See section 4.2 on p. 143 for methodology for recognition of MS trends, as well as Figures 3 and 4.

Palaeogeography, Palaeoclimatology, Palaeoecology 524 (2019) 137–149

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Conodont biostratigraphy and magnetic susceptibility of Upper Devonian Chattanooga Shale, eastern United States: Evidence for episodic deposition and disconformities

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A R T I C L E I N F O

Keywords:
Nashville Dome
Frasnian
Famennian
Ohio Shale
New Albany Shale
Kellwasser

A B S T R A C T

Recognition of stratigraphic hiatuses in fine-grained siliciclastic sedimentary rocks can be challenging but is feasible using high-resolution biostratigraphic and chemostratigraphic data within a regional correlation framework. In this case study of the Upper Devonian Chattanooga Shale in the Dupont GHS drillcore from the western margin of the Nashville Dome, the Upper Devonian Chattanooga Shale comprises several depositional units separated by intraformational hiatuses. These features are developed within a 13.3 m interval consisting of 4.2 m of Frasnian strata and 9.1 m of Famennian strata that unconformably overlie the Sellersburg Formation. Three Frasnian, seven Famennian, and one Tournaisian conodont biozones are recognized. The Frasnian-Famennian boundary is on a disconformity. To the northeast in the southern Illinois Basin, the New Albany Shale in the BCC drillcore consists of 35 m of Givetian and Frasnian strata and 30 m of Famennian strata that conformably overlie the Sellersburg Formation. One Givetian, four Frasnian, and three of the four lowest Famennian conodont zones are recognized. The Frasnian-Famennian boundary is conformable and constrained to within a 5 cm interval. Bulk magnetic susceptibility (MS) shows a long-term increase through most of the Frasnian. Shorter-term MS trends were observed in association with depositional pulses linked to global sea-level rises and highstand system tracts, characterized by total organic carbon (TOC) maxima — eight trends were resolved in the DGHS core, and six in the BCC. The high-frequency shifts in δMS likely represent Milankovitch-band sea-level and depositional cycles at a scale that cannot be resolved based on the condensed and irregular nature of the depositional packages. Gamma ray counts in the DGHS peak in association with the eight depositional cycles, with a TOC peak at the base of each cycle.

See section 4.2 on p. 143 for methodology for recognition of MS trends, as well as Figures 3 and 4.

1. Introduction

Identification of stratigraphic hiatuses in fine-grained siliciclastics can be challenging owing to the low amplitude of erosion surfaces and subtlety of expression in outcrop (Trabucho-Alexandre, 2015). Shale and mudstone successions that accumulate continuously without hiatuses generally exhibit regular, unbroken horizontal laminations, but various petrographic features can facilitate recognition of intraformational surfaces of erosion or non-deposition, including micro-cross bedding, micro-truncation surfaces, and lags of pyrite or other grain types (Schieber, 1998b, c). Recognition of small-scale gaps based on biostratigraphic data requires high-resolution fossil analysis in stratigraphic intervals that are sufficiently densely zoned, which applies mainly to limited portions of the geologic record such as the Late Devonian (Spalletta et al., 2017) and Early Jurassic (Howarth, 1962). Well-documented case studies of intraformational hiatuses in shale successions are few in number. Here, we undertake an analysis of depositional packages separated by intraformational hiatuses in the Upper Devonian Chattanooga Shale and New Albany Shale of the Illinois Basin on the western margin of the Nashville Dome.

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https://doi.org/10.1016/j.palaeo.2019.03.017
Received 31 July 2018; Received in revised form 18 February 2019; Accepted 10 March 2019
Available online 13 March 2019

The Chattanooga, New Albany, and Ohio shales were deposited within parts of the Appalachian Basin, Illinois Basin, and contiguous regions representing primarily quiet-water deposition of organic-rich fine-grained siliciclastic strata in tropical and epicontinental seas of southern North America during the Late Devonian (Cluff, 1980; Jaminski et al., 1998; Schieber, 1998a). These strata are important as hydrocarbon source and reservoir rocks, as well as confining strata (Broadhead et al., 1982; Strapoc et al., 2010). Several major extinction events are also present in these strata: the end-Givetian, the uppermost Frasnian Kellwasser events, and the end-Devonian. In addition, there are numerous globally recognized events marked by significant changes in sea level and development of organic-rich carbonates and black shales in this time interval, including the Taghanic and Geneseo in the Givetian Stage, and the Middlesex, Rhinestreet, and Kellwasser in the Frasnian Stage (Johnson et al., 1985; Algeo et al., 1995; Hallam and Wignall, 1999; House, 2002; Over, 2002; Becker et al., 2016).

Black shale and related gray shale and sandstones in Oklahoma, the Illinois Basin of Kentucky and Tennessee, and the Appalachian Basin of Alabama, Kentucky, Mississippi, and Tennessee are assigned to the Chattanooga Formation, named for strata initially described by Hayes (1891) near Chattanooga, Tennessee. While all Upper Devonian black shales in Tennessee are placed in the Chattanooga, the geographic discrimination of the Chattanooga, New Albany, and Ohio shales around the Nashville Dome and Cincinnati Arch in Kentucky was by necessity arbitrary, as designated by de Witt (1981; Fig. 1). Across Tennessee, the Chattanooga Shale consists of the Blocher, Flynn Creek, Dowelltown, and Gassaway members (Schieber and Over, 2005) and at least fourteen depositional sequences that have local to regional development (Schieber, 1998a; Fig. 2) and possible global expression as indicated by correlation to global black shale and extinction events (House, 2002). On the margin of the Nashville Dome, the Chattanooga Formation is typically 6 to 15 m thick (Hass, 1956; Conant and Swanson, 1961; Over, 1997) and contains numerous disconformities (Schieber, 1998a). In contrast, equivalent strata in the Appalachian and Illinois basins thicken, exceeding 650 m in eastern Tennessee (Dennison and Boucot, 1974), and disconformities become less prevalent.

Conodonts finely subdivide Upper Devonian strata, with 13 zones being recognized in the Frasnian (Klapper, 1989, 1997) and 21 zones in the Famennian (Ziegler, 1962; Spalletta et al., 2017; Fig. 2). Due to the low abundance of zone-defining conodonts in the studied cores, bulk magnetic susceptibility (MS) was also measured. Bulk magnetic susceptibility is a measurement of the concentration of ferromagnetic, diamagnetic, and paramagnetic minerals in a sample (Kodama et al., 2010) which in these marine strata is primarily due to detrital minerals that were contributed from the weathering of continental materials (Da Silva and Boulvain, 2006). MS shifts in response to detrital input linked to sea-level changes, with MS cycles present at a considerably higher frequency than conodont biozones. Positive or negative trends in MS reflect depositional or climatic variation where higher MS levels are associated with increased rates of weathering as well as increased influx of sediment into offshore areas during sea-level fall; lower MS levels are associated with sea-level rise (Crick et al., 2002). In conditions of relatively continuous and adequate sediment accumulation, Milankovitch-band changes in MS can be detected where eccentricity, obliquity, and precession cycles have been recognized, e.g., in Upper Devonian strata in New York (Tuskes et al., 2014). Abrupt shifts in MS values suggest breaks in sedimentation and unconformities (Robinson, 1993). Bulk MS stratigraphy can help to refine biostratigraphic zonations and enable more precise recognition of depositional sequences and regional correlation.

The purpose of this study is the documentation of depositional cycles and depositional packages of related strata in a 13.3-m-thick drillcore of the Upper Devonian Chattanooga Shale on the western flank of the Nashville Dome and comparison with a drillcore of the correlative portion of the New Albany Shale 200 km to the northeast, also on the western flank of the Nashville Dome, but notably thicker through the same stratigraphic interval. This will test the correlation potential of conodonts and MS as a framework in these organic-rich fine-grained strata, which have been shown to be irregularly distributed across the region (Schieber, 1998a), test global correlations based on a combination of biostratigraphic events and magnetic susceptibility trends tied to eustatic and global climate fluctuations, as well as demonstrate that correlation of strata is possible at a higher resolution than through the use of biostratigraphic zones alone.

2. Study cores

The DuPont GHS (DGHS) drillcore in Humphreys County, Tennessee, contains 13.3 m of Chattanooga strata in the 263.5′ to 306.8′ interval recovered. The contacts are abrupt, where black shale of the Chattanooga is draped over chert and limestone pebble conglomerate developed on top of the cherty biofloatstone and wackestone-mudstone of the Givetian Sellersburg Formation, which is the North Vernon Formation in Indiana (Droste and Shaver, 1986). Light gray mottled muddy wackestones and gray shales of the Maury Formation(?) lie on top of the uppermost black shale beds of the Chattanooga shale (Conant and Swanson, 1961). The Bullitt County, Kentucky, drillcore (BCC) consists of 40 m of Frasnian and lower Famennian strata assigned to the

