain Sandstone, and lower Bays Formation in exposure along the northeast side of northbound I-77 about 2 kilometers northwest of the interchange with I-81.

Bays Formation

1. Covered.

2. Siltstones and sandstones, red to greenish gray. Abundant vertical burrows in one bed near a ravine where V-7 probably occurs, but could not be dug out. Mostly covered.. 8±

3. Sandstones, predominantly lithic arenites, greenish gray, medium- to coarse-grained, medium to thick bedded with some thin beds of shale. Abundant biotite along bedding planes. Some cross lamination is present. Unit forms a prominent bed in the exposure.. 2.5

4. Millbrig K-bentonite bed. Sharp contact with underlying bed. Lower 10 to 15 cm is fine-grained yellow brown bentonitic clay. Next 35 to 40 cm is yellow brown tuffaceous material with abundant coarse-grained dark brown to black biotite grains. Upper 80 cm is finer grained bentonitic material but with still abundant biotite grains scattered throughout 1.33

5. Siltstone, red and greenish gray, medium bedded, with lesser amounts of interbedded sandstones and shales........................ 17

6. Sandstone, several beds of coarse quartz arenites with conglomeratic zones near the base. White to yellow to dark gray. Black chert pebbles are very noticeable in some beds (Walker Mountain Sandstone Member)... 6.5

Witten Formation

7. Limestone, moderately fossiliferous wackestones, thin to medium bedded,light gray. 9

8. Covered.

Section 13. Connor Valley Thickness (meters)

The Wassum Formation, Walker Mountain Sandstone, and lower Bays Formation along Frontage Road for I-81 just south of the "T" intersection with Rte. 100, which is about 500 meters north of the Rte. 100 interchange along I-81.

Bays Formation

1. Covered.

2. Millbrig K-bentonite bed. Deeply weathered pale sticky bentonitic clay at the top of the exposure. Bleached biotite is abundant in many samples along cleavage planes. Thickness is approximate because the hillslope is formed on the bed........................ 0.85

3. Sandstones, fine- to medium-grained, thin to medium bedded, olive green to greenish gray, with lesser amounts of interbedded thin bedded siltstones and shales. Strata are warped and faulted................... 18

4. Sandstone, includes 2 distinct beds of coarse quartz arenite with some conglomeratic zones, and lesser amounts of interbedded medium-grained sandstones to siltstones. White to yellow. Minor shell fragments. Abundant carbonate clasts up to 15 mm in length in the lowest bed. Black chert pebbles are very noticeable in some beds (Walker Mountain Sandstone Member)... 3.5

Wassum Formation

5. Limestone, thin bedded, nodular, with shaly partings. Predominantly medium gray, but the shaly partings are dark gray. Unit is in fault contact with the lower few meters of the Bays along a normal(?) fault at the north end of the exposure......................... 4

6. Covered.

Section 18. Hinds Creek Quarry Thickness (meters)

Upper Chickamauga Limestone exposed in the inactive quarry in the Lone Mountain Subdivision on Brushy Mountain Road 0.5 km northeast of the mouth of Hinds Creek near Clinton

Chickamauga Limestone (Eggleston facies)

1. Covered

2. Limestone, lime mudstones with lesser amounts of wackestones and packstones, medium to thick bedded, light gray. Fossiliferous beds rare. Variable argillaceous content, with a few shaly partings.. 2.5

3. Millbrig K-bentonite bed. Basal contact is very sharp. Lowest 8 to 10 cm is fine-grained, greenish gray plastic clay. Next 15 to 20 cm is gray tuffaceous material containing abundant coarse dark brown to black biotite. Next 70 cm is increasingly finer grained greenish gray bentonitic material, with visible biotite grains throughout. This zone includes some calcareous and cherty nodules and stringers. The uppermost 10 cm is gritty, hackly, greenish gray shale with a minor bentonitic component; this zone is gradational with the overlying shaly limestone.................. 1.1

