The Black Knob Ridge Section, Southeastern Oklahoma, USA: A Possible Global Stratotype-Section and Point (GSSP) for the Base of the Middle Stage of the Upper Ordovician Series

by

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Abstract

An excellent Global Stratotype Section and Point (GSSP) for the Middle Stage of the Upper Ordovician Series is defined at 4.0 meters above the base of the Bigfork Chert in the Black Knob Ridge section, southeastern Oklahoma. This point in this section is coincident with the first appearance of the graptolite *Diplacanthograptus caudatus*, which has proved to be a reliable datum for precise worldwide correlation. The FAD of *D. caudatus* occurs very near the first occurrences of *D. lanceolatus*, *Corynoides americanus*, *Orthograptus pageanus*, *O. quadrimucronatus*, *Dicranograptus hians*, and *Neurograptus margaritatus*. This rapid succession of biological events provides a secure basis for identification of the Middle Stage of the Upper Ordovician Series and for its global chronostratigraphic correlation. A name for the second stage of the Upper Ordovician Series still needs to be chosen.

In addition to graptolites, the Black Knob Ridge section also contains biostratigraphically important conodonts and chitinozoans. The conodonts and chitinozoans occur with graptolites on black shale bedding surfaces and allow for the precise correlation of the Middle Stage into regions that are represented by carbonate facies. The base of the Middle Stage occurs high in the *Amorphognathus tvaerensis* North Atlantic conodont zone and just below the base of the *Plectodina tenuis* North American Midcontinent conodont zone. It is also in close proximity to several important marker horizons - just above the Millbrig and Kinnekulle K-bentonite complexes in Eastern North America and Scandinavia, respectively, and just below the beginning of the Guttenberg (GICE) Upper Ordovician C\(^{13}\) excursion. These event and chemostratigraphic marker horizons provide an independent test on the global synchronicity of the base of the Middle Stage, and greatly increase our confidence in the usefulness of that level for chronostratigraphic correlation.
Introduction

The Ordovician Subcommission of the International Commission on Stratigraphy have recently redefined the base of the Upper Ordovician Series to be at the first appearance datum (FAD) of the graptolite species *Nemagraptus gracilis* in the Fågelsång GSSP section in Sweden. This designation recognized the tremendous utility for global correlation of the first appearance of a cosmopolitan species that occurs within a consistent succession of other first appearance datums (e.g., Finney and Bergström, 1986; Bergström et al., 2000). Current efforts are focused on subdividing the Upper Ordovician into three stages and choosing appropriate levels and stratotypes for the bases of the middle and upper stages.

In the upper part of the range of *N. gracilis*, a new fauna comprising *Climacograptus bicornis*, members of the *Orthograptus calcaratus* species group, and a profusion of large dicellograptinids and dicranograptinids appears (Finney and Bergström, 1986). This fauna, commonly referred to as the *Climacograptus bicornis* Zone fauna, is also widely known and can be precisely correlated within graptolite facies across the world. Unfortunately, the correlation of post-*Climacograptus bicornis* Zone rocks is one of the long-standing problems in Ordovician graptolite biostratigraphy. Faunal provincialism has led to the construction of numerous separate zonations, four in North America alone. Establishing detailed correlations between these various zonations has proved difficult and often contentious (e.g., Riva, 1969, 1974; Berry 1970, 1977; Bergström, 1978; Finney, 1986). Goldman (2003) noted that one graptolite species, *Diplacanthograptus caudatus*, is an easily recognizable, cosmopolitan taxon with a consistent FAD within a succession of first appearances of other graptolite taxa,
Figure 1.—Correlation of post-Nemagraptus gracilis Upper Ordovician graptolite biozones with a comparison of the stratigraphic ranges of some key index species. Data on graptolite ranges from Finney (1986), Goldman et al. (1999), Riva (1969, 1974), VandenBerg and Cooper (1992), Williams (1995), Zalasiewicz et al. (1995), and Chen et al. (2000).
and that the FAD of *D. caudatus* could define the base of a globally recognizable stage boundary that could be correlated with confidence (Figure 1). In most localities, the FAD of *D. caudatus* occurs very near the first occurrences of *D. lanceolatus*, *Corynoides americanus*, *Orthograptus pageanus*, *O. quadrimucronatus*, *Dicranograptus hians*, and *Neurograptus margaritatus*. This rapid succession of biological events following upon the abrupt demise of the diverse, cosmopolitan fauna of the underlying *C. bicorns* Zone provides a secure basis for identification of the base of the *D. caudatus* biozone and for its global chronostratigraphic correlation. Additionally, the FAD of *D. caudatus* is in close proximity to several important marker horizons - just above the Millbrig and Kinnekulle K-bentonite complexes in Eastern North America and Scandinavia, respectively; just below the base of the *Plectodina tenuis* conodont biozone; and just below the beginning of the Gutttenberg (GICE) Upper Ordovician C\(^{13}\) excursion (Young et al., 2003; Figure 2 herein). These event and chemostratigraphic marker horizons provide an independent test on the global synchronicity of the FAD of *D. caudatus*, and greatly increase our confidence in the usefulness of that biohorizon for chronostratigraphic correlation.

