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The mineralogy and stratigraphic setting of the Rocklandian (Upper Ordovician) Deicke and Millbrig K-bentonite beds along the Cincinnati Arch and in the southern Valley and Ridge

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THE MINERALOGY AND STRATIGRAPHIC SETTING OF THE ROCKLANDIAN (UPPER ORDOVICIAN) DEICKE AND MILLBRIG K-BENTONITE BEDS ALONG THE CINCINNATI ARCH AND IN THE SOUTHERN VALLEY AND RIDGE

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by

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I hereby recommend that the thesis prepared under my supervision by John T. Haynes

entitled The Mineralogy and Stratigraphic Setting of the Rocklandian (Upper Ordovician) Deicke and Millbrig K-Bentonite Beds along the Cincinnati Arch and in the Southern Valley and Ridge

be accepted as fulfilling this part of the requirements for the degree of Doctor of Philosophy

Approved by:

Warren D. Huff

Richard Hay

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ABSTRACT

Petrographic study of the non-clay minerals in the Deicke and Millbrig K-bentonite beds (altered volcanic ash) of Rocklandian age has revealed that the two beds can be distinguished on the basis of non-clay mineralogy. The Deicke contains a phenocryst assemblage of primarily labradorite, Fe-Ti oxides, apatite, and zircon, while the Millbrig contains a phenocryst assemblage of primarily andesine, quartz, biotite, apatite, and zircon. The Deicke is most likely an altered dacitic ash, while the Millbrig is probably an altered rhyodacitic ash.

A detailed investigation of samples from over 60 exposures in the southeastern United States has made possible the correlation of these two beds between the Cincinnati Arch and the Valley and Ridge, and along and across strike in the Valley and Ridge between Roanoke, Virginia and Birmingham, Alabama. Although the Millbrig is locally absent in the Jessamine Dome of Kentucky because of an erosional disconformity, it is the most widespread and persistent of the two beds. It occurs in all outcrop belts of the Valley and Ridge where Rocklandian strata are exposed, and it is recognized for the first time in the Bays Formation of Virginia and Tennessee, a clastic unit in the southeastern Valley and Ridge from which the Deicke is absent. This new stratigraphic work includes recommendations for reference sections to supplement the type

localities of the Deicke and Millbrig, which are in the upper Mississippi Valley. It is also recommended that the terms Deicke and Millbrig be formally recognized in this area, replacing the various alpha-numeric terms (V-3, T-3, etc.) now commonly used locally. Some of the findings have resulted in a reinterpretation of correlations suggested by some earlier workers, although the conclusions of other previous studies are substantiated.

Regional distribution patterns of authigenic feldspars and mixed-layer illite/smectite (I/S) clay, the compositions of which are temperature dependent, support previous studies which showed that maximum burial temperatures in the Appalachian basin during the Ordovician increased to the southeast. Authigenic K-feldspar occurs in both beds along the Cincinnati Arch and in the Valley and Ridge, whereas authigenic albite occurs only in the Valley and Ridge, where it is commonly a replacement rim on both primary plagioclase and authigenic K-feldspar. Ordering of the I/S, which reflects the illite:smectite ratio, increases to the southeast, changing from R1 ordering along the Cincinnati Arch to predominantly R3 ordering in the Valley and Ridge. This is a reflection of the increasing illite component in the two beds; illite comprises 70-80 percent of the I/S along the Cincinnati Arch, while in the Valley and Ridge, it comprises 80-95 percent. These correlations provide for the first time in this area a set of two time lines that can be traced over hundreds of kilometers. In the Valley and Ridge, the

Millbrig traverses the facies change from the northwestern carbonate sequence to the southeastern clastic sequence, and the paleogeographic and sedimentologic variations across much of the Appalachian basin at a single moment in time can now be observed with an exactness that is possible only with volcanic ashfall marker beds. The Deicke and Millbrig together bound an interval that contains a variety of sedimentary rocks, which because of the two time-lines above and below are in a unique stratigraphic position. This interval of strata will be ideal for detailed biostratigraphic, sedimentologic, geochemical, and paleoecologic investigations throughout the region.

ACKNOWLEDGMENTS

Many persons have greatly assisted me in this research, but I owe the most thanks to Prof. Warren D. Huff of the University of Cincinnati. He suggested that I study the mineralogy of the best known Ordovician K-bentonites along the Cincinnati Arch, and his interest and guidance have made this project not only possible, but very enjoyable throughout. In addition, most of my field work was supported by NSF Grant EAR-8407018 to Prof. Huff, and the financial assistance has been greatly appreciated. We've spent more than a few hours together discussing Ordovician geology in the field as well as while listening to bluegrass music and enjoying a beer, and through it all I've learned a great deal about geology and about scientific research, and about life in general. I know that I made the right choice when I chose to study geology years ago.

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I benefited also from discussions with Tom Hudson, Joan Cullen-Lollis, and Mike Trippi, graduate students at Cincinnati, on the geology of the Cincinnati Arch and the southern Valley and Ridge, and on the mineralogy of mixed-layer illite/smectite, the major clay in the K-bentonites.

I would like to thank my current employer, NUS Corporation of Gaithersburg, Maryland, for providing some much-appreciated typing and drafting assistance, as well as for allowing me the time off to present some of the results of this research at a conference in St. John's, Newfoundland, in August 1988.

While doing field work in July 1985, I stayed several days with a long-time friend, John Davis, in St. Paul, Virginia. In between my days in the field we managed to climb Mt. Rogers, play some bluegrass at an Abingdon watering hole, and generally enjoy ourselves immensely. Thanks for the room and board, and most of all the companionship, John, and someday we'll climb Mt. Mitchell.

Another long-time friend, Jeff Watson, accompanied me in the field for a week in February 1987, as well as for a weekend in July 1988. We had some memorable times camping in and traveling through the mountains of Virginia, and as I finally unraveled the stratigraphy of the K-bentonites in the eastern and central belts of the Virginia and Tennessee Valley and Ridge (on the third time out in that region), Jeff acted as devil's advocate for my speculations, and I appreciate his patience as well as his thoughtful insight.

Throughout all this time, my parents, Dr. and Mrs. Robert C. Haynes, Jr., of Charlottesville, Virginia, have continually encouraged me, and I can't thank them enough for their support. And, in the last year and a half, my wife, Janette Hansen, has also encouraged me and has endured the long hours I have worked while writing this text.

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INTRODUCTION

Numerous beds of altered volcanic ash occur in Rocklandian (Upper Ordovician) strata of eastern North America. They range in thickness from 2-3 cm to 1.5 m, and occur in both carbonate and clastic strata. Their principal constituent is a mixed-layer illite/smectite (I/S) clay that generally contains 75 to 90 percent illite. Thus these beds are described as potassium bentonites, or K-bentonites (Weaver, 1953), rather than as true bentonites.

Locally, many of the K-bentonite sequences have been correlated on the basis of thickness, texture, color, and their stratigraphic relation to marker beds such as formation boundaries or faunal zones (Rosenkrans, 1933, 1936; Fox and Grant, 1944; Huffman, 1945; Wilson, 1949; Miller and Fuller, 1954; Hergenroder, 1966, 1973; Milici, 1969; Milici and Smith, 1969; Benson and Stock, 1986). Most of these workers believed that the two thick beds known from exposures along the Cincinnati Arch are most likely present in the Valley and Ridge, and several attempts to correlate between these areas have been made using various criteria (e.g. Fox and Grant, 1944; Huffman, 1945; Milici, 1969). In addition, Rosenkrans (1936) and Hergenroder (1966, 1973) presented evidence for correlating beds along strike in the Valley and Ridge between Alabama and Virginia. Nevertheless, stratigraphic and structural complexities have historically prevented correlation efforts from being readily demonstrated between widely separated outcrops.

Recently, several K-bentonites in Rocklandian strata of the upper Mississippi Valley have been successfully correlated using chemical fingerprinting and detailed biostratigraphy and lithostratigraphy (Kolata et al., 1986). In addition, two of the most persistent beds from that region, the Deicke and Millbrig K-bentonite Beds, can be correlated with the two thickest Rocklandian K-bentonites along the Cincinnati Arch using geophysical well logs (Kolata et al., 1984). These two beds are widely known by geologists and drillers as the T-3 and T-4, or the Pencil Cave and Mud Cave K-bentonite beds, respectively.

The present study was undertaken to determine the detailed mineralogy, petrology, stratigraphy, and paleogeographic setting of the Deicke and Millbrig K-bentonites in the southeastern United States. Although the studies cited in the preceding paragraphs have described several Rocklandian K-bentonite sequences locally in the region, there has been no systematic areawide investigation of the beds' petrographic and mineralogic characteristics to determine whether this information is a quantitatively useful stratigraphic tool.

The goals of this research were: 1) to document the areal extent of the two beds and investigate their usefulness as isochrons in the Rocklandian of this region; 2) to refine, and where necessary reinterpret, the stratigraphy of the Rocklandian interval in which the K-bentonites occur; 3) to investigate and describe regional variations in mineralogy and petrology, and, to determine if the beds can be distinguished on a mineralogic basis; 4) to investigate the burial history of the beds based on study of authigenic minerals, and, 5) to gain a better understanding of Rocklandian tectonics and paleogeography in the Appalachian Basin. The Deicke and Millbrig are particularly well-suited for such a study because they are relatively thick and coarse grained, they contain mineral assemblages that reflect both the igneous and diagenetic environments that contributed to their present composition, and they occur in many exposures along the Cincinnati Arch and in the Valley and Ridge.

Stratigraphically, K-bentonites are potentially excellent isochrons, but except for the studies cited above that described local correlations, attempts to trace the Deicke and Millbrig beds regionally, such as from central Kentucky to western Virginia, or along strike in the Valley and Ridge from Virginia to Alabama, have commonly been hindered by the lack of distinguishing textures between individual beds that are readily recognizable at oucrops, as discussed by Kolata and others (1986). Past attempts at regional correlations have relied both on correlating the zone in which K-bentonites occur, or on correlating a specific bed or beds (Rosenkrans, 1936; Fox and Grant, 1944; Huffman, 1945; Miller and Fuller, 1954; Drahovzal and Neathery, 1971; Hergenroder, 1966, 1973, and Chowns and McKinney, 1980). Structural and stratigraphic complications are additional factors making correlations difficult using conventional field methods, especially in the Valley and Ridge. As a result, some errors in previous K-bentonite correlations were discovered and corrected during the present research; nevertheless, most of the earlier reports provided invaluable stratigraphic information such as detailed measured sections and lengthy descriptions of individual stratigraphic units.

The studies by Rosenkrans (1936) and Fox and Grant (1944) give very detailed descriptions of individual beds, including major differences in phenocryst mineralogy as ascertainable in hand specimens. These workers noted the abundant biotite in the bed now known as the Millbrig, and they noted the sandy, "arkosic" texture of the bed now known as the Deicke. These mineralogic differences were very useful in their correlations, as they recognized that in order to use the K-bentonites as marker beds, compositional differences between them must be identified. Nevertheless, there has been no detailed investigation of the feldspars in either bed, nor has there been a quantitative investigation of mineral types and abundances. Because of this, the present reseach investigated in detail the compositional differences of the Deicke and Millbrig, beginning with the obvious difference in the abundance of biotite cited by so many earlier workers, with the goal of determining more precisely the usefulness of the Deicke and Millbrig as stratigraphic markers. Using detailed analyses of non-clay minerals made with an electron microprobe, it can be shown that the two beds are recognizable on a mineralogic basis, and that they can be distinguished from each other on that basis. In addition, detailed field work shows that the two beds can be distinguished at many outcrops in the field as well throughout the Cincinnati Arch and in the Valley and Ridge from Alabama to west-central Virginia. Samples were first studied from along the Cincinnati Arch, where the overall geologic setting is relatively simple. The Deicke and Millbrig can be recognized consistently and, with very few exceptions, are the only two thick K-bentonites. Once differences from this region were documented, K-bentonites in the Valley and Ridge were studied. There, the stratigraphy and the structural setting are more complex, but based on study of many exposures and extensive thin-section study, correlation of the Deicke and Millbrig can be shown between the Cincinnati Arch and the western Valley and Ridge, with reinterpretation of some correlations suggested in previous studies. In the Valley and Ridge, the Millbrig can also be correlated between the carbonate sequence of the central and western belts with the clastic sequence of the easternmost belts. The Deicke, however, is absent from the clastic sequence.

The burial history of the Appalachian basin is complex, although some regional trends are known. Conodont color indices (CAI) show that maximum burial temperatures experienced by Ordovician strata increased to the southeast in general, and in the Valley and Ridge, from southwest to northeast (Harris et al., 1978). The present research shows that the clay minerals and authigenic feldspars in the Deicke and Millbrig K-bentonites also record these trends. Both the percent of illite in the I/S and the ordering of the I/S increase to the southeast, changes that occur with an increase in temperature as shown by Hoffman and Hower (1979 and Dypvik (1983), although Morton (1985) has challenged the mechanism by which illitization of smectite has traditionally been thought to occur. In addition, authigenic albite occurs in samples from the Valley and Ridge but not the Cincinnati Arch, whereas authigenic K-feldspar occurs in both areas. This also indicates that higher temperatures were reached in the Valley and Ridge than along the Cincinnati Arch, as albite authigenesis does not occur until temperatures of > 100°C are reached, whereas authigenic K-feldspar will form at much lower temperatures but will begin to dissolve at temperatures that favor albite authigenesis (Kastner and Siever, 1979; Gold, 1987).

The final major goal was to investigate Rocklandian paleogeography using the K-bentonite beds as stratigraphic markers. Study of vertical sequences at many individual outcrops together with correlations between outcrops shows that the K-bentonites are part of a very widespread regressive-transgressive sequence. They were deposited during the time of near maximum regression, and therefore they also mark very closely the onset of the deepening upward sequence. The carbonates immediately downsection from and enclosing the K-bentonites tend to be restricted intertidal to supratidal sediments with few fossils, but within a few meters upsection the overlying carbonates begin to contain a more normal marine faunal assemblage and deeper water sediments. A similar succession occurs in the clastic strata of the eastern belt, where the Millbrig and overlying K-bentonites are generally near the top of a thick redbed sequence that is overlain by below-wavebase normal marine carbonates; some K-bentonites occur in those strata as well (Kreisa, 1980). Variations occur, such as in the Birmingham, Alabama area, where normal marine sedimentation was continuing unbroken at the time the volcanic ash was deposited, but 3 m upsection of the Millbrig Silurian rocks rest disconformably on the Ordovician. This unconformity records localized uplift and erosion that is not observed elsewhere in the region (Bearce, 1973).

METHODS

Field work was carried out during August and December, 1984, March and July, 1985, February and March, 1986, February, May, and July, 1987, and July, 1988. K-bentonite samples were collected and examined from 62 exposures of Rocklandian strata, with several others visited but found unsatisfactory for sampling. Figure 1 shows the locations for the outcrops and wells from which outcrop and core samples were collected, as well as the locations of several outcrops that were examined but from which no samples were obtained. Extensive excavation was usually required at outcrops, as the K-bentonites weather recessively even in relatively new exposures. Float and other surficial material generally had to be cleared away, and the bed was then dug out with hand-held mattocks and shovels to expose relatively unweathered material. Where hand digging was inadequate to expose unweathered material, sampling was done as far back into the outcrop as possible. Samples were collected systematically from different intervals. It was usually possible to identify some phenocrysts with a hand lens, allowing for preliminary comparisons of each measured section. Previously described measured sections were used where possible, but if no satisfactory measured section existed, the section was measured and described to place the location of each K-bentonite accurately. In addition to samples obtained from field work for this research, 11

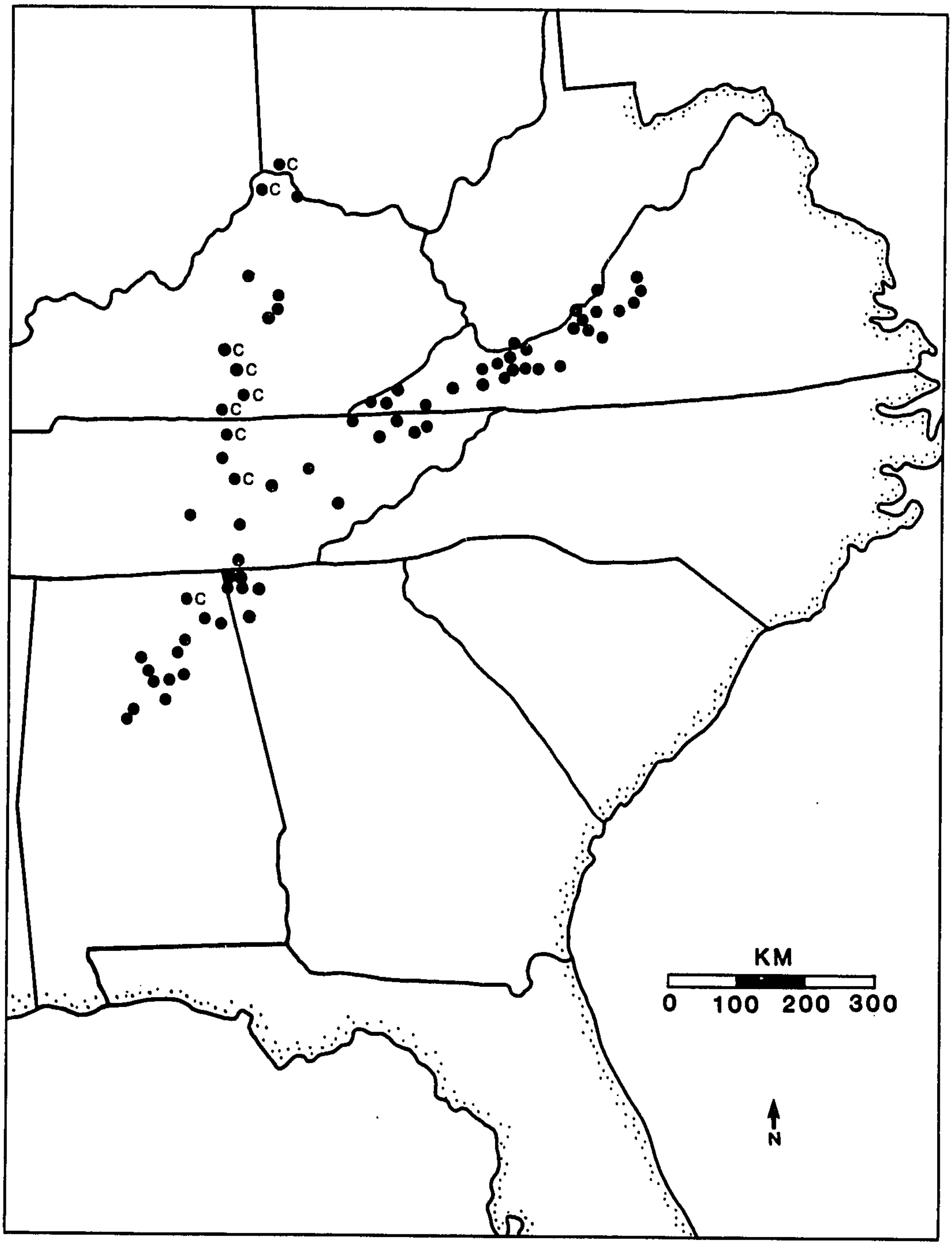


Figure 1. Location of outcrops and cores (c) from which Deicke or Millbrig samples were obtained.

samples from the collection of Prof. Warren D. Huff were studied. These were mostly core samples from along the Cincinnati Arch, with one core sample from the Valley and Ridge of Alabama.

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.

Samples were prepared for thin-sectioning by overnight drying in an oven at 60°C. Because most samples disintegrate in water and many contain enough smectite to cause them to expand when wetted, water was an unsatisfactory coolant and thin-sections had to be prepared dry and by hand grinding. The first step was to prepare a flat surface suitable for glueing to a petrographic slide. Well-indurated samples did not crumble during the initial grinding of a flat surface with coarse emory cloth. The flat face was ground smoother with successively finer grit emory cloth, using 320 and then 400 grit cloth. All grinding was done on a 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, glued to a frosted glass petrographic slide with epoxy, and allowed to dry overnight at room temperature. This chip was sawed off with a hacksaw or a trim saw using mineral oil or propanol as coolant, and the section was then ground down, again with successively finer grit emory cloth, to 30 μm. Final polishing for electron microprobe analysis was carried out with a polishing lap using 6, 3, and 1 μm diamond pastes with polishing oil as a coolant and lubricant.

Many samples crumbled after the first attempt at preparing a flat face with emory cloth. Pressure impregnation was used in an attempt to solve the problem. This worked with limited success, but 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 emory cloth, and then glued, sawed off, ground down, and polished, as described above.

Some samples were too weathered and 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, which allowed the clays to pass through, but retained the larger grains. The grains were dried overnight at 60°C and placed in vials for later examination under the petrographic or binocular microscope.

For X-ray diffraction (XRD) of clays, samples were first dispersed in deionized water using an ultrasonic bath and a rotary mixer. This was followed by gravity settling to collect the < 2 μm size fraction from suspension; after sitting for 3 hours and 50 minutes, the liquid was poured off and centrifuged, collecting the clay. Using a small spatula, this clay concentrate, which is the < 2 μm fraction, was placed onto petrographic well slides in a preferred orientation using the smear method. Identification of mixed-layer illite/smectites is based on the interpretation of XRD patterns of glycolated samples, so all samples were ethylene glycol solvated 4-5 days before analysis. Oriented samples were placed on a tray in a bell jar, with ethylene glycol pooled at the bottom. The 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 2-3 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 CuKα radiation. The scanning speed was 0.05 degrees per two second interval, and the scans were from 2° to 60° 2θ, with occasional scans re-run at slower speeds or between a smaller two-theta 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 μm-wide beams. Polished thin-sections were first coated with a carbon film, and particular grains that had been selected by optical microscopy for analysis were suitably marked on the slide to facilitate locating them in the reflected light used in the electron microprobe optical system. 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.

NOMENCLATURE

Many workers have examined Rocklandian K-bentonites in several localities throughout the eastern midcontinent, and several different nomenclature systems that attempted to organize the K-bentonites systematically have been introduced into the literature. These include the "T", "B", "R", "V", "N", and "S" systems of Wilson (1949), Fox and Grant (1944), Miller and Fuller (1954), Rosenkrans (1936), Kay (1956), and Perry, (1964) respectively. With these nomenclature systems, each K-bentonite bed described from a reference locality is given a sequential alpha-numeric name such as B-1, B-2, B-3, etc., depending on the location of the bed in the measured section. Some of the beds are widely recognized by their alpha-numeric names locally, such as T-3 and T-4 in Tennessee and V-3, V-4, and V-7 in southwest Virginia. Many authors have suggested correlations with other beds beyond the "type" area (Huffman, 1945; Milici and Smith, 1969; Drahovzal and Neathery, 1971), and the alpha-numeric terms are entrenched in the formal literature. The North American Commission on Stratigraphic Nomenclature (1983) accepts only the names of geographic localities as suitable for formal stratigraphic names, however, and the alpha-numeric terms used to designate the K-bentonite beds, as for example in Figure 43, are clearly inappropriate.

Using geophysical well logs, Huff and others (1986) and Kolata and others (1984) correlate 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. The present study continues that work eastward by correlating the Deicke and Millbrig beds between the Cincinnati Arch and the Valley and Ridge from Birmingham to Roanoke; the Deicke and Millbrig are now recognizable over much of the southeastern U.S. "Deicke" and "Millbrig" are terms that satisfy the requirements of the stratigraphic code, with type localities described by Willman and Kolata (1978) and redescribed by Kolata and others (1986), and it is therefore recommended that the terms "Deicke" and "Millbrig" be recognized in the Cincinnati Arch and the Valley and Ridge as formal stratigraphic names. Suitable reference localities that will supplement the type localities mentioned above are proposed in the "Discussion" chapter, and precise correlations throughout the region are described in the chapter on "Correlation", with the correlation charts therein showing the alpha-numeric terms that "Deicke" and "Millbrig" supercede. The alpha-numeric terms can still be useful throughout much of the region, however, because their meaning is widely understood in much the same way that "No. 9 Coal" is understood in Pennsylvanian strata. Therefore, the "V" series, "T" series etc., are referred to in parts of the following discussion that pertain to particular regions of the southeastern United States where those terms are most widely used.

As study of the K-bentonites in this area progresses and areawide correlations are documented for K-bentonites in addition to the Deicke and the Millbrig, it is likely that formal stratigraphic names will be required for more K-bentonites. These names will continue to replace the "V", "R" etc. systems now used.

Bentonites, K-bentonites, Metabentonites, Tuffs, and Altered Volcanic Ash

Over the years there have been many discussions on what to call beds of what appear to be altered volcanic ash. Knight (1898) introduced the word **bentonite** for clay beds in the Cretaceous Ft. Benton Formation of Wyoming; studies by Hewitt (1917) and Wherry (1917) showed that these particular beds, which are predominantly smectite, are derived from the alteration of volcanic ash. Many European geologists use the term bentonite to mean any smectite-rich clay, regardless of origin, which can be confusing. The term **metabentonite** was introduced by Ross (1928) to describe beds of altered volcanic ash that, because of the high illite content and apparent slickensides, he believed had been metamorphosed. This term came into widespread usage, often mistakenly, as other workers also mistook potassium metasomatism, slickensides, and slaty cleavage for evidence of metamorphism. The high illite content results from diagenetic changes in the sub-metamorphic realm, and slickensides and slaty cleavage are common in structurally disrupted regions such as the Valley and Ridge where regional metamorphism has not occurred. Ross, however, intended for the term to refer only to altered volcanic ash beds that showed definite evidence of metamorphism (Ross and Hendricks, 1945). The term metabentonite is still used mistakenly today, as many workers sometimes refer to altered volcanic ash beds that have not been metamorphosed as metabentonites (eg. Read, 1980; Dennison, 1983). Weaver (1953) introduced the term K-bentonite or **potassium bentonite** to emphasize the relatively high potassium content of certain bentonites. K-bentonites are common in Paleozoic rocks and are mineralogically distinct from true (Ca- and Na-smectite) bentonites. **Tuff** is a general term for consolidated or lithified volcanic ash, which is pyroclastic material less than 2 mm in diameter (Fisher and Schmincke, 1984). An **altered tuff** would refer to a bed of lithified volcanic ash that has been chemically or mineralogically altered. In practice it is usually not possible to determine if a bed of altered volcanic ash was lithified prior to alteration, so the distinction between an altered volcanic ash and an altered tuff is blurred. Obviously bentonites and K-bentonites are special subdivisions of the universe of altered volcanic ash; **tonsteins**, which are thin kaolinite-rich beds commonly of altered volcanic ash, are another special group (Fisher and Schmincke, 1984).

Roen and Hosterman (1982) suggest that beds of altered Devonian volcanic ash in the Appalachian basin be referred to simply as **ash** or **ash beds** rather than **bentonites**. They indicate that the emphasis on the volcanic origin of the beds rather than on their mineralogic characteristics had mistakenly led others to used the term bentonite for these beds, when in fact there is little smectite in the Devonian beds. They did not mention the term **K-bentonite.**

In an exchange of views on what constitutes appropriate use of these terms, Huff (1983) and Forsman (1984) pointed out that the existing use of descriptive modifers, primarily K for K-bentonite, adequately differentiates between the most common types of thin but widespread altered volcanic ash beds. Roen and Hosterman (1983, 1984) replied that use of these modifiers serves only to confuse the usage further. Although their point is well taken that authors should be more careful to avoid use of the terms bentonite or metabentonite when a bed is properly called a K-bentonite, their argument that modifiers are confusing and therefore a misuse of the term bentonite is unconvincing given the fairly precise meanings intended by the terms K-bentonite and metabentonite. In addition, Huff (1983) points out that the material in many of these beds of Paleozoic age, including the Devonian beds studied by Roen and Hosterman (1982), is not now ash, although it originally was; the material is altered volcanic ash. **Altered volcanic ash** is a broad and cumbersome term at best as noted by Hergenroder (1966), and use of the short, unambiguous, and specialized term **K-bentonite** is preferred when mixed-layer illite/ smectite is the primary clay mineral, as is the case with the beds described by Roen and Hosterman (1982).

Hay and others (1988) use the term tuff to describe beds of altered volcanic ash, including the Deicke and Millbrig, in the Upper Mississippi Valley. They use K-bentonite as a lithologic term referring to the mixed-layer illite/smectite clay that has formed from the alteration of volcanic ash, and **K-bentonite bed** as a stratigraphic term. Those beds are composed of either I/S or authigenic K-feldspar, both of which are secondary after the original volcanic ash, so the beds are technically altered tuffs rather than tuffs, assuming that the ash had been lithified prior to alteration, a difficult point to demonstrate. It seems that the term K-bentonite is most appropriate for those beds, because it is a specialized term that is meant to be used for beds with I/S as the main clay and as the primary component.

The Deicke and Millbrig in the present study area are considered to fit the description of K-bentonites because they contain I/S and are derived from the alteration of volcanic ash as indicated by the presence of volcanogenic minerals and relic shard textures. Technically, however, the lower parts of the beds, which may contain less than 20 percent total clay and are phenocryst-rich, are altered ash *sensu stricto*, and classification of that particular material as K-bentonite is incorrect because I/S is not the primary component even though it is the primary clay. This is a fine point and a simple technicality, and because the lower part of the Deicke and Millbrig are just one part of the entire bed, the beds are described as K-bentonites, given the overall predominance of I/S. The crystal-rich zones are just that, tuffaceous zones within a bed of altered volcanic ash that in sum fits the definition of a K-bentonite. In Figures 50-53, which are detailed vertical sections of the Deicke and Millbrig at selected exposures, the coarsest zones in each bed are referred to as tuff to distinguish them from the more clay-rich parts of the bed, but the entire bed is a K-bentonite.

GEOLOGIC SETTING

Stratigraphy

In the southeastern United States, the Deicke and Millbrig occur in both carbonate and clastic strata of Rocklandian age. Rocklandian strata have traditionally been considered Middle Ordovician in age, but revisions in the correlation of North American sections with the standard European (British) section indicate that they are in fact Late Ordovician in age (Ross et al., 1982). In the North American stratigraphic system, the Rocklandian is a Stage of the Mohawkian Series, which is also widely known by the more informal Series names Blackriverian (older) and Trentonian (younger). The Mohawkian is equivalent in age to the Caradocian of the European (British) system, which is Late Ordovician, and thus Rocklandian strata are also Late Ordovician in age.

The stratigraphy throughout the region varies in its complexity, but in the Valley and Ridge it is particularly complex. Carbonate strata predominate over most of the study area, with clastic rocks confined to the eastern belts of the Valley and Ridge (Fig. 2). The carbonate rocks in which the K-bentonites occur are part of a remarkably continuous unit that extends, although with numerous facies changes, from the central and western Valley and Ridge between Alabama and New York north to Quebec and west to the Cincinnati Arch, the Michigan basin and beyond, to the Ozarks of Missouri and to the Upper Mississippi Valley area

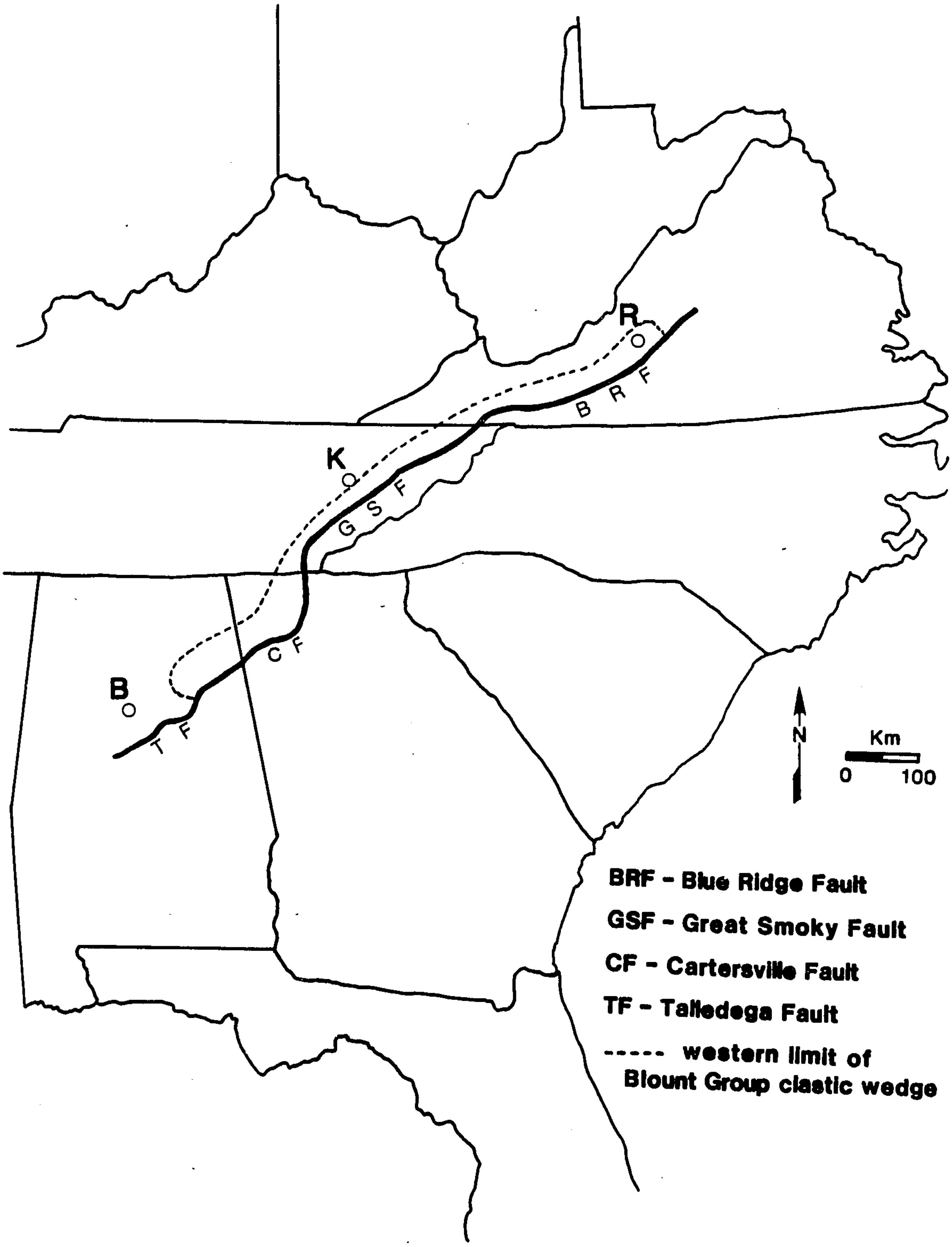


Figure 2. Area in which clastic sediments of the Blount Group occur in the southern Valley and Ridge. B, Birmingham; K, Knoxville; R, Roanoke.

of Iowa, Illinois, Wisconsin, and Minnesota. K-bentonites occur throughout this carbonate sequence.

In the study area, the carbonate rocks in which the Deicke and Millbrig K-bentonites occur are mainly assigned to the High Bridge Group in Kentucky, the Stones River Group in central Tennessee, the Chickamauga Group in eastern Tennessee, the Chickamauga Supergroup in northwest Georgia, the Stones River Group, Stones River Formation, and Chickamauga Limestone in Alabama, and the Moccasin, Eggleston, and Trenton Formations in upper northeast Tennessee, southwest Virginia, and southeast West Virginia.

The clastic rocks along the eastern Valley and Ridge in which the K-bentonites occur are assigned to the Blount Group. The Millbrig occurs in the Bays Formation in Virginia and Tennessee, and both beds occur in the Colvin Mountain Sandstone in Georgia and Alabama.

This lithofacies pattern in the Valley and Ridge, of carbonates in the northwest and clastics in the southeast, persists in Rocklandian strata from east-central Alabama to the just north of Roanoke, Virginia (Butts, 1926, 1940; Butts and Gildersleeve, 1948; Rodgers, 1953, 1971; Allen and Lester, 1957; Webb, 1965; Hergenroder, 1966; Drahovzal and Neathery, 1971; Dennison and Wheeler, 1975; Chowns and McKinney, 1980; Le Van and Rader, 1983; Chowns and Carter, 1983; Carter and Chowns, 1986). The following descriptions of the regional and local stratigraphic relations are taken from these sources and the references therein.

The Cincinnati Arch

Jessamine Dome

In outcrops and cores from the Jessamine Dome area of central Kentucky and southern Ohio, the Deicke and Millbrig occur in the upper part of the Tyrone Limestone and lowermost Lexington Limestone, with the Millbrig locally being relatively thin or absent because of an erosional disconformity. The beds are generally 4-6 meters apart. The section from the Black River Mine in Carntown, Kentucky, shows the stratigraphic relations in this area (Figure 3), although the Deicke is unusually thin and the thick K-bentonite above the Millbrig is usually missing from other exposures in the region. The Tyrone Limestone is the uppermost unit of the High Bridge Group, lying conformably above the Oregon Formation and, in most places, disconformably beneath the Curdsville Limestone Member of the Lexington Limestone.

Cressman (1973), Cressman and Noger (1976), and Cressman (1981) discuss the field relations of these strata in more detail.

Nashville Dome

In the Central Basin of Tennessee and surrounding areas the Deicke and Millbrig occur in the Carters Limestone, with the Deicke occurring at the boundary between the Lower and Upper Carters, and the Millbrig occurring at or just beneath

BLACK RIVER MINE

Pendleton County, Kentucky
Sect.34

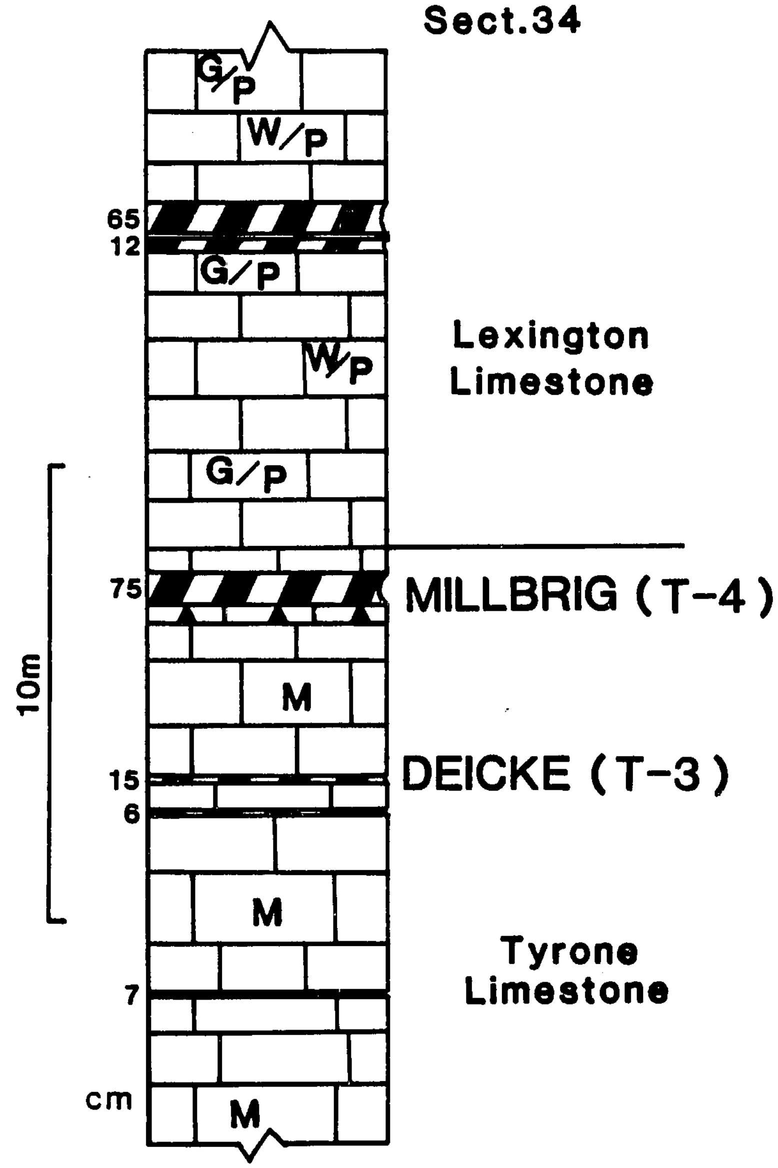


Figure 3. Details of the measured section in the entrance shaft at the Black River Mine in Carntown, Kentucky. The Deicke is relatively thin at this locality.

the contact between the Carters and the overlying Hermitage Formation. The section from Shelbyville, Tennessee, shows the stratigraphic relations in this area (Figure 4), although the Deicke is slightly thinner than in some other exposures as shown by Fox and Grant (1944) and Wilson (1949). The Carters conformably overlies the Lebanon Limestone. Wilson (1949) named the K-bentonites in this area T-1, T-2, etc., and although other numbering schemes were in use earlier in other regions, this "T" series is now used throughout much of the southeast. Wilson's work on the regional stratigraphy is the standard reference for this area.

The Valley and Ridge

Because of the complexity of the Valley and Ridge, the following discussion is divided into separate geographic and geologic regions. K-bentonites were sampled between Birmingham, Alabama, and Roanoke, Virginia at relatively close intervals except in Tennessee between Chattanooga and Knoxville east of the Sequatchie Valley, where exposures of the K-bentonites in Rocklandian strata were not located.

Sequatchie Valley

In the Sequatchie Valley of east central Tennessee, Milici (1969) applied the Central Basin stratigraphic nomenclature of Wilson (1949) to the Middle Ordovician sequence. The two K-bentonites are in the Carters

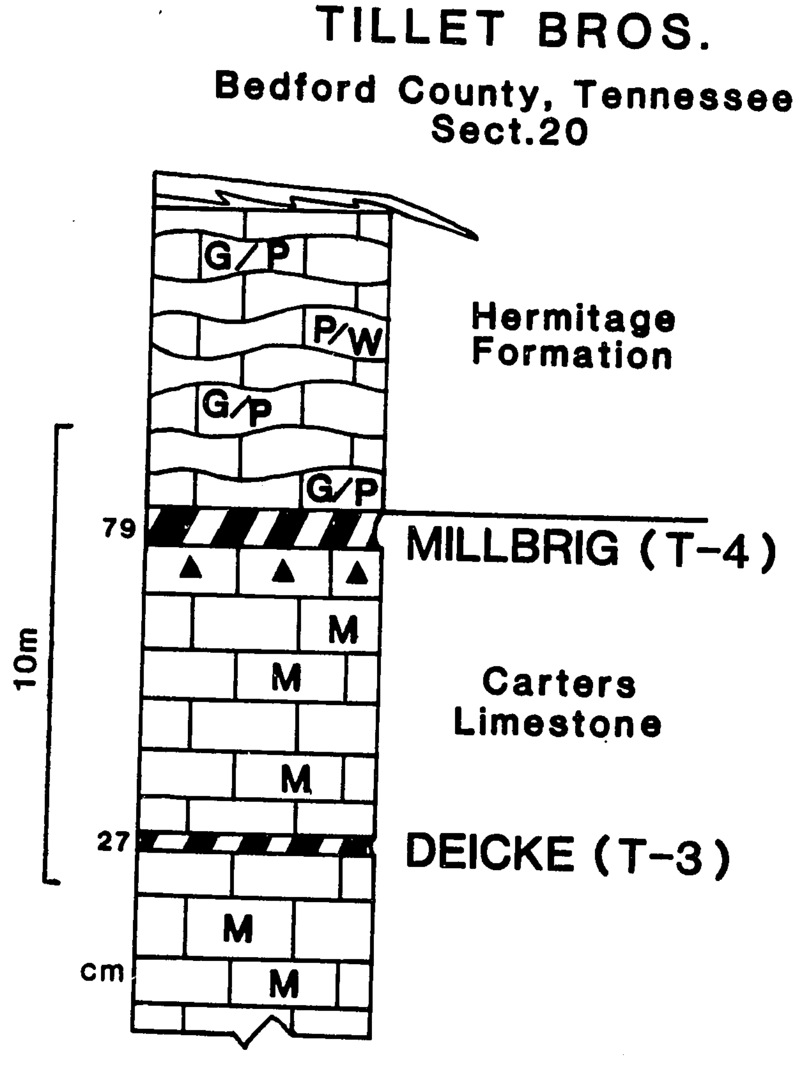


Figure 4. Details of the measured section in the Tillet Brothers Quarry near Shelbyville, Tennessee. This section is fairly typical of the Central Basin.

Limestone, with the Deicke located at the contact of the Lower and Upper Carters, and the Millbrig located about 4 m below the contact of the Carters and the overlying Hermitage Formation (Fig. 5). The Sequatchie Valley sequence is overall very similar to the Central Basin sequence with the exception that units are generally thicker, a reflection of the relative proximity of this area to the Valley and Ridge proper, where the Ordovician section -- as well as the entire Paleozoic section in general -- is markedly thicker relative to the equivalent section on the craton.

Alabama, Northwest Georgia, and Southeast Tennessee

Although Paleozoic rocks in the Valley and Ridge of this area are structurally disrupted by folds and faults, a convienent division into three strike belts is possible based on stratigraphic similarities in each (Chowns, 1986). These belts are shown in Figure 45 in Chapter VI. Significant differences occur in the Upper Ordovician sequences between the belts. In the western belt, which is bounded to the northwest by the Appalachian Plateau and to the southeast by the Clinchport and Helena faults, is a shallow water carbonate sequence (Drahovzal and Neathery, 1971; Benson, 1986). In the central belt, between the Clinchport and Helena faults and the Rome and Eden faults, is a predominantly clastic sequence of nonmarine to transitional redbeds and quartz sandstones. Southeast of this is the eastern belt, in which deep ramp marine

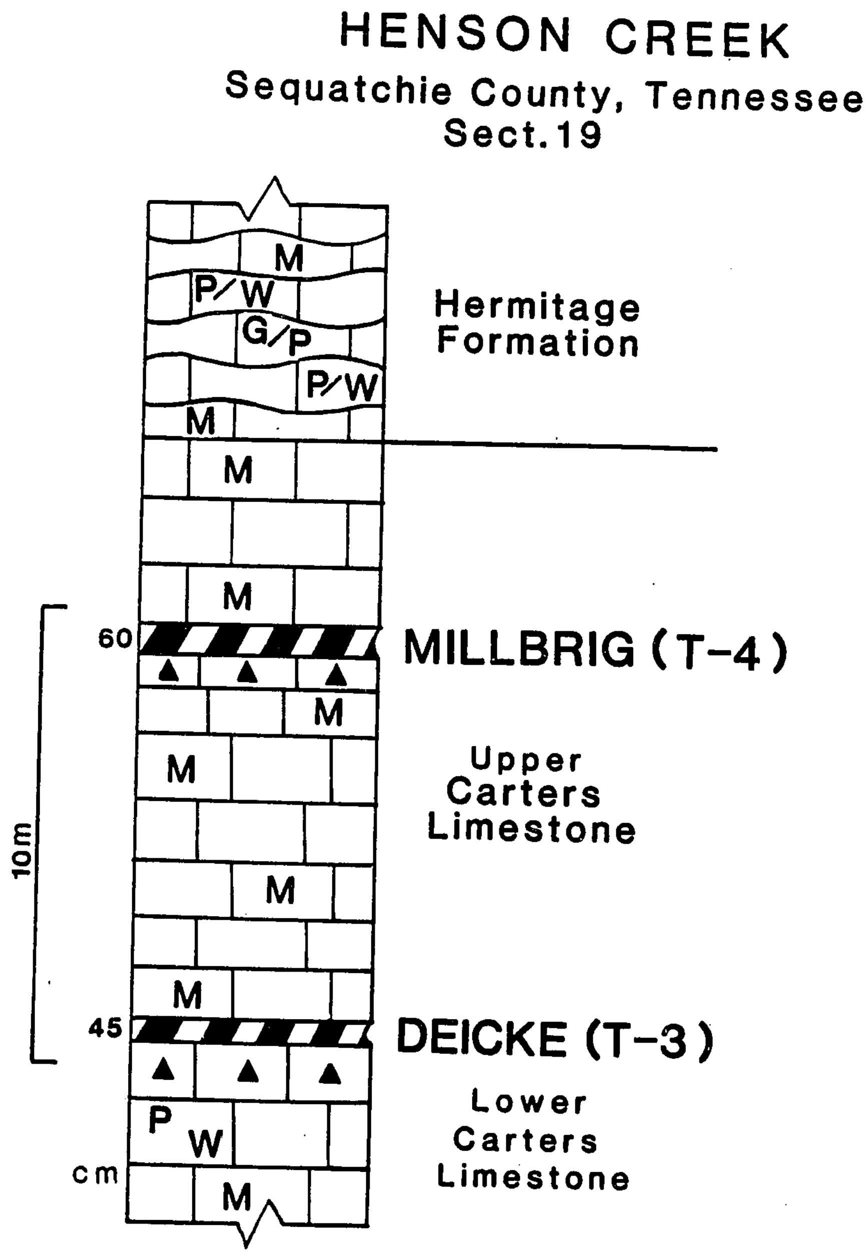


Figure 5. Details of the measured section along Henson Creek in the Sequatchie Valley of Tennessee. Although this section is in the western Valley and Ridge, the stratigraphy is nearly identical to Central Basin sections.

carbonates and basinal calcareous black shales occur. K-bentonites that correlate with the Deicke and Millbrig occur in the western and central belts, but correlation of the one K-bentonite collected from the eastern belt with those in the central and western belts is less certain.

Shallow Carbonate Sequence West of the Kingston Fault in the area around Chattanooga, in Lookout Valley, and around Chickamauga, the type locality for the Chickamauga Supergroup, the Rocklandian sequence is lithologically very similar to that seen in the Central Basin and the Sequatchie Valley of Tennessee, and Milici and Smith (1969) extended the Central Basin nomenclature into this area. The Deicke occurs at the contact between the Lower and Upper Carters, and the Millbrig occurs just beneath the contact of the Carters and the overlying Hermitage. Figure 6 is a measured section from the type area that shows these stratigraphic relations.

Between Ft. Payne and Gadsden in Alabama, the Lebanon, Carters, Hermitage, and Cannon cannot be recognized as in Georgia and Tennessee, and the Chickamauga is a group term rather than a supergroup. Rocklandian strata are simply assigned to the Stones River Formation, which is overlain by the Nashville Formation. Southwest of Gadsden more and more of the upper Nashville Formation is missing because of erosion, and in the Birmingham area, in fact, all of the strata that are elsewhere assigned to the Nashville

DAVIS CROSSROADS

Walker County, Georgia
Sect.22

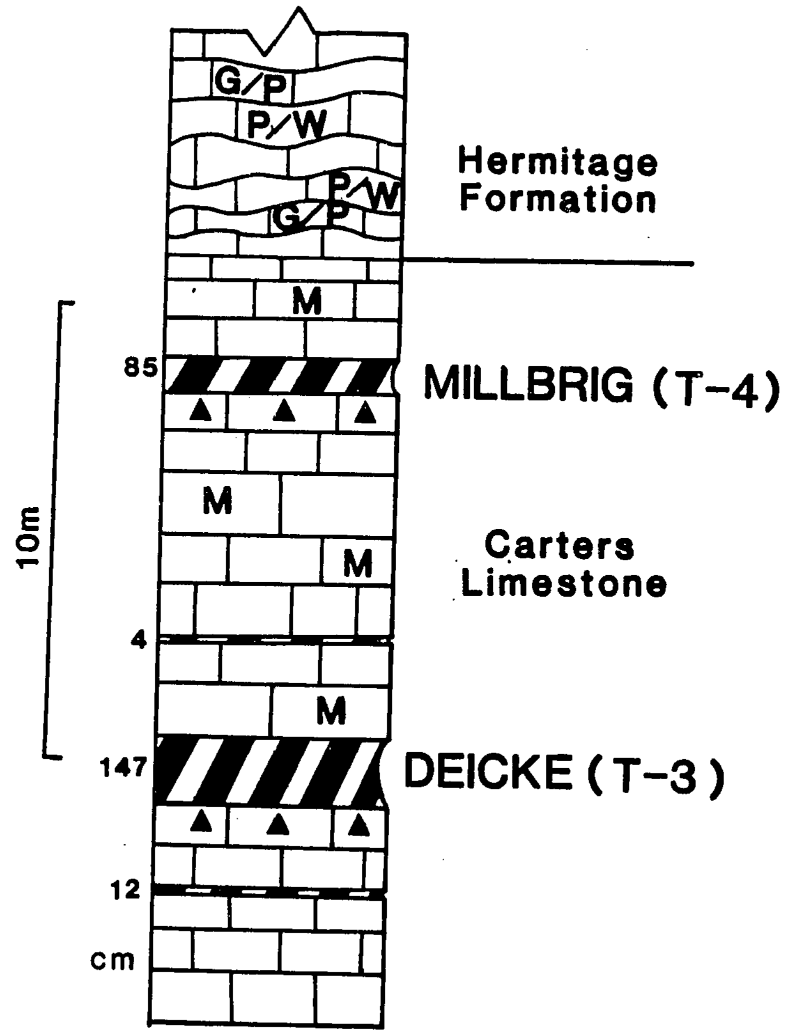


Figure 6. Details of the measured section along the dismantled TA&G railroad right-of-way in northwest Georgia. This is the thickest known exposure of the Deicke.

Formation are absent. As a result the entire unit is instead known simply as the Chickamauga Limestone.

Figures 7 and 8 are two stratigraphic sections from this area in Alabama. At the Big Ridge section, which is between Ft. Payne and Gadsden, the K-bentonites occur in the upper Stones River. Towards Birmingham they occur closer and closer to the contact between the Rocklandian and overlying strata until at Birmingham only 2-3 meters of Rocklandian strata occur above the Millbrig. These rocks are overlain by only 1 meter of Richmondian strata, and so the K-bentonites are 3-4 meters below the Silurian Red Mountain Formation. This is in marked contrast to sections farther northeast in the Big Wills Valley, where several tens of meters of Upper Ordovician strata occur between the K-bentonites and the basal Silurian (Milici and Wedow, 1977).

Clastic Sequence In the Armuchee Ridges of Georgia between the Clinchport and Rome Faults, clastics of the Greensport Formation and Colvin Mountain Sandstone occur. This is the central belt, and these rocks were previously assigned to the Bays and Moccasin Formations (Butts and Gildersleeve, 1948; Allen and Lester, 1957; Hergenroder, 1966; Cressler, 1970; Chowns and McKinney, 1980). The type areas for those units, however, are over 200 km away in northeast Tennessee and southwest Virginia, and Chowns and Carter (1983a) have suggested that the nomenclature for nearby sections in

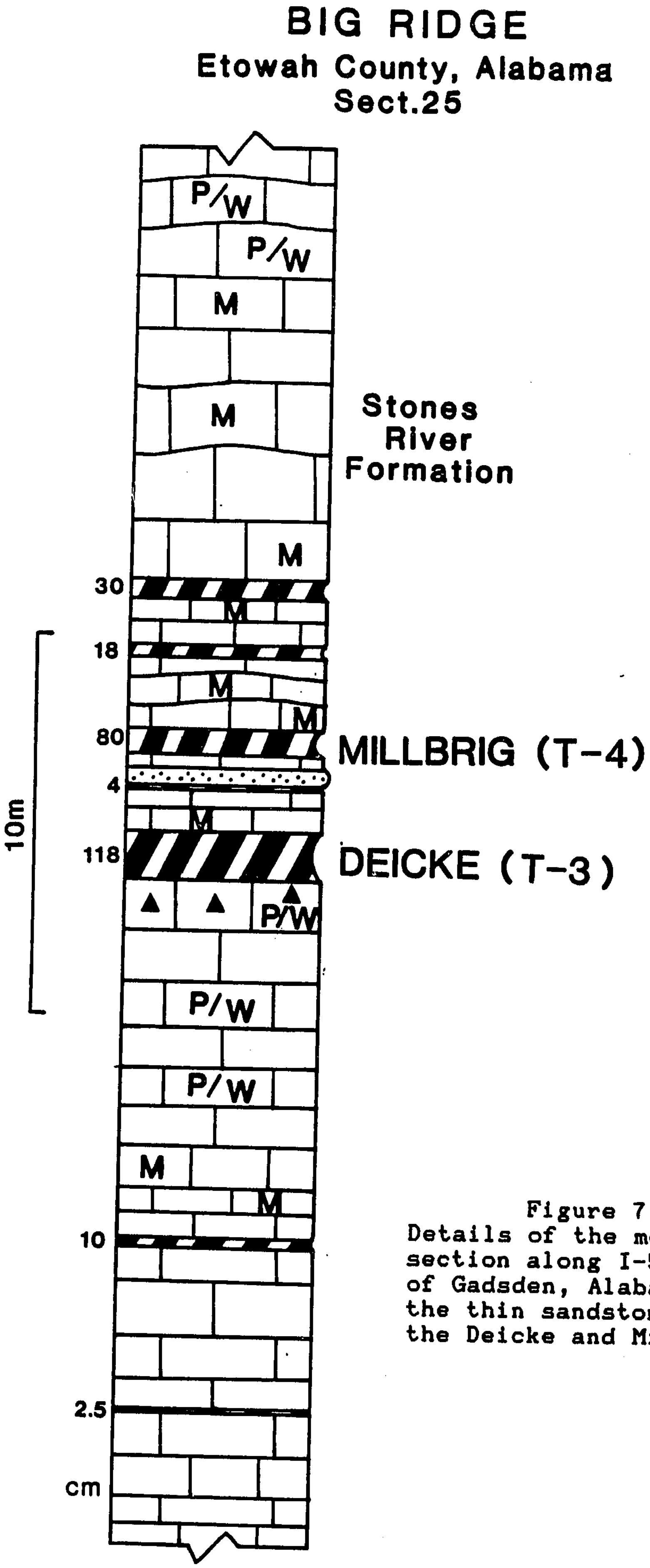


Figure 7.
Details of the measured section along I-59 north of Gadsden, Alabama. Note the thin sandstone between the Deicke and Millbrig.

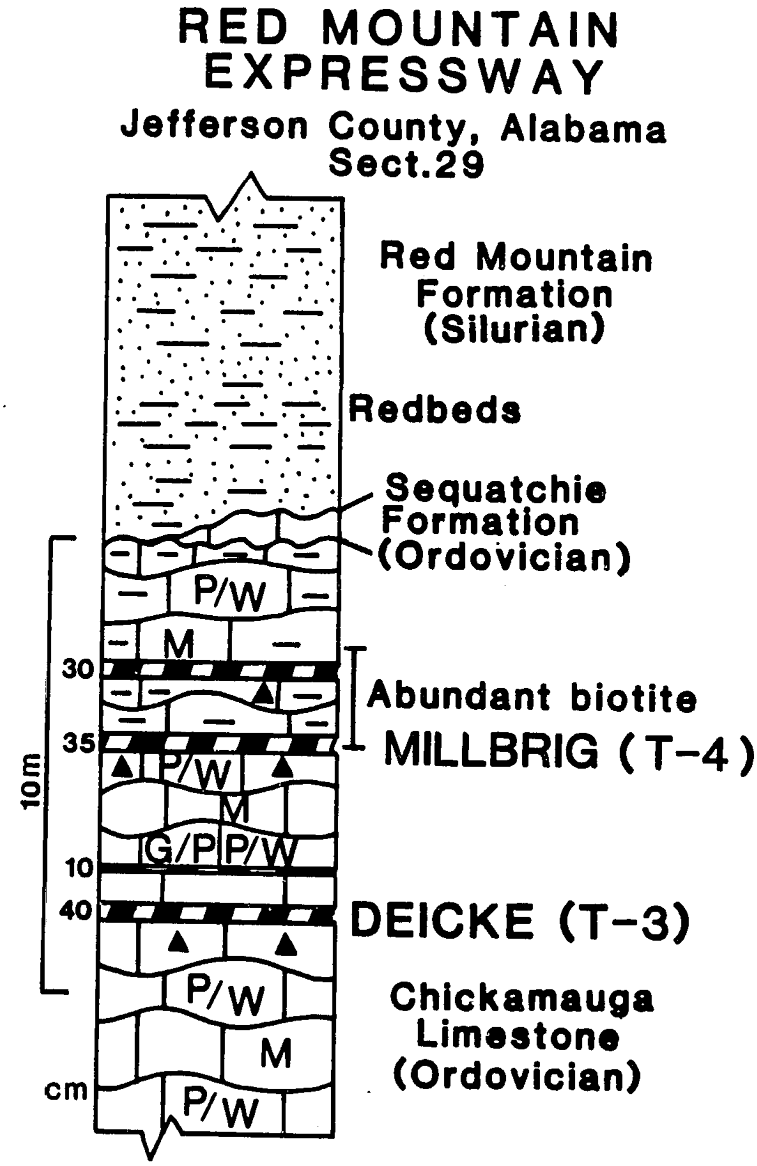


Figure 8. Details of the measured section along the Red Mountain Expressway, Birmingham. The Millbrig ash has been mixed in with the shaly carbonates over about 2 m of section. Note how close the Millbrig is to the Ordovician/Silurian contact.

Alabama is more appropriate for this area of Georgia. Although earlier workers reported K-bentonites from several exposures in these outcrop belts (Allen and Lester, 1957; Hergenroder, 1966; Cressler, 1970), the only K-bentonite found during field work for this study was the Deicke in an exposure on Horseleg Mountain, near Rome (Fig. 9). It occurs in the uppermost Greensport Formation, immediately below an approximately 1 m thick quartz arenite bed, the basal unit in the Colvin Mountain Sandstone.

At the Greensport Gap section in Etowah County, Alabama, Drahovzal and Neathery (1971) described two K-bentonites from the Colvin Mountain Sandstone, which overlies the Greensport Formation and is overlain by the Sequatchie Formation. Only the Deicke was found at this outcrop during the present study, but at the Alexander Gap section in Calhoun County two K-bentonites were found in the Colvin Mountain (Figure 10). This exposure is about 20 km northeast of Greensport Gap and along strike in the same outcrop belt. The two K-bentonites are thick enough to be equivalent to the Deicke and Millbrig, but both beds are extremely altered. No feldspars are present in either bed, but numerous ilmenite grains in the lower bed identify it as the Deicke. The upper bed contains no biotite, the distinguishing mineral of the Millbrig in hand specimen, and surprisingly it also contains no quartz grains. Nevertheless this bed is almost certainly the Millbrig, based on its stratigraphic position. It is hoped that chemical finger-

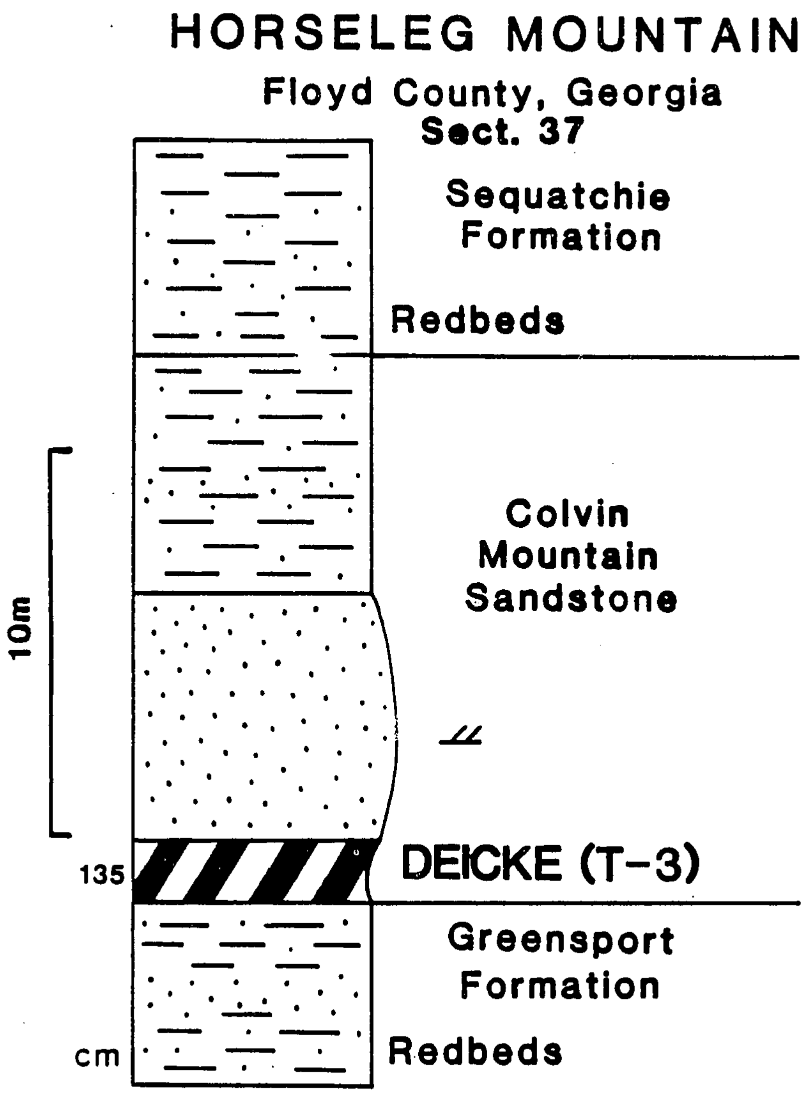


Figure 9. Details of the measured section along Mt. Alto Road, Rome. This is a reinterpretation of Chowns and Carter (1983a, 1983b), who identified this K-bentonite as the T-4 (Millbrig) based on the presence of abundant biotite. No biotite was observed in samples of this bed collected for the present study.

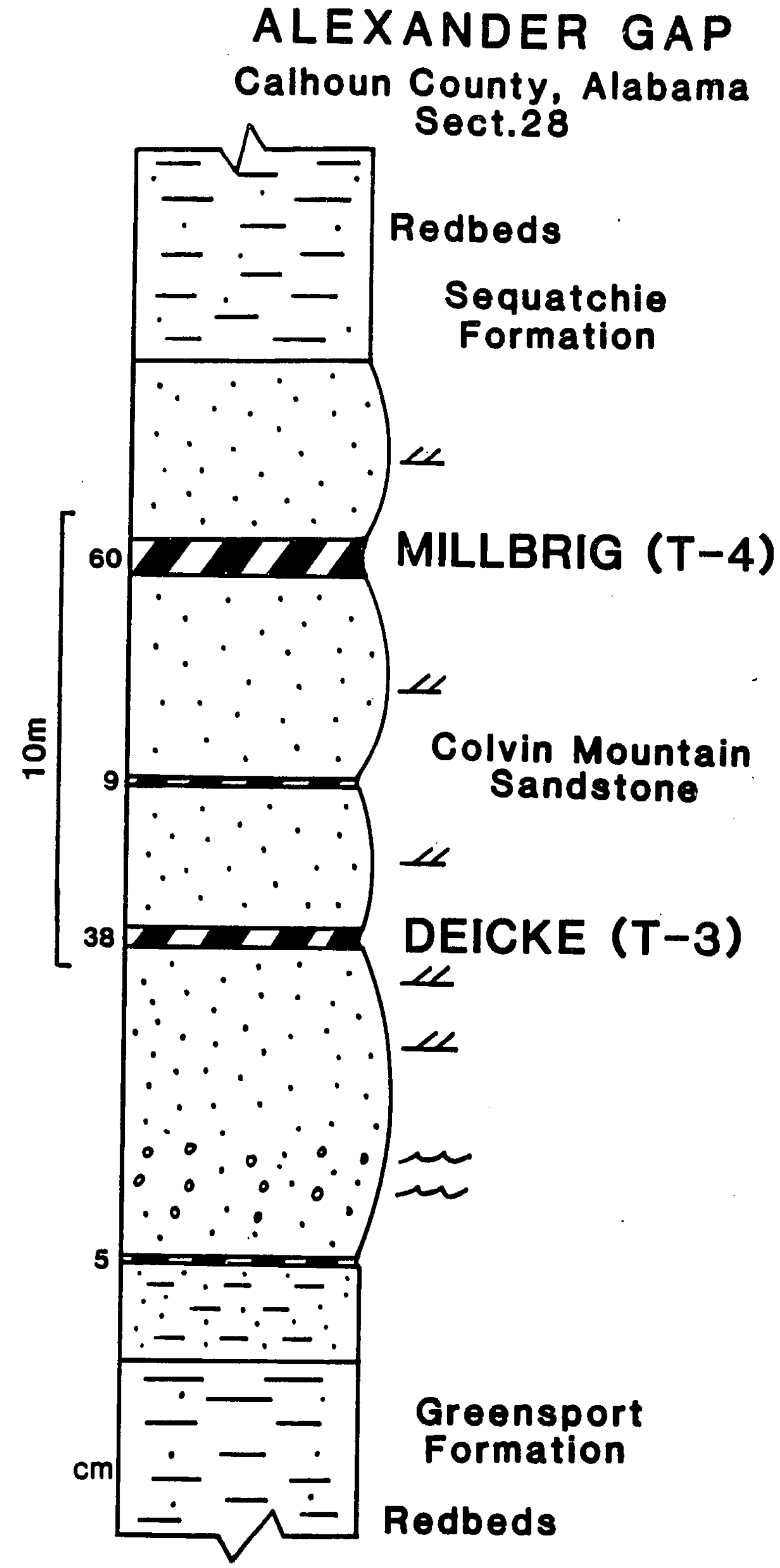


Figure 10. Details of the measured section at Alexander Gap, Alabama. Both the Deicke and Millbrig occur in quartz arenites of the Colvin Mountain.

printing studies will help to identify these very altered K-bentonites in the Colvin Mountain Sandstone, and assist in correlating them with the K-bentonites in the Chickamauga carbonates northwest of the Helena Fault.

Deep-water Carbonate and Black Shale Sequence: The Ragland Section Recent biostratigraphic studies of Hall and others (1986) on the conodonts of the Athens Shale and Little Oak Limestone of the eastern belt suggest that no Rocklandian age rocks are preserved in these formations. Erosion or non-deposition are the obvious reasons for this, given the occurrence of Rocklandian strata elsewhere in the Alabama Valley and Ridge. These findings imply that the Deicke and Millbrig equivalents will presumably not be found in these units in this region, and in fact only a very few occurrences of K-bentonite have been reported. Probably the best known of these are two K-bentonites from the Little Oak Limestone in an abandoned quarry near Ragland, as shown in Figure 11 (Butts, 1926; Drahovzal and Neathery, 1971). Conodont studies indicate that the Little Oak at this quarry is older than the upper Stones River Formation of the Chickamauga Group to the northwest, the interval in which the Deicke and Millbrig occur (Drahovzal and Neathery, 1971; Schmidt, 1982). During a visit to the quarry, only a single K-bentonite was found, in the upper part of the Little Oak 5-6 m beneath the contact with the overlying Devonian Frog Mountain Sandstone. This K-bentonite closely resembles the

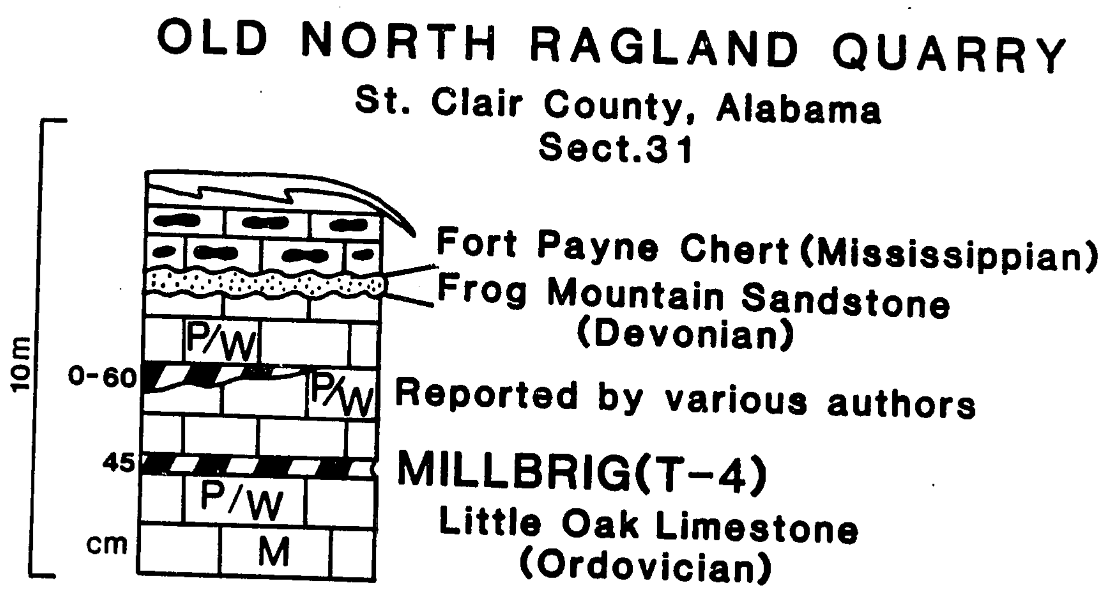


Figure 11. Details of the measured section in the abandoned quarry near Ragland, Alabama. The upper K-bentonite was not located during a visit to the quarry. Refer to Chapter VII for further discussion of this section.

Millbrig petrographically, as it contains abundant coarse biotite, but because the Little Oak here is biostratigraphically older than the Stones River Formation to the west, several interesting problems arise. These are discussed in detail in the section "The K-bentonite at the Old North Ragland Quarry, Alabama" of Chapter VII.

Southwest Virginia and Northeast Tennessee

As in Alabama and Georgia, Ordovician rocks in the Valley and Ridge of southwest Virginia and upper northeast Tennessee occur in three belts. Figures 46 and 47 in Chapter VI show these relations. The predominant lithologies differ from those farther south, however, as in the western and central belts, shallow water carbonate rocks occur, and in the eastern belt, clastics occur. The western belt is bounded to the west by the Appalachian Plateau and to the southeast by the Hunter Valley and St. Clair faults. The central belt is bounded on the northwest by those faults, and on the southeast by the Saltville and Pulaski faults. The eastern belt is bounded on the northwest by those faults, and on the southeast by the Blue Ridge and Great Smoky faults.

<u>Western Belt: the northern Powell Valley</u> K-bentonites occur in the Hardy Creek Limestone and the Eggleston and Trenton ("Martinsburg") Formations in this area. The stratigraphic relations are very similar over most of the

region, with the Deicke and Millbrig occurring in the upper Eggleston, 8-10 meters apart. The Millbrig occurs 2-3 meters beneath the Eggleston - Trenton ("Martinsburg") contact. Figure 12 shows the section at Hagan, Virginia, which is the best exposure in this area.

Central Belt In sections west of the Saltville Fault and east of the Powell Valley, K-bentonites occur in the Moccasin, Eggleston, and Trenton ("Martinsburg") Formations. The Deicke occurs in the upper 2-3 meters of the Moccasin Formation, and the Millbrig occurs 6-8 meters upsection, in the Eggleston Formation. These stratigraphic relations are recognizable from Thorn Hill, Tennessee, northeast to Giles County, Virginia, and Figure 13 is a measured section from the Plum Creek section in Tazewell County, Virginia, which is representative of this belt.

In Giles County the stratigraphic throw of the Saltville Fault is much less than farther south, and the stratigraphy of sections east of the fault is very similar to sections west of the fault. The Pulaski fault therefore becomes the boundary between the central and eastern belts.

Eastern Belt East of the Saltville fault and the Pulaski fault in the area mentioned above, K-bentonites occur in clastic rocks of the Bays Formation. Unlike the K-bentonites collected from the Colvin Mountain Sandstone in Alabama, however, where the K-bentonites are extremely

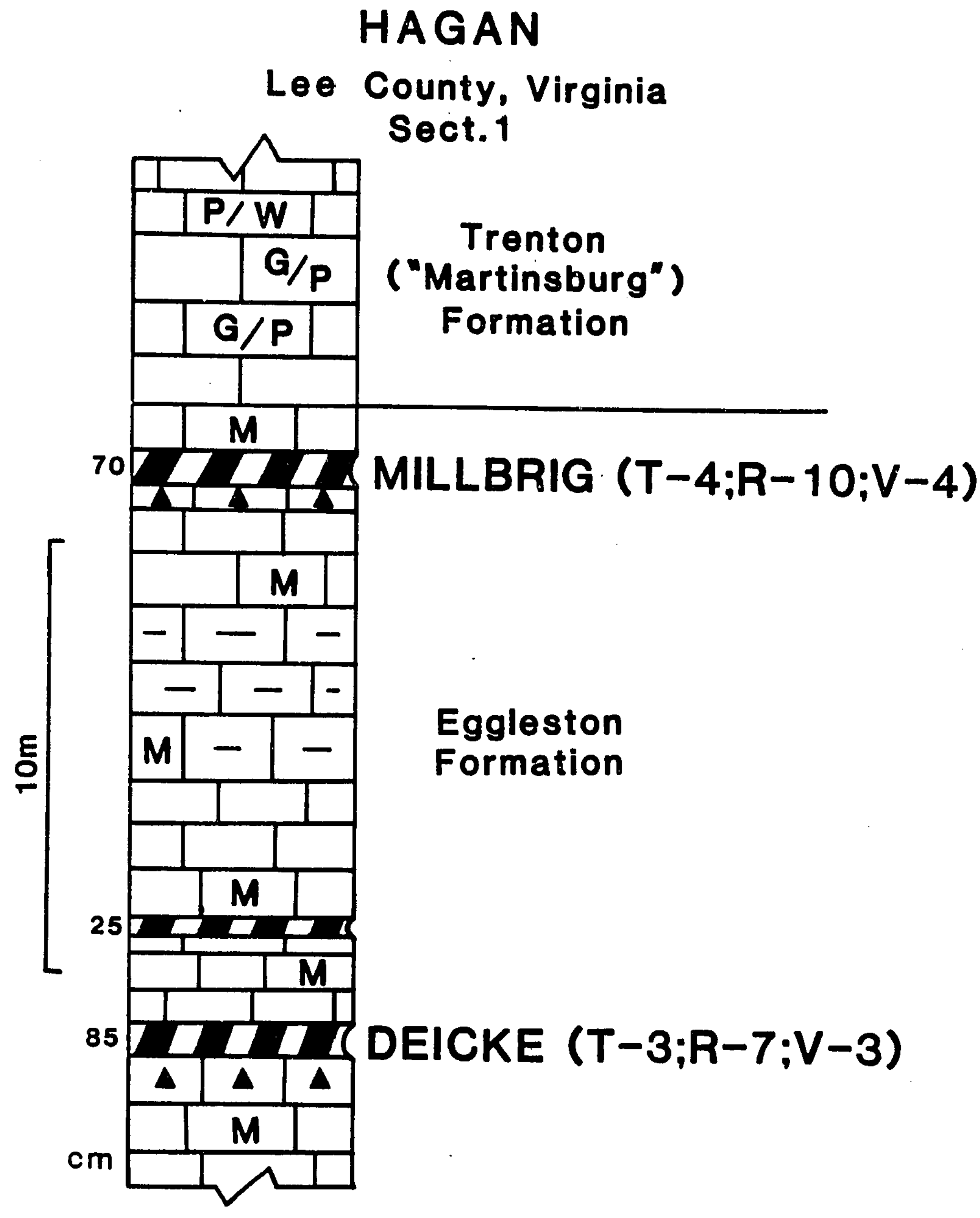


Figure 12. Details of the measured section along the railroad switchback at Hagan, Virginia. This section is very important in understanding the relationship of the Cincinnati Arch and Valley and Ridge sections.

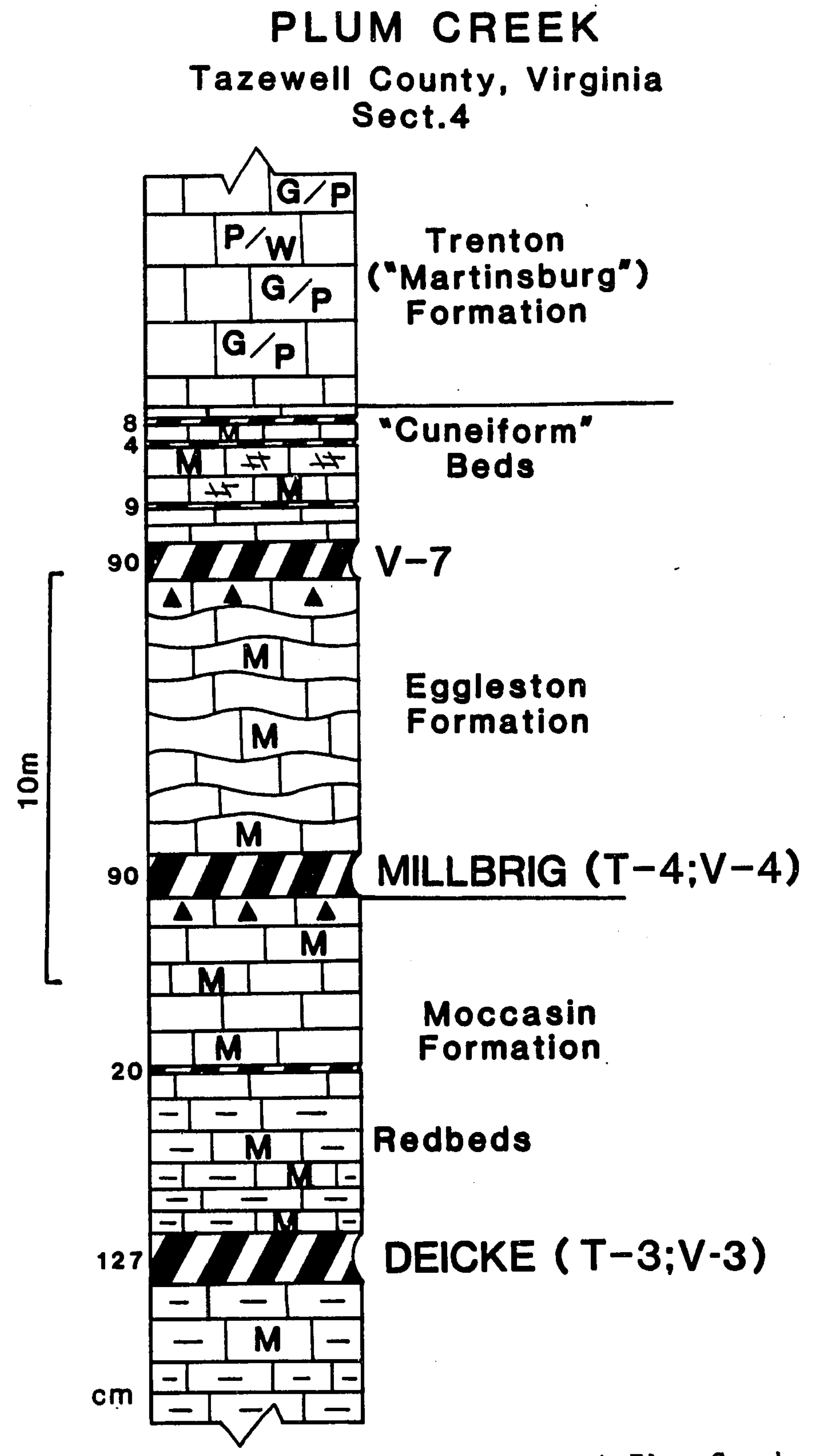


Figure 13. Details of the measured section at Plum Creek, Virginia. This is a key section for correlating the central belt with the western belt.

altered, the Millbrig is recognizable in hand specimens, and the Deicke is absent from the Bays. For the first time it can be shown that a K-bentonite can be correlated between the Eggleston Formation of the central and western belts and the Bays Formation of the eastern belt, as discussed in detail in the section "Reinterpretation of K-bentonite stratigraphy in Southwest Virginia and Northeast Tennessee" in Chapter VI.