4. Chert, black.. 0.02

5. Limestones as in unit 2................................ 8

6. Deicke K-bentonite bed. Basal contact is very sharp. Lowest 2 cm is a bright green plastic clay. Next 12 cm is grayish green tuffaceous material, coarse-grained, with abundant visible sand sized feldspar phenocrysts. Overlying that is 44 cm of lighter greenish gray bentonitic material, the upper few centimeters of which are a gritty, hackly greenish gray shale that is gradational with the overlying limestone.. 0.58

7. Chert, black.. 0.02

8. Limestones as in unit 2, not measured. About 3 m below unit 6 the exposure steepens to vertical along the quarry face, and this part of the section continues for over 15 m to the surface of the lake in the quarry.

Section 32. High Bridge Thickness (meters)

The upper Tyrone and lower Lexington Limestones near High Bridge in exposures along the Norfolk Southern (CNO&TP) Railroad right-of-way and along the top bench at road level in the quarry. Units 1 through the upper part of 4 are exposed along the railroad, units 5 through 7 are exposed at the top of the quarry.

Lexington Limestone (Curdsville Member)

1. Covered.

2. Limestone, nodular thin bedded fossiliferous grainstones and packstones, with lesser amounts of interbedded wackestones. Some thin shaly partings. 3

Tyrone Limestone

3. Millbrig K-bentonite bed. Sharp basal contact, upper contact is clearly erosional, as in several nearby exposures the bed is 80 cm thick. Lowest 14 cm is yellowish gray bentonitic clay. Next 8 cm is yellowish gray tuffaceous material with abundant bronze to brown coarse biotite grains. Upper 16 cm is finer grained bentonitic clay with visible biotite throughout.. 0.38

4. Chert, brown, discontinuous....................... 0.01

5. Limestone, fenestral lime mudstones, thick to massively bedded with thin planar laminations throughout............................ 7.5

6. Deicke K-bentonite bed. Lower 2 cm is bright green clay. Next 16 cm is grayish green tuffaceous material, coarse grained, with abundant sand sized feldspar phenocrysts. The upper 50 cm is finer grained greenish gray bentonitic clay...... 0.68

7. Chert, greenish black.................................. 0.08

8. Limestones as in unit 5, not measured. Over 20 meters of the Tyrone are exposed in the quarry walls.

Section 65. Peters Creek Thickness (meters)

The upper Liberty Hall Formation, Walker Mountain Sandstone, and lower Bays Formation in the low bluff where the two small creeks meet to form the headwaters of Peters Creek about 2.1 kilometers east of Hanging Rock.

Bays Formation

1. Sandstone, medium bedded, greenish gray to yellow brown with some interbedded red siltstones and shales. Mostly covered.. 30±

2. Sandstone, medium to very coarse-grained with conglomeratic zones, includes 2 beds of mature coarse-grained quartz arenite that contain 5 percent pyrite as blebs; where weathered, these blebs are limonitic. Interbedded with medium-grained sandstones, brownish gray. Lowest bed ranges from a quartz arenite containing flat micritic rip-up clasts to a pyrite cemented quartz sand that is very crumbly. These pyritiferous beds appear to occupy small scours or channels cut into the underlying

Liberty Hall (Walker Mountain Sandstone Member)................................	2.5

Liberty Hall Formation

3. Limestone, argillaceous with thin shaly partings. Light to medium gray, weathers yellowish gray. Appears to be thin bedded, but this is probably a function of weathering..	3
4. Covered.	