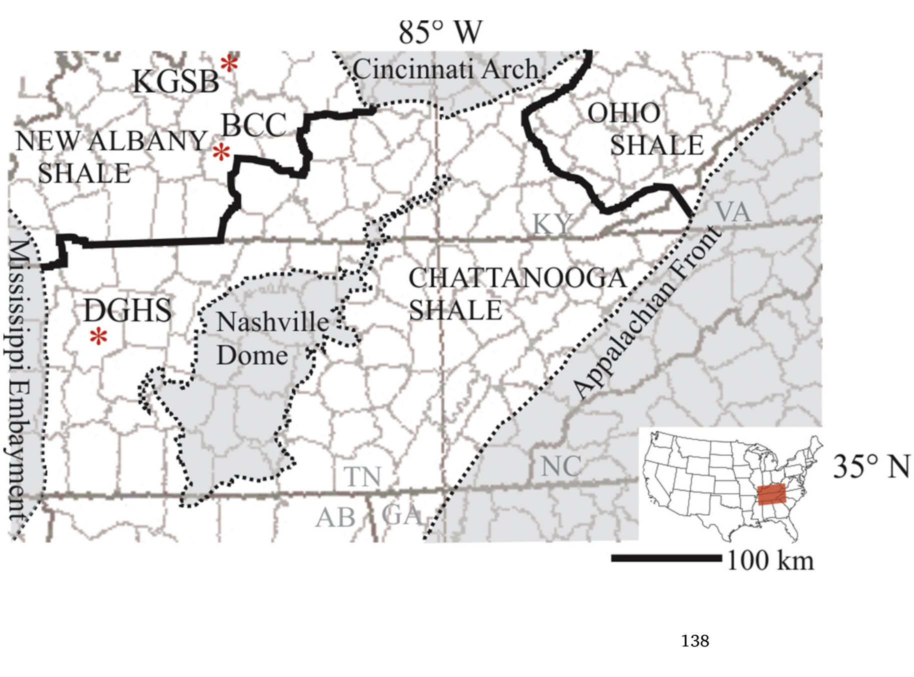

Fig. 1. Location of drillcores in relation to Nashville Dome and nomenclature distribution of Upper Devonian black shales in the eastern United States. County and state boundary map of Kentucky and Tennessee showing physiogeography - highs are gray, location of drillcore well sites, and distribution of Upper Devonian black shales. BCC = Bullitt County Core; DGHS = DuPont GHS well; KGSB = Kentucky Geological Survey Blan well (see Nuttall, 2013). Dotted line indicates outcrop edge, bold line is the demarcation between the Chattanooga, New Albany, and Ohio shales in the Appalachian and Illinois basins.

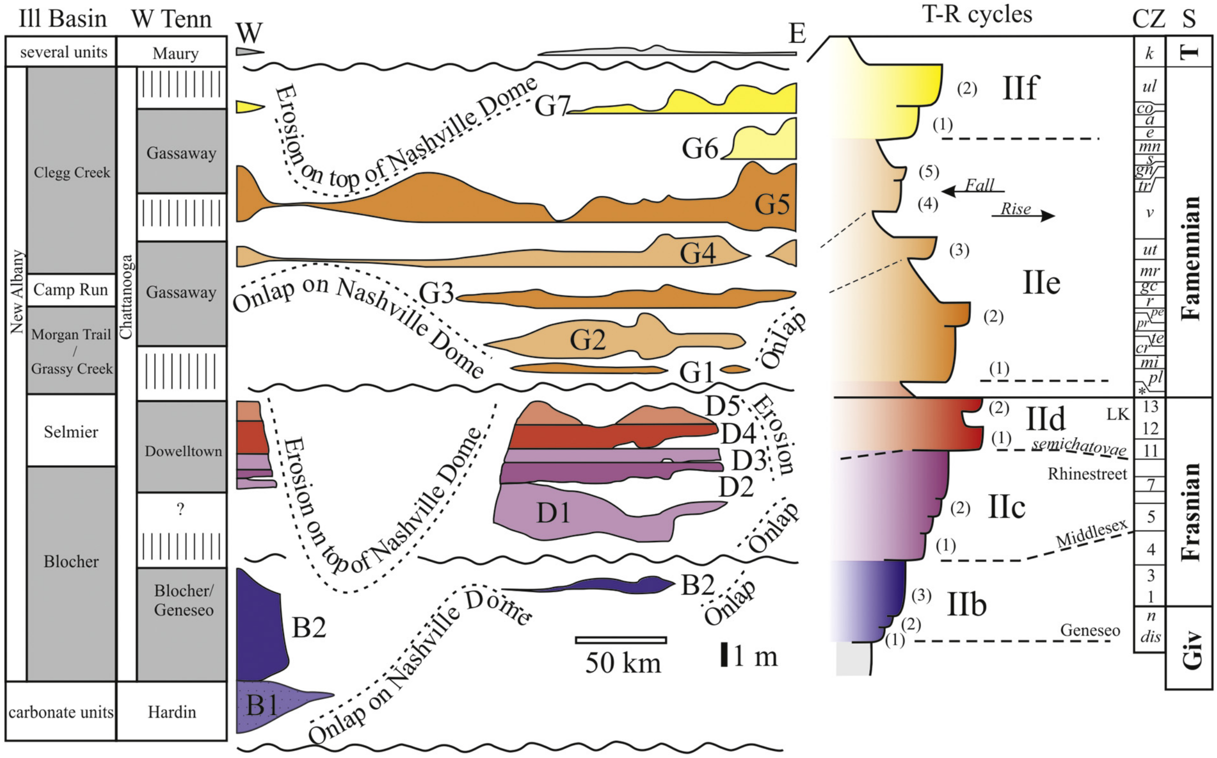

Fig. 2. General lithostratigraphy of Upper Devonian strata in the Illinois Basin and western Tennessee. Thickness, distribution, and stacking of Chattanooga strata across Tennessee from west to east showing onlap and erosion on Nashville Dome and eastern margin of the Appalachian Basin (modified from Schieber, 1998a) where B = Blocher; D = Dowelltown; G = Gassaway; and transgressive-regressive cycles of Johnson et al. (1985, 1996) and Whalen and Day (2010) tied to Chattanooga deposition and conodont zones of Becker et al. (2012) for the Givetian and Frasnian; Spalletta et al. (2017) for the Famennian and Tournaisian. CZ = conodont zones; S = stage; Giv = Givetian; T = Tournaisian; *dis* = *disparalis*; *n* = *norrisi*; * = *subperlobata* and *triangularis*; *pl* = *platys*; *mi* = *minuta*; *cr* = *crepida*; *te* = *termini*; *pr* = *prima*; *pe* = *pectinata*; *r* = *rhomboidea*; *mr* = *marginifera*; *ut* = *utahensis*; *v* = *velifer*; *gn* = *granulosis*; *s* = *styriacus*; *mn* = *manca*; *e* = *expansa*; *a* = *aculeatus*; *co* = *costatus*; *ul* = *ultimus*; *k* = *kockeli*.

New Albany Formation. Black shales of the Givetian Blocher Member are relatively conformable with the overlying shales of the Frasnian Selmier Member. Only the lower 5 m of the Grassy Creek Member were sampled of the 30-m-thick interval in this core. In nearby wells, including the Kentucky Geological Survey Marvin Blan 1 (KGSB) well, the entire New Albany ranges between 38 and 52 m thick (Nuttall, 2013).

3. Materials and methods

Samples from the 13.3-m-thick Chattanooga shale portion of the DGHS drillcore, as well as contiguous strata, and 40 m of New Albany shale from the BCC, were collected every 5 cm, and every 1 cm through the Frasnian-Famennian boundary interval in the BCC. Samples averaged 21.8 g from DGHS and 7.2 g from BCC, which were placed in small plastic bags, dried in a 50 °C oven overnight, massed to the nearest 0.1 mg, and analyzed for bulk-mass magnetic susceptibility using an AGICO MFK 1-A Multi-Function Kappa bridge calibrated to in-house standards. Each sample was measured three times, mass-normalized, the results in m^3/kg were averaged and converted to δMS based on the marine standard of Ellwood et al. (2011). Plotted data show original δMS data and splined-smoothed data using a three-value running average.

Conodonts were recovered by visual scanning of shale bedding surfaces, which were removed in small chips, cleaned with a needle or dissolved using weak HCl, and original material or resultant molds imaged on a scanning electron microscope (SEM) (Over et al., 1991). Carbonate strata from DGHS Box 72 0.73–0.87 m (300 g), Box 70 0.83–0.93 m (300 g), Box 68 0.32–0.38 m (350 g), and Box 55 260–261 ft (1700 g) were reduced to 1 cm long dimension chips and dissolved in buffered 10% formic acid for 24 h. The resultant residue was sieved and the 1.0 to 0.125 mm fraction was scanned for conodonts, which were removed and imaged.

A Core Labs spectral gamma core logger at the Department of Geology, University of Cincinnati, was used to generate total gamma and ^{40}K, ^{232}Th, and ^{238}U gamma profiles for the DGHS core. The instrument has a NaI detector and an automated data acquisition routine. The belt drive was reprogrammed to operate at an ultraslow speed (~6 h/m) in order to achieve the highest resolution and most stable integrated signal possible. The core was thus analyzed at a rate of 2–3 m/day. This configuration generated data series with a stratigraphic resolution of ~1 cm.

Carbon concentrations were measured using an Eltra 2000 C-S analyzer. Data quality was monitored via multiple analyses of several standards: USGS SDO-1 (TC = 9.68 wt%), in-house standard DBS-1 (TC = 3.50%), and a pure CaCO3 standard (TC = 12.00 wt%), yielding an analytical precision (2σ) of ± 2.5% of reported values for carbon. An aliquot of each sample was digested in 2 N HCl at 50 °C for > 6 h to dissolve carbonate minerals, and the residue was analyzed for total organic carbon (TOC) and total inorganic carbon (TIC) was obtained by difference.