Figures 14 and 15 are sections of the Bays in this area. The stratigraphic relation of the Millbrig to the Walker Mountain Sandstone is very important in understanding the stratigraphy of this area. The Walker Mountain is a marker bed that occurs in the Bays throughout the eastern belts, and in the Moccasin Formation in the north end of the central belt. It is a coarse-grained quartz arenite and quartz pebble conglomerate that is quickly recognized among finer grained sandstones, siltstones, and lime mudstones that predominate in the Bays and the Moccasin. In the Moccasin, the Deicke occurs immediately above the Walker Mountain, and the Millbrig and bed V-7 occur farther upsection. In the Bays, the Deicke is absent, and the Millbrig occurs 15-25 m upsection of the Walker Mountain and bed V-7 is 15-20 m above the Millbrig.

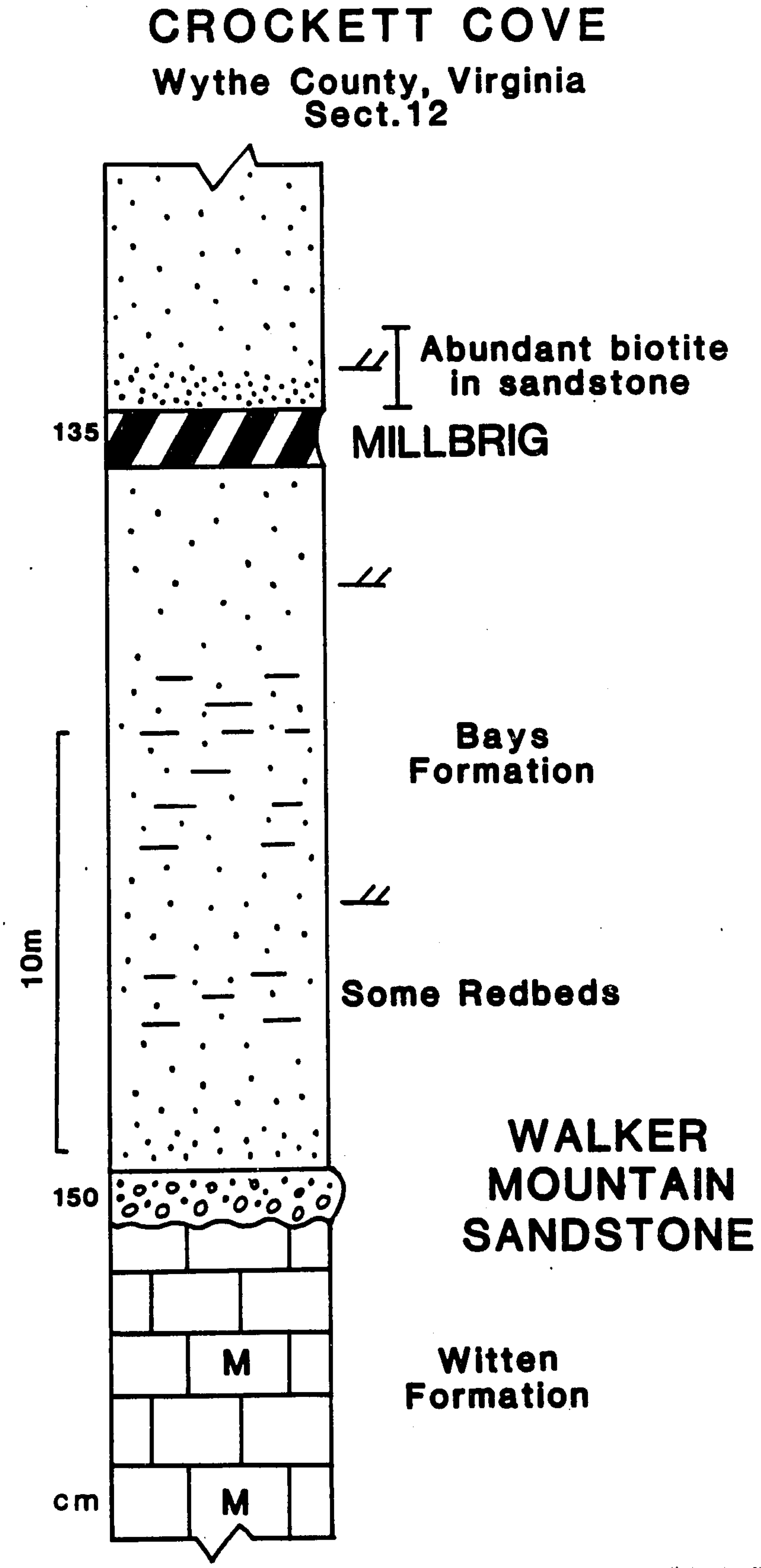


Figure 14. Details of the measured section along I-77 near Wytheville. Note the absence of the Deicke.

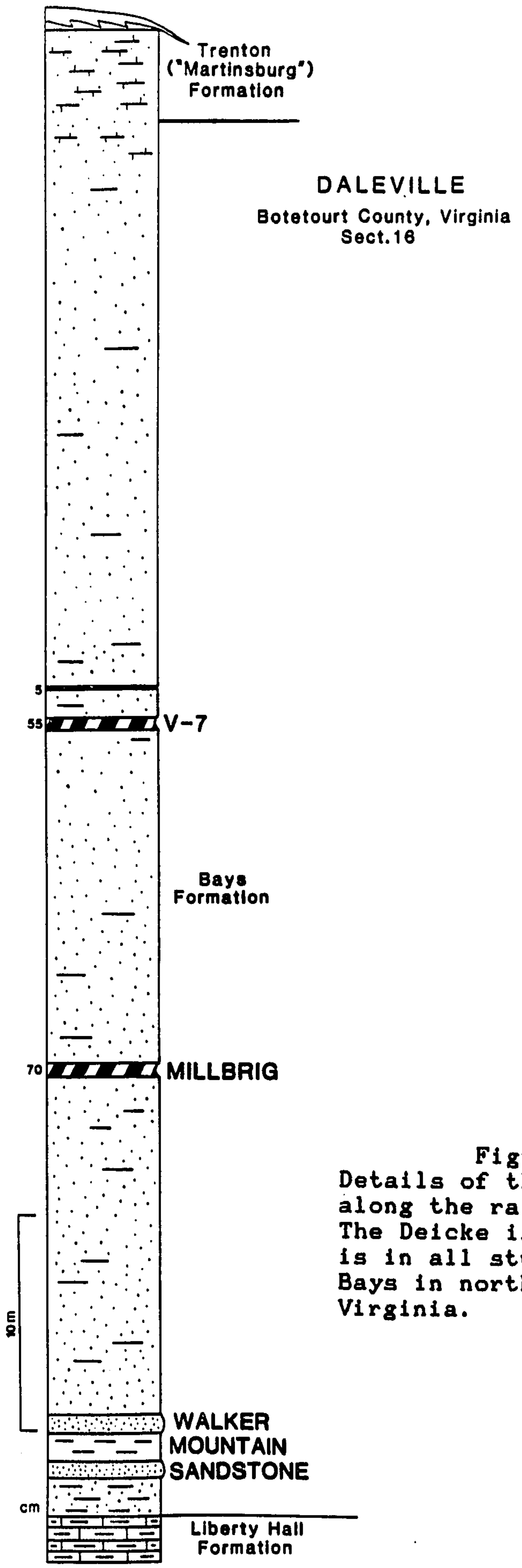


Figure 15.
Details of the measured section along the railroad near Daleville. The Deicke is again absent, as it is in all studied sections of the Bays in northeast Tennessee and Virginia.

Structure

Structural complications were of consequence in this study only where the normal stratigraphic sequence was disrupted on the outcrop scale. As this is a common occurrence in the Valley and Ridge, however, several promising exposures there were found to be unsuitable for detailed stratigraphic study.

The literature on the structural geology of the southern Appalachians, including the Valley and Ridge, is voluminous, and it provided invaluable information for this study. For more detailed discussion the reader is referred to Butts and Gildersleeve (1948), Woodward (1951), King and Ferguson (1960), Thomas and Drahovzal (1974), Kulander and Dean (1986), Benson and Stock (1986), and Bartholomew (1987), and the references cited therein. The following discussion is summarized from these sources.

Cincinnati Arch

Rocklandian strata along the Cincinnati Arch are in a structurally uncomplicated setting typical of outcrops in the North American craton. The beds are essentially flat-lying, with regional dips on the order of a few feet per mile. In some places, the strata are disrupted by high angle normal faults, such as along the Kentucky River where there is faulting associated with the Kentucky River fault zone.

Valley and Ridge

Outcrops in the Valley and Ridge province are in an area of very complex structure, as is typical for all foreland fold/thrust belts. Numerous maps that show the many folds and thrust faults which occur throughout the province are available from the U.S. and State Geological Surveys. Rocklandian strata are structurally disrupted to varying degrees depending on the proximity to fold axes, fault zones, etc., as are the other Paleozoic strata involved in the folding and thrusting. In Alabama, Georgia, and southeast Tennessee, there are few incompetent units in the Rocklandian, and severe structural disruption on the outcrop scale is relatively rare. In upper northeast Tennessee and southwest Virginia, however, argillaceous and shaly units are more abundant, and structural disruptions are more common. For example, pervasive axial plane cleavage is present in the Moccasin and Eggleston Formations in many outcrops. The K-bentonites are relatively thick in this region, but because they are the most incompetent units in the section they are often the locus for shearing, small-scale folding, and imbrication. This presented a problem at only three outcrops where further study was warranted for stratigraphic reasons, and of these three, only the Goodwins Ferry section in Giles County, Virginia, contained a K-bentonite that was crumpled and sheared beyond recognition in the field. This particular bed is in the proper stratigraphic position to be the Millbrig, but abundant biotite, the diagnostic mineral of the Millbrig in hand samples, is either lacking or is unrecognizable because of the intense shearing. Otherwise, internal deformation was not a major problem at most outcrops.

Imbrication of several large thrust sheets has led to the appearance of rapid changes in sedimentary facies, but this is actually caused by the telescoping effects associated with the thrusting. Stratigraphic charts compiled by Drahovzal and Neathery (1971) for Alabama, LeVan and Rader (1983) for Virginia, and Chowns (1983, 1986) for Georgia, illustrate how facies changes in the Ordovician are related to the major thrust sheets in those states.

PETROGRAPHY

Introduction

The initial petrographic study of the Deicke and Millbrig was undertaken along the Cincinnati Arch, and it was found that the beds contain distinctly different phenocryst assemblages, particularly in the lower parts of each bed, where the phenocrysts are coarser. Samples of K-bentonites collected from exposures in the Valley and Ridge were then studied, and the findings from this area were compared with the findings from the Cincinnati Arch samples. Mineralogic differences between the two K-bentonite beds provide a basis for field identification and correlation as well as important clues that help in determining the composition of the precursor ash. These petrographic differences are the primary basis for the correlation of the Deicke and Millbrig along the Cincinnati Arch and in the Valley and Ridge between Virginia and Alabama.

Non-clay Mineralogy

Compared with the literature on the clay mineralogy of these K-bentonites, relatively little information has been published on the non-clay mineralogy of these beds in either the Cincinnati Arch or Valley and Ridge regions. Most studies of these Rocklandian strata recognized either two or three K-bentonite beds that were much thicker than all others. These beds were greater than 50 cm thick, and thicknesses of 1 m or greater were reported. Of these two or three K-bentonites, the upper of the two, or the middle of the three, invariably contained abundant biotite, particularly in a noticeable coarse-grained zone in the lower or middle part of the bed. The lower thick bed also had a coarse-grained zone, but this zone occurred in the basal few centimeters of the bed, and it contained very little biotite (cf. Fox and Grant, 1944). Rosenkrans (1936), Reade (1959), Hergenroder (1966), Drahovzal and Neathery (1971), Gunal (1979), and Huff and Turkmenoglu (1981) described the non-clay minerals. Kunk and Sutter (1984) published radiometric ages for beds T-3 and T-4, the Deicke and Millbrig, respectively, obtained from $^{40}Ar/^{39}Ar$ dating of biotites from samples collected in Kentucky, Tennessee, and Alabama. None of these studies detailed mineral abundances or compositional differences, which is a main goal of this research.

Table 1 lists the non-clay minerals in the Deicke and Millbrig. Identification was made both optically and with electron microprobe analyses as discussed in following sections. Primary phenocrysts in the Millbrig are more abundant than those in the Deicke, perhaps because labradorite and magnetite are more susceptible to alteration than are andesine, biotite, and quartz. Surprisingly, primary potassium feldspars, which are common in felsic volcanic ash, were not observed; this absence is most likely the result of pervasive diagenetic alteration with subsequent formation of authigenic K-feldspar, which is

NON-CLAY MINERALOGY

MILLBRIG	DEICKE
Primary Phenocrysts	**Primary Phenocrysts**
Andesine (5-15%) Quartz (20-25%) Biotite (15-20%) Apatite (<1%) Zircon (<1%)	Labradorite (5-15%) Ilmenite (1-5%) Magnetite (1-5%) Quartz (<1%) Biotite (<1%) Apatite (<1%) Zircon (<1%)
Authigenic Minerals	**Authigenic Minerals**
Orthoclase - Or_{98-100} (20-60%) Albite (Valley and Ridge only) - Ab_{98-100} (0-20%) Pyrite (<1%) Hematite (<1%) Chlorite (<1%) Calcite (<1%)	Orthoclase - Or_{98-100} (30-70%) Albite (Valley and Ridge only) - Ab_{98-100} (0-20%) Leucoxene, Anatase, Rutile } (5-10%) Pyrite (<1%) Hematite (<1%) Calcite (1-5%) Gypsum (<1%)

Table 1. Abundances of non-clay minerals in the Deicke and Millbrig from the Cincinnati Arch and the Valley and Ridge.

abundant. Nevertheless, sanidine does occur in a sample of the Millbrig from Hagan, Virginia (R. Hay, pers. comm.)

Feldspars

Feldspars are the most abundant phenocrysts in the Deicke and Millbrig. Simple and polysynthetically twinned primary plagioclase, untwinned authigenic plagioclase, and untwinned authigenic K-feldspar occur. Grain sizes vary greatly; the feldspars average less than 0.5 mm long in samples from the Jessamine Dome and from the west-central Valley and Ridge in Virginia, and they average between 0.5-1.0 mm long in samples from the Nashville Dome and the Valley and Ridge from southwestern Virginia to Alabama. This regional increase in average grain size to the south and southeast corresponds with increased thicknesses of each bed in this direction as well.

The modal percentage of feldspars present varies with location as well. In the Jessamine Dome and the west-central Valley and Ridge of Virginia they average less than 30 percent of the phenocryst population, while in samples from the Cumberland Saddle, the Nashville Dome, and the Valley and Ridge between Alabama and southwest Virginia they comprise as much as 60 percent of the population. A major exception occurs in samples from the clastic sediments present in the eastern belts of the Valley and Ridge. Feldspars comprise from zero to about 20 percent of the phenocrysts in samples from the Colvin Mountain Sandstone, and from 10 to 40 percent in samples from the Bays Formation. In this area only the Millbrig is present, and alteration is greater than in samples from the carbonate belts farther west. This is perhaps because circulation of meteoric waters was more pervasive here, or that the pH of post-depositional pore fluids was lower in these sediments than in the carbonates. Both of these are considered likely scenarios, and are discussed in the "Burial History" section of Chapter VII.

Identification of feldspars was initially made using oils to determine refractive indices of various grains from grain separates, and then more quantitatively with electron microprobe analyses. Selected grains in 10 thin-sections were analyzed. Grains were chosen for analysis based primarily on texture. Twinned, zoned, and untwinned grains, and grains in various stages of alteration, were all analyzed. Figure 16 summarizes the probe findings in a ternary plot of data, and Table 2 lists several representative analyses from different grains. These analyses are of relatively unaltered grains. The presence of several different feldspars is clearly shown by these data, supporting textural observations made with the microscope. Data points in the two fields labeled "andesine" and "labradorite" were obtained exclusively from zoned or polysynthetically twinned plagioclases. Grains in these fields had compositions close to those reported in Table 2. These compositions are typical of igneous

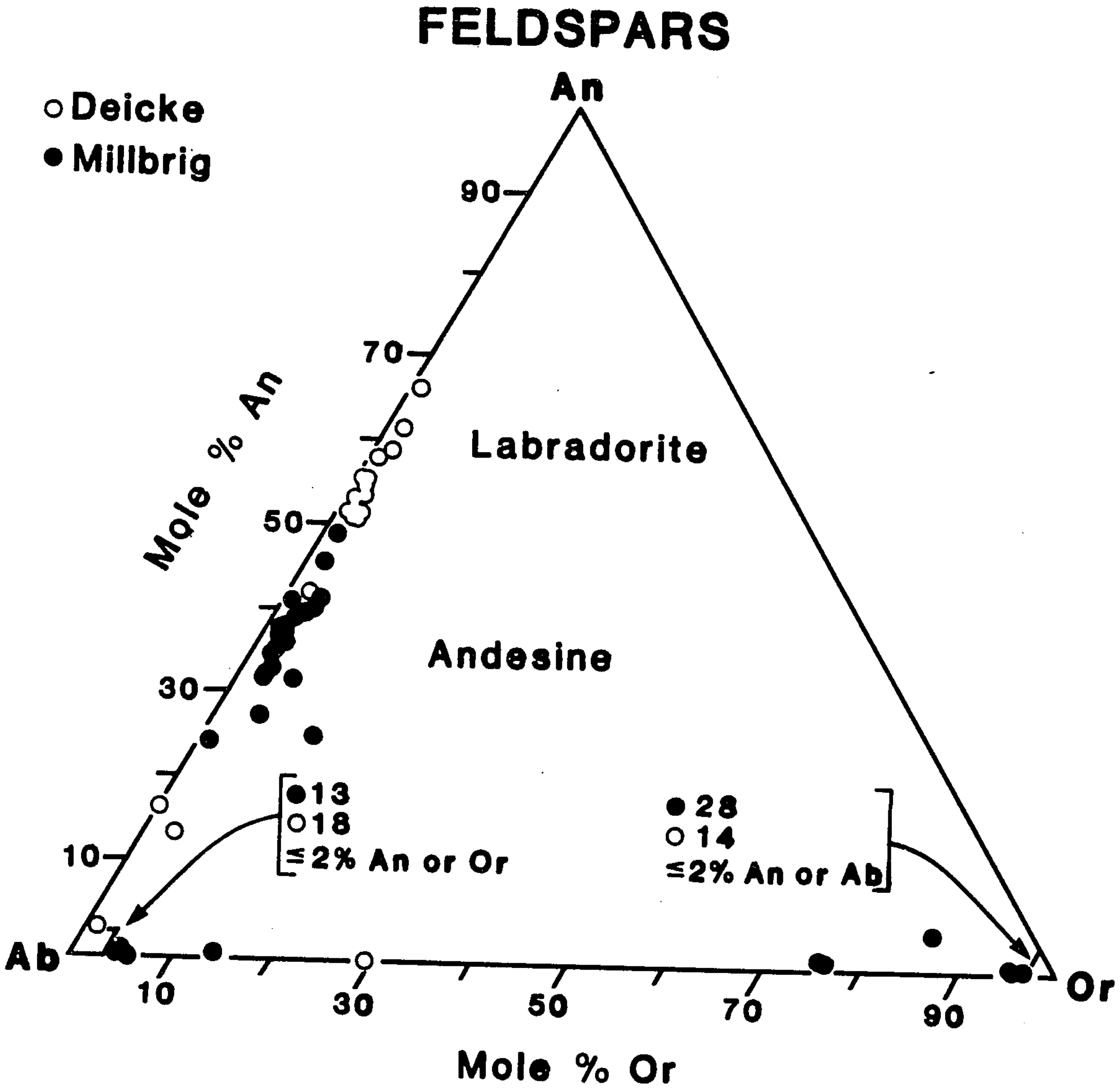


Figure 16. Ternary diagram plotting the results of microprobe analyses on feldspars of selected Deicke and Millbrig samples. Note the separation of points into a labradorite field (Deicke) and an andesine field (Millbrig), and the abundance of authigenic feldspars of extreme purity.

Sample	An_{54} Labradorite GA: WL 3-1[1]	An_{62} Labradorite TN10[1]	An_{35} Andesine AL17[2]	An_{45} Andesine TN11-1[2]	An_8 Albite AL14-1[2]	An_1 Albite GA:WL3-1[1]	Or_{98} K-feldspar AL17[2]	Or_{99} K-feldspar KB-34[2]
				weight %				
SiO_2	55.12	54.85	59.88	57.41	71.07	68.26	64.12	64.63
Al_2O_3	28.07	28.78	25.09	26.43	19.31	19.76	18.77	19.28
CaO	11.35	12.13	7.59	9.32	0.00	0.15	0.00	0.05
Na_2O	5.13	3.97	7.24	5.98	11.11	11.09	0.20	0.13
K_2O	0.45	0.30	0.71	0.38	0.00	0.23	16.84	16.16
Total	100.12%	100.03%	100.51%	99.52%	101.49%	99.49%	99.93%	100.25%

1. Deicke sample
2. Millbrig sample

Table 2. **Representative feldspar compositions as determined by microprobe analyses of primary and secondary grains, and overgrowths.**

plagioclases, which invariably consist of solid solutions between the albite and anorthite end members, occasionally with a minor orthoclase component. Labradorite and andesine occur in the triclinic albite-anorthite (Ab-An) solid-solution series, in which andesines are defined as having 30-50 percent An component and labradorites as having 50-70 percent An component. All untwinned and unzoned grains plotted in the two corner fields, which represent the albite end-member field in the Ab-An solid-solution series, and the orthoclase (Or) end member field in the Ab-Or solid-solution series. All grains in these two end member fields had compositions nearly identical to those given in Table 2.

The apparent gap in miscibility seen between albite and orthoclase in Figure 16 is thought to be the result of the selective diagenetic removal of primary K-feldspars, chiefly sanidine. Miscibility gaps are characteristic of plutonic rocks, which the Deicke and Millbrig are obviously not, so the apparent gap reflects post-depositional changes in the mineralogy of the bed.

Untwinned plagioclase grains were identified as albite based on compositions determined by electron microprobe analyses. In thin-sections, albite, K-feldspar, and quartz are distinguished on the basis of interference color under cross nicols, using the standard Michel-Levy chart. In addition, albite and K-feldspar grains are in general more altered than quartz grains and the feldspars usually contain more inclusions and impurities, which further serve to distinguish these various grains. Table 2 gives the compositions for two grains each of authigenic albite and authigenic K-feldspar. Albite was thus readily recognizable in thin-section, and in grains where albite and K-feldspar occur together, the difference in interference colors allows for identification of the two minerals (cf. Fig. 20).

In all samples, authigenic K-feldspar (untwinned) is the most common feldspar, comprising up to 95 percent of all feldspars in some samples. Twinned or zoned plagioclases comprise up to 60 percent of some samples. Least abundant is albite (untwinned), which is absent in samples from along the Cincinnati Arch, and comprises up to 30 percent of some samples from the Valley and Ridge.

In the Deicke most of the relatively unaltered twinned and zoned plagioclase grains are broken, but crystal faces can be seen along the unbroken edges. Some well-preserved euhedral grains are present (Fig. 17). The twinned and zoned plagioclases in the Millbrig are texturally very similar to those in the Deicke.

Based on their texture the twinned and zoned plagioclases are considered primary phenocrysts. Zoned and polysynthetically twinned euhedral plagioclase grains are characteristic of modern acid volcanic rocks. The euhedral shape indicates that these crystals were among the first to form in a cooling magma, when there was ample space to crystallize unrestricted by other crystal faces. The zoning records either 1) fluctuation in the fugacity of water, 2)

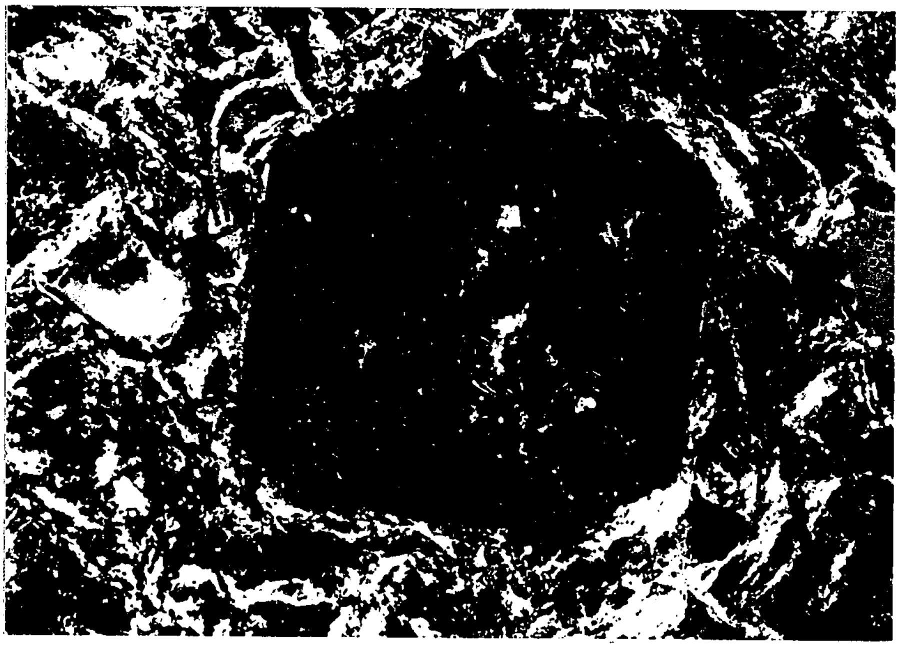


Figure 17. Photomicrograph of a zoned euhedral labradorite grain in the Deicke from the Hinds Creek Quarry, Tennessee. The grain has been partly replaced by calcite and mixed-layer illite/smectite. Note also the characteristic appearance of the mixed-layer illite/smectite, which is the whitish fibrous-appearing mineral that surrounds the feldspar. Horizontal field of view is 2.5 mm. Cross-polarized light.

fluctuation in temperature, or 3) magma mixing. The zoning in a single crystal is exhibited as many compositional bands with different extinction angles. Low temperature authigenic plagioclases from sedimentary environments do not show zoning (Kastner and Siever, 1979). Polysynthetic twinning is also a characteristic of igneous plagioclases; twinning in plagioclases is after the X-Carlsbad law and the simple albite law (Kastner and Siever, 1979). Further evidence supporting an igneous origin for the zoned and polysynthetically twinned plagioclases comes from their compositions, primarily andesines and labradorites, as discussed below.

In both beds, many of the twinned and zoned plagioclases have been partly replaced by untwinned K-feldspar or albite (Figs. 18 and 19). Replacement results in "two-feldspar" grains where moderately to highly altered primary plagioclases co-exist with unaltered and untwinned authigenic albite or K-feldspar. Albite commonly replaces the primary plagioclase along zones of twinning or zoning (Fig. 19). In addition, authigenic albite and authigenic K-feldspar also co-exist in many grains (Figure 20). Authigenic albite and K-feldspar also occur as individual grains; perhaps such grains are complete replacements of a primary feldspar.

Albitized K-feldspar grains with textures very similar to that in Figure 20 are illustrated and described by Morad (1988a) from Upper Proterozoic sandstones of Norway. In

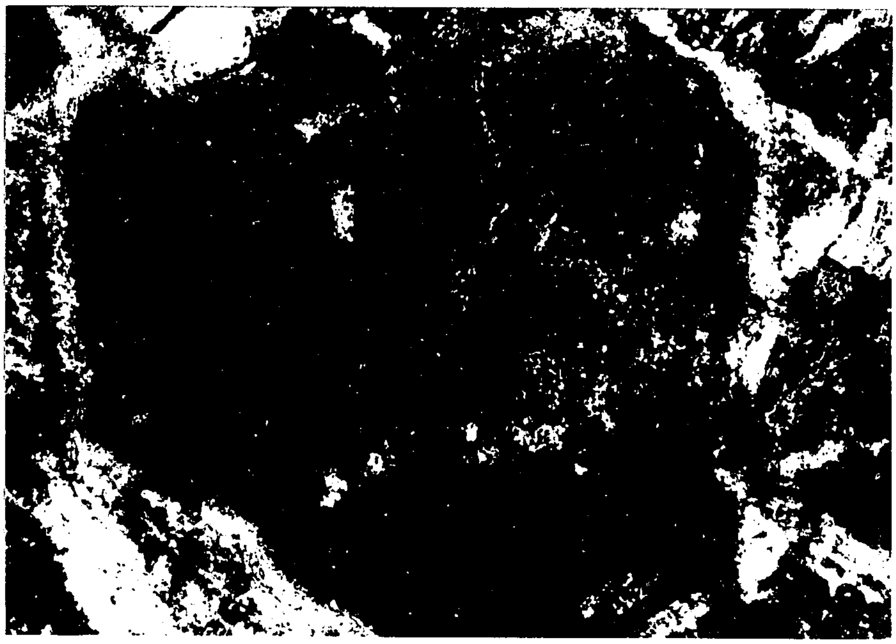


Figure 18. Photomicrograph of authigenic K-feldspar replacing a primary andesine grain in the Millbrig from Big Ridge, Alabama. The andesine is polysynthetically twinned. K-feldspar is dark gray mineral at base of the twinned plagioclase. Horizontal field of view is 2.5 mm. Cross-polarized light.

Figure 19. Photomicrograph of authigenic albite replacing a primary labradorite grain in the Deicke from Davis Crossroads, Georgia. The albite is the white areas that are aligned along the planes of zoning. The labradorite grain is being altered, but its euhedral outline is still apparent, and as shown in Table 2, it is still labradoritic in composition. Horizontal field of view is 2.5 mm. Cross-polarized light.

Figure 20. Photomicrograph of authigenic albite that appears to be replacing authigenic K-feldspar in the Millbrig from Big Ridge, Alabama. The albite is the white areas that contrast with the splotchy gray K-feldspar. The differences in interference colors and texture are the keys in identifying these authigenic feldspars with the petrographic microscope. Horizontal field of view is 2.5 mm. Cross-polarized light.

those sandstones, detrital microclines have been albitized, and evidence indicates that the alteration is post-depositional rather than an inherited texture from albitized source rocks. There is no doubt that the albitization of feldspars in the Rocklandian K-bentonites is post-depositional; as the beds are obviously derived from potassium-rich volcanic ash the replacement of primary plagioclase by authigenic feldspars is secondary, because magmatic replacement would have resulted in a replacement phase that was also K-rich, which albite is obviously not. Also, the feldspars in the K-bentonites are not detrital as they would be in a sandstone, so there is no problem with inherited textures from source rocks.

Authigenic K-feldspar has a ragged or tattered appearance, readily distinguishing it from albite, which is much clearer. These differences are shown in Figure 20. The authigenic K-feldspar was not studied further to determine its exact crystallographic identity.

In the "two-feldspar" grains albite commonly occurs around the edges of the grains, suggesting that it formed later than the K-feldspar. Grains of this type do not occur in samples from the Cincinnati Arch. Albite is completely absent in samples from this area. K-feldspar grains comprise up to 80 percent of the feldspar population in Cincinnati Arch samples, with twinned or zoned primary plagioclase making up the remainder. In samples from the carbonates of the western Valley and Ridge, however, albite is commonly observed, and up to 25 percent of the feldspars are "two-feldpar" grains, containing both authigenic K-feldspar and albite, or one or both of these feldspars as overgrowths or replacements around the edges of primary plagioclases.

Several important findings regarding the feldspars are evident. Most signficant with respect to the goals of this research, it is clear that the two beds can quite readily be distinguished by the composition of the primary plagioclase phenocrysts. In the Deicke, these are overwhelmingly labradorites, whereas in the Millbrig they are overwhelmingly andesines, and as seen in the Figure 16 the fields are distinctly separate. This is a significant finding for several reasons. In any igneous rock, the composition of primary feldspars is very useful in drawing inferences about the composition of the original melt. Because feldspars are ubiquitous and they consist of solid solutions between the An-Ab-Or end members, they offer abundant and readily obtainable information on the chemistry of the magma. Although no systematic traverses of a single grain were done with the electron microprobe, several grains in both the Deicke and Millbrig were analyzed more than once, and although minor compositional changes were observed, the grains in the Deicke were consistently An_{50-70} throughout, and those in the Millbrig were An_{30-50} throughout. The presence of zoned labradorites in the Deicke thus suggests that the original magma was of an intermediate composition relative to the Millbrig magma, which is inferred to have been more felsic in composition. This is discussed in more detail in Chapter VIII.

In contrast to the identifiable difference between the primary plagioclases of the two beds is the abundance of end-member albite and orthoclase in both beds. Composition of these does not vary significantly between the two beds, and thus the presence of these feldspars is not diagnostic of the Deicke or the Millbrig. These grains are authigenic based on their textural relations with the primary labradorites and andesines, their lack of zoning or polysynthetic twinning, and their compositional purity, a distinguishing trait of authigenic feldspars formed in low temperature, sedimentary environments (Kastner and Siever, 1979). The origin and significance of these grains is discussed in detail in the "Burial History" section of Chapter VII.

Fe-Ti Oxides and Other Opaque Minerals

Samples of the Deicke contain Fe-Ti oxides and opaque minerals in abundances ranging from 5-10 percent of the phenocryst population. They make up less than 1 percent of the population in the Millbrig. Examination of several polished thin-sections of Deicke samples showed that pyrite, ilmenite, anatase/rutile, and leucoxene are present. Only pyrite occurs in the Millbrig. The most common Fe-Ti oxide is anatase or rutile, which is a replacement after ilmenite

(Fig. 21). These grains are commonly euhedral to subhedral (Figs. 22 and 23), 0.2-0.5 mm in length, and nearly opaque in transmitted light but whitish gray in reflected light. Under cross nicols, they appear as clusters of very small, highly birefringent grains. They are identified as anatase and possibly rutile on the basis of their habit, reddish-brown color, high-order interference colors, and association with relict euhedral grains of ilmenite or leucoxene. Figures 21 and 22 show the euhedral outline of the original grain, which is thought to have been an ilmenite. Figure 23 shows one of these anatase or rutile clusters, but the euhedral outline is suggestive of a pyroxene rather than ilmenite. Pyroxene would not be unexpected in a dacitic ash, so it is possible that the Fe-Ti oxides in the Deicke are replacing both ilmenite and pyroxene phenocrysts. It is very unlikely that any of the original grains were biotite, however, as suggested by Samson and others (1988) for the Deicke in the Upper Mississippi Valley, because 3-8 m upsection from the Deicke throughout this region is the biotite-rich Millbrig, in which no alteration of biotite to rutile or anatase has been observed.

In some samples of the Deicke from the Colvin Mountain Sandstone in Alabama and Georgia, euhedral, unaltered grains of black ilmenite are present. In grain separates they are readily identified with a binocular microscope.

Studies of detrital titanomagnetite grains in sandstones indicate that anatase and rutile pseudomorph ilmenite

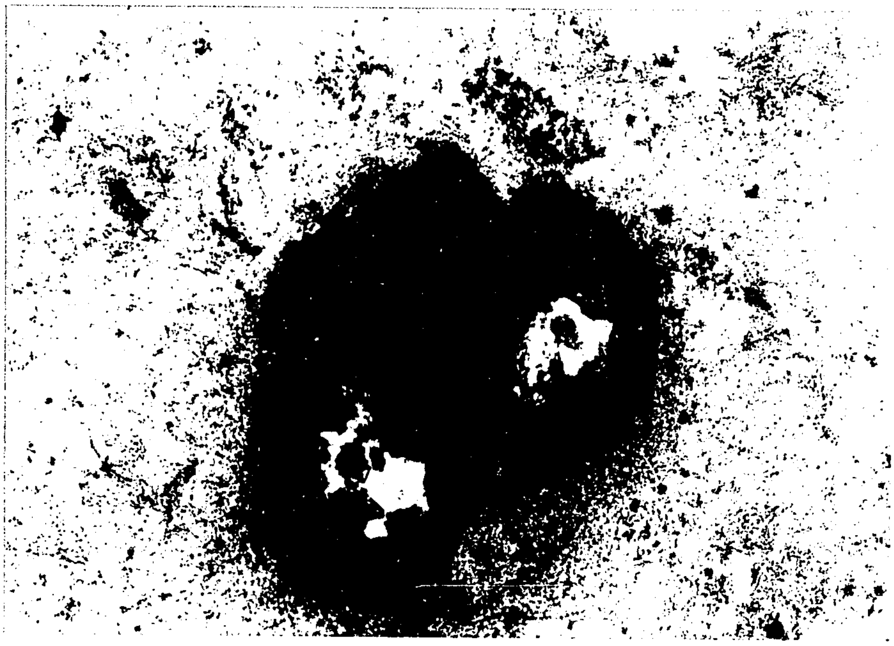


Figure 21. Photomicrograph of a cluster of anatase (and rutile?) crystals in the Deicke from the Black River Mine, Kentucky. These crystals are growing into a void, which is the white area in the center of the 2 largest grains. Horizontal field of view is 2.5 mm. Plain-polarized light.

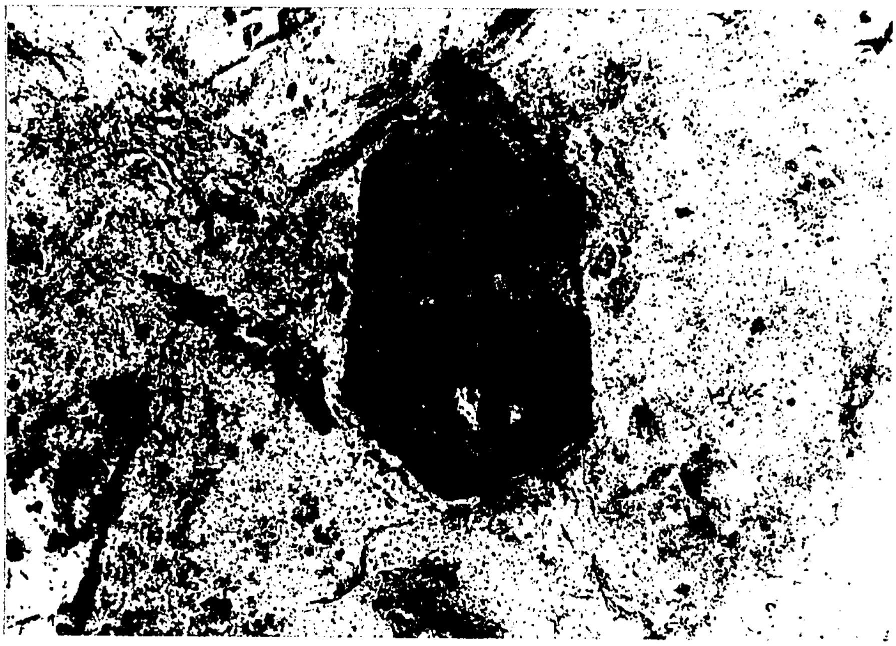


Figure 22. Photomicrograph of anatase crytals in the Deicke from Trenton, Georgia, that have almost completely replaced a euhedral ilmenite grain. In cross-polarized light, these grains are readily identified by their very high-order interference colors. Horizontal field of view is 2.5 mm. Plain-polarized light.

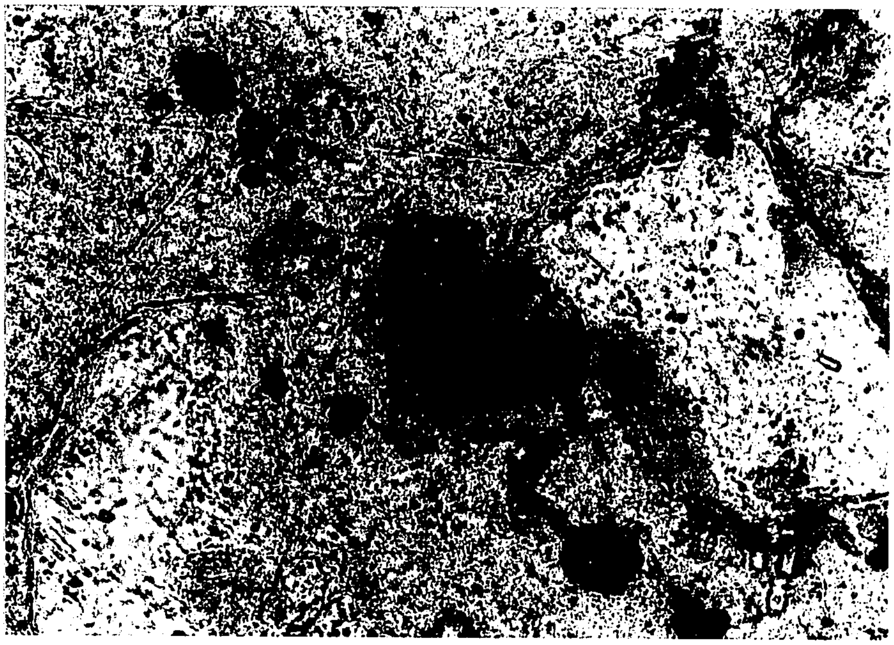


Figure 23. Photomicrograph of anatase crystals in the Deicke from a core in Gallatin County, Kentucky, that have replaced a pyroxene grain, whose euhedral outline is readily apparent. Horizontal field of view is 2.5 mm. Plain-polarized light.

lamellae in these grains, and pyrite replaces the host magnetite (Morad, 1988b). In grains of this type, the intergrown psuedomorphs are so fine-grained as to be nearly opaque in transmitted light, and are therefore best studied in reflected light.

The alteration of Fe-Ti oxides in sedimentary environments is a relatively complex process as discussed by Morad and Aldahan (1986) and Morad (1988b). The history of the Fe-Ti oxides in the Deicke is disussed further in Chapter VIII.

Pyrite is an authigenic mineral that in the Deicke occurs in several shapes, including small grains 0.1-0.3 mm long, and larger irregularly shaped void fillings that have an intricate boxwork appearance in polished samples. The small isolated grains may be pseudomorphous after magnetite. In the Millbrig, pyrite occurs in biotite grains as small cubes, < 0.1 mm long, that are commonly sandwiched by individual sheets of biotite.

Quartz

All Millbrig samples contain abundant quartz phenocrysts of the same size as the feldspars (Fig. 24). Quartz is approximately 25 percent of the phenocryst population. By comparison, Deicke samples contain less than 1 percent quartz phenocrysts. The quartz grains are subhedral to anhedral, and are unaltered, a characteristic that distinguishes quartz from K-feldspar and untwinned

Figure 24. Photomicrograph of an angular quartz phenocryst in the Millbrig from Shelbyville, Tennessee. The quartz phenocrysts in the Millbrig are characteristically angular, like this grain. Horizontal field of view is 2.5 mm. Cross-polarized light.

plagioclase. The difference in interference colors among the three minerals is the other chief distinguishing characteristic that is useful for thin-section study. There is no evidence of strain (undulatory extinction) except in a very few quartz grains in some K-bentonites from the Bays Formation in the eastern Valley and Ridge in Virginia. No overgrowths were seen.

Biotite

In hand specimens of the Millbrig, abundant coarse biotite flakes up to 1.5 mm long are the most obvious mineral. Biotite makes up approximately 30 percent of the phenocryst population in most samples of the Millbrig, and less than 1 percent of the population in the Deicke. Crystals tend to be elongated, occurring both as small slivers and larger flakes (Fig. 25). The largest phenocrysts in all samples are biotite crystals.

In core samples and samples from some of the less weathered outcrops, the biotite is very dark brown to black, and at a glance appears very unaltered. The biotites are commonly pleochroic and range in color from pale green to deep brown, but most are red-brown. In thin-sections cut parallel to bedding, the pseudohexagonal outline common to basal sections is evident in many grains (Fig. 26).

Even in samples that appear virtually unaltered, however, some chloritization has occurred, as STEM studies of biotites from the Millbrig show that chloritization is

Figure 25. Photomicrograph of a biotite phenocryst in the Millbrig from Ft. Payne, Alabama. Note the "birch-bark" texture that is characteristic of micas in thin-section. Horizontal field of view is 2.5 mm. Cross-polarized light.

Figure 26. Photomicrograph of apatite and zircon grains embedded in a biotite phenocryst in a core sample of the Millbrig from Gallatin County, Kentucky. Pleochroic halos around the zircons are readily apparent. This thin-section was cut parallel to bedding, so the euhedral outline of the biotite is clearly seen. Horizontal field of view is 2.5 mm. Plain-polarized light.

ubiquitous along individual sheets of biotite (M. Kunk, pers. comm.). In general, samples collected at outcrops are more weathered than cores, and the biotites commonly are a deep golden or bronze color rather than dark brown or black, but the grains are still readily identifiable as biotite. In samples from the Bays Formation in Virginia and Tennessee, chloritization is more extensive and the biotites are pale green flakes, but their texture clearly identifies them as altered biotites (Fig. 40).

Biotite grains, whether chloritized or not, are aligned parallel to bedding and are commonly compacted around feldspar and quartz grains (Fig. 27). This alignment presumably reflects both depositional fabric and a reorientation fabric normal to stresses during compaction and alteration of the glassy matrix. Millbrig samples from the Valley and Ridge did not show significant alignment of biotites parallel to axial plane cleavage of folds.

Microprobe analyses of several relatively unaltered biotite grains show that the MgO:FeO weight % ratio (FeO as total iron) is less than 2:1, indicating a normal composition for biotite, rather than phlogopite. Table 3 shows an analysis of several biotite grains from four samples of the Millbrig. TiO_2 values are relatively high, while MnO values are low. The samples were not analyzed for OH- or F-. Table 3 includes an analysis for a more altered biotite from the Millbrig (AL14-1). Compared with the other three analyses, the amounts of K, Mn, Fe, and Ti have

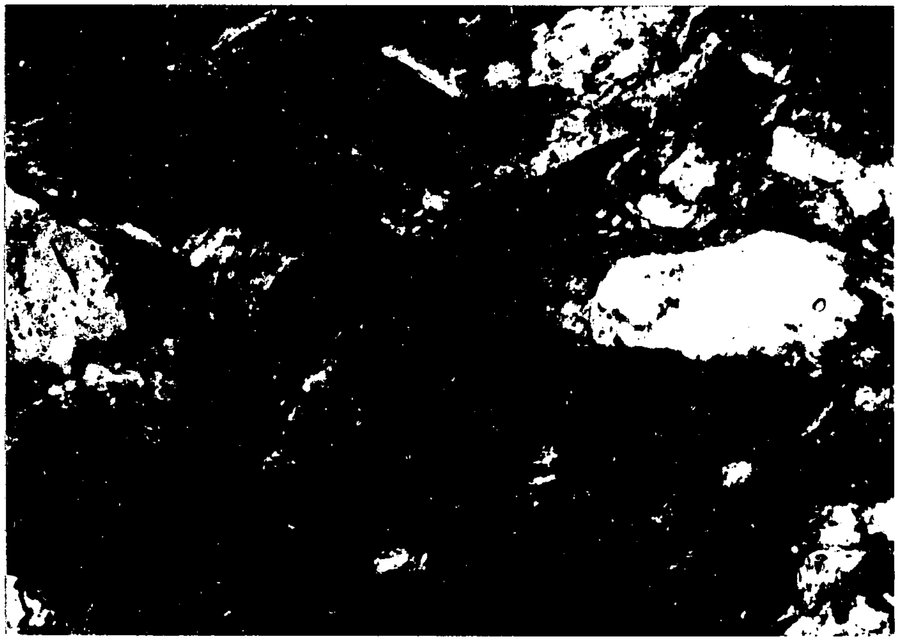


Figure 27. Photomicrograph of a biotite grain in the Millbrig from Ft. Payne, Alabama, that has been squeezed around adjacent quartz and feldspar grains. This thin-section was cut perpendicular to bedding, and it gives an idea of the amount of compaction undergone by the K-bentonites. Horizontal field of view is 2.5 mm. Cross-polarized light.

Sample	Biotite			
	BRM-T4	TN 11-1	AL 9-1	AL 14-1
	weight %			
SiO_2	35.50	36.09	35.49	36.13
TiO_2	4.07	3.60	4.25	3.05
Al_2O_3	13.94	13.59	13.97	14.28
FeO	25.70	21.56	25.12	17.75
MnO	0.43	0.46	0.36	0.00
MgO	8.18	8.77	8.57	16.14
CaO	0.01	0.00	0.01	0.18
Na_2O	0.36	0.70	0.36	0.72
K_2O	8.90	8.56	8.78	1.38
Total	97.09%	93.32%	96.91%	89.63%

Table 3. Biotite compositions as determined by microprobe analyses of 4 Millbrig samples

decreased, while Mg, Na, and Ca have increased. These changes are expected with the chloritization of biotites, although in this case the alteration is not complete, because significant amounts of K and Ti are still present. In thin-section, biotites from the Ft. Payne sample have a greenish tint along many of the cleavage planes, also suggesting that chloritization has occurred. This is not evident in hand samples, however, where the biotites appear brown.

Phillips and Griffen (1981) note that green biotite is an intermediate stage in the alteration of biotite, and the grains from the Ft. Payne sample are considered to be between unaltered biotites and these intermediate biotites. Further alteration leads to the formation of chlorite, with the total exclusion of K and decreases in the amounts of Fe and especially Ti and Mn in the crystal. When biotites are completely altered to chlorite, the Fe and Ti ions released from the biotite crystals are commonly incorporated in authigenic rutile or leucoxene and magnetite. The absence of these minerals in the Millbrig samples from Ft. Payne and other localities is another indication that chloritization of biotites has not gone to completion, as the Ti and Fe are still part of the biotite crystal structure.

Ti and Mn are only trace elements in octahedral coordination in chlorites, a contrast to their often significant octahedral component in biotites. As shown in Table 3, the marked decrease in Mn is especially apparent in the biotites analyzed from Millbrig samples, as it was not even detected in the analysis of the Ft. Payne sample.

The composition of chlorites and chloritized biotites from the Millbrig in the Bays Formation was not determined because of the inferior quality of the thin-sections and the failure of the chlorites and altered biotites to take a polish suitable for electron microprobe analysis. The noticeable green color of these grains in thin section and hand sample, however, suggests that chloritization has been more extensive in this area than farther west.

Many of the grains in samples from the Bays also exhibit a vermiform, or expanded texture, suggesting that partial alteration to vermiculite has occurred along individual sheets within a single biotite grain (Fig. 40). These grains are discussed in more detail in the "Clay Mineralogy" section.

Accessory Minerals and Shard Pseudomorphs

All Deicke and Millbrig thin-sections examined contain less than 1 percent zircon and apatite phenocrysts. They are typically euhedral, reflecting their volcanic origin. The zircons are colorless with high relief in plane light. Under crossed nicols the characteristic high-order interference color is seen. Apatite crystals are also colorless in plane light, but under crossed nicols they show a low-order interference color. Both zircons and apatites appear unaltered, as is expected from their chemical stability. These are the smallest crystals observed, with lengths ranging from less than 0.1 mm up to 0.5 mm. Both zircon and apatite commonly occur in prismatic forms with a length to width ratio of about 5 or 6 to 1 for apatites and about 3 to 1 for zircons. Apatite and zircon crystals are commonly embedded in biotite grains as shown in Figure 26. Figure 28 shows an exceptionally large euhedral zircon crystal that is nearly as large as the adjacent feldspars; most zircon grains are considerably smaller.

Other accessory minerals are calcite and gypsum, both secondary. Calcite occurs in two forms. At structurally disrupted outcrops pink to white calcite veins cut across the K-bentonites in many places. On the microscopic level, calcite commonly occurs as a replacement of primary plagioclase grains and as blebs and patches surrounded by clay. Calcite is present in Deicke samples in abundances up to 15-20 percent, but it rarely makes up more than 5 percent of Millbrig samples. This form of calcite is more common in outcrop samples than cores. It is nearly absent in samples collected from the eastern clastic belts of the Valley and Ridge, but in the western carbonate belts it is ubiquitous in samples of the Deicke.

Gypsum was observed in two thin sections of the Deicke as small clusters of blade-like, prismatic crystals with a radial habit. These clusters are growing into a void in the samples and are not replacing a pre-existing mineral.

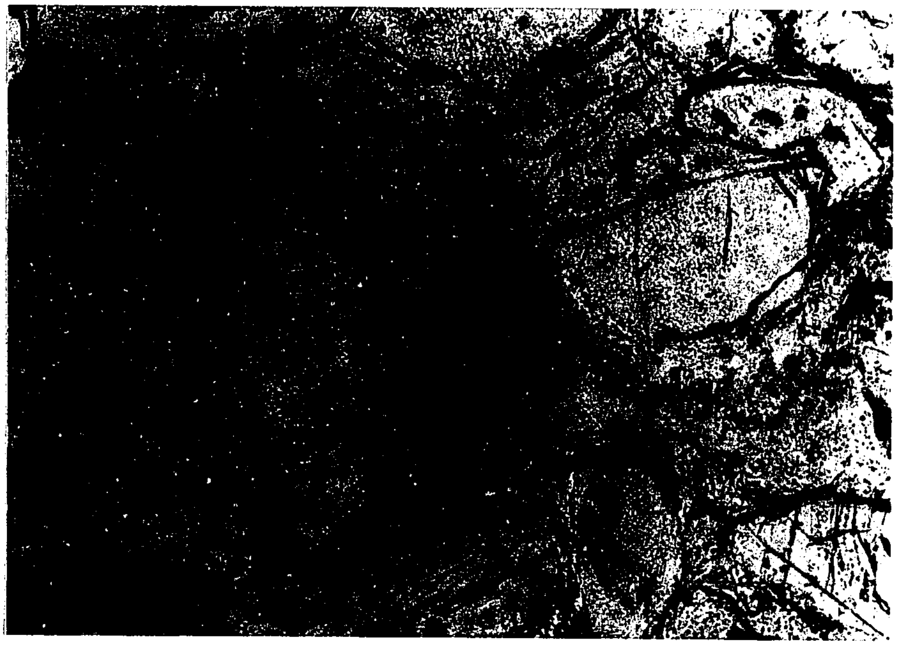


Figure 28. Photomicrograph of a large euhedral zircon grain in a core of the Deicke from Casey County, Kentucky. Note that this zircon is nearly as long as the adjacent feldspars. Most zircons in the K-bentonites are much smaller than this one. Horizontal field of view is 2.5 mm. Plain-polarized light.

Glass shard pseudomorphs are present in a 20 cm thick K-bentonite in the Bays Formation at the Catawba section (Figure 29), and in the Millbrig from the Big Walker Lookout section. The pseudomorphs are opaque in plane-polarized light except along their edges, where an orange red color is evident, suggesting that they are composed of hematite. The hematite may just be a coating on the pseudomorphed shards, but this could not be determined by thin-section study. The shard pseudomorphs are mostly less than 0.1 mm long, significantly smaller than the phenocrysts; however, this size difference is not uncommon in volcanic ash (Fisher and Schmincke, 1984).

The 20 cm thick bed at Catawba contains some biotite, and it occurs 2.5 m upsection of the biotite-rich Millbrig, which is anomalously thin, only 4 cm thick. Examination of the overlying sandstones, however, shows that they contain abundant biotite reworked from the original ash, which explains the apparent thinness of the Millbrig. Because the 20 cm thick K-bentonite occurs immediately above these tuffaceous sandstones, it may actually be a part of the Millbrig ashfall. The occurrence of shard psuedomorphs in the thick K-bentonite at the Big Walker Lookout section suggests this possibility.

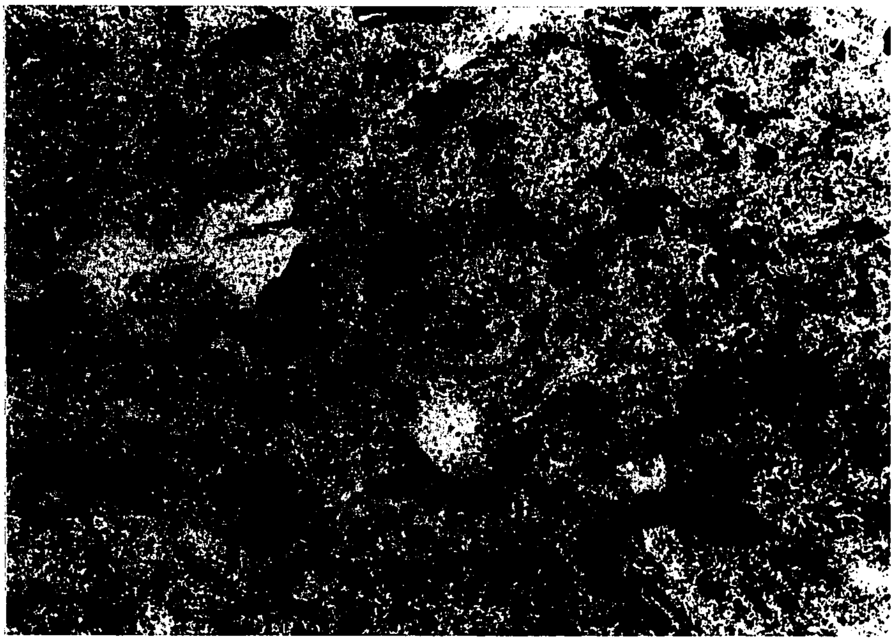


Figure 29. Photomicrograph of pseudomorphed glass shards in the Millbrig from Catawba, Virginia. Note the particularly characteristic shard shape in the center of the photo. These opaque grains are relatively small, and appear to be composed of an iron oxide. Horizontal field of view is 2.5 mm. Plane-polarized light.

Clay Mineralogy

Mixed-layer illite/smectite

In thin-section the matrix of the K-bentonites appears as a highly birefringent, microcrystalline mineral. In samples cut parallel to bedding this mineral has a roughly grid-like texture, as shown in Figures 17, 24, and 25. Phenocrysts are surrounded by the matrix, and in thin-sections cut normal to bedding it is evident that the I/S has been squeezed around feldspars, opaques, and the other relatively large non-platy grains.

Based on analysis of X-ray diffraction patterns as discussed below, the matrix is identified as mixed-layer illite/ smectite (I/S) clay, which is commonly found in Paleozoic K-bentonites (Huff, 1963; Lounsbury and Melhorn, 1964; Hergenroder, 1966; Huff and Turkmenoglu, 1981; Huff et al., 1988). Identification of the clay as mixed-layer I/S is based on the positions of the 00*l* reflections on powder X-ray diffraction (XRD) patterns. The clays in the Deicke and Millbrig along the Cincinnati Arch have been investigated in many previous studies, so all but 5 X-ray diffraction analyses were of samples from the Valley and Ridge, where the clays of the K-bentonites have not been studied in much detail. XRD patterns were produced by X-ray analysis of oriented and glycol-solvated mounts of the < 2.0 μm size fraction of selected Deicke and Millbrig samples, 2 samples of bed V-7, and 5 other K-bentonites. The results of these analyses are presented in Table 4.

SAMPLE	Peak Position (°2ΘCuKα)						Δd_1	Δd2	Δ2Θ_2 in degrees 2Θ	BB1	BB2	% Smectite from Figure: 29	30a	30b	Ordering from Figure: 31a	31b	31c	31d
DEICKE Cincinnati Arch (= □)																		
BB5-5-1	6.898	9.173	16.869	26.648	44.639	46.570	2.275	1.931	7.696	>4	>4	19	23	28	R1	R1	R1	R1
Valley and Ridge: carbonate sections (= O)																		
AL 7	7.087	8.926	17.148	26.705	45.174	--	1.839	--	8.222	>4	<4	8	12	18	--	R1/R3	R1/R3	R1/R2
GA:DD 2-1	7.433	9.030	17.198	26.711	45.055	--	1.597	--	8.168	>4	>4	12	13	15	--	R1/R3	R1/R3	R3
TN:CL 1-1	--	8.769	17.386	26.689	45.285	--	<1	--	8.617	<4	<4	4	5	12	--	R3	R3	R3
VA:SC 1-1	--	8.666	17.480	26.514	44.998	--	<1	--	8.714	<4	--	11	5	9	--	R3	R3	R3
VA:RL 2-1	6.990	9.036	17.009	26.573	44.896	--	2.046	--	7.973	>4	>4	12	17	21	--	R1/R3	R1/R3	R1/R2
VA:TZ 1-7	--	8.744	17.261	26.549	45.059	--	<1	--	8.517	<4	--	10	8	13	--	R3	R3	R3
VA:BL 1-1	--	8.768	17.426	26.634	45.202	--	<1	--	8.658	<4	--	7	5	12	--	R3	R3	R3
VA:GI 4-0	--	8.815	17.404	26.654	45.245	--	<1	--	8.589	<4	--	5	5	12	--	R3	R3	R3
Valley and Ridge: Colvin Mountain Sandstone sections (= ●)																		
AL:CH 1-2	7.445	9.102	17.100	26.654	44.916	--	1.657	--	7.998	>4	>4	15	14	17	--	R3	R1/R3	R2/R3
AL:ET 1-2	--	8.771	17.694	26.700	45.454	--	<1	--	8.923	<4	--	5	2	illite	--	R3	R3	R3
MILLBRIG Cincinnati Arch (= □)																		
BB 5-2-3	6.910	8.936	16.983	26.671	44.672	46.227	2.026	1.555	8.047	>4	>4	18	19	24	R1	R1	R1	R1
KRI 5-0	6.784	9.183	16.897	26.606	44.330	46.595	2.399	2.265	7.714	>4	>4	25	21	26	R1	R1	R1	R1
TN 7-3	6.791	9.362	16.791	26.572	44.394	46.576	2.571	2.182	7.429	>4	>4	22	24	29	R1	R1	R1	R1
TN 7-4	6.816	9.080	16.814	26.505	44.380	46.971	2.264	2.591	7.734	>4	>4	18	21	27	R1	R1	R1	R1

TABLE 4. Peak positions and indicator parameters used to identify the nature of the mixed-layer I/S in selected samples

SAMPLE	Peak Position (°2ΘCuKα)						Δd_1	Δd2	$\Delta 2\Theta_2$ in degrees 2Θ	BB1	BB2	% smectite from Figure: 29	30a	30b	Ordering from Figure: 31a	31b	31c	31d
Valley and Ridge: carbonate sections (= O)																		
GA:DD 2-2	--	9.214	16.833	26.655	44.686	46.608	--	2.118	7.619	--	>4	18	24	29	R1	--	--	--
GA:WL 3-2	7.541	8.829	17.172	26.646	44.971	--	1.288	--	8.343	<4	--	12	12	16	--	R3	R1/R3	R3
TN:CL 1-2	7.224	8.817	17.201	26.614	45.223	--	1.593	--	8.384	<4	<4	9	12	14	--	R3	R1/R3	R2/R3
VA 4-1	7.027	9.050	17.138	26.597	44.966	--	2.023	--	8.088	>4	--	13	13	15	--	R1/R3	R1/R3	R1/R2
VA:LE 1-2	--	8.543	17.284	26.673	44.663	--	<1	--	8.741	--	>4	17	10	13	--	R3	R3	R3
VA:SC 1-2	--	8.785	17.287	26.662	45.115	--	<1	--	8.502	<4	--	8	10	13	--	R3	R3	R3
VA:BL 2-1	6.869	9.116	16.994	26.548	44.736	--	2.247	--	7.878	>4	--	18	16	20	--	R1/R3	R1	R1
VA:GI 1-1	--	8.741	17.450	26.551	45.198	--	<1	--	8.709	<4	--	6	3	9	--	R3	R3	R3
Valley and Ridge: Colvin Mountain Sandstone and Bays Formation sections (= ●)																		
AL:CH 1-4	7.400	9.150	16.849	26.495	44.731	46.091	1.750	1.360	7.699	<4	--	15	21	26	R1/R3	R3	R1/R3	R3
GA:FL 1-1	--	8.775	17.535	26.662	45.425	--	<1	--	8.760	<4	--	7	2	7	--	R3	R3	R3
VA:SM 1-4	7.536	9.022	17.212	26.610	44.897	--	1.486	--	8.190	<4	--	12	10	15	--	R3	R1/R3	R3
VA:WY 2-1	7.646	8.920	17.224	26.646	45.064	--	1.244	--	8.304	<4	<4	11	10	15	--	R3	R1/R3	R3
VA:WY 1-1	--	8.740	17.588	26.607	45.267	--	<1	--	8.848	<4	--	5	3	illite	--	R3	R3	R3
VA:RO 1-3	7.600	9.032	17.118	26.662	44.810	--	1.432	--	8.086	<4	--	13	16	18	--	R3	R1/R3	R2/R3
VA:BT 2-1	7.710	8.715	17.131	26.663	45.289	--	1.005	--	8.416	<4	--	5	12	16	--	R3	R1/R3	R3
V-7 Carbonate section (= O)																		
VA:TZ 2-3	--	8.702	17.160	26.531	44.717	--	<1	--	8.458	<4	--	13	13	15	--	R3	R3	R3

TABLE 4. (Cont'd) Peak positions and indicator parameters used to identify the nature of the mixed-layer I/S in selected samples

SAMPLE	Peak Position (°2ΘCuKα)						Δd_1	Δd2	$\Delta 2\Theta_2$ in degrees 2Θ	BB1	BB2	% smectite from Figure: 29	30a	30b	Ordering from Figure: 31a	31b	31c	31d
Bays Formation sections (= ●)																		
VA:RO 1-2	7.671	8.960	17.176	26.615	44.883	--	1.289	--	8.216	<4	<4	13	12	16	--	R3	R1/R3	R3
VA:BT 2-2	7.600	8.849	17.536	26.662	45.420	--	1.249	--	8.687	<4	--	7	3	7	--	R3	R1/R3	R3
OTHER K-BENTONITES																		
Valley and Ridge: carbonate sections (= O)																		
AL:ET 2-4	7.177	8.922	16.948	26.646	44.930	--	1.745	--	8.026	>4	--	13	18	22	--	R1/R3	R1/R3	R1/R2
AL:ET 2-5	7.003	8.797	17.287	26.653	45.293	--	1.794	--	8.490	>4	--	6	9	13	--	R1/R3	R1/R3	R1
GA:WL 3-3	7.415	8.769	17.210	26.641	45.173	--	1.354	--	8.441	>4	--	10	12	15	--	R3	R1/R3	R2/R3

TABLE 4. (Cont'd) Peak positions and indicator parameters used to identify the nature of the mixed-layer I/S in selected samples

I/S ordering is an important parameter that is an indication of the illite:smectite ratio. C-axis ordering is a function of the ratio of illite layers to smectite layers, and the arrangement of these layers relative to each other in the phyllosilicate crystal structure (Reynolds and Hower, 1970; Reynolds, 1980). There are 3 or 4 different types of ordering: 1) random or R0 ordering, 2) short-range or R1 ordering, and 3) long-range or R3 ordering (Reynolds, 1980). "R" stands for "Reichweite" number, as discussed by Reynolds and Hower. An intermediate long-range ordering known as ISI or R2 ordering has also been reported by Reynolds (1980), which is referred to by Srodon et al. (1986) as R1/R3 ordering. Because Srodon's graphical methods are used in the present research to determine the type of ordering, R1, R1/R3, and R3 are the terms used except as noted for Figure 36.

Determination of the ordering gives a practical estimate of the I/S component ratio; R0 ordered samples contain 10 to 50 percent illite, R1 ordered samples contain 50-85 percent illite, and R3 ordered samples contain > 85 percent illite.

Using the techniques of Srodon (1980, 1984), which have been summarized by Srodon and Eberl (1986), the nature of the I/S interstratifications was determined by interpretation of gylcolated XRD patterns of the < 2 μm clay fraction. Table 4 lists the peak positions as determined from the XRD tracings, the Δd_1, Δd_2, $\Delta 2\Theta_2$, BB1, and BB2 values as determined using techniques discussed by Srodon (1980) and Srodon and Eberl (1986), and the % smectite and ordering of the analyzed samples as determined graphically using various plots of Srodon (1980, 1984). The values in this table were used in plotting points on Figures 30 through 36.

Even samples that may appear to be nearly pure illite based on peak positions may contain a small expandable component, however, as shown by the following indicators that appear with glycolation of mixed-layer I/S, but not with pure illite (Srodon and Eberl, 1986):

1) the 001 reflection is more asymmetric and has a shoulder on the low-angle side;

2) the 001 reflection is displaced to a higher angle, and the 002 reflection is displaced to a lower angle;

3) the intensity of the 001 reflection decreases relative to 003, which is typically the strongest peak. Figure 38 shows the XRD pattern for a Millbrig sample from the Bays Formation that contains < 10% smectite; the diffraction tracing pattern is very similar to that obtained with pure illite.

All 3 methods described by Srodon (1980) to interpret I/S XRD patterns were followed, taking into account where possible the differences in sample preparation of the present research. The major difference was that Srodon studied the < 1 μm and 0.2 μm fractions of clays, whereas only the < 2μm fraction of the Deicke and Millbrig were studied. Also, the determination of the proper thickness of the ethylene glycol-smectite layer using Srodon's iterative methods was difficult because of the highly illitic compositions of these samples. With so little smectite, there is a single peak around 45.05° to 45.25° 2Θ, rather than 2 peaks between 42° and 48° 2Θ, which are used for identification of samples with greater percentages of smectite.

With these differences noted, then, the first step was to plot the peak between 42°-45° or 45°-48° 2Θ against the peak between 26°-27° 2Θ as shown in Figure 30, giving a first approximation of the illite:smectite ratio, and thus the ordering of the I/S interstratification. According to Srodon (1980), the values for % smectite obtained using these peaks are slightly affected by the domain size of the individual clay particles, and are strongly affected by the manner of interstratification and ethylene glycol-smectite layer thickness. This plot indicates that most samples contain smectite with expanded dimensions between 16.9-17.2 A thick and the Cincinnati Arch samples contain a significantly higher smectite component than Valley and Ridge samples. These findings agree with those of Elliott and Aronson (1987), who reported I/S compositions for several Deicke and Millbrig samples from the Cincinnati Arch and the Valley and Ridge.

Almost all samples from the Valley and Ridge contain less than 20% smectite, with some plotting very close to

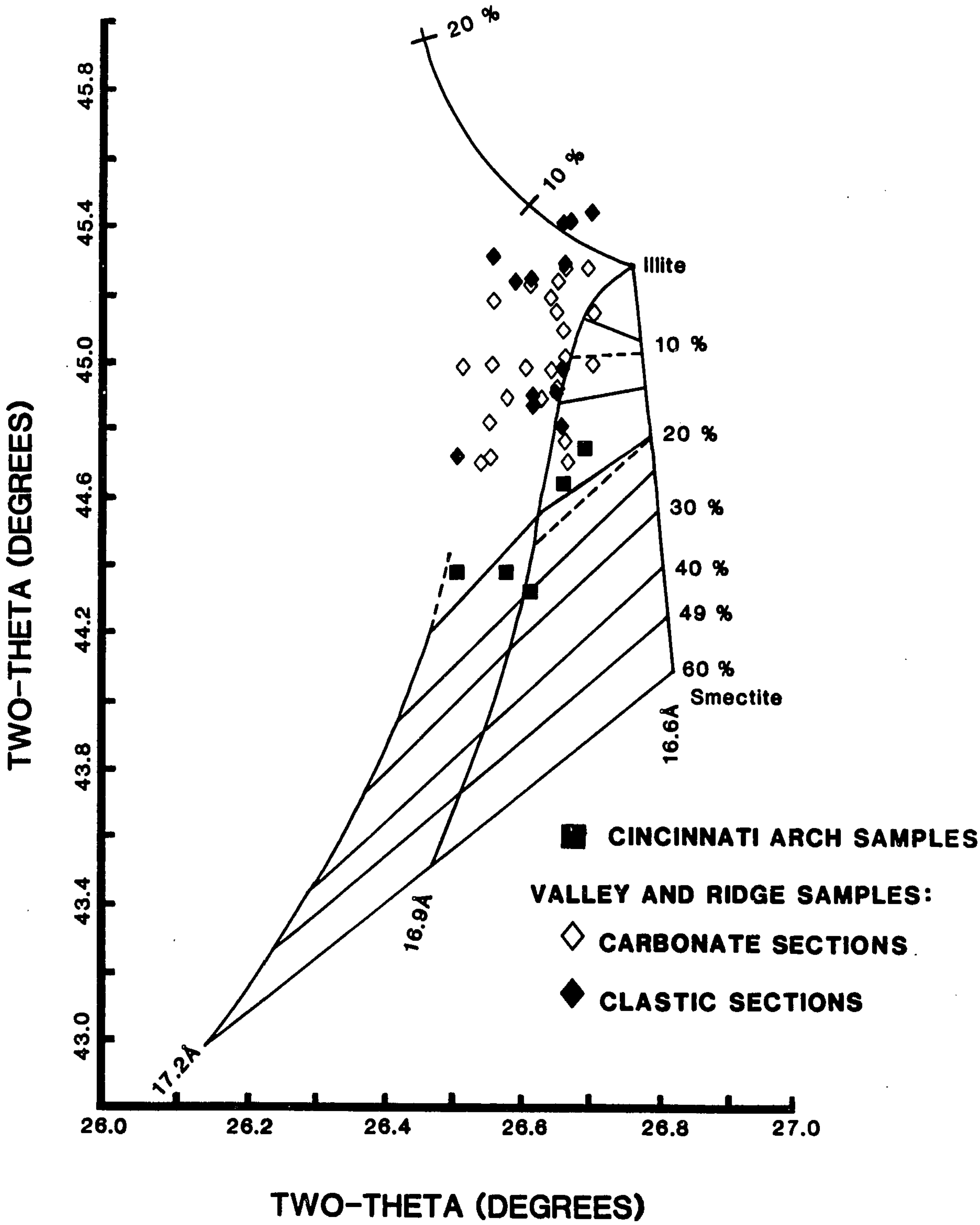


Figure 30. 2-theta values from Table 4 plotted on a graph developed by Srodon (1980) to determine the percent smectite in a given I/S sample. The Cincinnati Arch samples contain more smectite than the Valley and Ridge samples, which are divided into samples from the clastic and carbonate sections.

pure illite. It is evident that these samples are compositionally very close to where the change between R1 and R3 ordering occurs. Also, note that a given sample from a clastic sequence along the eastern Valley and Ridge contains a lower smectite component than an equivalent sample from the carbonate sections to the west, and that samples from Virginia overall contain less smectite than samples from southeast Tennessee, Georgia, and Alabama. Samples from the Bays Formation in Virginia and the Eggleston Formation in the New River Valley contain the least smectite of any samples.

An second interpretation of the illite:smectite ratio is obtained by plotting the strong 15.4°-17.7° 2Θ peak against the 26°-27° 2Θ peak as shown in Figures 31 and 32. These two graphs are shown because there are significant variations between them. They are based on graphs in two papers by Srodon (1980; 1984) and it was desirable to check one against the other. Values for % smectite obtained from Figure 31 (Srodon, 1980) are uniformly lower by about 2-5% than those obtained from Figure 32 (Srodon, 1984), an important difference. In addition, Figure 32 does not show the field for samples with thicknesses between 16.9-17.2 A, whereas Figure 31 includes that field, which is where most of the samples from the present research plotted. The values obtained from plots using these particular peaks are strongly affected by the manner of interstratification and ethylene glycol-smectite layer thickness as well as domain

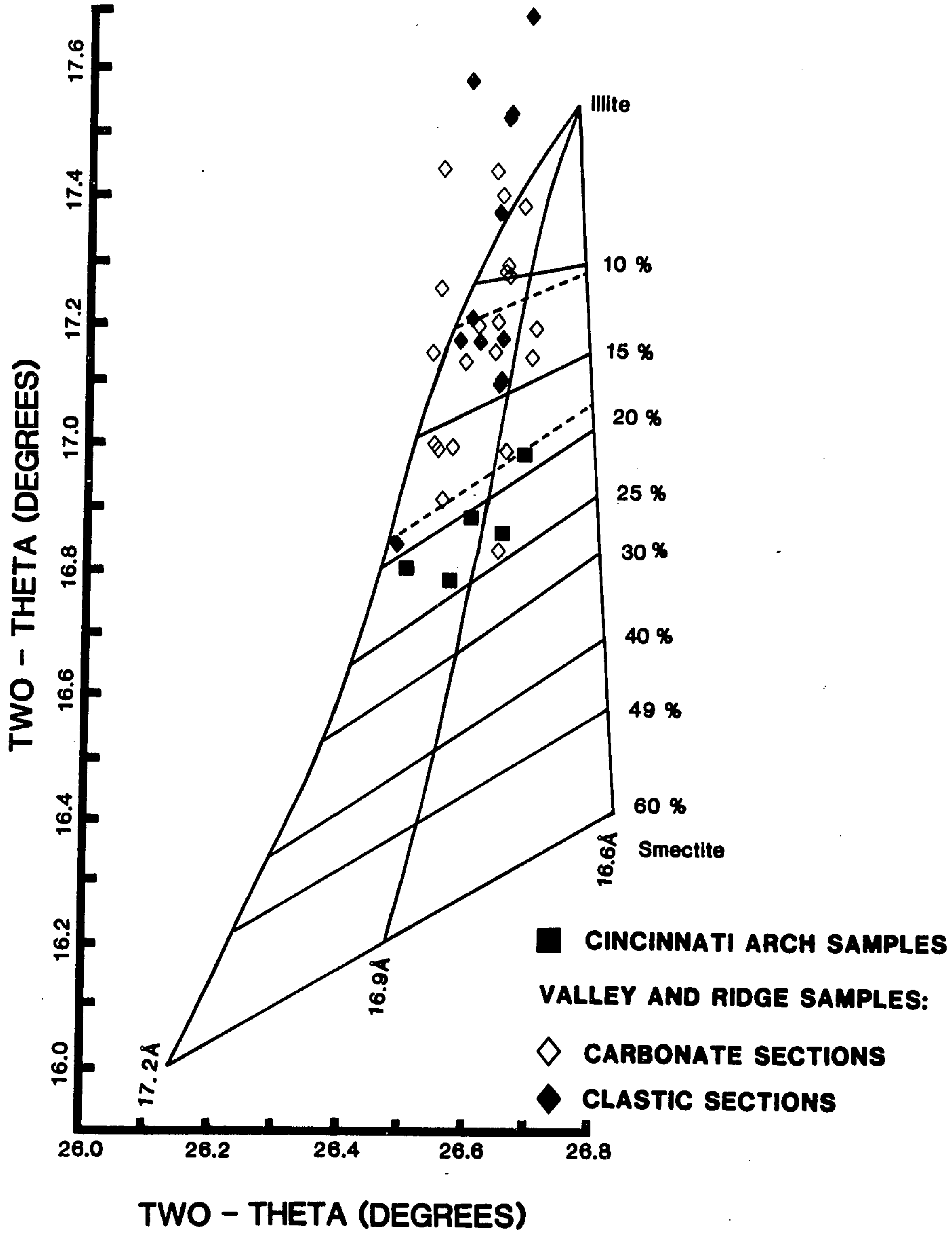


Figure 31. 2-theta values from Table 4 plotted on an alternate graph developed by Srodon (1980) to determine the percent smectite in a given I/S sample. The trends are the same as those in Figure 30.