Finally, new isolated three-dimensionally preserved material of *D. caudatus* (Goldman and Wright, 2003) has clarified the proximal end morphology and phylogenetic relationships of this taxon. *Diplacanthograptus caudatus* is part of a well-studied sub-clade comprising *C. bicorns* (Hall) - *D. lanceolatus* (VandenBerg) - *D. caudatus* (Lapworth) - *D. spiniferus* (Ruedemann) and *C. tubuliferus* Lapworth (VandenBerg, 1990). At the 2003 meeting of the International Symposium on the Ordovician System in San Juan, Argentina, the Subcommission recommended that the
Figure 2.— Correlation chart showing proposed chronostratigraphic relations between Upper Ordovician graptolite zones, conodont zones, and important event and chemostratigraphic marker horizons in the principal localities discussed in the text. Adapted from Webby et al. (2004).
base of the second (middle) stage of the Upper Ordovician Series be defined at a level in the stratotype section that corresponds to the FAD of Diplacanthograptus caudatus.

Global Stratotype-Section and Point (GSSP) Proposal

1. Geologic Setting

The Upper Ordovician rocks that crop out in the Ouachita Mountains of west-central Arkansas and southeastern Oklahoma are composed primarily of graptolite-rich shales associated with deep-water limestones and cherts (Ethington et al., 1989). These strata were deposited in the deep marine environment of the Ouachita Geosyncline off the southern margin of Laurentia (Finney, 1988). The rich graptolite faunas have traditionally been used to correlate these rocks with other Upper Ordovician successions in North America and around the world.

In southeastern Oklahoma Upper Ordovician strata are exposed along Black Knob Ridge, a low narrow ridge at the extreme western end of the Ouachita Mountains (Hendricks et al., 1937; Finney, 1988). The units exposed along Black Knob Ridge are, in ascending order, the Womble Shale, Bigfork Chert, and Polk Creek Shale. The base of the Ordovician succession is in fault contact with the Pennsylvanian Atoka Formation and the Silurian age Blaylock Sandstone disconformably overlies the top of the sequence (Ethington et al., 1989). An excellent exposure of the Womble to Polk Creek succession occurs on a hill slope approximately 5 kilometers north of the town of Atoka, SW1/4, Section 31, T. 1S, R. 12E, Atoka County, Oklahoma; 34° 25’ 22” N, 96°04’30” W (Figure 3).
Figure 3.—Locality map for the Black Knob Ridge Section. The section is located 5 kilometers north of the town of Atoka, SW1/4, Section 31, T. 1S, R. 12E, Atoka County, Oklahoma; 34° 25’ 22” N, 96° 4’ 30” W.
This exposure, which we refer to as the Black Knob Ridge (BKR) section, extends along strike for several hundred meters, is readily accessible, contains a continuous graptolite succession across the *Climacograptus bicornis* – *Diplacanthograptus caudatus* zonal boundary, and yields biostratigraphically important conodonts and chitinozoans.

At the BKR section, approximately 50 meters of black, graptolite-rich Womble Shale are exposed (Figure 4). The upper Womble is composed of soft, tan to chocolate brown weathering shale and bedded chert. In addition to graptolites, these beds contain conodonts, chitinozoans, sponge spicules, inarticulate brachiopods, and well-rounded quartz sand grains.

Conformably overlying the Womble Shale are approximately 145 meters of Bigfork Chert (Figures 4 and 5). The contact between the two units appears gradational. The base of the Bigfork Chert is a 0.5 meter interval of hard, splintery black shale that contains abundant conodonts and chitinozoans. The Bigfork Chert is composed of nodular and bedded chert, intercalated with black shale and siliceous limestone. Because limestone beds are absent in the shale below and above the Bigfork Chert, its upper boundary is placed at the last limestone bed in the section (Finney, 1988). The limestone is medium bedded, siliceous, fine- to coarse-grained skeletal calcarenites. Fossils include graptolites, conodonts, chitinozoans, sponge spicules, inarticulate brachiopods, and radiolarians (Hendricks et al., 1937) with skeletal fragments of peltmatazoans and brachiopods (Finney, 1988). There is no evidence of a depositional break within the Bigfork Chert at the study section.

The Polk Creek Shale overlies the Bigfork Chert with an apparently conformable contact. Although the Polk Creek has not been measured at the BKR section, Hendricks
et al., (1937) measured 43 meters at the Atoka city trash dump and Dworian (1990) recorded 32 meters from a locality along Black Knob Ridge south of the proposed stratotype section.

Figure 4.— The Black Knob Ridge Section. A) The base of the *Diplacanthograptus caudatus* Zone. The hammer marks the FAD of *D. caudatus*. B) The Upper Womble Shale and Bigfork Chert at the Black Knob Ridge Section. The contact between the two units is placed at the first organic-rich, siliceous shale that forms a prominent ledge. This bed is extremely rich in graptolites and conodonts.
Figure 5.—Stratigraphic column with a range chart of graptolites, conodonts, and chitinozoans for the Black Knob Ridge section. Note that the base of the Diplacanthograptus caudatus zone is placed at the first appearance of D. caudatus four meters above the base of the Bigfork Chert. The C. bicornis–D. caudatus zonal boundary occurs high in the Amorphognathus tetensii conodont zone.
2. Access

The BKR section is located on the private property of Mr. and Mrs. Doug Howard. Mr. and Mrs. Howard have always allowed access to geologists visiting and studying the section and they have agreed to make the section permanently available to scientific study and field trips. A letter signed by Mr. Howard agreeing to access to the section is attached to this proposal (see appendix 1). The section can found by driving northeast from Atoka for 5 kilometers on U.S. Route 69, turning right onto Venta Allen Road, and making an immediate left-hand turn onto an unpaved road. After approximately 0.5 km, turn right onto the Howard property. This unpaved road leads directly to the BKR section.