4. Results

The DGHS core yielded 81 conodont and macrophyte samples, from which eleven biostratigraphic intervals were recognized, three in the 4.2-m-thick Frasnian interval, seven in the 9.1-m-thick Famennian interval, and one Tournaisian zone in the overlying Maury Formation. Bulk MS from 425 samples ranged from 4.91×10^{-9} to 4.47×10^{-8} m^3/kg. The BCC yielded 64 conodont samples, from which nine biostratigraphic intervals were recognized, two in the upper

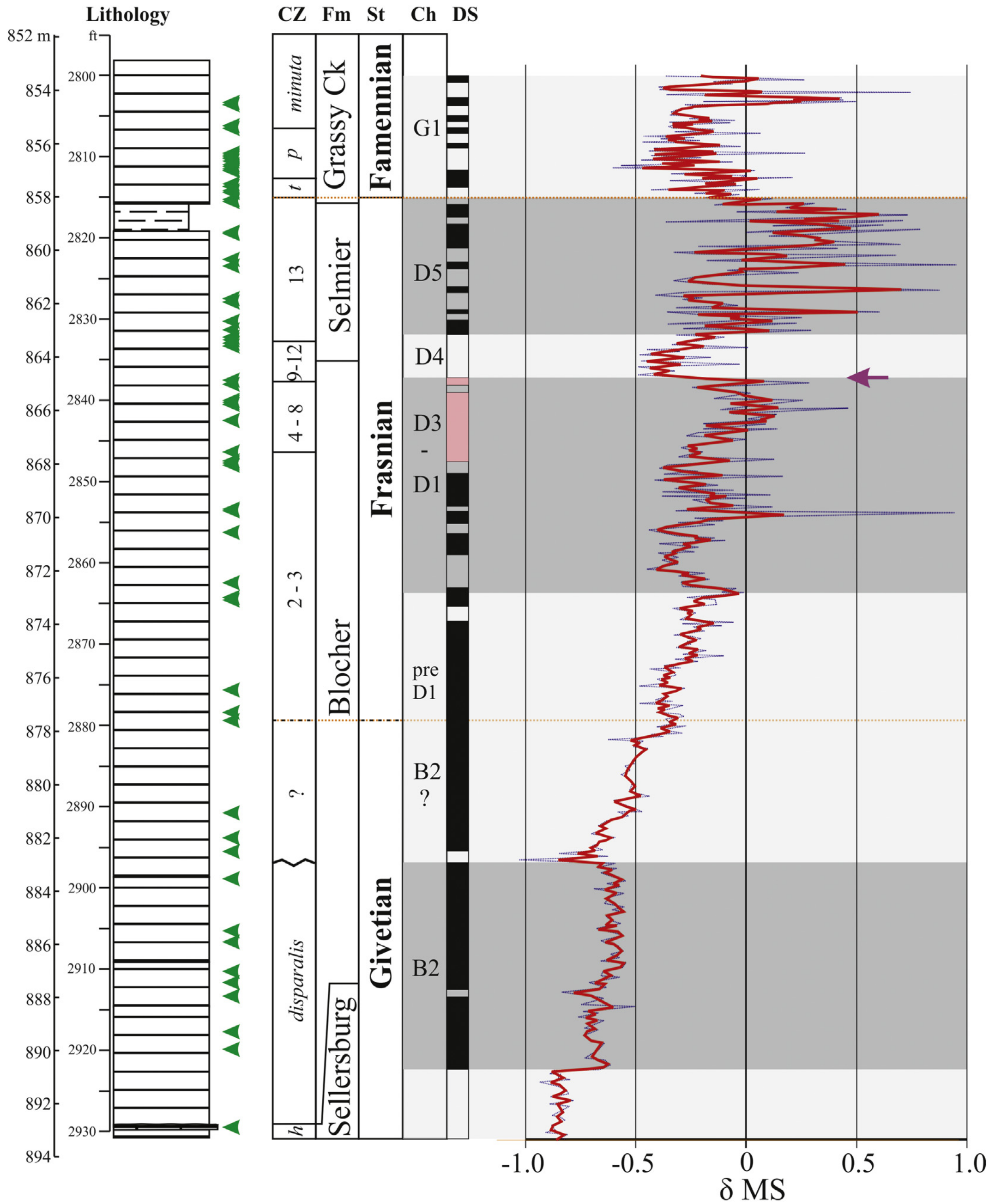

Fig. 3. General lithology, zonation, and magnetic susceptibility of BCC. Schematic diagram of the Bullitt County Core interval general lithology, conodont sample intervals, conodont zonation where *h* = *hemiansatus*, *t* = *triangularis*, *p* = *platys*; lithostratigraphy, stages where the dotted orange line marks the Givetian-Frasnian boundary and the Frasnian-Famennian boundary; Chattanooga Formation subdivisions in relation to bulk MS general trends in alternating light gray bands where B = Blocher, D = Dowelltown, and G = Gassaway; positive and negative δMS shifts where black are positive shifts and light gray are negative shifts, the pink highlighted interval correlates to same interval in the DGHS core (Fig. 4) — the purple arrow marks the FZ 11 shift; and bulk MS plot where the thin blue line is raw data, the thick red line is the spline curve. See Fig. 4 for lithological symbols. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Givetian, four in the 24-m-thick Frasnian interval, and three in the lower Famennian. Bulk MS from 1002 samples ranged from 3.66×10^{-9} to 5.09×10^{-7} m^3/kg. The average standard error for bulk MS analyses was 1.85×10^{-10}. The gamma profile produced eight distinct broad peaks, often with narrower and lower peaks superimposed on the broad peaks. The lowest values correspond to carbonate and sandy intervals. Total organic carbon (TOC) ranged from zero to a maximum of 16.1 wt%, with an average TOC = 8.3 wt%.

4.1. Biostratigraphy

Conodonts recovered from the bedding planes and carbonates allow recognition of several biozones, but due to the relative rarity of age-definitive taxa the zonal boundaries are imprecise or only suggest ranges for assignment of the strata (Figs. 3, 4). The Frasnian zonation of Klapper (1989) and Klapper and Kirchgasser (2016) was followed herein; the zonation scheme of Spalletta et al. (2017) was used for Famennian strata. The Givetian *disparalis* Zone was initially proposed by Ziegler and Klapper (1982) and the Tournaisian *sandbergi* Zone was erected by Sandberg et al. (1978). The Frasnian and Famennian

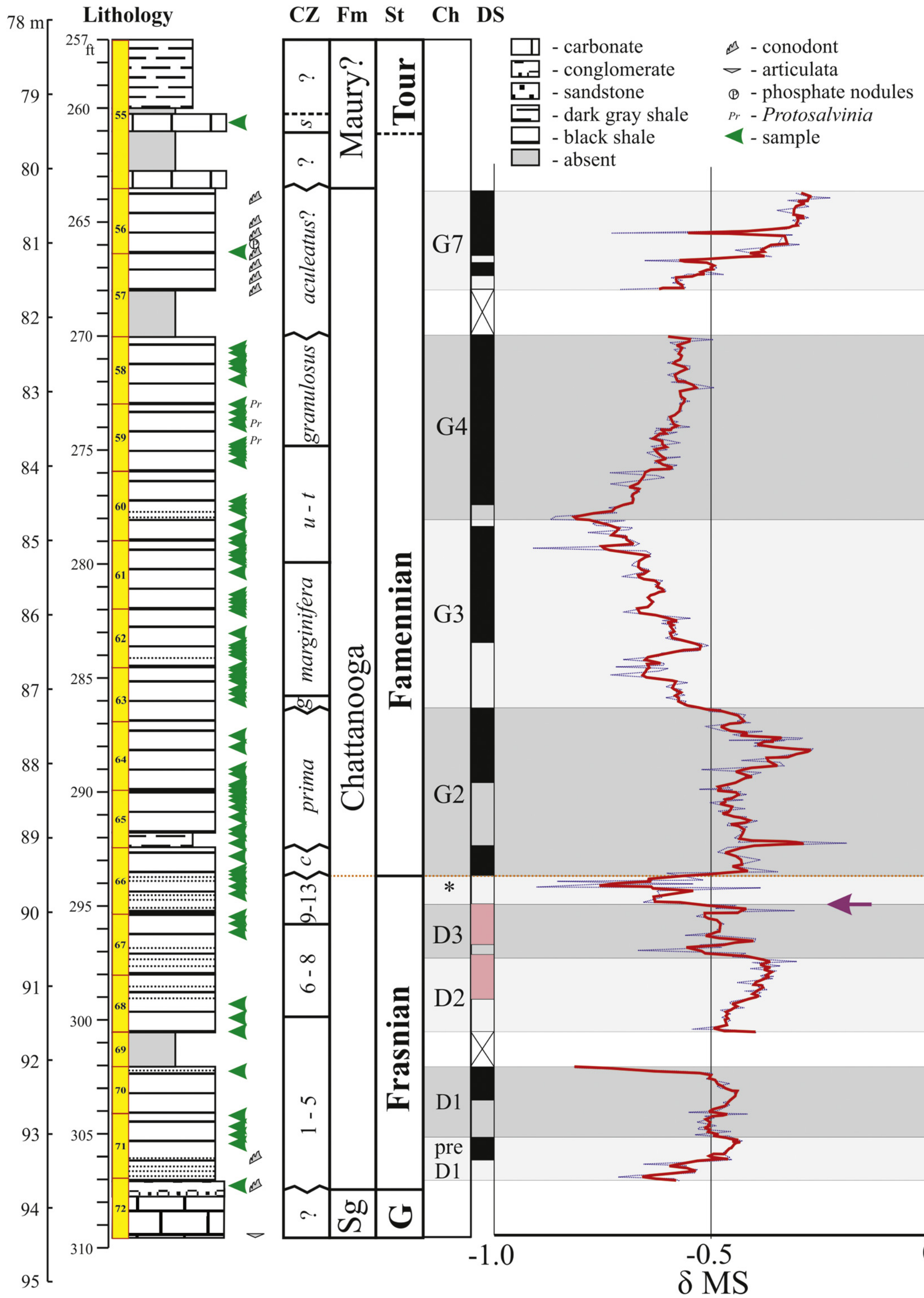

Fig. 4. General lithology, zonation, and magnetic susceptibility of DGHS. Schematic diagram of the Humphreys County DuPont GHS core interval general lithology, conodont sample intervals, conodont zonation (CZ) where *c* = *crepida*, *g* = *gracilis*, *u* = *utahensis*, *t* = *trachytera*, *s* = *sandbergi* and significant disconformities are shown by a jagged line between zones; lithostratigraphy where Sg = Sellersburg; stages where Tour = Tournaisian, G = Givetian, and the orange line marks the Frasnian-Famennian boundary; Chattanooga Formation subdivisions in relation to bulk MS trends in alternating light gray bands where D = Dowelltown, and G = Gassaway, * = condensed D4 and D5; positive and negative δMS shifts where black are positive shifts and light gray are negative shifts, the pink highlighted interval correlates to same interval in the BCC (Fig. 3) — the purple arrow marks the FZ 11 shift; and bulk MS plot where the thin blue line is raw data, the thick red line is the spline curve. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

conodont fauna is dominated by species of *Palmatolepis*, which are typical of offshore quiet-water conditions; *Bispathodus* and *Branmehla* in the upper Famennian are also associated with offshore settings (Sandberg, 1976; Girard et al., 2014, 2017).