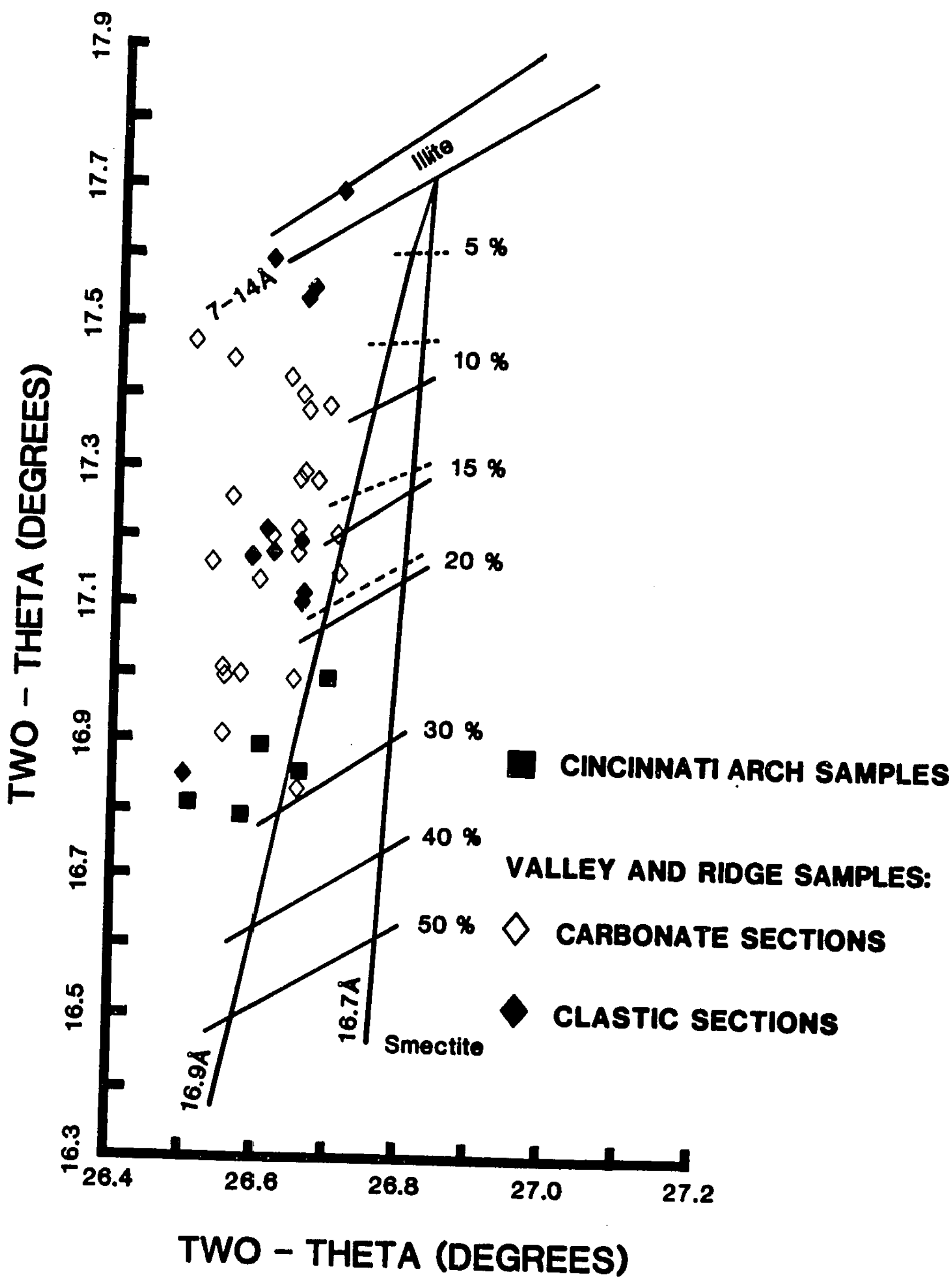


Figure 32. 2-theta values from Table 4 plotted on a modified version of Figure 31, as developed by Srodon (1984). Note that the percent smectite given by this graph is uniformly about 5 percent higher than that for Figure 31.

size (Srodon, 1980), unlike values obtained from the peaks used in Figure 30.

These two graphs indicate that some of the Cincinnati Arch samples contain almost 30% smectite, and that the Valley and Ridge samples range from < 10% to around 25% smectite. Two Millbrig samples from the Valley and Ridge, one from the Carters Limestone in northwest Georgia (GA:DD 2-2), and one from the Colvin Mountain Sandstone in Alabama (AL:CH 1-4), plot among the Cincinnati Arch samples. Sample GA:DD 2-2 is from Dade County, Georgia, which lies astride the boundary between the Valley and Ridge and the Cumberland Plateau. This area, being on the western edge of the Valley and Ridge and in an area where the post-Ordovician overburden is less than in many other areas, may have been less deeply buried than most areas of the Valley and Ridge. Therefore the I/S would be expected to be somewhat more similar compositionally to samples from the Cincinnati Arch. The connection between I/S composition, specifically the % of smectite in a sample, and depth of burial is discussed in more detail in Chapter VIII. The anomalously high smectite component, 15-25 % (depending on whether Figure 30, 31, or 32 is used), observed in sample AL:CH 1-4 is not readily explained, as the Millbrig and Deicke in sections farther west in carbonate sequences, contain only 8-10 % smectite (Elliott and Aronson, 1987). And, other samples from the Colvin Mountain Sandstone (AL:CH 1-2, AL:ET 1-2, and GA:FL 1-1) contain 10-15 % less smectite.

Once the first estimate of % smectite is obtained from these graphs, another set of parameters can be used to obtain a more precise estimate of the ordering in the samples. Figures 33 through 36 are 4 separate graphs with points plotted for the samples.

Figure 33 uses a parameter termed Δd_2 by Srodon (1980), which is the difference in degrees 2Θ of the 2 reflections between 42° and 48°. This value is used to give a range of smectite content, and it could be determined only for samples from along the Cincinnati Arch, as the others contained too little smectite for separation into 2 distinct peaks in this interval to occur. Although this is the preferred method for determining the nature of the I/S interstratification because Δd_2 is independent of domain size and is only slightly affected by the ethylene glycol-smectite layer thickness (Srodon, 1980), it was unfortunately not useful for most samples from the Valley and Ridge, which is where the clays in these K-bentonites have been studied least. The five samples from the Cincinnati Arch, and samples GA:DD 2-2 and AL:CH 1-4 discussed above could all be plotted in Figure 33 because two peaks between 42° and 48°2Θ could be discerned from the XRD tracings for these samples. This is another indicator of a relatively higher smectite component than in other samples from the Valley and Ridge, because the peak between 42°-45°2Θ is weakly developed when little smectite is present, and when the thickness of the ethylene glycol-

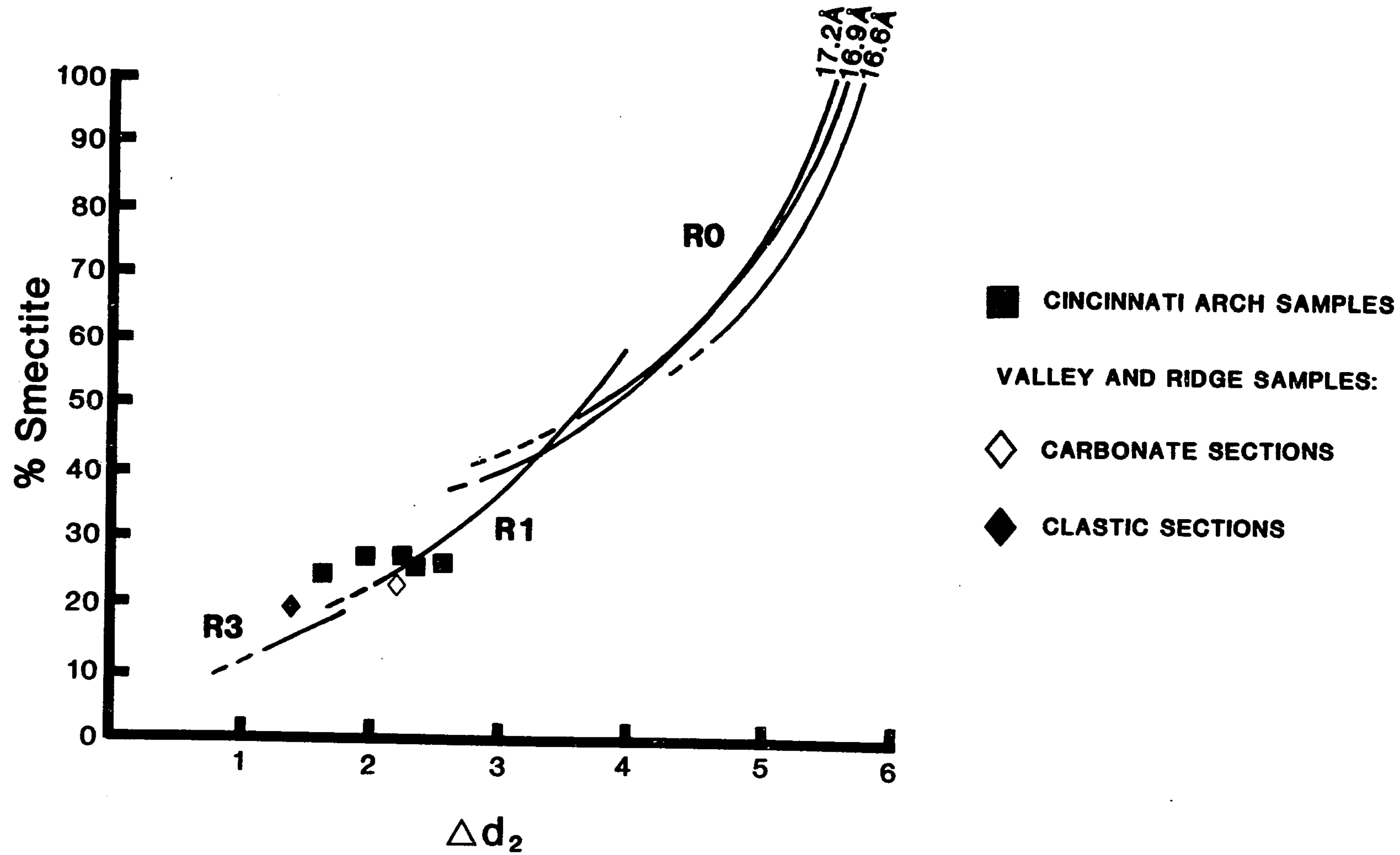


Figure 33. First plot for determing the ordering of a given I/S sample using parameters given in Table 4 and as discussed in the text.

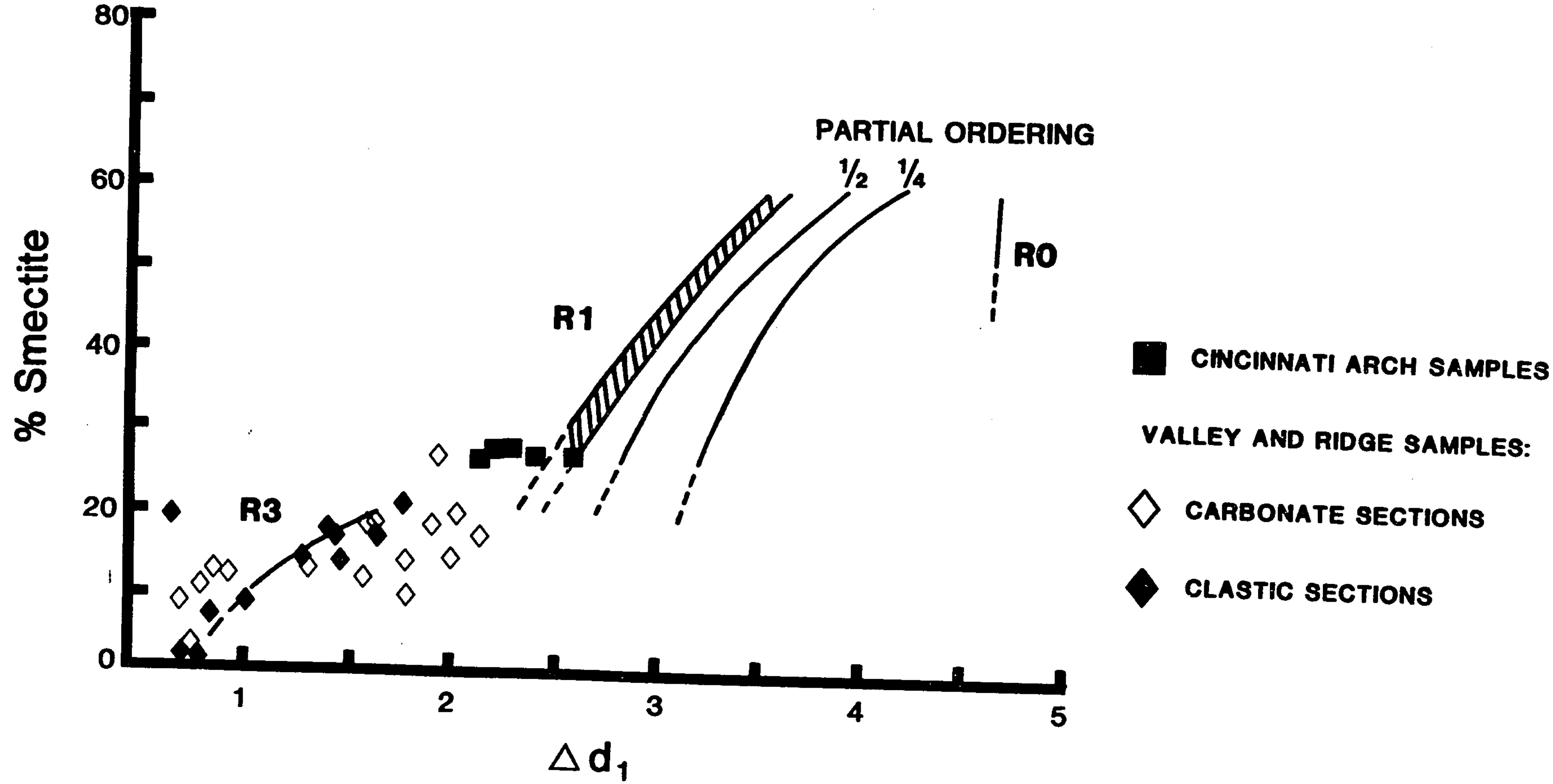


Figure 34. Second plot for determining the ordering of a given I/S sample using parameters from Table 4.

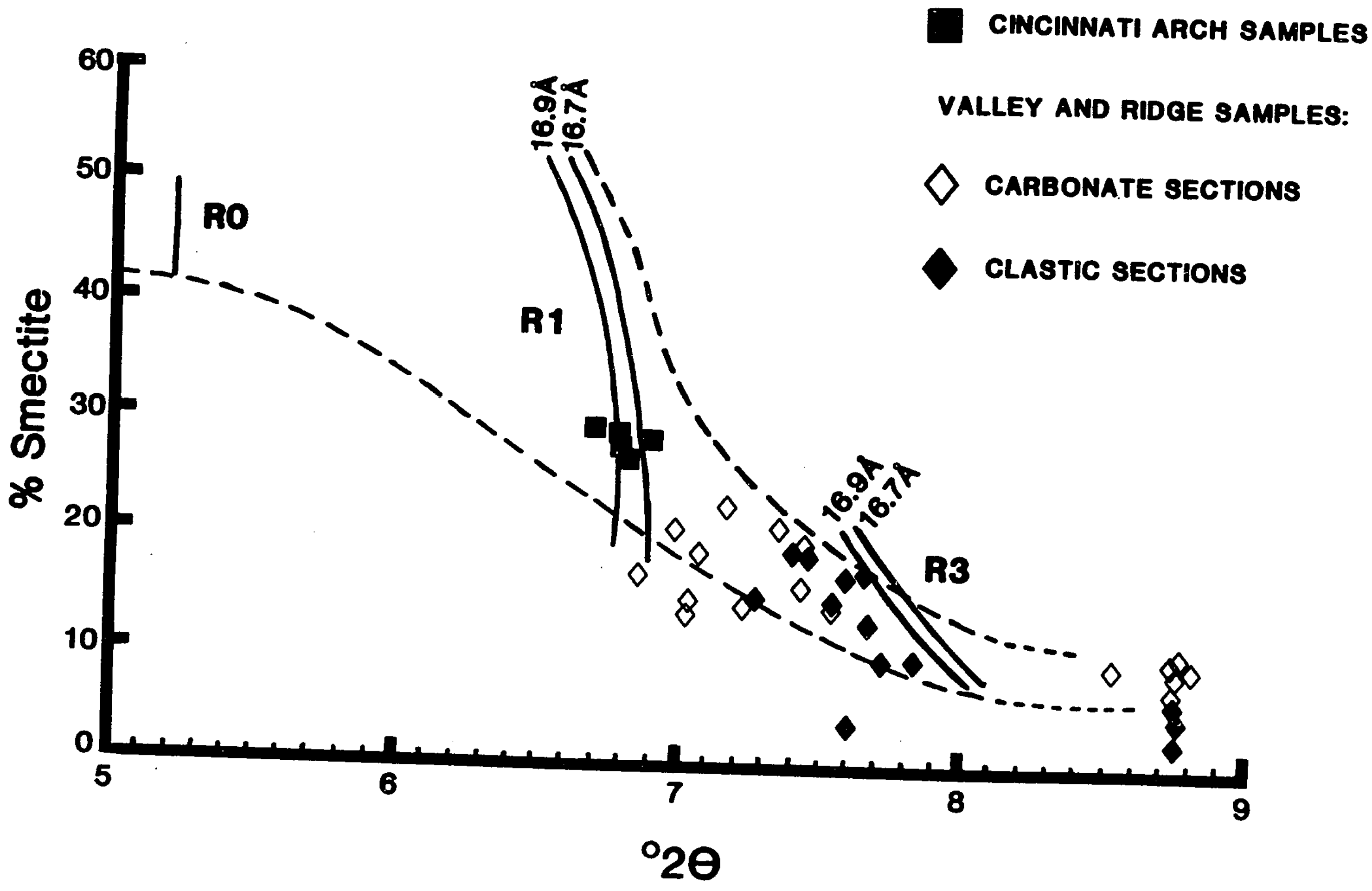


Figure 35. Third plot for determining the ordering of a given I/S sample. Note that ordering increases from the Cincinnati Arch samples to the Valley and Ridge. The cluster of samples at about 8.8°2Θ are all from Virginia, where samples with the longest-range ordering were found to occur.

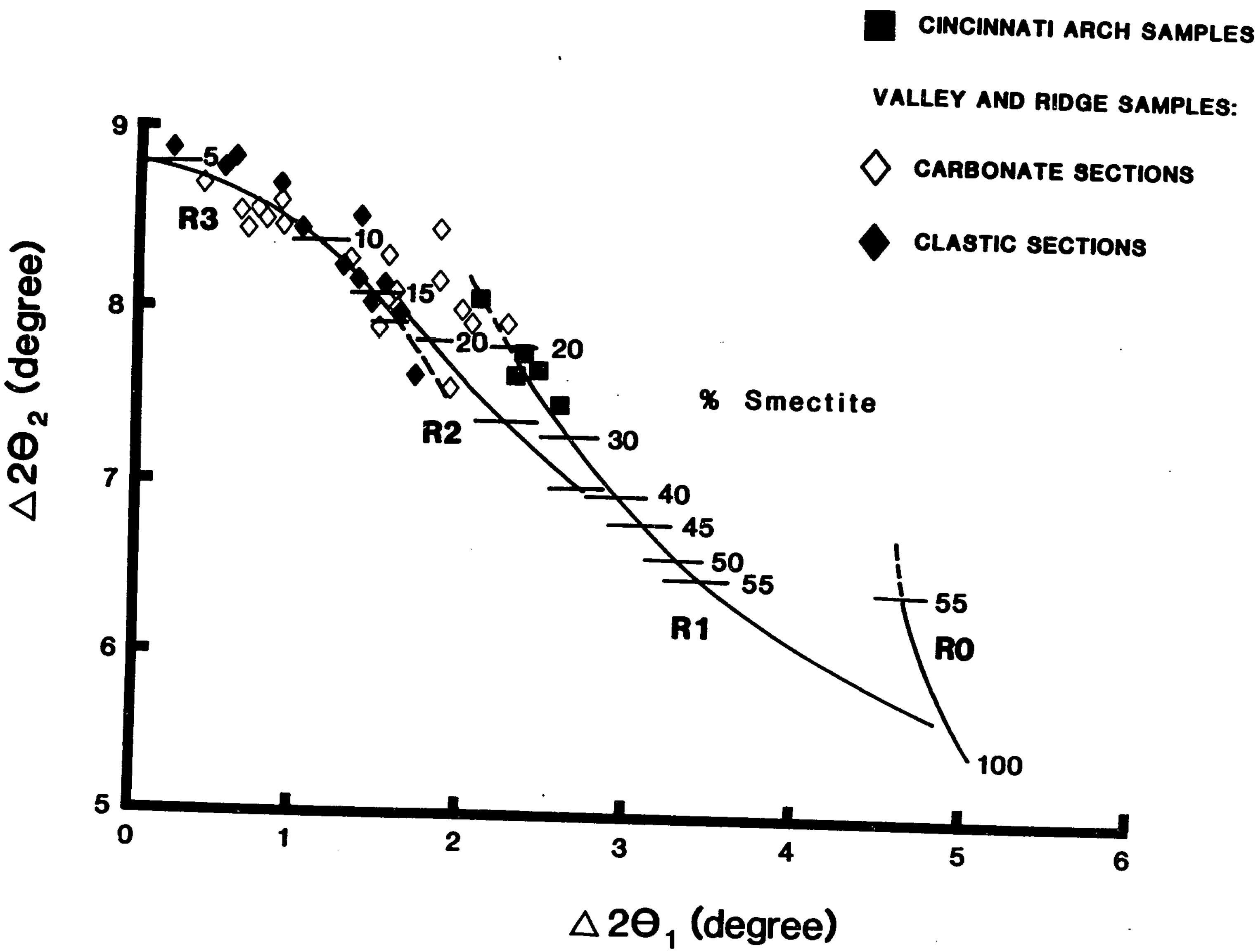


Figure 36. Fourth plot for determining I/S ordering.

smectite complex is 17.2 A. Judging from the distribution of points in Figures 29 and 30, many of the Valley and Ridge samples are composed of an approximately 17.2 A-thick complex, and the low smectite values are also substantiated by these figures.

The second parameter used is Δd_1 of Srodon (1980), which is the difference in degrees 2Θ of the 2 reflections between 5.2°-8.2°2Θ and 8.8°-10.4°2Θ. This is also used to obtain an approximation of the degree of ordering and a range of smectite content, as shown in Figure 34. Unlike Δd_2, Δd_1 can be determined for many samples from the Valley and Ridge. It is evident that many of these samples contain a mixture of R1 and R3 ordering, and some are probably R1/R3 ordered, while others are solely R3 ordered.

A third method of determining ordering is shown in Figure 35, where the reflection between 5.2°-8.0°2Θ is plotted against % smectite (as determined initially from Figures 30 and 31) to determine the ordering. Again, the samples are a mixture of R1, R1/R3, and R3 ordering. In addition, several samples plotted to the right of the R3 field; XRD tracings of these samples all contained only a single peak between 6° and 10°2Θ. The peaks all have a 2Θ value close to 8.75°, which gives a d-spacing of 10.1, the value for the 001 illite peak. Therefore, these samples contain so little smectite that, using this plot, the ordering cannot be determined. Using the low-angle reflection as required by Figure 35 is probably the least reliable method to determine the ordering of an I/S sample with less than 10 % smectite.

Figure 36 shows the points plotted on a fourth graph. This particular graph was not developed by Srodon, but by Watanabe (1981); Srodon and Eberl (1986) modified the graph, however, to include a curve for R3 ordering, where the original graph contained curves for only random, R1, and R2 ordering. The values plotted on this graph are 2 parameters referred to as $\Delta 2\Theta_1$ and $\Delta 2\Theta_2$ by Srodon and Eberl (1986), which are the differences in degrees 2Θ between the 001 illite reflection and the adjacent I/S reflection, and between this I/S reflection and the 002 illite reflection, respectively. The value of $\Delta 2\Theta_1$ is the same as that for Δd_1, and they are recorded under that term in Table 4. This plot also indicates that the samples studied are R1 and R3 ordered, and there is in fact less scatter about the curves defining R1 and R3 ordering than in Figures 33, 34, or 35. This suggests that perhaps the comparison of the $\Delta 2\Theta_2$ values is the best method for determining ordering in I/S samples containing relatively little smectite, as these K-bentonites do.

As shown in Figure 35, and discussed above, the low angle peak from several of the Valley and Ridge samples is higher than 8.2° 2Θ, which is where Srodon's original figure ended. Because these samples plot in "uncharted territory", an alternate method to determine ordering in samples with a very small expandable content can be used. This method uses parameters called BB1 and BB2 (Srodon, 1984), which are defined as

> "...the joint breadth of the 001 (BB1) or 004 (BB2) illite and adjacent I/S reflections, measured in degrees 2Θ from where the tails of the peaks join the X-ray background. The BB parameters are independent of the illite:I/S ratio and change abruptly when the type of ordering changes. If a BB parameter is > 4°, then [R1] ordering is present; if it is < 4°, then the I/S is [R3] ordered, and expandability is approximately 15 %."

Obviously the BB parameters must be calculated from the XRD patterns themselves, and Figure 37 shows an example of how this is done. With many of the patterns, one of the BB parameters could not be measured because of weak reflections, but in all cases the other one could be measured. Ordering for the samples as determined from these parameters is shown in Table 4.

Figure 38 shows XRD patterns for Millbrig samples from the Tyrone Limestone of the Cincinnati Arch in Kentucky, the Eggleston Formation in the western Valley and Ridge of Virginia, and the Bays Formation in the eastern Valley and Ridge of Virginia. The change in ordering from R1 or R1/R3 to R3 to the southeast is evident. The peak pattern for the easternmost sample, VA:WY1-1, indicates that there is > 90 percent illite because the 001 and 002 peaks are only slightly asymmetric, with a very weak shoulder on the low angle side of the 001 peak and on the high angle side of the 002 peak.

Figure 39 shows XRD patterns for the Millbrig in the Carters Limestone from the Central Basin in Tennessee and the northwestern

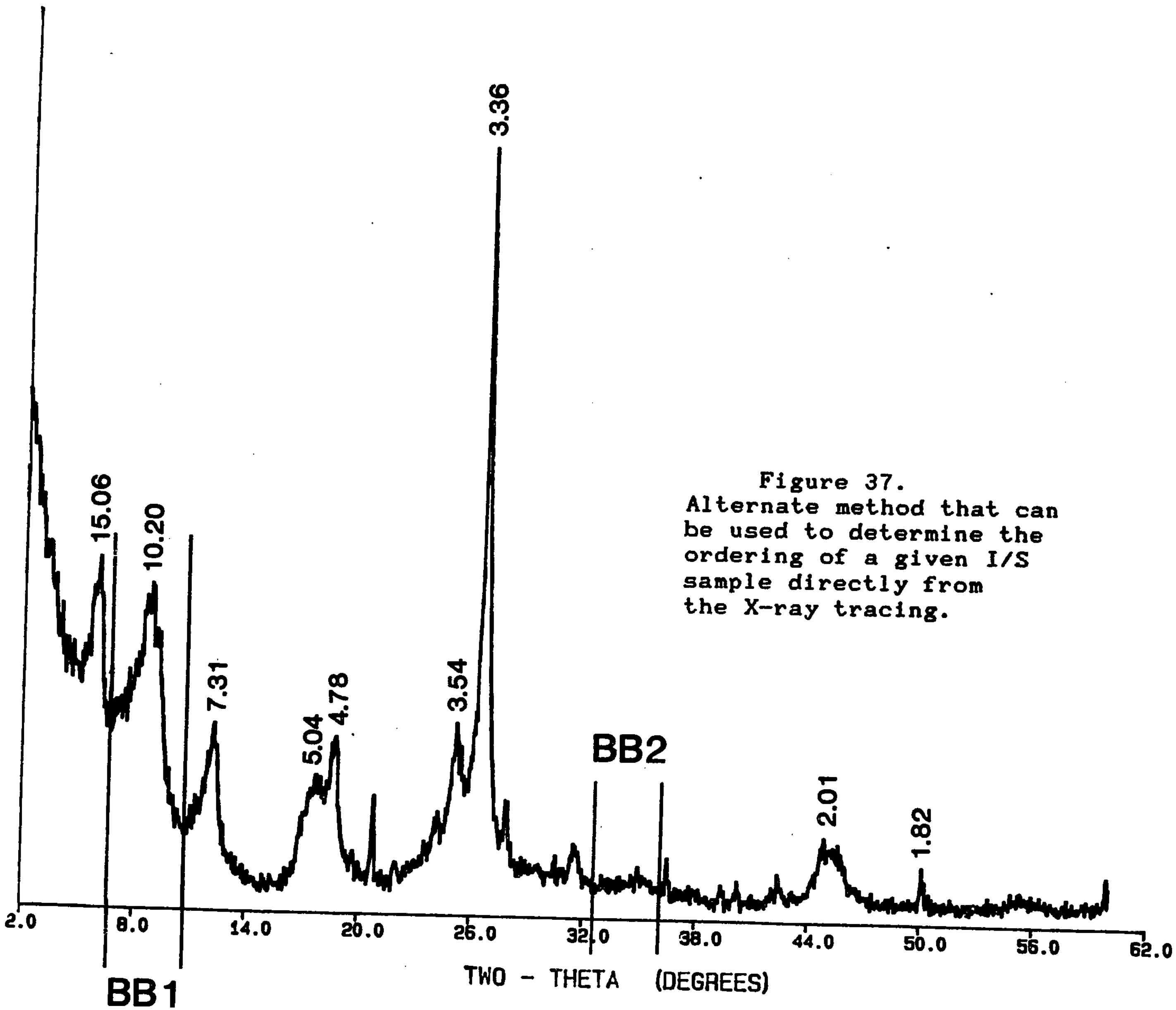
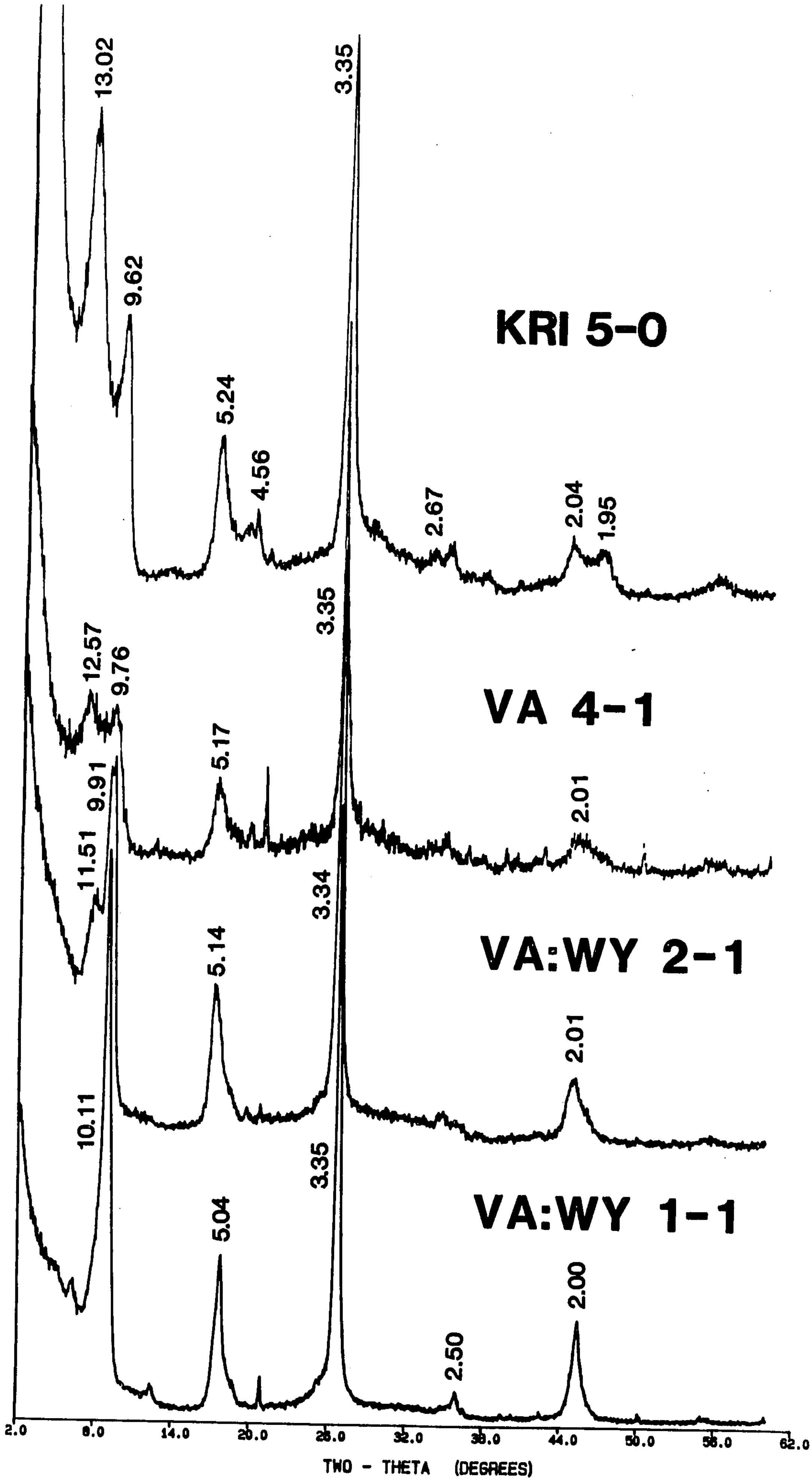


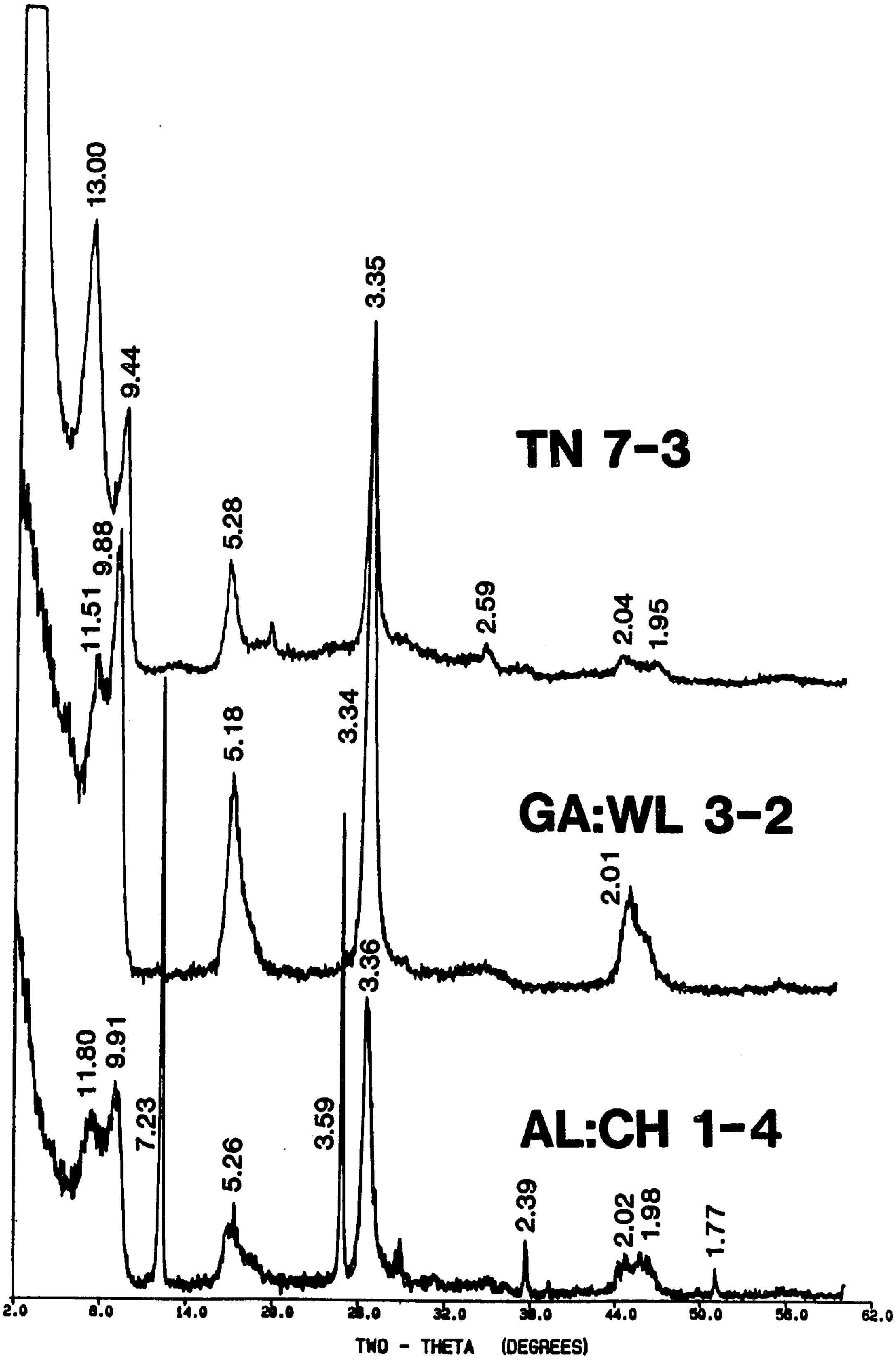
Figure 37.
Alternate method that can be used to determine the ordering of a given I/S sample directly from the X-ray tracing.

Figure 38. X-ray tracings of the clay fraction of 4 glycolated Millbrig samples from Kentucky to Virginia, with d-spacings shown. Actual peak positions are given in Table 4. KRI 5-0 is from the Tyrone Limestone at the High Bridge section near the Kentucky River, VA 4-1 is from the Eggleston Formation at Hagan, Virginia, VA:WY 2-1 is from Crockett Cove, Virginia, and VA:WY 1-1 is from Conner Valley, Virginia, both in the Bays Formation. Note that the samples become more illitic from northwest to southeast, so that the tracing for VA:WY 1-1 is nearly like that for pure illite. The locations of these sections are shown in Figure 47.



KRI 5-0
13.02
9.62
5.24
4.56
3.35
2.67
2.04
1.95
VA 4-1
12.57
9.76
5.17
3.35
2.01
VA:WY 2-1
11.51
9.91
5.14
3.34
2.01
VA:WY 1-1
10.11
5.04
3.35
2.50
2.00
2.0
8.0
14.0
20.0
26.0
32.0
38.0
44.0
50.0
56.0
62.0
TWO - THETA (DEGREES)

Figure 39. X-ray tracings of the clay fraction of 3 glycolated Millbrig samples from Tennessee to Alabama, with d-spacings shown. Actual peak positions are given in Table 4. TN 7-3 is from the Carters Limestone at the Tillet Bros. Quarry near Shelbyville, Tennessee, GA:WL 3-2 is from the Carters at Davis Crossroads, Georgia, and AL:CH 1-4 is from the Colvin Mountain Sandstone at Alexander Gap, Alabama. Although ordering increases from northwest to southeast, it does not increase as much as farther north (cf. Fig. 38). This reflects the lower burial temperatures experienced by the Alabama and Georgia sections compared to the Virginia sections. The locations of these sections are shown in Figure 45.


13.00
9.44
3.35
TN 7-3
5.28
9.88
11.51
2.59
2.04
1.95
5.18
3.34
GA:WL 3-2
2.01
3.36
11.80
9.91
7.23
3.59
AL:CH 1-4
5.26
2.39
2.02
1.98
1.77
2.0
14.0
62.0
TWO - THETA (DEGREES)

Valley and Ridge in Georgia, and from the Colvin Mountain Sandstone at Alexander Gap, Alabama. Note that the I/S in the sample from the Colvin Mountain, the Bays equivalent, contains a higher percent of expandable layers than the I/S in the Bays K-bentonites. Also, the maximum ordering in samples from Alabama and Georgia is less than the maximum in the equivalent strike belts in Virginia, and the smectite content of the I/S from the Alabama and Georgia samples is slightly higher than in the Virginia samples.

Other Clays

In addition to mixed-layer illite/smectite, other clays identified from XRD patterns are kaolinite, and possibly chlorite, vermiculite, corrensite (mixed-layer chlorite/smectite), and hydrobiotite (mixed-layer biotite/vermiculite). K-bentonites from the Colvin Mountain Sandstone in Alabama and Georgia contained abundant, well-crystallized kaolinite. The kaolinite peaks for sample AL:CH 1-4 are clearly evident in Figure 39. This kaolinite is probably derived from the alteration of feldspars and smectite as discussed in the "Burial History" section of Chapter VII. Though common elsewhere in the region, feldspars are completely absent in samples AL:CH 1-2 and 1-4 from Alexander Gap, and they are extremely altered in samples AL:ET 1-2 from Greensport Gap and GA:FL 1-1 from Horseleg Mountain, all of which are in the Colvin Mountain Sandstone.

Kaolinite was also present in minor amounts in some of the Millbrig samples from the Bays Formation in Virginia and

Tennessee. It was identified on XRD tracings, but could not be distinguished in the matrix in thin-sections. Instead, many of the biotites appear to have been altered along 001 cleavage planes to kaolinite, and perhaps vermiculite. As shown in Figure 40, these grains have an expanded, vermiform texture, with interlayers apparently of vermiculite or kaolinite. Because these grains still contain some biotite layers, they may be a biotite/kaolinite aggregate, or a mixed-layer biotite/vermiculite, which is known as hydrobiotite. Biotite grains that have altered to biotite-kaolinite aggregates are described by Snall (1977) from Silurian K-bentonites of Gotland. Those grains have a vermiform texture and are oriented at random relative to bedding, whereas separate biotite grains are oriented parallel to bedding. This is the same texture seen in the Bays sample in Figure 40, but conclusive identification of the grains as biotite-kaolinite aggregates or mixed-layer biotite/vermiculite could not be made based on XRD patterns.

Some K-bentonite samples had an anomalous peak or peaks that appear to indicate the presence of small quantities of chlorite or corrensite, or both (Figs. 37 and 41), although a conclusive identification could not be made.

An unusual texture observed in one sample of the Millbrig is shown in Figure 42. This patch of wavy clay with a sweeping extinction pattern occupies a space as large or larger than adjacent feldspar, quartz, and biotite phenocrysts, and it is thus large enough to have once been a primary grain in the ash. It is conceivable that these spaces were once occupied by large pumice

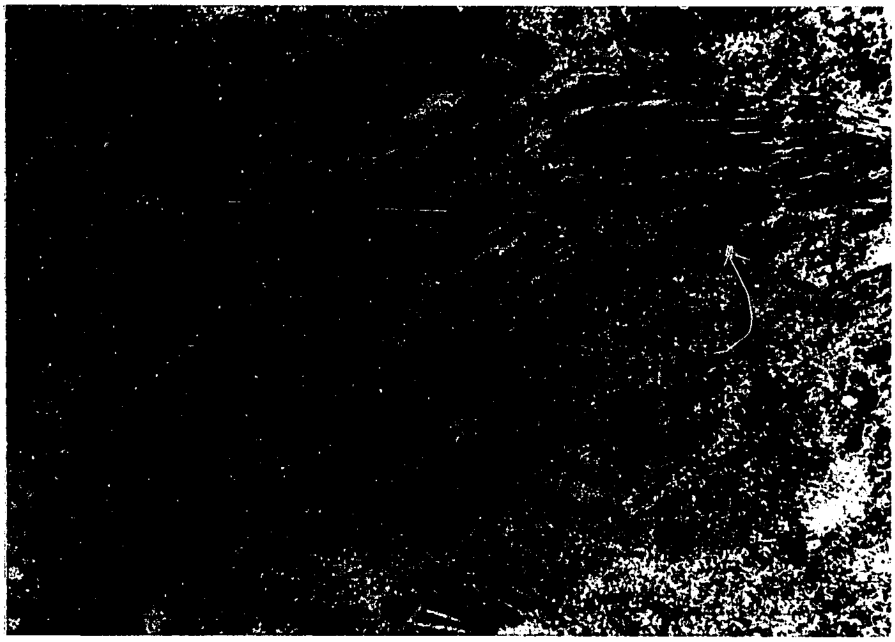


Figure 40. Photomicrograph of biotites in the Millbrig from Chatham Hill, Virginia. The vermicular, or expanded, texture, suggests that the biotites are greatly altered, and based on their appearance in thin-section there is significant chlorite present and some kaolinite as well.

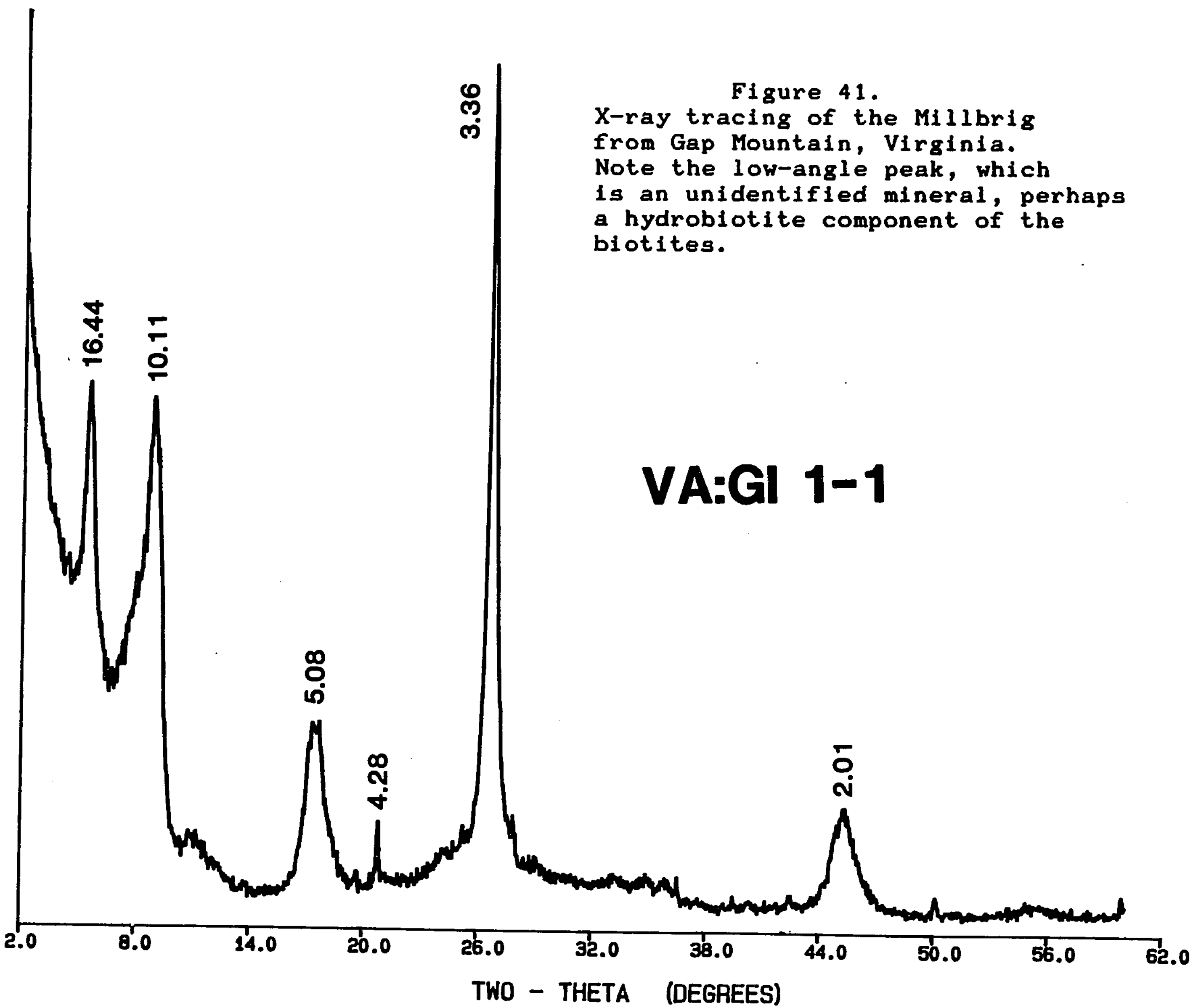


Figure 41.
X-ray tracing of the Millbrig from Gap Mountain, Virginia. Note the low-angle peak, which is an unidentified mineral, perhaps a hydrobiotite component of the biotites.

Figure 42. Photomicrograph of a possible relict pumice fragment that is now mixed-layer I/S, in the Millbrig from Tidwell Hollow, Alabama. The space occupied by this grain is bigger than the space occupied by the adjacent quartz and feldspar grains, and the linear, orderly, texture of the clay suggests that is may have been a single pumice fragment prior to post-depositional alteration and de-vitrification. Horizontal field of view is 2.5 mm. Cross-polarized light.

fragments carried aloft during the eruption and deposited with the smaller but hydraulically equivalent quartz and feldspar phenocrysts.

Color

Color of the K-bentonites varies noticeably in the study area. Observed variations are really differences in the color of the clay, as indicated by the array of colors in the clay mineral mounts prepared for X-ray diffraction. Color variations are noticeable from region to region as well, as samples collected from outcrops and cores along the Cincinnati Arch tend to be various shades of green and blue-green, which is also the color of samples collected in the carbonates of northeast Alabama, northwest Georgia, and southeast Tennessee. Samples from the Eggleston Formation in Virginia and northeast Tennessee, an argillaceous carbonate unit, tend to be more brownish yellow, while samples from the Moccasin and Bays Formations in this same area are brownish red. The color of almost all shales is dictated primarily by the presence or absence of ferrous or ferric iron (Potter et al., 1980). The variations in the color of the K-bentonites, which like shales are fine-grained, clay-rich rocks, are also most likely caused by differences in the oxidation state of the iron oxides adsorbed onto the clays, but a detailed study has not been done.

The difference in colors confuses attempts to identify the Deicke, Millbrig, and V-7 K-bentonites in southwest Virginia and northeast Tennessee. As discussed in more detail in the section

"Reinterpretation of K-bentonite Stratigraphy in Southwest Virginia and Northeast Tennessee", recognition and correlation of the K-bentonites between the three major outcrop belts in this area has historically been hindered by, among other things, the sudden changes in color of K-bentonites from one thrust sheet to the next. In the present study, this was initially a problem with the Deicke, which in the westernmost belts occurs in the Eggleston Formation and is greenish gray, but in the central belts where it occurs in or just above the uppermost redbeds of the Moccasin Formation it is brownish red.

CORRELATION

Discussion of Previous Studies

The presence of several K-bentonites in Rocklandian strata of the southern Valley and Ridge has made correlations based solely on lithologic criteria between that area and the Cincinnati Arch, where there are fewer K-bentonites, very difficult to demonstrate, although Fox and Grant (1944) and Milici and Smith (1969) did recognize textural differences among the various beds and were able to correlate strata between the two areas successfully. In flat-lying Rocklandian strata along the Cincinnati Arch, the Deicke and Millbrig are the only persistent and relatively thick (greater than 30 cm) K-bentonites. The Deicke occurs in the Tyrone Limestone or Upper Carters Limestone 6-8 m below the Millbrig, which occurs at or near the contact with the overlying Lexington Limestone or Hermitage Formation. Therefore, with careful examination of a few exposures to study and learn the differences between these units the location of the K-bentonite beds at other exposures can accurately and readily be predicted. Their color and composition in this area are very predictable as well; both are dark green to greenish gray. Young (1940), Wilson (1949), Gunal (1979), Huff (1983), Kolata and others (1984), Huff and others (1986), and Samson and others (1988) discuss correlations of the K-bentonites along the Cincinnati Arch, while Rosenkrans (1936), Fox and Grant (1944), Huffman (1945), Miller and Fuller (1954), Allen and Lester (1957), Hergenroder (1966, 1973), Drahovzal and Neathery (1971), Chowns and McKinney (1980), Chowns (1983), Jenkins (1984), and Benson and Stock (1986) discuss correlations of the K-bentonites in the Valley and Ridge.

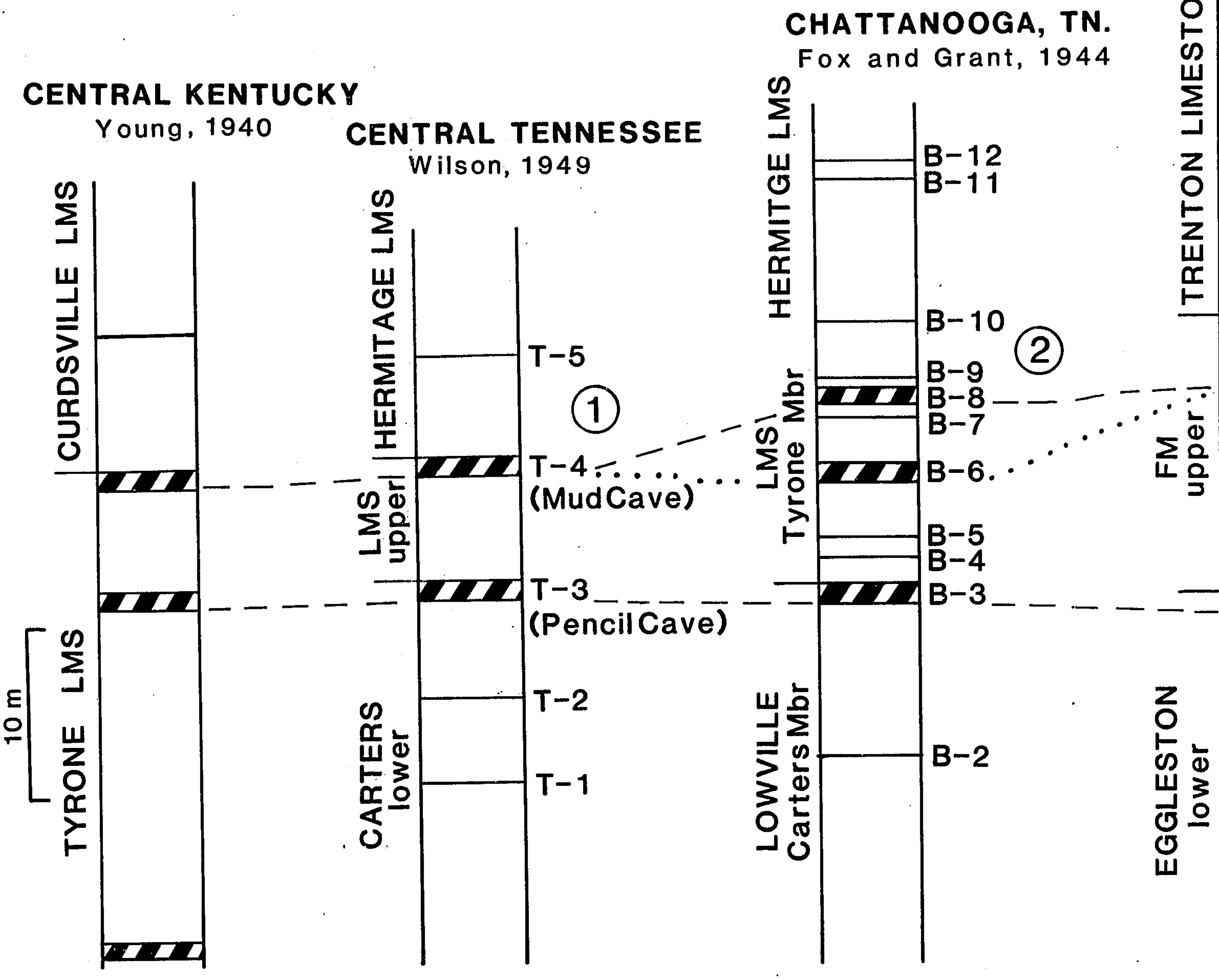
Only a few studies have presented detailed lithologic, stratigraphic, or petrographic evidence to support the correlation of K-bentonites between the Cincinnati Arch and the Valley and Ridge. Beds T-3 and T-4, the Deicke and Millbrig respectively, were correlated between the Central Basin of Tennessee and the Chattanooga area of southeast Tennessee and northwest Georgia by Fox and Grant (1944), Milici (1969), and Milici and Smith (1969). As discussed by Milici and Smith (1969) and as shown in Plate 2, the Rocklandian sequence around Chattanooga is very similar lithologically to the Central Basin sequence and so correlation is relatively easy. Elsewhere in the Valley and Ridge, however, such determinations are not made as easily. More than two thick K-bentonites occur, the sequence is not flat-lying as it is along the Cincinnati Arch, and structural complexities are commonly a problem at exposures. Color is of little use, as some K-bentonites are red, some are yellowish tan to brownish gray, and still others are a very pale green or orange. Also, K-bentonites on one thrust sheet commonly are a different color than those on an adjacent sheet.

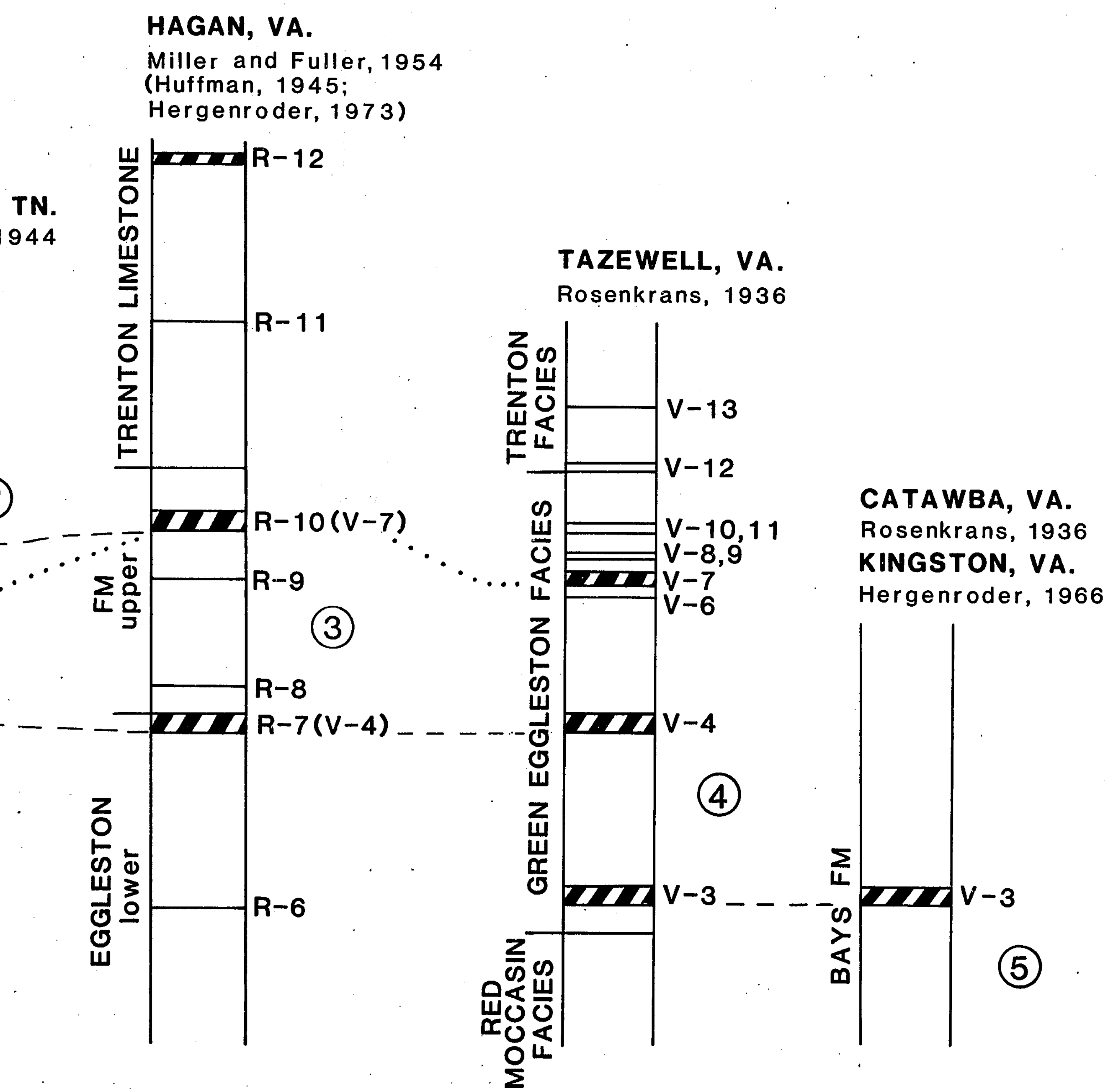
The several authors mentioned above were aware that K-bentonites had been reported from Rocklandian strata elsewhere in the southeastern United States, and many of them included figures and tables of suggested correlations between the area studied by them and one or more of the other areas. Figure 43 is a summary of some of these suggested correlations, and it gives an indication of the number of K-bentonites that occur in the Rocklandian in this region.

Figure 44 is a revised correlation chart based on the results of the present study. Along with Plates 1 through 6, it is intended to serve as a reference when referring to earlier publications. Figure 43 is discussed in detail along with the following discussion, and Figure 44 will be discussed in more detail in the subsequent section "Reinterpretation of K-bentonite Stratigraphy in Southwest Virginia and Northeast Tennessee".

Rosenkrans (1936) introduced the "V" system of nomenclature for K-bentonites ("V" for Virginia), and suggested correlations based on detailed physical stratigraphy. He described thirteen K-bentonites in the Moccasin, Eggleston, and Trenton Formations. The beds he termed V-3, V-4, and V-7 were relatively thick and laterally persistent. The bed designated as V-3 typically consists of interbedded maroon and greenish-gray or yellowish clay-rich layers. This distinct color is present only where the bed occurs in the Moccasin Formation, however; evidently the iron oxide that imparts a red color to the Moccasin has also permeated the K-bentonite. The bed Rosenkrans termed V-4 is recognizable because of its thickness and abundant biotite.

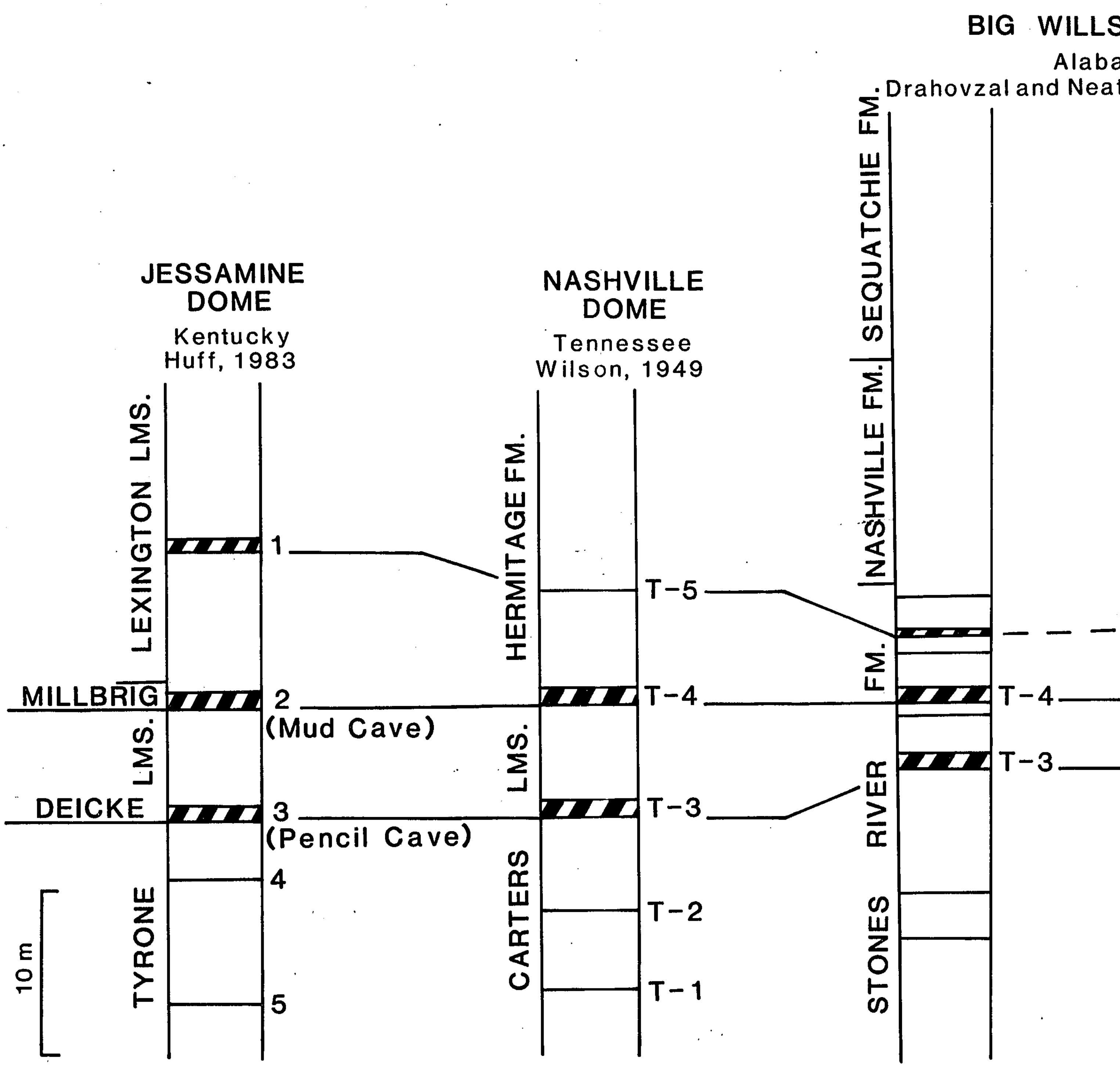
Figure 43. K-bentonite correlation chart presented by M... and Fuller (1954) with additions made by the pre... author to include additional important studi... the K-bentonites of this area. Refer to text fo... discussion of the numbers, which highlight reinterpretations of the correlations. Comp... ...ch Figure 44, the revised correlation chart.

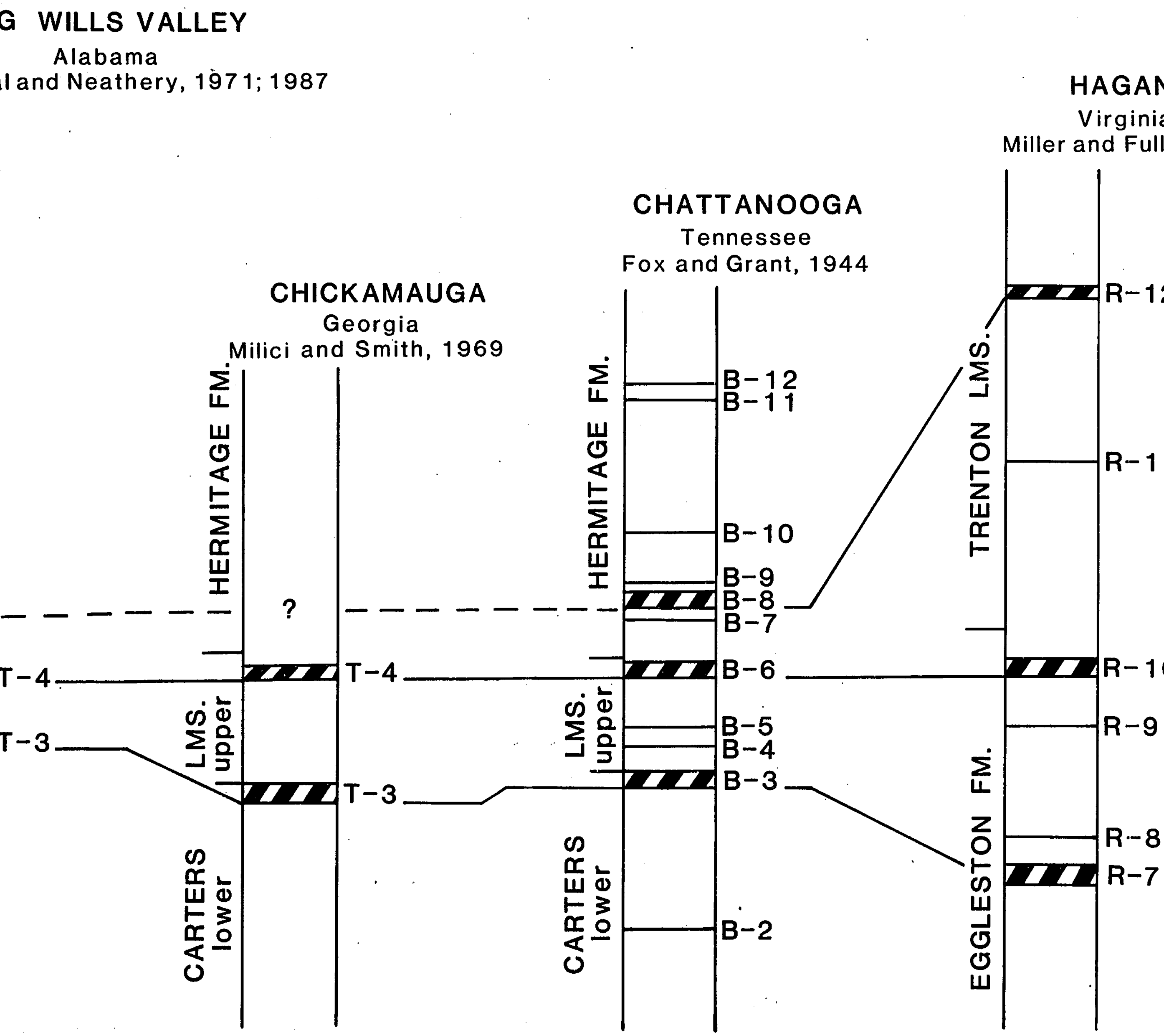

CHATTANOOGA, TN.
Fox and Grant, 1944
CENTRAL KENTUCKY
Young, 1940
CENTRAL TENNESSEE
Wilson, 1949
CURDSVILLE LMS
TYRONE LMS
10 m
HERMITAGE LMS
upper LMS
lower CARTERS
T-5
T-4
(MudCave)
T-3
(PencilCave)
T-2
T-1
1
HERMITGE LMS
LMS\ Tyrone Mbr
LOWVILLE Carters Mbr
B-12
B-11
B-10
B-9
B-8
B-7
B-6
B-5
B-4
B-3
B-2
2
TRENTON LIMESTONE
upper FM
lower EGGLESTON



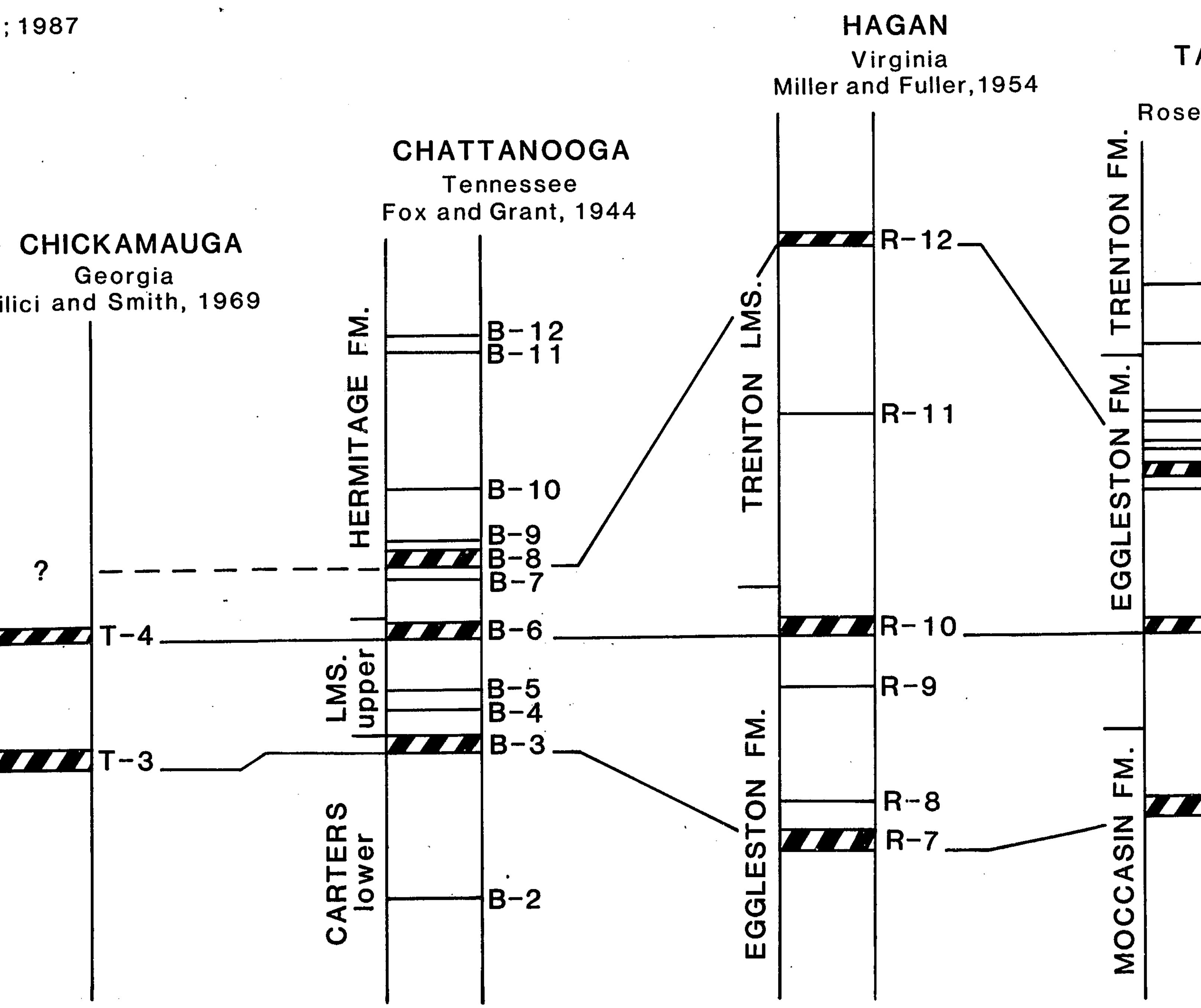
HAGAN, VA.
Miller and Fuller, 1954
(Huffman, 1945;
Hergenroder, 1973)
TN.
1944
TRENTON LIMESTONE
R-12
R-11
R-10 (V-7)
FM upper
R-9
R-8
R-7 (V-4)
EGGLESTON lower
R-6
3
TAZEWELL, VA.
Rosenkrans, 1936
TRENTON FACIES
V-13
V-12
V-10,11
V-8,9
V-7
V-6
GREEN EGGLESTON FACIES
V-4
4
V-3
RED MOCCASIN FACIES
CATAWBA, VA.
Rosenkrans, 1936
KINGSTON, VA.
Hergenroder, 1966
BAYS FM
V-3
5

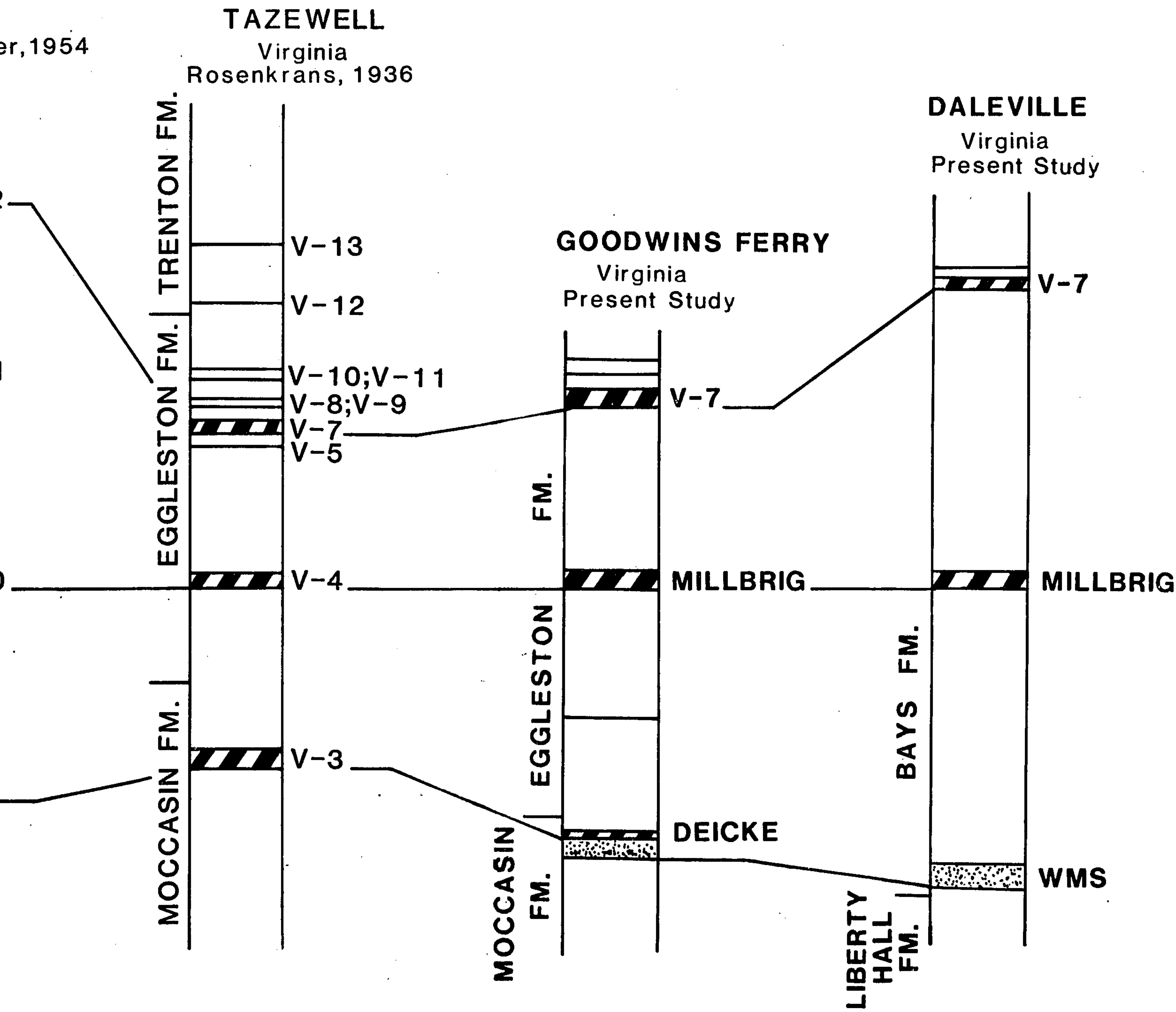
Figure 44. Revised correlation chart for several well-known measured sections in which Rocklandian K-bentonites occur. This chart is based on the results of the present study, much of which is summarized in the cross-sections shown on Plates 1 through 6.


BIG WILLS
Alaba
Drahovzal and Neat
JESSAMINE DOME
Kentucky
Huff, 1983
NASHVILLE DOME
Tennessee
Wilson, 1949
LEXINGTON LMS.
MILLBRIG
LMS.
DEICKE
TYRONE
1
2
(Mud Cave)
3
(Pencil Cave)
4
5
10 m
HERMITAGE FM.
LMS.
CARTERS
T-5
T-4
T-3
T-2
T-1
SEQUATCHIE FM.
NASHVILLE FM.
FM.
RIVER
STONES
T-4
T-3



G WILLS VALLEY
Alabama
l and Neathery, 1971; 1987
HAGAN
Virginia
Miller and Full
CHATTANOOGA
Tennessee
Fox and Grant, 1944
CHICKAMAUGA
Georgia
Milici and Smith, 1969
HERMITAGE FM.
CARTERS LMS.
upper
lower
TRENTON LMS.
EGGLESTON FM.
?
T-4
T-3
B-12
B-11
B-10
B-9
B-8
B-7
B-6
B-5
B-4
B-3
B-2
R-12
R-11
R-10
R-9
R-8
R-7


; 1987
CHICKAMAUGA
Georgia
ilici and Smith, 1969
?
T-4
T-3
CHATTANOOGA
Tennessee
Fox and Grant, 1944
HERMITAGE FM.
upper
LMS.
CARTERS
lower
B-12
B-11
B-10
B-9
B-8
B-7
B-6
B-5
B-4
B-3
B-2
HAGAN
Virginia
Miller and Fuller, 1954
TRENTON LMS.
EGGLESTON FM.
R-12
R-11
R-10
R-9
R-8
R-7
TRENTON FM.
EGGLESTON FM.
MOCCASIN FM.
Rose


er,1954
TAZEWELL
Virginia
Rosenkrans, 1936
TRENTON FM.
EGGLESTON FM.
MOCCASIN FM.
V-13
V-12
V-10;V-11
V-8;V-9
V-7
V-5
V-4
V-3
GOODWINS FERRY
Virginia
Present Study
V-7
MILLBRIG
DEICKE
EGGLESTON FM.
MOCCASIN FM.
DALEVILLE
Virginia
Present Study
V-7
MILLBRIG
WMS
BAYS FM.
LIBERTY HALL FM.

It occurs in the lower Eggleston Formation, about 10 m upsection from V-3, and is usually underlain by a blocky, brittle layer of dark chert. Bed V-7, the third thick bed, is recognizable by its occurrence at the base of the "cuneiform" beds of the Eggleston, discussed below. V-7 occurs about 10 m upsection from V-4, and 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. Rosenkrans found the other K-bentonites more difficult to recognize consistently from outcrop to outcrop, however, because none were nearly as thick as these three. 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. It was also obvious that not every outcrop contained all previously recognized K-bentonites. The presence of the chert layers directly beneath the thicker K-bentonites in carbonate sequences was one major criteria that Rosenkrans relied on to support his correlations. Markers other than individual K-bentonites were also useful for correlation, such as the interval in which the Moccasin redbeds grade upward into the olive and tan rocks of the Eggleston, the interval in the Eggleston where several thin K-bentonites occur in a group of highly jointed beds that are referred to as the "cuneiform beds" (because of their supposed resemblance to cuneiform writings), and the contact between the poorly fossiliferous Eggleston and the abundantly fossiliferous Trenton ("Martinsburg") Formation. Rosenkrans showed that five K-bentonites were consistently associated with the "cuneiform" beds, and he named this interval of strata the "cuneiform group" of the Eggleston. This "group" was correlated from the New River south to Tazewell County, a distance of over 100 km.

As shown in Figure 43 (number 4), Rosenkrans suggested that V-4 and V-7 were probably correlative with the two thick K-bentonites that occur in equivalent strata along the Cincinnati Arch, and with the two thick K-bentonites in the Bays Formation at Rocky Face, Georgia. Bed V-3 was considered to be limited in occurrence to the Moccasin Formation of southwest Virginia and northeast Tennessee, with an occurrence in the Bays Formation near Roanoke as well (Figure 43, number 5).