3. Graptolite Biostratigraphy

Graptolites have been collected and described from the Ordovician rocks of the Ouachita Mountains for over a century (e.g., Gurley, 1892a,b; Ulrich, 1911; Miser and Purdue, 1929; Decker, 1935; Hendricks et al., 1937; Ruedemann, 1908, 1947; Finney, 1986, 1989). Finney (1986, 1988) and Ethington et al. (1989) revised the pioneering studies and provided stratigraphic ranges for graptolites in the uppermost Womble Shale and overlying Bigfork Chert from the Stringtown Quarry section at the north end of Black Knob Ridge. Most recently, Goldman et al. (2002) described the graptolite ranges and diversity patterns from the Womble Shale and Big Fork Chert at the BKR section.

3.1. Description of the Boundary Interval.—The upper Womble shale contains an abundant graptolite fauna that is referable to the Climacograptus bicornis Zone (Figure 5). Diagnostic elements of this fauna include C. bicornis, C. bicornis tridentatus,
Orthograptus whitfieldi, O. calcaratus ssp., Archiclimacograptus modestus, Dicranograptus spinifer, D. contortus, D. arkansasensis, Normalograptus brevis, and Nemagruptus gracilis. The transition between the C. bicornis Zone and the underlying N. gracilis Zone has not yet been found at Black Knob Ridge.

Climacograptus bicornis, C. bicornis tridentatus, Archiclimacograptus modestus, and Dicranograptus arkansasensis range upward into the lowermost 3.1 meters of the Bigfork Chert. Three and two-tenths meters above the base of the Bigfork Chert, Orthograptus quadriruncronatus makes its first appearance. The base of the Middle Stage of the Upper Ordovician Series is placed at the FAD of Diplacanthograptus caudatus, 4.0 meters above the base of the Bigfork Chert (Figure 5). At this horizon, several taxa diagnostic of the D. caudatus Zone first appear (Plate 1). These are D. caudatus, Orthograptus pageanus, Neurograptus margaritatus, and Corynoides americanus. Dicranograptus hians was found 2.0 meters higher up. Diplacanthograptus spiniferus and Climacograptus tubuliferus debut at 9.8 and 52.5 meters, respectively, above the base of the Bigfork Chert (Finney, 1986 and personal communication).

There is no evidence of a hiatus or sedimentological discontinuity in the C. bicornis – D. caudatus boundary interval. Less than 1 meter (0.9 m) separates the uppermost collection of C. bicornis Zone graptolites from the FAD of D. caudatus. This 0.9 m interval is characterized by thickly bedded chert and siliceous limestone, and no identifiable graptolites were identified in this interval after an intensive search. Thus, the boundary interval at Black Knob Ridge is graptolite-rich and contains a very well defined base to the D. caudatus Zone.
4. Conodont Biostratigraphy

Conodonts have been known from the Black Knob Ridge since Hendricks et al.’s (1937) description of the geology at Black Knob Ridge. Harlton (1953) also reported the occurrence of conodonts at BKR. However, as Repetski and Ethington (1977), and Ethington et al. (1989) reported, these early studies did not identify the conodonts, and their stratigraphic occurrences were not documented precisely. Bradshaw (1974) identified a conodont fauna of Midcontinent aspect from the Bigfork Chert at BKR. She reported occurrences to the genus-level, and identified fauna of *Panderodus*, *Belodina*, *Drepanodus*, *Oistodus*, and *Phragmodus* from siliceous limestone beds. More recently, Krueger (2002) reported on the occurrence of conodonts from the Stringtown Quarry approximately 3 kilometers north of the BKR section. The fauna that Krueger reported from the limestone beds is also of Midcontinent aspect.

Recently, we collected samples for conodonts across the Womble-Bigfork boundary at BKR, and discovered that there are well-preserved conodonts on the shale bedding planes in both the Womble Shale and Bigfork Chert that are typical of the North Atlantic Fauna (Plate 2). The limestone beds in the lower part of the Bigfork at the BKR section are completely silicified and, therefore, have not been dissolved for conodonts. The uppermost Womble Shale contains an abundant, low diversity conodont fauna, with biostratigraphically important conodonts. The fauna contains elements of *Amorphogathus tvaerensis* and *Icriodella* cf. *I. Superba* (Plate 2). The presence of *I. cf. I. superba* with *A. tvaerensis* demonstrates that the uppermost Womble at BKR is within the *B. alobatus* Subzone of the *A. tvaerensis* Zone (Figure 2), which is the uppermost part of the *A. tvaerensis* Zone (Bergström, 1982). The previously reported highest fauna from the
Womble (Repetski and Ethington, 1977; Ethington et al., 1989) are from a different locality and represents the *B. gerdae* Subzone of the *A. tvaerensis* Zone, which is the subzone below the *B. alobatus* Subzone (Figure 2). The uppermost Womble Shale at BKR also contains *Periodon grandis*, *Drepanoistodus suberectus*, *Dapsilodus* sp. aff. *D. mutatus*, *Oistodus* sp., and *Panderodus* sp.

The conodont fauna from lowermost Bigfork Chert at BKR consists of *A. tvaerensis*, *Periodon grandis*, *Protopanderodus* cf. *P. liripipus*, *Drepanoistodus suberectus*, *Dapsilodus* sp. aff. *D. mutatus*, *Phragmodus* sp., and *Panderodus* sp. (Plate 2). This fauna is nearly identical to the fauna from the upper Womble, with the exception of relatively abundant specimens of *P. cf. P. liripipus*. Of interest is the occurrence of 2 specimens of *Amorphognathus* sp. approximately 5.7 meters above the base of the Bigfork Chert. These specimens are morphologically similar to *A. superbus*, however unquestionable identification is not possible from the material at hand.