APPENDIX II

FIELD AND ANALYTICAL METHODS

The present study was part of a regional investigation during which K-bentonites were collected from Ordovician strata throughout the southeastern U.S. Samples were collected and examined from 62 exposures of Rocklandian strata, with many other exposures visited but found unsatisfactory for sampling. The 24 sections listed in Appendix I were studied as part of this overall project. Where possible, measured sections from previous reports were used, with some of the most useful being the numerous sections in the papers by Miller and Brosgé (1954), Miller and Fuller (1954), Hergenroder (1966), and Kreisa (1980). I checked the accuracy of the measurements in these papers during field work and all of the K-bentonites were measured or remeasured. In most cases each bed or unit in a measured section had been given a number by the geologist who wrote the description, and thus any samples that I collected from a particular section could be tied in with the existing description for future reference. For example, the thick K-bentonite at the Chatham Hill section, which I have identified as the Millbrig on the basis of its abundant biotite and quartz in the lower 20 centimeters, is from units 58 and 59 of Hergenroder's measured section (1966, Chatham Hill section, p. 261) and from unit 10 of the Bays Formation in Kreisa's measured section (1980, Walker Mountain section, p. 300). At nine exposures no satisfactory measured section existed, so I measured and described the section. Field work in southwest Virginia and the nearby areas of West Virginia, Tennessee, and Kentucky was carried out during August, 1984, March and July, 1985, February and March, 1986, February, May, and July, 1987, July, 1988, and February, 1991.

Before satisfactory samples could be collected, a certain amount of excavation was usually required, because the K-bentonites are rapidly covered even in relatively new exposures. Where the Rocklandian K-bentonites occur in a limestone sequence, as for example at the High Bridge section in the Cincinnati Arch and the Hagan and Plum Creek sections in the western and central belts of the Valley and Ridge province, the thickest beds, which are the Deicke and Millbrig, are usually underlain by a brown or black hackly, brittle chert. This chert forms a resistant ledge in the exposure. Locating the chert layers was usually the first and easiest step when looking for the thicker K-bentonites at an outcrop in these areas. Chert layers are not present in the clastic rocks of the Bays Formation, although some evidence that silicification of the underlying rock has occurred was seen at some exposures.

The K-bentonites weather very readily and form recessed intervals in outcrop. Therefore, to obtain a relatively fresh sample I usually had to do a substantial amount of digging. Float and other surficial material had to be cleared away, and then the bed dug out with hand-held mattocks and shovels to expose relatively unweathered material. Where hand digging was inadequate to expose unweathered material, samples were collected as far back into the outcrop as possible. Samples were collected systematically from different intervals and the overall thickness, as well as the thickness of each visually distinct zone, of the K-bentonite was measured. It was usually possible to identify some phenocrysts, usually biotite and sometimes feldspar and quartz, with a hand lens. On this basis preliminary comparisons of each measured section could usually be made in the field. The Millbrig is consistently recognizable on this basis, and the Goodwins Ferry section is the only one where V-4 is present, but no biotite was visible. The exposure at that section is very structurally disrupted and samples of the K-bentonite I have identified as the Millbrig are extremely sheared and crushed, so it is likely that the biotite has been adversely affected by the shearing and grinding of the rock.

Thin-section analysis was the primary means of laboratory investigation, using the petrographic microscope and the electron microprobe. Some grain separates were also prepared. The analysis of clay minerals was done separately, by powder X-ray diffraction. Several samples of the Walker Mountain Sandstone from both its type area along Big Walker Mountain and from outcrops on the Cove Mountain and Pulaski thrust sheets where I have identified it as the sequence of conglomeratic sandstones at the base of the Bays Formation were also examined petrographically.