Rosenkrans may have reached this conclusion because V-3 is not underlain by chert as are V-4 and V-7, whereas the two beds reported elsewhere in the southern Appalachians are associated with an underlying chert layer. The conclusion was probably reinforced by the sequence of K-bentonites in the section at The Narrows of the New River in Giles County, Virginia. Rosenkrans relied on this 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 15-20 cm thick, which is markedly thinner than in most sections to the southeast and southwest. The exposure at

The Narrows is the westernmost outcrop of Ordovician strata in the Valley and Ridge at this latitude, and Rosenkrans may have reasoned that if the K-bentonite beds were traced from there 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 is greatly deteriorated from weathering, but there is no reason to doubt the observations of Rosenkrans. At the Bluefield section, in the same outcrop belt 40 km to the southwest, V-3 is exposed in the upper redbeds of the Moccasin and is about 25 cm thick. And, at the Goodwins Ferry section 20 km to the east, V-3 is 30 cm thick, whereas to the south at the Rocky Gap, Cove Creek, Plum Creek, and other sections it is nearly 1 m thick (cf. Figure 13).

Rosenkrans only briefly mentioned sections in the Powell Valley, and he did not mention the section at Hagan, in Lee County, Virginia (Figure 12). There the three thick K-bentonites are present, and all are of normal thickness compared with other sections in the region. The Hagan section, in the western outcrop belt, is actually closer to the Cincinnati Arch than is the section at The Narrows, which is in the central belt. This evidence suggesting that bed V-3 thins to the north and northwest is further supported by the sequence at the Black River Mine, Carntown, Kentucky. Here the Deicke, which is equivalent to bed V-3, is 15 cm thick, and thinning of the bed in this direction is further supported.

Bed V-3 is therefore more widespread than was originally thought by Rosenkrans, persisting to the south and west, but not east into the Bays. This areal distribution is the complete opposite of what was suggested in his text, and as shown in Figure 43 at numbers 4 and 5.

Nevertheless, the important work by Rosenkrans established excellent stratigraphic control for the central belts 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 this area.

Bates (1939) studied several Ordovician sections in the north end of the Powell Valley, and two thick K-bentonites were described in the Lowville Limestone, which underlies the Trenton Limestone. The sections in this area are very similar to the Hagan section (Figure 43), which can be used as a reference. In the upper bed, which occurred 17 ft (6 m) below the Lowville-Trenton contact (the Eggleston-Trenton contact of current usage), the presence of a micaceous zone was noted. This bed is in the correct stratigraphic position to be the biotite-rich Millbrig, suggesting that the lower bed is the Deicke.

Young (1940) described four K-bentonites in the Highbridge and Lexington Groups of the Jessamine Dome (Figure 43). Three of the K-bentonites occurred in the

Tyrone Limestone, the upper unit of the Highbridge, and one occurred in the Curdsville Limestone of the Lexington. The two thickest beds were in the Tyrone, with the upper of the two occurring right at the contact of the Tyrone and the Curdsville. The lower one was 2.0 ft (0.6 m) thick, and the upper one was 2.5-3.0 ft (0.75-1.0 m) thick. These are the T-3 and T-4 K-bentonites, or Pencil Cave and Mud Cave beds of drillers.

Fox and Grant (1944) studied the Ordovician strata around Chattanooga, Tennessee, describing fourteen K-bentonites, twelve of which occurred in the Lowville and Hermitage Limestones (Carters Limestone and Hermitage Formations of current usage, respectively). 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 were 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 43. Thicknesses were given as 2.75 ft (0.8 m) for bed B-3, 2.25-4.0 ft (0.7-1.2 m) for B-6, and 0.3-2.5 ft (0.1-0.75 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, while samples of bed B-6 contained biotite as the most abundant mineral, with quartz and feldspars present in abundance as well. Based on the petrographic work done for the present study that is summarized in Table 1, it is clear that bed B-3 is the Deicke, and bed B-6 is the Millbrig. Bed B-8 is very likely equivalent to bed V-7, as both contain significant amounts of biotite, and are the first thick K-bentonites above the biotite-rich Millbrig (beds B-6 and V-4).

Beds B-3 and B-6 were correlated with the 2 thick K-bentonites reported by Bates (1939). As shown in Figure 43, using the Hagan section to represent Bates's sections, Fox and Grant would have correlated B-3 with bed R-7, and B-6 with bed R-10 (dashed and dotted lines respectively below number 2). B-3 and B-6 were also correlated with the 2 thick K-bentonites of the Nashville Dome. Wilson (1949) later named the two beds T-3 and T-4, and these correlations are shown on Figure 43 (below number 1) as a dashed line between B-3 and T-3 and a dotted line between B-6 and T-4.

Huffman (1945) described the Middle Ordovician limestones in the Powell Valley of Lee County, Virginia, including a section at Harrogate just over the state line in Claiborne County, Tennessee. These rocks were then correlated with equivalent strata described from the Jessamine Dome of central Kentucky. At the Hagan and Harrogate sections Huffman recognized two thick K-bentonites in the Eggleston formation, both approximately 3 ft (1 m) thick. The upper K-bentonite bed occurred at the base of the Curdsville Formation (Trenton Limestone of current usage and as shown on Figure 12) and contained abundant biotite. Huffman believed that these two K-bentonites were equivalent to beds V-4 and V-7 of Rosenkrans's central belt sequence, as shown in Figure 43 in parentheses next to beds R-7 and R-10 (number 3). A thin K-bentonite separating 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 43. Evidently Huffman felt that the correlations were justified by the occurrence of 3-5 m of "cuneiform" beds overlying the upper thick K-bentonite, which were in turn overlain by the fossiliferous rocks of the Curdsville. This is similar to the sequence that was described in detail by Rosenkrans in the central belt, so the correlation of the upper bed at Hagan with V-7 appeared logical. The correlation also seemed valid on the basis of thickness and the presence of chert layers beneath the two beds in both regions. Figure 43 (number 3) shows these suggested correlations as dashed and dotted lines, respectively.

Huffman also suggested that the two thick K-bentonites at Hagan 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 as shown in Figure 43. Following Rosenkrans (1936), Huffman suggested that bed V-3 did not persist from the Valley and Ridge to the Cincinnati Arch.

The present research has shown that the upper bed at Hagan is equivalent to bed T-4, the Millbrig, of the Cincinnati Arch, and to bed V-4 of Rosenkrans rather than to bed V-7 as was suggested by Huffman. This indicates that the "cuneiform" beds and the Eggleston-Trenton contact are transgressive to the southeast, where they occur higher in the section as documented by Rosenkrans.

Huffman's study is particularly important because it was apparently the first to describe the section at Hagan, with its well-exposed K-bentonite sequence, in detail.

Wilson (1949) described the Ordovician sequence in central Tennessee, and the "T" system of K-bentonites 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. These beds were 1.0-2.0 ft (0.3-0.6 m) and 2.5 ft (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 in Figure 43 (below number 1) 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 this region. 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. This 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.

In 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 is very important, as it provides the stratigraphic framework to use in attempting correlations from the west towards the east, between the Cincinnati Arch and the western Valley and Ridge. For example, Milici (1969) and Milici and Smith (1969) used Wilson's stratigraphic sequence in the Sequatchie Valley farther east in Tennessee and the tri-state area around Chattanooga.

Miller and Fuller (1954) studied the geology of the Rose Hill area of Lee County, Virginia, introducing yet another nomenclatural system for the K-bentonites, 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) as shown in Figure 43. Like Huffman (1945), Miller and Fuller described the exposure at Hagan in detail, assigning beds R-7 and R-10 to the upper member of the Eggleston Formation, and bed R-12 to the lower part of the

Trenton Limestone. Beds R-7 and R-10, both underlain by dark chert layers, are unquestionably the same beds described by Huffman as V-4 and V-7. Bed R-10 was reported to contain abundant biotite, and bed R-12 also contained some biotite.

In an attempt to unify the various nomenclatural systems then in use, Miller and Fuller included an illustration (their Plate 26) showing correlations between Hagan and various other well-described sections. These were the Tazewell section of Rosenkrans farther east in the Valley and Ridge, the eastern Tennessee section of Fox and Grant, the central Kentucky section of Young, and the central Tennessee section of Wilson. This was the first attempt at correlating the different sections around the region. Their suggested correlations are summarized in Figure 43, which is adapted in part from their Plate 26.

Based on the findings of the present research, several of the suggested correlations were correct, and several were incorrect; these are discussed in detail in the following section on a suggested reinterpretation of K-bentonite stratigraphy in this area.

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

Allen and Lester (1957) described the Ordovician of northwest Georgia and correlated sections across the entire Valley and Ridge. These correlations relied partly on the occurrence of a thick K-bentonite with an underlying chert layer in many of the sections. Only one such bed was noted, and because these authors used numbers rather than names to distinguish between their recognized geologic units (the K-bentonite was bed "zero"), precise correlation with present-day units is difficult. The Davis Crossroads section (Figure 6), which was described in their report, is representative of the carbonate sections discussed by these authors. A K-bentonite was reported in several sections of the Bays Formation in the eastern belts, but as mentioned previously, none were located during the present study except at Horseleg Mountain near Rome, in an outcrop not mentioned by Allen and Lester.

Hergenroder (1966, 1973) studied the Bays Formation over its entire area of outcrop. His research was particularly important because of the accuracy and detail of his measured sections, many of which were used extensively in the field for the present study. Although mainly a stratigraphic and petrographic study of the Bays, the importance of the various K-bentonites was noted and discussed. 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, R-7 and R-10, at Hagan (Hergenroder, 1966, pl.

12). Because no K-bentonites were located in the Bays of northernmost Georgia and southeast Tennessee, this correlation could not be checked. And, following the correlations of Huffman (1945) and Miller and Fuller (1954), Hergenroder believed that R-10 at Hagan correlated with bed V-7 of the central belt, as shown in Figure 43 (number 3), although he noted that the silicified zones which commonly occur at the base of the K-bentonites are more difficult to identify in the clastic sediments of the Bays. As discussed below, this correlation has been found incorrect during the present investigation.

In his 1973 paper, 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."

The correlation of the upper thick bed at Hagan (which is V-4, not V-7) with T-4 near Gadsden and Birmingham is in agreement with the findings of the present research; as mentioned previously, the section at The Narrows is too weathered to be of much use.

Like Rosenkrans (1936), Hergenroder reported an occurrence of bed V-3 in the Bays near Roanoke, as shown in Figure 43 (number 5). The exposure cited by Hergenroder was made during highway construction and is now very weathered and mostly covered, and no K-bentonites were found during the present study. V-3 is the Deicke, however, and it does not occur in the Bays, so the bed described by Hergenroder was probably bed V-4 or V-7.

Milici (1969) and Milici and Smith (1969) studied the Chickamauga Supergroup in its type area near Chattanooga and in the nearby Sequatchie Valley of Tennessee. The T-3 and T-4 K-bentonites of Wilson (1949) were recognized and correlated from the Central Basin to the Sequatchie Valley and beyond to northwest Georgia. This correlation is essentially the same as shown in Figure 43 (number 1) between the sections of Wilson (1949) and Fox and Grant (1944).

Drahovzal and Neathery (1971), Chowns and McKinney (1980), Chowns and Carter (1983a), Lee (1983), Ward (1983), Jenkins (1984), and Benson and Stock (1986) described the Rocklandian sequence of Alabama and northwest Georgia. Several K-bentonites occur in the Chickamauga Group carbonates of the western belt, and the thickest are recognized as beds T-3 and T-4 of Wilson (1949), and, in this study, as the Deicke and Millbrig. Figures 6, 7, and 8 show sections in this region. The presence of abundant biotite in T-4 at these sections is noted by these authors, and the various stratigraphic columns described from several sections were very helpful in the present study.

In addition to the K-bentonites present in the Chickamauga carbonates, some of these authors suggested that 2 K-bentonites in the Colvin Mountain Sandstone to the southeast are correlative with T-3 and T-4, and cross-sections in Chowns and McKinney (1980), Chowns and Carter (1983a), and Benson and Stock (1986) all show T-4 as a datum in correlations between the carbonate sections (Big Wills Valley, Alabama and Chickamauga, Georgia) and the Colvin Mountain Sandstone or Bays Formation (Greensport Gap, Alabama, and Horseleg Mountain and Dalton, Georgia). The presence of small grains of biotite in the upper K-bentonite at Greensport Gap and abundant biotite in the bed at Horseleg Mountain and Dalton was considered sufficient criteria to justify the correlation of T-4 between these different outcrop belts. The lower bed was then correlated with T-3, with additional evidence from the Big Ridge section, where Chowns and McKinney (1980) reported a 0.05 m thick quartz arenite bed between T-3 and T-4 that is texturally and compositionally similar to the arenites of the Colvin Mountain Sandstone. This thin sandstone, which is shown in Figure 7, is in the correct stratigraphic position to represent a distal pinch-out of the Colvin Mountain lithofacies, and thus the available evidence suggested to these authors that the two thick K-bentonites at Greensport Gap and elsewhere in the Colvin Mountain are T-3 and T-4.

As discussed in Chapter VI, only the Deicke is recognizable at the Alexander Gap, Greensport Gap, and Horseleg Mountain sections.

Gunal (1979) examined several K-bentonite samples from cores and outcrops in Kentucky and north-central Tennessee from the Cumberland Saddle and Jessamine Dome along the Cincinnati Arch, and described several thin-sections. Most samples were from the Pencil Cave and Mud Cave K-bentonites, which were correlated between outcrops and cores using trace element chemistry and lithostratigraphic relations. Many of the core samples and some of the outcrops studied by Gunal were examined in the present study.

Huff (1983) used trace element chemistry to correlate the Pencil Cave, Mud Cave, and other K-bentonites from core samples collected in the Jessamine Dome and Cumberland Saddle in southwest Ohio, Kentucky, and north-central Tennessee. Huff's Table 1 showed suggested correlations of K-bentonites in the region, including the work by Wilson (1949), Huffman (1945), and Fox and Grant (1944). Except for the heretofore commonly used correlation of Huffman, which is incorrect, the correlations shown in that table are supported by the findings of the present research.

Kolata and others (1984), and Huff and others (1986) used subsurface geophysical well logs to correlate the Deicke and Millbrig from their type area in the Upper Mississippi Valley, through the subsurface of the south end of the Illinois Basin, and with outcrops along the Cincinnati Arch, where the beds are more widely known as T-3 and T-4 (Wilson, 1949). It is this subsurface correlation work that established the foundation which supports the suggested nomenclatural changes discussed herein, whereby the alphanumeric terms T-3, V-3, etc., are replaced by the terms "Deicke" and "Millbrig".

Samson and others (1988) worked primarily with the Deicke and Millbrig in the Upper Mississippi Valley, successfully correlating these beds on the basis of apatite chemistry. They also studied apatites from two samples of T-3 from the Nashville Dome and one sample of an unknown K-bentonite (which is thought by this author to be the Millbrig) from the Valley and Ridge near Gadsden, Alabama, suggesting that correlation of the Deicke of the Upper Mississippi Valley with T-3 could be shown on this basis. The unknown sample did not correlate with the Deicke or Millbrig on the basis of apatite chemistry. Several other discrepencies between their data and the findings of the present research are addressed in Chapter VII.

Regional Correlation

The discovery and discretionary use of marker beds is one of the principal physical methods used in stratigraphy, for without them correlation of measured sections is very difficult. The limitations of potential isochrons such as a distinct faunal zone, an unconformity, or a distinctive lithologic horizon are generally well understood, and although some correlation is usually possible with them, they fall short of being ideal markers (Krumbein and Sloss, 1963). This leads to unresolved stratigraphic problems, hindering the understanding of a region's geologic history.

Layers of airfall sediment such as volcanic ash or dust from a meteor impact are nearly ideal marker beds, however, because of their potential for dispersal over large areas and the geologically instantaneous nature of their deposition. Problems can arise if several layers are deposited within a relatively short time span, a very unlikely problem with meteoritic dust, but potentially a very real problem with volcanic ashfalls. Observations of modern volcanic eruptions show that, with some active volcanoes, major eruptions that occur over many months or years consist of several eruptive phases, many of which produce enough windborne ash that could be a potentially recognizable marker bed for future stratigraphers (Fisher and Schmincke, 1984). Such a time span is a geological instant, and recognition of separate eruptions in the rock record depends on local and regional sedimentation rates, wind or water currents active at the time of deposition, and post-depositional changes. The preservation potential of individual ashfalls is therefore not the same everywhere that the ash accumulates, but beds of this sort are potentially excellent marker beds and they have been used extensively as such by geologists, for example the study by

Rose and Chesner (1987). Bentonites and K-bentonites, the alteration products of airfall volcanic ash, are thus ideal marker beds, and they can be very useful for basin analysis and paleogeographic and paleotectonic reconstructions.

Careful study of the petrographic and stratigraphic variations between the Deicke and the Millbrig has made it possible to correlate these two beds between the Cincinnati Arch and the Valley and Ridge, and along strike in the Valley and Ridge between Roanoke, Virginia, and Birmingham, Alabama. The Millbrig is the most widespread and persistent of the two beds in this area, but the potential of both as markers is now realized over a very wide area. Although it is the composition of the beds that ultimately serves to distinguish the Deicke from the Millbrig, it is significant that samples of both K-bentonites from Cincinnati Arch exposures are texturally very similar to equivalent samples from the Hagan, Hinds Creek Quarry, Big Ridge, and many other sections in the western Valley and Ridge. In other words, petrographic study quantitatively verifies what is apparent from a careful study of hand specimens. Some previous researchers such as Bay and Munyan (1935), Rosenkrans (1936), Fox and Grant (1944), and Milici and Smith (1969) noted these observable differences in samples from various exposures, and used these characteristics as aids in correlation.

Along strike in the Valley and Ridge, and between the western Valley and Ridge sections and those farther east, correlations are not as easily made, however, because significant textural changes occur, and these affect what is observed in thin-section. In Alabama and Georgia, K-bentonites in the eastern clastic strata are very altered, and not recognizable in hand sample or in thin-section as either the Deicke or Millbrig. Because of this, correlations between the eastern and western belts in this area are relatively tenuous. In the western belts, however, the beds can be correlated along strike to Virginia. In northeast Tennessee and southwest Virginia, K-bentonites in the clastic strata are less altered, and some textural similarities remain between these beds and those in the carbonate strata of the central and western belts. Although the stratigraphic relations between the belts are complex, a rethinking of many earlier interpretations of the K-bentonite sequence in this region is warranted based on the findings of the present study.

Cincinnati Arch to the Valley and Ridge

Plates 1 through 6 contain 6 new cross-sections based on many measured sections of Rocklandian strata, including two cross-sections (Plates 1 and 2) that correlate the Deicke and Millbrig in measured sections between the Cincinnati Arch and the western Valley and Ridge. The Deicke and Millbrig are identified in the sections, and the Millbrig is datum. Names such as Pencil Cave, T-4, etc, that are used regionally to identify these beds are also shown in parentheses. Thicknesses for all K-bentonites observed in each section are also included. Location maps for each cross-section are shown in Appendix 2, and Figures 45 and 47 show the locations of each section in more detail.

Identification of the two beds in this region is based on stratigraphic position and on differences in phenocryst mineralogy discussed previously. The Deicke normally occurs 7-10 m below the Carters-Hermitage or Tyrone-Lexington contact, which is represented by a very abrupt change in lithology. The poorly fossiliferous, fenestral, massive lime mudstones of the Carters and Tyrone grade abruptly into the abundantly fossiliferous grainstones and packstones of the Hermitage and Lexington. The Millbrig is normally found at or within 1-2 m below this contact. Both beds commonly form noticeable recesses in outcrop. In the subsurface they make very prominent deflections on wireline logs relative to the surrounding carbonate rocks, and thus are very useful for subsurface correlation in this region.

In the Valley and Ridge, the Hagan section in the western belt is perhaps the most important measured section in the region for several reasons. The most westerly exposures of Rocklandian strata in the Valley and Ridge are in the western belt, and sections there are lithologically and faunally transitional between sections farther east and those farther west along the Cincinnati Arch. Of these exposures, the Hagan section is one of the best in the western belt, and there is no doubt as to where in the section the Deicke and Millbrig are located, as demonstrated by the agreement of measured sections reported in several previous studies (Huffman, 1945; Miller and Fuller, 1954; Kreisa, 1980). Significantly, the Deicke and Millbrig at Hagan texturally resemble samples of those beds from the Cincinnati Arch more than they resemble any of the K-bentonites in sections described by Rosenkrans (1936), even though the central belt sections are geographically much closer to Hagan than are the Cincinnati Arch sections. In addition, samples of the Deicke and Millbrig from the western outcrop belts of Alabama and Georgia, which also resemble samples from the Cincinnati Arch, can be readily matched with samples from Hagan. But it is the Hagan section, not the Alabama or Georgia sections, that is the key in extending the correlation of the Deicke and Millbrig from the shelf carbonate sequence of the western outcrop belts with the redbed sequence of the central and eastern belts (Figures 45, 46, and 47). This is a sequence of transitional marine carbonates and clastics that is best developed in the Virginia-Tennessee area and is discussed in detail in the following sections.

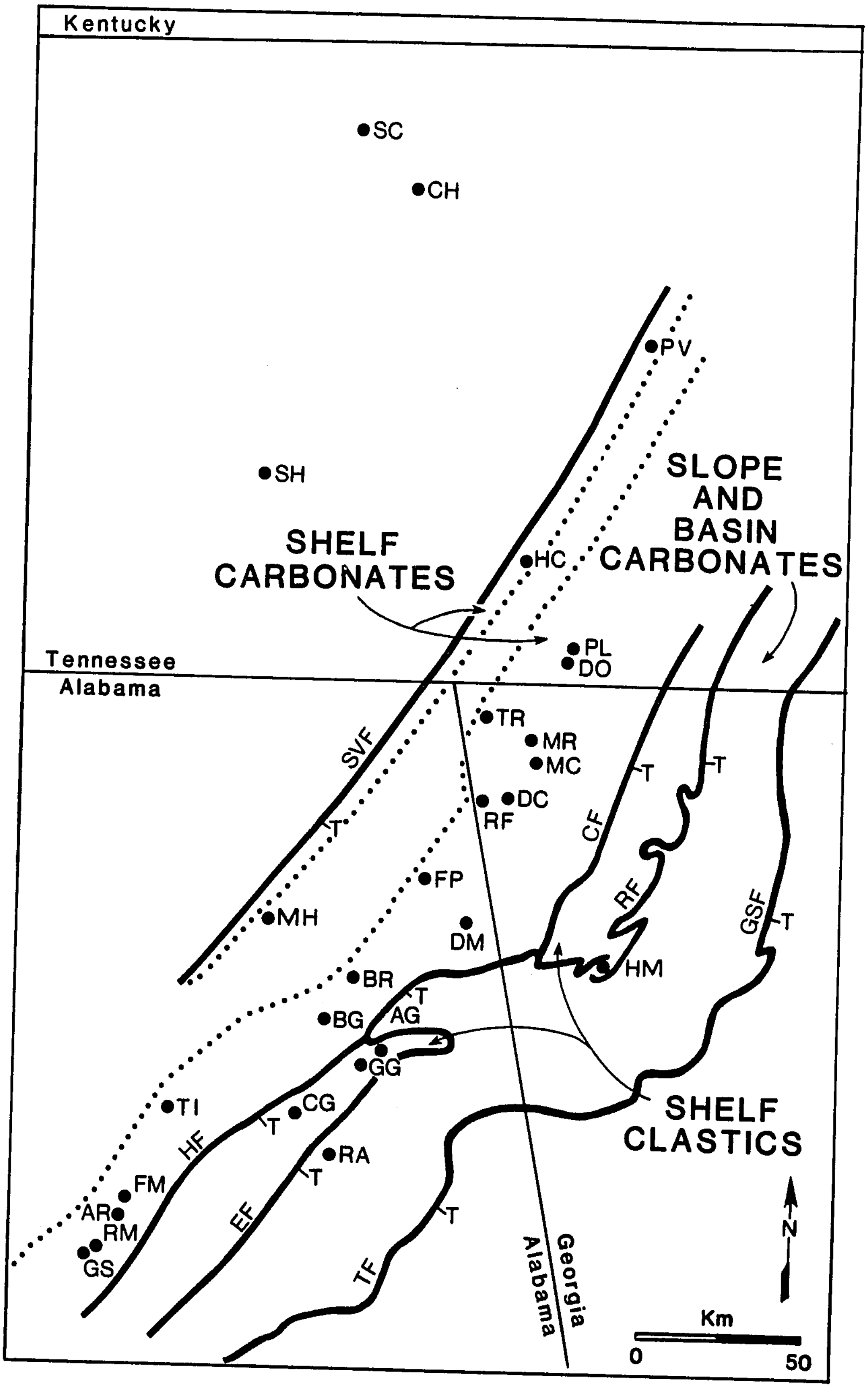
The Carters-Hermitage or Tyrone-Lexington sequence is recognizable at Hagan as the Eggleston-Trenton sequence, and the lithologies are remarkably similar between the 2 regions, as noted by Huffman (1945). At Hagan, three thick K-bentonites are present; two in the Eggleston about 8 m apart (R-7 and R-10 of Miller and Fuller, 1954), and one in

Figure 45.

Location of most outcrops that were studied in Alabama, Georgia, and Tennessee, including some from which no K-bentonites were found. The lithofacies distribution for the Rocklandian in this region is also shown. Note that the clastics which overlay the slope and basin carbonates at one time have now been removed, leading to the apparent incongruity of having carbonate sequences sandwiching a clastic sequence (Benson and Stock, 1986). The Millbrig and Deicke occur in the shelf carbonates and clastics, and the Millbrig may occur in the slope carbonates, based on examination of the exposure of the Little Oak Limestone at Ragland, Alabama.

SC, South Carthage; CH, Center Hill Dam; SH, Shelbyville (Tillet Bros. Quarry); PV, Pikeville (Stephens Rd.); HC, Henson Creek; PL, Playground (Windsor St. Quarry); DO, Dodds Av. Quarry; MH, Murphy Hill (Marshall Co. core); GS, Green Springs; RM, Red Mountain Expressway; AR, Argo; FM, Fosters Mountain; TI, Tidwell Hollow; CG, Cox Gap; RA, Ragland; GG, Greensport Gap; AG, Alexander Gap; BG, Bruton Gap; BR, Big Ridge; DM, Dirtsellar Mountain; FP, Ft. Payne; HM, Horseleg Mountain; RF, Rising Fawn; DC, Davis Crossroads; MC, Mill Creek; MR, McLemore Cove (Old Bethel Church); TR, Trenton.

SVF, Sequatchie Valley fault; HF, Helena fault; EF, Eden (Coosa) fault; TF, Talledaga fault; CF, Clinchport fault; RF, Rome fault; GSF, Great Smoky (Cartersville) fault.



Kentucky
SC
CH
PV
SLOPE AND BASIN CARBONATES
SH
SHELF CARBONATES
HC
PL
DO
Tennessee
Alabama
TR
MR
MC
SVF
T
DC
RF
CF
T
T
FP
RF
MH
DM
GSF
T
HM
BR
T
AG
BG
GG
SHELF CLASTICS
TI
CG
T
HF
RA
T
FM
AR
RM
GS
EF
T
TF
Georgia
Alabama
N
Km
0
50

Figure 46.

Western, central, and eastern belts in the Valley and Ridge of southwestern Virginia and northeastern Tennessee. Major stratigraphic changes occur between these belts, which are mostly bounded by faults. The Millbrig occurs in outcrops in all 3 belts, but the Deicke is absent from sections in the eastern belt.

H, Hagan; T, Tazewell; R, Roanoke.

PM, Pine Mountain fault; WV, Wallen Valley fault; HV, Hunter Valley fault; SC, St. Clair fault; SV, Saltville (Bland) fault; PL, Pulaski fault; BR, Blue Ridge fault; GS, Great Smoky fault.

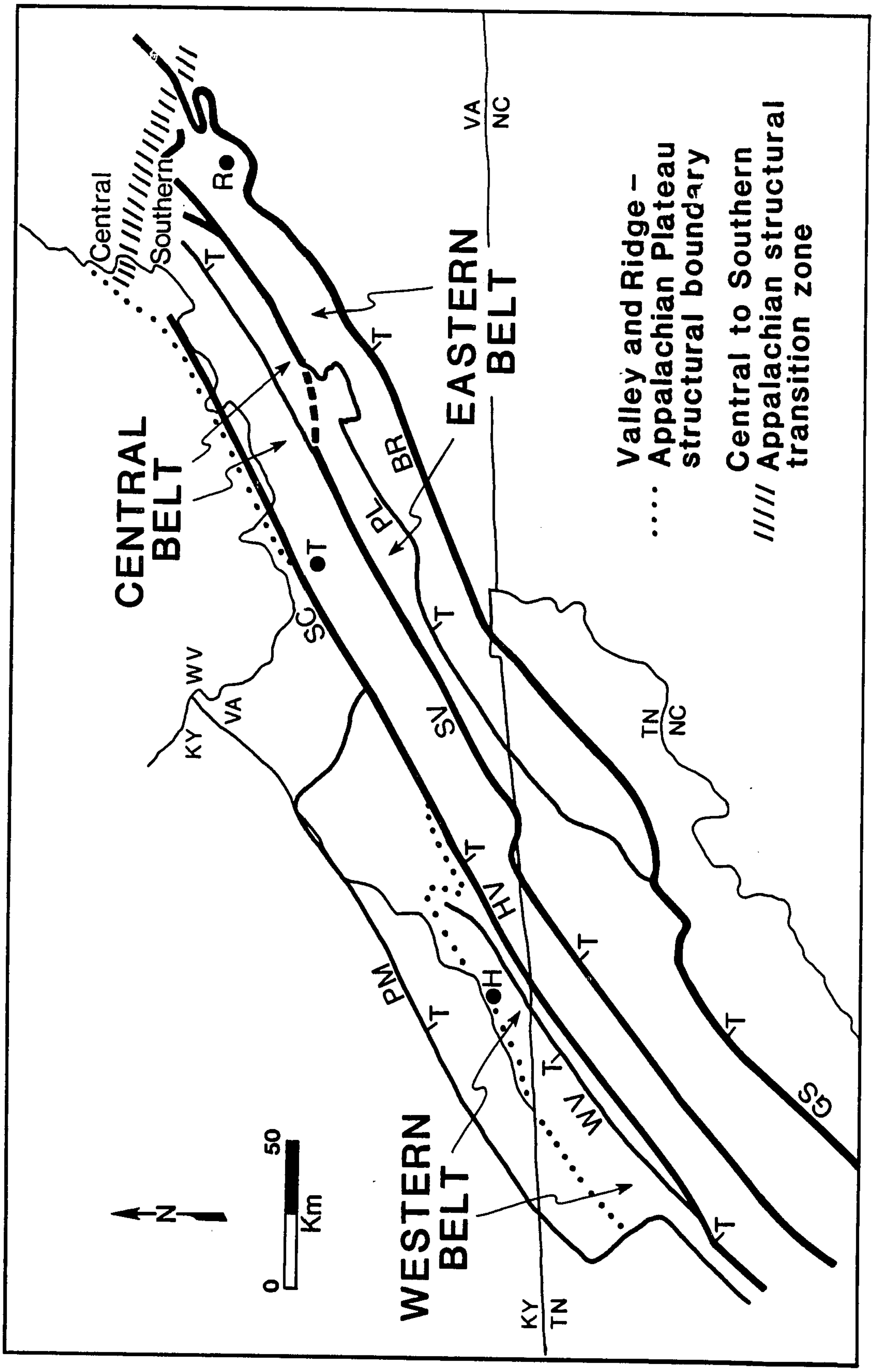
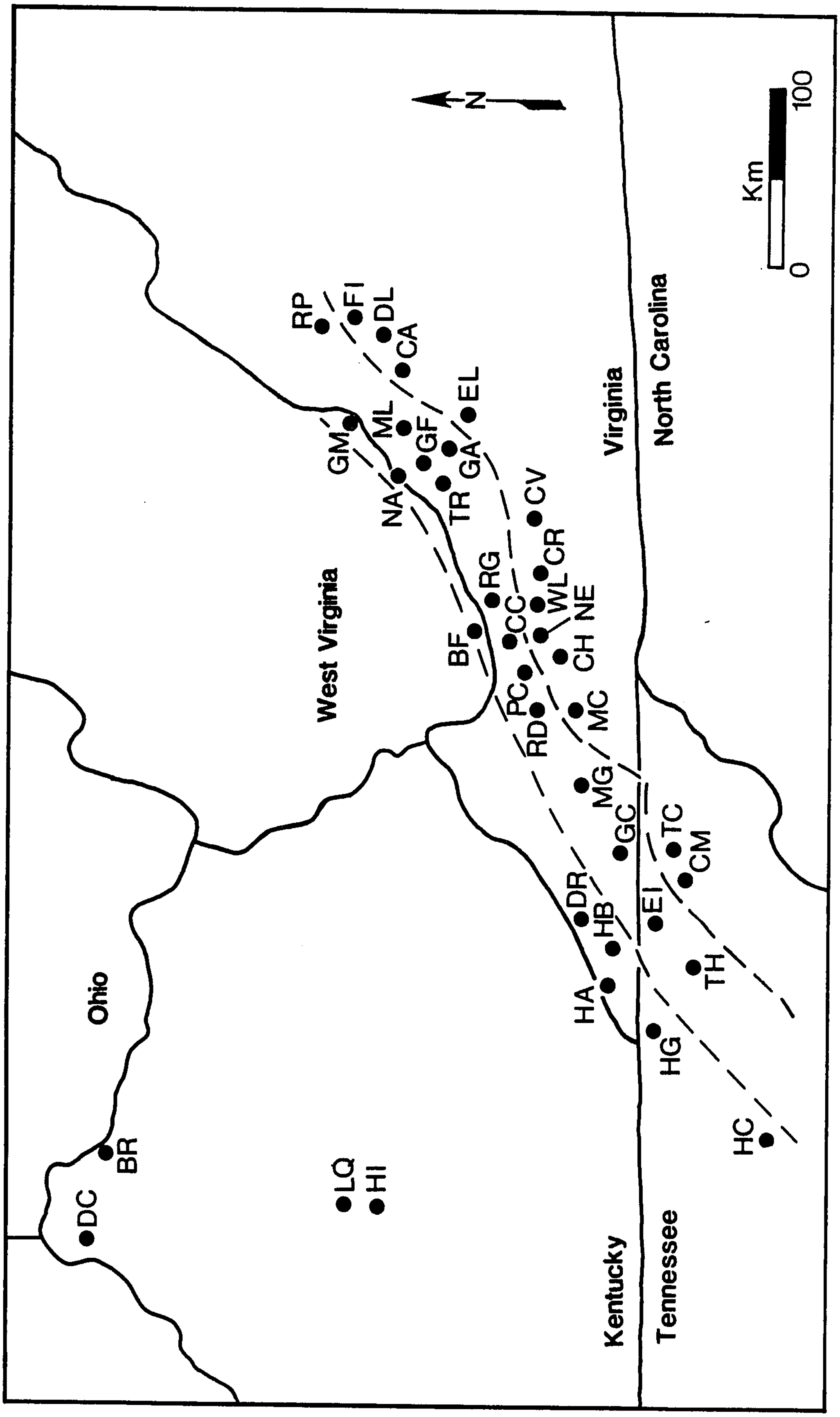

CENTRAL BELT
EASTERN BELT
WESTERN BELT
Central
Southern
R
T
H
SC
PL
BR
SV
HV
WV
PM
GS
VA
NC
WV
VA
KY
TN
NC
KY
TN
N
0
50
Km
Valley and Ridge – Appalachian Plateau structural boundary
Central to Southern Appalachian structural transition zone

Figure 47.

Location of most outcrops that were studied in Kentucky, Tennessee, and Virginia, including some from which no K-bentonites were found. The dashed lines represent the approximate boundaries between the western, central, and eastern belts in the Valley and Ridge as shown in detail in the preceding illustration.

DC, Dravo Corp. (Gallatin Co. 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, Conner Valley; EL, Ellett; CA, Catawba; DL, Daleville; FI, Fincastle.


N
Km
0
100
Ohio
West Virginia
Virginia
North Carolina
Kentucky
Tennessee
RP
FI
DL
CA
EL
ML
GM
GF
GA
NA
TR
CV
CR
RG
CC
WL
NE
BF
CH
PC
RD
MC
MG
GC
TC
CM
DR
HB
EI
HA
TH
HG
HC
BR
DC
LQ
HI

the Trenton (R-12 of Miller and Fuller), about 20 m above the upper bed in the Eggleston. The upper of the three beds is at present very poorly exposed and no samples were obtained. Petrographic study shows that the lower bed, R-7, is equivalent to the Deicke K-bentonite (T-3) of the Cincinnati Arch (no appreciable biotite or quartz; a fair amount of opaques; original plagioclase is chiefly labradorite) and R-10 is equivalent to the Millbrig K-bentonite (T-3) of the Cincinnati Arch (abundant biotite and quartz; few opaques; original plagioclase is chiefly andesine). The upper bed, R-12, was reported to contain some biotite by Miller and Fuller (1954).

The correlations in Plate 1 can be shown on this basis with relative ease considering the distance between Hagan and the Jessamine Dome (Figure 47); similarly, correlation of the Nashville Dome sections with the Sequatchie Valley section in the Valley and Ridge as shown in Plate 2 is made relatively easily considering the intervening distance.

It is apparent from these correlations that the thickness of the two beds can vary significantly over the area, an observation previously made by Gunal (1979). Variations from one outcrop to the next probably reflect differing preservation potentials, differences in post-depositional erosion, or a combination of these and other unrecognized factors.

In addition, the thickness of the interval between the beds is variable. Between central Tennessee and northwest

Georgia, the interval stays essentially the same, suggesting that, at least during the time represented by the interval, sedimentation rates were no greater in this particular area of the Valley and Ridge than along the Cincinnati Arch. Between central Kentucky and southwest Virginia, however, the interval becomes markedly thicker. This perhaps indicates that sedimentation rates during this time were greater to the northeast in Virginia than in Alabama and Georgia. Alternately, it suggests that some erosion was occurring in Alabama and Georgia. Because no litho-stratigraphic evidence was observed that would suggest an erosional unconformity or unconformities in this interval, a difference in sedimentation rates is the preferred explanation for the thickening of the interval between the two beds towards Virginia.

With identification of the two K-bentonites over such a wide area, many conclusions about depositional patterns at the time of eruption can be made. For example, along the Cincinnati Arch and the western belt of the Valley and Ridge in Virginia, the carbonates of the Tyrone Limestone, Carters Limestone, and Eggleston Formation are generally restricted, supratidal carbonates, with a sparse, limited fauna. Fenestrae are very common in many beds. The lateral persistence of the supratidal lithofacies is helpful in demonstrating regional correlations of the K-bentonites. This subject is discussed in more detail in "Rocklandian Paleogeography at the Time of Ashfalls" in Chapter VII.

The Valley and Ridge from Alabama to Southwest Virginia Along Strike

Plate 3 shows correlations of the Deicke and Millbrig K-bentonites along strike in the carbonate rocks of the more northwestern belts of the Valley and Ridge from Alabama to Virginia. As shown, the correlations from Birmingham, Alabama, to Hagan, Virginia, are essentially the same as those suggested by many previous authors (eg. Milici and Smith, 1969; Drahovzal and Neathery, 1971; Chowns and McKinney, 1980; Chowns, 1983; Benson and Stock, 1986), with the addition of several measured sections to the cross-section. The Deicke and Millbrig are identifiable as beds T-3 and T-4 of common usage in these western belts. Between the Bruton Gap and Davis Crossroads sections, several thinner K-bentonites occur below, between, and above the Deicke and Millbrig; some of these contain abundant biotite, but there is no doubt about the identification of the 2 thick beds. Because the thicknesses of the Deicke and Millbrig are fairly consistent, there is little probability that these thinner beds could be stringers of reworked ash from the Millbrig, as is the case at the Red Mountain Expressway section. These thin beds most likely represent lesser ashfalls that were not thick enough to be preserved in all areas as were the Deicke and Millbrig. It is in these sections also that the Deicke reaches its greatest observed thickness, 1.5 m at the Davis Crossroads section.

And, at the Big Ridge section, the interval between the two beds is the thinnest observed anywhere, about 3 m. By comparison, at the Hagan section to the northeast the interval between the two is almost 15 m.

The two sections southwest of Bruton Gap shown in Plate 3 are very different from the others. At those sections, the surrounding Chickamauga Limestone contains an abundant, open marine fauna and is a subtidal sequence probably deposited in a moderately deep ramp setting, which is in contrast to the poorly fossiliferous, restricted subtidal to supratidal rocks of the Carters Limestone and Eggleston Formation to the northeast of Gadsden (Chowns and McKinney, 1980; Kreisa, 1980). The absence of the Deicke at the Green Springs section suggests increased wave or current energy in this area during deposition as compared with the quieter peritidal environments to the northeast. The thinness of the Deicke and the abundant reworked biotite in the rocks overlying the also thin Millbrig at the Red Mountain Expressway section also attest to increased wave or current energy.

The Green Springs and Red Mountain Expressway sections are only 4.5 km apart, and yet the vertical sequences at each are remarkably different from each other. Such relatively rapid changes are more common in a transitional facies such as this than in peritidal facies as in the Carters. At the Tidwell Hollow section (Figure 45) the Deicke is again absent, and the strata below the Millbrig, while containing some supratidal beds, also contain higher energy sediments such as ooid grainstones and flat-pebble conglomerates (Benson and Stock, 1986), suggesting that the ash might have been reworked as at the Green Springs section.

Across strike

This discussion will focus on correlation of the K-bentonites across strike in Alabama and Georgia, as the discussion for Virginia and Tennessee is covered in the following section. The Millbrig is recognizable in the Tidwell Hollow and Bruton Gap sections, and it is quite likely that the upper of the 2 thick K-bentonites at the Alexander Gap section is the Millbrig. Unlike in Virginia and northweast Tennessee where many good exposures were located in all the strike belts (cross-sections 4, 5, and 6), only 3 exposures in the eastern belts of Alabama and Georgia were found suitable for study, and the Alexander Gap section was the best of these.

Previous studies cited above have suggested that the 2 K-bentonites present in some exposures of the Colvin Mountain Sandstone are equivalent to beds T-3 and T-4 in the Stones River Group to the northwest. The present research suggests that these correlations are correct, at least in Alabama, at Greensport and Alexander Gaps. The presence of ilmenite and the absence of biotite or quartz in the K-bentonite collected from the Horseleg Mountain section suggests that that bed is the Deicke rather than the Millbrig; Chowns and Carter (1983b) and Carter and Chowns (1986) believed it was T-4, the Millbrig. Unfortunately, K-bentonites were not found at Dalton and some other important localities where they have been reported previously in these clastic strata.

The thin quartz arenite between the Deicke and Millbrig at the Big Ridge section (Figure 7), which was located by this author, is considered supporting evidence that the two K-bentonites in the Colvin Mountain at Alexander Gap are the Deicke and Millbrig, or T-3 and T-4 of the previous studies.

If the correlations as shown are correct, it is evident that sedimentation rates and depositional environments were much different in the southeastern belt based on the interval between the Millbrig and the next thick K-bentonite upsection. At the Bruton Gap section only 1.4 m of limestone separates these two beds, whereas at Alexander Gap several meters of sandstone are present between the beds. The changes in depositional environments are obvious; between the two exposures is the eastern limit (in Rocklandian time) of the great carbonate bank that extended over much of the craton during much of the Ordovician. Figure 45 shows the distribution of carbonate and clastic strata in this area and its relation to the major thrust faults. Imbrication of thrust sheets has placed the carbonate and sandstone facies much closer to each other than they originally were, although the presence of the thin quartz arenite bed in the carbonates at the Big Ridge section (Plate 3) indicates that the two facies were not separated by too great a distance. Erosion of the Rocklandian shelf clastics has occurred in the easternmost belts, exposing the underlying slope and basin carbonates, which are evidently older than Rocklandian (Hall et al., 1986). This is the reason for the lack of sections in this area in Figure 45, with the exception of the anomalous section at Ragland, which is discussed in detail elsewhere.

Other exposures of Rocklandian strata in this area that were studied are the sections at Argo, Fosters Mountain, Cox Gap, Greensport Gap, and Dirtsellar Mountain in Alabama, at McLemore Cove, Mill Run, Trenton, and Dalton in Georgia, and two small quarries in the city of Chattanooga, Tennessee.

Reinterpretation of K-bentonite Stratigraphy in Southwest Virginia and Northeast Tennessee

Many good exposures of Rocklandian strata occur in the Valley and Ridge of southwest Virginia and upper northeast Tennessee, and examination of them for the present study suggests that a significant reinterpretation of some of the earlier stratigraphic interpretations in this area is necessary. The petrographic differences between the Deicke, Millbrig, and V-7 K-bentonite beds as discussed in previous sections, and stratigraphic relations as observed in the field, are the bases of the suggested reinterpretations. In northeast Tennessee and southwest Virginia, K-bentonites in many exposures of the Blount Group clastics of the eastern Valley and Ridge can be correlated with great certainty with K-bentonites in the carbonate strata across strike to the northwest, unlike in Alabama and Georgia as discussed above. Although many of the geologists who have worked in this region compiled convincing field evidence that supported their correlations of K-bentonites in the carbonates of the central and western belts, this is the first time that such extensive correlations have been shown along strike in the clastics of the eastern belt, and between the clastics of this belt and carbonates of the central and western belts.

Figures 43 and 44 show several "before and after" correlations using stratigraphic columns from many important papers cited in the preceding section, and the cross-sections in Plates 1 through 6 show details of many measured sections examined for the present study. The reinterpretations are shown in Figure 44, and the cross-sections were constructed based on the evidence disussed herein. Figures 46 and 47 show how the Valley and Ridge of this area is grouped into western, central, and eastern belts, and the location of the many exposures that were studied.

In addition to the Deicke, Millbrig, and V-7, other thinner K-bentonites occur in Rocklandian strata in this area, and as discussed in the previous section, many studies of all of them have been made over the past 50 years. The potential of altered volcanic ash beds to be stratigraphic markers has long been recognized, and several previous studies of these particular K-bentonite beds showed that precise correlations were possible locally, but difficulties in correlating most beds over longer distances (150 km and greater) prevented a regional stratigraphic synthesis of the K-bentonite sequence. The studies by Rosenkrans (1936) and Hergenroder (1966, 1973) were exceptions, as both geologists proposed correlations along strike of K-bentonites in the Bays from southwest Virginia to Georgia, and correlation of one or more K-bentonites across strike from the clastic to carbonate sequences. Rosenkrans's conclusions were widely accepted by most subsequent workers, including Hergenroder.

Correlation between the western and central belts

Even though there are many K-bentonites, it was obvious to all geologists who studied these strata that the thickest beds, which are the Deicke, Millbrig, and V-7, are likely to be the most laterally persistent, and these are the beds on which correlations have most frequently been based. During the present study, five exposures studied contained the three K-bentonites (Gate City, Rosedale, Plum Creek, Cove Creek, and Goodwins Ferry; see Figure 47); all five are in the central outcrop belt. Plate 3 shows these sections.

As discussed above, the section at Hagan in the western belt is very important, even though the upper of the three thick K-bentonites described from there by Miller and Fuller (1954) is very poorly exposed at present and samples could not be collected. Unlike the correlation of K-bentonites between the Cincinnati Arch and Hagan, 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, even with scrutiny of outcrops and thin-sections.

In the five key sections of the central belt, the sequence is very different in appearance from the Hagan section. The lower of three thick K-bentonite beds is the readily recognized V-3 of Rosenkrans, occurring within or 1-2 m above the uppermost redbeds of the Moccasin Formation, and the K-bentonite itself consists of interbedded red, green and yellow-gray clay, with some phenocrysts. The next thick bed, V-4 of Rosenkrans (1936), is in the Eggleston Formation, 5-8 m above V-3 in the five key sections. It contains abundant coarse biotite, feldspar, and quartz phenocrysts. The abundant biotite is its distinguishing textural feature, and thus it would logically be the Millbrig equivalent based on this texture. Bed V-7 is 5-8 m upsection from V-4, immediately below the "cuneiform beds" of the Eggleston. V-7 contains abundant biotite and quartz, but the grains of both are finer-grained than in V-4. The lowest bioclastic grainstone of the Trenton ("Martinsburg") Formation occurs 1-3 m upsection of V-7. The Plum Creek section shown in Figure 13 is typical, and with careful field study, correlation of measured sections in the central belt is relatively easy, as convincingly documented 50 years ago by Rosenkrans (1936). Plate 3 shows the correlation of the Deicke and Millbrig in the central belt between the Gate City and Goodwins Ferry sections. In addition to the sections shown in Plate 3, parts of the central belt sequence can also be seen at the Thorn Hill, Eidson, Little Moccasin Gap, Bluefield, Narrows, Gap Mills, Trigg, Mountain Lake Turnoff, and Gap Mountain sections as well.

Assuming that bed R-7 at Hagan is equivalent to bed V-3 simply because they are the first thick K-bentonite in each section, it is obvious that the characteristic red and yellow colors of V-3 is absent in R-7 at Hagan, which is greenish gray. This is easily explained by the pinch-out to the west of the redbeds of the Moccasin Formation. The Moccasin is absent in the Powell Valley, having been replaced by the gray carbonates of the Hardy Creek Limestone and a thicker Eggleston Formation (Miller and Fuller, 1954; Le Van and Rader, 1983). Thus there are no surrounding red sediments to tint V-3 as in the central belts, and in color the bed at Hagan more closely resembles the Deicke (T-3) K-bentonite of the Cincinnati Arch. The sections that Rosenkrans chose to document the two-color nature of bed V-3 were all from exposures where the Moccasin or Bays was present. These units contain much reddish strata, and once the redbeds pinch out along or across strike, the distinct color of bed V-3 would likely disappear as well. Plate 5 shows the correlation of the K-bentonites at the Hagan section in the western belt with those at the Gate City section in the central belt. The disappearance of the Moccasin redbeds to the west is readily apparent.

Unlike the marked differences between bed V-3 at Plum Creek and bed R-7 at Hagan, beds V-4 and R-10 are very similar in appearance. Samples of bed V-4 from the Gate City, Rosedale, Plum Creek, Cove Creek, Rocky Gap, and Gap Mountain sections contain abundant coarse-grained biotite and quartz, 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 this area that contains abundant bronze, gold, dark brown, or black biotite grains up to 1.5 mm in length. The biotite is immediately noticed in the field, and the bed is consistently recognizable on this basis (much as bed V-3 is recognizable on the basis of color), as many previous studies have noted. At the Goodwins Ferry section V-4 is present but is so sheared and crushed that if any biotite remains it was not seen.

Because this texture is so regionally consistent, it is this bed that most convincingly establishes the correlation between the western and central belt K-bentonite sequences. Compositionally, there is no difference in samples from the two belts, and samples of bed V-4 from the Gate City section are essentially indistinguishable from samples of bed R-10 from the Hagan section. Petrographic and stratigraphic evidence conclusively support the correlation of bed V-4 with bed R-10 at Hagan and the other Powell Valley sections in Virginia and Tennessee. Because R-10 correlates with the Millbrig (T-4), then by association bed V-4 is also the Millbrig.

Stratigraphically, this correlation of bed R-10 with bed V-4 implies that bed V-3 is equivalent to bed R-7, even though the two beds are very different texturally. Petrographic evidence, although not unequivocal, strongly supports the stratigraphic evidence for this correlation as well. Thin-section study shows that V-3 samples from the Thorn Hill, Eidson, Gate City, Plum Creek, and Cove Creek sections contain little quartz and almost no biotite. Ghosts of numerous feldspar grains are preserved, although generally weathered and highly altered, suggesting that the rock was originally feldspar-rich. Because of the pervasive alteration, quantitative analyses were not attempted. Numerous red-brown iron oxide specks are present; these could be secondary hematite after ilmenite or leucoxene, which are both common in the Deicke. North of the Cove Creek section, bed V-3 becomes finer grained and thin-section study reveals little about the phenocryst mineralogy. The bed does, however, retain its distinctive coloration and its stratigraphic position near the top of the Moccasin as far north as Giles County, although it becomes thinner, as shown in Plates 3 and 6. It can therefore be recognized on those criteria into the New River Valley, where it also becomes associated with the Walker

Mountain Sandstone, as shown in Plate 6. North of the New River, the red color rapidly disappears as a facies change occurs, and the redbeds of the Moccasin interfinger with and are eventually replaced by the gray carbonates of the Nealmont Formation (Woodward, 1951; Kay, 1956; Perry, 1972). Thus, although the diagnostic minerals listed in Table 1 could not be conclusively identified in every sample of V-3, the petrographic evidence that is available supports correlation of this bed with R-7 at Hagan, which contains the mineralogic assemblage typical of the Deicke in that area and the Cincinnati Arch.

Bed V-7 is the third thick K-bentonite in this area. Petrographic study of it was first undertaken with study of V-4, prior to study of V-3, because during initial field work it was believed that V-7 was the Millbrig equivalent, as Rosenkrans (1936), Huffman (1945), and Miller and Fuller (1954) had suggested (Figure 39). This bed contains abundant biotite, which was expected assuming that it was the Millbrig, but a problem arose when it was discovered that beds V-4 and V-7 both contain abundant biotite. Bed V-4 contains more abundant biotite, and the grains are consistently larger. Based on these initial observations, it was difficult to explain why, if bed V-4, bed R-7, and the Deicke (T-3) were equivalent as had been previously assumed, there was essentially no biotite or quartz in samples from along the Cincinnati Arch, but in the Valley and Ridge both phenocrysts were present in abundance. A possible reason was differences in hydraulic equivalence among phenocrysts during settling of the volcanic ash, but the feldspar grains of the Deicke (T-3) in Cincinnati Arch samples are very similar in size to phenocrysts in Valley and Ridge samples of beds R-10 and V-4 (0.2-0.8 mm long). This suggests that phenocrysts of this size and specific gravity were transported by winds at least that far west. If similar-sized biotite and quartz grains were in the ash, they should also have been transported that far, particularly biotite grains, with their platy habit. Because quartz and biotite do occur rarely in Deicke (comprising less than 1 percent of all thin-sections examined), there is no doubt that the ash contained these phenocrysts. The Deicke ash is more mafic than the Millbrig ash, however, so little quartz and biotite is expected. The few quartz and biotite grains present were transported with the bulk of the ash, which was composed primarly of glass fragments, feldspars, and ferromagnesian and Fe-Ti minerals. In this case then, nothing was seen to suggest that a biotite-rich K-bentonite in the Valley and Ridge should be biotite-poor along the Cincinnati Arch, and it became clear that the earlier correlations followed during initial field work were incorrect.

Because bed V-4 correlates with the Millbrig (T-4; R-10) rather than the Deicke (T-3; R-7), V-7 must correlate with a K-bentonite upsection from the Millbrig. As no K-bentonites as thick as the Deicke and Millbrig occur upsection of the Millbrig in the Cincinnati Arch region, it is unclear at this time with which bed V-7 would correlate. The section at the Black River Mine, Carntown, Kentucky (Figure 3), on the eastern side of the Cincinnati Arch contains several K-bentonites, and petrographic study identified the Deicke and Millbrig. The 0.7 m thick bed upsection from the Millbrig may be equivalent to bed V-7.

It is worth noting that with the reinterpretation 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. Previously, it was bed V-4 that was thought to correlate with T-3 and B-3, as shown in Figure 43 (number 4). In addition, T-4 now is equal to V-4, the next thick K-bentonite upsection in the two regions where these systems have commonly been used. This is additional evidence that the first two thick K-bentonites in much of the region are the third and fourth K-bentonites in the section overall, lending further support to the reinterpretation.

Correlation between the central and eastern belts

As shown in Plate 4, there is a thick K-bentonite in the Bays Formation at the Daleville, Crockett Cove, Chatham Hill, and Terrill Creek sections that occurs 15-25 m upsection from the Walker Mountain Sandstone, and at these sections the interval between the Walker Mountain and this thick K-bentonite is completely exposed. In addition, much of the Bays below the Walker Mountain is exposed at the Chatham Hill and Nebo sections, and no K-bentonites were observed in that interval. At the Crockett Cove, Conner Valley, Ellett, and Daleville sections, the Walker Mountain is the lowest bed of the Bays, resting on the Witten Formation (Crockett Cove), Wassum Formation (Conner Valley), or the Liberty Hall Limestone (Ellett and Daleville). The thick K-bentonite above the Walker Mountain contains abundant biotite that is chloritized to varying degrees, but is still recognizable as biotite. Many other sections of the Bays contain a similar thick, biotite-rich K-bentonite as well. Although it is grayish red at most sections, it is grayish white with red mottles at the Terrill Creek section, and greenish gray at the Crockett Cove and Daleville sections. Biotite in samples from these three exposures is bronze to black in color, rather than the blue-green color of the chloritized biotites from most of the other sections. As a result, the samples from Crockett Cove and Daleville texturally very much resemble samples of V-4, the Millbrig, from the central and western belts. Quartz and feldspar phenocrysts occur in samples of the bed from the Daleville section, although the feldspars are highly altered. Sandstones overlying the bed at the Crockett Cove section contain abundant biotite both along bedding planes and throughout the rock in the 2-3 m immediately above the K-bentonite. Petrographic evidence thus indicates that this first K-bentonite above the Walker Mountain Sandstone in the eastern belts is the Millbrig. Conclusive evidence is found at the Daleville section, where almost the entire Bays Formation is exposed. There, two biotite-rich K-bentonites occur several meters upsection from the Walker Mountain, the lower bed being the coarser-grained of the two. These beds logically correlate with the Millbrig (V-4) and V-7 of the central belt.

At the Catawba section, the Millbrig occurs near the base of the exposure, and it is anomalously thin, only 0.1 m thick. Closer examination, however, shows that the overlying 0.5 m thick sandstone contains abundant coarse grained biotite both along bedding planes and scattered throughout the rock. This suggests that the ash was extensively reworked and dispersed in the overlying sands. Even though the actual K-bentonite bed is very thin, samples of the bed are texturally very similar in appearance to samples of V-4, the Millbrig, from the central belt. The sandstones overlying the Millbrig at the Crockett Cove section also contain abundant coarse grained biotite, but there the Millbrig is of normal thickness.

Study of seven sections of the Bays where the Walker Mountain Sandstone and several meters of overlying strata are exposed (Daleville, Ellett, Conner Valley, Crockett Cove, Nebo, Chatham Hill, and Terrill Creek) indicates that the Deicke is absent in the entire eastern belt, and that the first K-bentonite above the Walker Mountain is the Millbrig. This conclusion is supported with evidence discussed below from four sections in the central belt (Trigg, Goodwins Ferry, Mountain Lake Turnoff, and Gap Mountain) where the Walker Mountain is present as a tongue of the Bays in the Moccasin Formation. Presumably the Deicke ash was deposited in this region but was not preserved as a separate bed in the Bays. Evidently it was reworked into the overlying sands or completely eroded away. The lack of biotite in the Deicke means that reworked ash would not be as noticeable in the surrounding strata, as is the case with the reworked biotite of the Millbrig at the Crockett Cove and Catawba sections discussed above. The phenocrysts of the Deicke are more unstable chemically in sedimentary environments than those of the Millbrig, and because the Bays contains significant amounts of feldspar throughout (Hergenroder, 1966), there is less chance that any reworked Deicke ash would be recognized in the rocks immediately upsection of the Walker Mountain Sandstone. No obvious unconformity occurs in this interval, although removal by erosion cannot be ruled out. For whatever reason, then, the Deicke is absent in exposures of the Bays.

As is the case with attempts to correlate the K-bentonite sequence of the western belt with that of the central belt, the K-bentonites that occur in the eastern belts in the Bays Formation cannot, at first examination, be easily correlated with the K-bentonites in the Moccasin, Eggleston, and Trenton Formations. Rosenkrans (1936) and Hergenroder (1966) reported that V-3 occurred in the Bays near Roanoke, but Hergenroder cautioned that color is of no use in supporting correlations because at the majority of Bays outcrops all K-bentonites are red. Nevertheless, detailed field study of K-bentonites at eleven sections in the eastern belt and four in the central belt, combined with thin-section analysis of samples from these outcrops, shows that the K-bentonites in the Bays can be correlated with those in the central belts. These correlations are shown in cross-sections 6 and 7, where it is seen that beds V-4, the Millbrig, and V-7, rather than bed V-3 as suggested by Rosenkrans and Hergenroder, occur in the Bays.

The Terrill Creek, Gate City, Chatham Hill, Crockett Cove, Ellett, Gap Mountain, Goodwins Ferry, and Daleville sections were most important in working out the stratigraphic relations between the two belts. The Walker Mountain Sandstone Member and the first fossiliferous beds at the base of the Trenton Formation are very important marker beds that support the suggested correlations. Correlation is best shown from west to east, beginning with the Goodwins Ferry and Gap Mountain sections of the central belt in Giles County. As shown in Plate 6, the Millbrig (V-4), V-7, the Walker Mountain Sandstone, and the Moccasin-Eggleston and Eggleston-Trenton contacts occur in both sections. The Deicke (V-3) is exposed at the Goodwins

Ferry section, but is covered at the Gap Mountain section. At the Goodwins Ferry section, the Deicke occurs directly above the Walker Mountain Sandstone, and although this interval is mostly covered at the Gap Mountain section, Hergenroder (1966) reported V-3 there. The Walker Mountain Sandstone is readily found at that exposure, suggesting that the Deicke would be located if the strata above the Walker Mountain were better exposed. At the Mountain Lake Turnoff and Trigg sections, also in the central belt, the Deicke occurs immediately above the Walker Mountain Sandstone, just as at the Goodwins Ferry section.

From these outcrops, the Walker Mountain Sandstone can be traced into the Bays Formation, where it occurs at the base of the Bays in the Ellett section about 35 km east of the Gap Mountain section. Overlying the Walker Mountain are 5-6 m of well-exposed siltstones and very fine-grained sandstones, with minor interbedded shales. There are no K-bentonite beds in this interval, so the Deicke is missing from the Ellett section.

The Eggleston-Trenton contact can also be followed into the eastern belts, where it becomes the Bays-Trenton contact, and beds V-4 and V-7 also can be followed into the Bays, as shown by the Daleville section. This contact is most important in southwesternmost Virginia and northeast Tennessee in the Bays Mountains, because as shown in Plate 5, the Walker Mountain Sandstone does not occur in the central belt in this area. Therefore, although the Millbrig is recognized at the Hagan, Gate City, and Terrill Creek sections, bed V-7 was not observed in the Bays and there is less cumulative stratigraphic evidence to support the correlation than in the New River Valley. The base of the Trenton is thus a very important marker, as it can be located throughout the area in all three outcrop belts.

Correlation of the K-bentonites is thus demonstrated between the central and eastern belts, and more specifically between the major facies changes that occur across the Saltville and Pulaski faults. The two thick K-bentonites that occur in the Bays are the Millbrig (V-4) and bed V-7. This is the first time that this correlation has been demonstrated, and it is also the first time that bed V-7 has been recognized in the Bays.

Revision of earlier interpretations

Figure 43 summarizes correlations suggested by Rosenkrans (1936), Young (1940), Fox and Grant (1944), Huffman (1945), Wilson (1949), Miller and Fuller (1954), and Hergenroder (1966; 1973) between southwest Virginia and northeast Tennessee, and other sections. Some of the specific correlations discussed in previous sections are shown with numbers. This figure is based partly on Plate 26 of Miller and Fuller (1954). In that illustration, bed R-10 is shown correlating with bed B-8 of Fox and Grant (1944), but the accompanying text indicated that the correlation was with bed B-6. Beds R-10 and B-6 are equivalent to bed T-4, the Millbrig, of the Cincinnati Arch, and so the text, rather than the figure, was correct. Figure 43 (numbers 1 and 2) shows the incorrect correlation of R-10 with B-8 and B-8 with T-4, (dashed line). This is how Miller and Fuller's illustration showed the correlations. The correct correlation of R-10 with B-6, and B-6 with T-4 (dotted line) is also shown, as this was how the correlation was described in their text. The correlation of bed R-7 with bed B-3 of Fox and Grant, bed T-3 of Wilson (1949), and the lower thick K-bentonite of Young (1940) is also supported by the present study. The correlation of bed R-10 with bed T-4 of Wilson and with the upper thick bed of Young is also considered correct.

Huffman (1945) suggested that the lower thick K-bentonite at Hagan, bed R-7 of Miller and Fuller, correlated with bed V-4 of the central belt. Miller and Fuller agreed with this correlation; unlike Huffman, however, they believed that bed R-10 did not correlate with bed V-7, but with a higher bed in the central belt sequence, although they did not suggest an alternate correlation. Number 3 on Figure 43 shows these correlations.

In their illustration, Miller and Fuller incorrectly labeled bed T-4 as the Pencil Cave, and T-5 as the Mud Cave, when in fact they are beds T-3 and T-4 respectively. Also, upon close examination of the original illustration, it is apparent that the thicknesses for T-4 and T-5 shown were inadvertently reversed, as T-4 is reported as being only 4 inches thick, while T-5 is reported as 2.5 feet thick. These errors are not shown in Figure 43, but rather the correct sequence and thicknesses are shown (number 1) as described by Wilson (1949).

Rosenkrans (1936) and Hergenroder (1966) suggested that a K-bentonite in the Bays Formation near Roanoke was bed V-3, as shown at number 5 on Figure 43. This correlation is incorrect, as bed V-3, which is the Deicke, does not occur in the Bays in this area. The bed they observed was either the Millbrig (V-4) or V-7.

Figure 44, a revised chart of these same sections that is based on the results of the present research, shows these correlations as they are now interpreted. Important sections in Alabama and Georgia are also included to make the regional correlation more complete. Refer also to Plates 1 through 6 for details of the interval in which the Deicke and Millbrig occur.

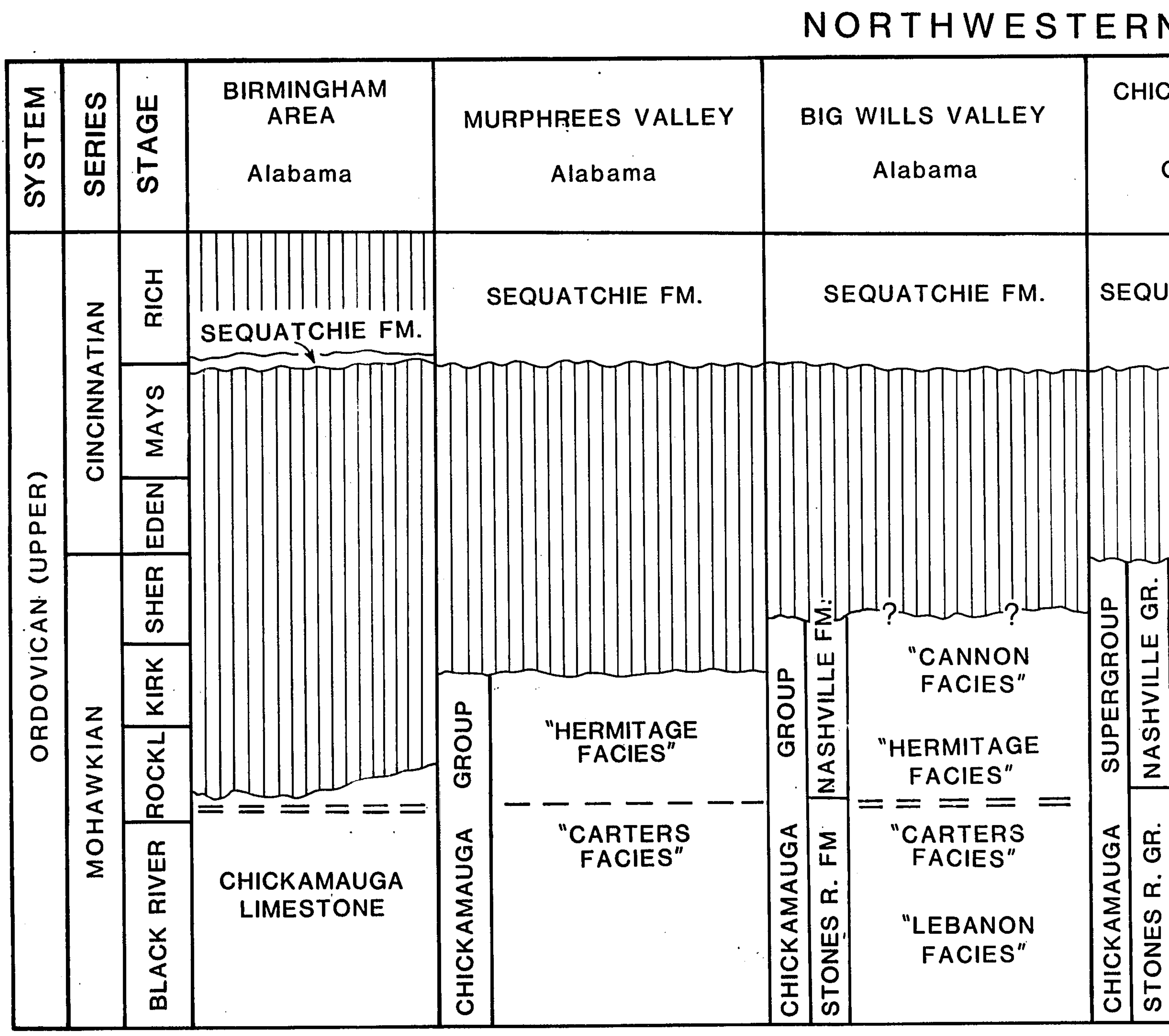
Use of the Two Beds as Time Markers

With the identification of the Deicke and Millbrig in sections of Rocklandian strata from the Cincinnati Arch and throughout the Valley and Ridge from Birmingham to Roanoke, the potential of the K-bentonites as marker beds is realized to a greater extent than ever before. Subtle variations in the stratigraphic sequence from one area to the next can be more readily observed, and a sequence of strata bounded by two well-defined time lines is now available for detailed sedimentologic, paleontologic, paleogeographic, and geochemical study over a very widespread area. Figures 48 and 49 show the position of the Deicke, Millbrig, and V-7 K-bentonite beds over the Valley and Ridge between Birmingham and Roanoke.

As noted above, it is the Hagan section that proved to be the key exposure for correlating the K-bentonites from the Cincinnati Arch through the carbonate strata of the western Valley and Ridge and into the clastic rocks of the eastern belts. Because such a widespread correlation can now be shown, a unification of the many different alpha-numeric nomenclatural schemes currently used is possible, as shown in Figure 44. It is expected that additional study will further refine the stratigraphic sequence, and for example, bed V-7 will be found to correlate with one of the thick K-bentonites above the Millbrig in several of the Alabama sections, for example the Ft. Payne and Bruton Gap sections shown in Plate 3.

Figure 48.

Correlation chart for the K-bentonites in strata along the northwestern belts of the Valley and Ridge. Carbonate strata predominate in these belts. This chart is based primarily on the cross-section shown in Plate 3 and study of many exposures in the region. Note that between Birmingham and the Lookout Valley in northwest Georgia the unconformity that occurs between the Chickamauga Limestone and the Sequatchie Formation becomes less and less pronounced, to where the entire sequence becomes conformable. The position of the K-bentonites in the various sections confirms this observation.


NORTHWESTERN
SYSTEM
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BIRMINGHAM AREA
Alabama
MURPHREES VALLEY
Alabama
BIG WILLS VALLEY
Alabama
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ORDOVICAN (UPPER)
CINCINNATIAN
MOHAWKIAN
RICH
MAYS
EDEN
SHER
KIRK
ROCKL
BLACK RIVER
SEQUATCHIE FM.
CHICKAMAUGA LIMESTONE
SEQUATCHIE FM.
CHICKAMAUGA GROUP
"HERMITAGE FACIES"
"CARTERS FACIES"
SEQUATCHIE FM.
CHICKAMAUGA GROUP
NASHVILLE FM.
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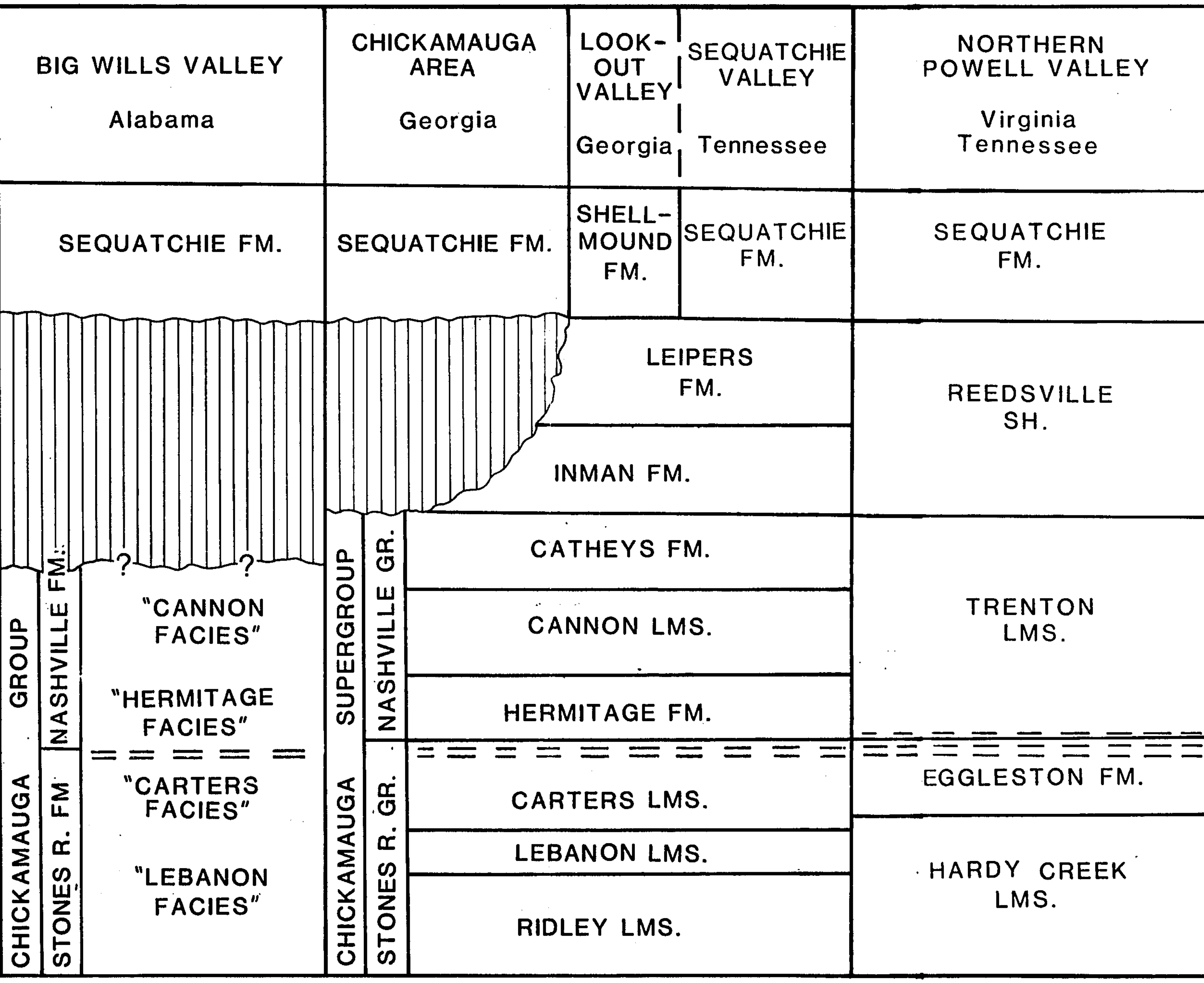
NORTHWESTERN VALLEY AND RIDGE: VIRGINIA T



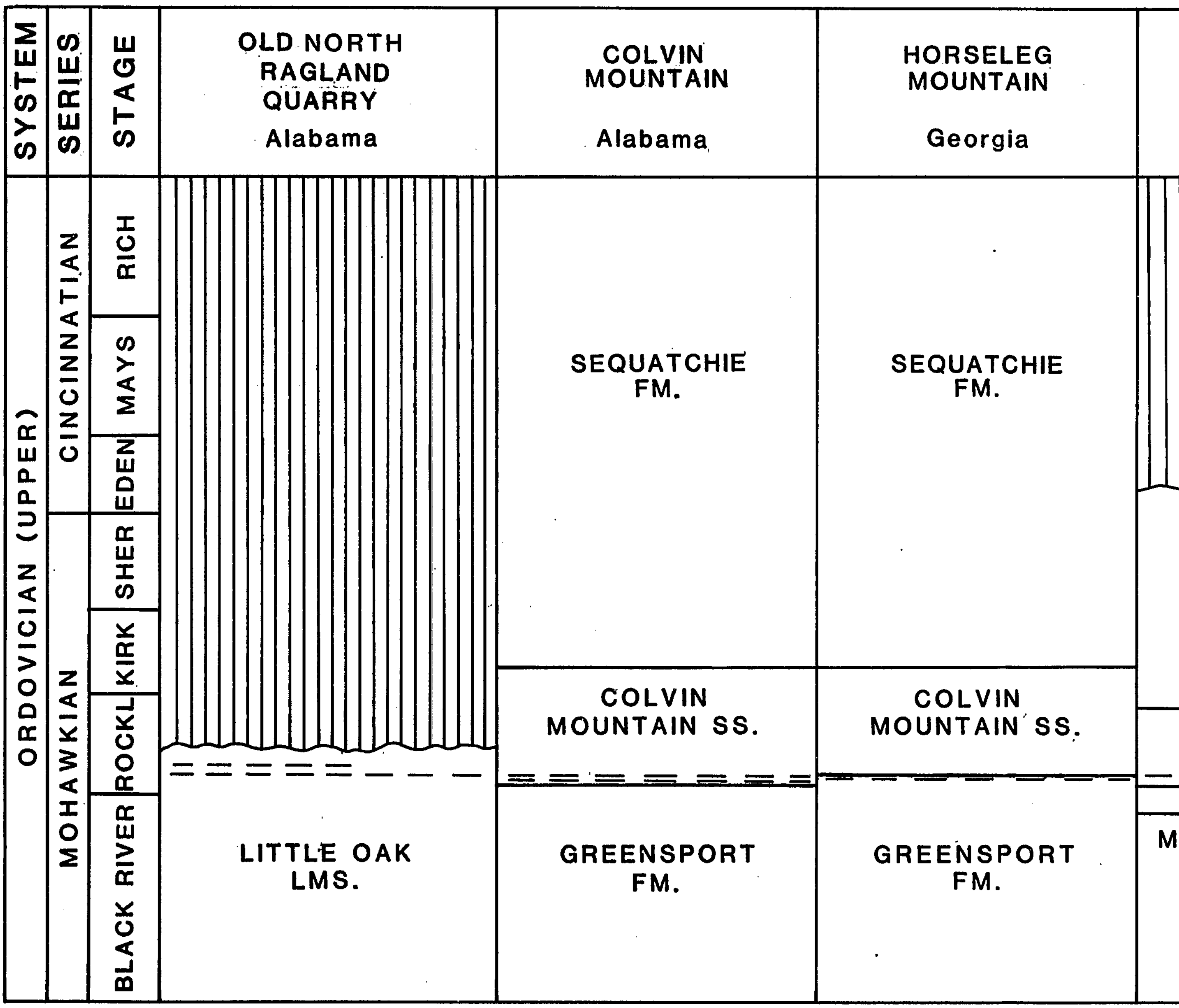
A TO ALABAMA

CLINCH VALLEY Virginia Tennessee	NEW RIVER VALLEY Virginia	RICH PATCH VALLEY Virginia	
JUNIATA FM.	JUNIATA FM.	JUNIATA FM	
TRENTON ("MARTINBURG") FM.	TRENTON ("MARTINSBURG") FM.	OSWEGO SS.	
		REEDSVILLE SH.	
		DOLLY RIDGE FM.	
EGGLESTON FM. (TN / VA)	EGGLESTON FM.	EGGLESTON FM.	V-7 M D
MOCCASIN FM.	WALKER MOUNTAIN SS. MOCCASIN FM.	EDINBURG FM.	
WITTEN FM.	WITTEN FM.		

Figure 49.

Correlation chart for the K-bentonites in strata along the southeastern Valley and Ridge. Clastics of the Blount Group predominate in this belt. Refer to Figures 9 and 10, and the cross-section shown on Plate 4. Note that the Deicke is present in the Colvin Mountain Sandstone in Alabama and Georgia, but it is absent from the Bays Formation in Tennessee and Virginia. Although many authors have previously shown detailed correlation charts for various K-bentonite sequences in the carbonate belts, this is the first time that correlation charts for the K-bentonites in the clastic belts have been illustrated in the detail shown in this figure and in Plates 4, 5, and 6.

SOUTHEASTERN VALL



STERN VALLEY AND RIDGE: VIRGINIA TO ALABAMA

HORSELEG MOUNTAIN Georgia	BAYS MOUNTAINS Tennessee	SOUTHWESTERN BIG WALKER MOUNTAIN Virginia	CROCKETT COVE Virginia
SEQUATCHIE FM.		JUNIATA FM.	JUNIATA FM.
	TRENTON ("MARTINSBURG") FM.	TRENTON ("MARTINSBURG") FM.	TRENTON ("MARTINSBURG") FM.
COLVIN OUNTAIN SS.	BAYS FM.	BAYS FM.	BAYS FM.
REENSPORT FM.	MIDDLE SANDSTONE MBR. BAYS FM.	WALKER MOUNTAIN SS. BAYS FM.	WALKER MOUNTAIN SS. WITTEN FM.