The biostratigraphically significant conodonts known from BKR suggest that the *Climacograptus bicornis - Diplacanthograptus caudatus* zonal boundary is located in the *B. alobatus* subzone of the *Amorphognathus tvaerensis* conodont zone. This correlation is consistent with the graptolite – conodont zonal relationships described from Europe and eastern North America by Bergström (1971, 1986) and Goldman et al. (1994). We think that further collecting will undoubtedly result in a more precise conodont biostratigraphy and an increased resolution in the correlation between the conodont and graptolite biozones at this site.
5. Chitinozoan Biostratigraphy.—Upper Ordovician Chitinozoans of Oklahoma have been described by Grahn and Miller (1986) from the Bromide Formation and by Jenkins (1969) from the Viola Springs Formation. These studies were all made from samples collected in the carbonate facies of the Arbuckle Mountains. Chitinozoans have been previously noted but not described from weathered shale surfaces in the Womble Shale and Bigfork Chert at Black Knob Ridge (Finney, 1988). Flattened chitinozoans are abundant and visible on the weathered surfaces of the organic-rich shale beds that also contain our conodont samples. Additionally, hydrofluoric acid dissolution of shale beds across the *C. bicornis – D. caudatus* zonal boundary has yielded a low diversity, poorly preserved, but biostratigraphically significant fauna (Plate 3).

Our lowermost sample, 4 meters below the Bigfork Chert, contained *Conochitina minnesotensis*, *Cyathochitina* cf. *C. kuckersiana*, *Desmochitina minor*, and *Euconochitina* cf. *E. conulus*. A sample 1.0 meter below the Bigfork Chert yielded *Desmochitina minor* and *Euconochitina* sp., and the uppermost Womble Shale sample, 0.1 meter below the Bigfork Chert, contained *Eisenackitina* sp., *Belonechitina micracantha*, *Cyathochitina kuckersiana*, *Euconochitina* aff. *E. tanvillensis*, *Desmochitina minor*, *Lagenochitina* cf. *L. capax*, *Belonechitina* n. sp. A, and the prasinophyte *Leiosphaeridia* sp. Samples 2 meters above the base of the Bigfork Chert contained *Leiosphaeridia* sp.; those at the base of the *D. caudatus* Zone (4 meters above the base of the Bigfork Chert) had *Conochitina minnesotensis*, *Belonechitina micracantha*, *Cyathochitina* sp., *Desmochitina minor*, *Lagenochitina* aff. *L. dalbyensis*, *Euconochitina* cf. *E. conulus*, and *Leiosphaeridia* sp.; and our uppermost sample at 6 meters yielded *Belonechitina wesenbergensis brevis*, *Belonechitina* cf. *B. robusta*,...
Calpichitina lata, Cyathochitina kuckersiana, Desmochitina minor and unidentifiable conical forms.

Because of the poor preservation of the isolated specimens (see Plate 3), confident correlations are difficult to make. However, the chitinozoan fauna from the boundary interval at Black Knob Ridge does show a broad similarity to Baltoscandian faunas from the Haljala to Keila stages (time slices 5b and 5c of Webby, et al., 2004; and see Nõlvak and Grahn, 1993, and Paris, 1990). This agrees well with the graptolite and conodont data and further work should produce a more refined chitinozoan biostratigraphy.

6. Event and Chemostratigraphy

The BKR section has recently been sampled for organic $\delta^{13}C$. There is an interesting trend toward higher $\delta^{13}C$ values (a +2.5 per mil excursion) just above the boundary interval (Figure 6 herein; Leslie et al., 2004). This trend occurs in a similar stratigraphic position as the GICE $\delta^{13}C$ excursion (Patzkowsky et al., 1997; Young et al, 2003). However, whereas at most other localities the GICE $\delta^{13}C$ excursion has been described from carbonate carbon in limestones, the $\delta^{13}C$ data obtained at Black Knob Ridge is from organic carbon in the shale horizons. Further work is necessary to confirm that the observed trend at BKR indeed represents the GICE $\delta^{13}C$ excursion and additional samples are currently being analyzed.

Recent work at Black Knob Ridge has also resulted in the discovery of a K-bentonite bed in the Upper Womble Shale (C. bicorns graptolite Zone) approximately 8 meters below the Bigfork Chert. This is a similar stratigraphic position to the Hagan, Virginia K-bentonite complex (including the Deike and Millbrig K-bentonites; Haynes et
al., 1996). Huff (person. commun., 2004) has confirmed that the clay layer is a K-bentonite and is currently evaluating its potential for geochemical fingerprinting.

Figure 6.-- $\delta^{13}$C and %‰ total organic carbon data obtained from shale horizons across the boundary interval at Black Knob Ridge.

7. Supplemental Sections

Upper Ordovician rocks are exposed in the Arbuckle Mountains of south-central Oklahoma 60 kilometers west of Black Knob Ridge. These strata were deposited within, and on, the platforms bordering the Southern Oklahoma Aulacogen and represent a much shallower depositional environment than the deep-water shale, chert, and limestone of the Ouachita Mountains (Finney, 1988). During the Late Paleozoic the Ouachita strata were thrust cratonward leaving the distinctly different facies of the Ouachita and Arbuckle Mountains juxtaposed geographically (Finney, 1988). The BKR Section can, however, be correlated into the carbonate-rich facies of the Arbuckle Mountains using graptolite
biostratigraphy. Thus, the BKR section, which contains a fauna dominated by graptolites, can be correlated with nearby sections that contain a more complete conodont zonation and are part of Sweet’s (1979, 1984, 1995) graphic correlation framework.