In DGHS, the onset of Chattanooga black shale deposition consists of 2.3 m of strata that lies on a disconformity over the Sellersburg Formation at 93.64 m. The contact consists of black shale with a few sandy stringers draped over a lithic pebble conglomerate developed on

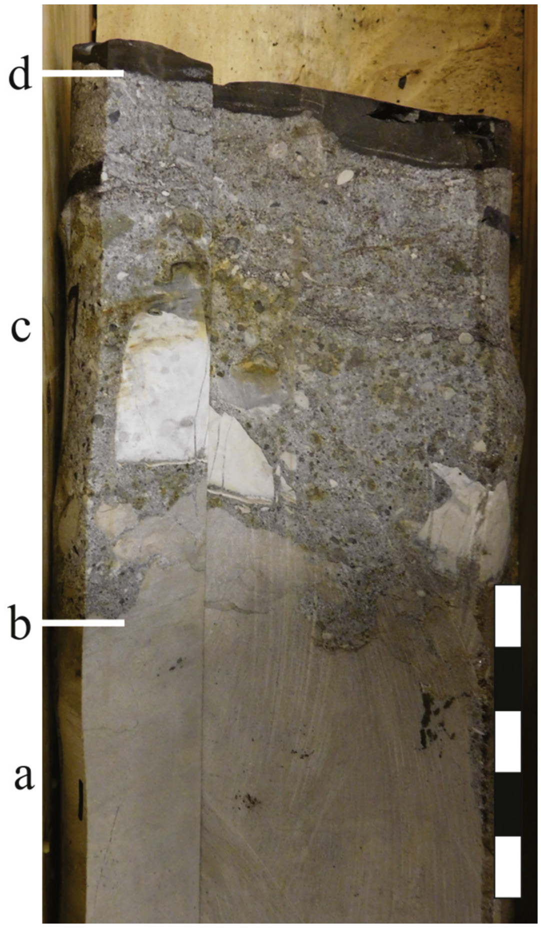

Fig. 5. Base of Chattanooga in DGHS core. A 15-cm interval of DGHS core that shows karst surface of the Givetian Sellersburg Limestone overlain by a chert and lithic pebble conglomerate draped by the Chattanooga Shale. a = Sellersburg, b = karst surface with several centimeters of relief; c = conglomerate; d = base of Chattanooga at 307.22 ft (93.64 m).

a karst surface of light gray cherty carbonate containing the brachiopod *Devonochonetes* (Fig. 5). The conglomerate contains the conodonts *Ancyrognathus rotundiloba*, *Polygnathus ordinatus*?, *Schmidtognathus wittekindti*, and *Zieglerina unilabius* (Fig. 6), which indicate the possible presence of the oldest Frasnian Zone, i.e., FZ 1. However, reworking of the fauna in the conglomerate, which is common at the base of black shale successions (Baird and Brett, 1986; Over, 2007), may mean that black shale deposition started as late as FZ 5. This would correspond to the eustatic rise associated with transgressive-regressive (TR) cycle IIc_1 of Johnson et al. (1985, 1996) and Whalen and Day (2008; Fig. 2), which correlates with the Middlesex Formation black shale in the Appalachian Basin, recognized as a global event (House, 2002).

The next age-determinate conodonts are *Palmatolepis bohemica* and *Pa. slavai*, indicative of FZ 6 through FZ 8. These occur within a 1.25-m-thick interval at 91.42 m that is characterized by several sandy laminae. These strata correspond to TR IIc_2 and the start of Rhinestreet Formation black shale deposition in the Appalachian Basin.

The strata between 90.15 and 89.50 m consist of sandy black shale yielding *Ancyrodella nodosa*, *Ad. curvata*, *Palmatolepis punctata*, *Pa. housei*, and *Pa. ljaschenkoae*. The fauna is upper Frasnian, where *Pa. ljaschenkoae* indicates deposition no earlier than FZ 9.

A lag bed at 89.50 m that contains Famennian conodonts, as well as *Pa. winchelli*, is indicative of FZ 12 to the end-Frasnian. This interval in the DGHS core corresponds to three TR cycles: (1) the upper IIc_2, which marks the middle Rhinestreet deepening — likely the D3 Dowelltown unit of Schieber (1998a), (2) IId_1, which corresponds to the global *Pa. semichatovae* transgression (Sandberg et al., 2002), and (3) IId_2, which is the Pipe Creek (=Lower Kellwasser) transgression of the upper Frasnian (Schindler, 1990; Over, 1997).

In the BCC drillcore, the Givetian-Frasnian interval of the New Albany Formation that is equivalent to the Chattanooga Shale is 35 m thick. New Albany deposition began with 12 m of strata containing *Klapperina disparalis*? and *Polygnathus varcus*-group species above strata that contain *Po. l. linguiformis* gamma 1a morphotype of Walliser and Bultynck (2011; see Hogancamp and Over, 2013). This is the Blocher Member, assigned to the *disparalis* Zone, which overlies the Sellersburg Formation, which is *hemiansatus-ansatus* Zone. The Blocher corresponds to the Geneseo transgression and TR cycle Ia, as well as higher strata. Frasnian strata are recognized by the first occurrence of *Ancyrodella soluta* at 877.63 m, which indicates FZ 2 (Fig. 7).

The first occurrence of *Palmatolepis transitans* 10 m higher at 867.53 m indicates strata no lower than FZ 4. This thick shale package corresponds to the TR cycle IIb_1, IIb_2, and possibly the start of IIc_1. The 2.5 m of strata starting with the horizon that contains *Pa. transitans* at 865.7 m also yielded *Pa. punctata*, *Pa. reimersi*, and *Pa. bohemica*. This portion of the Selmier Member corresponds to TR cycle IIc_2.

The next meter of strata is marked by the occurrence of *Pa. ljaschenkoae*, an indication of the start of FZ 9 at 864.88 m, associated with *Ancyrodella hamata* (=*Ad. buckeyensis*) and *Ancyrognathus triangularis*, that ranges from FZ 11 into lower FZ 13 and suggests a very condensed interval.

The uppermost 5 m of Frasnian strata are in FZ 13, recognized by *Pa. boogaardi*, *Pa. hassi* ss, *Pa. winchelli*, and *Pa. extensa*. The Frasnian-Famennian boundary at 857.84 m is not marked by a disconformity, and *Palmatolepis subperlobata* and *Pa. triangularis*, the first Famennian conodonts, occur 5 cm above the last Frasnian conodont (Fig. 8A).

Famennian strata in the DGHS core are 9.1 m thick. The lowermost Famennian conodonts occur in a lag bed within a sandy interval above a thin sandstone bed at 89.50 m (Figs. 8B, 9). *Ancyrognathus sinelamina*, *Palmatolepis lobicornis*, *Pa. perlobata*, *Pa. quadrantinodosalobata*, *Pa. regularis*, and the Frasnian conodont *Pa. winchelli* were recovered. Based on the occurrence of *Pa. quadrantinodosalobata*, this stratum can be no lower than the *crepida* Zone. *Palmatolepis prima* was found 46 cm higher at 89.04 m, indicating the *prima* Zone; also found in this interval was *Pa. parawolskae*, which does not range higher than the *prima* Zone. These strata correspond to the late first pulse of the TR IIe_1 deepening and the second IIe_2 pulse (Fig. 2).

The occurrence of *Pa. inflexa* ~1.8 m higher at 87.19 m is indicative of the *gracilis* Zone, which is closely followed by the first occurrence of *Pa. quadrantinodosa* at 87.13 m, indicating the *marginifera* Zone. These strata correspond to the IIe_3 deepening pulse.

The *utahensis* Zone is recognized ~2 m higher at 85.22 m by the occurrence of *Pa. grossi*, which is also associated with *Pa. distorta* and *Pa. lepta* that do not range higher than the *granulosus* Zone. The occurrence of the enigmatic plant *Protosalvinia* in this interval, starting at 83.66 m, ~1.5 m above the first occurrence of *Pa. grossi*, is characteristic of the *granulosus* Zone (Over et al., 2009) and corresponds to the IIe_4 deepening pulse.

The uppermost Famennian strata contain specimens of *Branmehla* sp., *Bispathodus* sp. and *Palmatolepis gracilis*. These taxa are long ranging, but typical of the *aculeatus* Zone, which corresponds to the IIf_1 cycle, commonly well developed in the black shales of the southern United States (Over, 2007; Over and Ruppel, 2012). The youngest conodonts are from a carbonate bed in the Maury Formation, ~90 cm above the last black shale beds of the Chattanooga Shale. *Polygnathus com. communis*, *Protognathodus kockelli*, *Siphonodella cooperi*, and *Si. quadruplicata* were recovered (Fig. 10), indicative of the Tournaisian *sandbergi* Zone.