RGINIA TO ALABAMA

VESTERN /ALKER NTAIN ginia	CROCKETT COVE Virginia	ROANOKE AREA Virginia	FINCASTLE AREA Virginia
TA FM.	JUNIATA FM.		
NTON NSBURG") M.	TRENTON ("MARTINSBURG") FM.	TRENTON ("MARTINSBURG") FM.	MARTINSBURG FM.
S FM.	BAYS FM.	BAYS FM.	FINCASTLE CONGLOMERATE
MOUNTAIN SS. S FM.	WALKER MOUNTAIN SS. WITTEN FM.	EDINBURG (LIBERTY HALL) FM.	PAPERVILLE SH.

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DISCUSSION

Petrology of the Deicke and Millbrig Precursor Ashes and the Origin of the K-bentonites

In hand samples, the presence of abundant biotite and quartz immediately distinguishes the Millbrig from the Deicke, which is itself recognizable by the presence of abundant Fe-Ti oxides. Some inferences about the original composition of the volcanic ash that has altered to the Deicke and Millbrig K-bentonites is possible based on these mineralogic differences, and on the observed differences in primary plagioclase compositions shown in Figure 16. In addition, speculation about the tectonic setting of the vents from which the ash was erupted is possible from observation of the mineralogy, spatial distribution, and internal stratigraphy of the beds. Post-depositional changes such as the alteration of original glass and the ubiquitous alteration of many feldspars, although masking many of the clues that aid in a petrologic description of less altered volcanic rocks, have not destroyed all of the clues that are helpful in describing the original ash. The mineralogy of the two beds indicates that the Deicke and Millbrig K-bentonites are derived from ashes of acid to intermediate composition.

Both beds are relatively thin but very widespread with one or more fining upward sequence, suggesting that the original ashes were airfall deposits rather than pyroclastic flow (ash-flow) deposits. This indicates that the ashes were erupted as great volumes of pyroclastic material from volcanoes that were most likely in a convergent margin setting.

The quartz and andesine in the Millbrig indicate derivation from a felsic ash, and the abundant biotite narrows the choice further; the original ash was most likely a rhyodacite. Although rhyodacites and other felsic ashes commonly contain both plagioclase and K-feldspar as primary phenocrysts, the absence in the Millbrig (and in the Deicke) of primary K-feldspar such as sanidine is not thought to reflect the composition of the original magma. The presence of biotite and quartz indicates that the magma contained abundant silica, aluminum, and potassium. Therefore, K-feldspar phenocrysts were probably present, but have since been removed by post-depositional processes. Most of the biotite, apatite, and zircon crystals are euhedral or, if broken, contain crystal faces or edges, suggesting that these grains were the first to crystallize, and were followed by crystallization of feldspar and quartz.

Although biotite in volcanic rocks is commonly highly altered and resorbed (Phillips and Griffen, 1981), the magma from which the Millbrig ash was derived was evidently more hydrous than many magmas as indicated by the presence of relatively unaltered biotites. With biotite being the only ferromagnesian mineral present, the end composition of the magma was evidently enriched in Fe and Mg, and was hydrous as well. No trace of amphiboles, pyroxenes, or other higher temperature mafic phenocrysts was observed, either as resorbed grains, highly altered cores, or otherwise. Because the Fe:Mg ratio in biotites increases with late crystallization in a magma (Phillips and Griffen, 1981), and given the relatively high Fe:Mg ratios shown in Table 3, the magma must have evolved considerably by the time eruption occurred, assuming that the composition of the biotites remained in equilibrium with the magma up to the eruption. It is evident that as the magma evolved prior to eruption, conditions favored the formation of biotite over other mafic minerals. Certainly the hydrous nature of the magma would have favored biotite over pyroxene, and evidently the prevailing P, T, and X conditions favored the formation of biotite over hornblende.

Labradorite and Fe-Ti oxides in the Deicke, together with the lack of abundant quartz, suggests that the original ash was more intermediate than the Millbrig ash. The Deicke is therefore most likely derived from a dacite or latite.

The presence of labradorite, which is more typical of andesites or basalts, points out an interesting finding. Andesites and basalts commonly contain ferro-magnesian minerals such as olivine, amphibole, pyroxene, or biotite in varying abundances (Moorhouse, 1959; Best, 1982). In contrast, the Deicke contains abundant iron-titanium minerals. There are no resorbed grains or highly altered cores of olivine, amphibole, pyroxene, or biotite, the common magnesium-bearing phenocrysts, to suggest their original presence. As shown in Figure 23, however, some of the Fe-Ti oxides appear to be anatase pseudomorphs after pyroxene, an observation that is substantiated by R. Hay (pers. comm.). All magnesium in the Deicke is now in the illite/smectite, suggesting that much of the magnesium in the original ash was in the volcanic glass. If pyroxenes were present, they also would likely have contained magnesium and iron, which is now in the clays and in Fe-Ti oxides and pyrite. Presumably the calcium, sodium, and potassium, all lithophile elements, were being incorporated into feldspars, although as noted above there are no primary K-feldspars, only many secondary ones.

Assuming that the Millbrig contained K-feldspar (now gone), quartz, biotite, and andesine phenocrysts, and the Deicke contained pyroxene (now gone), labradorite, and ilmenite phenocrysts, the assumption that the Millbrig is altered rhyodacitic ash and the Deicke is altered dacitic ash is supported by the mineralogic suites of some well-studied Cenozoic volcanic ashes (Heiken, 1972; Scarfe et al., 1982, Fisher and Schminke, 1984; Self et al., 1984; Rose and Chesner, 1987).

The composition of the original glass remains speculative for both the Deicke and Millbrig, although trace element distribution can give additional insight into their composition. Based on a plot of Zr/TiO2 - Nb/Y ratios, Huff and Turkmenoglu (1981) suggested that Ordovician K-bentonites (including Millbrig and Deicke samples) from along the Cincinnati Arch were derived from a trachyandesitic ash, with some samples derived from rhyodacitic/dacitic and rhyolitic ashes. Considering the phenocrysts present, it is obvious that the Millbrig is not derived from a trachyandesite, but this cannot be ruled out as a possible precursor of the Deicke ash given the near absence of quartz, especially if K-feldspar phenocrysts were originally present. Ongoing investigation of the trace elements in the K-bentonites will no doubt reveal additional information about the possible precursor ashes of these two beds.

The thinness but remarkable lateral extent of the Deicke and Millbrig is the most convincing evidence that these beds are ashfall deposits rather than pyroclastic flows, which tend to be much thicker with more complex stratigraphy, and are commonly welded to some extent. Most importantly, pyroclastic flows are deposited within a radius of several tens of km maximum from the vent, whereas windborne ash can accumulate in deposits several cm or more thick thousands of km from the vent (Fisher and Schmincke, 1984). There is no evidence of welding in the Deicke or the Millbrig, and no volcanic bombs or other near-vent deposits seem to have been present in the precursor ashes.

The Deicke and Millbrig K-bentonite beds contain some clues about the relative duration and relative volume of the eruptions that produced the original ashes. Figures 50 to 53 show details of the internal stratigraphy of the Deicke and Millbrig at selected outcrops.

At the Big Ridge section shown in Figure 50, the normal grading of the Deicke is clearly evident. The basal contact of the bed with the underlying rock, usually a chert layer, is always very sharp. The 1-2 cm thick layer of phenocryst-poor, plastic clay is present at the base of the bed throughout much of the region, immediately overlying the chert. Above this is a zone of coarse phenocrysts that grades upward into successively finer grained material. The upper contact of the bed is much less sharp than the lower contact, presumably because the upper few cm of ash was reworked into the overlying sediments. This sequence characterizes the Deicke in almost all exposures that were examined in the western carbonate belt of the Valley and Ridge from the Powell Valley in Virginia (the Hagan section) to the Big Wills Valley in Alabama (the Bruton Gap section). It suggests that the ash was erupted during a single, and very large, eruption; the grading is a result of sorting that occurred as the ash settled from the atmosphere in response to gravity.

Figure 51 shows the Deicke at the Gate City section, where the phenocrysts are much smaller than in exposures farther south, but the thin plastic clay is still present at the base. The normal grading of the bed is less noticeable in the Moccasin Formation redbeds of southwest Virginia and northeast Tennessee, and north of Gate City the thin clay is usually absent, but the bed can still be readily identified because of its red color as discussed previously.

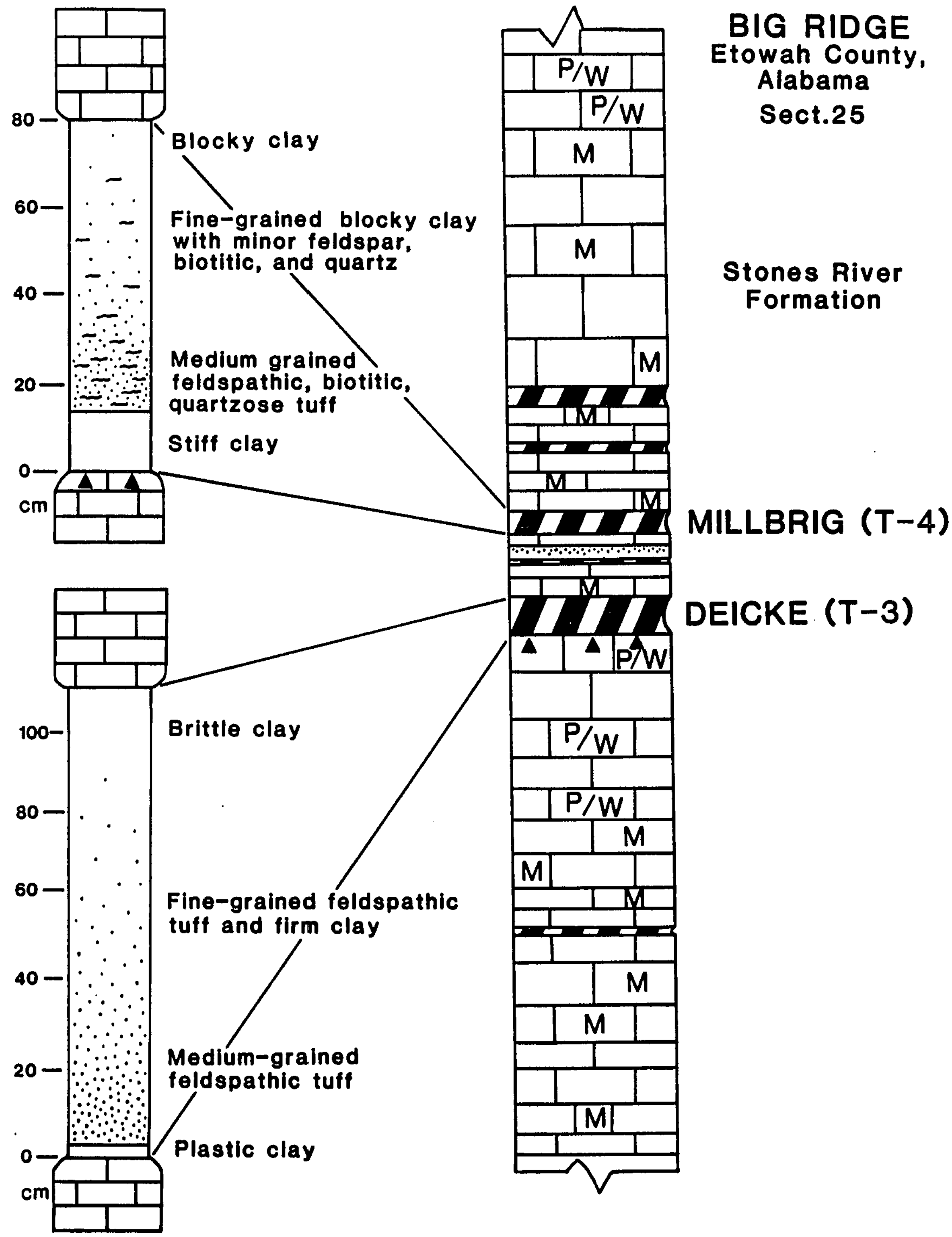


Figure 50. Details of the vertical sequence of the Deicke and Millbrig at the well-exposed section at Big Ridge, Alabama.

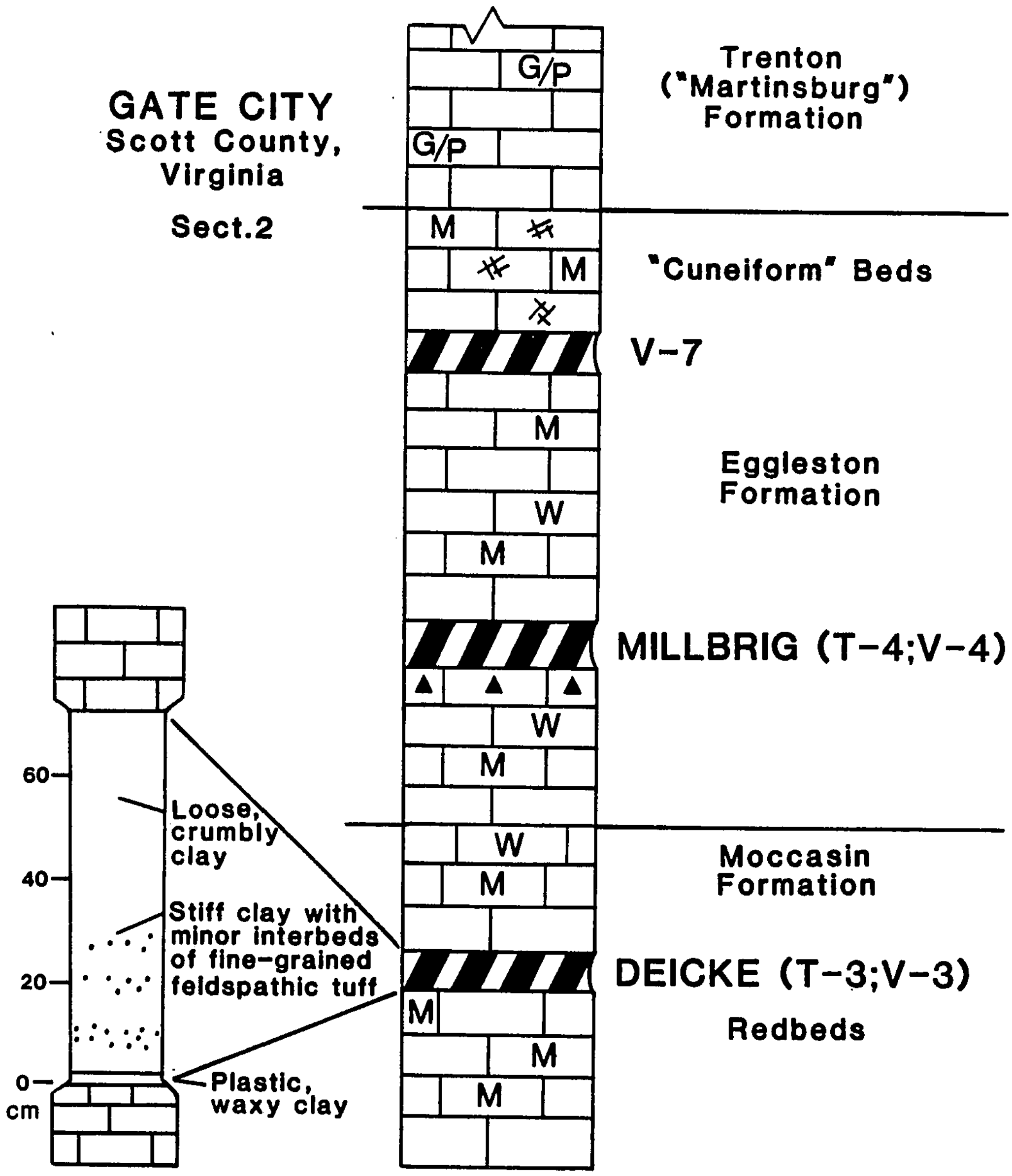


Figure 51. Details of the vertical sequence of the Deicke at Gate City, Virginia. The thin basal layer of plastic clay is characteristic of the Deicke throughout the region.

Whereas the Deicke is a simple normally graded bed, the internal stratigraphy of the Millbrig is more complex. The exposure at Big Ridge shown in Figure 50 is characteristic of the Millbrig in carbonate strata throughout much of the region. The contact of the bed with the underlying rock, again, most commonly a silicified (by chert) lime mudstone, is very sharp. Above this is a 6 to 8 cm thick layer of fine-grained clay, which was most likely a glass-rich ash. This is followed by a 15 to 20 cm thick layer that contains the coarsest phenocrysts found in the bed; this second layer generally grades upward rather abruptly into successively finer grained, and thus more clay-rich, material. The upper contact of the bed is, like the Deicke, less distinct than the lower contact because the ash was reworked into the overlying sediments. This sequence suggests that the first layer of ash to accumulate was phenocryst poor, and therefore shard rich, and that the following layer of ash contained a much higher volume of phenocrysts. This second layer is normally graded and suggests simple gravity sorting, like the sequence present in the Deicke. Throughout this region, therefore, the Millbrig appears to consist of two separate ashfalls, a lower clay-rich layer that was presumably a shard-rich ash, and an upper layer that is phenocryst-rich at the base grading into a more clay-rich zone to the top.

Where the Millbrig occurs in the clastic strata of the eastern Valley and Ridge, the sequence is very similar as shown in Figure 52, the Crockett Cove section. There, a layer of coarse phenocrysts occurs near the base of the bed, but even in the upper parts of the bed there is still a relative abundance of coarse phenocrysts. The presence of abundant biotite in the sandstones immediately overlying the bed, particularly along bedding planes, is clear evidence that some reworking of the ash occurred, and is the most plausible explanation for the poorly defined upper contact of the bed in many exposures.

There is evidence that the Millbrig contains two additional ashfall deposits. In a quarry near Shelbyville in the Nashville Dome, three separate fining upward sequences containing a phenocryst-rich layer grading into a clay-rich layer are present, as shown in Figure 53. There is a fourth layer, the lowest, which is clay-rich with no underlying phenocryst-rich layer, similar to the sequence observed in the Millbrig at Big Ridge and elsewhere. The upper two graded units are relatively thin compared with the lower graded unit and the lowermost clay-rich layer. These two graded beds were not observed elsewhere, but their thinness suggests that they would have been obliterated by significant reworking. The surrounding carbonates of the Carters Limestone were deposited in a relatively low-energy tidal environment, and reworking of the ash was evidently minor. This exposure at Shelbyville is the clearest evidence that, unlike the Deicke, the Millbrig is composed of more than one ashfall, and it is indicates that at least

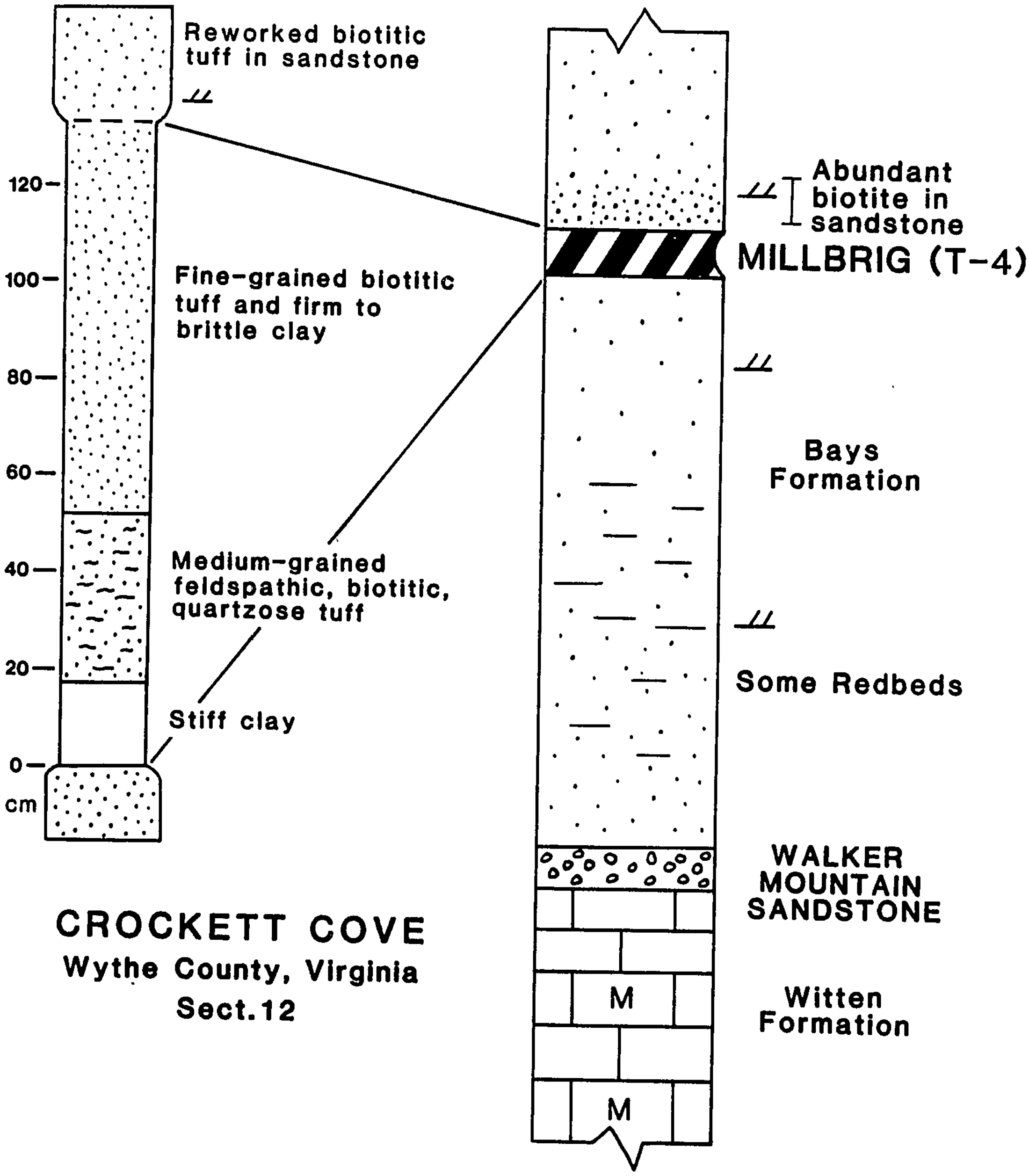


Figure 52. Details of the vertical sequence of the Millbrig at Crockett Cove, Virginia. The overlying sandstone contains abundant biotite throughout, indicating that the uppermost ash was reworked.

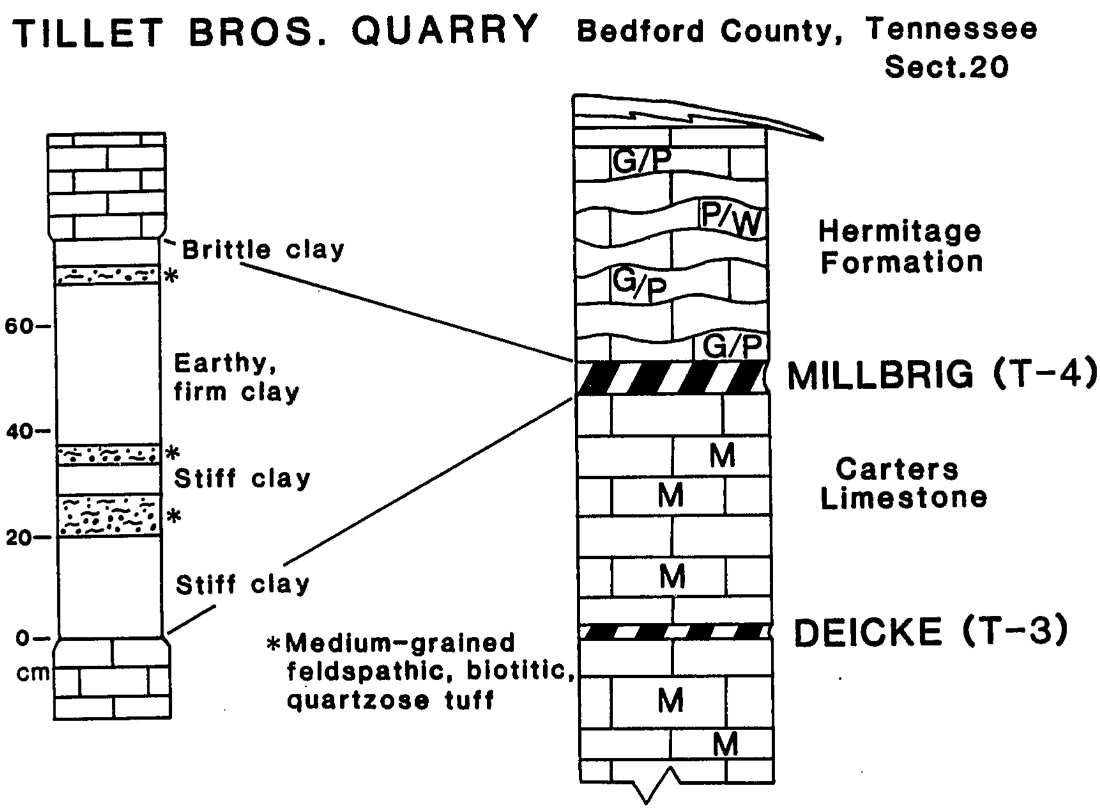


Figure 53. Details of the vertical sequence of the Millbrig at the Tillet Brothers Quarry near Shelbyville, Tennessee. This is the only known exposure of the Millbrig that contains the discrete thin layers of coarse-grained biotitic tuff above the thicker layer of coarse-grained tuff that normally occurs 8-20 cm above the base of the bed.

four separate events of ashfall accumulation occurred, beginning with a shard-rich ash and followed by at least three phenocryst-rich ashes. West of the Cincinnati Arch probably only one ashfall is present in both the Deicke and Millbri, as indicated by their thinness and relative textural homogeneity in the upper Mississippi Valley.

The Deicke and Millbrig precursor ashes were deposited over a very large area, estimated to be at least 600,000 km2 (D. Kolata, pers. comm.). These beds are now recognized from Birmingham, Alabama to Roanoke, Virginia (Plate 3), a distance of about 800 km, and from St. Paul, Minnesota south to Missouri (Kolata et al., 1986), and east to the Cincinnati Arch and the Valley and Ridge (Kolata et al., 1984; Plates 1 and 2, this study), a distance of about 1300 km. Obviously much more pyroclastic material must have been deposited between the present easternmost exposures of the beds and the actual volcanic vents. Considering this additional material, the Deicke and Millbrig K-bentonites are comparable in volume and aerial extent to some of the largest eruptions known. Fresh ash from the Tambora eruption of 1815 was reported in accumulations of 1 cm up to 1000 km from the vent, and at least 175 km3 of pyroclastic material was erupted in a 24 hour period, one of the largest eruptions of ash from an explosive volcanic event during the last 10,000 years (Self et al., 1984). By comparison, ash from the Toba eruption 75,000 years ago has been found 3100 km distant, and a minimum of 800 km3 of ash alone is thought to have been erupted (Rose and Chesner, 1987). When compaction of the Deicke and Millbrig is considered, a conservative estimate for the present volume of each bed is 330 km3 (D. Kolata, pers. comm.). Add to this the volume of additional ash and other pyroclastic material that is now metamorphic rock in the Piedmont of the eastern U.S., or has perhaps been subducted, eroded, or otherwise lost to study, it is apparent that both the Deicke and Millbrig ashes were the product of eruptions that were probably comparable in volume and lateral extent to the Toba eruption.

The volcanoes from which this ash erupted may have been part of a continental margin in a convergent tectonic setting, although without additional trace element data to compare these beds with modern pyroclastic ashfalls, this cannot be definitively resolved. Felsic magmas are commonly generated in subduction zones, and volcanic rocks generated in these settings are typically comprised of andesitic to rhyolitic pyroclastic material (Fisher and Schmincke, 1984).

Burial History as Inferred from Petrographic Evidence

The new findings on the petrography of the Deicke and Millbrig can be used to draw inferences about the post-depositional burial history of the two beds, which began as volcanic ash and ended up as K-bentonites. Important evidence that helps explain the observed spatial variations in authigenic feldspar and clay mineral compositions comes from studies of modern and ancient sedimentary basins.

Changes in feldspar and I/S mineralogy in the two beds across the study area from northwest to southeast suggest that the beds were exposed to significantly higher burial temperatures in the Valley and Ridge than along the Cincinnati Arch. These findings are in agreement with the work by Harris and others (1978), which established thermal gradients for the Ordovician of this region based on changes in conodont colors. Thermal gradients as determined for Ordovician strata reflect in large part the systematic increase in thickness of the sediment pile from west to east across the Appalachian Basin, although some interesting anomalies discovered by Harris and others (1978) are discussed in the following section.

Feldspars

Petrographic study of samples as discussed previously shows that authigenic albite is present in samples from the Valley and Ridge, where the entire Paleozoic sequence is thousands of meters thick, but that albite is absent in Cincinnati Arch samples, where the Paleozoic sequence is much thinner. Huff and Turkmenoglu (1981), while mentioning the abundant K-feldspar in some K-bentonites from the Cincinnati Arch, also did not observe any albite in their samples. If albite had been present in these beds at some previous time, petrographic evidence should indicate its former presence. This evidence could include relict albite grains, patches of albite within secondary feldspar (or other) grains, or "floating" grains (the space that results when a grain dissolves completely), but no evidence for albite was seen. Although it is perhaps reasonable to argue that any albite which was once present has since been replaced by authigenic K-feldspar, which is abundant in the region, some traces of albite would be expected to remain. Studies of rocks in which various authigenic minerals have formed, dissolved, and reformed show that traces of the earlier phases are observable in thin-section, either because actual slivers of the mineral still remain, or later mineral phases have psuedomorphed earlier ones (Walker, 1984; many papers in Scholle and Schluger, 1979). This evidence suggests that albite was never present along the Cincinnati Arch.

Several studies of feldspathization, particularly albitization, in sedimentary basins show that the formation of authigenic albite versus K-feldspar is closely tied to maximum burial temperatures, and therefore to the geothermal gradient and depth of burial. Gold (1987), Fisher and Land (1986), Boles (1982), Land and Milliken (1981), and Hower and others (1976) have studied feldspars from Tertiary strata of the U.S. Gulf Coast; Table 5 summarizes the pertinent findings. Unlike those studies, which had to be concerned with differentiating detrital feldspar cores from authigenic feldspar rims etc., the volcanic origina of feldspars in the Deicke and Millbrig in the carbonate sequences is clear. All feldspars present are either

Authors	Region	Formation and Age	Zone of Albitization		Zone of K-feldspar Disappearance		Zone of Intermediate Plagioclase Disappearance	
			Depth (m)	Temperature (°C)	Depth (m)	Temperature (°C)	Depth (m)	Temperature (°C)
Hower et al. (1976)	Texas Gulf Coast	Anahuac and Frio Formations (Miocene and Oligocene)	*	--	3100-3500	80-90	--	--
Land and Milliken (1981)	South-central Texas Gulf Coast	Frio Formation (Oligocene)	3350-4270	120-150	3600-4600	130-160	3600-4200	130-150
Boles (1982)	South Texas Gulf Coast	Frio Formation (Oligocene)	2500-2800	110-120	--	--	2600-2900	115-125
		Wilcox Group (Eocene)	≤3660	≤150	--	--	--	--
Walker (1984)	East flank of the Front Range, Colorado	Fountain Formation (Pennsylvanian)	≤3500	--	3100-3500	--	3100-3500	--
Fisher and Land (1986)	South-central Texas Gulf Coast	Wilcox Group (Eocene)	2500-3500	120-160	2800-3200	140-150	2600	130
Gold (1987)	South-east Louisiana Gulf Coast	Unspecified Miocene sandstones	3600->5000	100->150	4800-5600	125-140	3600-5000	100-130

*Authors noted that albite was present at all depths, but that it was more abundant in samples from greater depths.

Table 5. Depths and temperatures of albitization and accompanying feldspar diagenesis as reported in 6 studies.

primary phenocrysts associated with the original ash, or authigenic feldspars formed during burial diagenesis; there has been no transport and redeposition of feldspars.

As shown in Table 5, albitization of detrital plagioclase grains and dissolution of detrital K-feldspar grains occur with greater frequency at increasing depths, and regardless of depth albitization of original intermediate plagioclase begins occurring at temperatures of 110-140°C given a suitable pore water chemistry. As temperatures rise above this range, albite remains stable, but intermediate plagioclase and K-feldspar disappear relatively rapidly (Hower et al., 1976). The reported range of temperature at which intermediate plagioclases disappear is thus relatively slight. This narrow range is important when comparing depths (and thus lithostatic pressure) at which albitization is occurring in the studies. In the areas studied by Land and Fisher, and Boles, 110°C was reached at around 2500 m, while in Gold's study area 110°C was not reached until a depth of around 4000 m.

In a similar study of older strata, albitization of K-feldspars was reported by Walker (1984) in samples from two cores of the Pennsylvanian Fountain Formation near Denver, Colorado. Although a discussion of composition versus depth and temperature was not included, the core samples were from depths of around 3300 m; assuming an average geothermal gradient in this area, the minimum temperature at that depth would be around 100°C. Authigenic albite was present in both cores, and Walker notes that in many thin-sections K-feldspar is completely absent. This depth (and probable temperature), which is evidently where albitization occurs and K-feldspar begins to disappear in the Fountain, closely matches the results of the Gulf Coast studies.

These findings support the contention of Hay (1966), who argued that albite authigenesis in sedimentary and volcanic/volcaniclastic rocks occurs at depths greater than about 3300 m, and that the volume of authigenic albite present increases with greater depths of burial. For albitization to occur, a minimum temperature of about 110°C evidently must be reached according to these studies. At lower temperatures, albite authigenesis apparently does not take place.

Authigenic K-feldspar is the other authigenic feldspar present in the Deicke and Millbrig. Mineralogic studies of modern and ancient basins also suggest reasons for the observed distributions of feldspars in the two beds between the Cincinnati Arch and the Valley and Ridge. An important finding of these studies is that, while authigenic albite formation is not favored until temperatures of around 110°C or higher are reached, authigenic K-feldspar can form under near-surface conditions in shallowly buried sediments, at relatively low temperatures. Hay (1962) studied authigenic K-feldspar in tuffs and tuffaceous claystones of the Tertiary John Day Formation in northern Oregon and reported that primary intermediate plagioclase was replaced by K-feldspar (orthoclase, in that case) of essentially end-member composition. The orthoclase occurs in strata that were probably buried under no more than 750 m of rock, and may have been buried under only 130 m. Temperatures would have been between 20-40°C. Studies of authigenic K-feldspar in the Ordovician Tribes Hill Formation of New York (Buyce and Friedman, 1975), the Ordovician St. Peter Sandstone of northern Illinois and Wisconsin (Odom et al., 1979) and Permo-Triassic sandstones of Great Britain (Waugh, 1978; Ali and Turner, 1982) also suggest that these grains formed at relatively low temperatures in sediments which have never been deeply buried.

Evidence from field studies of feldspathization in sedimentary basins thus suggests that authigenic K-feldspar will form at relatively low temperatures and relatively shallow burial depths, whereas albite authigenesis requires higher temperatures and greater depths of burial. Additionally, authigenic albite persists at temperatures at and above the range in which dissolution of K-feldspar and primary intermediate plagioclase occurs. In the present study, the lack of albite along the Cincinnati Arch combined with the abundance of K-feldspar suggests maximum burial temperatures for that region of less than 110°C, implying that, assuming a normal geothermal gradient, maximum burial depth was less than about 2000 m along the Cincinnati Arch. Conversely, the abundance of authigenic albite in much of the Valley and Ridge implies that temperatures throughout most of that region reached at least 110°C. This is expected, given the thicker Paleozoic sequence there as compared with the Cincinnati Arch. The maximum temperature reached in the Valley in Ridge is uncertain, but the presence of K-feldspar and primary intermediate plagioclase in the western belts suggests that it was not much higher than 140°C in those belts, based on the findings shown in Table 5. In the eastern belts, where the K-bentonites occur in clastics of the Blount Group, a maxiumum temperature cannot be determined based on feldspars, because so few were observed in thin section. Morad (1988a) describes detrital microcline grains which, although albitized to a great extent, are still recognizable in Precambrian sandstones of Norway that have evidently been subjected to burial temperatures of 250-350°C. Obviously the results of the Gulf Coast studies may not apply universally, but they are very useful in helping to explain many of the observations in the two K-bentonites.

Thermal gradients alone do not cause basin-wide variations in feldspar mineralogy of the Deicke and Millbrig of course, for without chemically suitable pore waters sub-metamorphic temperature changes will do little to the existing minerals. Therefore the geochemistry of feldspathization reactions needs to also be considered. Equilibrium thermodynamics can help to predict the assemblages that are favored given certain geochemical conditions. Many studies have pointed out, however, that because the equilibrium solubilities of smectite and illite are poorly known, feldspar authigenesis in sedimentary and volcanic/volcaniclastic rocks where these minerals are thought to be involved in the reaction is not as readily explained with thermodynamics. Nevertheless, the combination diagrams of Helgeson, Garrels, and Mackenzie (1969) as discussed by Kastner and Siever (1979) are very useful in understanding feldspar authigenesis in low temperature environments. These diagrams are shown in Figure 54. It is clear from the activity diagrams that authigenesis of albite and K-feldspar is favored under the geochemical conditions that prevail in interstitial waters, which is the setting in which authigenesis presumably occurred in the Deicke and Millbrig.

These and other studies discussed below discuss many chemical reactions can occur under sedimentary conditions. Albitization of plagioclase can occur as follows:

1) $Na^{+} + H_4SiO_4 + NaAlSi_3O_8 \cdot CaAl_2Si_2O_8 =$

$$2NaAlSi_3O_8 + Al(OH)_4^{-} + Ca^{2+}$$

Replacement of plagioclase by K-feldspar is similar:

2) $2K^{+} + H_4SiO_4 + NaAlSi_3O_8 \cdot CaAl_2Si_2O_8 =$

$$2KAlSi_3O_8 + Al(OH)_4^{-} + Na^{+} + Ca^{2+}$$

The Ca released during the above reaction may form calcite, which is abundant in many samples of the K-bentonites, so another possible reaction of plagioclase would be:

3) $3K^{+} + 2H_2CO_3 + 3NaAlSi_3O_8 \cdot 2CaAl_2Si_2O_8 + 2H_2O =$
$3Na^{+} + 3KAlSi_3O_8 + 2Al_2Si_2O_5(OH)_4 + 2CaCO_3$

If sufficient Na or K were present, under the right geochemical conditions the kaolinite produced from this reaction could form additional authigenic feldspar:

4) $Al_2Si_2O_5(OH)_4 + 2K^{+} + 4H_4SiO_4 = 2KAlSi_3O_8 + 9H_2O + 2H^{+}$

5) $Al_2Si_2O_5(OH)_4 + 2Na^{+} + 4H_4SiO_4 = 2NaAlSi_3O_8 + 9H_2O + 2H^{+}$

In addition to replacing plagioclase, albite can replace an igneous K-feldspar grain such as sanidine:

6) $Na^{+} + (K,Na)AlSi_3O_{8(san)} = NaAlSi_3O_8 + K^{+}$

Primary sanidine is not preserved in the Deicke and Millbrig K-bentonites, but it is likely that sanidine was present in the original ash and has since been replaced by authigenic albite or K-feldspar. Replacement of an igneous K-feldspar grain by an authigenic K-feldspar involves the uptake of some K and the release of Na, with the formation of a nearly pure K-feldspar:

7) $K^{+} + (K,Na)AlSi_3O_{8(san)} = KAlSi_3O_{8(auth)} + Na^{+}$

Primary igneous K-feldspars such as sanidine or microcline contain minor Na in solid solution. During albitization some Na ions may be released to solution along with the K ions, but most would probably be incorporated in the newly forming albite grain. A significant additional source of Na is required for the formation of albite from K-feldspar, and if the K-feldspar being albitized is itself authigenic, even more Na would be required for albite authigenesis, as these K-feldspars contain very low amounts of Na:

8) $>>Na^{+} + KAlSi_3O_{8(auth)} = NaAlSi_3O_8 + K^{+}$

Because the Deicke and Millbrig are K-bentonites, they are assumed to have originally contained abundant volcanic glass, which presumably altered to smectite at some time after burial. Smectite can alter to authigenic albite or K-feldspar as follows:

9) $Na(Al_5Mg)Si_{12}O_{30}(OH)_6 + 4Na^{+} + 3H_4SiO_4 =$
$5NaAlSi_3O_8 + 8H_2O + 2H^{+} + Mg^{2+}$

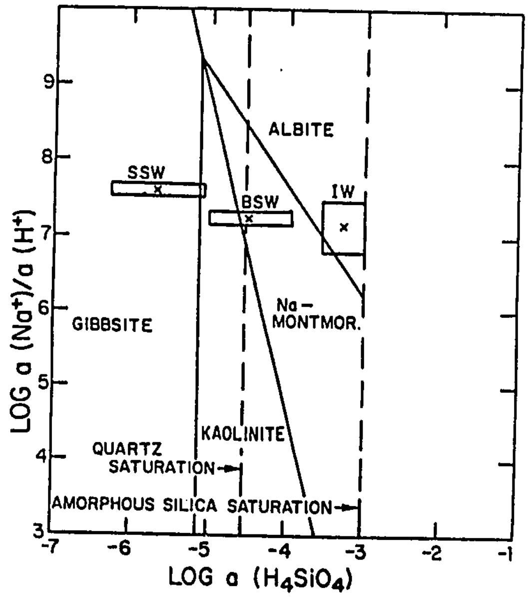
10) $Na(Al_5Mg)Si_{12}O_{30}(OH)_6 + 5K^{+} + 3H_4SiO_4 =$
$5KAlSi_3O_8 + 8H_2O + 2H^{+} + Na^{+} + Mg^{2+}$

The reactions in equations 1, 2, 3, and 8 appear to have occurred in the Deicke and Millbrig based on thin-section analysis of several samples from the Valley and Ridge, and the reations in equation 4, 5, 6, 7, 9, and 10 may have occurred as well based on the probable composition of the precursor ashes as discussed previously.

Feldspar authigenesis requires a supply of Al, Si, and K or Na ions, as evident from the above equations. In the marine environment sea water is an abundant source of K and Na ions, with sources of Si ions being biogenic silica or volcanic glass. Aluminum, which is less mobile in sedimentary environments, is thought to come from the alteration of various detrital aluminosilicates. Changes in pH will determine the activity of H^+ and OH^-, which may be important in determining the direction in which many of the above reactions will proceed.

In an early study of K-feldspar (orthoclase) authigenesis in Cenozoic tuffs, Hay (1962) noted that although theoretical calculations available at that time indicated that a minimum K^+/H^+ activity ratio of 10^9 was necessary for the formation of orthoclase at temperatures of 20-40°C, the actual K^+/H^+ ratio in the tuffs was more likely 2.5 to 3 orders of magnitude less, yet authigenic orthoclase formed in abundance nonetheless. Citing data on the composition of oil-field brines and on K-feldspar authigenesis at shallow depths in deep-sea cores, Hay (1962) suggested that the K^+/H^+ ratio in the interstitial waters of the tuffs had been closer to $10^{5.5}$ to 10^{6}, supporting his contention based on field observations that authigenic K-feldspar could form at low temperatures when the K^{+}/H^{+} ratio in the surrounding aqueous solution was significantly lower than 10^{9}. As shown in Figure 54, more recent calculations than those available for citation by Hay in 1962 have supported Hay's view on the necessary and sufficient geochemical requirements in aqueous environments that will favor feldspar authigenesis. The fields in the two diagrams for interstitial water are within the albite and K-feldspar stability fields when the activity of amorphous silica is between 10^{-3} and $10^{-4.5}$. Given the abundance of volcanic glass in tuffs and other volcanic and volcaniclastic rocks, amorphous silica would likely be present in interstitial waters in sufficient concentrations to favor feldspar authigenesis. The paper by Kastner and Siever (1979) summarizes this problem, suggesting that the minimum geochemical requirements for authigenic feldspars to form are: 1) an aqueous solution in which a source of Al is present, most likely as $Al(OH)_4^-$; 2) the presence of aluminosilicate minerals, if a dissolved Al species is not stable, and 3) the K^{+} and/or Na^{+} to H^{+} and H_4SiO_4 ratio must be relatively high.

In some low temperature environments, there is the geochemical problem of identifying suitable sources of the Na and K ions that are necessary for authigenic albite and K-feldspar (and I/S as well) to form. This problem is particularly perplexing in carbonate rocks containing



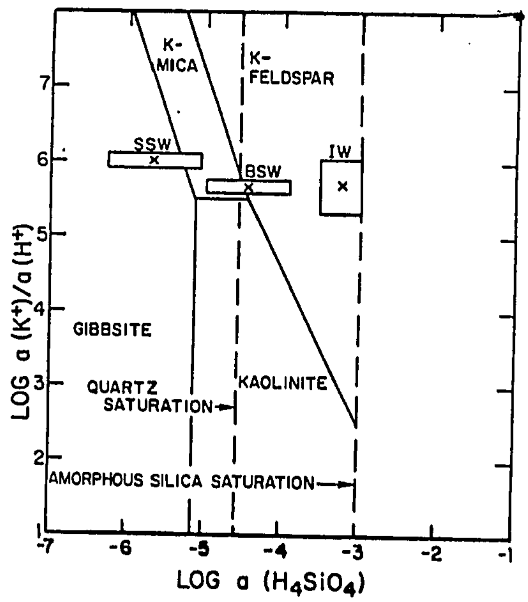


Figure 54. A) Activity diagram for the system Na_2O-Al_2O_3-SiO_2-H_2O at 0°C, unit activity of water, and 1 atm. B) Activity diagram for the system K_2O-Al_2O_3-SiO_2-H_2O at 0°C, unit activity of water, and 1 atm. From Kastner and Siever (1979, Figs. 3 and 4) after Helgeson, Garrels, and Mackenzie (1969).

SSW = surface sea water, BSW = bottom sea water, IW = interstitial water.

authigenic feldspars, as there is very little potassium or sodium available, unlike shales and other clastics, which contain relative abundances of clays and detrital aluminosilicate minerals. Alteration of felsic volcanic glass, a metastable material, releases Ca, Na, K, and Si ions, and Buyce and Friedman (1975) suggested that the alteration of pyroclastic material (now gone) was the source of the potassium, aluminum, and silicon that was incorporated into authigenic K-feldspar in an Ordovician carbonate of New York. Authigenic feldspars are relatively common in many carbonate rocks, but pyroclastic material is much less common. This problem was addressed by Kastner and Siever (1979), who showed that authigenic feldspar could form in a limestone that contains only 5 % biogenic silica and 5 % detrital aluminosilcate minerals (smectite, illite, quartz, and feldspar), and with an interstitial water composition similar to seawater except for slightly higher H_4SiO_4 activity.

The source of the necessary Na, K, Al, and Si ions in the Deicke and Millbrig is assumed to have been the original volcanic glass in the precursor ashes, with some contribution coming from the original phenocrysts, particularly feldspars, many of which are now partly or totally replaced. Jezek (1976) reported that the maximum K O content of glass shards from ash layers on the Fiji Plateau was slightly less than 5 % of the total, so it is evident that, unless the glass in the Deicke and Millbrig precursor ashes contained an unusually high K_2O content, an additional source of K would have been required for feldspar authigenesis, as well as for illitization. This is especially true where the beds are found in carbonates such as the Tyrone Limestone of the Jessamine Dome, which is quarried on account of its extreme purity, having a very low SiO_2 content. In the clastics of the Bays Formation, of course, more potassium would likely have been available.

The lack of overgrowths on the quartz phenocrysts of the Deicke is surprising considering the amount of silica that must have been mobilized in the past. The presence of chert layers, which are commonly several cm thick, immediately beneath the K-bentonite beds in carbonate strata (e.g. Plate 1) and the silica-cemented sandstones immediately beneath the beds in clastic strata attest to the mobilization and subsequent precipitation of a significant volume of SiO_2. This excess silica was most likely released to solution during devitrification of the original volcanic glass (Fisher and Schmincke, 1984) and during the illitization of smectite (Perry and Hower, 1970; Boles and Franks, 1979).

The geochemical conditions favoring authigenic albite formation at low temperatures are theoretically only slightly different from those favoring authigenic K-feldspar formation (Kastner and Siever, 1979). Given a pore water with a suitable $K^+/K^+ + Na^+$ ratio, it is instead differences in pore-water temperature -- rather than composition -- that are theoretically more significant in determining the compositions of authigenic feldspars formed in sedimentary environments. As stated by Kastner and Siever (p. 162):

> ... the geochemical environment of authigenic albite formation does not need to differ appreciably from the geochemical environment of authigenic K-feldspar formation. A continuous change in the $K^+/(K^+ + Na^+)$ ratio may cause an abrupt mineralogical change. Albite will be stabilized by an isochemical increase in temperature, which would shift the equilibrium $K^+/(K^+ + Na^+)$ ratio toward the K side. Thus, medium to higher temperature diagenetic environments are more favorable for the formation of authigenic albite.

Therefore, when pore-water chemistry conditions conducive to forming authigenic feldspars as shown in equations 1-10 are present, temperature will be the main factor that decides which way the various reactions will proceed, and thus which feldspars will dissolve and which will form authigenically. This experimental evidence supports the findings of feldspathization in sedimentary basins shown in Table 5.

Evidently pressure has little effect on the reactions at these low temperatures as discussed by Kastner and Siever and as shown in Table 5, where the feldspathization reactions are temperature dependent rather than depth, and therefore pressure, dependent.

In summary then, the total lack of albite in samples from along the Cincinnati Arch suggests that either maximum burial temperatures were never high enough for authigenic albite to precipitate, or, that post-depostional geochemical conditions along the Cincinnati Arch differed significantly from those in the Valley and Ridge.

Based on various lines of evidence, arguments in favor of the latter have been suggested that during the Late Pennsylvanian to Early Permian, Paleozoic rocks of the eastern and midwestern U.S. were soaked with hot potassic brines derived from the dewatering of muds/shales in the Appalachian and Ouachita orogenic belt, part of which is now the Valley and Ridge (Hearn and Sutter, 1985; Leach and Rowan, 1986; Oliver, 1986; Duane and de Wit, 1988). It is hypothesized that as these brines migrated cratonward, they reacted with the host rocks, driving the illitization of smectite in bentonites, making them K-bentonites (Elliott and Aronson, 1987), and as the brines cooled and reacted with the host rocks, various authigenic minerals were formed, including authigenic K-feldspar (Hearn and Sutter, 1985; Leach and Rowan, 1986; Duane and de Wit, 1988). Roedder (1979), in a discussion of fluid inclusion evidence for widespread movement of brines through sedimentary rocks, suggested that many Mississippi Valley type ore deposits formed from such brines, as did crystal-lined geodes, many carbonate and quartz cements, some saline and sulfur deposits, and the minerals from such well-known collecting localities as Herkimer, New York and Clay Center, Ohio. Roedder did not specifically mention the dewatering of sediments in an active orogenic zone as a possible source of such brines, but it is clear that his observations are consistent with that idea as put forth in the more recent papers.

As explained by that hypothesis, the lack of albite in the Deicke and Millbrig along the Cincinnati Arch would reflect the cooling of the brines as they migrated away from the orogenic belt; the formation of K-feldspar instead of albite would become favored thermodyamically at these lower temperatures. K/Ar ages of mixed-layer illite/ smectite reported by Elliott and Aronson (1987) for selected samples of the T-3 (Deicke) and T-4 (Millbrig) K-bentonites in the southern Appalachians show that illitization occurred during the Late Pennsylvanian to Early Permian. This is the same as the K/Ar age reported by Hearn and Sutter (1985) for authigenic K-feldspar in the Conococheague Limestone (Cambrian) of western Maryland.

Migrating brines can explain many of the observations in the Appalachian basin, and they provide a convenient source of potassium for K-feldspar authigenesis in the carbonate rocks along the Cincinnati Arch, but the hypothesis does not as easily explain the feldspar distributions of the Gulf Coast Tertiary (Table 5). That area is not and has never been adjacent to an active orogenic belt, and no brines have been squeezed through those strata as the result of regional orogenic activity. While brines are present in the Gulf Coast sequence, those brines are static compared to the migrating brines hypothesized by the above studies to have moved through the

Appalachian and Ouachita foreland basins. The data listed in Table 5, together with the preceding discussion on the geochemistry of feldspar authigenesis, imply that the distribution of albite versus K-feldspar and primary plagioclase in the Tertiary sections is closely linked to temperature, which is a function of geothermal gradient. With regard to the K-bentonites, then, the distribution of authigenic feldspars suggests not only that the K^+/H^+ activity ratio in interstitial water of the K-bentonites and the surrounding carbonate strata favored feldspar authigenesis, but that maximum burial temperatures in the Valley and Ridge were higher than those in the Cincinnati Arch.

Changes in conodont color are very important clues in understanding the possible burial history of the Appalachian basin. Epstein and others (1977) determined that conodont colors change in response to temperature, not pressure. Their usefulness in understanding the thermal history of an area is well known, and the map by Harris and others (1978) and the article by Harris (1979) show the utility of the conodont color alteration index (CAI) in reconstructing the maximum burial temperatures experienced by Ordovician rocks throughout the Appalachian basin. Table 6 compares the CAI values from Harris and others (1978) with the feldspar and clay mineralogy of Deicke and Millbrig samples that were examined for the present study, including the samples listed in Table 4. It is evident that there is generally good

Sample	Conodont CAI Value (Harris et al., 1978)[1]	Authigenic Feldspar Mineralogy	Intermediate Plagioclase Present	Average % Smectite (from Table 4)	Average Ordering (fromTable 4)
DEICKE					
Cincinnati Arch					
BB5-5-1 (Kentucky)	≤1	K-feldspar	Y	23	R1
N-6 (Ohio)	≤1	K-feldspar	Y	-	-
BRM T-3 (Kentucky)	≤1	K-feldspar	Y	-	-
C-114 (Kentucky)	≤1	K-feldspar	Y	-	-
KY-VSE T-3 (Kentucky)	≤1	K-feldspar	Y	-	-
KY 6-1 (Kentucky)	≤1	K-feldspar	Y	-	-
TN 3-3 (Tennessee)	≤1	K-feldspar	Y	-	-
TN 1-2 (Tennessee)	≤1	K-feldspar	Y	-	-
CHT-3 (Tennessee)	≤1	K-feldspar	Y	-	-
T-3 Rep. (Tennessee)	≤1	K-feldspar	Y	-	-
Valley and Ridge: carbonate sections					
AL 7 (Alabama)	3	K-feldspar Albite	Y	13	R1/R3
AL 12-1 (Alabama)	2.5-3	K-feldspar Albite	Y	-	-
AL KB-35 (Alabama)	2-2.5	K-feldspar	Y	-	-
GA:DD 1-1 (Georgia)	2.5-3	K-feldspar	Y	-	-
GA:DD 2-1 (Georgia)	2.5-3	K-feldspar	Y	13	R1/R3
GA:WL 3-1 (Georgia)	2.5-3	K-feldspar Albite	Y	-	-
TN:HM 2-1 (Tennessee)	2-2.5	K-feldspar Albite	Y	-	-

Table 6. Relations of conodont CAI values, feldspar mineralogy, and clay mineralogy of selected samples.

Sample	Conodont CAI Value (Harris et al., 1978)[1]	Authigenic Feldspar Mineralogy	Intermediate Plagioclase Present	Average % Smectite (from Table 4)	Average Ordering (fromTable 4)
TN10 (Tennessee)	1.5-2	K-feldspar Albite	Y	-	-
TN 14-2 (Tennessee)	2.5-3	ID	ID	-	-
TN:HK 3-1 (Tennessee)	2.5-3	ID	ID	-	-
TN:CL 1-1 (Tennessee)	1.5-2	K-feldspar	ID	8	R3
VA 2-1 (Virginia)	2	K-feldspar Albite	ID	-	-
VA:SC 1-1 (Virginia)	2.5	K-feldspar Albite	Y	8	R3
VA:RL 2-1 (Virginia)	3.5	ID	ID	17	R1/R3
VA:TZ 1-7 (Virginia)	2.5-3	K-feldspar	ID	10	R3
VA:TZ 2-1 (Virginia)	2.5-3	ID	Y	-	-
VA:BL 1-1 (Virginia)	2.5-3	ID	ID	8	R3
VA:GI 4-0 (Virginia)	3.5-4	ID	ID	7	R3
Valley and Ridge: Colvin Mountain Sandstone sections					
AL:CH 1-2 (Alabama)	3-3.5	NP	N	15	R1/R3
AL:ET 1-2 (Alabama)	3-3.5	NP	N	2	R3
MILLBRIG Cincinnati Arch					
BB 5-2-3 (Kentucky)	≤1	K-feldspar	Y	20	R1
BRM T-4 (Kentucky)	≤1	K-feldspar	Y	-	-
KRI 5-0 (Kentucky)	≤1	K-feldspar	Y	24	R1
TN 3-8 (Tennessee)	≤1	K-feldspar	Y	-	-

Table 6. Relations of conodont CAI values, feldspar mineralogy, and clay mineralogy of selected samples. (Continued)

Sample	Conodont CAI Value (Harris et al., 1978)[1]	Authigenic Feldspar Mineralogy	Intermediate Plagioclase Present	Average % Smectite (from Table 4)	Average Ordering (fromTable 4)
TN 7-3 (Tennessee)	≤1	K-feldspar	Y	25	R1
TN 7-4 (Tennessee)	≤1	K-feldspar	Y	21	R1
Valley and Ridge: carbonate sections					
AL 3-4 (Alabama)	2-2.5	K-feldspar Albite	Y	-	-
AL 4 (Alabama)	2-2.5	ID	ID	-	-
AL KB-34 (Alabama)	2-2.5	K-feldspar Albite	Y	-	-
AL 9-1 (Alabama)	3	K-feldspar Albite	Y	-	-
AL:BL 1-1 (Alabama)	2.5-3	K-feldspar Albite	N	-	-
AL 14-1 (Alabama)	2.5-3	K-feldspar Albite	Y	-	-
AL 17 (Alabama)	2.5-3	K-feldspar Albite	Y	-	-
GA:DD 2-2 (Georgia)	2.5-3	K-feldspar Albite	Y	24	R1
GA:WL 3-2 (Georgia)	2.5-3	K-feldspar Albite	Y	13	R3
TN 11-1 (Tennessee)	1.5-2	K-feldspar Albite	Y	-	-
TN:CL 1-2 (Tennessee)	1.5-2	ID	ID	12	R1/R3
VA 4-1 (Virginia)	2	K-feldspar Albite	Y	14	R1/R3
VA:LE 1-2 (Virginia)	2-2.5	ID	ID	13	R3

Table 6. Relations of conodont CAI values, feldspar mineralogy, and clay mineralogy of selected samples. (Continued)

Sample	Conodont CAI Value (Harris et al., 1978)[1]	Authigenic Feldspar Mineralogy	Intermediate Plagioclase Present	Average % Smectite (from Table 4)	Average Ordering (fromTable 4)
VA:SC 1-2 (Virginia)	2.5	K-feldspar Albite	Y	10	R3
VA:TZ 1-8 (Virginia)	2.5-3	K-feldspar Albite	Y	-	-
VA:BL 1-2 (Virginia)	2.5-3	K-feldspar	Y	-	-
VA:BL 2-1 (Virginia)	3-3.5	Albite	Y	18	R1/R3
VA:GI 1-1 (Virginia)	3.5-4	Albite	N	6	R3
Valley and Ridge: Colvin Mountain Sandstone and Bays Formation sections					
AL:CH 1-4 (Alabama)	3-3.5	NP	N	20	R1/R3
GA:FL 1-1 (Georgia)	3-3.5	K-feldspar	N	5	R3
VA:SM 1-4 (Virginia)	3-3.5	ID	ID	12	R3
VA:WY 2-1 (Virginia)	3.5-4	ID	ID	12	R3
VA:WY 1-1 (Virginia)	3.5-4	ID	ID	3	R3
VA:RO 1-3 (Virginia)	4.4-5	ID	ID	15	R1/R3
VA:BT 2-1 (Virginia)	4-4.5	ID	ID	11	R3
V-7 Carbonate section					
VA:TZ 2-3 (Virginia)	2.5-3	ID	ID	14	R3
Bays Formation sections					
VA:RO 1-2 (Virginia)	4-4.5	ID	ID	14	R3
VA:BT 2-2 (Virginia)	4-4.5	K-feldspar	N	6	R3

Table 6. Relations of conodont CAI values, feldspar mineralogy, and clay mineralogy of selected samples. (Continued)

Sample	Conodont CAI Value (Harris et al., 1978)[1]	Authigenic Feldspar Mineralogy	Intermediate Plagioclase Present	Average % Smectite (from Table 4)	Average Ordering (fromTable 4)
OTHER K-BENTONITES Valley and Ridge: carbonate sections					
AL:ET 2-4 (Alabama)	2.5-3	K-feldspar Albite	Y	18	R1/R3
AL:ET 2-5 (Alabama)	2.5-3	K-feldspar Albite	Y	12	R1/R3
GA:WL 3-3 (Georgia)	2.5-3	K-feldspar Albite	Y	12	R1/R3

1. Many of the exposures from which K-bentonites were collected are shown as measured sections on the map of Harris and others (1978), and the CAI value was easily obtained. The CAI values for exposures not shown were determined as closely as possible using an appropriately scaled overlay.

ID = indeterminable from sample analysis; either too fine-grained or too altered
NP = none present

Table 6. Relations of conodont CAI values, feldspar mineralogy, and clay mineralogy of selected samples. (Continued)

agreement between the increase in burial temperatures as suggested by the CAI values and by the areal variations in the feldspar and clay mineral assemblages. The data indicate that in Virginia the K-bentonites were exposed to higher maximum burial temperatures than in Alabama and Georgia, and that K-bentonites were buried deeper in the present-day southeastern Valley and Ridge than in the northwestern Valley and Ridge. There are some variations in the pattern, as is quite evident upon examining the map by Harris and others (1978), and by comparing the % smectite of, for example, sample AL:CH 1-2, which is from the Colvin Mountain Sandstone at Alexander Gap, with sample AL 7, which is from the Stones River Limestone at Big Ridge. The difference is actually only 6-8 % smectite, but it is significant enough to suggest that maximum burial temperatures experienced by the rocks at Big Ridge were slightly higher than those experienced by the Alexander Gap strata. Interestingly, this small area of higher burial temperatures is also noted on the map by Harris and others (1978). A similar anomaly occurs with sample VA:RO1-3, from the Bays Formation at Catawba, as compared with sample VA:BT 2-1 from the Bays at Daleville, about 30 km away. The reason(s) for these deviations are not known.

It can be argued that a hot brine migrating from southeast to northwest through the Appalachian basin could have caused the the variations in conodont colors shown by Harris and others (1978). In theory, the brine would be cooler in the direction it was migrating, which is away from the orogenic zone; these are the general thermal gradients shown by conodont color changes, which go from CAI < 1 along the Cincinnati Arch to CAI > 5 along much of the eastern Valley and Ridge. There are anomalies that must be accounted for, however. Just east of the eastern edge of the Valley and Ridge, CAI values of 2 are present in the Cades Cove, Tuckaleechee Cove, and Wear Cove Windows in the Great Smoky Mountains, where Ordovician carbonates are exposed beneath the metamorpic rocks of the Great Smoky thrust sheet. Harris and others (1978) interpreted these findings as indicating that those particular Ordovician rocks were originally located along the eastern edge of the Appalachian foreland basin, and were never buried as deeply as the Ordovician rocks now exposed in the easternmost Valley and Ridge, which were deposited farther west and subsequently buried much deeper. These findings also suggest that in the vicinity of the windows the Great Smoky thrust sheet was relatively thin and did not appreciably add to the depth of burial of these underlying carbonates.

If the entire Appalachian basin has been soaked with brines from the orogenic belt, then it is logical that the carbonates exposed in these windows would have a CAI of at least 4 to 5, if not higher, because they are much closer to the orogenic zone than any other rocks in the area, and the brines are thought to have affected both carbonate and clastic rocks.

In a recent study by Kesler and others (1988), evidence is presented which indicates that brine migration was occurring in parts of the Appalachian basin at more than one time during the Paleozoic, and that mineralizing brines in east Tennessee formed episodically over a 125-m.y. interval by the dewatering of sediments accumulated in the Sevier basin. Kesler and others (1988) present a burial curve for sediments of the Sevier basin that shows the likely thermal evolution of these sediments based on fluid-inclusion homogenization temperatures. The curve indicates that brines having a temperature of 70° - 130°C could have been generated by dewatering of the Sevier basin between 460 and 350 m.y. ago, while brines having a temperature of 110° - 170°C could have been generated between 385 and 310 m.y. ago. Together with additional evidence discussed by Kesler and others (1988), it is clear that brines migrating from the Sevier Basin of east Tennessee during the latter part of the Taconic Orogeny (Blountian phase) formed the fluorite-barite ores at the Sweetwater district, one of the major Mississippi Valley-type (MVT) deposits of eastern Tennessee. These were the lower temperature, older brines; mineralization at the Copper Ridge and Mascot-Jefferson City districts, other major MVT deposits in the region, likely occurred prior to or during the Alleghanian Orogeny as the higher temperature, younger brines moved through the basin. Overall, the major dewatering of the Sevier basin occurred prior to that orogeny.

These findings have an important bearing on the present study. Under sedimentary conditions, feldspar authigenesis is favored by a suitable $K^+/K^+ + Na^+$ ratio and in the case of albite, a minimum temperature of around 110°C. If brines with a temperature of 70° - 130°C were expelled from the Sevier basin during Ordovician to Mississippian time, temperatures would have been favorable for authigenesis of both K-feldspar and albite. As both these minerals occur in the Deicke and Millbrig in the western Valley and Ridge, including the "two-feldspar" grains in which albite and K-feldspar coexist, it is very probable that their formation could be related to the migration of brines from the Sevier basin.

Some problems remain, however, which cannot be resolved based on the findings of the present study. First, two-feldspar grains occur in the Deicke and Millbrig from Virginia to Alabama, and the distance traveled by the expelled brines is unknown. Could the grains observed in Alabama have been formed by the older, cooler brine, or are they from the younger, hotter brine? Or are they completely unrelated to the dewatering of the Sevier basin? Absolute ages of the authigenic K-feldspars will have to be determined for these questions to be answered. Second, the data of Elliott and Aronson (1987) show that illitization of the Deicke and Millbrig occurred in the Late Paleozoic. If, as seems possible, authigenic feldspars were forming 100 m.y. prior to the illitization, what is the connection between the two episodes of authigenesis? The ages of illitization reported by Elliott and Aronson (1987) agree with ages for authigenic K-feldspar in Cambrian carbonates of western Maryland reported by Hearn and Sutter (1985), which points to the possiblity of a very complex history of feldspar authigenesis and illitization throughout the Appalachian basin. For example, it is possible that in some localities, particularly in eastern Tennessee, the authigenic feldspars in the Deicke and Millbrig formed between 450 m.y. and 310 m.y. ago. Elsewhere in the basin the feldspathization may have occurred over a relatively short period of time, about 310 m.y. to 295 m.y. ago, which is when the illitization of the Deicke and Millbrig occurred according to Elliott and Aronson (1987), and when K-feldspar authigenesis occurred in Cambrian carbonates of Maryland described by Hearn and Sutter (1985). Unfortunately, conodont colors cannot help to resolve the timing of feldspathization or illitization, because the color is dependent on only temperature, not chemical composition, and the time at which the color change occurred cannot be determined.

Hot saline brines do migrate along zones of structural weakness from active tectonic areas (Ocean Drilling Project Leg 110 Scientific Party, 1987), and there is much evidence which suggests that saline brines migrated through much of the great thickness of Paleozoic strata in the Appalachian basin throughout much of the Paleozoic Era. Obviously, it will be very important to obtain the relative and absolute ages of the authigenic K-feldspars in the Deicke and Millbrig.

Clay Minerals

As shown in Table 4, Table 6, and Figures 38 and 39, there is a systematic increase from the Cincinnati Arch to the Valley and Ridge, and from northwest to southeast across the Valley and Ridge, in the ordering of the I/S and in the ratio of illite to smectite. The illite:smectite ratio in the I/S of the Deicke and Millbrig increases in the direction that the CAI values increase, supporting the evidence of Harris and others (1978) that burial temperatures were higher to the southeast. Table 6 shows the relation between conodont CAI values and the I/S ratios for the K-bentonites shown in Table 4.

Study of I/S in sedimentary basins has shown that it may be a sensitive indicator of diagenetic changes below 300°C. Based on various analyses of samples of equivalent strata from along the Sweetgrass Arch and the Disturbed Belt in Montana, Hoffman and Hower (1979) showed that the maximum burial temperature along the Sweetgrass Arch was < 60°C, whereas 70 km west, maximum burial temperatures exceeded 100°C in the Disturbed Belt. They noted that changes in the clay mineralogy of bentonites between the two sample areas was the most conclusive evidence for the temperature increase. Illite content (and thus K_2O content) increased as burial temperatures increased, and the ordering changed from random ordering (R0) to regular ordering (R1). As shown in their Figure 11, I/S in samples from the Sweetgrass Arch contains a maximum of 50 % illite, with the majority containing zero to 25 % illite, and the interstratification is R0 ordered. By contrast, the I/S in samples from the Disturbed Belt commonly contain up to 90 % illite, with most samples containing 60 to 80 % illite, and the interstratification is R1 ordered. The "classical" smectite bentonites along the Sweetgrass Arch, where maximum burial temperature was < 60° C, have become potassium-bentonites (K-bentonites) in the Disturbed Belt, where maximum burial temperatures exceeded 100° C.

Dypvik (1983) studied clays from cores and cuttings of 10 wells drilled in Mesozoic and Tertiary sediments of the North Sea, and his findings are very similar to those of Hoffman and Hower (1979). The important difference is that while Hoffman and Hower documented the smectite to I/S transition for equivalent strata that have had different burial histories but are now both exposed in outcrop, Dypvik's study was of a vertical sequence of different-aged sediments that are presently buried to depths of up to 3000 m, with burial temperatures as high as 140° C. Table 1 of Dypvik shows that there is a systematic increase in illite content in I/S as a function of depth and temperature, and that pure smectite is absent below 2000 to 2500 m.

I/S in K-bentonites begins as a felsic volcanic glass, which readily alters to smectite in many geochemical environments (Fisher and Schmincke, 1984). With a source of K and Al ions, smectite will react to form mixed layer illite/smectite (Kastner, 1971; Hoffman and Hower, 1979):

11) $$Na(Al_5Mg)Si_{12}O_{30}(OH)_{6\,(sm)} + 2K^+ + 3Al(OH)_2^+ = K_2(Al_8Si_{10})O_{30}(OH)_{6\,(i/s)} + 2SiO_2 + 2H_2O + Na^+ + Mg^{2+} + 2H^+$$

This reaction occurs is favored at moderate pH because of the stability field of $Al(OH)_2^+$ (Drever, 1984). As clearly shown in the studies by Hoffman and Hower (1979) and Dypvik (1983) discussed above, smectite will react to form mixed-layer illite/smectite in sedimentary environments as temperature increases, provided that there is a source of potassium. This reaction is explains the presence of I/S in the Deicke and Millbrig, and it also explains the presence of chert layers beneath the beds throughout the region. If the source of K ions is limited, however, smectite may react at lower pH to form kaolinite in addition to quartz and illite/smectite:

12) $$2Na(Al_5Mg)Si_{12}O_{30}(OH)_{6\,(sm)} + 2K^+ + 4H^+ = Al_2Si_2O_5(OH)_4 + K_2(Al_8Si_{10})O_{30}(OH)_{6\,(i/s)} + 12SiO_2 + 2Na^+ + 2Mg^{2+} + 3H_2O$$

This reaction can explain the presence of both I/S and kaolinite in K-bentonites from the Colvin Mountain Sandstone

This reaction can explain the presence of both I/S and kaolinite in K-bentonites from the Colvin Mountain Sandstone and the Bays Formation as discussed for Table 4 and Figure 39. Whereas the free SiO_2 formed chert beds beneath the K-bentonites in carbonate strata, it most likely formed silica cement in the surrounding sandstones and siltstones where the K-bentonites are in clastic strata. The presence of free H ions indicates a pH below 7, and reaction 11 is probably somewhere between reaction 10, which is probably the most common alteration reaction of smectite, and the reaction that produces tonsteins, which are kaolinized volcanic ash layers that formed in an acidic environment (Millot, 1970), where there presumably were no free K ions.

The findings of Hoffman and Hower (1979) and Dypvik (1983) on the smectite to illite/smectite transformation help to explain the compositional variations of I/S in the Deicke and Millbrig K-bentonites. The present geologic settings of the Cretaceous bentonites in Montana and the Ordovician K-bentonites in the southeastern U.S. are nearly identical in many ways. Equivalent bentonites/K-bentonites in both areas can be followed from a tectonically undisturbed area (Sweetgrass Arch, Montana; Cincinnati Arch, Kentucky and Tennessee) into an adjacent fold and thrust belt (Montana Disturbed Belt; Valley and Ridge). As the beds are traced into the fold and thrust belts, the clay mineralogy in both regions records an increase in burial temperatures (Table 2 and Figures 8, 10, 11, and 12 of

Hoffman and Hower; Table 4 and Figures 38 and 39, this study). The differences in maximum burial temperatures are very similar (< 60°C along the Sweetgrass and Cincinnati Arches; 100° to 200°C in the Disturbed Belt, and 100° to > 300°C in the Valley and Ridge). The main difference is in clay mineral composition, as bentonites along the Sweetgrass Arch are true bentonites, composed predominantly of smectite, while those along the Cincinnati Arch contain a high percentage of illite and are termed K-bentonites. Illite content in the I/S of the de facto K-bentonites in the Disturbed Belt, however, is only 10 to 20 % less than the illite content of the I/S in the Ordovician K-bentonites from many localities in the Valley and Ridge. This evidence strongly suggests that the two regions have had remarkably parallel burial histories. The consistently lower percent illite in the Cretaceous bentonites of the Disturbed Belt is probably a reflection of the lower maximum burial temperatures compared with the Valley and Ridge.

Hoffman and Hower (1979) show that the higher temperatures in the Disturbed Belt most likely resulted from burial under imbricating thrust sheets. In a following study of the K-bentonites in the Disturbed Belt, Altaner and others (1984) suggested that the potassium required to form the I/S was derived from the surrounding rocks, which are predominantly shales.

Like the evidence from study of the feldspars, then, variations in the illite/smectite compositions of the Deicke and Millbrig strongly suggest that the beds were subjected to increasingly elevated temperatures to the southeast. The observed variations across the Appalachian basin, however, do not directly support, nor do they disprove, the suggestions of Elliott and Aronson (1987), who suggested a K-rich brine as the source and driving force behind illitization of the I/S in the K-bentonites. Evidence from the Cretaceous bentonites in Montana in a similar tectonic setting indicates that the surrounding rocks contained sufficient potassium to account for the systematic increases in the ordering of I/S in bentonites/K-bentonites across the Sweetgrass Arch and into the Disturbed Belt. The clastics of Bays Formation contain detrital feldspars (Hergenroder, 1966), and could have provided potassium for illitization of the K-bentonites in those strata, but potassium is nearly absent in the carbonates to the northwest, and the migrating brine hypothesis does support the data of Elliott and Aronson (1987).

Because I/S is sensitive to sub-metamorphic temperature increases as reflected by an increase in the illite:smectite ratio and the ordering (Hoffman and Hower, 1979; Dypvik, 1983), the observed changes in I/S in the Deicke and Millbrig across the Appalachian Basin can be adequately explained in that context, as maximum burial temperatures were consistently higher to the southeast as reported by Harris and others (1978).

In a study of the illitization in the Gulf Coast Tertiary, however, Morton (1985) presented Rb-Sr ages for I/S in the Frio Formation that directly contradict the prevailing theory as outlined in the preceding paragraphs on the smectite to illite transition. In a single well with a relatively homogenous sequence, Morton found that the < 0.05 μm-size fraction of samples below 10,500 ft (3,200 m) were of uniform age regardless of depth or, most importantly, temperature. This pattern was explained by suggesting that illitization occurs rapidly following a favorable change in pore-water chemistry, and that the extent of illitization is dependent on the temperature at which the clay is exposed to at that moment in time. This means that the deepest clays contained the most illite, and the shallower ones contain proportionately less illite. Subsequent changes in pore-water chemistry halt the reaction, "freezing" the reaction and locking in the isotopic signature. Burial under an additional 7,000 to 8,000 ft (2,200 -2,500 m) of overburden has not resulted in further illitization.

Morton's study presents a new model for the smectite to illite transition that supercedes the ideas of Hoffman and Hower (1979), Dypvik (1983), and many others, who favored the idea of gradual illitization occurring with progressively deeper burial. With respect to the findings reported on the clay mineralogy of the Deicke and Millbrig in the present study, it is evident that illitization of smectite does not necessarily require a migrating brine. The Gulf of illitization in-situ. Obviously, the feldspar distributions shown in Table 5 result from temperature related differences, but the question now is this: what is the age of the authigenic albite and K-feldspar reported in these studies? If these minerals are about the same age as the I/S studied by Morton (1985), then the idea of gradual diagenetic changes will have to be re-examined, with the possibility that such changes occur rapidly at some moment in time when suitable temperatures and pore-water compositions are reached, and further changes do not affect the mineral assemblages significantly.

Fe-Ti Oxides

Although the feldspars and clay minerals are the most useful indicators of sub-metamorphic diagenetic changes in the Deicke and Millbrig, some important information can be inferred from the Fe-Ti oxides of the Deicke as well. Much of the inferences are based on the work by Morad and Aldahan (1986) and Morad (1988b). The study by Morad (1988b) was of detrital ilmenite and other Ti-minerals in Jurassic sandstones of the Norwegian sea. The samples were all from cores of rocks that are presently 1600-5000 m beneath the ocean floor. This range of burial depth is very similar to Ordovician rocks of the Appalachian Basin as suggested by conodont CAIs (Harris et al., 1978), suggesting that the rocks in this Jurassic sequence may presently be undergoing a burial history similar to that inferred for the Ordovician of much of the southern Appalachians. Morad (1988b) reports that authigensis of anatase and rutile begins at burial depths of less than approximately 2000 m and continues as burial depths increase. Ilmenite alters to TiO_2 as follows:

13) $FeTiO_3 + 2H^+ = TiO_2 + H_2O + Fe^{2+}$

This is obviously favored at low Eh; the ferrous iron that is produced will most likely react with sulfides to form pyrite, and therefore the reaction is probably:

14) $FeTiO_3 + 2H_2S = TiO_2 + FeS_2 + H_2O + H_2$

There is a significant amount of pyrite in the Deicke, and it is likely that much of it is a product of this reaction.

The pyroxenes that were present in the original Deicke ash were most likely titanaugites, and as they altered, the Fe and Ti were released along with the other constituents. This Fe and Ti could have been incorporated into authigenic ilmenite and other Fe-Ti minerals such as rutile and anatase, which are observed to have pseudomorphed pyroxene grains (Fig. 23).

From the evidence discussed in the preceding sections, it is clear that the Ordovician of the Cincinnati Arch was never buried under more than about 1500 m of overburden, but in the Valley and Ridge a minimum of 1000 additional m of overburden was present at the time of maximum burial, with

3000 to 4000 additional m probably being present in many areas (Harris et al., 1978). The authigenic Ti-oxides in the Deicke are best observed in samples from the Cincinnati Arch, whereas samples from the Valley and Ridge are more altered and grains such as the ones in Figures 21-23 are less common except in the western most outcrop belts. This difference in spatial distribution suggests that alteration of the Fe-Ti oxides occurred throughout the study area, but that the resulting textures are best preserved along the Cincinnati Arch, where advanced stages of diagenesis were limited by the relatively low maximum burial temperatures, and further alteration and perhaps destruction of the authigenic anatase and rutile was not favored geochemically.

These conclusions are consistent with those based on the findings concerning the authigenic feldspars and clay minerals, but as with them, there are some unanswered questions. The actual TiO_2 polymorph(s) that are present are not known. As discussed by Morad and Aldahan (1986), authigenic rutile and anatase come in many colors and shapes, and various intermediate alteration products occur, with each successively enriched in titanium and depleted in iron. A study of these grains using a STEM would help to identify more exactly the various Fe-Ti oxides present.

Summary

Based on petrographic observations and on the studies discussed above, a suggested paragenetic sequence is as follows. Burial depth of the Deicke and the Millbrig was at the most 1000-3000 m basinwide up to the Late Mississippian. During this time, the original volcanic glass devitrified, forming smectite and authigenic K-feldspar partly or completely replaced primary andesine or labradorite (and perhaps primary sanidine as well) in both the present-day Cincinnati Arch and Valley and Ridge. Replacement may have begun when the overburden was only a few hundreds of meters, as this has been shown to be possible by Hay (1962) and Waugh (1978). Depending on the temperature and composition of brines being expelled from the Sevier basin during this time, albite may also have been forming in parts of the Valley and Ridge. The transformation of the smectite to mixed-layer I/S could have begun during this time, although the data of Elliott and Aronson (1987) suggest that illitization occurred primarily during the Late Paleozoic.

From the Ordovician to perhaps the Middle or Late Mississippian temperatures would have been between 20 and 60° C, assuming a normal geothermal gradient for this region. K-feldspar authigenesis may have occurred into Mississippian time in the Valley and Ridge, as Upper Ordovician, Silurian, and Devonian strata reach a maximum thickness of 3000-3500 m in the study area, although in most of the Southern Appalachians south of Roanoke this part of the section is thinner than it is in northwest Virginia, West Virginia, and Pennsylvania (Harris, 1979). Therefore, it is possible that these burial depths did not occur in much of the Valley and

Ridge study area until the Late Mississippian or Pennsylvanian, when the thick section of coal-bearing clastic strata was deposited along nearly the entire length of the Southern Appalachians. Throughout this time burial depths along the Cincinnati Arch never exceeded approximately 1200 m.