The Upper Ordovician limestones of the Arbuckle Mountains comprise the Bromide, Viola Springs, and Welling formations, in ascending order. The Viola Springs and Welling formations (which together comprise the Viola Group) are well known for yielding three-dimensionally preserved graptolites (e.g. Finney, 1986). One outcrop along the west side of U.S. Highway 99 approximately 5.5 km south of Fittstown, Oklahoma contains a graptolite succession that is nearly identical (although much less complete) to that of the BKR section. This locality (NW1/2 SW1/4 sec. 12, T. 1N, R. 6E, Pontotoc County) was described by Alberstadt (1973, Section D), Finney (1986, 1988), and Sweet (1983), and is referred to as Section D, herein (Figure 7).

**7.1.—Graptolite Biostratigraphy of Section D.** The lower 0.5 meters of the Viola Springs Formation at Section D consists of siliceous laminated calcareous mudstones (Unit 1, subunit 1L of Alberstadt, 1973) that contain abundant graptolites of the *Climacograptus bicornis* Zone. Our collections include *C. bicornis*, *Dicranograptus spinifer* (= *D. nicholsoni longibasalis* Ruedemann and Decker), *Rectograptus* n. sp., and *Corynoides calicularis*. A horizon 5 cm higher yielded *Orthograptus quadrimumcronatus* and *Lasiograptus harknessi* in addition to the previously mentioned species (Figure 8). The presence of *O. quadrimumcronatus* indicates that this collection represents the uppermost part of the *C. bicornis* Zone.

Above 0.55 meters the lithology changes to skeletal calcisiltites and calcarenites with nodular and bedded chert (Unit 1, subunit 1C of Alberstadt, 1973). This lithofacies
Figure 7.—Locality map for supplemental section, Section D. The locality is 5.5 km south of Fittstown, Oklahoma (NW1/2 SW1/4 sec. 12, T. 1N, R. 6E, Pontotoc County).
Figure 8.— Stratigraphic column with a range chart of graptolites, conodonts, and chitinozoans for Section D. See text for explanation.
dominates the section for the next 40 meters and the beds are nearly devoid of graptolites. Finney (1986) reported the presence of _D. spiniferus_ at 35 meters above the base of the Viola Springs at Section D, and we collected _Diplacanthograptus caudatus, Cryptograptus insectiformis, Corynoides_ sp., and _Orthograptus_ sp. at 43 meters. Collections at 51 meters contain _Diplacanthograptus caudatus, Geniculograptus typicalis_, and _Orthoretiolites hamí_. The large gaps in graptolite collections and the truncation of the base of the range of _D. caudatus_ indicates that Section D is not suitable as a stratotype section. It is best used as a supplemental section that facilitates correlation of the _D. caudatus_ Zone into a shallower water conodont biofacies. Our graptolite information indicates that the contact between Bromide Formation and the overlying Viola Springs Formation is similar in age to the Womble Shale – Bigfork Chert contact at Black Knob Ridge and agrees with the correlations proposed by Finney (1988). In the BKR section, _Climacograptus bicornis_ Zone graptolites range up into the lowermost part of the Bigfork Chert. The base of the _Diplacanthograptus caudatus_ Zone occurs 4 meters above the base of the Bigfork Chert, and is within the uppermost part of the _Amorphognathus tvaerensis_ North Atlantic conodont Zone. At Section D, _Climacograptus bicornis_ Zone graptolites occur in the first 0.55 meters of the Viola Springs Formation. The FAD of _O. quadriruncronatus_ at 0.55 meters indicates that these beds represent the very top of the _C. bicornis_ Zone. The horizon at Section D that is synchronous with the base of the _Diplacanthograptus caudatus_ Zone at BKR likely lies in an interval devoid of graptolites. However, the conodonts at Section D provide good biostratigraphic control.
7.2.—Conodont Biostratigraphy of Section D. Sweet (1983) presented a detailed conodont biostratigraphy of Section D. He used Oberg’s (1966) conodont samples from the Viola Springs, and added to those samples 4 from the underlying Corbin Ranch Submember of the Pooleville Member of the Bromide Formation. Section D is part of Sweet’s (1983, 1984, 1995) graphically correlated sections, allowing for correlation by means of conodont graphic correlation into Section D.

The lowermost part of the Viola Springs contains a typical *P. undatus* Zone fauna that is dominantly of Midcontinent faunal aspect containing *P. undatus*, *Plectodina aculeata*, and *Belodina compressa*. Additionally, there are species that are more typical of the North Atlantic Province: *Icriodella superba*, *Periodon grandis*, and *Amorphognathus tvaerensis*. These species are the dominant members of the North Atlantic Fauna Province species present in the upper Womble and lower Bigfork at BKR.