Only the lower five meters of the 30-m-thick Famennian Grassy Creek Member strata in the BCC was sampled and collected. Numerous conodonts allowed clear recognition of three conodont zones, but not the lowest, and typically very narrow, *subperlobata* Zone, which marks

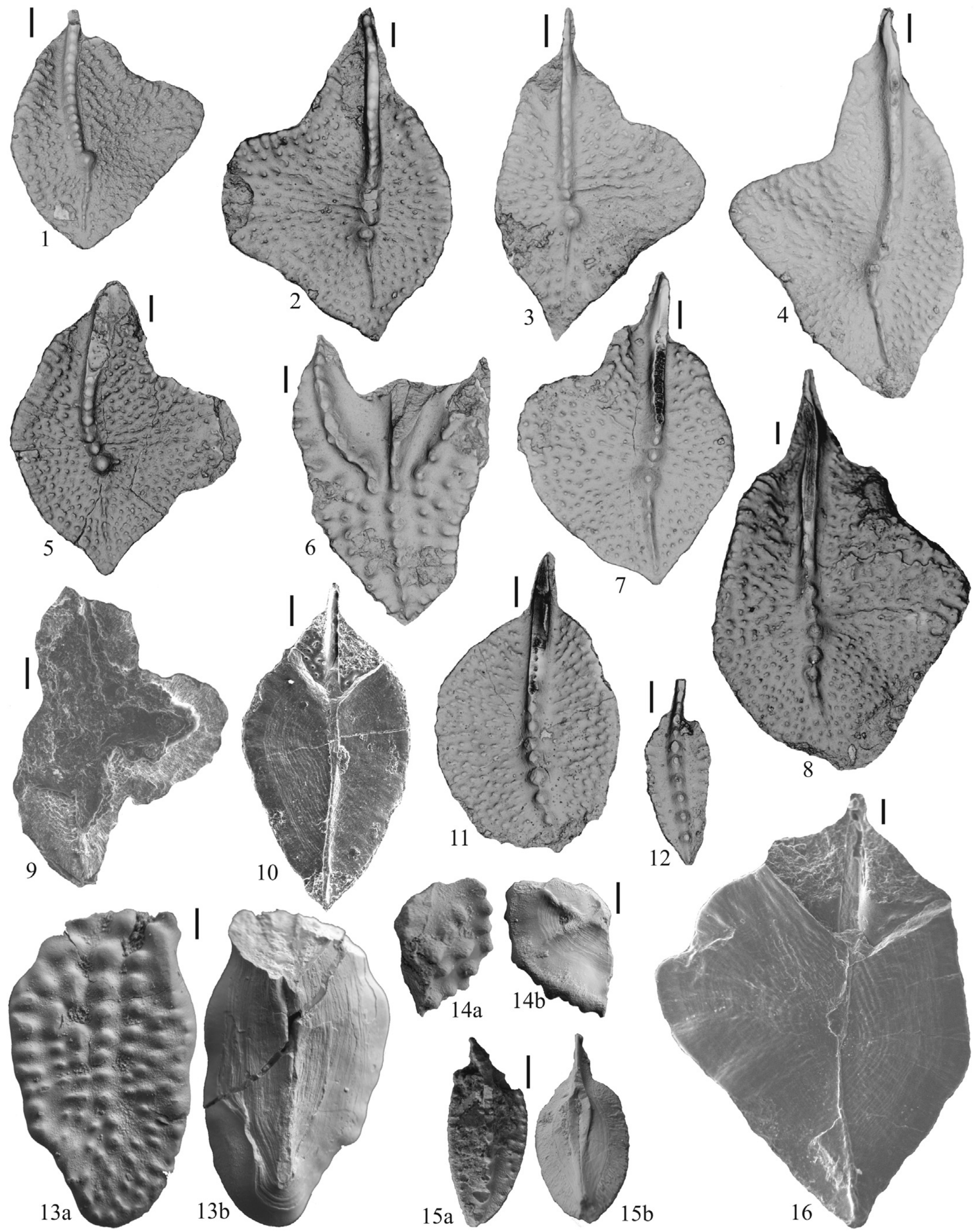

Fig. 6. Conodonts from the DGHS core. Scanning electron microscope digital images of Givetian and Frasnian conodont P_1 elements from the DGHS core. All specimens are inverse mirrored element molds in shale except 9, 10, 13–16; all are upper views with the exception of 9, 10, 13b, 14b, 15b and 16. Scale bar is 0.1 mm. (1) *Palmatolepis housei* Klapper, 2007; sample 67–0.85. (2, 5) *Palmatolepis punctata* (Hinde, 1879); (2) sample 67–0.65; (5) sample 67–0.85. (3) *Palmatolepis reimersi* Bardashev and Bardasheva, 2012; sample 67–0.75. (4) *Palmatolepis ljaschenkoae* Ovnatanova, 1976; sample 67–0.65. (6) *Ancyrodella nodosa* Ulrich and Bassler, 1926; sample 67–0.65. (7) *Palmatolepis bohemica* Klapper and Foster, 1993; sample 67–0.65. (8) Palmatolepis slavai Bardashev and Bardasheva, 2012; sample 68–0.21; (9) *Klapperina disparilis* (Ziegler and Klapper in Ziegler et al., 1976); sample 71–0.60. (10) *Mesotaxis falsiovalis* Sandberg et al., 1989; sample 71–0.89. (11) *Mesotaxis*? sp.; sample 68–0.23. (12) *Polygnathus dengleri* Bischoff and Ziegler, 1957; sample 71–0.79. (13) *Polygnathus ordinatus*? Bryant, 1921; upper and lower views; sample 72–0.73. (14) *Ancyrodella rotundiloba* (Bryant, 1921); fragment of inner anterior platform upper and lower views; sample 72–0.73. (15) *Schmidtognathus wittekindti* Ziegler, 1965; upper and lower views; sample 72–0.73. (16) *Klapperina ovalis* (Ziegler and Klapper in Ziegler et al., 1964); lower view; sample 68–0.01. Illustrated specimens are reposited in the paleontological collections in the Department of Geological Sciences at SUNY-Geneseo.

the base of the Famennian. It may be present, but sampling was not able to resolve the interval (Fig. 8A). The *triangularis* Zone was delineated by the first occurrence of *Pa. triangularis* which was found with *Pa. subperlobata*. This is overlain by the *platys* Zone, recognized by the occurrence of *Pa. del. delicatula*, as well as *Ancyrognathus sinelamnina* and *Pa. perlobata* - early morph. The uppermost zone recognized was the *minuta* Zone, indicated by *Pa. regularis* and *Pa. tenuipunctata*. These strata correspond to the initial Famennian IIe_1 deepening (Fig. 2).