If it had not been forming already, authigenic albite probably began to form during the Carboniferous in the eastern part of the basin (present-day Valley and Ridge) as the overburden thickness increased. The albite partly or completely replaced primary andesine or labradorite and existing authigenic K-feldspar (and primary K-feldspar, assuming that the ash originally contained it). Albitization probably began either as continued sedimentation led to greater and greater burial depths throughout the Late Paleozoic, and temperatures in Ordovician rocks reached the threshold of albitization, around 110° C, or when migrating brines of that temperature from the Sevier basin moved through the basin. At those temperatures the smectite to I/S transition might have continued, producing I/S with increasing percentages of illite as documented by Hoffman and Hower (1979) and Dypvik (1984), or, if the model proposed by Morton (1985) for illitization were correct, the illitization occurred in a relatively short time span, a scenario supported by the data of Elliott and Aronson (1987). Regardless of the mechanism, maximum temperatures were reached along the southeastern edge of the Valley and Ridge, where the illite:smectite ratio commonly exceeds 9:1. During this time geochemical conditions along the Cincinnati Arch continued to be favorable for authigenic K-feldspar formation only.

As the studies of the Gulf Coast Tertiary (Table 5) clearly demonstrate, K-feldspar begins to disappear when temperatures reach a certain level, about 140° C, given the appropriate geochemical conditions. The Gulf Coast studies show that albite authigenesis continues to occur at depths below which K-feldspar is absent, and thus, it is interesting that K-feldspar is still present in many samples from the Valley and Ridge, sometimes in samples where albite is present. This suggests that the critical depth and temperature for dissolution of K-feldspar was not reached in at least the western Valley and Ridge, or if it was reached it was not maintained for a long enough period. Most samples from the eastern belts are too weathered to identify K-feldspar conclusively in them.

As uplift began in the Late Paleozoic or Mesozoic and erosion began removing overlying strata, a process that is continuing in this region at the present, the sediments were exposed to increasingly shallower depths and lower temperatures. Although albite authigenesis would no longer have been occurring, it is possible that K-feldspar authigenesis began again. If geochemical conditions were still favorable, with a potassium source for replacing original and authigenic feldspars alike, then this could have been easily accomplished. More likely, however, the K^+ activity had decreased to a level that no longer favored authigenesis of K-feldspar, and older authigenic albite and K-feldspar grains were "frozen" in the textural relationships seen at present, recording the maximum burial temperatures experienced by the strata.

Sedimentology of Adjacent Strata, and Rocklandian Paleogeography at the Time of the Ashfalls

The stratigraphic interval between the Deicke and Millbrig K-bentonites contains strata that were deposited in generally very shallow water. Strata above and below the K-bentonites include both shallow water and deep water sediments. The carbonate rocks of the western Valley and Ridge and the Cincinnati Arch were deposited on a broad cratonic platform and along the platform margin. The clastic rocks of the eastern Valley and Ridge were shed from a highlands area that was to the east and southeast of the present-day Valley and Ridge (Rodgers, 1971). They record a regional orogeny in the southern Appalachians, the "Blountian" phase of the Taconic Orogeny, which preceded the better-known "Hudsonian" phase of the north-central Appalachians (Rodgers, 1953). The following discussion is based in part on descriptions in the literature, and on personal observation of many outcrops in the study area.

An inner platform, supratidal flat setting (standard facies belt 8 of Wilson, 1975) is suggested for the Tyrone Limestone of Kentucky, the Carters Limestone of Tennessee and northwest Georgia, and the Stones River Limestone north of Gadsden, Alabama. Fenestrae are very common (the Tyrone is known locally as the "birdseye" limestone) along with mudcracks, cryptalgalamination, and a near total lack of body or trace fossils. The absence of trace fossils has produced an evenly laminated, massive brownish gray rock with almost no bioturbation, which is indicative of supratidal environments (Shinn, 1983). There was extensive subaerial exposure over much of the Cincinnati Arch, as indicated by the absence of the Millbrig at an erosional unconformity between the Carters Limestone and Hermitage Formation along the western edge of the Arch, and its occurrence immediately beneath the unconformity in many other areas (Wilson, 1949; Milici and Smith, 1969).

In the Valley and Ridge near Birmingham, Alabama, the interval between the 2 beds contains carbonate strata of the Chickamauga Limestone that were deposited in a more normal marine subtidal setting. The nodular, shaly beds are thin- to medium-bedded, dark gray, and they are strikingly similar in appearance to the Lantz Mills Formation of northern Virginia, a deep ramp carbonate (Read, 1980). At Birmingham, the Chickamauga Limestone contains a diverse and abundant normal marine fauna (Chowns and McKinney, 1980), and is in every way a contrast with the Stones River Limestone farther north. Biotite from the Millbrig is present in the carbonates immediately upsection, suggesting reworking, possibly by storms, given the abundance of broken and reworked fossil fragments as well. These carbonates were likely deposited in a middle shelf setting above storm wave base (standard facies belt 2 of Wilson, 1975).

The Carters Limestone of north Georgia grades along strike into the Eggleston Formation of northeast Tennessee and Virginia. In the western belt of the Powell Valley, the Eggleston is a light gray, medium-bedded limestone that contains a moderately restricted marine fauna (Huffman, 1945). Some bioclastic grainstones and packstones are interstratified with the lime mudstones. This is an inner platform carbonate (still standard facies belt 2 of Wilson, 1975) but it is not as restricted as the Tyrone Limestone to the west.

In the central belt, the Eggleston is a sequence of olive to gray lime mudstones with few fossils of low diversity, although rare thin bioclastic grainstones occur. It is, however, less restricted than the underlying Moccasin Formation in which the Deicke occurs. The Moccasin is a sequence of lime mudstones with a significant argillaceous content. It is similar to the Eggleston except that the beds are reddish gray rather than olive, and the Moccasin contains even fewer grainstone beds, being otherwise devoid of fossils. is region both the Moccasin and the Eggleston are characterized by abundant fenestrae. These units formed in a restricted intertidal to supratidal flat setting (standard facies belts 8 and 9 of Wilson, 1975) that deepened to the west as shown by the increasing diversity and abundance of fossils and the disappearance of the red and olive lime mudstones (Kreisa, 1980), and shallowed to the east, where the Bays Formation clastics occur.

The carbonate sequences in the western Valley and Ridge are in contrast to the equivalent clastic rocks to the southeast. East of Birmingham across the Helena fault, the K-bentonites occur in the well-rounded, well-sorted, medium- to coarse-grained quartz arenites of the Colvin Mountain Sandstone. Trough cross-bedding, symmetric ripples, and vertical burrows occur in these sands, which together with the compositional and textural maturity indicates deposition and reworking in a high energy marine environment (Jenkins, 1984). Quartz cement is common. This unit is very similar to the Tuscarora Sandstone of Virginia, suggesting deposition as an upper shoreface and foreshore sand. In that environment the sands would be constantly shifted about by waves, producing a mature quartz arenite.

The quartz arenite lithofacies of the Colvin Mountain persists into northwest Georgia, where it thins and is replaced by the finer-grained redbeds of the Bays Formation. Because the Deicke is absent in the Bays, the sequence between the Millbrig and the Walker Mountain Sandstone will be described. The Bays is comprised predominantly of red and greenish-gray shales, siltstones, and fine-grained arkosic sandstones, which are mostly unfossiliferous except for occasional Lingula specimens in the upper part. In the Salem Synclinorium the Bays contains more sandstones than in most of the other belts, and those sandstones are medium- to coarse-grained, and greenish gray with relatively few redbeds. At Conner Valley and Crockett Cove the lower and middle Bays is also more coarse-grained than most other areas and greenish gray beds are much more common than redbeds.

The Bays is interpreted as predominantly a coastal plain sequence deposited by a series of sluggish rivers that prograded out over wide mudflats. These mudflats were formed as the final step of basin filling, which had been occurring since the early Middle Ordovician (Read, 1980). This basin was deepest in the eastern Valley and Ridge and is recorded there by a thick sequence of thin-bedded graptolitic shaly black carbonates. These grade vertically into the red and green siltstones and sandstones of the Bays Formation, and the transition interval is well exposed in the Conner Valley, Ellett and Daleville sections. To the west the basin was shallower, and peritidal sediments underlie the Bays at Crockett Cove and the Moccasin in all areas of its occurrence. Deposition on the mudflats was apparently conducive to thorough oxidation of iron in the sediment, perhaps from subaerial exposure and circulation of meteoric waters subsequent to deposition. In the Conner Valley section and the Salem Synclinorium area the basin had evidently not quite been filled, and the sand was being deposited subaqueously rather than onto a mudflat. In those areas the sediment was never exposed to the atmosphere and thus never oxidized, hence the preservation of the greenish gray color, which indicates the presence of ferrous iron. At the Crockett Cove section, the sandstones of the Bays resemble those at Conner Valley and in the Salem Synclinorium, but they overlie fenestral, shallow water carbonates rather than basinal carbonates. This indicates that the sand was deposited across the carbonate mudflats, but sedimentation must have been rapid enough to bury a sufficient volume of sand and prevent pervasive oxidation of the iron in the lower and middle Bays. The presence of mostly coarse-grained sandstones and the relative lack of redbeds as compared with the Bays in most other outcrops supports this explanation.

The Walker Mountain Sandstone (and its equivalent in the Bays Mountains, the middle sandstone member) is a mature well-sorted medium- to coarse-grained sandstone to quartz-pebble conglomerate. The middle sandstone of the Bays Mountains is texturally very similar to the Colvin Mountain Sandstone and is over 15 m thick, whereas the Walker Mountain Sandstone is generally much thinner, from 0.5 to 2 m in most areas. At Chatham Hill it occurs in the middle of the Bays, but farther northeast at Crockett Cove and Conner

Valley, it occurs at the base of the Bays, resting disconformably on the Witten and Wassum Limestones. At Ellett, farther northeast still, it again occurs at the base of the Bays, but it overlies the Liberty Hall Limestone. At Goodwins Ferry to the west of Ellett it occurs in the redbeds of the uppermost Moccasin Formation just beneath the Deicke. The middle sandstone was deposited in a shallow marine setting very similar to the Colvin Mountain Sandstone, which it closely resembles in texture and composition. The Walker Mountain Sandstone, however, is a beach deposit that fringed the seaward side of a mudflats and coastal plain complex, which was probably comprised of numerous but small coalesced deltas. The presence of a beach deposit, the Walker Mountain Sandstone, and well-sorted, compositionally mature shoreface sands, the middle sandstone member and the Colvin Mountain Sandstone, suggests that this was a wave-dominated deltaic/coastal plain environment as opposed to a tidal- or river-dominated environment. The depositional setting thus was perhaps similar to the present-day Texas coast, where many small rivers enter the Gulf of Mexico, and the delta plain is a wave-dominated setting with barrier islands and their sandy beaches separating the open ocean from the silts and muds of the rivers and the back-barrier lagoons.

Paleogeographically, the strata between the Deicke and Millbrig are a small part of a widespread regressive sequence. That sequence, in turn, is one of several in the

Ordovician of this region, as shown in Figure 55. There were 3 regressive and 2 transgressive sequences, numbered from 1 to 5, which span most of the Ordovician of this region. Interestingly, the 2 K-bentonites were deposited very close in time to the change from a regressive to a transgressive sequence. The K-bentonites occur in the interval where sequence 3, a regressive sequence, passes vertically upward into sequence 4, a transgressive sequence.

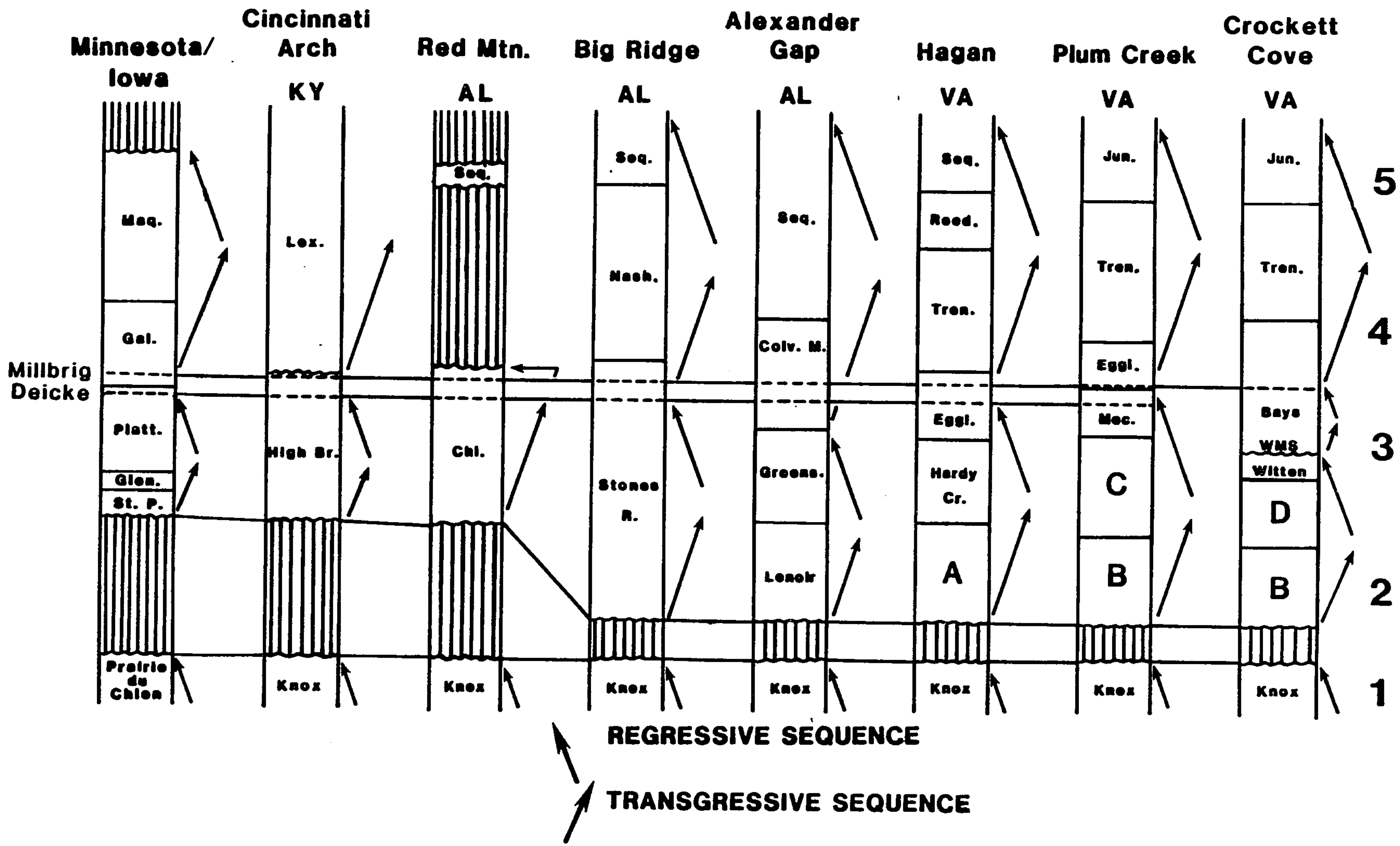
The Deicke and Millbrig occur near the top of the regressive sequence along the Cincinnati Arch as shown in Figure 55. In some sections the Millbrig actually occurs at the Carters-Hermitage contact and it is literally at the top of the regressive sequence, as shown in Figure 4. The Hermitage and its equivalent, the Lexington Limestone, record a deepening of the water column, whereas the Carters and its equivalent the Tyrone Limestone record mudflat conditions, as in fact do much of the Stones River and High Bridge Groups of which these units are a part, respectively. The overlying Nashville and Lexington Groups were deposited under more normal marine conditions, and these grade into various Cincinnatian strata in which several transgressive-regressive sequences occur.

In northeastern Alabama, northwest Georgia and southeast Tennessee the sequence is very similar. As shown in Figure 55, the K-bentonites occur near the top of the Stones River Formation and the Stones River Group, in a section of those units that records restricted shallow

Figure 55.

Summary chart of the position of the Deicke and Millbrig relative to the transgressive and regressive sequences that persist in the Middle and Upper Ordovician throughout eastern North America. The Deicke was deposited at very nearly the shallowest interval that occurred in sequence 3, which was primarily a regressive sequence. The Millbrig was deposited as sequence 4, a transgressive sequence, was beginning. With the K-bentonites used as time lines, this illustration shows that the change from a regressive to a transgressive sequence (3 to 4) occurred relatively rapidly across much of eastern and central North America.

A - Dot Limestone (base) to Ben Hur Limestone (top)
B - Blackford Limestone (base) to Benbolt Limestone (Plum Creek) or Rich Valley Formation (Crockett Cove) (top)
C - Benbolt Limestone (base) to Witten Formation (top)
D - Rich Valley Formation (base) to Wassum Formation (top)


Minnesota/ Iowa
Cincinnati Arch KY
Red Mtn. AL
Big Ridge AL
Alexander Gap AL
Hagan VA
Plum Creek VA
Crockett Cove VA
5
4
3
2
1
Maq.
Gal.
Platt.
Glen.
St. P.
Prairie du Chien
Lex.
High Br.
Knox
Seq.
Chi.
Nash.
Stones R.
Colv. M.
Greene.
Lenoir
Reed.
Tren.
Eggl.
Hardy Cr.
A
Jun.
Moc.
C
B
Bays
WMS
Witten
D
Millbrig
Deicke
REGRESSIVE SEQUENCE
TRANSGRESSIVE SEQUENCE

marine to mudflat environments. Downsection, more normal marine sediments occur (sequence 2 on Figure 55) as do additional peritidal deposits, with the basal conglomeratic Attalla Chert Conglomerate Member overlying the Knox unconformity, which formed as part of sequence 1 on Figure 55. Above the Nashville Group are the redbeds of the Sequatchie Formation, which record another regional regression. The Sequatchie is equivalent to the Juniata Formation of Virginia and Tennessee and to various Cincinnatian strata along the Cincinnati Arch.

The sections around Birmingham discussed earlier record a somewhat different depositional history than that experienced by the rest of the region. The Chickamauga is a thinner, condensed section of normal marine carbonate sediments, including the Attalla, which overlies the Knox unconformity. As shown in Figure 55 there is little evidence to suggest that a regressive sequence occurred after the initial transgressive sequence above the Knox unconformity, unlike at other sections in the region. The K-bentonites occur near the top of the unit, but instead of being overlain by a thick transgressive sequence like the Nashville Group to the northeast, there is a major unconformity 3-4 m above the Millbrig, with the Silurian Red Mountain Formation overlying a 0.5 m thick Sequatchie Formation. Evidently there was a period of uplift in this region, probably after some deposition of the Nashville Group equivalent, as there is no indication of a shallowing water column in the rocks above the Millbrig. This uplift resulted in the erosion of most of the Upper Ordovician sequence, and as shown in Figure 48 the unconformity persists for several tens of miles to the northeast, although less and less of the section is missing in that direction. Uplift was even greater to the south and east of Birmingham, as at Ragland (Figure 11) the Ordovician Little Oak Limestone is unconformably overlain not by Silurian strata, but Devonian.

In the central belt of Alabama and Georgia the transgressive-regressive sequence is also recorded by the strata. Overlying the Knox unconformity in Alabama is a gray carbonate identified as the Lenoir Limestone, but in part of northwest Georgia the equivalent strata are red carbonates similar in appearance to the Holston Formation of Tennessee. Above this is the Greensport Formation, a sequence of sparsely fossiliferous redbeds. This is the top of a regressive sequence (sequence 3 on Figure 55), and it is overlain by the Colvin Mountain Sandstone and its high-energy quartz arenites, which record a deepening water column (sequence 4) and the transition from a mudflat setting to a nearshore sand-dominated environment. The Colvin Mountain shallows upward into a second redbed sequence (sequence 5), the Sequatchie Formation.

To the northeast in Virginia the K-bentonites again occur in the transition interval between a regressive and a transgressive sequence. The Knox unconformity extends into that region, and as described by Read (1980) and Ruppel and Walker (1984) it is overlain by a transgressive sequence that eventually resulted in deposition of deep-ramp nodular limestones of the Benbolt Formation in the northwestern Valley and Ridge and basinal even-bedded limestones and black shales of the Sevier Shale and Liberty Hall Limestone in the southeast (sequence 2 on Figure 55). This is followed by a regressive sequence (sequence 3) that culminated with deposition of the Moccasin and Bays redbeds in the central and eastern belts, and the Hardy Creek Limestone in the western belt. K-bentonites are present throughout the transition interval between sequences 3 and 4 (Figure 55), which includes the uppermost Moccasin, the Eggleston, and the Trenton ("Martinsburg") Formation in the western and central belts, and the Bays and Trenton ("Martinsburg") Formations in the eastern belt.

A fifth, regressive, sequence occurs upsection of the K-bentonites throughout much of the Valley and Ridge, where the normal marine carbonate sediments of the Trenton ("Martinsburg") Formation grade into the redbeds of the Juniata Formation.

The position of the K-bentonites relative to the quartz arenites can be used to infer the direction of relative sea-level rise. At Alexander Gap in Alabama, a thick K-bentonite thought to be the Millbrig occurs within the quartz arenites of the Colvin Mountain several meters upsection from the Greensport-Colvin Mountain contact, but at Horseleg Mountain near Rome, Georgia it occurs exactly at the contact, between the uppermost redbed of the Greensport and the lowest quartz arenite bed of the Colvin Mountain. Although K-bentonites were not located near Dalton, Georgia, Hergenroder (1966) reported a K-bentonite about 20 ft upsection from a 6-ft thick white conglomeratic sandstone in a section just north of Dalton. This is the position of the Millbrig relative to the middle sandstone and the Walker Mountain Sandstone farther north in Tennessee and Virginia, and because the Deicke is not present in the Bays this bed at Dalton is most likely the Millbrig. In the Bays Mountains of Tennessee, the Millbrig is about 30 m above the middle sandstone member, at Chatham Hill near Marion, Virginia it is about 25 m above the Walker Mountain Sandstone, at Crockett Cove, it is about 17 m above the Walker Mountain, and Daleville it is about 15 m above the Walker Mountain. At Crockett Cove the Walker Mountain rests disconformably on peritidal carbonates of the Witten Limestone, suggesting a period of subaerial exposure prior to the transgression. Elsewhere such as at Chatham Hill and in the Salem Synclinorium, however, the beach environment prograded out over the red mudflats where sedimentation had been relatively continuous (Chatham Hill) or over the basinal carbonates where clastic sedimentation was just beginning (Salem Synclinorium).

Assuming that the sandstone is a reworked nearshore sand in the Bays Mountains and a beach deposit in Virginia, it is evident using the Millbrig as a time line that transgression occurred from the southwest to the northeast. This is the direction indicated in Alabama and Georgia as well, but it seems that the quartz arenites of the Colvin Mountain are slightly younger than those of the middle sandstone and the Walker Mountain Sandstone in the Bays farther north.

Type and Reference Sections for the Deicke and Millbrig

Correlations by Kolata and others (1984) showed the equivalence of the Deicke and Millbrig K-bentonite Beds between the Upper Mississippi Valley, where the type localities for the beds are, and the Cincinnati Arch. Based on the petrographic and stratigraphic evidence discussed herein, the correlations of the Deicke and Millbrig can be extended from the Cincinnati Arch to the Valley and Ridge, and along strike in the Valley and Ridge from Birmingham to Roanoke. In Upper Mississippi Valley the 2 beds range from 1 to 15 cm thick, and they contain a very few fine-grained phenocrysts, whose study by Allen (1929) documented the volcanic origin of the beds. In exposures along the Cincinnati Arch and in the Valley and Ridge, by contrast, the beds are commonly 80 to 120 cm thick, and contain abundant coarse-grained phenocrysts.

Willman and Kolata (1978) designated the type locality for the Deicke as an exposure along the Meramec River in Missouri about 35 km southwest of St. Louis, and the type locality for the Millbrig as an exposure along the Galena River in Illinois about 20 km southeast of Dubuque, Iowa. Kolata and others (1986) give detailed descriptions of these and other localities in the Upper Mississippi Valley where the Deicke and Millbrig K-bentonites can be observed.

Because of the significant changes in the composition and particularly the texture of the beds between the Upper Mississippi Valley, the Cincinnati Arch, and the Valley and Ridge from Birmingham to Roanoke, the type localities for the Deicke and Millbrig in the Upper Mississippi Valley should be supplemented by reference sections in the latter regions. These sections, designated in accordance with Article 8 of the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983), will be useful to illustrate the lateral changes in the beds from region to region. Suggested reference sections are as follows:

Cincinnati Arch:

- Highbridge, Mercer County, Kentucky
- South Carthage, Smith County, Tennessee

Valley and Ridge, carbonate sections:

- Red Mountain Expressway, Jefferson County, Alabama
- Big Ridge, Etowah County, Alabama
- Hagan, Lee County, Virginia
- Plum Creek, Tazewell County, Virginia

Goodwins Ferry and Gap Mountain, Giles County, Virginia

Valley and Ridge, clastic sections:

Alexander Gap, Calhoun County, Alabama

Crockett Cove, Wythe County, Virginia

Locations for these sections are given in Chapter XI, the Appendix.

At the Highbridge and South Carthage sections, the persistence of lithofacies in the enclosing platform carbonate strata is apparent; the Tyrone-Curdsville sequence is readily matched to the Carters-Hermitage sequence, as discussed in Chapters IV and VI. At both sections also the Deicke and Millbrig are relatively thick and contain abundant phenocrysts, and they are very well-exposed. The Red Mountain Expressway section is probably the finest exposure of the Ordovician to Mississippian sequence in the Southeast. The platform margin sequence of the Chickamauga Limestone is completely exposed, and the effect of reworking in the higher energy depositional setting is apparent; both beds are thinner than elsewhere in the region, and biotite from the Millbrig occurs throughout the carbonate bed overlying it. In addition, the Ordovician-Silurian unconformity marking the absence of the Nashville Group and most of the Sequatchie Formation is well-exposed upsection from the Millbrig. The Big Ridge section shows the more "normal" sequence for the region, and its similarity to the Highbridge and South Carthage sections is apparent with careful study. The Deicke and Millbrig occur in the upper Stones River Formation, which consists predominantly of restricted supratidal deposits. In addition, the thin quartz arenite bed suggested by Chowns and McKinney (1980) to be a distal tongue of the Colvin Mountain Sandstone occurs between the Deicke and Millbrig. Although the Deicke and Millbrig are closer together vertically than at any other exposure studied herein, that is a very inconsquential drawback to use of the Big Ridge section as a reference section. The Alexander Gap section of Jenkins (1984) is the best exposure of the Colvin Mountain Sandstone, and it contains both the Deicke and Millbrig, which are readily located as recessed zones in the massively weathering quartz arenites. The section at Hagan is very well known, and is the type locality for the Hardy Creek Limestone and the Hagan Shale (Miller and Fuller, 1954). The Deicke and Millbrig are readily found, and the similarities between that section and the Highbridge section are readily apparent. Both beds occur in the Eggleston Formation, and the Eggleston-Trenton contact is only a few m upsection from the Millbrig. The exposure at Plum Creek was used by Rosenkrans (1936) as a key section for his correlations of K-bentonites in the region, and although more structurally complex than some sections, it is still well enough exposed to be a very useful reference section. The Deicke and

Millbrig outcrop on the southeast limb of a syncline that contains convolutely folded beds of the Trenton ("Martinsburg") Formation in its axis. Bed V-7 is exposed on the northwest limb, along with several of the thinner K-bentonites that overlie it and are beds V-8 to V-11 of Rosenkrans's (1936) "cuneiform" group. At this section, the Deicke occurs in the uppermost redbeds of the Moccasin Formation and is itself red and yellow, the characteristic description of bed V-3 of Rosenkrans (1936), and a change from the Hagan section, where it is a greenish gray color. The Millbrig and V-7 occur in the Eggleston Formation, and the Eggleston-Trenton contact is just upsection from V-7. The Millbrig is yellowish gray in color, a noticeable change in color from Hagan, where it is a medium gray color. Also, a comparison of this section with the Hagan section shows the magnitude of the facies changes that have occurred in this stratigraphic interval across a distance of just a few ten's of km. At Goodwins Ferry, the Deicke is still in the Moccasin redbeds, but it immediately overlies the conglomeratic Walker Mountain Sandstone and it is only 30 cm thick, which is noticeably thinner than in sections to the south. Faulting and shearing of the Eggleston have essentially obliterated the Millbrig at Goodwins Ferry, unfortunately, but bed V-7, with its underlying dark chert layer, is quickly spotted, and the Eggleston-Trenton contact can be readily found just upsection of V-7. To see the Millbrig in this area, go to the Gap Mountain section, where the entire Eggleston and much of the lower Trenton ("Martinsburg") where the Millbrig and V-7 are of normal thickness. The Gap Mountain section is only 5 km from the Goodwins Ferry section. The lower Bays Formation is completely exposed at the Crockett Cove section, with the Walker Mountain Sandstone overlying the Witten Limestone, and the Millbrig 17 m upsection from the Walker Mountain.

These reference sections illustrate best the stratigraphic variations in the K-bentonites and the enclosing strata in the study area. Together with the various incomplete sections shown in Plates 1 through 6 and described in Chapter XI, geologists studying these rocks should better understand this important stratigraphic interval.

The lack of reference sections in the Valley and Ridge of Georgia and Tennessee is a reflection both of the better exposures in Alabama and Virginia that adequately illustrate regional stratigraphic relations, and of the general lack of outcrops with K-bentonites between Chattanooga and Knoxville. As work continues on the K-bentonites it is expected that suitable sections will be found. The Tellico-Sevier belt of east Tennessee, where the Bays outcrops in a narrow zone along the edge of the Great Smoky Mountains, is an area that particularly needs more study. K-bentonites were present at several exposures described by Rodgers (1953), Neuman (1955), and Hergenroder (1966) in that belt, but none were found during field work in that area. The damming of the Tellico and Little Tennessee Rivers of snail darter controversy has flooded many of the exposures described in the above studies, and with outdated maps and rerouted roads, no new exposures could be located during the little time available for field work in that area.

The K-bentonite at the Old North Ragland Quarry, Alabama

At a small abandoned quarry near Ragland, Alabama, there is a thick K-bentonite in the Little Oak Limestone of Ordovician age. Butts (1926) noted this bed and a second one that pinched out within the quarry, suggesting that they might be equivalent to K-bentonites in the Chickamauga Group to the northwest, but conodont biostratigraphy indicates that the Little Oak at the quarry is older than the equivalent Chickamauga strata (Drahovzal and Neathery, 1972; Schmidt, 1982). According to those studies, the Chickamauga is characterized by midcontinent conodont faunas 7 and 8, and is Mohawkian in age, whereas the Little Oak is characterized by faunas 5 and 6 and is Whiterockian in age on that basis.

Only one K-bentonite was found during a visit to the quarry. That bed is about 50 cm thick and it contains abundant biotite visible in hand specimen, obviously suggesting the possibility that it is equivalent to the Millbrig. The samples were not analyzed in detail owing to circumstances beyond control, but even without detailed petrographic data a case can be made that this bed could logically be the Millbrig based on lithostratigraphic evidence, even though the biostratigraphic evidence suggests it is not.

The quarry is in the frontal tier of the Coosa deformed belt, a narrow linear zone of structurally complex imbricated thrust sheets characterized by rapid facies changes across strike (Thomas and Drahovzal, 1974). The Eden (Coosa) fault separates the quarry from the Coosa Synclinorium to the north, but the Ragland section is only 15 to 20 km from the western limb, along which occur the Colvin Mountain Sandstone sections at Alexander Gap and elsewhere. Farther northwest across the Coosa Synclinorium is the Helena Fault, which separates the Colvin Mountain and Chickamauga sequences as shown in Figure 45. Although separated by these faults, a comparison of the Ragland section with the Red Mountain section at Birmingham suggests some interesting if circumstantial evidence for correlating the K-bentonites. As shown in Figure 56 (which assumes the equivalence of the two beds to begin with) these two sections are very similar in that only a few meters of Ordovician strata are found above the youngest K-bentonite, which at Birmingham is unquestionably the Millbrig. A major pre-Devonian unconformity is present at both sections, the magnitude and areal extent of which have been discussed by Butts (1926), Kiefer (1970), and Thomas and Drahovzal (1974). Those studies show that at many sections east of the Helena and Eden (Coosa) faults, most or all of the

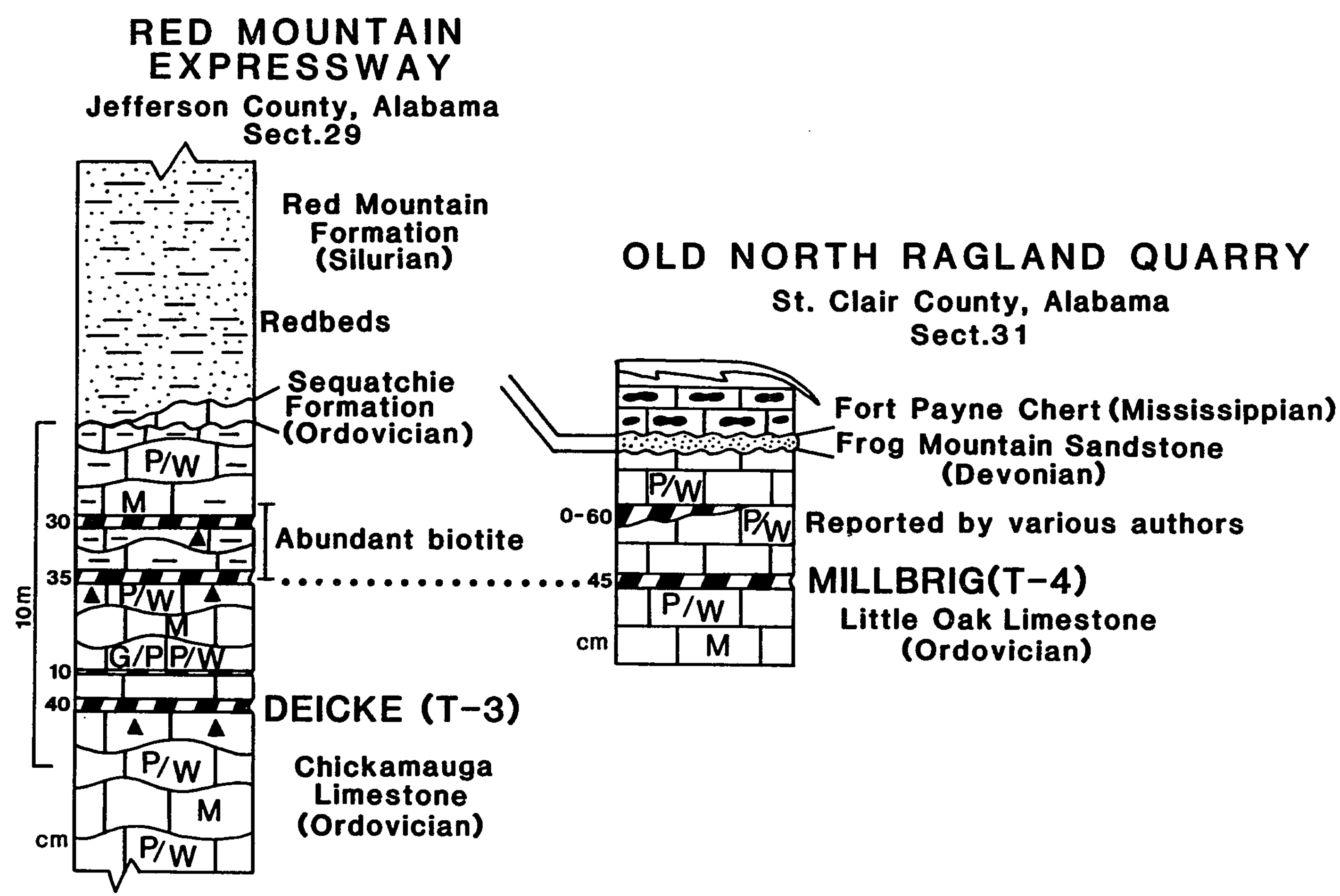


Figure 56. Possible correlation of the Millbrig between the Birmingham and Ragland sections. Note the proximity of the K-bentonites to the major unconformity upsection. Refer to Figure 45 for section locations.

Middle and Upper Ordovician is missing, as well as the Silurian. The basal Devonian Frog Mountain Sandstone commonly overlies this unconformity, as at Ragland (Fig. 56) and elsewhere throughout the Coosa deformed belt (Thomas and Drahovzal, 1974).

From these studies and from study of the Birmingham and Ragland sections it is evident that erosion was most likely occurring in both the Ragland and Birmingham areas during the Late Ordovician. During this time, uplift was apparently occurring and overlying sediments were being removed; at Birmingham, erosion removed sediments to within only a few meters of the uppermost K-bentonite, which is the Millbrig. In the Ragland area, erosion seems to have continued into the Silurian, or may in fact not have begun until then, making this area's history more difficult to interpret, but in Birmingham sedimentation resumed at this time, with deposition of the famous ironstones. Although erosion continued in the Ragland area and elsewhere in the Coosa deformed belt until the Devonian, the K-bentonite at Ragland was never eroded, probably because the rate of erosion decreased as uplifted areas were worn down. As at Birmingham, though, overlying sediments were removed to within only a few meters of the K-bentonite. As there are no widespread deposits of extrabasinal limestone conglomerates in the region of Upper Ordovician age, chemical weathering must have been more prevalent than mechanical weathering, or, the basin in which the eroded limestone fragments were being deposited was not preserved in the rock record, or, strata in such a basin do not presently outcrop and are not known in the subsurface.

Considering that deposition of the Silurian ironstones, which are partly marine, began in the Birmingham area in the Early Silurian, regional erosion rates and the influx of detrital sediments to any nearby basin apparently were less than during the Late Ordovician. Thus, chances are that if the Ragland K-bentonite was not eroded during that time, it survived any further erosion during the Silurian. Regionally, this unconformity becomes less and less pronounced to the northwest as shown in Figure 48, indicating that the erosional hiatus was of shorter duration in these areas, certainly not lasting through the Silurian or even the Late Ordovician in many places.

For the K-bentonite at the Ragland quarry to be the Millbrig, this section must have been in an area where carbonate sediments were accumulating during the time of K-bentonite deposition, and then during the subsequent period of major regional erosion, this area had to somehow escape being eroded as deeply as many surrounding areas, where in places the Frog Mountain rests on the Lower Ordovician Newala Formation (Thomas and Drahovzal, 1974). Biostratigraphic studies have established the age of the Little Oak as Middle Ordovician (Whiterockian, as defined by the revised stratigraphic chart by Ross et al., 1982)(Butts, 1926; Drahovzal and Neathery, 1971; and Schmidt, 1982).

Hall and others (1986) studied a section of the Little Oak southwest of Ragland, and reported a Whiterockian age for those strata based on the conodonts; however, neither the base nor the top of the section were exposed. Although these meticulous biostratigraphic studies indicate that the Little Oak is everywhere older than the Chickamauga, conodont time-lines are stratigraphically not nearly as precise as K-bentonite time-lines. This is demonstrated by a comparison of the suggested correlations of Hall and others (1986) based on the conodont studies, and on the positions of the K-bentonites. As shown in Figure 57, which is Figure 8 of Hall and others, the top of the Chickamauga Group is, based on conodont biostratigraphy, youngest at Tidwell Hollow, older at Red Mountain, and oldest at Gadsden. (For reference, these sections are the Tidwell Hollow, Red Mountain Expressway, and Big Ridge sections of this study). At Tidwell Hollow and Big Ridge, the Millbrig occurs about 30 m below the top of the contact between the Chickamauga Group and the Sequatchie Formation, but at the Red Mountain Expressway the Millbrig is only 4 or 5 m below the top of the Chickamauga, which is the unconformity between the Chickamauga and the Silurian ironstones discussed above. The Stones River and Nashville Groups at Big Ridge are shown incorrectly in Figure 57 as being entirely Black Riverian in age, when in fact the strata from the Deicke upwards are Rocklandian in age based on the age of the K-bentonites, which are exact timelines that cut

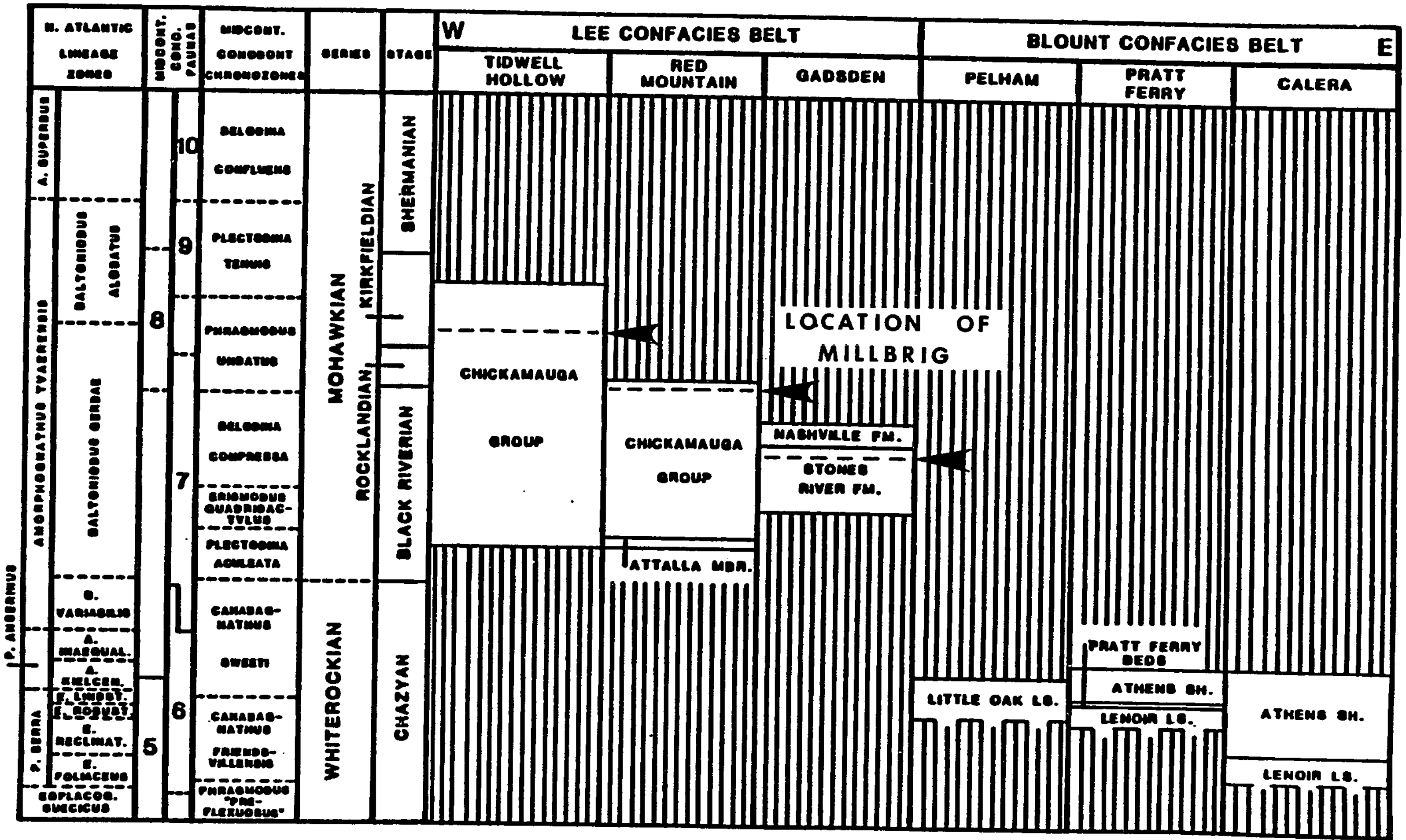


Figure 57. Correlations for 6 Alabama Valley and Ridge sections on the basis of conodont biostratigraphy (from Hall et al., 1986). Note the Millbrig's position at each section in the Lee Confacies Belt as determined by the present study (arrows). As an ideal isochron, the Millbrig is obviously not time-transgressive as shown. This significant discrepency points out the need for a rethinking of correlations based solely on conodonts now that a regional K-bentonite stratigraphic framework has been established.

across all facies changes. Conversely, the Red Mountain section is shown as containing Ordovician strata younger than the Nashville, which is also incorrect because there is at present very little Chickamauga remaining between the Millbrig and the Ordovician-Silurian unconformity at the Expressway. Sedimentologically, the Chickamauga at Red Mountain is more similar to the Nashville Group (open marine, ramp carbonates with a diverse and abundant fauna) than to the Stones River Group (peritidal, restricted marine carbonates with a sparse fauna). This is in agreement with evidence which suggests that the open marine environment was transgressive to the north and northeast (Fig. 55), it indicates that the lithofacies present in most of the upper Chickamauga Limestone at the Red Mountain Expressway is the lithofacies that farther north is the lithofacies that is present in the Hermitage Formation and the other units of the Nashville Group. The stratigraphic location of the K-bentonites makes this argument compelling.

Conodont time lines, although cutting across many facies and very useful as markers, are not indiscriminant of all facies changes as are volcanic ash beds, altered or unaltered.

A more probable cause for the discrepencies between the inferences drawn by Hall and others (1986) based on their conodont studies and the inferences drawn by the positions of the K-bentonites is that the Red Mountain section represents a more normal marine environment along the platform edge, and so a more diverse fauna would be expected. This would allow for a mixing of conodonts from various areas, but it would not affect the deposition of the volcanic ash, except for some minor reworking relative to the platform areas. There is in fact mixing of conodonts as reported by Hall and others (1986). The assemblage recovered from the Red Mountain Expressway contains a mixture of the Lee (90%) and Blount (10%) Confacies Belts (as designated by Jaanusson and Bergstrom, 1980), which represents a mixing of Midcontinent and North Atlantic forms.

Fauna from the Little Oak Limestone, by contrast, are all of North Atlantic character, a point about which much is made by Hall and others (1986). They in fact note that there are few diagnostic species in common between the Chickamauga and Little Oak/Athens sections as shown in Figure 57. Sedimentologically, however, the Little Oak fits into the shelf to basin sequence with the Chickamauga, being a downslope ramp deposit with an abundant and diverse normal marine fauna. The absence of Midcontinent forms may simply reflect differences in water temperature between the platform and platform margin settings, preferred by Midcontinent forms, and the deeper water, off-shelf settings favored by North Atlantic forms.

Some additional supporting evidence for the correlation shown in Figure 56 comes from radiometric ages obtained for biotites from the Ragland K-bentonite by M. J. Kunk of the

U.S. Geological Survey, which give an age of around 453 million years using the $^{40}Ar/^{39}Ar$ method (M. Kunk, pers. comm.). This age is identical to ages previously obtained for the Millbrig (T-4) and other adjacent K-bentonites in the southeastern U.S., as determined by earlier studies (Kunk and Sutter, 1984). Samples for those analyses were obtained from the Millbrig at the Black River Mine, South Carthage, and Big Ridge sections of the present study.

Interpretations using the K-bentonites should be seriously considered, because it is logical that the Ragland K-bentonite should correlate with a known K-bentonite from other Ordovician sections in the region, of which there are many. If this bed is Whiterockian, why are there no other K-bentonites reported from equivalent strata elsewhere in Alabama, Georgia, Tennessee, or elsewhere? Perhaps the Ragland K-bentonite, if it is not the Millbrig, was deposited during the time that much of the Valley and Ridge was subaerially exposed, forming the present Knox Unconformity. Laurence (1944) reported altered volcanic ash in a paleosinkhole on the Knox Unconformity, and bed B-1 of Fox and Grant (1944), which was reported by them to occur 2-3 m above the unconformity, contained biotite, quartz, and feldspar. Perhaps these isolated occurrences of altered volcanic ash represent the same bed now preserved at Ragland. Even so, an argument can be made that the bed at Ragland, occurring near the top of a Middle Ordovician carbonate unit, is either the Millbrig or one of the 2 or 3 relatively thick K-bentonites found above it in sections to the northwest.

Correlation with K-bentonites North of Roanoke, Virginia

North of the New River Valley and west of the Salem synclinorium in Virginia and West Virginia, the redbeds of the Moccasin Formation grade into the gray carbonate rocks of the Nealmont Formation, and the Eggleston Formation is also replaced by the Nealmont (Kay, 1956). Exposures in the Rich Patch Valley are transitional between those to the south and north of the valley, and that is the northernmost area where the Eggleston is recognized. Lesure (1957) reported a bentonite in the Eggleston in an exposure that was examined in detail during the present study (Figure 47). A K-bentonite about 60 cm thick, with an underlying chert layer, was located just downsection of the contact between the Eggleston and Trenton ("Martinsburg") Formations. The bed is relatively fine-grained, very dark gray in color, and has a "cooked" or "baked" appearance. This texture is most likely a result of the higher maximum burial temperatures experienced by these strata compared with those to the south (Harris et al., 1978). A thin-section of this bed was not made, but based on the proximity of the K-bentonite to the Eggleston-Trenton contact, it is probably bed V-7, as shown in Figure 48. Although the Millbrig was not exposed at that outcrop, it is probably present in the area based on its thickness in exposures to the south in the New River Valley at Goodwins Ferry and Gap Mountain. As discussed below, the Deicke becomes thinner in this direction, and it may or may not be present in this area or farther north. Exposures to the north of the Rich Patch Valley were not studied in detail for this study.

In the Salem synclinorium to the east, the clastic rocks of the Bays Formation extend as far northeast as Daleville, about 15 km north of Roanoke. There, the Millbrig and V-7 K-bentonites are present at the Daleville section (Figure 15). This is the northeastern edge of the synclinorium, and the next exposures of Rocklandian strata to the northeast are in the Pine Hills syncline of the Fincastle synclinorium. This is about 15 km north of the Daleville section and across the Glebe Mills fault, which is a cross fault off the Salem fault, itself a branch of the Pulaski fault system (Bartholomew, 1987). The section is markedly different there, as shown in Figure 58. The Martinsburg Formation is the key unit, being present above the Bays Formation at the Daleville section, and above the Fincastle Conglomerate Member at the Fincastle section. The Paperville Shale underlies the conglomerate and is equivalent to the Liberty Hall Limestone underlying the Bays at the Daleville section. Sandstones in the Fincastle Conglomerate (the matrix, not the detrital clasts) are texturally and compositionally similar to sandstones in the Bays (Karpa, 1974) and the unit is thus considered at least partly equivalent to the Bays. It is not a typical Bays

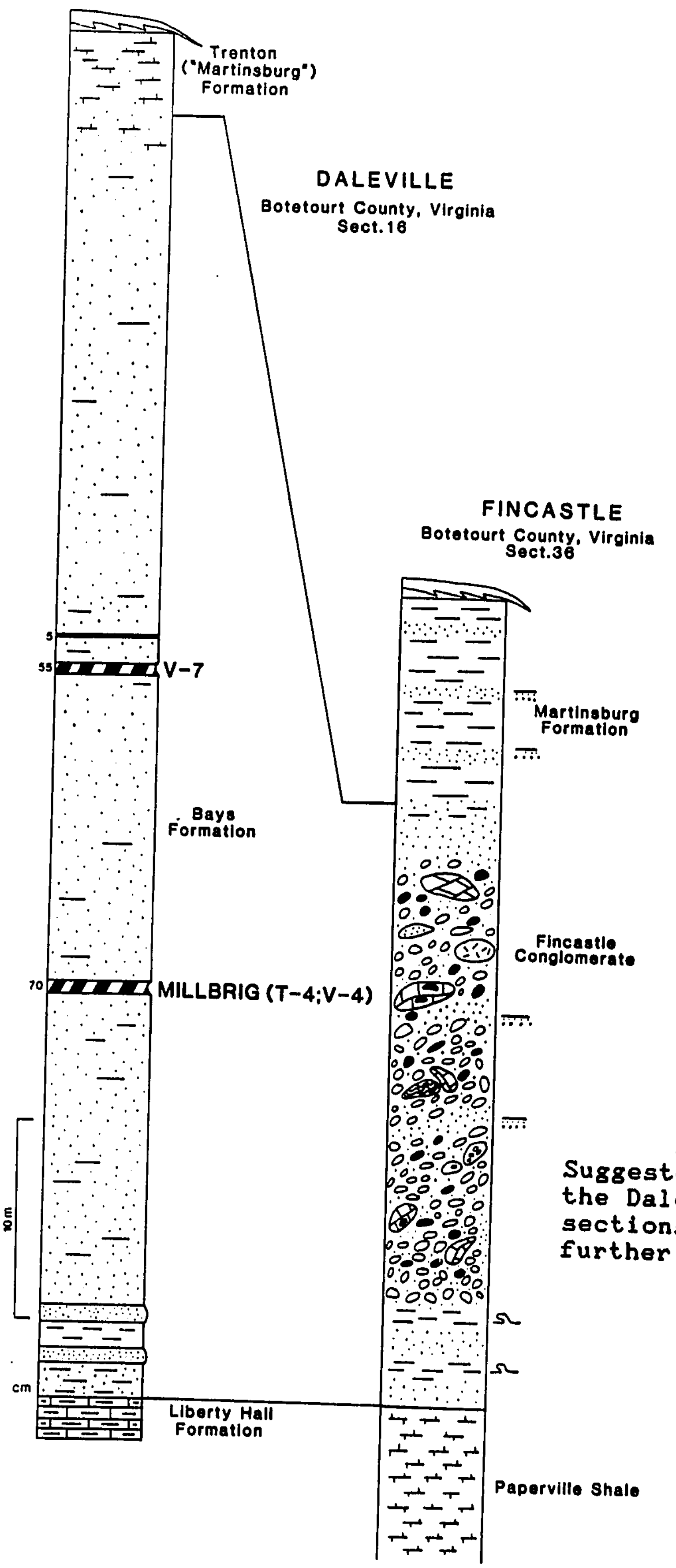


Figure 58.
Suggested correlation of the Daleville and Fincastle sections. Refer to text for further discussion.

lithology, however, and for mapping purposes the unit is known as the Fincastle Conglomerate Member of the Martinsburg Formation (Rader and Gathright, 1986). It is nevertheless the unit in which Rocklandian K-bentonites should be found.

The unit is completely exposed in two roadcuts on opposite limbs of the Pine Hills syncline, but no K-bentonites were found during a visit to both outcrops. The Fincastle Conglomerate is interpreted as a submarine fan complex by Rader and Gathright (1986), and if the precursor volcanic ashes of the Deicke, Millbrig, and V-7 K-bentonites had been deposited in this environment, they would have been extensively reworked judging from the energy levels implied by the large clasts (long axis up to 43 cm) in the unit. Because previous studies have documented K-bentonites in Rocklandian strata northeast of this area (Giles, 1927; Rosenkrans, 1933), it is assumed that the Millbrig and V-7 extend farther north, and that they are absent locally at the Fincastle section because the ash was reworked and dispersed soon after deposition.

The Deicke may extend farther north as well, but it is thinning in this direction and if present it will probably be a much thinner bed than in southwest Virginia, Tennessee, Georgia, and Alabama. Perry (1972) describes Rocklandian K-bentonites in the Germany Valley of Pendleton County, West Virginia, noting the presence of 2 beds in the Nealmont Formation, one of which is 1.1 ft thick. This bed is most likely the Millbrig or V-7, but additional studies will be necessary to determine the proper correlation.

Comparison of the Deicke and Millbrig with Other Paleozoic K-bentonites

The Deicke and Millbrig are widespread K-bentonites in the Ordovician of eastern North America. K-bentonites are known from Ordovician rocks in Scandinavia, and from rocks in other Paleozoic systems as well, and a brief comparison of some of these other K-bentonites with the Deicke and Millbrig suggests several similarities. One of the oldest reported beds is a K-bentonite in the Upper Cambrian Lamotte Sandstone of Missouri (Beall and Ojakangas, 1967). Quartz grains were very scarce, even though the Lamotte is a quartz arenite. The bed contains a heavy mineral suite of zircon, hornblende, sphene, tourmaline, and epidote. Zircon grains, comprising 89 % of the suite, are elongate prisms unlike any zircons in the Lamotte, and reflect the volcanic origin of the bed. Mixed-layer I/S with an illite:smectite ratio of 80:20 is the major constituent of the bed. This bed is unusual because it occurs in a mature quartz arenite, similar to the K-bentonites in the Colvin Mountain Sandstone at Alexander Gap, Alabama, and is the only other documented occurrence of a K-bentonite in quartz arenites known to this author.

An altered vitric tuff of Arenigian age in Sweden was studied by Vortisch (1980). Pyrite, anatase, and calcitized shards of Mg-poor calcite are the non-clay minerals present. Unlike normal K-bentonites, however, the clay in this bed is mixed-layer illite/beidellite, with 30-40 % beidellite. There is almost no Mg in the clay, as Al replaces it in the octahedral position. Vortisch suggests that the mineral assemblage in the bed is a reflection of the primary sea-water or interstitial pore-water composition, which was Mg-poor. The shards were psuedomorphed by the Mg-poor calcite during early diagenesis, and subsequent P-T changes have not altered the bed further. This bed is interesting because it contains identifiable shard psuedomorphs, which are very rare in Paleozoic K-bentonites and altered tuffs, and it contains anatase, as does the Deicke.

Hagemann and Spjeldnaes (1955) described several K-bentonites from the Oslo-Asker district, Norway. Most beds contain biotite grains, either in a thin layer at the or scattered throughout. Quartz phenocrysts are abundant, and feldspar, zircon, hematite, apatite, and titanite (sphene) are accessories. X-ray tracings were run on ethylene glycol solvated samples, but as discussed by Hagemann and Spjeldnaes the illite:smectite ratio was indeterminable from the results, which were difficult to interpret because there appeared to be such as small amount of montmorillonite. Nevertheless, they reported that A. M. Bystrom of the Geological Survey of Sweden later obtained X-ray tracings which indicated that the samples were principally illite. These beds are similar in both phenocryst and clay mineral composition to the Millbrig, particularly in the Valley and Ridge where the illite:smectite ratio is commonly 9:1.

At Kinnekulle, Sweden, there area several K-bentonite beds that have been intensively studied (Bystrom, 1956; Velde and Brusewitz, 1982; Brusewitz, 1986; Kunk et al., 1984). There are several different beds present in Ordovician and Silurian strata, including one bed known as the "big bed" that is 2 m thick. Random ordered (RO) I/S constitutes 80 % or more of the bed, with up to 54 % smectite present in some samples. Quartz is the major phenocryst, comprising 5-20 % of the bed, with biotite (some partly chloritized) and sanidine comprising 2-5 %, and kaolinized plagioclase and pyrite the rest. The big bed is actually made up of 3 separate ashfalls deposited in succession (M. Kunk, pers. comm.). Several interesting similarities of this bed with the Millbrig are immediately apparent. Biotite and quartz phenocrysts are the most abundant in the big bed, and they are very abundant in the Millbrig, but most interesting is the observation that the big bed is comprised of 3 separate ashfalls. Study of Figure 49, the Millbrig at Shelbyville, Tennessee, shows that the Millbrig is also comprised of 3 separate ashfalls. This suggests the very real possibility that the Millbrig and the big bed are the same K-bentonite, a possiblity supported by the close agreement of radiometric ages, 454 Ma for the Millbrig (Kunk and Sutter, 1984) and 455 for the big bed (Kunk et al., 1984), based on $^{40}Ar/^{39}Ar$ dating of biotites from the Millbrig and biotites and sanidines from the big bed.

Snall (1977) studied over 200 K-bentonites in drill cores from Gotland. The beds ranged in thickness from less than 1 mm to 38 cm, and many of the beds are nothing more than a bedding plane with a layer of biotite grains on it. I/S is the main clay present, but kaolinite occurs in abundance in some samples. Biotite is the most common phenocryst, and it commonly occurs as aggregates with kaolinite. Quartz also occurs in the coarser fraction of most beds, and K-feldspar, pyrite, apatite, zircon, and anatase are all present as accessories in varying amounts, with anatase sometimes present in amounts of 2-3 % of the rock. The aggregates of biotite and kaolinite are similar in appearance to biotites observed in some Millbrig samples from the Bays Formation.

Silurian K-bentonites in the Welsh Borderland, U.K., were studied by Teale and Spears (1986). These beds contain I/S, with about 80 % illite, as the main component, and some kaolinite is also present. The most important finding that is of importance to the present study is their observation that in clastic-dominated sequences volcanic material can be very difficult to recognize given the reworking that occurs. This is the favored reason for the absence of the Deicke in the Bays Formation and its probable absence in the Colvin Mountain Sandstone.

The Devonian of the eastern U.S. contains several K-bentonites, the most widespread of which is the Tioga. It is actually an interval in which several altered ash beds occur (Dennison, 1983), and it extends from northern New York south to West Virginia and west to the Illinois basin (Roen and Hosterman, 1982). It contains I/S as the main clay mineral, with over 85 % illite. The Tioga occurs in both carbonate and clastic rocks, and when in carbonates it contains I/S but no kaolinite, biotite, or quartz, and in clastics it contains I/S, kaolinite, biotite, and quartz. According to Dennison and Textoris (1971) bleached biotite is visible in hand specimens and thin-section, comprising up to 70 % of the phenocrysts in some zones. Plagioclase, quartz, apatite, and zircon also occur. The thickest section is in northern Virginia, where over 70 m of section contain reworked pyroclastic material, and biotite grains are up to 2 mm in diameter. The thickest individual K-bentonite is 30 cm thick. The abundance of biotite again suggests a similarity to the Millbrig, and the large vertical interval through which pyroclastic material is found is similar to the Rocklandian sequence of eastern North America. The presence of kaolinite only in areas where the Tioga is in clastic strata is like the difference observed in the Millbrig between the Chickamauga and Eggleston and the Colvin Mountain and Bays. Roen and Hosterman (1982) note that kaolinite is an alteration product of volcanic ash and it does not form in an alkaline environment.

In these various studies, several of the beds are similar in composition to the Millbrig, but none is very similar to the Deicke, with its unusual phenocryst assemblage of labradorite and ilmenite/titanomagnetite, with quartz, biotite, zircon, and apatite present as minor accessories. In addition, some of the unusual findings of the present study, such as the kaolinite-rich K-bentonites in the quartz arenites of the Colvin Mountain Sandstone and the absence of the Deicke in the Bays Formation have parallels in several of the beds described from elsewhere.

Use of Apatite Chemistry to Correlate the Deicke and Millbrig

The study by Samson and others (1988) suggested that Deicke and Millbrig samples from the Upper Mississippi Valley could be correlated on the basis of apatite chemistry. In addition to samples from the Upper Mississippi Valley, 3 K-bentonite samples from the Cincinnati Arch were also analyzed. A sample from Tennessee that they indicated was of bed T-3 is described as containing only apatite, zircon, and biotite as unaltered phenocrysts, and an unidentified sample from Alabama was reported also to contain only these three minerals as unaltered phenocrysts. The correct identification of T-3 from the Nashville Dome cannot be checked, although judging from their map it is possibly from the exposure at South Carthage, Tennessee, where the Deicke (T-3) is well exposed. The unknown sample from Gadsden, Alabama, which was only identified as the third K-bentonite from the bottom of the section, is certainly T-4, however. The sample number, MJK81-30, indicates that this bed comes from M. J. Kunk of the U.S. Geological Survey; this same sample was described in a paper by Kunk and Sutter (1984) that described the results of 40Ar/39Ar dating of biotites from T-3 and T-4 in Kentucky, Tennessee, and Alabama. Sample MJK81-30 of Samson and others (1988) is clearly T-4, the Millbrig, at Big Ridge, as shown in Kunk and Sutter's Figure 2, where sample 30 is T-4.

An important problem with the findings of Samson and others (1988) is the lack of any reported feldspar and Fe-Ti oxide phenocrysts in the T-3 samples from Tennessee, and the lack of feldspar and quartz phenocrysts in T-4 from Big Ridge, which, as described herein, are abundant in the Deicke and Millbrig K-bentonites, T-3 and T-4, respectively. It is possible that these samples were collected from the upper zones of each K-bentonite, where the phenocrysts are much finer-grained. Alternatively, it is possible that these minerals were somehow lost in the grain separation process, but it is difficult to understand how this could happen, as simple dispersion and wet-sieving techniques were used. These are techniques that were used to prepare grain separates for the present research, and even in smaller size fractions significant quartz and feldspar grains were present. The apparent lack of these otherwise abundant phenocrysts in Deicke and Millbrig samples needs better explanation.

Another problem is that Samson and others (1988) plot the apatite chemistry for three known K-bentonites (Deicke, Millbrig, and Nasset, from the Upper Mississippi Valley) and the unknown sample MJK81-30 in their Figure 3, and it is evident that all four samples plot in separate fields, which they cite as evidence for the utility of apatites in correlating K-bentonites. Sample MJK81-30, rather than plotting separately from the Millbrig samples as it indeed does, ought to plot with them, unless there is a shift in trace element chemistry between these regions, specifically in the rare-earth elements used for correlation, which was undetected by Samson et al. Recent chemical fingerprinting analyses (W. Huff, personal communication) of samples collected during field work for the present study indicates that there is in fact a shift in trace element ratios between the Upper Mississippi Valley and the Cincinnati Arch and Valley and Ridge. This shift may reflect the increasing importance of phenocrysts relative to illite/smectite as samples are collected from northwest to southeast in the midcontinent region. Whatever the reason for the observed differences, additional work with many more samples from the Cincinnati Arch and the Valley and Ridge should be done to build up a more extensive data base before further correlations between the Upper Mississippi Valley and the eastern midcontinent are proposed on the basis of apatite chemistry alone.

CONCLUSIONS

1) The 2 thickest K-bentonites in Rocklandian strata of the southeastern United States, which have been previously correlated with the Deicke and Millbrig K-bentonite Beds of the Upper Mississippi Valley, can be distinguished on the basis of phenocryst composition. The Deicke contains labradorite and Fe-Ti oxides as the major primary phenocrysts, and the Millbrig contains andesine, biotite, and quartz as the major primary phenocrysts. Biotite and quartz are present as accessory minerals in the Deicke, and zircon and apatite are accessory minerals in both beds. The Deicke is an altered dacitic ash, and the Millbrig is an altered rhyodacitic ash.

2) The systematic increase in the ordering and the illite: smectite ratio of the I/S from northwest to southeast suggests that maximum burial temperatures were highest in the southeast.

3) The Deicke and Millbrig can be recognized and correlated between the Cincinnati Arch and the Valley and Ridge, and along strike in the Valley and Ridge from Birmingham, Alabama, to Roanoke, Virginia. Some previously suggested correlations are revised on the basis of petrographic criteria. In the Valley and Ridge of southwest Virginia and upper northeast Tennessee a stratigraphic reinterpretation

shows that the three thickest K-bentonites can be correlated along and across strike throughout this region. The lowest bed is the Deicke, and it occurs in the Eggleston Formation in the western belt, and in or just above the uppermost Moccasin Formation in the central belt. It is known in these areas as R-7 or V-3, and is absent from the Bays Formation of the eastern belt. The middle bed is the Millbrig, and it is present in strata of all three belts of the Valley and Ridge, occurring in the Eggleston Formation in the western and central belts and in the Bays Formation in the eastern belt. It is known as bed R-10 or V-4. The upper K-bentonite also occurs in all three belts, and is known as R-12 or V-7. This upper bed is probably equivalent to the bed known as B-8 in the Valley and Ridge farther south, but this correlation is not as certain.

4) It is recommended that the names "Deicke K-bentonite Bed" and "Millbrig K-bentonite Bed" be used for the 2 widespread K-bentonites present along the Cincinnati Arch, and for the 2 lower of the 3 thick K-bentonites in the Valley and Ridge because they correlate with the Deicke and Millbrig of the Upper Mississippi Valley, and alpha-numeric names are inappropriate for stratigraphic units. Use of the name Deicke replaces the terms T-3 and "Pencil Cave" along the Cincinnati Arch, B-3 in the Chattanooga area, R-7 in the Powell Valley sections of the western belt of the Valley and Ridge, and V-3 in the central belt of the Valley and Ridge.

Use of the name Millbrig replaces the terms T-4, "Mud Cave", B-6, R-10, and V-4 in the above areas, respectively.

5) For the first time, K-bentonites in the Bays Formation in the eastern belt of the Valley and Ridge have been correlated with those in the central and western belts in this area. Because fewer K-bentonites occur in the Bays and because the Bays is a clastic sequence, both of which are a contrast to the carbonate sequences of the western and central belts in the Valley and Ridge, this correlation has been more difficult to make than those in and between the central and western belts. Nevertheless, based on the presence of abundant biotite and on the stratigraphic relation of the Walker Mountain Sandstone and the Bays Formation-Trenton Formation contact to the K-bentonites at several sections in Virginia and Tennessee, it is clear that the Millbrig K-bentonite (V-4) and bed V-7 both occur in the Bays Formation. Once recognized, their usefulness as consistent markers in many exposures of the Bays becomes apparent.

6) In the Colvin Mountain Sandstone of Alabama and Georgia, the Deicke is identifiable based on the presence of ilmenite grains, and at the Alexander Gap section in Alabama the thick K-bentonite upsection from the Deicke is most likely the Millbrig, although all phenocrysts have been altered beyond recognition.

7) These correlations integrate the Rocklandian sequences of this area. They provide a set of time lines that will be useful in detailed biostratigraphic, sedimentologic, geochemical, and paleogeographic studies of these strata. The changes in depositional environments across the Appalachian basin that were present at the time the Deicke and Millbrig precursor ashes were deposited can be inferred in some detail using the 2 beds as subparallel time lines between the Valley and Ridge and the Cincinnati Arch. Although many earlier studies have used the interval of strata in which K-bentonites, including the Deicke and Millbrig, occur as a general time line, the correlation of these 2 beds across such a large area allows for a paleogeographic reconstruction of a single moment in time across a very large area.

8) The various feldspars and clay minerals in the beds suggest that the beds have been buried more deeply in the Valley and Ridge than along the Cincinnati Arch, and most deeply along the eastern Valley and Ridge. This finding is in agreement with the temperature gradients suggested by the conodont color alteration index as determined for this region.

9) Significant changes in the texture and composition of the Deicke and Millbrig occur between their type localities

in the Upper Mississippi Valley and the southeastern U.S. Study of these beds will be facilitated by several reference sections in that area that will show the character of the 2 beds in the various structural and stratigraphic settings in which they occur.

10) The Deicke is a normally graded bed of altered volcanic ash, and it represents the accumulation of ash from a single but very large eruption. The Millbrig, however, usually shows evidence that it consists of at least 2 separate ashfalls, and an additional 2 thin graded beds that represent separate ashfalls are preserved above the main coarse-grained zone in an exposure near Shelbyville, Tennessee.

SUGGESTIONS FOR FURTHER STUDY

1) Absolute ages of the authigenic K-feldspars would help to determine the burial history of these beds in the context of current understanding of the burial history of the Appalachian Basin. Because the feldspars in the K-bentonites are either primary igneous phenocrysts or overgrowths on these grains, the problem with cores of detrital feldspar grains that is commonly encountered in studies of authigenic feldspars in clastic strata is not a concern, and analytically determined ages will be that much more reliable.

2) Additional field work north of Roanoke should be the key in working out the correlations of K-bentonites in strata of that region with the ones discussed herein. The abrupt facies change that occurs between Roanoke and Lexington, Virginia, has historically been a dividing area for studies, but K-bentonites undoubtedly occur across this zone, and based on the findings of this study it is probable that the Millbrig and bed V-7 will be recognizable in sections north of Roanoke.

3) Study of geophysical well logs from the Appalachian basin of West Virginia, eastern Kentucky and Tennessee, and northern Alabama could be useful in determining the lateral extent west of the Valley and Ridge of the K-bentonites above the Millbrig, some of which like V-7 are as thick as the Deicke and the Millbrig.

4) A clay mineralogy study of samples collected in vertical traverses of the beds should be done to investigate possible changes in the clay between the edges and the center of the beds. This would be similar to the study of Altaner and others (1984), although the clay mineralogy data reported by Elliott and Aronson (1987) for Deicke samples collected in traverses at 2 exposures in the region showed only minor variations across the bed.

5) Additional microprobe analyses of the phenocrysts will probably reveal more information on their genesis and diagenesis. The Fe-Ti oxides, zircons, and apatites in particular may contain useful information on the chemistry of the original ash, and the biotite in the Millbrig might be useful as a supplemental correlation tool if phenocryst compositions can be shown to be consistent across the region.

6) Field studies should be continued in central east Tennessee to trace the K-bentonites from the Chattanooga region northeast into the area north of Knoxville, and to the east of that area. Outcrops in the Tellico-Sevier belt should be re-examined in particular, as the Bays Formation in that area is transitional between the Bays farther north and the Colvin Mountain Sandstone of north Georgia. Outcrops in north Georgia should also be studied to investigate the changes in the Colvin Mountain Sandstone north of Rome, where the only K-bentonite in the sandstone in Georgia was found.

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APPENDIX 1

The following are section numbers (including those shown on Figures 3-15, 50-53, 56, and 58, and Plates 1-6), with a description of the locality, and the Deicke, Millbrig, and V-7 samples collected with their identifying numbers. Note that not all sections shown in Figures 45 and 47 are included, because at some outcrops neither the Deicke, the Millbrig, nor V-7 were located.

1) Hagan, Lee County, Virginia

Eggleston Formation along east side of the CSX (ex-L&N) Railroad right-of-way near county road 621 about 0.8 km north of intersection with U.S. 58. Kreisa (1980) gives more details for locating this section.

Deicke: VA 2-1
Millbrig: VA 4-1

2) Gate City, Scott County, Virginia; Gate City 7.5' quad.

New section for K-bentonites. Moccasin and Eggleston Formations at west end of Gateway Plaza just off combined U.S. Highways 23, 58, and 421 immediately before the gap through Clinch Mountain used by the highway and the Southern Railway.

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

3) Rosedale, Russell County, Virginia

Moccasin and Eggleston Formations along northeast side of old (up embankment from new) Rt. 80, 2.3 km west of intersection with U.S. 19 at Rosedale. Kreisa (1980) gives more details for locating this section.

Deicke: VA:RL 2-1
Millbrig: VA:RL 2-2

4) Plum Creek, Tazewell County, Virginia

Moccasin and Eggleston Formations along southeast side of Rt. 16 between Frog Level and Thompson Valley above Plum Creek. Hergenroder (1966) gives more details for locating this section.

Deicke: VA:TZ 1-7
Millbrig: VA:TZ 1-8
V-7: VA:TZ 1-1

5) Cove Creek, Tazewell County, Virginia; Cove Creek 7.5' quad.

New section for K-bentonites. Moccasin and Eggleston Formations along Rt. 614 at first hairpin turn in road southeast of intersection with Rt. 61

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

6) Rocky Gap, Bland County, Virginia; Rocky Gap 7.5' quad.

New section for K-bentonites. Moccasin and Eggleston Formations along southwest side of U.S. 52 (Frontage Rd. for I-77) about 1.5 km south of Rocky Gap.

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

7) Goodwins Ferry, Giles County, Virginia

Moccasin and Eggleston Formations along southeast side of Rt. 625 on east bluff of the New River, just uphill from Norfolk Southern (ex-N&W; ex-VGN) railroad grade crossing. Hergenroder (1966) gives more details for locating this section.

Deicke: VA:GI 4-0
V-7: VA:GI 4-1

8) Mountain Lake Turnoff, Giles County, Virginia

Moccasin and Eggleston Formations along northeast side of westbound U.S. 460 about 1.5 km west of intersection with Rt. 42. Hergenroder (1966) gives more details for locating this section.

Deicke: VA:GI 2-0

9) Terrill Creek, Hawkins County, Tennessee

Bays Formation along northeast side of road above Terrill Creek in gap between Hennard and River Mountains. Hergeroder (1966) gives more details for locating this section.

Millbrig: TN:HK 2-1

10) Chatham Hill, Smyth County, Virginia

Bays Formation along northeast side of Rt. 16 on Big Walker Mountain about 3.7 km south of Chatham Hill. Hergenroder (1966) gives more details for locating this section.

Millbrig: VA:SM 1-3 through 1-6

11) Big Walker Lookout, Bland County, Virginia; Big Bend 7.5' quad.

New section for K-bentonites. Moccasin Formation along south side of U.S. 21/52, on northwest slope of Big Walker Mountain at first hairpin turn going south over the mountain.

Millbrig: VA:BL 2-1

12) Crockett Cove, Wythe County, Virginia; Wytheville 7.5' quad.

New section for K-bentonites. Bays Formation along northeast side of northbound I-77 about 2 km northwest of interchange with I-81.

Millbrig: VA:WY 2-1

13) Conner Valley, Wythe County, Virginia

Bays Formation along east side of Rt. 726 in Connor Valley at west end of small hill that road and creek skirt to the south about 1.3 km north-northeast of Crockett Knob. Hergenroder (1966) gives more details for locating this section.

Millbrig: VA:WY 1-1

14) Gap Mountain, Giles County, Virginia

Moccasin and Eggleston Formations along northeast side of Norfolk Southern (ex-N&W; ex-VGN) railroad right-of-way along the east side of the New River just downriver from the rapids over the Clinch Sandstone. Hergenroder (1966) gives more details for locating this section.

Millbrig: VA:GI 1-1
V-7: VA:GI 1-2

15) Catawba, Roanoke County, Virginia

Bays Formation along southwest side of Rt. 311 at foot of Catawba Mountain. Hergenroder (1966) gives more details for locating this section.

Millbrig: VA:RO 1-4
V-7: VA:RO 1-3

16) Daleville, Botetourt County, Virginia

Bays Formation along the east side of the N&W Railroad Lone Star Spur about 0.8 km due west of Lord Botetourt High School. Hergenroder (1966) gives more details for locating this section.

Millbrig: VA:BT 2-1
V-7: VA:BT 2-2

17) Harrogate, Claiborne County, Tennessee

Eggleston Formation exposed along the southwest side of the right-of-way of the dismantled CSX (ex-L&N) Railroad about 0.5 km southeast of the former grade crossing at Myers School. Huffman (1945) gives more details for locating this section.

Deicke: TN:CL 1-1
Millbrig: TN:CL 1-2

18) Hinds Creek Quarry, Anderson County, Tennessee; Clinton 7.5' quad.

New section for K-bentonites. Chickamauga Limestone exposed in abandoned quarry on Brushy Mountain Road in Lone Mountain subdivision.

Deicke: TN 10
Millbrig: TN 11

19) Henson Creek, Sequatchie County, Tennessee

Carters Limestone exposed along southeast side of Henson Creek near Davis Chapel Cemetery. Milici (1969) gives more details for locating this section.

Deicke: TN:SQ 1-1
Millbrig: TN:SQ 1-2

20) Tillet Bros. Paving Co. Quarry, Bedford County, Tennessee; Shelbyville 7.5' quad.

New section for K-bentonites. Carters Limestone and Hermitage Formation exposed in Tillet Bros. quarry on Rt. 41 Alt. 8 km southeast of Shelbyville

Deicke: TN 6
Millbrig: TN 7-1 through 7-6

21) South Carthage, Smith County, Tennessee; Gordonsville 7.5' quad.

New section for K-bentonites. Carters Limestone and Hermitage Formation exposed on west side of Rt. 53 about 3.7 km south of intersection with Rt. 70N, and along north side of Rt. 70N at intersection

Deicke: TN 1-1 through 1-3
Millbrig: TN 2 and TN 4

22) Davis Crossroads, Walker County, Georgia

Carters Limestone and Hermitage Formation along the dismantled TA&G Railway right-of-way about 0.8 km southeast of the grade crossing with Rt. 341 at the Barwick Mill. Allen and Lester (1957) and Milici and Smith (1969) give more details for locating this section.

Deicke: GA:WL 3-1
Millbrig: GA:WL 3-2

23) Rising Fawn, Dade County, Georgia

Carters Limestone and Hermitage Formation along the west side of the Norfolk Southern (ex-Southern) railroad right-of-way about 2 km south of Rising Fawn, in the second cut from the north (first cut is of Mississippian strata). Allen and Lester (1957) give more details for locating this section.

Deicke: GA:DD 2-1
Millbrig: GA:DD 2-2

24) Fort Payne, Dekalb County, Alabama

Stones River Group along southeast side of northbound I-59 just north of Interchange 222. Drahovzal and Neathery (1971) give more details for locating this section.

Deicke: AL 12-1 through 12-4
Millbrig: AL 14-1 and 14-2

25) Big Ridge, Etowah County, Alabama

Stones River Group along northeast side of northbound I-59 in cut through Big Ridge about 22 km northeast of Gadsden-Attalla exit. Drahovzal and Neathery (1971) give more details for locating this section.

Deicke: AL 7-1 through 7-5
Millbrig: AL 9-1 and 9-2

26) Bruton Gap, Etowah County, Alabama

Stones River Group along northeast side of road through Bruton Gap in Big Ridge. Ward (1983) gives more details for locating this section.

Deicke: AL:ET 2-1
Millbrig: AL:ET 2-6

27) Tidwell Hollow, Blount County, Alabama

Chickamauga Group along northwest side of Rt. 15 just west of Tidwell Hollow about 5 km southeast of Locust Fork. Benson and Stock (1986) give more details for locating this section.

Millbrig: AL:BL 1-1

28) Alexander Gap, Calhoun County, Alabama

Colvin Mountain Sandstone along east side of northbound U.S. 431 in Alexander Gap just south of the initial downgrade through the gap. Jenkins (1984) gives more details for locating this section.

Deicke: AL:CH 1-2
Millbrig: AL:CH 1-4

29) Red Mountain Expressway, Jefferson County, Alabama

Chickamauga Limestone in Red Mountain Museum roadcut along U.S. 31, the Red Mountain Expressway, through Red Mountain in Birmingham. Many authors have described this section, including Drahovzal and Neathery (1971) and Benson and Stock (1986); both of these give more details for locating this section.

Deicke: AL 1
Millbrig: AL 3-1 through 3-7

30) Green Springs, Jefferson County, Alabama

Chickamauga Limestone along west side of southbound I-65 just north of Green Springs exit. Lee (1983) gives more details for locating this section.