The *P. undatus* Zone fauna is followed by a *P. tenuis* Zone fauna that contains not only the zonal indicator *P. tenuis*, but also includes the biostratigraphically important taxa *Polyplacognathus ramosus* and *Rhodesognathus elegans*. These species occur in samples below the first appearance of *D. caudatus*. At approximately 58.5 meters above the base of the Viola Springs is the first occurrence of *Belodina confluens*, the index of the *B. confluens* Zone. This sequence of first appearance datum’s of zonal indicator species along with additional biostratigraphically important species make Section D a valuable supplemental section. In addition, the more cosmopolitan and long-ranging species *Dapsilodus* cf. *D. mutatus*, *Panderodus* sp., and *Drepanoistodus suberectus* are present at both Section D and BKR.
7.3.—**Chitinozoan Biostratigraphy of Section D.** The Viola Springs Formation at Section D also contains a diverse and well-preserved chitinozoan fauna. Nineteen limestone samples (approximately 0.3 to 0.4 kg in weight) from the upper Bromide and Viola Springs formations were processed for chitinozoans. The lagoonal “bird’s-eye” facies of the Upper Bromide contained no chitinozoans, nor did samples of Viola Springs limestone between 5 and 43 meters (see Figure 8). This latter interval was also barren for graptolites likely indicating diagenetic processes that were attacking organic-walled fossils. Previous studies of chitinozoans from the Arbuckle Mountains of Oklahoma documented older assemblages from the Bromide Formation (Grahn and Miller, 1986) and younger Viola Springs assemblages from Sycamore Creek (Jenkins, 1969). This is the first report of chitinozoan faunas that span the age gap between these two earlier reports.

Rich chitinozoan assemblages appear just above the top of the Bromide Formation in a 5 to 10 cm thick detritus-rich limestone that marks the base of the Viola Springs Formation, and in the interval of 43 to 51 meters above the base of the latter formation (Plates 4 and 5). These samples yielded hundreds to thousands of well-preserved specimens. The lower productive interval, between 0 and 1.4 meters above the base of the Viola Springs, contained *Conochitina minnesotensis, Desmochitina minor, Belonechitina micracantha, Pistillachitina* sp., *Cyathochitina kuckersiana, Eisenackitina aff. E. rhenana, Belonechitina* n. sp. C, *Calpichitina lata, Conochitina tigrina, Conochitina dolosa, Spinachitina cervicornis, Desmochitina amphorae, Belonechitina* n. sp. A, *Desmochitina* cf. *D. piriformis, Belonechitina* cf. *B. cactacea, Spinachitina*
alaticornis, Belonechitina n. sp. B, Belonechitina wesenbergensis brevis, and Angochitina n. sp. A.

This fauna contains several biostratigraphically important taxa that have short vertical distributions in Baltoscandia. The presence of Spinachitina cervicornis, and the fact that Desmochitina amphorae, Conochitina dolosa, and Conochitina tigrina do not range above the lower Keila Stage in Baltoscandia (Nolvak and Grahn, 1993) indicates that the lowermost Viola Springs limestone at Section D belongs to S. cervicornis chitinozoan Zone and is no younger than the lower Keila. This is in complete agreement with the graptolite and conodont biostratigraphy (upper C. bicornis graptolite Zone and the Phragmodus undatus conodont zone).

The upper productive interval contains Conochitina minnesotensis, Desmochitina minor, Desmochitina cf. D. piriformis, Cyathochitina kuckersiana, C. calix, Belonechitina cactacea, B. robusta s.l., B. wesenbergensis brevis, Calpichitina lata, Spinachitina? n. sp. A, Clathrochitina? n. sp., Angochitina capillata, and Angochitina n. sp. A. These faunal assemblages suggest that the base of Diplacanthograptus caudatus correlates with the middle of the Keila Stage in the Baltoscandian succession (lower part of time slice 5c of Webby et al., 2004). Further work is still needed, however, to clarify the exact position of the FAD of D. caudatus with respect to the Baltoscandian chitinozoan zonation.

7.4.—Event and Chemostratigraphy of Section D. The GICE δ13C excursion has also been reported from Section D. Young et al. (2003) noted that the δ13C excursion occurs just above the base of the P. tenuis conodont zone. As noted above, samples for carbon isotope analysis have recently been analyzed from the BKR section and, pending
corroboration, seem to provide an independent confirmation on our graptolite and conodont correlations.

8. Global Correlation of the Base of the Middle Stage of the Upper Ordovician Series

An examination of other important Upper Ordovician graptolite localities reveals that the first appearance datum of *Diplacanthograptus caudatus* occurs in a highly consistent position relative to associated taxa (Figure 1), and hence, provides a suitable level for the base of the Middle Stage of the Upper Ordovician Series. As noted earlier, the FAD of *D. caudatus* occurs in rapid succession with all or a sub-set of the following other graptolite first occurrences - *D. lanceolatus*, *Corynoides americanus*, *Orthograptus pageanus*, *O. quadrimucronatus*, *Dicranograptus hians*, and *Neurograptus margaritatus*. A quick review of the post-*C. bicornis* graptolite successions at several key localities is provided below.

8.1. Scotland.—The classic graptolite sequence in the Southern Uplands of Scotland has been thoroughly revised by Williams (1982, 1994) and Zalasiewicz et al. (1995). *D. caudatus* appears in rapid succession with *D. spiniferus*, *Neurograptus margaritatus*, *Orthograptus quadrimucronatus*, *O. pageanus* and *Dicranograptus clingani*. Zalasiewicz et al. (1995) placed the base of their *clingani* biozone at the FAD of *D. caudatus* and subdivided the zone into a *caudatus* subzone and a *morrisi* subzone for correlation purposes. They also noted that the overlying *Pleurograptus linearis* Zone is best recognized not by the nominal species, which is restricted to very few horizons and it is difficult to identify
in fragmentary material, but by the presence of *Climacograptus styloideus* and *Climacograptus tubuliferus*.