4.2. Magnetic susceptibility stratigraphy

Variations in magnetic susceptibility (MS) profiles can be used to

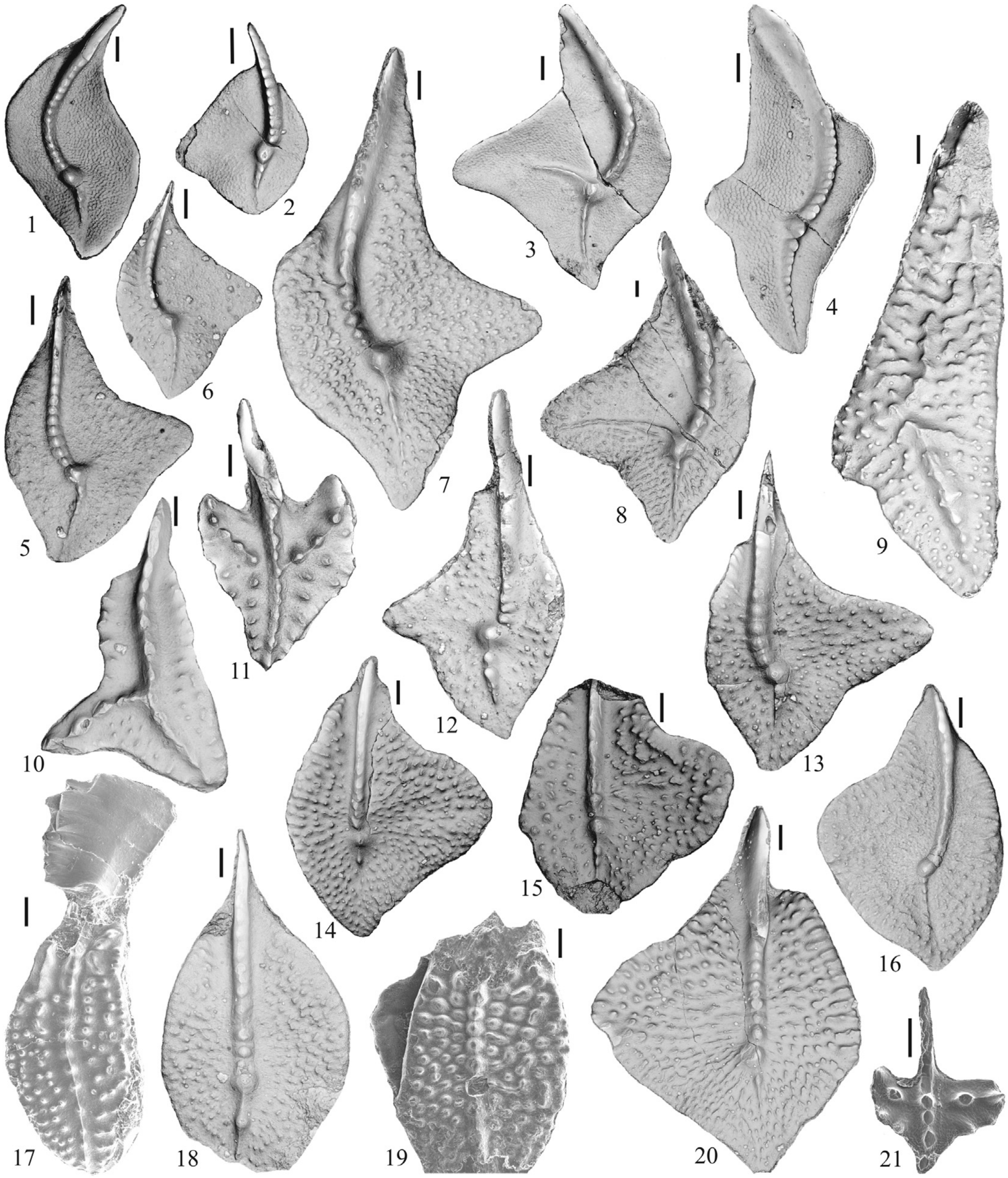

Fig. 7. Conodonts from the BC core. Scanning electron microscope digital images, upper views of conodont P_1 elements from the BCC. All specimens are inverse mirrored element molds in shale. Scale bar is 0.1 mm. (1) *Palmatolepis regularis* Cooper, 1931; sample 2806.5′. (2) *Palmatolepis delicatula delicatula* Branson and Mehl, 1934a; sample 2811.7′. (3) *Palmatolepis subperlobata* Branson and Mehl, 1934a; sample 2809.9′. (4) *Palmatolepis tenuipunctata* Sannemann, 1955; sample 2803.5′. (5) *Palmatolepis boogaardi* Klapper and Foster, 1993; sample 2832.8′. (6, 8) *Palmatolepis triangularis* Sannemann, 1955; (6) sample 2814.3′; (8) sample 2809.6′. (7) *Palmatolepis perlobata* Ulrich and Bassler, 1926; sample 2810′. (9) *Ancyrognathus sinelaminus* (Branson and Mehl, 1934a); sample 2810′. (10) *Ancyrognathus triangularis* Youngquist, 1945; sample 2833.2′. (11) *Ancyrodella hamata* Ulrich and Bassler, 1926; sample 2832.6′. (12) *Palmatolepis extensa* Ziegler and Sandberg, 1990; sample 2819.3′. (13) *Palmatolepis hassi* Müller and Müller, 1957; sample 2832.8′. (14) *Palmatolepis reimersi* Bardashev and Bardasheva, 2012; sample 2840.4′. (15) *Palmatolepis bohemica* Klapper and Foster, 1993; sample 2840.1′. (16) *Palmatolepis ljaschenkoae* Ovnatanova, 1976; sample 2837.5′. (17) *Polygnathus limitaris* Ziegler and Klapper in Ziegler et al., 1976; sample 2890.8′. (18) *Mesotaxis falsiovalis* Sandberg et al., 1989; sample 2853.6′. (19) *Klapperina disparilis*? (Ziegler and Klapper in Ziegler et al., 1976); sample 2919.8′. (20) *Palmatolepis transitans*, Müller, 1956; sample 2840.1′. (21) *Ancryodella soluta* Sandberg et al., 1989; sample 2862.4′. Illustrated specimens are reposited in the paleontological collections in the Department of Geological Sciences at SUNY-Geneseo.

analyze sedimentation patterns and recognize stratigraphic disconformities. Whalen and Day (2010) recognized four types of MS trends in their study of Frasnian strata on the Alberta Platform and adjacent platform margin and basin settings: lateral trends, variation between depositional setting, long-term stratigraphic increases and decreases, and variation due to sea-level change. Statistically significant shifts were recognized based on criteria outlined by Ellwood et al. (2007) where departures from background must contain at least two points and increase or decrease by a factor of at least 2% of the total range of variation in the data set. Whalen and Day (2010), due to a relatively narrow range of values, used 5% variation to delineate positive and negative δMS shifts. We recognize a fifth trend, where the abrupt displacement of the δMS curve signifies a possible disconformity where continuous trends are offset by missing strata.

The Frasnian δMS plot from BCC, based on the conodont data and numerous displacements, has several disconformities and the accumulation rate is clearly variable (Fig. 3); the DGHS δMS plot, significantly more so, where only 4.2 m of Frasnian strata are present (Fig. 4).

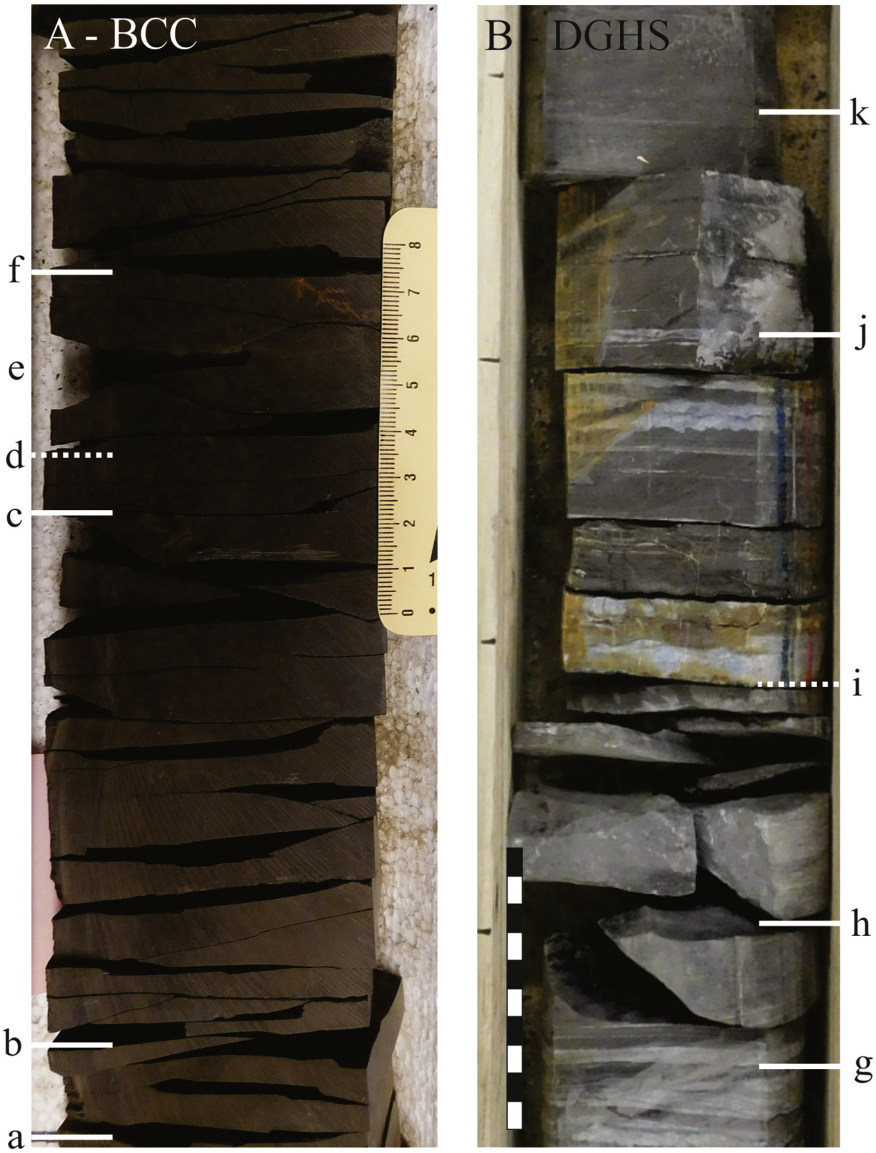

Fig. 8. Frasnian-Famennian boundary interval in the New Albany Shale from BCC and Chattanooga Shale from DGHS. A. 25 cm interval of BCC across the Frasnian-Famennian Boundary, scale in centimeters. a = 2815 ft (858 m) in drillcore; b = level of *Palmatolepis bogartensis*; c = level of youngest Frasnian conodont - *Pa. winchelli*; d = Frasnian-Famennian boundary horizon based on positive shift in δMS; e = interval of diminutive conodonts, possibly the recovery fauna of the *subperlobata* Zone; f = first occurrence of Famennian conodonts *Pa. subperlobata* and *Pa. triangularis* marking the base of the *triangularis* Zone. B. 30 cm interval of the DGHS core across the Frasnian-Famennian boundary, scale in centimeters. g = rippled sandy laminae in dark silty shales; h = horizon of Frasnian conodonts *Ancyrodella*, *Ancyrognathus*, and *Palmatolepis*; i = Frasnian-Famennian boundary horizon at base of 2 cm sandstone bed based on lithological change and negative shift in δMS; j = lag horizon containing Frasnian and Famennian conodonts, including *Ancyurognathus sinelamina*, *Pa. perlobata*, and *Pa. regularis*, no lower than the *minuta* Zone; k = horizon with *Pa. quadrantinodosalobata* and *Pa. tenuipunctata*, no lower than the *crepida* Zone.

This is in distinct contrast to the 300- to 500-m-thick Frasnian strata studied in western Alberta (Whalen and Day, 2010). Even with this distinct difference in thickness, the δMS long-term trend is similar in shape and change in magnitude, especially between FZ 1 and 11 where there is a long-term increase from δMS -0.5 to 0 in BCC, a similar but more subtle increase in DGHS, and similar to the trends in several Alberta sections, especially the basin settings at Marmot Crack and section AB off the Miette Platform (Whalen and Day, 2010; Fig. 11).

The lateral change between DGHS and BCC δMS is only comparable in a few intervals - the FZ 4–8 and 6–8 intervals, and the shift associated with the FZ 9–12 interval, where there is a general increase in δMS and then an essentially vertical trend with no significant change (pink highlighted interval in Figs. 3, 4). In the DGHS core the range of values go from −0.67 to −0.30 compared to −0.41 to +0.46 in the BCC, offset by ~0.2 to 0.5. The reasons for this lateral difference are unclear, but may be related to the sediment source, where the closer proximity to the Cincinnati Arch of the BCC may have led to higher δMS at certain times. The abrupt offset at the top of this trend (marked with a purple arrow on the δMS curve in Figs. 3, 4) may be equivalent to the F19 FZ 11 negative δMS shift recognized in Alberta (Whalen and Day, 2010).

Basic trends in δMS tend to be asymmetrical, where the bases are more negative and narrow whereas the upper portions are broader and more positive. This is interpreted as deposition of the black shale packages during the highstand systems tract where the initial deepening has relatively low clastic input and low accumulation rates followed by increased sediment under essentially progradational conditions and input of greater ferromagnetic materials. This is also demonstrated by the total organic carbon (TOC) values (Fig. 11) that are higher at the bases of the black shale pulses, such as at the bases of preD1, G2, and G3. All six large-scale trends in the BCC show this positive shift. In the DGHS core four Frasnian trends generally follow this pattern, the uppermost Frasnian is highly condensed and the δMS signal is irregular.