Because of their smectite content, thin-sections of bentonites and K-bentonites are notoriously difficult to prepare, and thus some special techniques were used. Most samples disintegrated in water when wetted; therefore, water was an unsatisfactory coolant and most thin-sections had to be prepared dry and by hand grinding. This was done as follows. Samples were first dried overnight at 60°C. After drying, a flat surface suitable for bonding to a petrographic slide was prepared by grinding the sample on emery cloth laid on a clean glass plate. Well-indurated samples such as those from cores did not crumble during the initial grinding of a flat surface with coarse emery cloth. This flat face was then ground smoother with successively finer grit emery cloth, using 320 and then 400 grit cloth. All grinding was done on the glass plate to maintain a flat surface. After the final grinding and rough polishing with 600 grit cloth, the flat surface was brushed clean of dust with a soft-bristle toothbrush, bonded to a frosted glass petrographic slide with epoxy, and allowed to dry overnight at room temperature. This chip was sawed off with a rotary trim saw using mineral oil or propanol as coolant, and the section was then ground down, by hand again, with successively finer grit emery cloth, to a thickness of 30 microns. Fifty-eight thin sections were prepared using this method.

The less indurated samples crumbled after the first attempt at preparing a flat face with emery cloth. Impregnation with petrographic epoxy in a pressurized chamber was used in an attempt to solve the problem. This worked with only limited success, however. When it did work, the impregnated samples were first sawed on a trim saw with mineral oil as coolant, and the flat face of the sawed surface was ground using emery cloth, and then glued, sawed off, ground down, and polished, as described above. Twenty-four thin sections were prepared using this method.

Final polishing for electron microprobe analysis was carried out with a polishing lap using 6.0, 3.0, and 1.0 micron diamond pastes with polishing oil as a coolant and lubricant. Of the 82 thin sections made, 25 were polished in this manner.

Some samples were too weathered or poorly indurated to make thin-sections, even with pressure impregnation, so grain separates were prepared. Damp samples were soaked in kerosene for an hour, the kerosene was poured off, and water was added. This immediately dispersed the clays, and the mixture was then wet-sieved through a 200 mesh screen, allowing the clays but not the larger phenocrysts to pass through. The grains thus remaining on the screen were placed in glass dishes and then were dried overnight at 60°C and stored in labeled vials for later examination under the petrographic or binocular microscope.

X-ray diffraction (XRD) patterns were produced by X-ray analysis of oriented glycol-solvated mounts of the less than 2.0 micron size fraction of selected Deicke and Millbrig samples, two samples of K-bentonite V-7, and five other K-bentonites. To obtain the less than 2.0 micron size clay fraction, bulk K-bentonite samples were first dispersed in deionized water using an ultrasonic bath and a rotary mixer. This mixture was then placed in a beaker and allowed to stand for 3 hours and 50 minutes, at which a small quantity of the upper part of time the liquid was poured off and centrifuged. This liquid contains the less than 2.0 micron size clay fraction. Using a small spatula, this clay was smeared onto petrographic well slides, a technique that produces a preferred orientation of the clay minerals.

Identification of mixed-layer illite/smectite is based on the interpretation of XRD patterns of glycolated samples, so all samples on the glass slides were ethylene glycol-solvated from four to five days before analysis. This was done by placing the glass slides with their oriented samples on an elevated tray with legs inside a glass bell jar with ethylene glycol pooled at the bottom. The glass lid was sealed with a silicone sealant, and the jar was placed in an oven overnight at 60°C. The jar was then removed from the oven and placed aside for three to four days, still closed, until the samples were analyzed. X-ray diffraction was done at the University of Cincinnati on a Siemens D-500 automated diffractometer using CuK radiation. The scanning speed was 0.05 degrees per two second interval, and the scans were from 2° to 60° 2, with occasional scans re-run at slower speeds or between a smaller interval.

Microprobe analyses were carried out at the University of Illinois on a JEOL 2-channel electron microprobe and at the University of Cincinnati on an ARL 3-channel electron microprobe, both of which have 5.0 micron-wide beams. Polished thin-sections were first coated with a carbon film, and particular grains that had been chosen for analysis by viewing with the petrographic microscope were suitably marked on the slide to facilitate locating them in the optical system of the electron microprobe. The slides were then affixed to a brass holder with a carbon or silver paste that provides electrical continuity between the thin-section and the machine, and the paste was then allowed to dry. When dry, the slides were loaded into the sample chamber and the analyses begun.