The section at Hartfell Score (Zalasiewicz et al., 1995) is the only one we know in which *D. spiniferus* appears coincident with *D. caudatus* as opposed to occurring later (as at Dobb’s Linn, see Williams, 1994). It is also worth noting that 1.5 to 2.0 meters of barren gray shale separate the underlying *wilsoni* biozone from the *clingani* zone at Hartfell (Zalasiewicz et al., 1995, fig. 2). Although the FAD of *D. spiniferus* at Hartfell Score is anomalously low, the FAD of *D. caudatus* is consistent in its position relative to other key index taxa (see Figure 1).

**8.2. Australasia.**—In Australia, *D. caudatus* appears with *N. margaritatus* just below the base of Eastonian 1 (Ea1), the *Diplacanthograptus lanceolatus* Zone. Thus, the base of the Middle stage of the Upper Ordovician correlates with a level near the top of Gisbornian 2 in the Australasian sequence. Ea1 is characterized by the appearance of *D. lanceolatus*, *Corynoides americanus*, *Orthograptus pageanus*, *Dicranograptus hians*, and *O. quadrimucronatus* (VandenBerg and Cooper, 1992). The *D. lanceolatus* Zone is succeeded by the *Diplacanthograptus spiniferus* Zone (Ea2), and the *Dicranograptus kirki* Zone (Ea3).

**8.3. Newfounland.**—Ordovician graptolites from the Lawrence Harbour Formation in north-central Newfoundland have been described by Erdtmann (1976) and Williams (1995). The graptolite succession is most similar to that of Australia, although Williams (1995) adopted the British zonal scheme (see Figures 1 and 2). It is important to note that while Williams uses the Scottish zonation, he recognizes the *D. clingani* Zone based
primarily on the presence of D. caudatus, D. lanceolatus, D. spiniferus; and the P. linearis Zone based on the occurrence of Climacograptus tubuliferus.

8.4. Kalpin, Xinjiang, China.—Chen et al. (2000) provided a detailed graptolite range chart from the Qilang and Yingan formations in the Dawangou section, Kalpin, western Xinjiang. D. caudatus appears with D. lanceolatus, and O. quadrimucronatus in the lowermost Yingan Formation (Chen et al., 2000, fig. 3) suggesting a precise correlation with the base of the Middle Stage at Black Knob Ridge.

8.5. Eastern North America.—The classical New York State-Quebec graptolite sequence described by Ruedemann (1908, 1912, 1925) and Riva (1969, 1974) contains one of the best known and most provincial faunas in post-C. bicorns Zone rocks. Riva’s (1969, 1974) C. americanus Zone can be correlated with Black Knob Ridge and other regions by the presence of D. caudatus, C. americanus, O. pageanus, and O. quadrimucronatus. Above the C. americanus Zone, faunas in eastern North America become increasingly endemic and difficult to correlate (Riva, 1974; Goldman et al., 1995).

8.6. Scandinavia.—Diplacanthograptus caudatus is rare in the Upper Ordovician rocks of Scandinavia. Graptolite faunas in post – C. bicorns age rocks are generally of low diversity and contain numerous endemic species (Hadding, 1915; Nilsson, 1977; Williams and Bruton, 1993; Pålsson, 2001). However, Thorslund (1940) reported D. caudatus in association with Dicranograptus clingani, Dicellograptus pumilus, Corynoides sp., Archiclimacograptus compactus, Amplexograptus vasae, Normalograptus brevis, N. pulchellus, C. rugosus, Orthograptus calcaratus vulgatus, Rectograptus pauperatus, and Neurograptus margaritatus from the Örâ Shale in
Jämtland. This fauna indicates a *D. clingani* Zone age and suggests a correlation with the *D. caudatus* Zone.

Hadding (1913) and Nilsson (1977) identified specimens of “*C. caudatus*” in much older strata (*H. teretiusculus* Zone) in the Koängen Core from Scania, southern Sweden. Those specimens belong to an undescribed species of *Proclimacograptus* Maletz.

**8.7. Correlation into Platform Successions.**—As previously noted, the black shale horizons at Black Knob Ridge commonly contain conodonts and chitinozoans in addition to graptolites. These conodont and chitinozoan faunas make it possible to correlate the boundary level into predominantly calcareous shallow water strata with considerable precision. Indeed, the BKR section contains both North Atlantic and Midcontinent province conodonts and, thus, both sets of conodont zones can be correlated with the boundary level. The base of the second stage of the Upper Ordovician falls in the *B. alobatus* subzone of the *Amorphognathus tvaerensis* Zone (North Atlantic zonation) and in the uppermost *Phragmodus undatus* Zone (Midcontinent Zonation). The $\delta^{13}$C excursion and the presence of K-bentonites also offer the potential for high-resolution correlations into graptolite-poor facies.