Millbrig: AL 4

31) Old North Ragland Quarry, St. Clair County, Alabama

Little Oak Limestone in abandoned quarry on southwest end of low ridge just north of mouth of Trout Creek in Coosa River. Drahovzal and Neathery (1971) give more details for locating this section.

Millbrig?: AL:SC 1-1

32) Highbridge, Mercer County, Kentucky

Tyrone Limestone exposed in cuts along Norfolk Southern (CNO&TP) railroad right-of-way north and south of the High Bridge over the Kentucky River. Gunal (1979) gives more details for locating this section.

Millbrig: KRI 5-0

33) Lexington Limestone Quarry, Jessamine County, Kentucky; Nicholasville 7.5' quad.

New section for K-bentonites. Tyrone and Lexington Limestones exposed in quarry adit; quarry is west of Nicholasville on Catnip Hill Road off U.S. 27

Deicke: KY 6-1 through 6-6
Millbrig?: KY 7

34) Black River Mine, Pendleton County, Kentucky

Tyrone and Lexington Limestones exposed in entrance shaft to the Black River Mine at Carntown. Kunk and Sutter (1984) give more details for locating this section.

Deicke: BRM T-3
Millbrig: BRM T-4

35) Core; Gallatin County, Kentucky

Tyrone Limestone in core. Huff (1963; 1983a) describes this core in more detail.

Deicke: BB 5-5-1
Millbrig: BB 5-2-3

36) Fincastle, Botetourt County, Virginia

Fincastle Conglomerate Member of the Martinsburg Formation exposed in 2 cuts along US 220 just north of Fincastle, Virginia. Karpa (1974) and Rader and Gathright (1986) give more details for locating this section.

K-bentonites appear to be absent at both exposures; section included in Appendix because of its use in Figure 58.

37) Horseleg Mountain, Floyd County, Georgia

Greensport Formation and Colvin Mountain Sandstone exposed at S-curve along Mt. Alto Road. Chowns and Carter (1983a; 1983b) give more details for locating this section.

Deicke: GA:FL 1-1

38) Core; Hamilton County, Ohio

Tyrone Limestone in core. Huff (1983a) describes this core in more detail.

Deicke: N-5
Millbrig: N-2

39) Taylor Avenue Quarry, Franklin County, Kentucky

Tyrone Limestone in Taylor Avenue Quarry in Frankfort, which is on Rt. 1211 just south of CSX (ex-L&N) railroad bridge over the Kentucky River. Gunal (1979) gives more details for locating this section.

Deicke: KY 10-1 through 10-4

40) Shakertown, Mercer County, Kentucky; Wilmore 7.5' quad.

New section for K-bentonites. Tyrone and Lexington Limestones exposed along Rt. 33 just north of bridge, about 1.5 km south of intersection with US 68 at Shakertown.

Millbrig: KY:ME 1-1

41) Core; Marion County, Kentucky

From the collection of Prof. Warren Huff

Deicke: C-114 T-3
Millbrig: C-114 T-4

42) Core; Casey County, Kentucky

From the collection of Prof. Warren Huff

Deicke: C-113 T-3
Millbrig: C-113 T-4

43) Core; Russell County, Kentucky

From the collection of Prof. Warren Huff

Millbrig: C-211

44) Core; Monroe County, Kentucky

From the collection of Prof. Warren Huff

Deicke: KY 1-3
Millbrig: KY 1-4

44) Core; Clay County, Tennessee

From the collection of Prof. Warren Huff

Deicke: TN 3-3
Millbrig: TN 3-8

45) Core; DeKalb County, Tennessee

From the collection of Prof. Warren Huff

Deicke: CHT-3

46) Core; Marshall County, Alabama

From the collection of Prof. Warren Huff

Deicke: KB-35
Millbrig: KB-34

47) Greensport Gap, Etowah County, Alabama

Colvin Mountain Sandstone exposed along the east side of Rt. 77 in the cut through Beaver Creek Mountain. Jenkins (1984) gives more details for locating this section.

Deicke: AL:ET 1-2

48) Dirtsellar Mountain, Cherokee County, Alabama

Stones River Group exposed in small quarry off of Rt. 75. Drahovzal and Neathery (1971) give more details for locating this section.

Millbrig: AL 17

49) Trenton, Dade County, Georgia; Trenton 7.5' quad.

Carters Limestone exposed along northwest side of entrance ramp to southbound I-59 from Rt. 136 at bridge over I-59 just west of "downtown" Trenton.

Deicke: GA:DD 1-1

50) Mill Creek, Walker County, Georgia

Carters Limestone along east side of Rt. 193 about 100 m north of bridge over Mill Creek. Nearby section along Mill Creek is described by Milici and Smith (1969).

Deicke: GA:WL 1-1

51) Old Bethel Church, Walker County, Georgia

Carters Limestone in small borrow pit along McLemore Cove Rd. just northeast of Old Bethel Church, directly beneath powerline right-of-way and across the road from electrical substation. Milici and Smith (1969) describe this section, which outcrops for some distance along the right-of-way.

Millbrig: GA:WL 2-1

52) Dodds Avenue quarry, Hamilton County, Tennessee; Chattanooga 7.5' quad.

New section for K-bentonites. Carters Limestone exposed in small borrow pit along East 26th Street at intersection with Dodds Avenue, in Chattanooga.

Deicke: TN:HM 1-1

53) Windsor Street quarry, Hamilton County, Tennessee; Chattanooga 7.5' quad.

New section for K-bentonites. Carters Limestone exposed along east side of old quarry, which is now a childrens' playground, on Windsor Street just east of intersection with Dodson Road, in Chattanooga.

Deicke: TN:HM 2-1

54) Stephens Road, Bledsoe County, Tennessee; Melvine 7.5' quad.

New section for K-bentonites. Carters Limestone exposed in roadcut along Stephens Road about 2.2 km from intersection with US 127 near Litton.

Deicke: TN 12-1 through 12-3

55) Thorn Hill, Grainger County, Tennessee

Moccasin Formation along US 25E on northwest slope of Clinch Mountain. Hergenroder (1966) gives more details for locating this section.

Deicke: TN 14-1 through 14-4

56) Eidson, Hawkins County, Tennessee

Moccasin and Eggleston Formations exposed along the south side of Rt. 70 on northwest slope of Clinch Mountain. Hergenroder (1966) gives more details for locating this section.

Deicke: TN:HK 3-1

57) Hurricane Bridge, Lee County, Virginia

Hardy Creek and Eggleston Formations exposed along north side of Rt. 654 south of Hurricane Bridge over the Powell River. Miller and Fuller (1954) give more details for locating this section.

Deicke: VA:LE 1-1
Millbrig: VA:LE 1-2

58) Dryden, Lee County, Virginia

Trenton Limestone exposed along west side of CSX (ex-L&N) railroad right-of-way at big bend in Powell River near Dryden. Miller and Fuller (1954) give more details for locating this section.

V-7: VA:LE 3-1

59) Bluefield, Mercer County, West Virginia

Moccasin Formation exposed along south side of US 52 on northwest slope of East River Mountain just east of Bluefield. Woodward (1951) gives more details for locating this section.

Deicke: WV:ME 1-1

60) The Narrows, Giles County, Virginia

Eggleston Formation exposed along north side of westbound US 460 in The Narrows of the New River. Kreisa (1980) gives more details for locating this section.

V-7: VA:GI 3-1

61) Trigg, Giles County, Virginia

Moccasin, Eggleston, and Trenton Formations exposed along Rt. 730 just west of intersection with Rt. 622. Hergenroder (1966) gives more details on locating this section.

Deicke: VA:GI 5-1
V-7: VA:GI 5-2

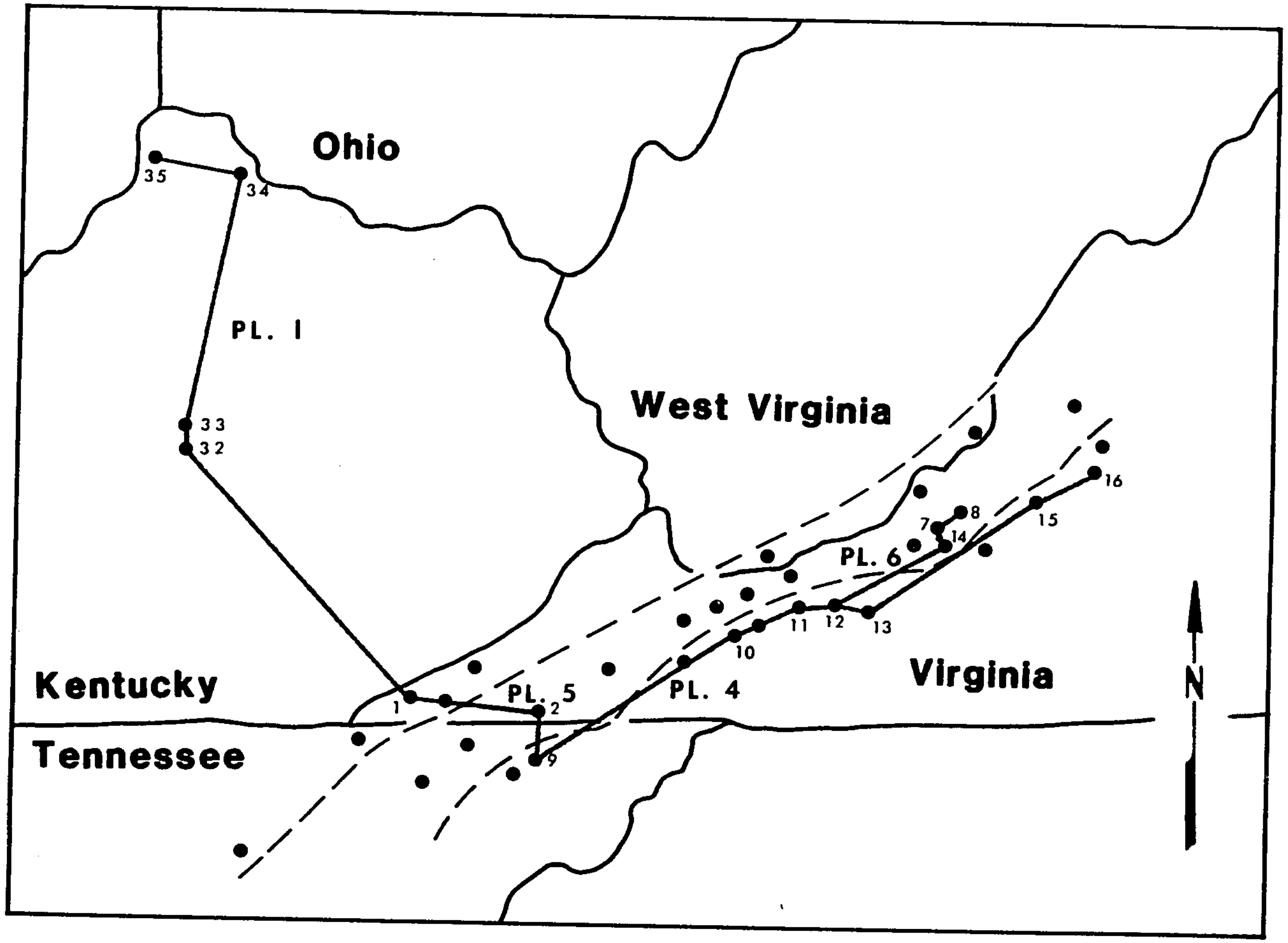
62) Rich Patch Valley, Alleghany County, Virginia

Eggleston and Trenton Formations exposed along north side of Rt. 616 about 1.5 km northeast of Cliff Dale Chapel. Lesure (1957) gives more details for locating this section.

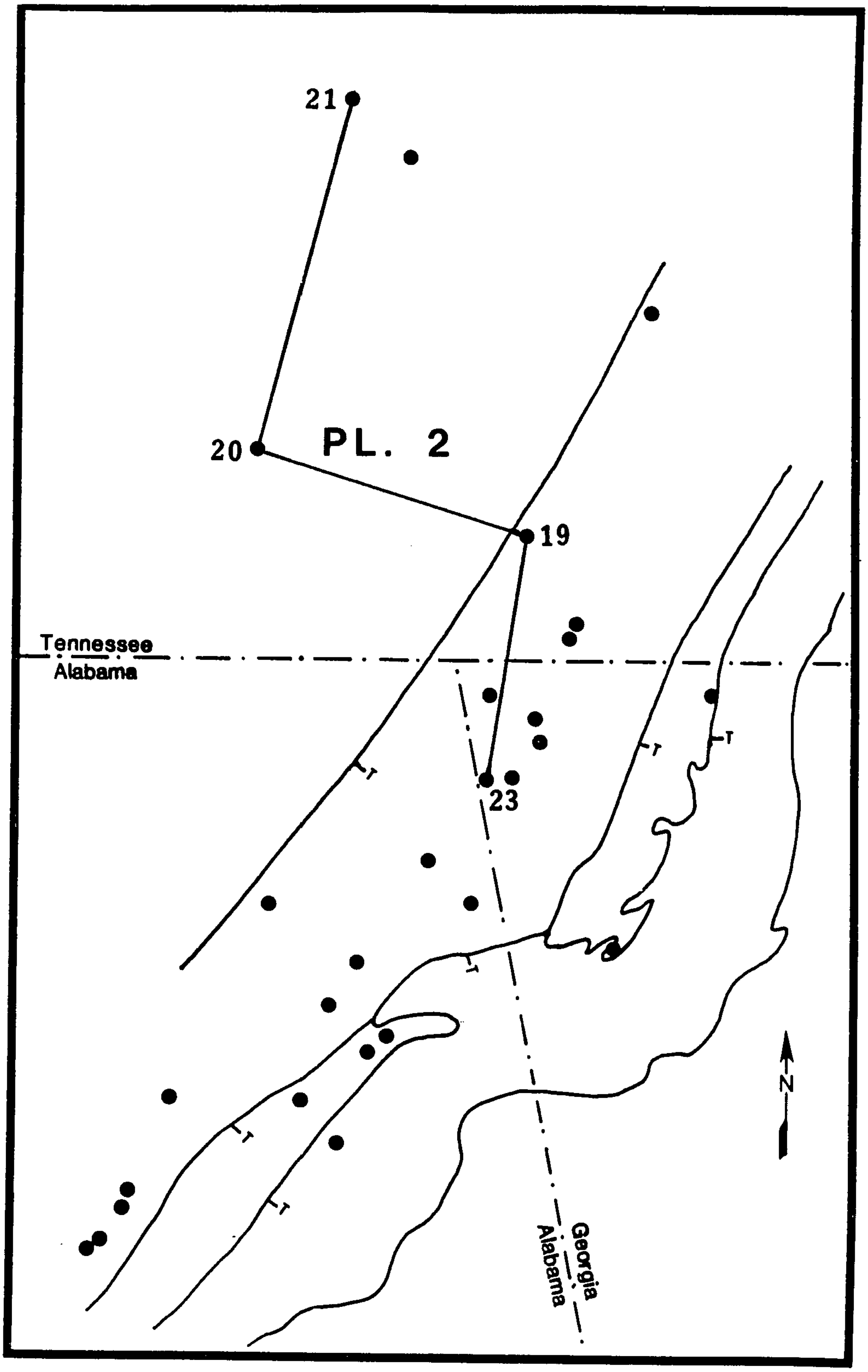
V-7: VA:AL 1-1

APPENDIX 2

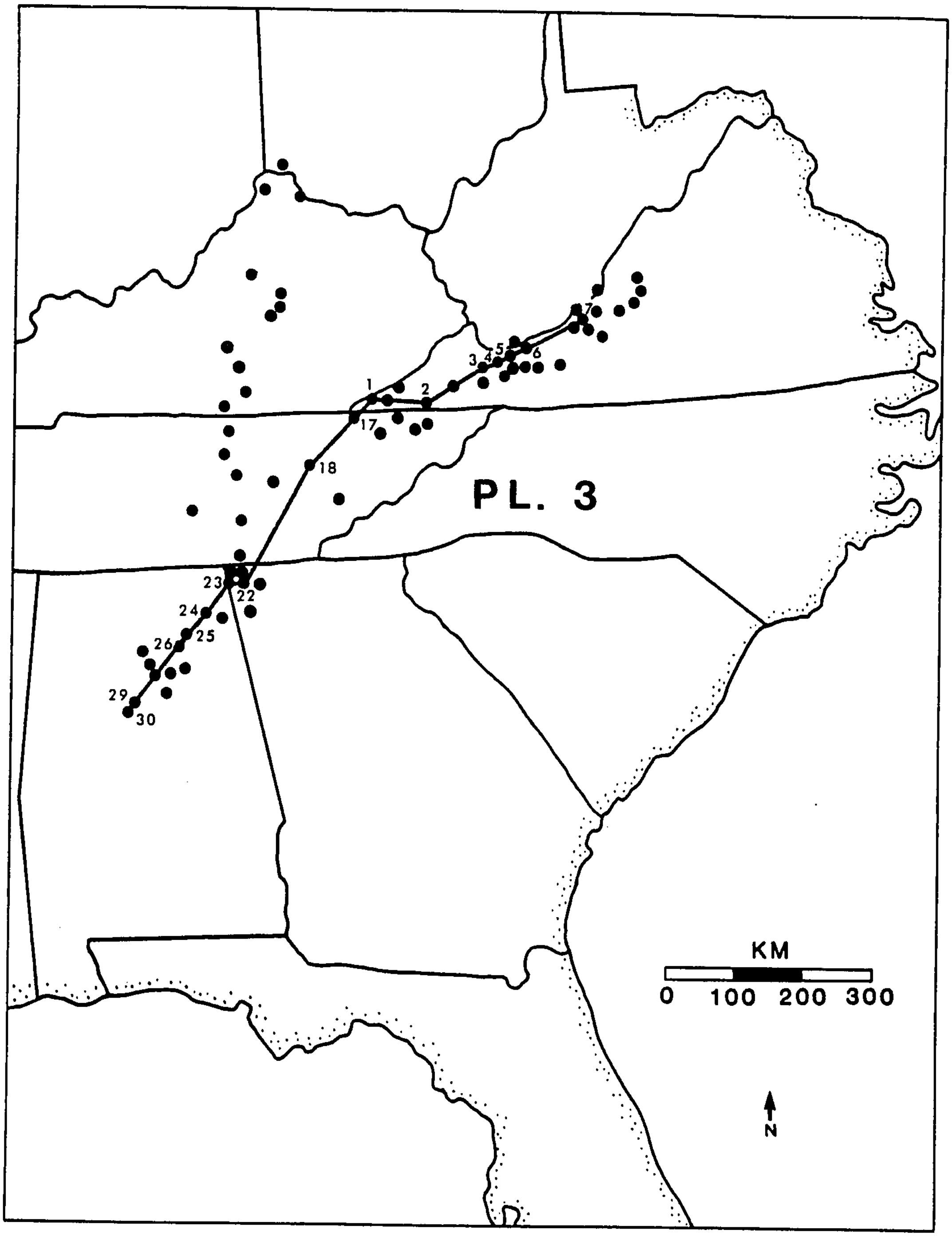
On the following three pages are maps showing the location of the cross-sections in Plates 1 through 6, which are in the pocket. Refer to Figures 45, 46, and 47 in the text for identification of all sections, which are simply shown as dots in the maps.



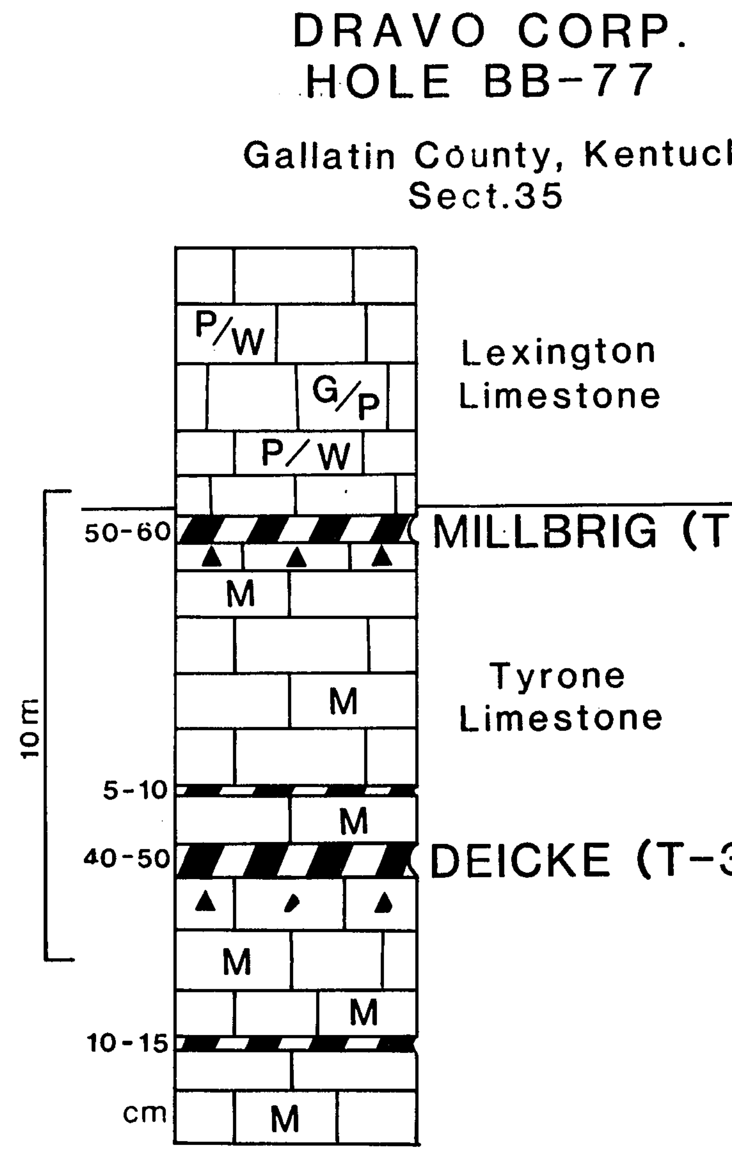
Location of cross-sections on Plates 1, 4, 5, and 6, with section numbers shown.

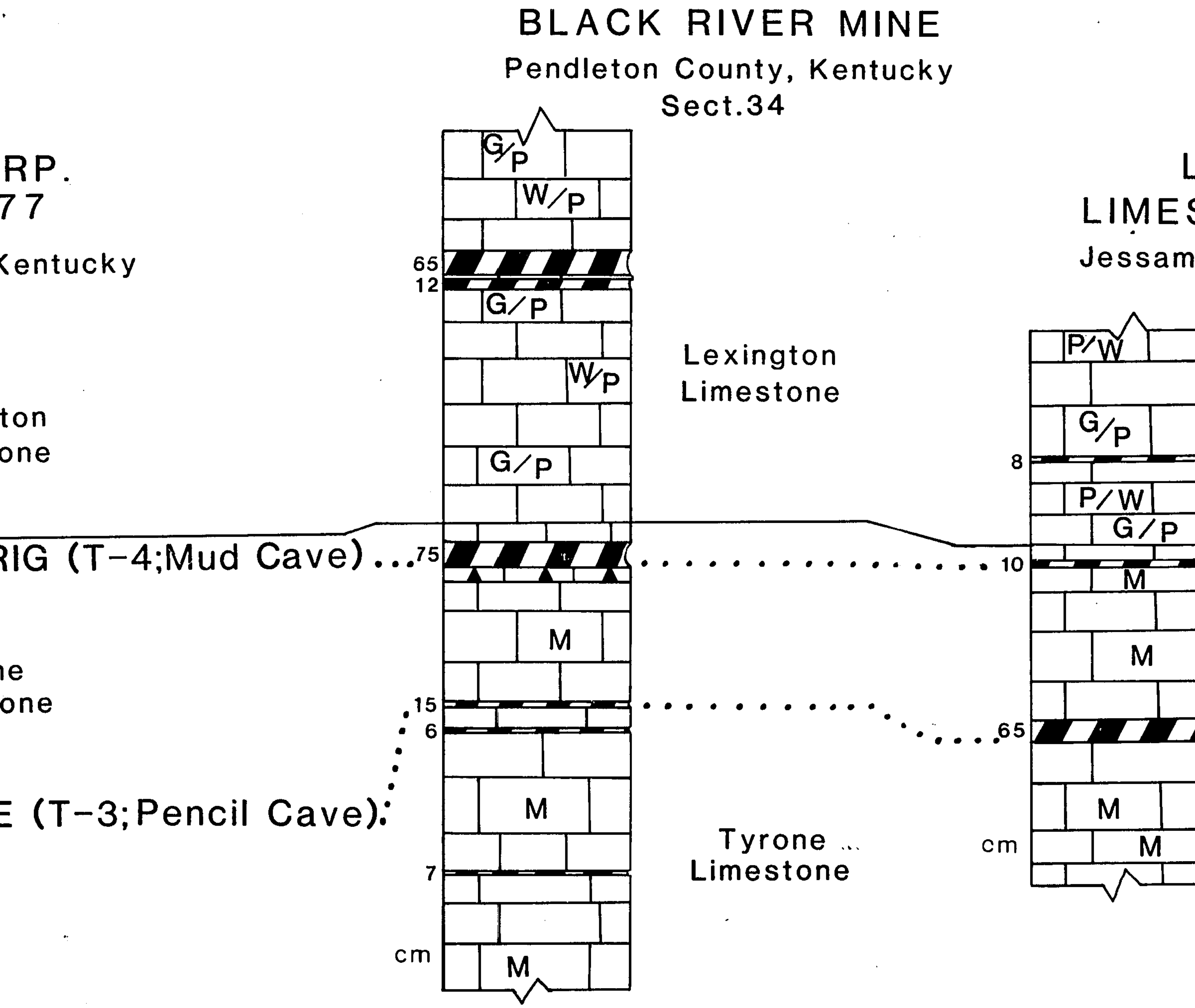


Location of cross-section on Plate 2, with section numbers shown.



Location of cross-section on Plate 3, with section numbers shown.


DRAVO CORP.
HOLE BB-77
Gallatin County, Kentuck
Sect.35
P/W
G/P
P/W
Lexington
Limestone
MILLBRIG (T
50-60
M
Tyrone
Limestone
M
10 m
5-10
M
DEICKE (T-3
40-50
M
M
10-15
cm
M



BLACK RIVER MINE
Pendleton County, Kentucky
Sect.34
RP.
77
Kentucky
ton
one
RIG (T-4;Mud Cave)...
ne
one
E (T-3;Pencil Cave)
G/P
W/P
65
12
Lexington
Limestone
75
M
15
6
Tyrone
Limestone
7
cm
L
LIMES
Jessam
P/W
8
P/W
G/P
10
65

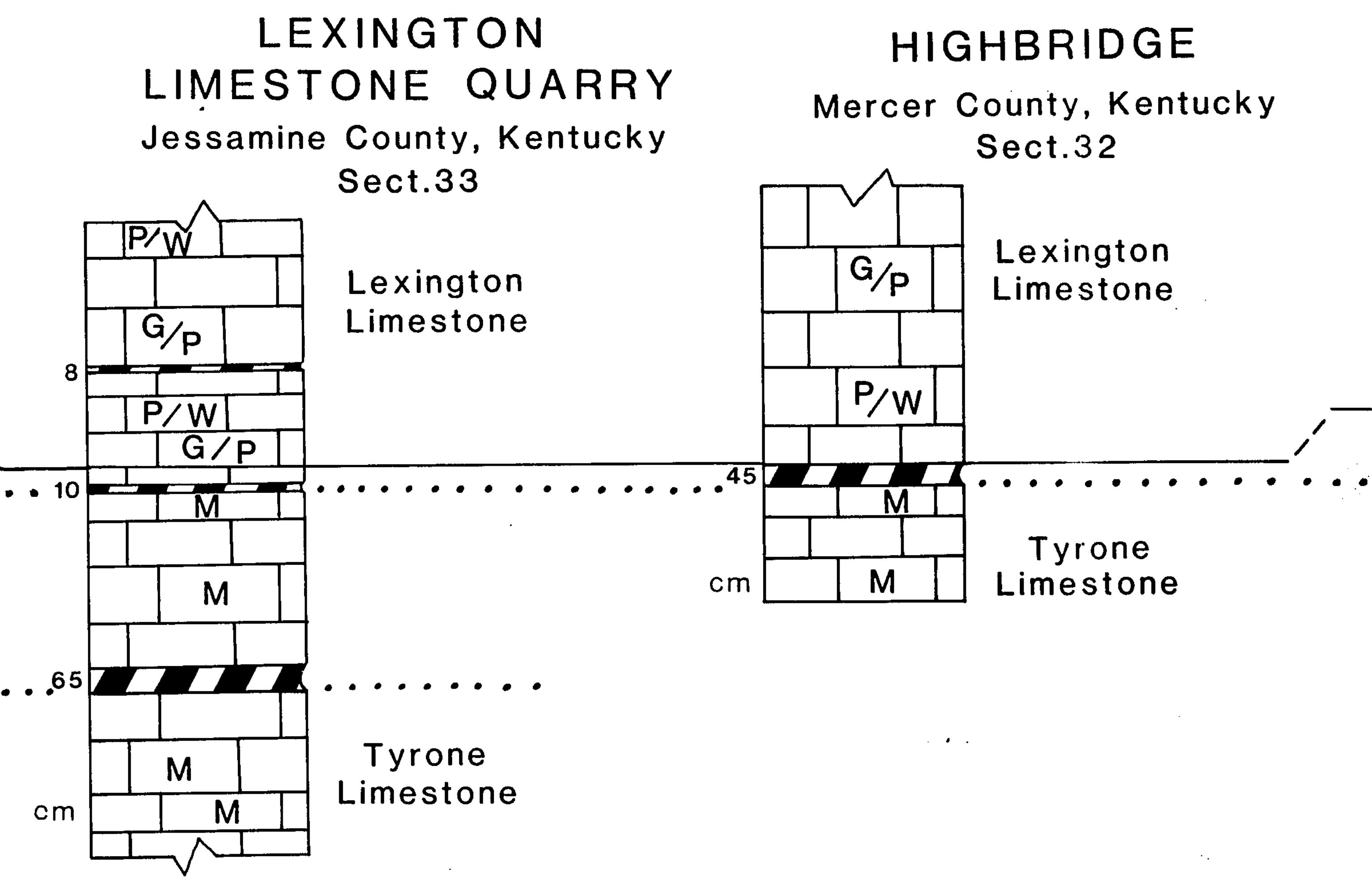
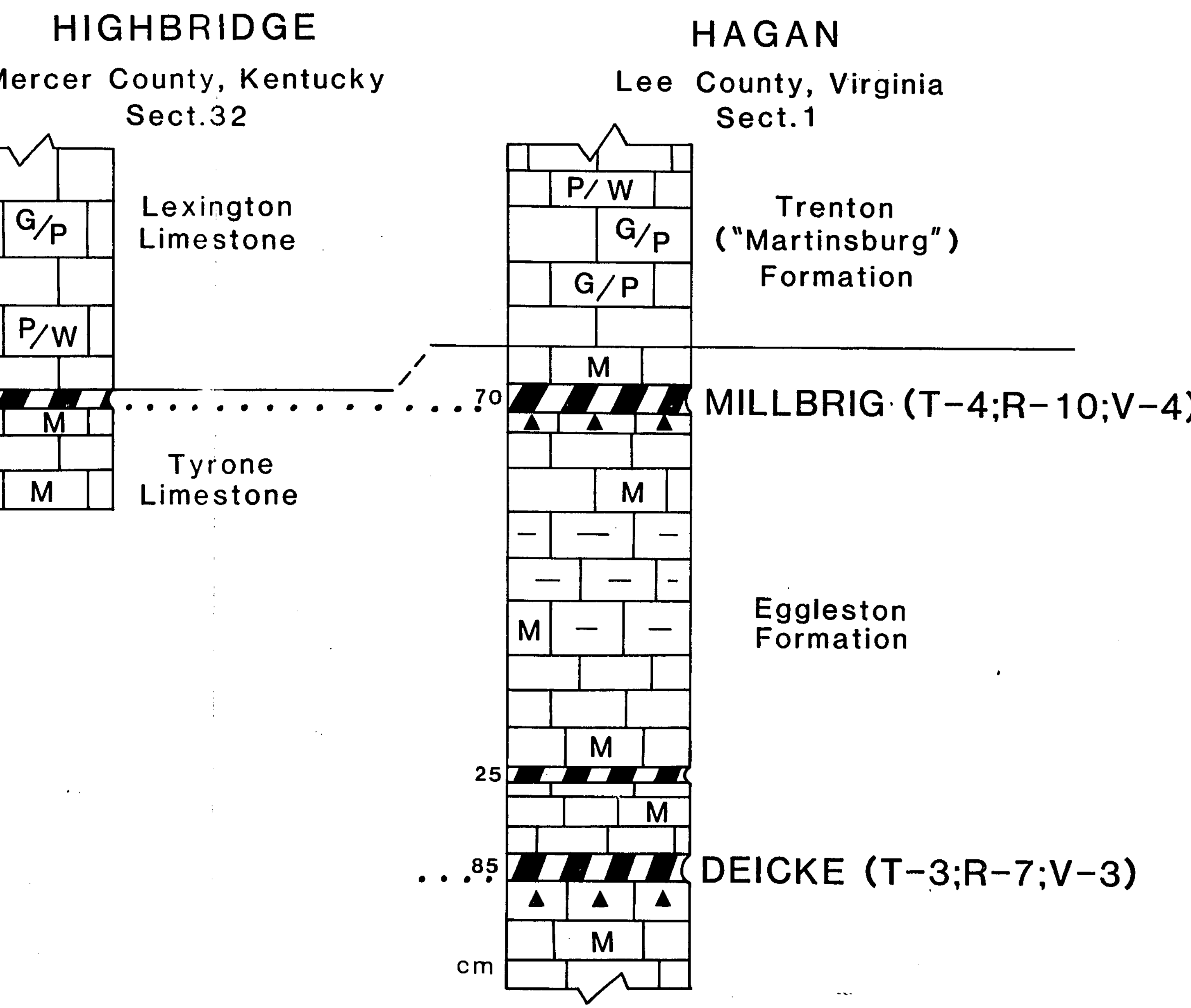

LEXINGTON
LIMESTONE QUARRY
Jessamine County, Kentucky
Sect.33
P/W
G/P
8
P/W
G/P
10
M
M
65
M
M
cm
Lexington
Limestone
Tyrone
Limestone
HIGHBRIDGE
Mercer County, Kentucky
Sect.32
G/P
P/W
45
M
M
cm
Lexington
Limestone
Tyrone
Limestone

PLATE I


HIGHBRIDGE
Mercer County, Kentucky
Sect.32
G/P
P/W
M
M
Lexington Limestone
Tyrone Limestone
HAGAN
Lee County, Virginia
Sect.1
P/ W
G/P
G/P
M
M
M
M
M
M
Trenton ("Martinsburg") Formation
70
MILLBRIG (T-4;R-10;V-4)
Eggleston Formation
25
85
DEICKE (T-3;R-7;V-3)
cm

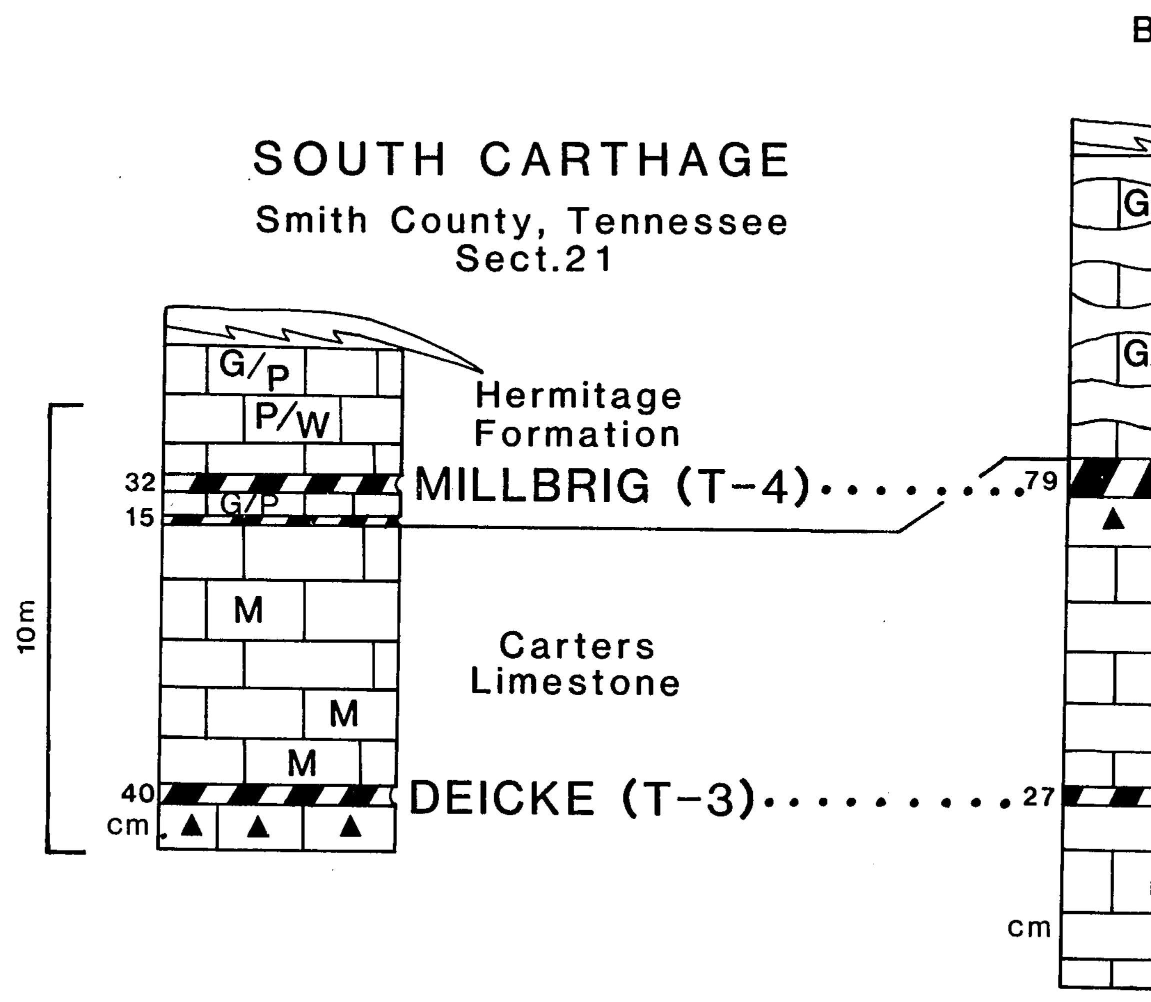
PLEASE NOTE:

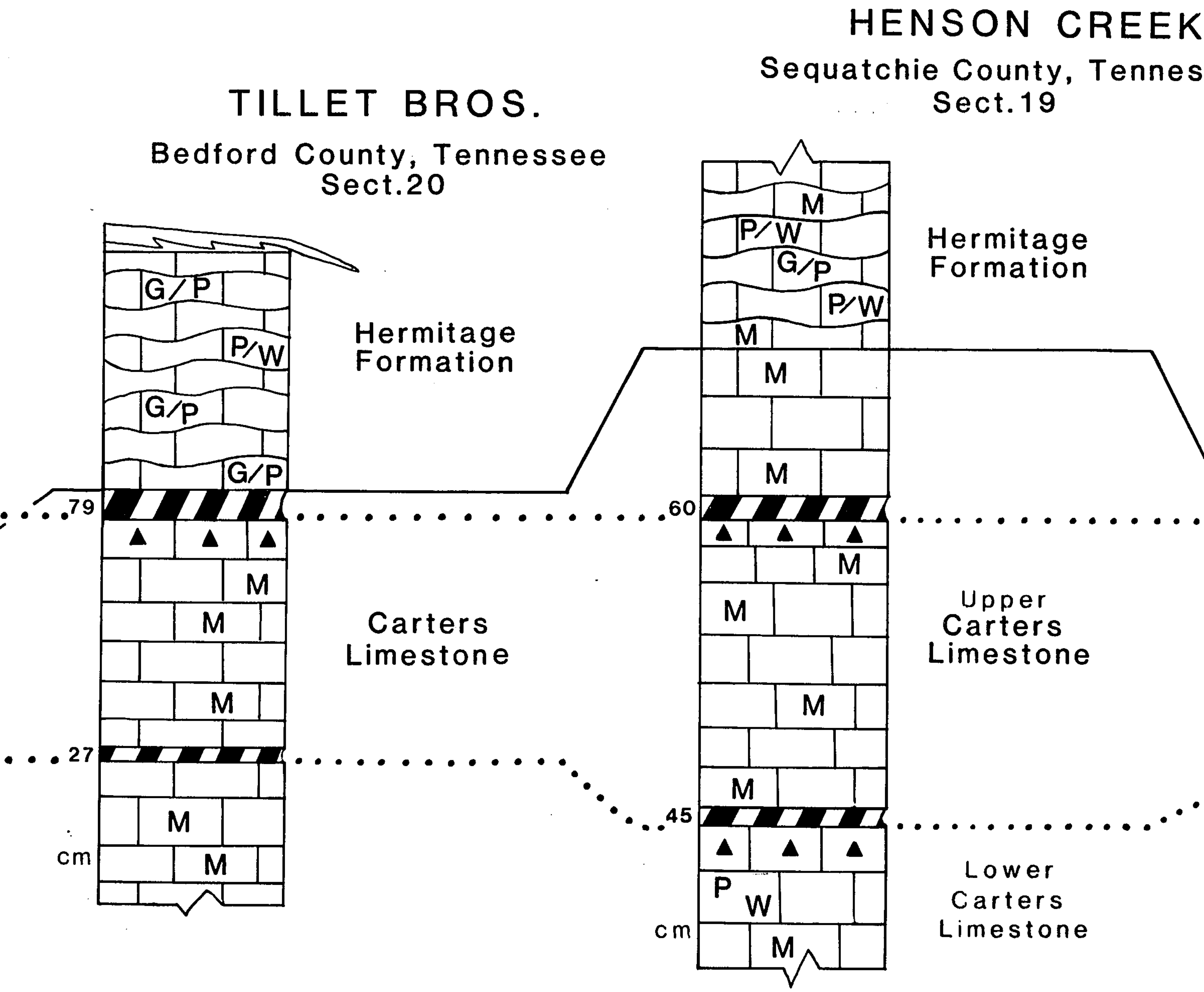
Oversize maps and charts are filmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

The following map or chart has been refilmed in its entirety at the end of this dissertation (not available on microfiche). A xerographic reproduction has been provided for paper copies and is inserted into the inside of the back cover.

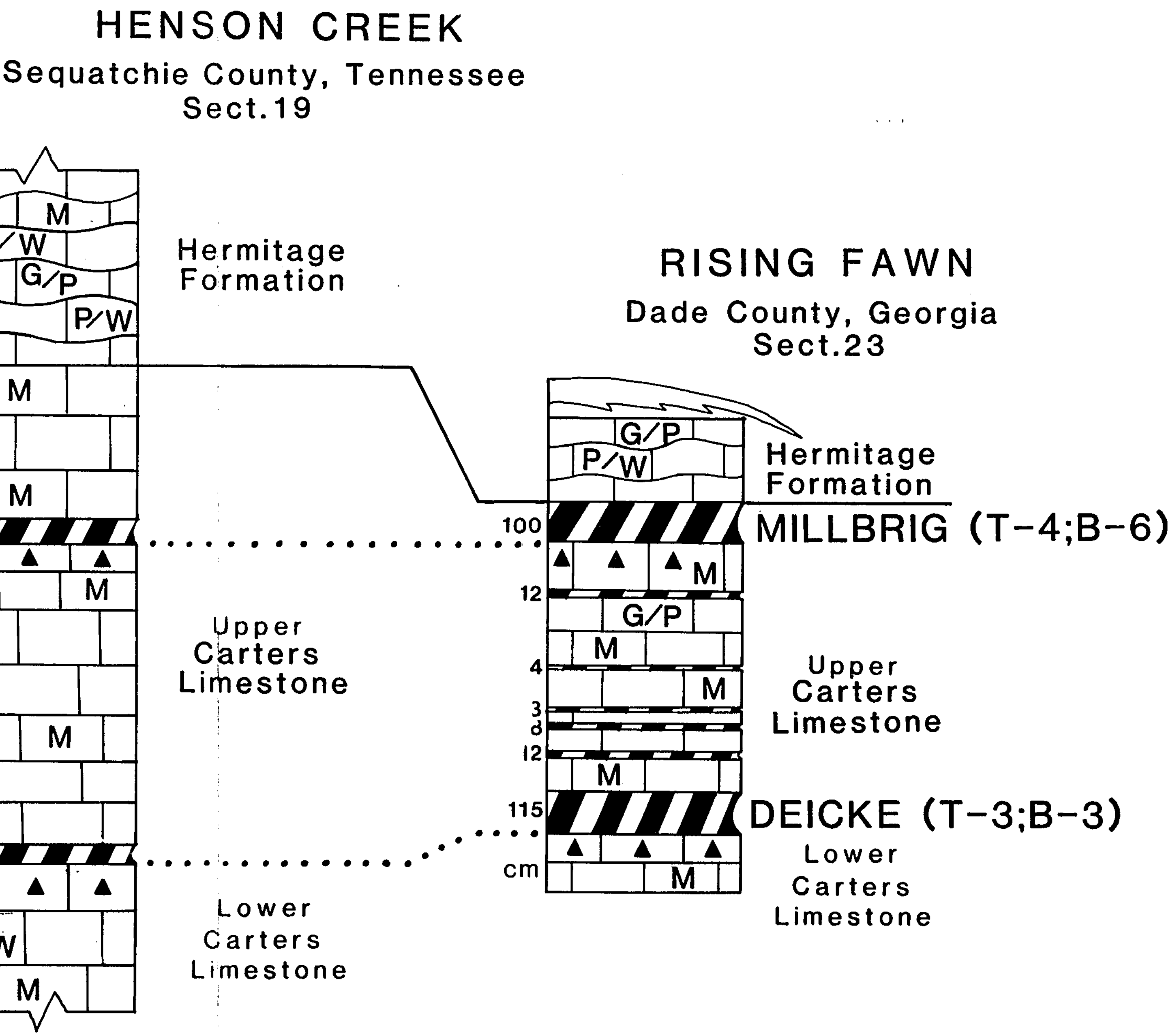
Standard 35mm slides or 17" x 23" black and white photographic prints are available for an additional charge.

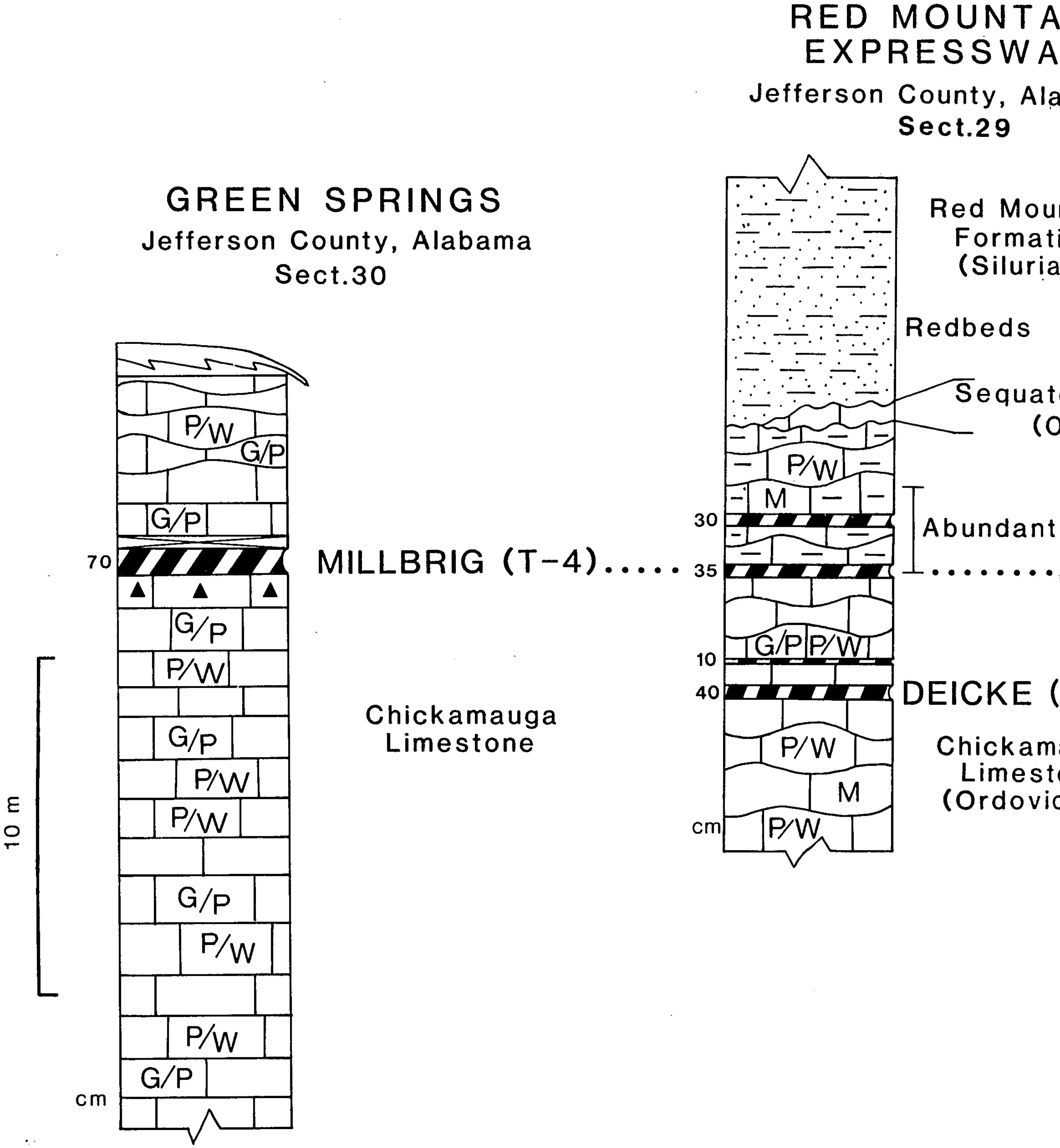

SOUTH CARTHAGE
Smith County, Tennessee
Sect.21
G/P
P/W
Hermitage
Formation
32
15
G/P
MILLBRIG (T-4)
79
10m
M
Carters
Limestone
M
M
40
cm
DEICKE (T-3)
27
cm
B
G
G

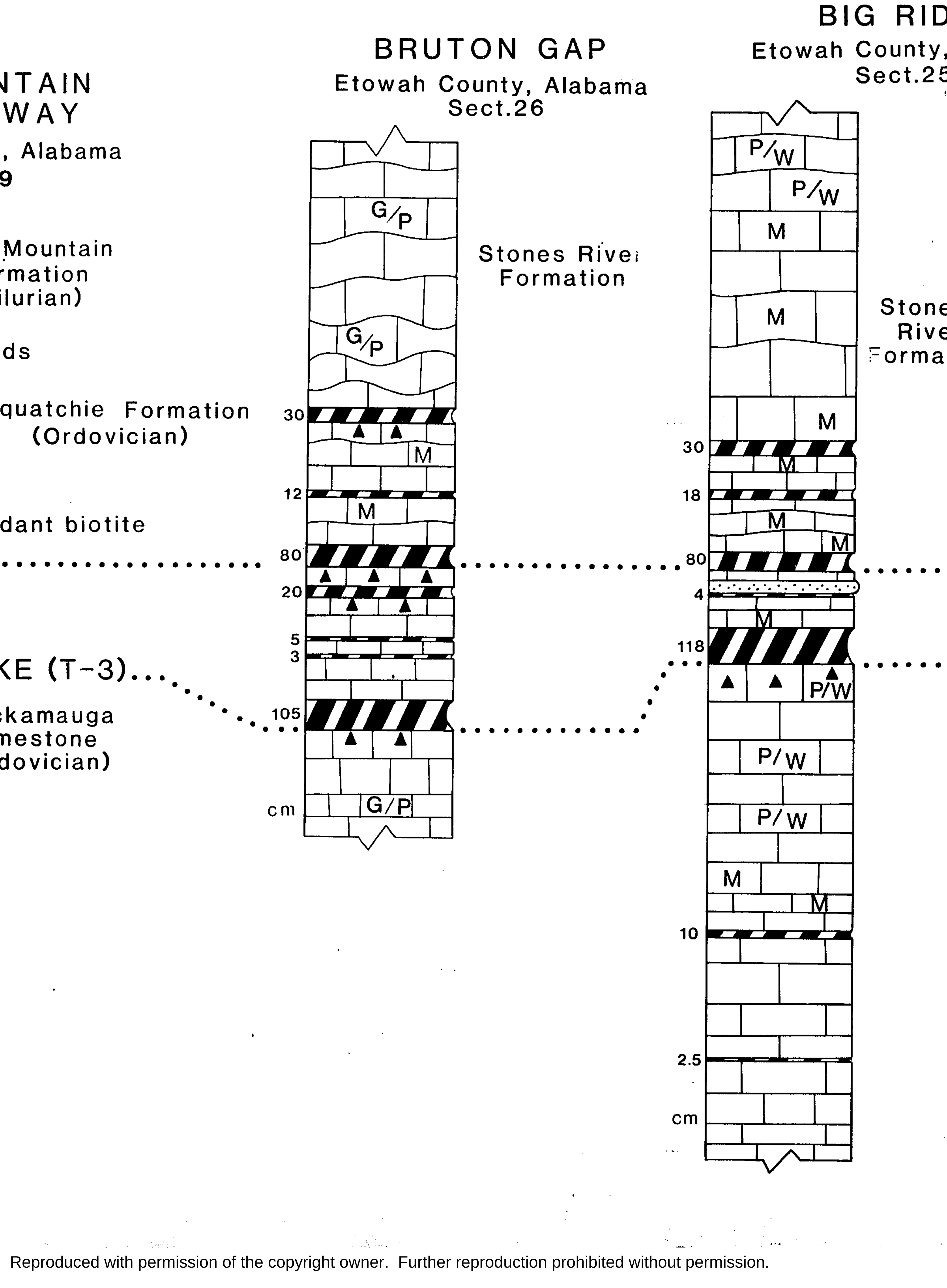


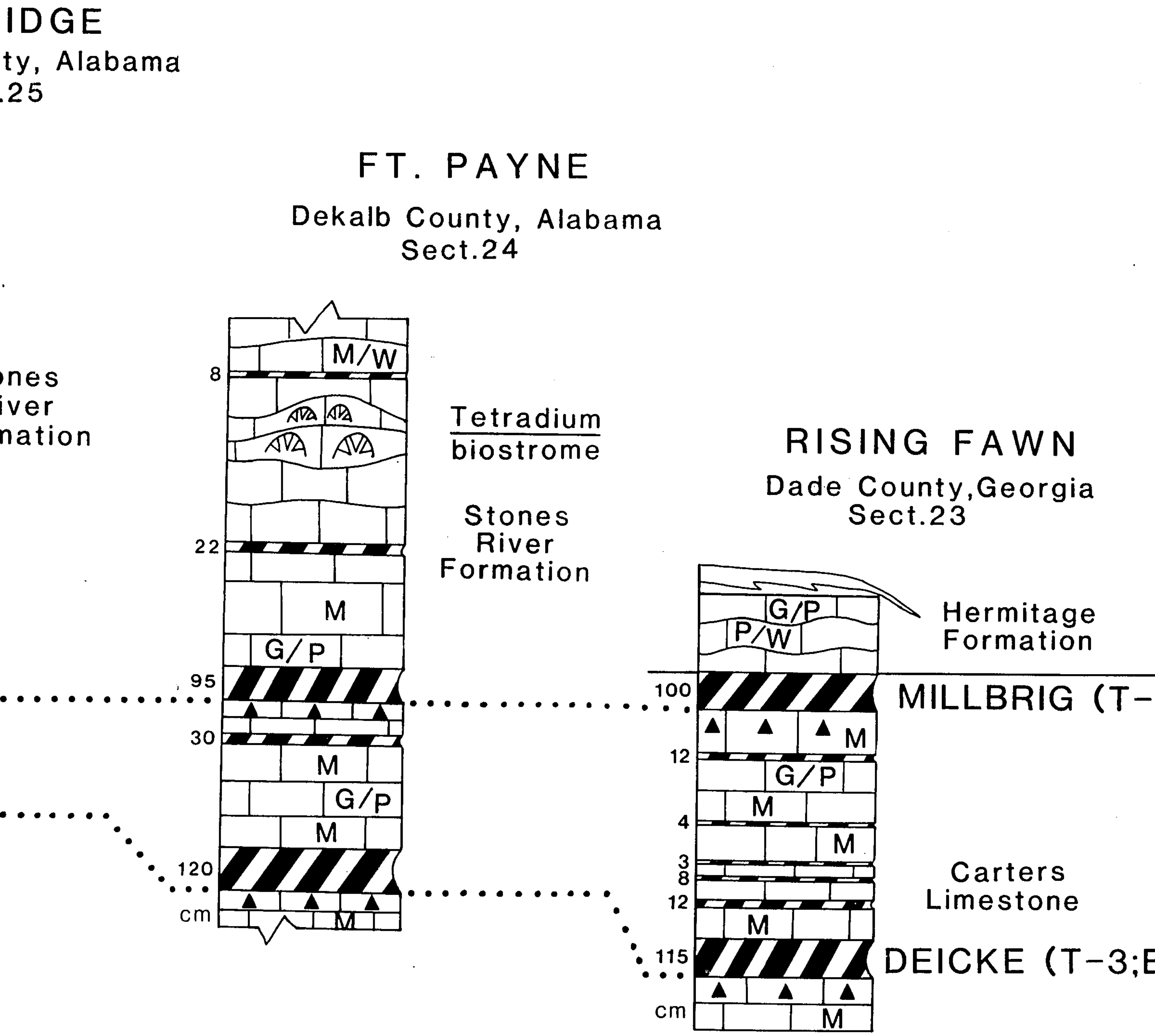
HENSON CREEK
Sequatchie County, Tennes
Sect.19
TILLET BROS.
Bedford County, Tennessee
Sect.20
Hermitage
Formation
Carters
Limestone
Upper
Carters
Limestone
Lower
Carters
Limestone
G/P
P/W
M
W
P
79
27
60
45
cm

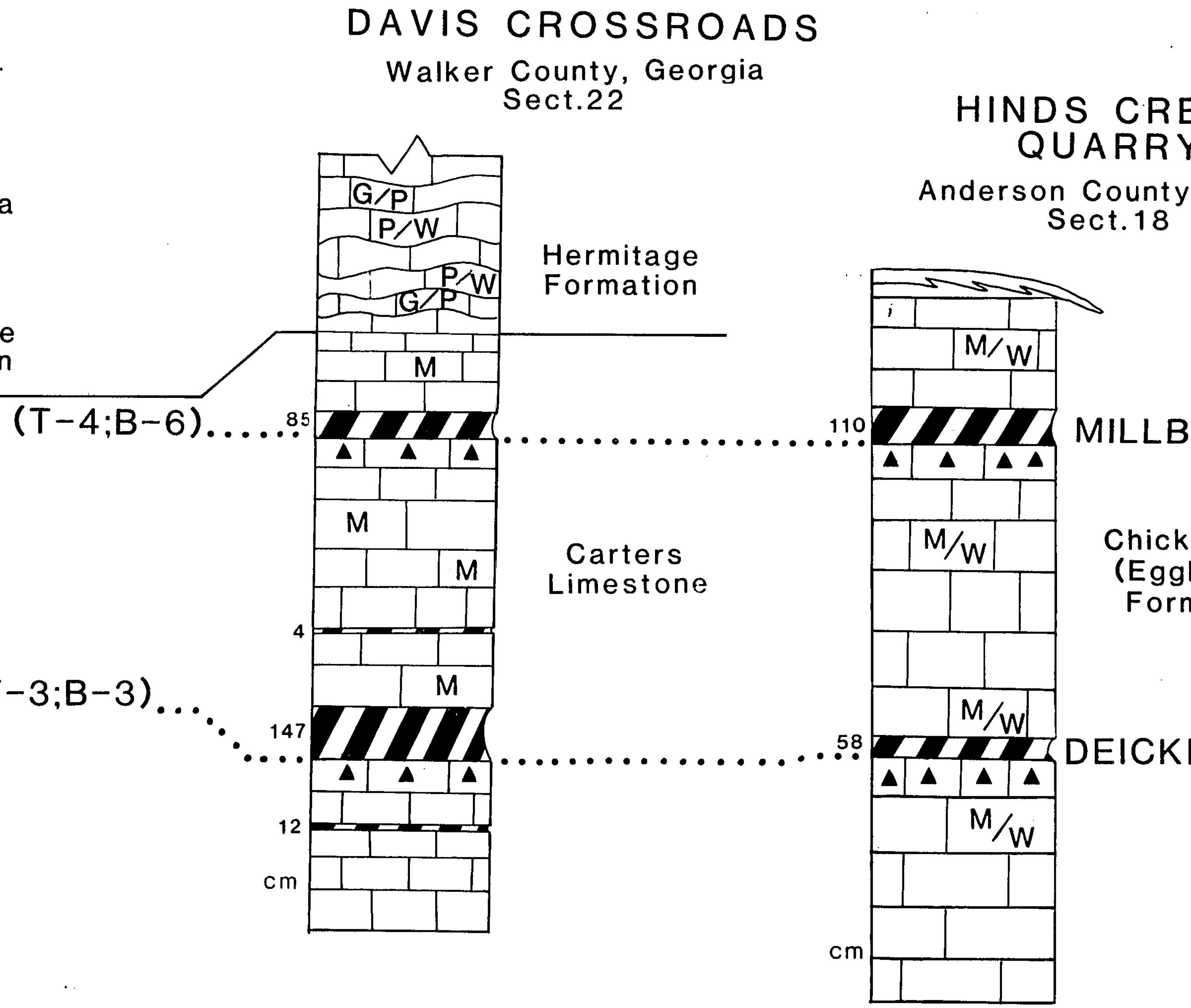
PLATE 2

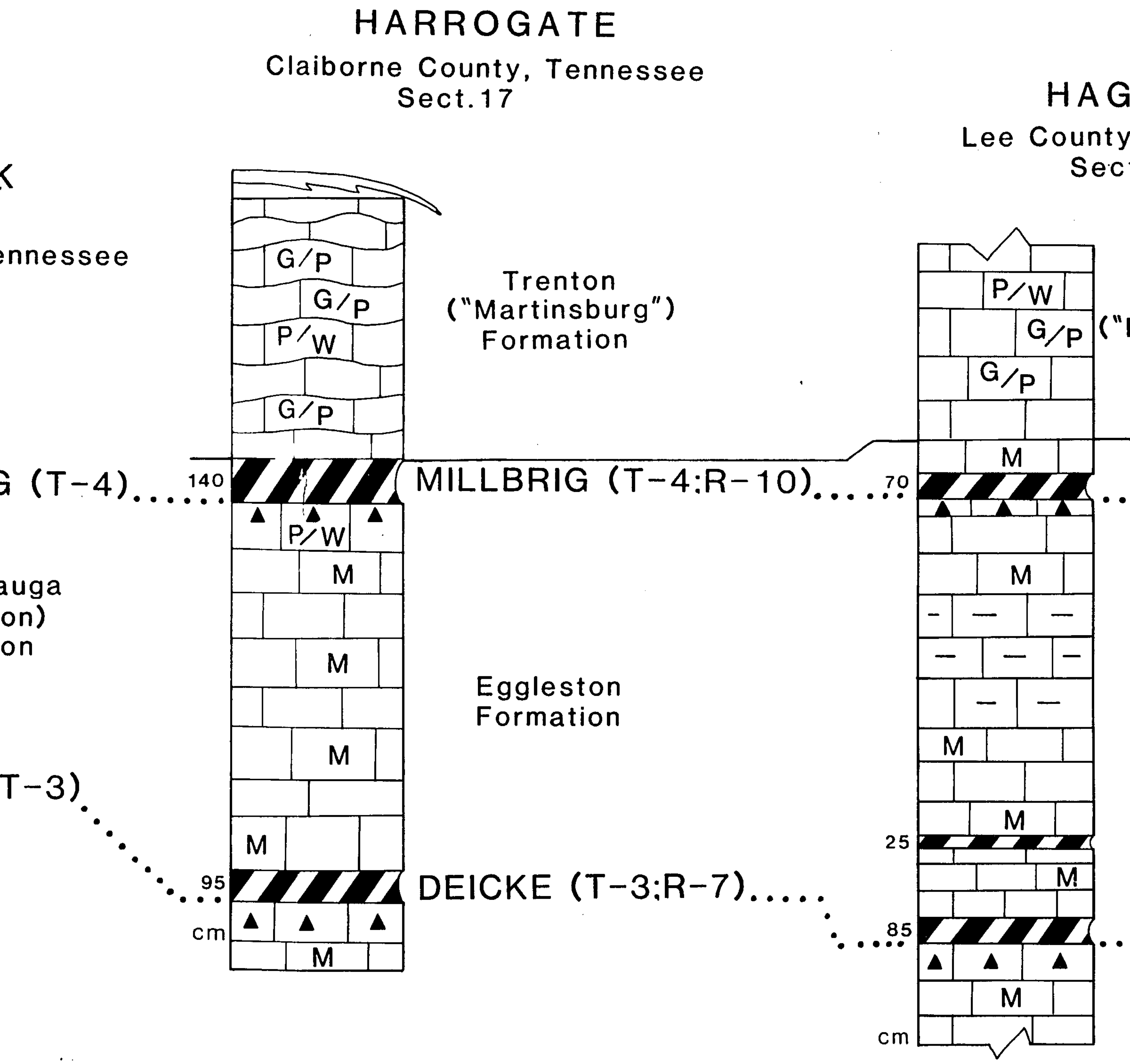

HENSON CREEK
Sequatchie County, Tennessee
Sect.19
M
P/W
G/P
P/W
M
M
Hermitage Formation
Upper Carters Limestone
M
M
Lower Carters Limestone
M
RISING FAWN
Dade County, Georgia
Sect.23
G/P
P/W
Hermitage Formation
100
MILLBRIG (T-4;B-6)
M
12
G/P
M
4
M
3
12
M
Upper Carters Limestone
115
DEICKE (T-3;B-3)
cm
M
Lower Carters Limestone

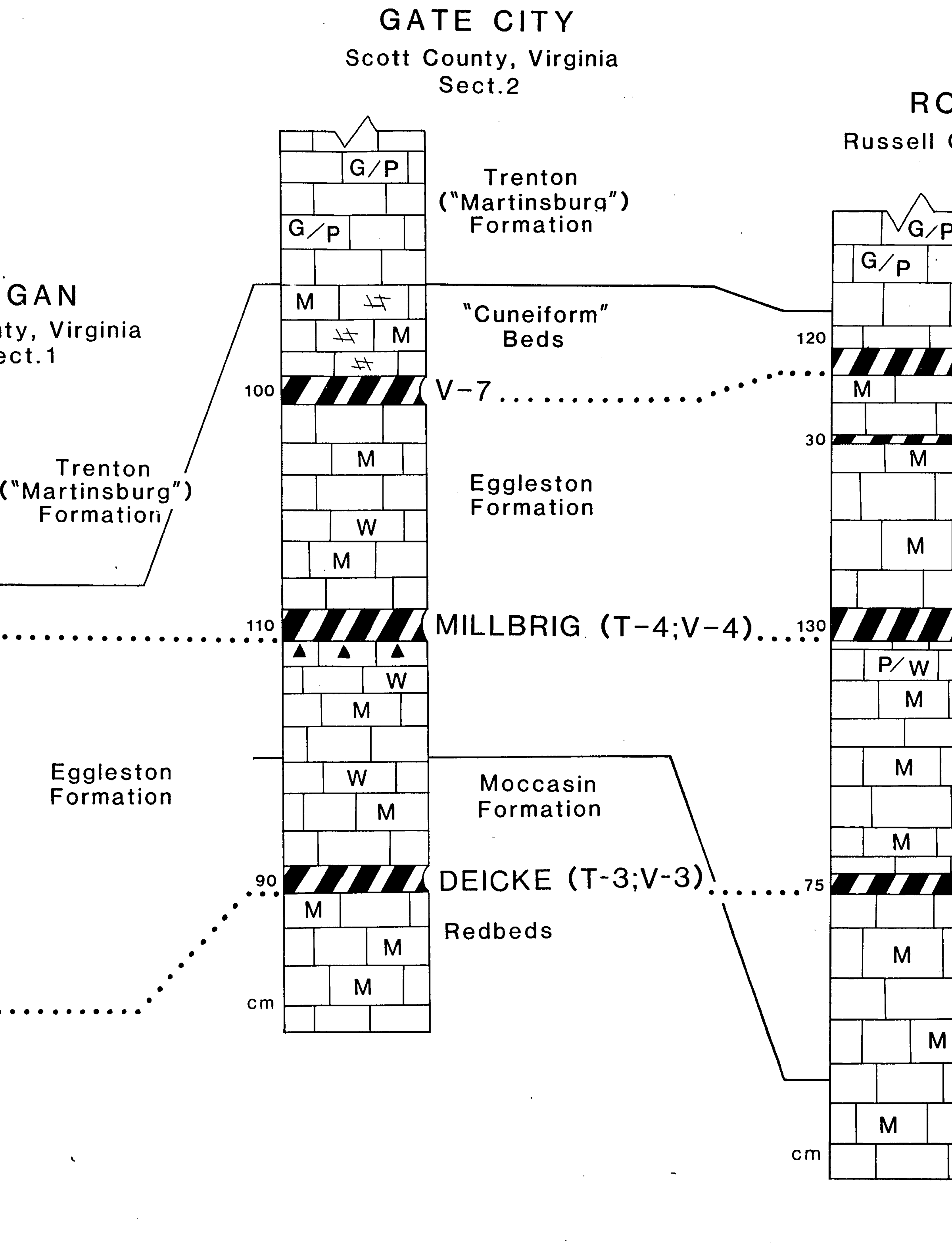

RED MOUNTA
EXPRESSWA
Jefferson County, Ala
Sect.29
GREEN SPRINGS
Jefferson County, Alabama
Sect.30
P/W
G/P
70
MILLBRIG (T-4).....
G/P
P/W
10 m
Chickamauga
Limestone
cm
Red Mou
Formati
(Siluria
Redbeds
Sequat
(O
M
30
Abundant
35
G/P
P/W
10
40
DEICKE (
Chickama
Limest
(Ordovic

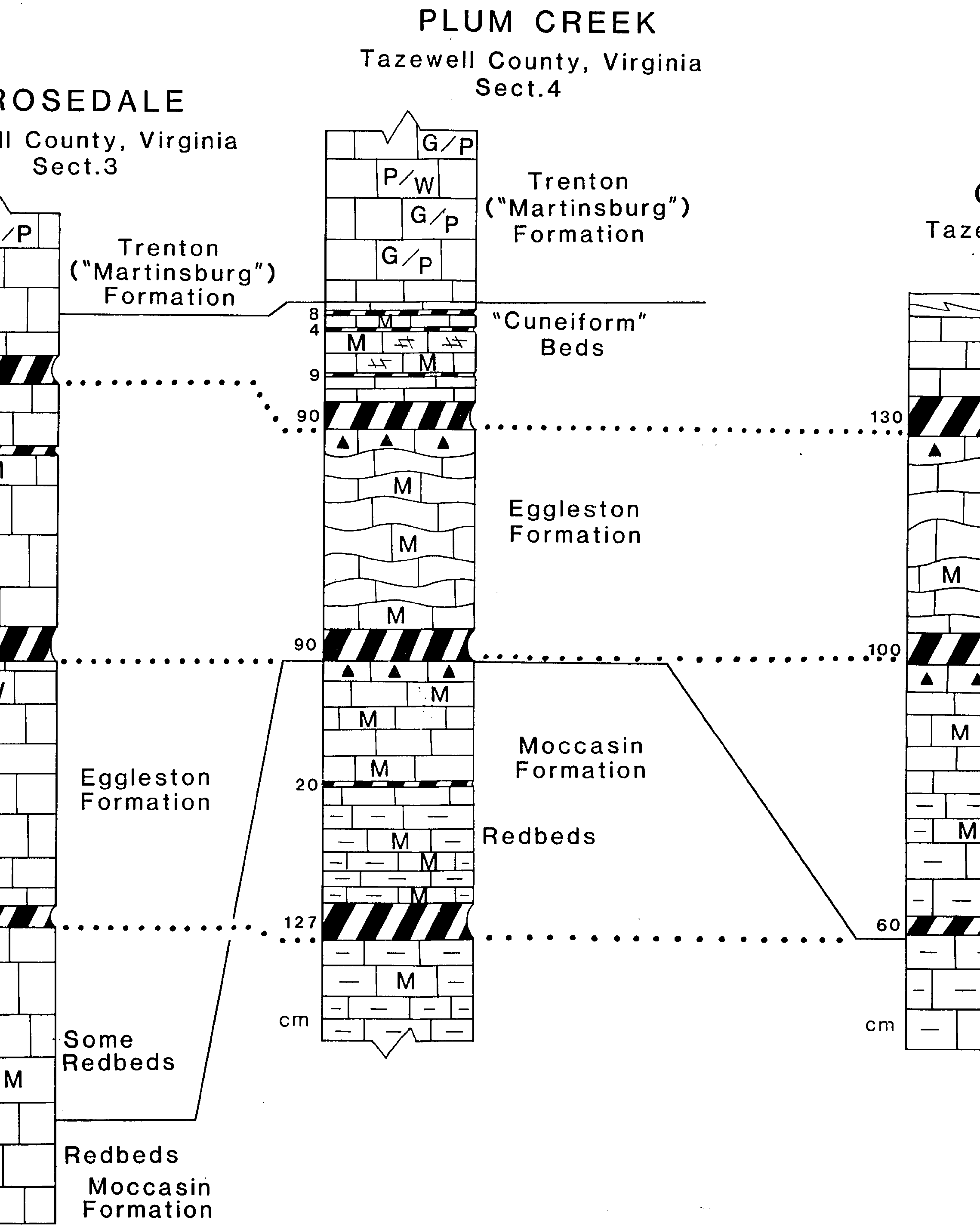

NTAIN
WAY
, Alabama
9
Mountain
rmation
ilurian)
ds
quatchie Formation
(Ordovician)
dant biotite
KE (T-3)...
ckamauga
mestone
dovician)
BRUTON GAP
Etowah County, Alabama
Sect.26
Stones River
Formation
G/P
G/P
M
M
G/P
30
12
80
20
5
3
105
cm
BIG RID
Etowah County,
Sect.25
Stone
Rive
Forma
P/W
P/W
M
M
M
M
M
M
M
P/W
P/W
P/W
M
M
30
18
80
4
118
10
2.5
cm


IDGE
ty, Alabama
.25
ones
iver
nation
FT. PAYNE
Dekalb County, Alabama
Sect.24
M/W
8
Tetradium
biostrome
Stones
River
Formation
22
M
G/P
95
30
M
G/P
M
120
cm
M
RISING FAWN
Dade County,Georgia
Sect.23
G/P
P/W
Hermitage
Formation
100
MILLBRIG (T-
M
12
G/P
M
4
M
3
8
12
Carters
Limestone
M
115
DEICKE (T-3;E
cm
M


DAVIS CROSSROADS
Walker County, Georgia
Sect.22
HINDS CRE
QUARRY
Anderson County
Sect.18
Hermitage
Formation
Carters
Limestone
Chick
(Eggl
Forn
G/P
P/W
P/W
G/P
M
M
M
M
M/W
M/W
M/W
M/W
(T-4;B-6)
-3;B-3)
85
4
147
12
cm
110
58
cm
MILLB
DEICKI
a
e
n


HARROGATE
Claiborne County, Tennessee
Sect. 17
Trenton
("Martinsburg")
Formation
G/P
G/P
P/W
G/P
140
MILLBRIG (T-4;R-10)
P/W
M
M
M
Eggleston
Formation
M
95
DEICKE (T-3;R-7)
cm
M
HAG
Lee County
Sec
P/W
G/P
G/P
M
70
M
M
M
25
M
85
M
cm
K
ennessee
G (T-4)
auga
on)
on
T-3)


GATE CITY
Scott County, Virginia
Sect.2
G/P
G/P
Trenton
("Martinsburg")
Formation
"Cuneiform"
Beds
M
M
100
V-7
M
Eggleston
Formation
W
M
110
MILLBRIG (T-4;V-4)
W
M
W
M
Moccasin
Formation
90
DEICKE (T-3;V-3)
M
Redbeds
M
M
cm
GAN
ty, Virginia
ect.1
Trenton
("Martinsburg")
Formation
Eggleston
Formation
RO
Russell
G/P
G/P
120
M
30
M
M
130
P/W
M
M
M
75
M
M
M
cm


PLUM CREEK
Tazewell County, Virginia
Sect.4
ROSEDALE
ll County, Virginia
Sect.3
Trenton
("Martinsburg")
Formation
"Cuneiform"
Beds
Eggleston
Formation
Moccasin
Formation
Redbeds
Some
Redbeds
G/P
P/W
M
8
4
9
90
20
127
130
100
60
cm
Taze

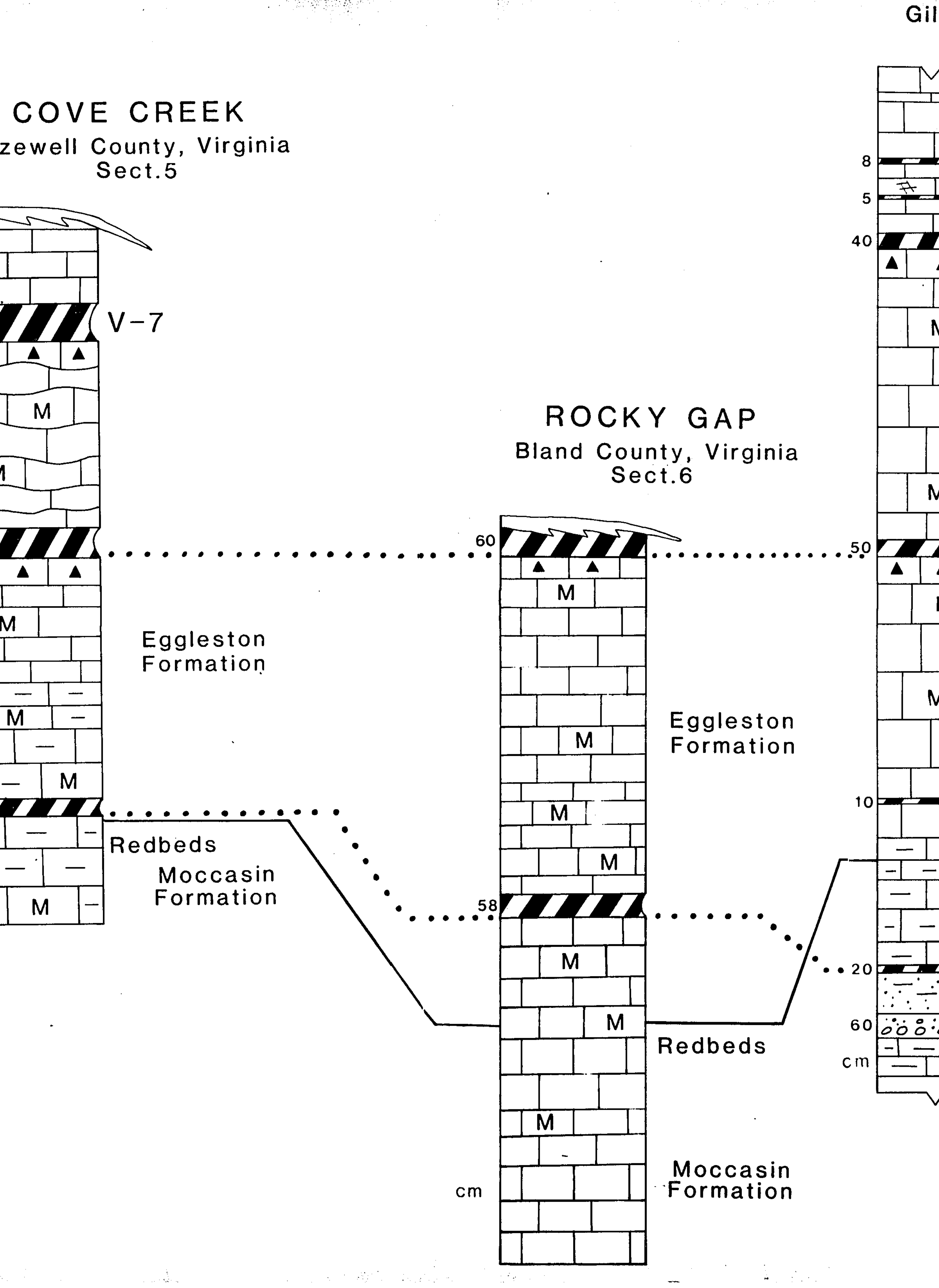
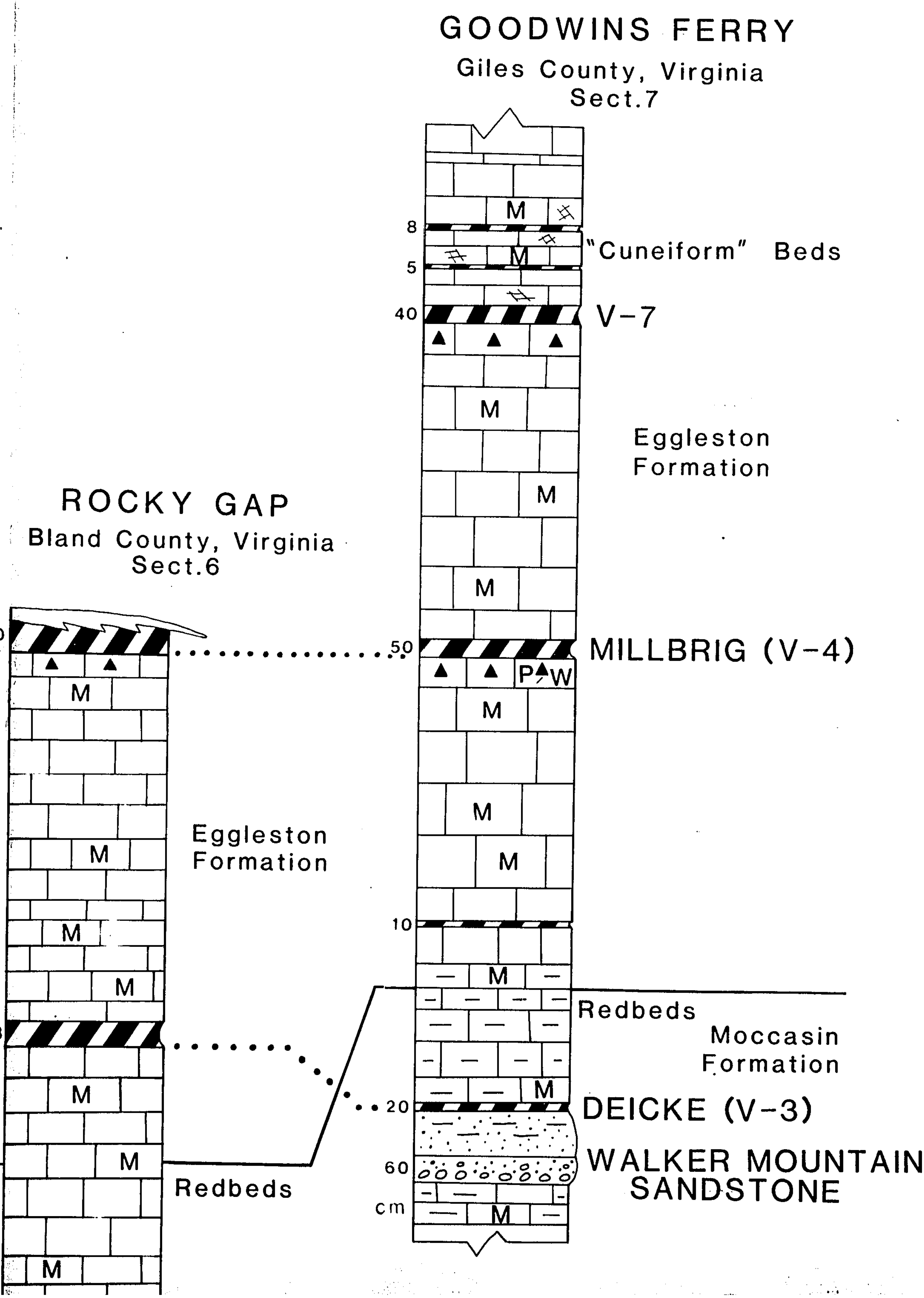