The Frasnian-Famennian boundary in BCC was resolved by conodonts within 5 cm where there are no evident depositional breaks. Magnetic susceptibility data, collected at 1 cm intervals, shows a negative shift of δ0.2 in the lower part of the 5 cm boundary interval where we tentatively place the boundary horizon. This is consistent with a negative MS shift at the Frasnian-Famennian boundary at LaSerre and in Oklahoma (Crick et al., 2002). In DGHS, the boundary is at a disconformity, indicated by a significant offset in the δMS.

In the Famennian, the lowermost transgressive event is missing, and the lower two trends (G2 and G3 in Fig. 4) are essentially static with some variation within δ0.3 for G2 and negative shift from δ-0.5 to -0.8

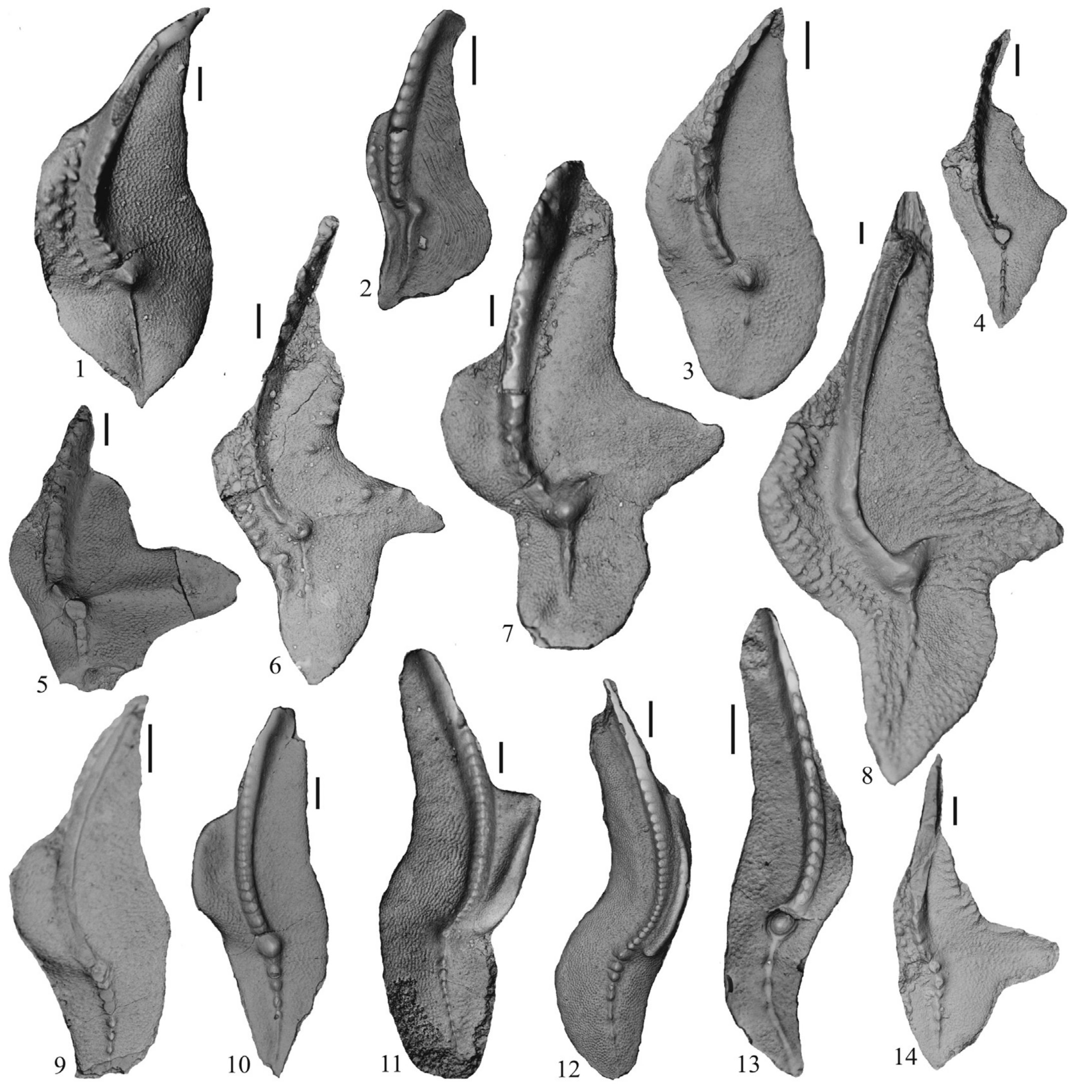

Fig. 9. Conodonts from the BC core. Scanning electron microscope digital images, upper views of Famennian conodont P_1 elements from the DGHS core. All specimens are inverse mirrored element molds in shale. Scale bar is 0.1 mm. (1) *Palmatolepis quadrantinodosa* Branson and Mehl, 1934a; sample 63-0.69. (2) *Palmatolepis marginifera* Helms, 1959 ➔ *Palmatolepis utahensis* Ziegler and Sandberg, 1984; sample 61-0.22. (3) *Palmatolepis inflexa* Müller, 1956; sample 62-0.29. (4) *Palmatolepis parawolskae* Johnston and Chatterton, 2001; sample 64-0.30. (5) *Palmatolepis lobicornis* Schülke, 1995; sample 65-0.78. (6) *Palmatlepis grossi* Ziegler in Kronberg et al., 1960; sample 61-0.71. (7, 8) *Palmatolepis schindewolfi* Müller, 1956; (7) smooth morph, sample 62-0.18; (8) sample 63-0.41. (9, 10) *Palmatolepis prima* Ziegler and Huddle, 1969; (9) sample 65-0.40; (10) sample 64-0.06. (11) *Palmatolepis glabra* Ulrich and Bassler, 1926; sample 62-0.29. (12) *Palmatolepis distorta* Branson and Mehl, 1934a; sample 58-0.03. (13) *Palmatolepis falcata* (Helms, 1959); sample 58-0.36. (14) *Palmatolepis quadrantinodosalobata* Sannemann, 1955; sample 66-0.60. Illustrated specimens are reposited in the paleontological collections in the Department of Geological Sciences at SUNY-Geneseo.

in G3. This may have been due to continued sea-level rise, or, as in all these strata, the occurrence or incomplete preservation of large-scale cycles. The upper two Famennian trends (G4 and G7 in Fig. 4) show a rapid rise at the base of δ0.2 and then only a slight rise in G4, and a positive shift from δ-0.6 to -0.3 in G7 are low to more positive δMS where there is a significant biostratigraphic gap between the strata.

Superimposed on all of the long-range trends are higher-frequency shifts in δMS. In the intervals of continuous and relatively thick deposition, as in B2, pre-D1, and D5, these are interpreted as Milankovitch-band climate-driven sea-level changes. Without related and confining absolute date values and the assumption of continuous deposition, the scale of the cycles cannot be determined, but the δMS shifts are consistent with eccentricity (~100 kyr) cycles recognized in Upper Devonian strata of western Canada (Danielsen et al., 2014) and New York State (Tuskes et al., 2014).

4.3. Gamma values and TOC

The gamma profile for the DGHS Chattanooga core exhibits high values, near or above 200 API, which are typical for organic-rich black shales. The overall trend is an upward increase, where values in the Gassaway Member are significantly higher than in the Dowelltown Member (Fig. 11). The profile shows eight distinct broad peaks, which are, for the most part, mirrored by the total organic carbon values where high TOC corresponds to high total gamma values. Several of the sharp declines in the gamma profile correspond to declines in δMS (e.g., base of pre D1, base of D3, base of G4, and lower portion of G7), which are associated with carbonates, sandier intervals, and apparent disconformities. The lows are followed by abrupt to steady increases in gamma values. Total organic carbon averages 8.3 wt% through the DGHS Chattanooga interval, peaking at 16.1 wt% at the base of the Gassaway Member near the start of the IIe_2 transgression, and remaining high for most of the Famennian (Fig. 11). There is no consistent long-term or short-term relationship between δMS and TOC,

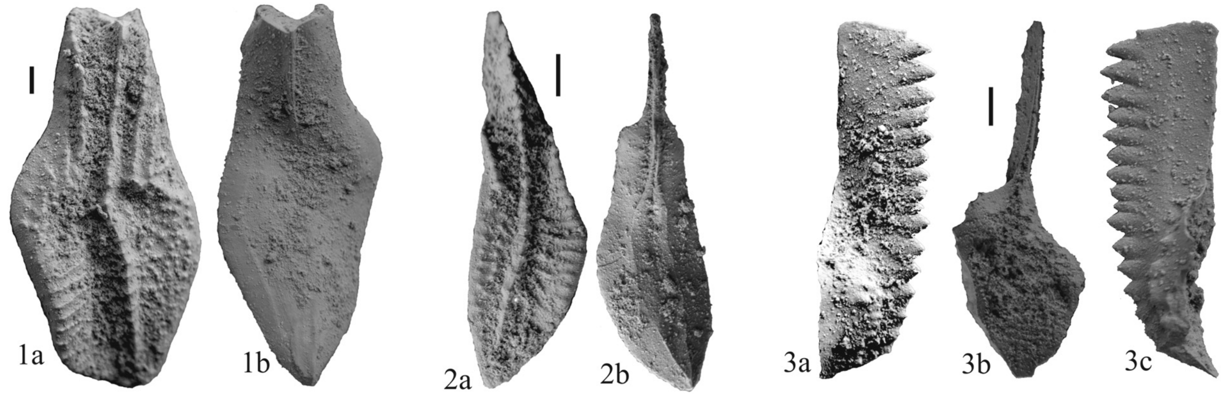

Fig. 10. Conodonts from the DGHS core. Scanning electron microscope digital images of Tournaisian conodont P_1 elements from the DGHS core. Scale bar is 0.1 mm. (1) *Siphonodella quadruplicata* (Branson and Mehl, 1934b); upper and lower views; sample 55-260/261. (2) *Siphonodella cooperi* Hass, 1959; upper and lower views; sample 55-260/261. (3) *Protognathodus kockeli* (Bischoff, 1957); outer lateral and lower views; sample 55-260/261. Illustrated specimens are reposited in the paleontological collections in the Department of Geological Sciences at SUNY-Geneseo.