**9. Conclusions**

The Black Knob Ridge Section contains an excellent record of the *Climacograptus bicornis* - *Diplacanthograptus caudatus* zonal boundary, the level that was chosen by the Ordovician Subcommission as the base of the Middle Stage of the Upper Ordovician Series. The boundary interval is abundantly fossiliferous, and the FAD of *D. caudatus* is precisely located at four meters above the base of the Bigfork Chert.
The first appearance of *D. caudatus* occurs within a succession of other graptolite first occurrences, including *Corynoides americanus*, *Dicranograptus hians*, *Orthograptus quadrimucronatus*, *O. pageanus*, and *Neurograptus margaritatus*, which are remarkably consistent worldwide. Additionally, the shales above and below the graptolite zonal boundary contain biostratigraphically important conodonts and chitinozoans. The conodonts and chitinozoans can be correlated with nearby sections of the Viola Springs Formation that contain a more complete conodont zonation and are part of Sweet’s (1979, 1984, 1995) graphic correlation framework. Thus, the biostratigraphic level of the base of the *D. caudatus* Zone (and hence the base of the middle Upper Ordovician Stage) can be precisely correlated into both graptolitic shale and shallower platform sections. Finally, the proposed stratotype section is well exposed, easily accessible, and the biostratigraphy can be independently tested with carbon isotope chemostratigraphy.

**Acknowledgements**

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PLATE 1.—Graptolites from Black Knob Ridge. 1-8, graptolites from the *Climacograptus bicornis* Zone, 1, 6) *Archiclimacograptus modestus*, 2,3,7) *Climacograptus bicornis*, 4,5) *Dicranograptus spinifer* (= *D. nicholsoni longibasalis*), 8) *Corynoides calicularis*; 9-15, graptolites from the *Diplacanthograptus caudatus* Zone, 9) *Dicranograptus hians* and *Cryptograptus insectiformis*, 10, 11) *Neurograptus margaritatus*, 12, 13) *Diplacanthograptus caudatus*, 14, 15) *Orthograptus pageanus*. Scale bar on each photograph is 1 mm.
PLATE 2.—Conodonts from Black Knob Ridge. Scale bar in all images is 0.5 mm. 1-2 part and counterpart of a *Periodon grandis* bedding plane association 0.3 meters below the top of the Womble Shale. 3-8 *Periodon grandis* 0.3 meters below the top of the Womble Shale. 9-10 *Icriodella cf. I. superba* 0.3 meters below the top of the Womble Shale. 11 *Phragmodus* sp. from base of Bigfork Chert, 12 *Dapsilodus* sp. 0.3 meters below the top of the Womble Shale, 13-14, *Drepanoistodus suberectus* 0.3 meters below the top of the Womble Shale. 15-16 *Amorphognathus* sp. 5.7 m above the base of the Bigfork Chert. Note the absence of the accessory posterior lobe. This suggests that 15 and 16 may be *A. superbus*. Additional collecting is needed to verify this interpretation. 17-22 *Amorphognathus tvaerensis* from 0.3 meters below the top of the Womble Shale.
PLATE 4.--Chitinozoans from the lowermost Viola Springs Formation at Section D. The scale bar is 0.1mm, except figs 18, 19, 20, 21, where the bar is 0.05 mm. The distribution of specimens is shown in Figure 7. 1, Cyathochitina kuckersiana (Eisenack), 2-4, Belonechitina micracantha (Eisenack), 5-6, ?Belonechitina sp., 7, Cyathochitina calix (Eisenack), 8, Conochitina tigrina Laufeld, 9, Belonechitina sp. n. A, 10, Conochitina dolosia Laufeld, 11, Conochitina minnesotensis (Stauffer), 12, Belonechitina sp. n. B, 13, Pistillachitina sp., 14, Spinachitina cf. S. cervicornis (Eisenack), 15, Belonechitina sp. n. C, 16, Belonechitina wesenbergensis brevis (Eisenack), 17, Belonechitina wesenbergensis elongata (Eisenack), 18-19. Eisenackitina aff. E. rhenana (Eisenack), 20, Belonechitina cactacea (Eisenack), 21, Belonechitina cf. cactacea (Eisenack).
PLATE 5.-- Chitinozoans from the lowermost Viola Springs Formation at Section D. The length of the bar is 0.1 mm, except figs 1a, 3a, 10a, 11a, 13, 14, 15, 17, 18, 19, where the bar is 0.05 mm. The distribution of species is shown in Figure 7. 1, 4, Gen. et sp. n. 1 (Clathrochitina ?), 2-3, Belonechitina robusta (Eisenack) s.l., 5-6, Spinachitina alaticornis (Jenkins), 7, Desmochitina minor Eisenack, 8-9, Angochitina sp. n. A, 10-11, Gen. et sp. n. 2 (Spinachitina ?), 12, Angochitina capillata Eisenack, 13, 16, Calpichitina lata (Shallreuter), 14, Desmochitina cf. ovulum Eisenack, 15, Desmochitina amphorea Eisenack, 17, 18, Desmochitina minor Eisenack, 19, Desmochitina cf. piriformis Laufeld.
December 14, 2004

Doug Howard
RT 3 Box 3190
Atoka, Oklahoma 74525

Stanley C. Finney, Professor
Department of Geological Sciences
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Dear Dr. Finney:

As you know, I have always granted access to geologists wishing to study the rocks exposed on that part of Black Knob Ridge that is on my property. Thus, I have no objection to these rock exposures, known as the Black Knob Ridge section, being considered as a Global Stratotype Section and Point (GSSP). I understand that in order for this section to be considered and to be approved as a GSSP certain requirements must be met. These requirements are that 1) a marker (or plaque) will be permanently fixed to the rock exposure, 2) that the section will be preserved, and 3) that there will be free access to the section for research by geologists of all nationalities. With this letter, I agree that a marker can be permanently fixed to the rocks and I will allow access to this section to geologists of all nationalities. Given the nature of the hillside exposure, I doubt that vegetation will grow over it; thus, it will be preserved.

Sincerely,

Doug Howard

Appendix 1.—Letter of permanent access to the Black Knob Ridge section.