Gil
COVE CREEK
zewell County, Virginia
Sect.5
V-7
M
Eggleston
Formation
Redbeds
Moccasin
Formation
ROCKY GAP
Bland County, Virginia
Sect.6
60
58
Eggleston
Formation
Redbeds
Moccasin
Formation
cm
8
5
40
50
10
20
60
cm

PLATE 3


GOODWINS FERRY
Giles County, Virginia
Sect.7
"Cuneiform" Beds
V-7
Eggleston Formation
MILLBRIG (V-4)
Redbeds
Moccasin Formation
DEICKE (V-3)
WALKER MOUNTAIN SANDSTONE
8
5
40
50
10
20
60
cm
ROCKY GAP
Bland County, Virginia
Sect.6
Eggleston Formation
Redbeds
M
P W

PLEASE NOTE:

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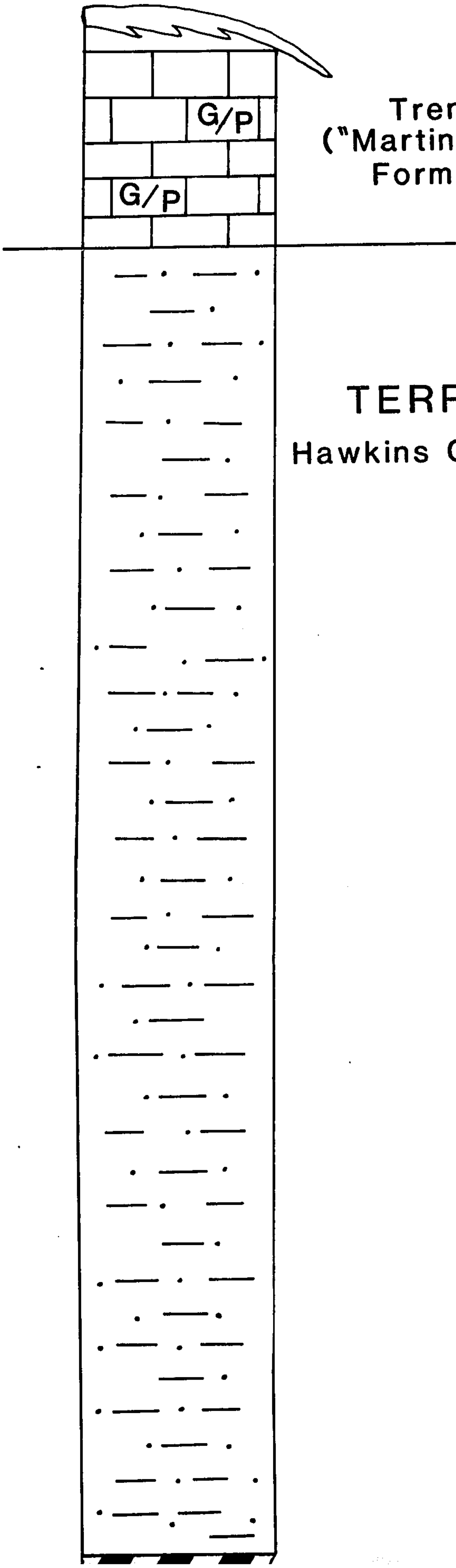
UMI

PLATE 4



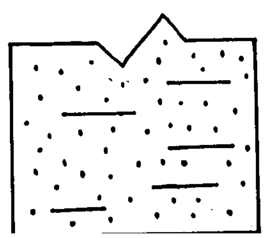
Trenton
("Martinsburg")
Formation

TERRILL CREEK

Hawkins County, Tennessee
Sect.9

CHATHAM HILL

Smyth County, Virginia
Sect.10

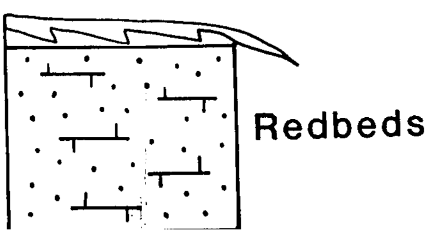


4

LL
ginia

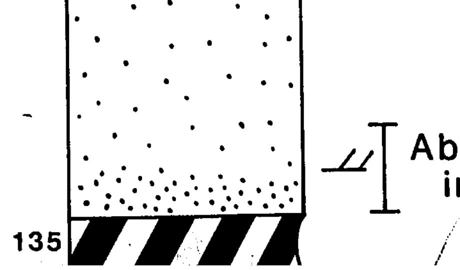
BIG WALKER LOOKOUT

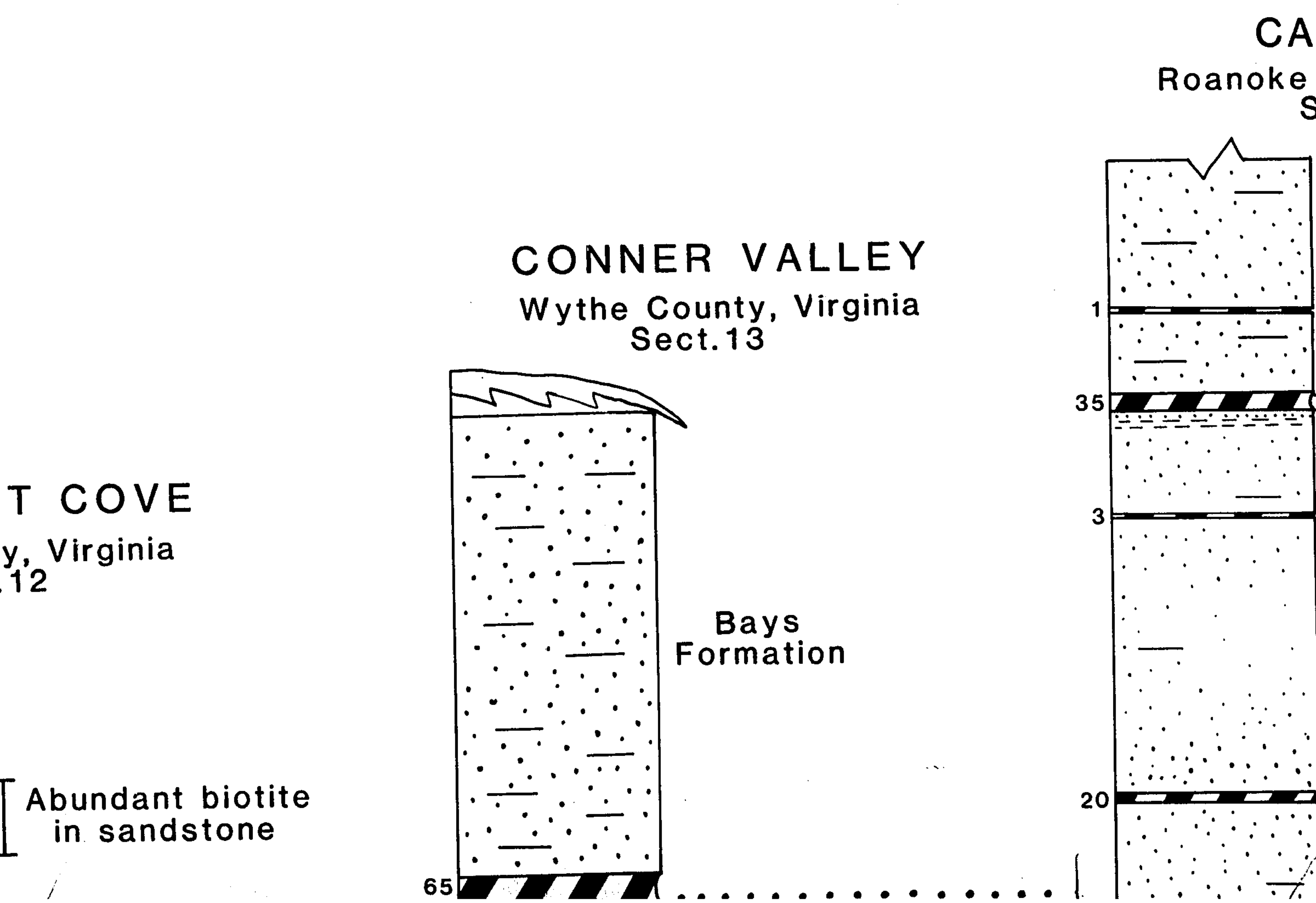
Bland County, Virginia
Sect.11

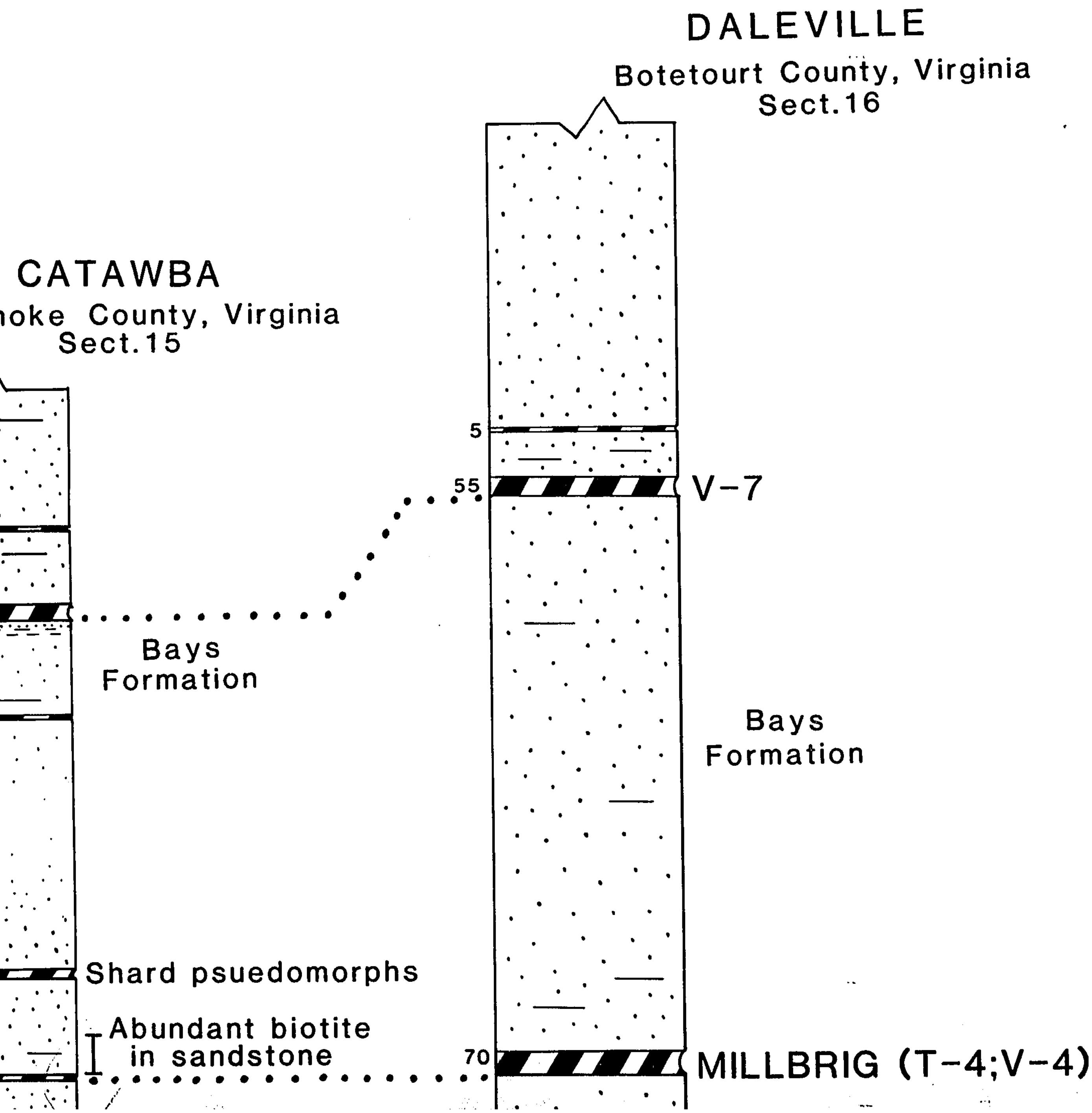


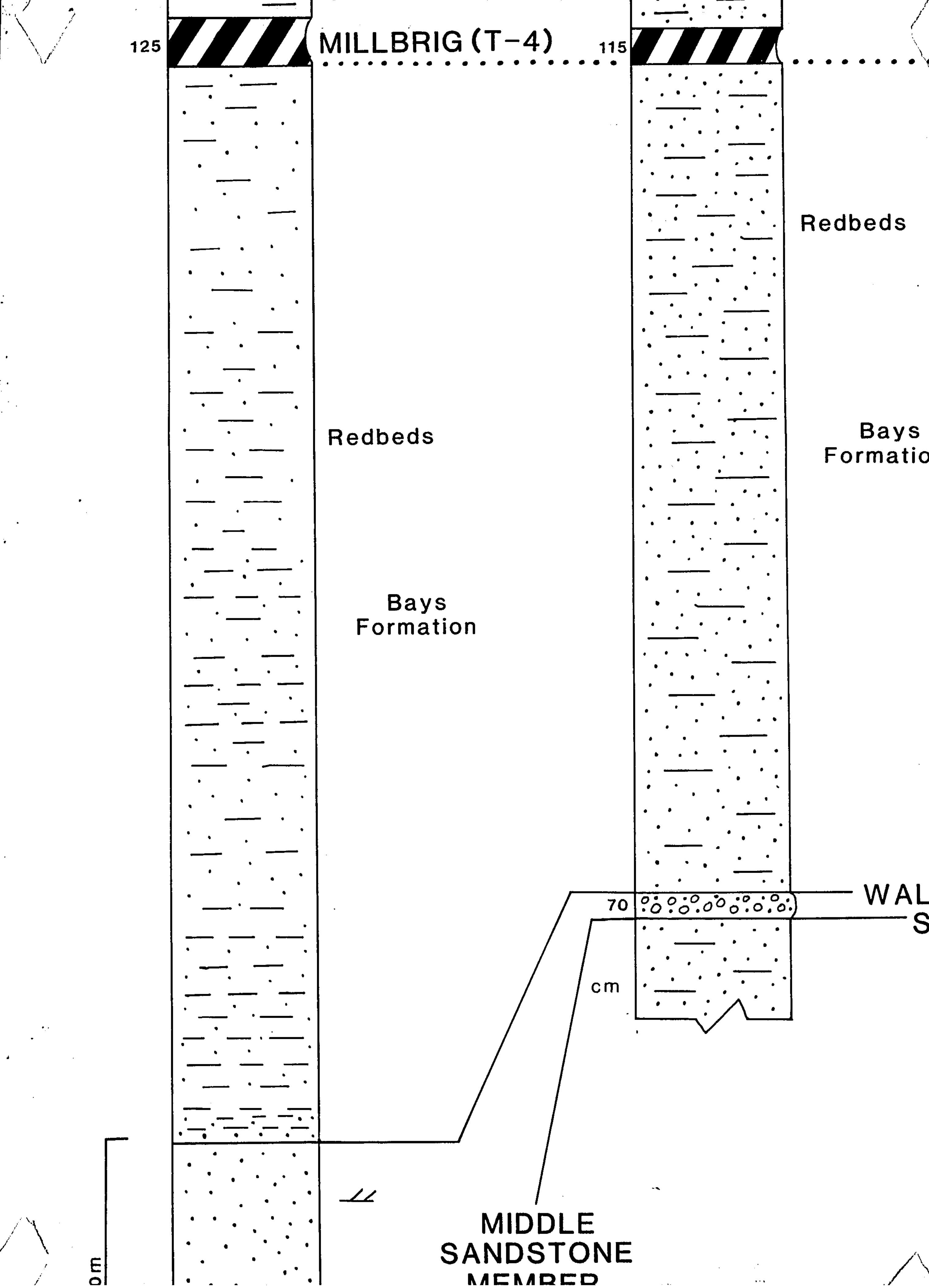
CROCKETT

Wythe County, V
Sect.12

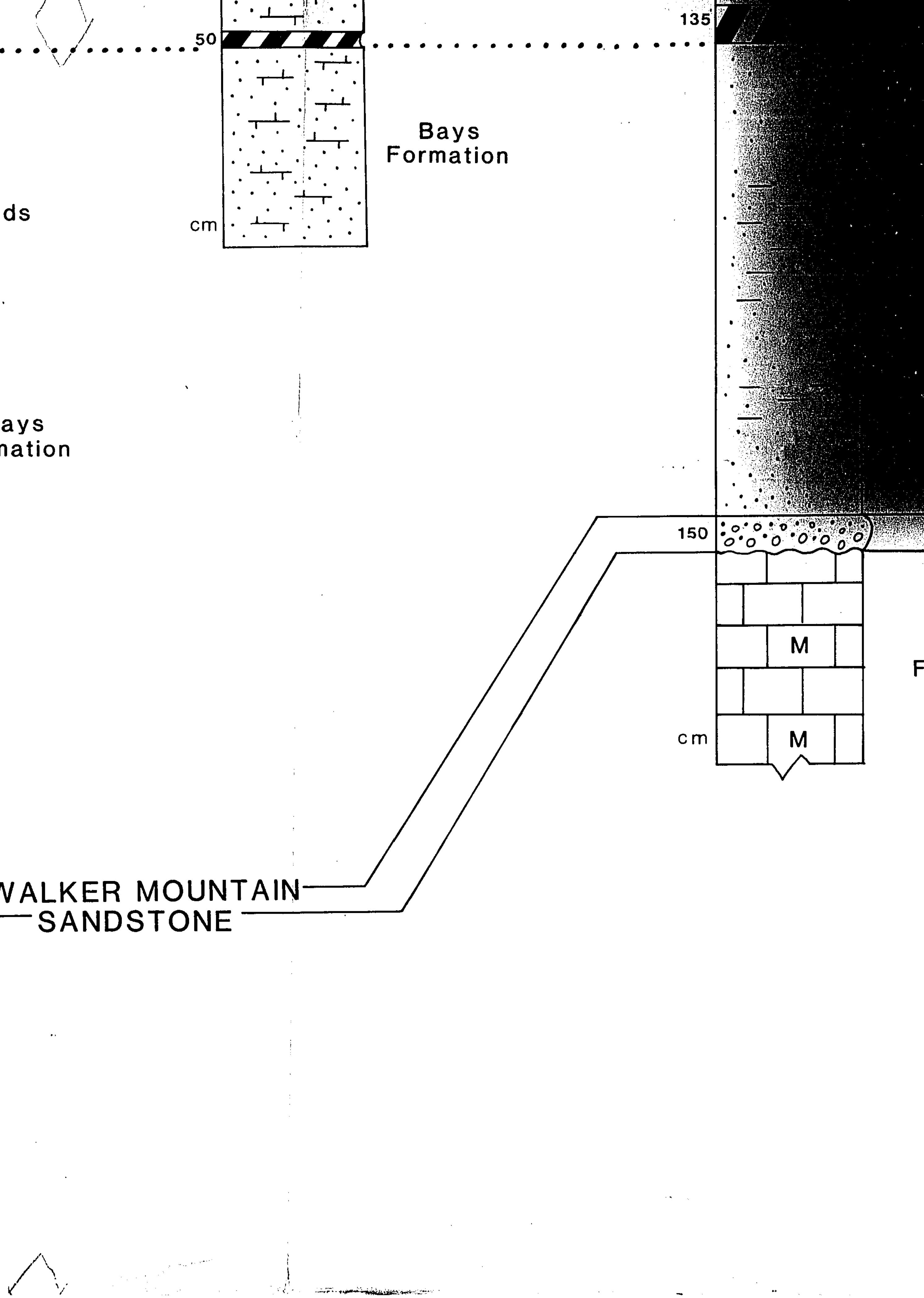


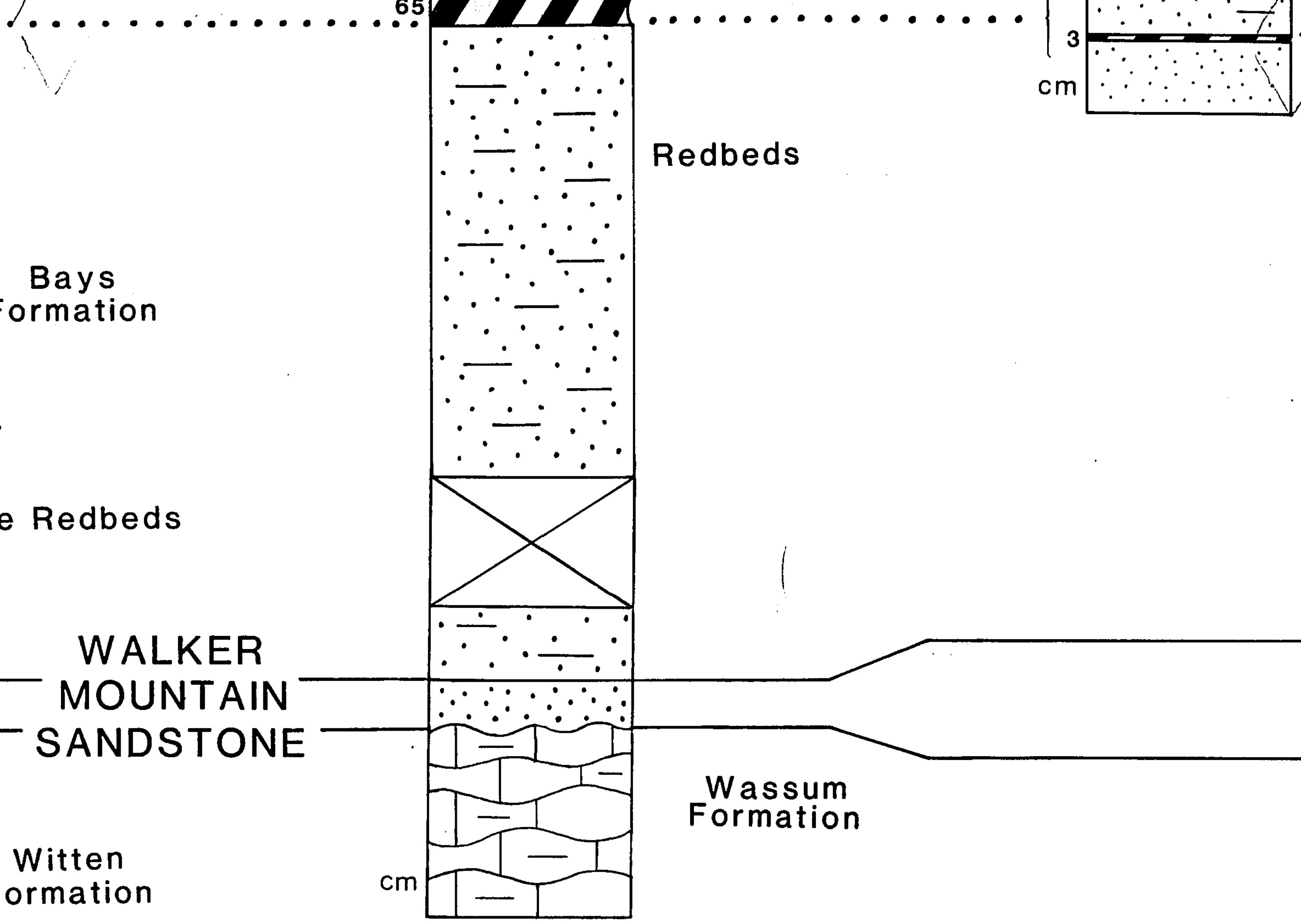

CA
Roanoke
S
CONNER VALLEY
Wythe County, Virginia
Sect.13
T COVE
y, Virginia
.12
Bays
Formation
Abundant biotite
in sandstone
1
35
3
20
65

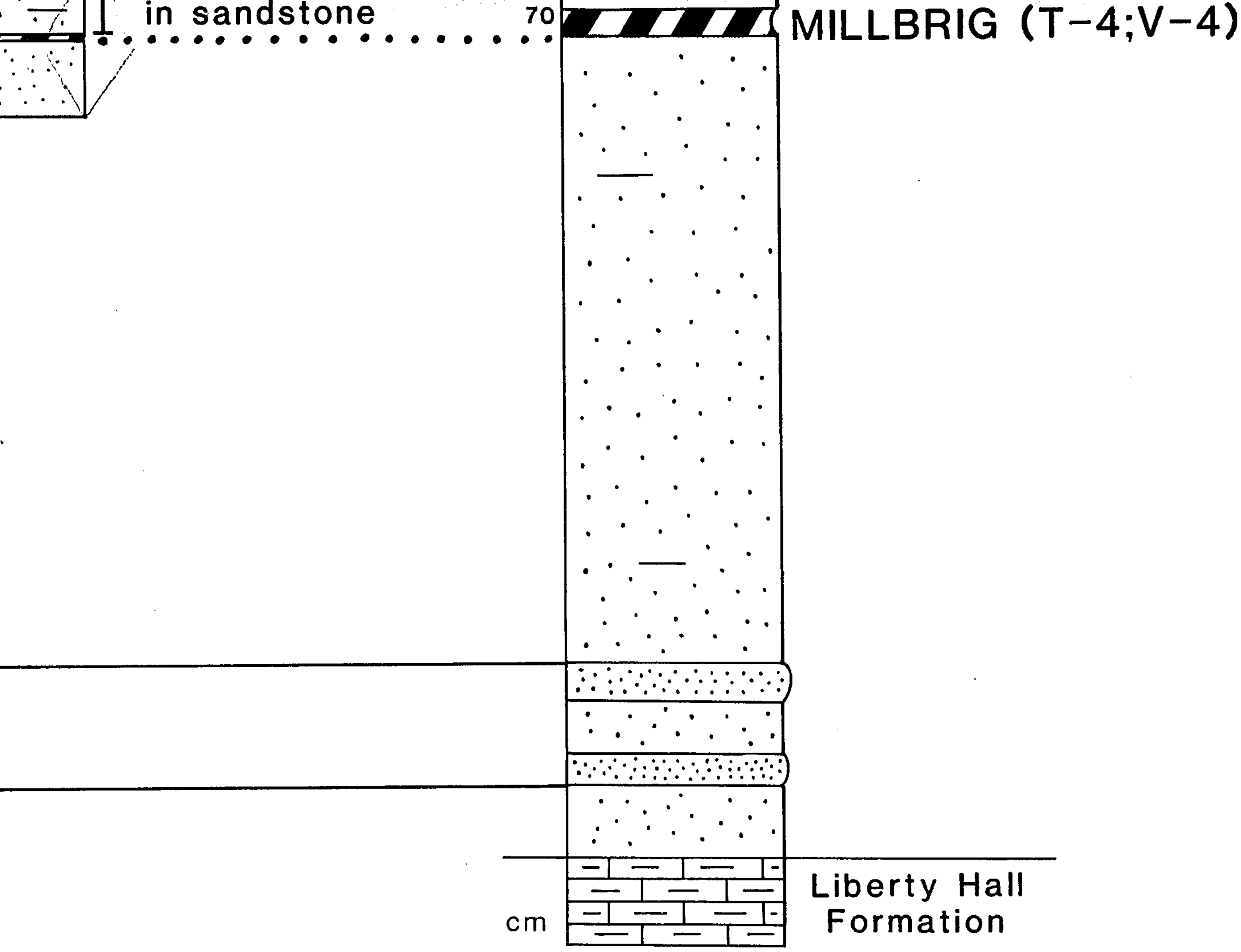

DALEVILLE
Botetourt County, Virginia
Sect.16
CATAWBA
noke County, Virginia
Sect.15
5
55
V-7
Bays
Formation
Bays
Formation
Shard psuedomorphs
Abundant biotite
in sandstone
70
MILLBRIG (T-4;V-4)



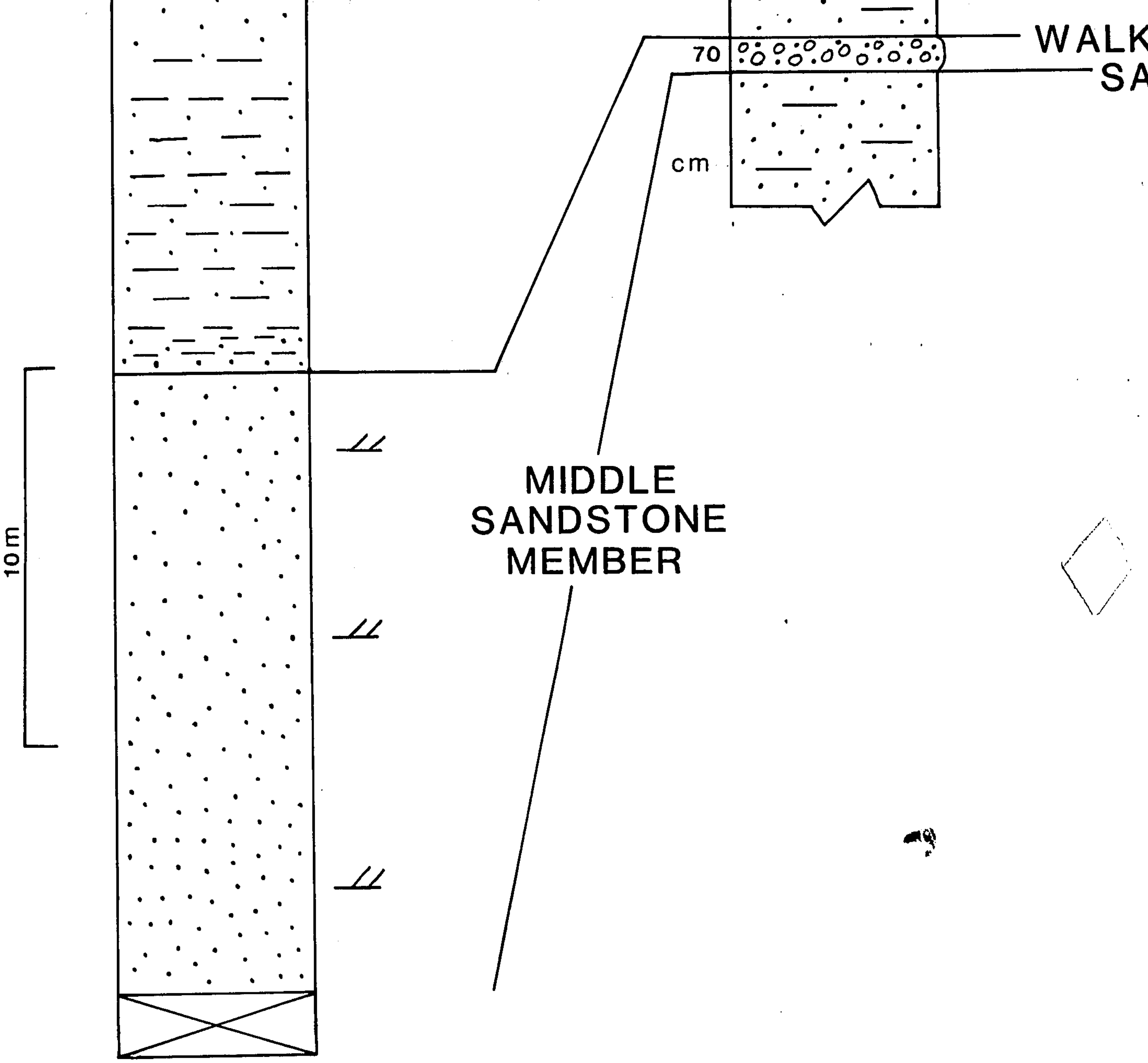
125
MILLBRIG (T-4)
115
Redbeds
Bays
Formation
Redbeds
Bays
Formatio
70
WAL
S
cm
MIDDLE
SANDSTONE


50
Bays
Formation
cm
ds
ays
nation
135
150
M
M
cm
F
VALKER MOUNTAIN
SANDSTONE


65
3
cm
Redbeds
Bays
Formation
e Redbeds
WALKER
MOUNTAIN
SANDSTONE
Wassum
Formation
Witten
ormation
cm



in sandstone
70
MILLBRIG (T-4;V-4)
Liberty Hall
Formation
cm


WALK
SA
70
cm
10 m
MIDDLE
SANDSTONE
MEMBER

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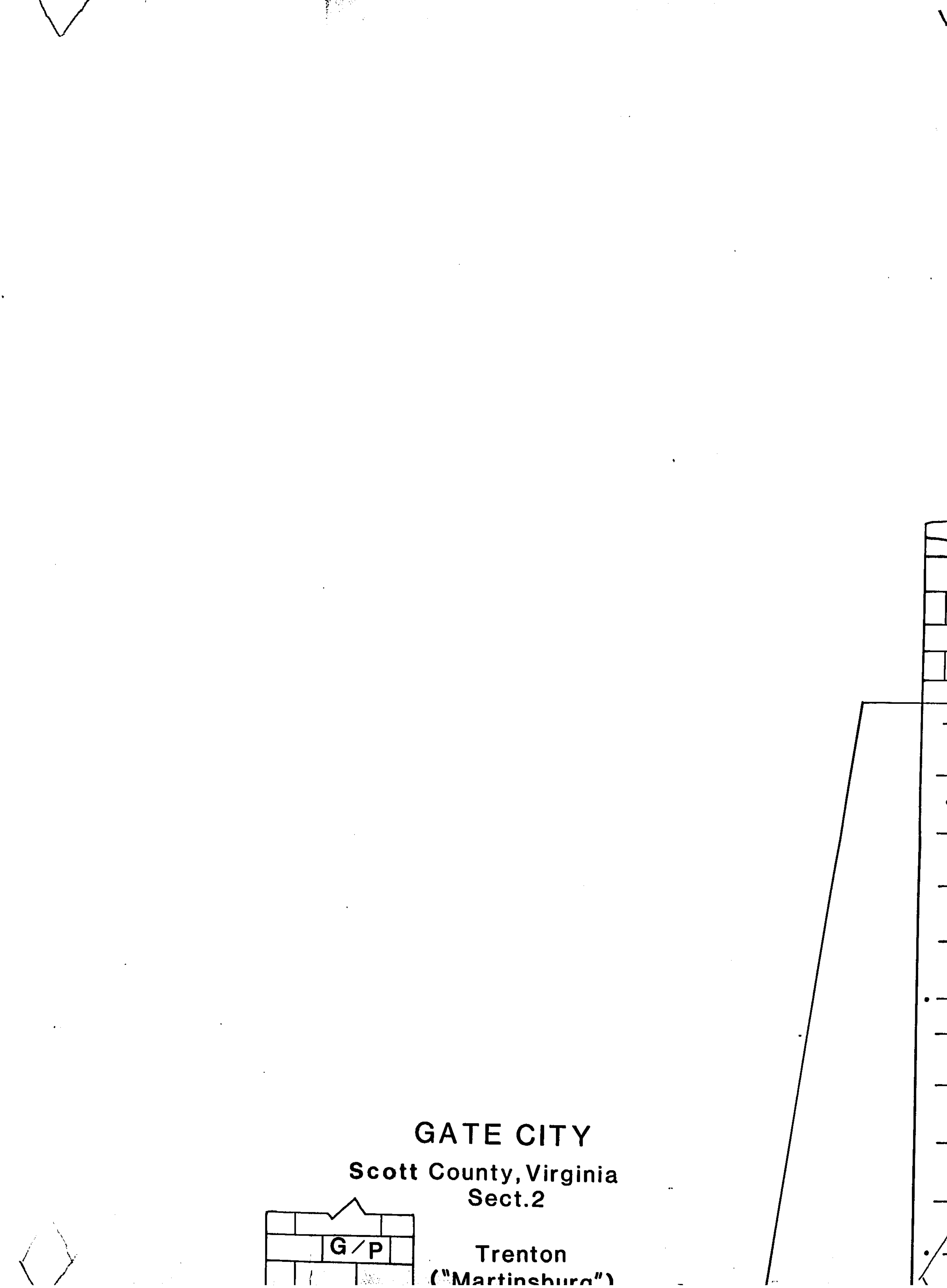
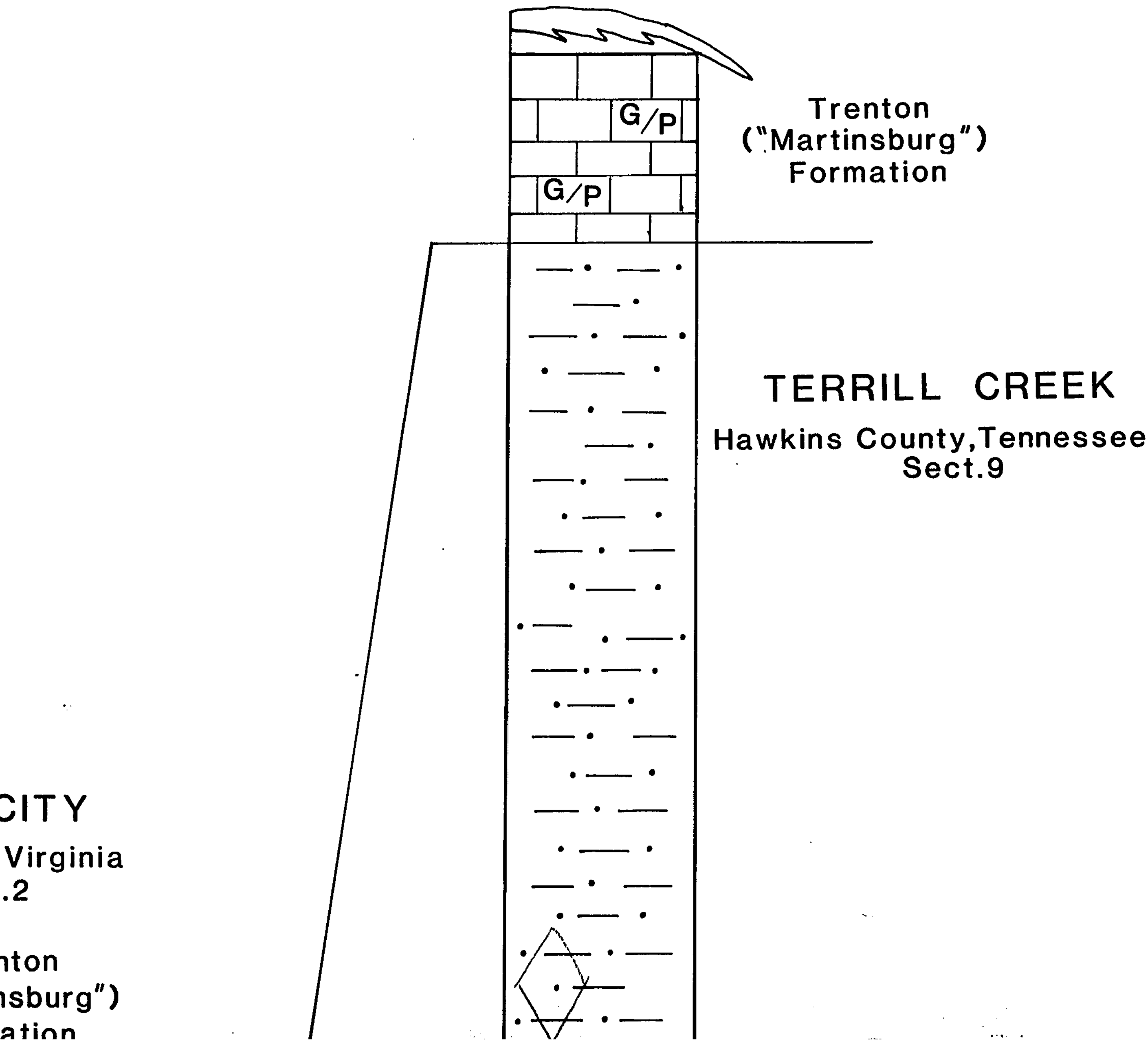

GATE CITY
Scott County, Virginia
Sect.2
G/P
Trenton
("Martinsburg")

PLATE 5

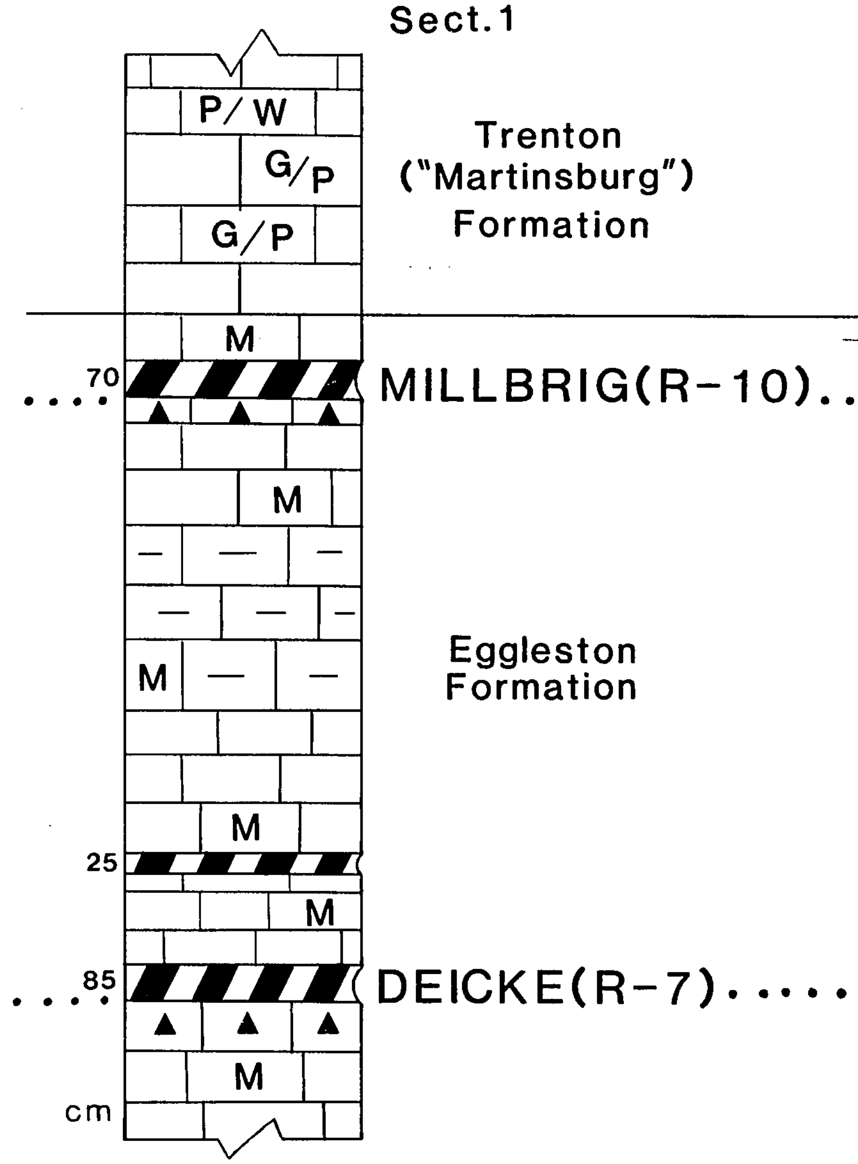


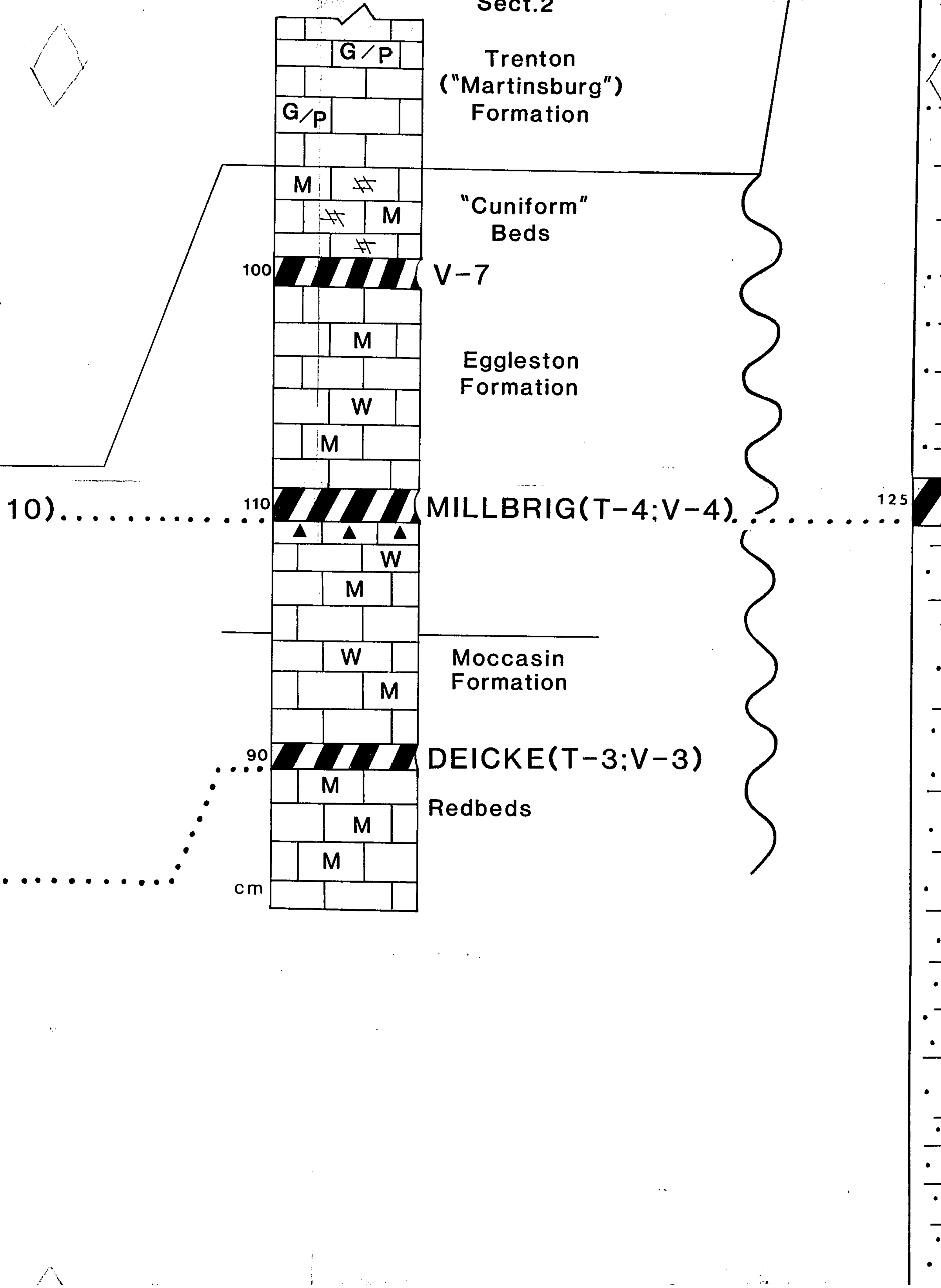
G/P
G/P
Trenton
("Martinsburg")
Formation
TERRILL CREEK
Hawkins County,Tennessee
Sect.9
CITY
Virginia
.2
nton
nsburg")
ation

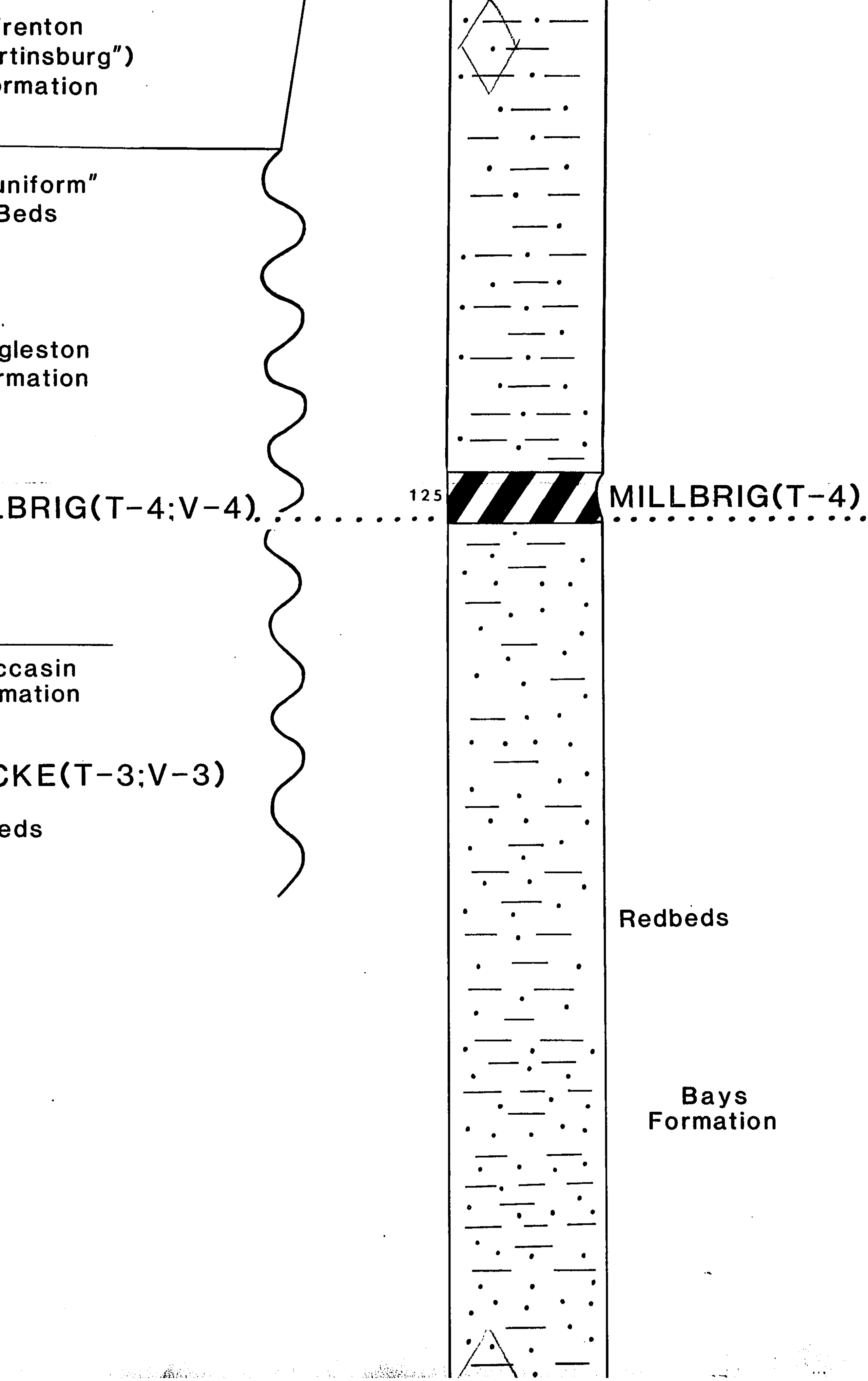
HAGAN

Lee County, Virginia

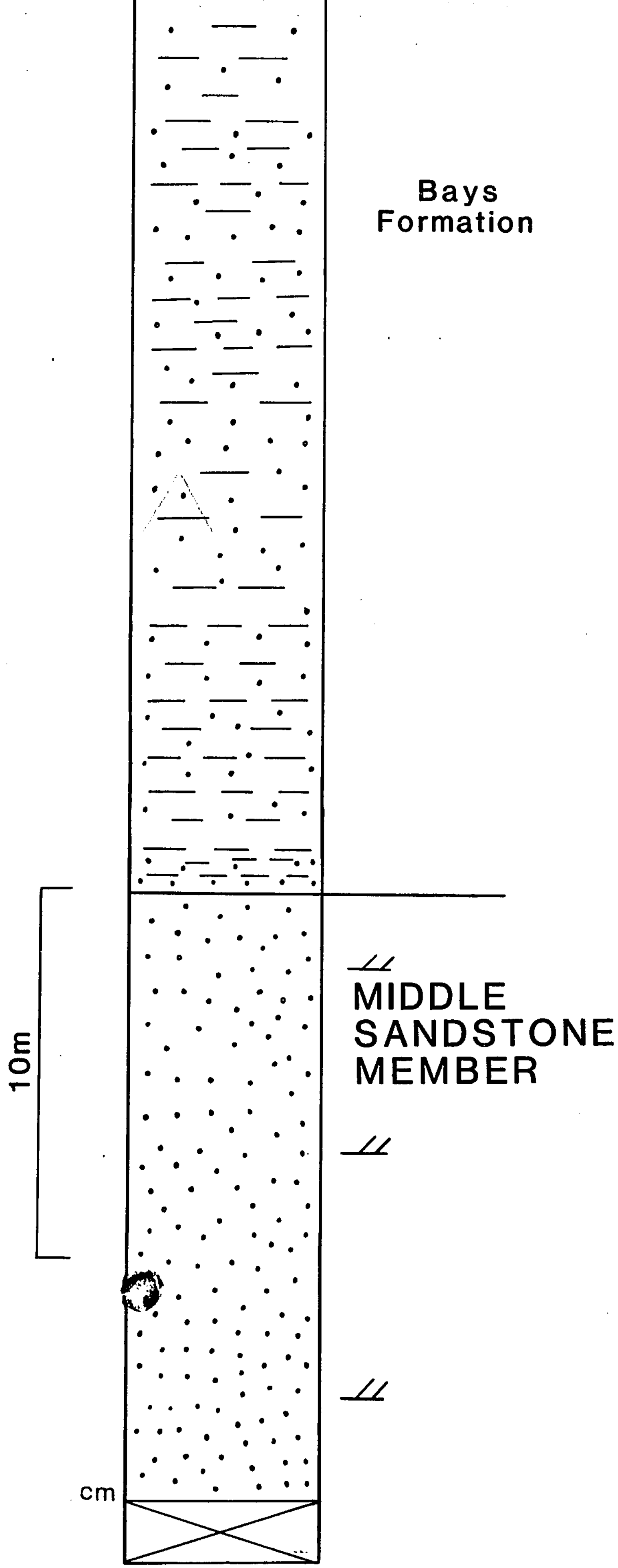
Sect. 1




Sect.2
G/P
G/P
Trenton
("Martinsburg")
Formation
M
M
"Cuniform"
Beds
100
V-7
M
W
M
Eggleston
Formation
110
10)
MILLBRIG(T-4;V-4)
125
W
M
W
M
Moccasin
Formation
90
DEICKE(T-3;V-3)
M
M
M
Redbeds
cm



renton
rtinsburg")
rmation
niform"
Beds
gleston
rmation
.BRIG(T-4;V-4)
ccasin
mation
CKE(T-3;V-3)
eds
125
MILLBRIG(T-4)
Redbeds
Bays
Formation


Bays
Formation
MIDDLE
SANDSTONE
MEMBER
10m
cm

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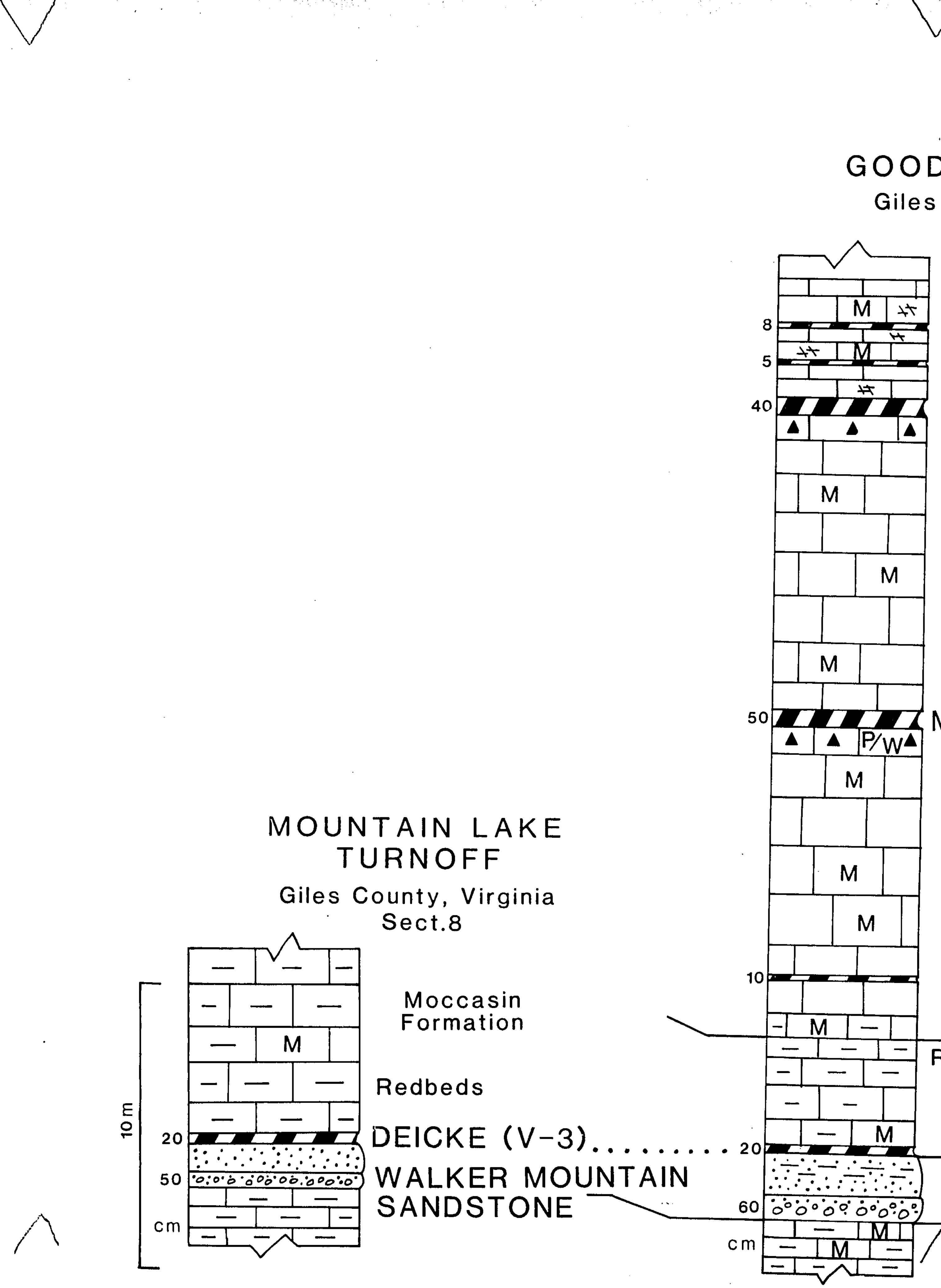
UMI


GOOD
Giles
M
8
5
40
50
P/W
10
20
60
cm
MOUNTAIN LAKE
TURNOFF
Giles County, Virginia
Sect.8
Moccasin
Formation
Redbeds
DEICKE (V-3)
WALKER MOUNTAIN
SANDSTONE
10 m
20
50
cm

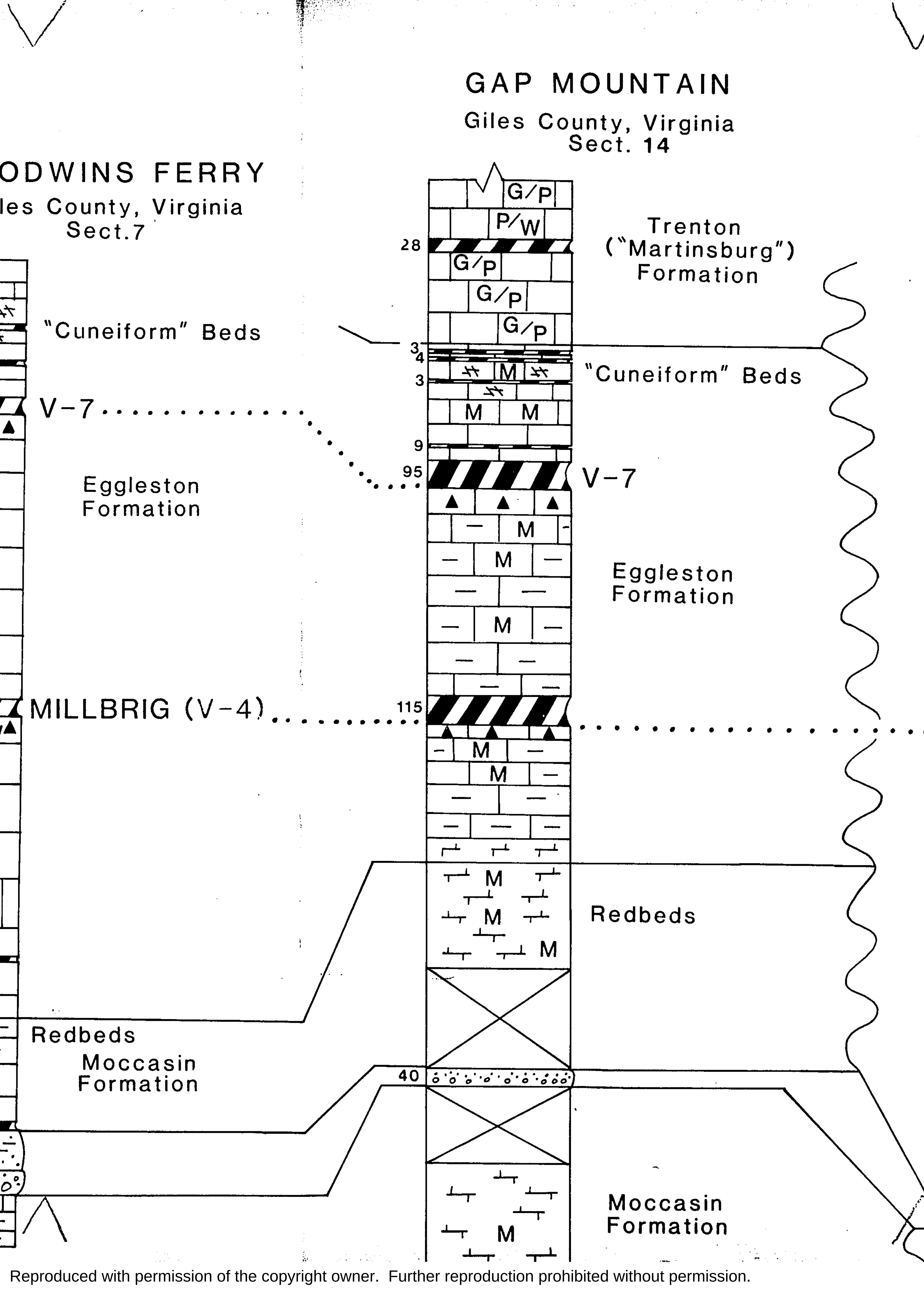
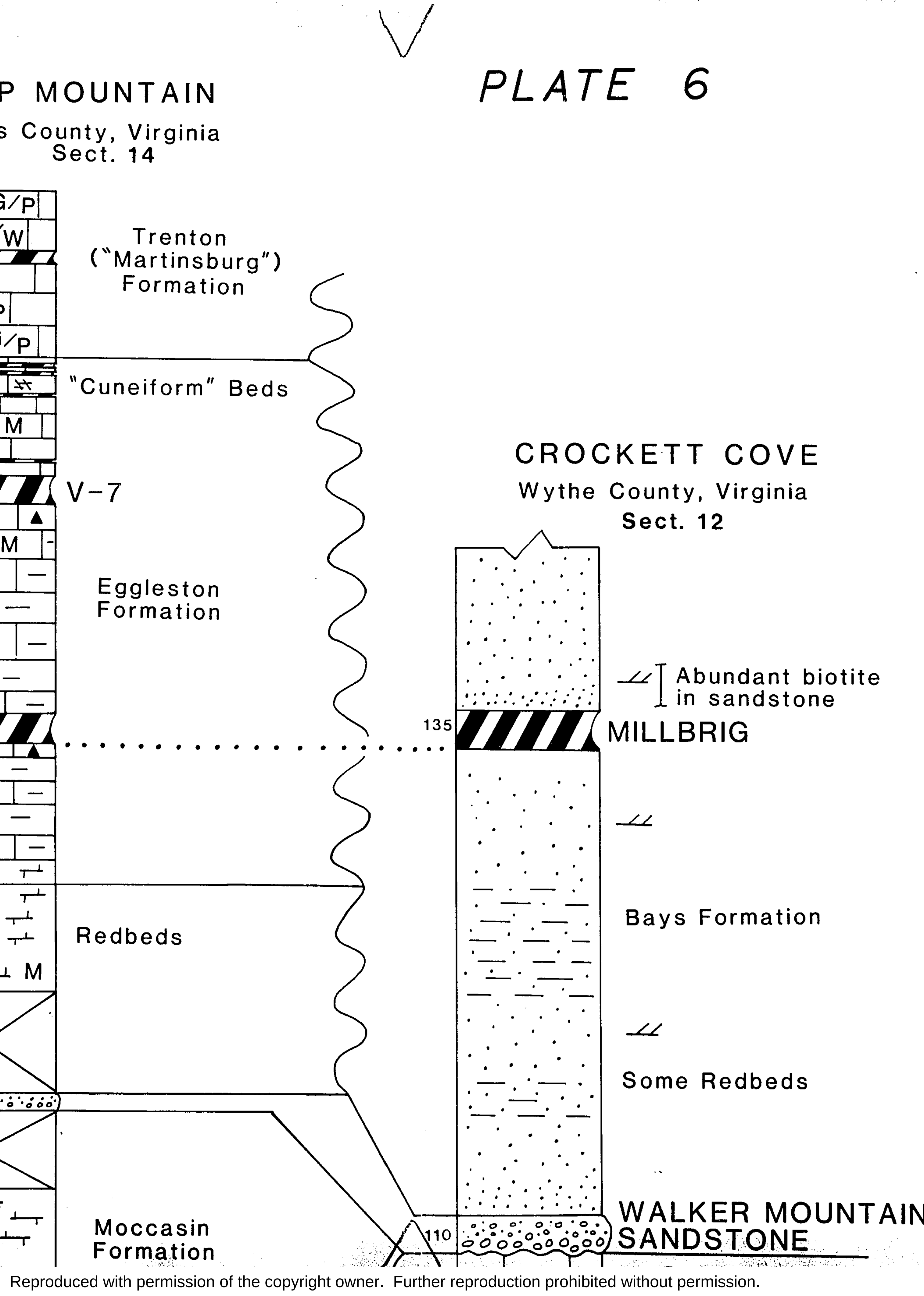
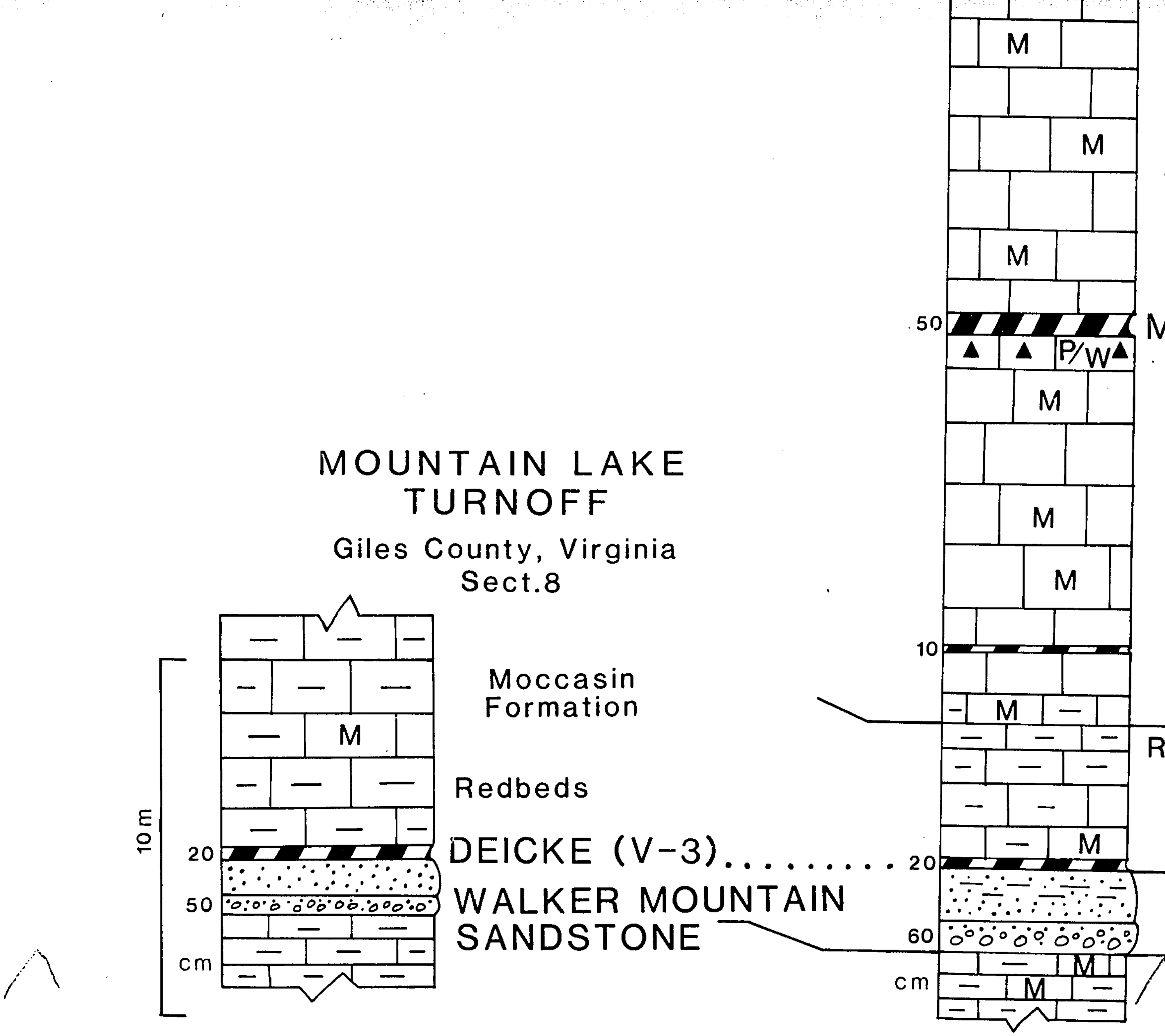

GAP MOUNTAIN
Giles County, Virginia
Sect. 14
ODWINS FERRY
les County, Virginia
Sect.7
"Cuneiform" Beds
V-7
Eggleston Formation
MILLBRIG (V-4)
Redbeds
Moccasin Formation
G/P
P/W
28
Trenton ("Martinsburg") Formation
3
4
3
9
95
115
40
M
Redbeds
Moccasin Formation

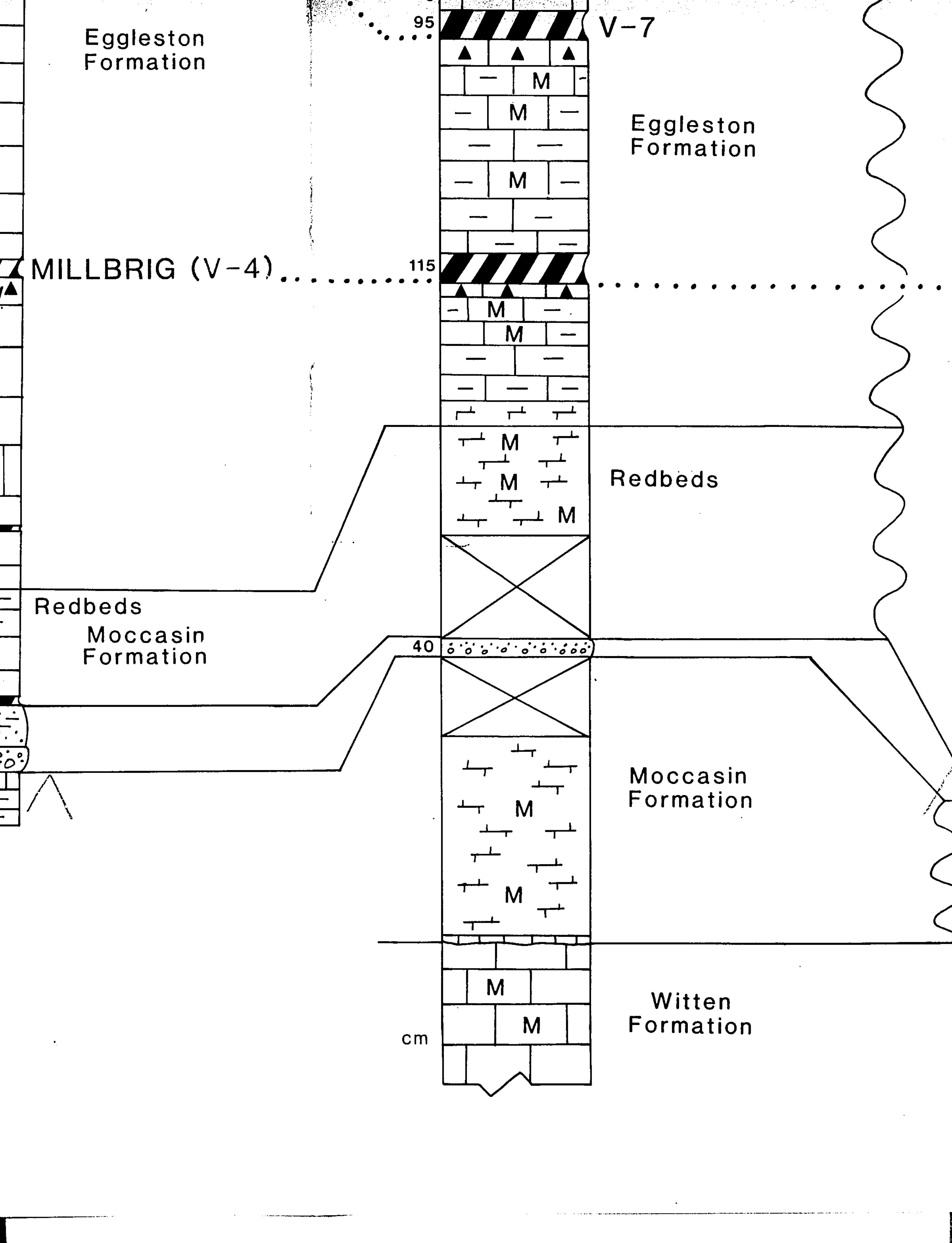
PLATE 6



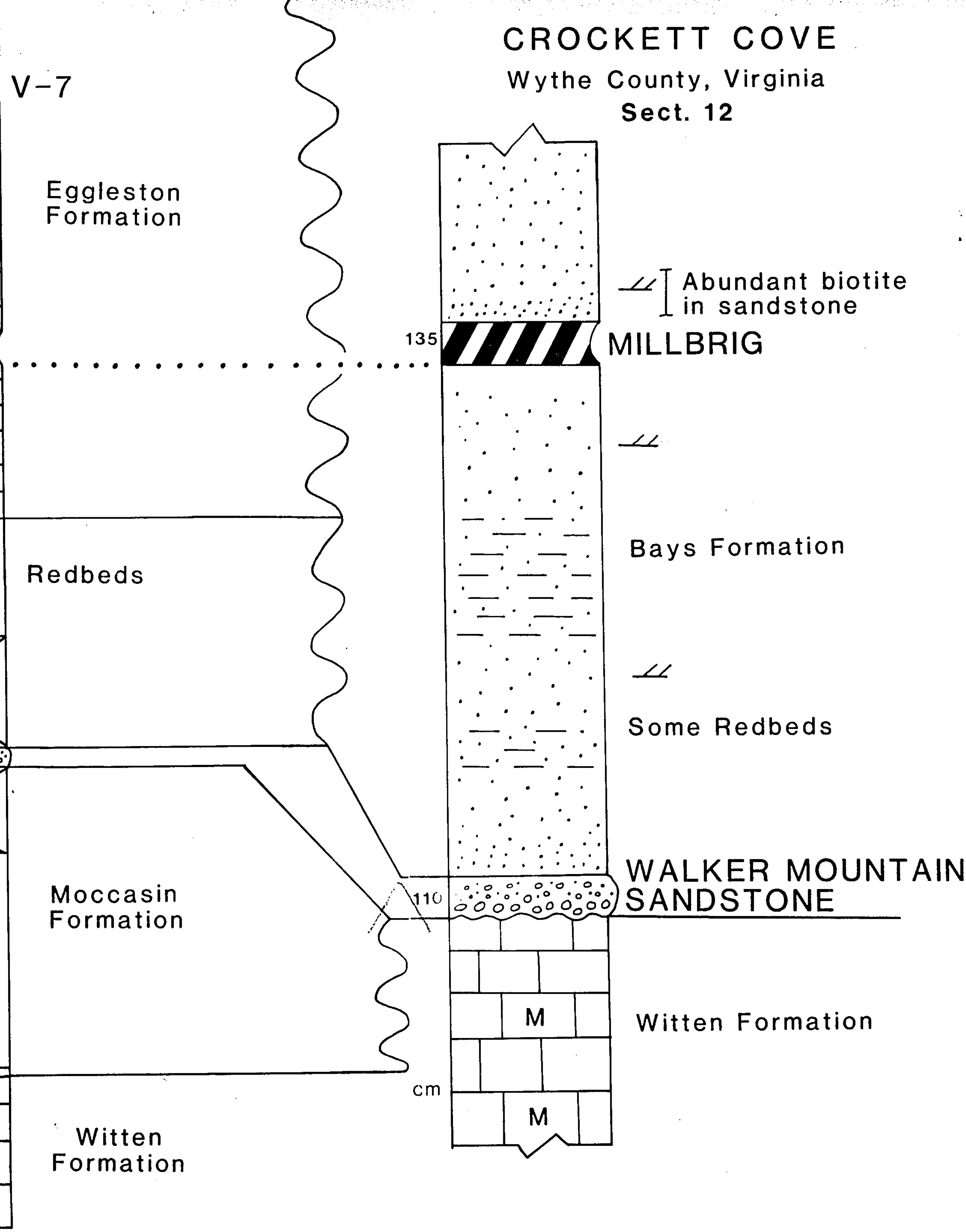
P MOUNTAIN
s County, Virginia
Sect. 14
Trenton
("Martinsburg")
Formation
"Cuneiform" Beds
V-7
Eggleston
Formation
Redbeds
Moccasin
Formation
CROCKETT COVE
Wythe County, Virginia
Sect. 12
Abundant biotite
in sandstone
135
MILLBRIG
Bays Formation
Some Redbeds
110
WALKER MOUNTAIN
SANDSTONE



MOUNTAIN LAKE TURNOFF
Giles County, Virginia
Sect.8
Moccasin Formation
Redbeds
DEICKE (V-3)
WALKER MOUNTAIN SANDSTONE
10 m
20
50
cm
M
P/W
10
20
50
60
cm



Eggleston Formation
95
V-7
M
Eggleston Formation
MILLBRIG (V-4)
115
M
Redbeds
Redbeds
Moccasin Formation
40
Moccasin Formation
M
Witten Formation
cm


V-7
CROCKETT COVE
Wythe County, Virginia
Sect. 12
Eggleston Formation
Abundant biotite in sandstone
135
MILLBRIG
Redbeds
Bays Formation
Some Redbeds
Moccasin Formation
110
WALKER MOUNTAIN SANDSTONE
M
Witten Formation
cm
M
Witten Formation