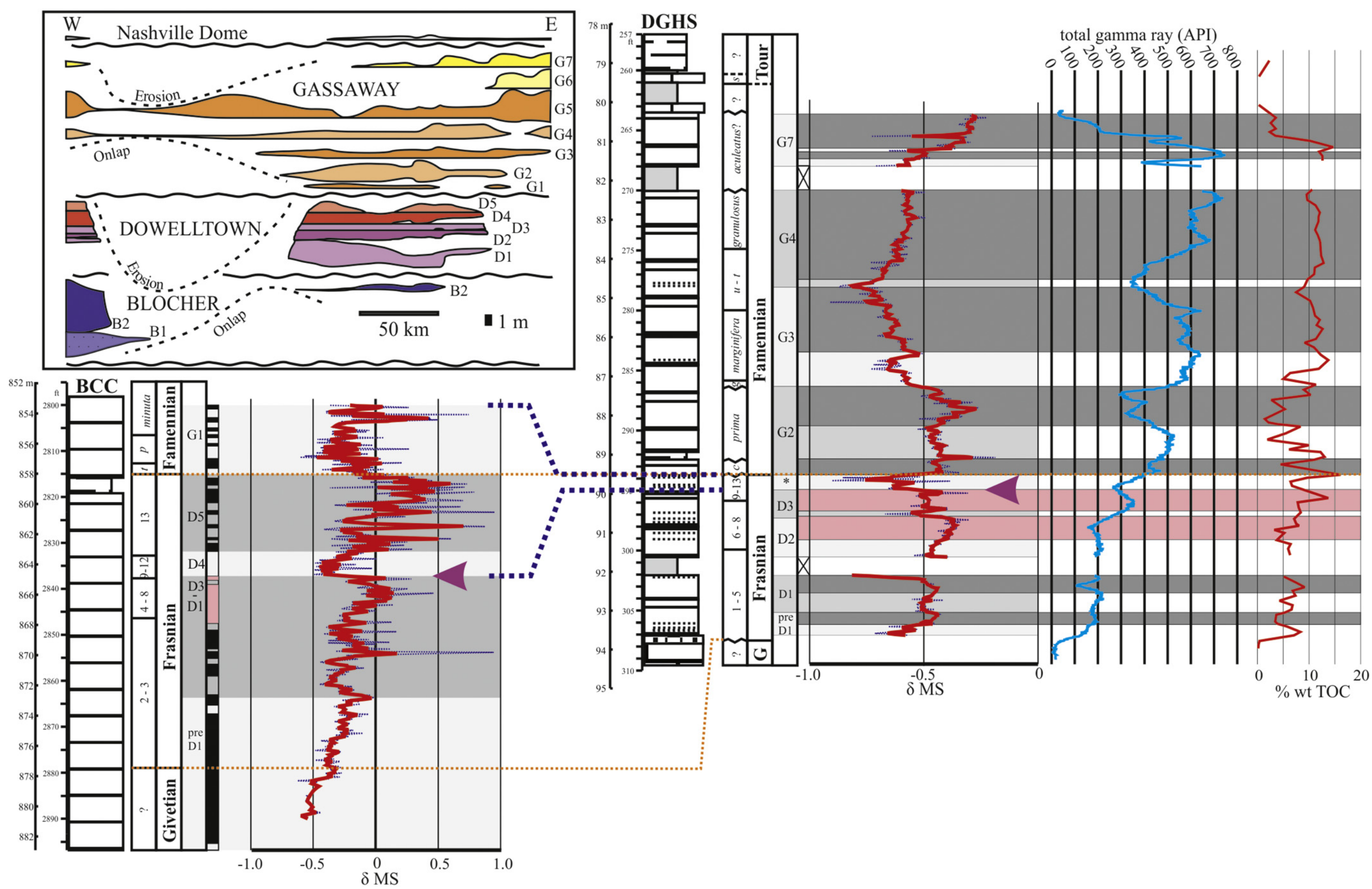

Fig. 11. Correlation of BCC to DGHS strata (see Figs. 3, 4), δMS, gamma-ray, and TOC where DGHS positive δMS shifts (black and pink) have been extended across total gamma and TOC profiles. Chattanooga Shale sequence stratigraphy from Schieber (1998a). See Fig. 4 for lithologic symbols. Narrow dashed orange lines are boundaries of Frasnian strata; wide dashed violet lines mark the confident lithologic correlation of BCC to DGHS. Note difference in scale between columns. Note: permission was not given to use the gamma ray log from the BC core. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

suggesting controls other than sea level and sediment input on productivity and preservation of organic material. The eight broad gamma peaks, or nine if the preD1 and D1 packages are separated, correspond to eight Chattanooga depositional packages (Fig. 2). The small gamma spectral peak in the uppermost *prima* Zone may correspond to regional changes, but its relationship to T-R cycles is unclear.

5. Disconformities and depositional packages

Superimposed on the long-term δMS and gamma spectra trends, and often bounding each trend, are disconformities. These are documented by the absence and condensed nature of the conodont zones between strata, where zones are recognized, as well as field studies where sharp disconformable surfaces bound the black shale packages. Schieber (1998a, 2004) delineated fourteen disconformity-bound black shale intervals in the Chattanooga Shale, which were tied to sea-level changes (Fig. 2). All fourteen do not occur at any one locality due to paleotopographic relief or erosion/non-deposition, and here a possible fifteenth package is recognized in the lower Dowelltown. Based on the depositional packages indicated by the δMS profile and age control based on conodont biostratigraphy, these packages are designated in the cores by the initial of the member (e.g., D for Dowelltown). The DGHS core does not contain the Blocher Member; only the lower Dowelltown is well developed, and there are thin intervals of the upper four Dowelltown units. It is questionable if the uppermost Dowelltown (D5) is present. The base of the Gassaway is missing, and then four of the upper six Gassaway packages are present, each separated by a disconformity indicated by an abrupt shift in δMS as well as missing conodont zones. The BCC is much thicker through the upper Givetian and Frasnian; the Blocher is present, as well as thick lower and upper Frasnian packages. The assignment of the three lower Dowelltown packages are tentative. A pre-D1 interval, which corresponds to FZ 1 to FZ 4, is equivalent to the IIb_2 and IIb_3 TR cycles also recorded by the Penn Yan and West River shales in the Appalachian Basin and the Flume-Maligne in Alberta. The D1, D2, and D3 intervals are either condensed or missing, although the distinctive negative δMS shift found in both cores may be the FZ 11 shift noted by Whalen and Day (2010). Only the lower Famennian G1 package was described and recognized from the core, which has the typical shape of low to more positive δMS following the deepening that starts in the *platys* Zone with the IIe_1 transgression.

6. Conclusions

Conodont biozonation provides evidence of breaks and condensed intervals in black shale deposition and local to regional development of stratigraphic packages where units correspond to Upper Devonian transgressive and highstand depositional systems. Notable are lower Dowelltown strata not found elsewhere in the Chattanooga Shale. Within this biostratigraphic framework, long-term MS trends in the Frasnian are marked by a gradual increase from FZ 1 to FZ 11, where there is an abrupt negative shift. A similar trend was noted in basin settings in western Canada. The values of this shift are offset slightly in the two cores indicative of different source areas where the New Albany Shale in the BCC is slightly more positive than the Chattanooga Shale in the DGHS core. Shorter-term trends show δMS negative to more positive shifts associated with black shale depositional pulses interpreted as highstand deposition and increased clastic material. Gamma values and TOC increase through the Frasnian and remain relatively high in Famennian strata. Eight peaks in gamma spectra correspond to the eight Chattanooga depositional packages. Shorter high-frequency δMS shifts superimposed on the longer-term shifts, also seen in the gamma spectra, are likely Milankovitch-band cycles, but the scale cannot be resolved with current data. The Frasnian-Famennian boundary in the DGHS core is on a disconformity of Famennian *crepida* Zone strata resting on condensed FZ 12–13 strata. In the BCC the boundary is conformable, within a likely continuous black shale interval of FZ 13 through to the *triangularis* Zone, where the *subperlobata* Zone is possibly present in a narrow interval, but was not identified by conodonts.

Acknowledgments

Funding for this project was provided by the U.S. National Science Foundation (EAR-0618003). G.J.G. thanks the U.S. NASA Postdoctoral Program. We thank Albert Horton and the Tennessee Geological Survey for loan of the DGHS drillcore; Lei Zhang, Wenchao Yu, and Jiangsi Liu for assistance in the field; and two anonymous reviewers for critiques of the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.palaeo.2019.03.017.

References

Algeo, T.J., Berner, R.A., Maynard, J.B., Scheckler, S.E., 1995. Late Devonian oceanic anoxic events and biotic crises: "rooted" in the evolution of vascular land plants. GSA Today 5 (3), 45–66.
Baird, G.C., Brett, C.E., 1986. Erosion on an anaerobic seafloor. Significance of reworked pyrite deposits from the Devonian of New York State. Palaeogeogr. Palaeoclimatol. Palaeoecol. 57, 157–193.
Bardashev, I.A., Bardasheva, N.P., 2012. Platform Conodonts from the Givetian-Frasnian Boundary (Middle-Upper Devonian). Donish Publishing House, Dushanbe, Tajikistan (91 pp.).
Becker, R.T., Gradstein, F.M., Hammer, O., 2012. The Devonian Period. In: Gradstein, F.M., Ogg, J.G., Schmitz, M., Ogg, G. (Eds.), The Geologic Time Scale 2012. Elsevier, Oxford, pp. 559–601.
Becker, R.T., Königshof, P., Brett, C.E., 2016. Devonian climate, sea level and evolutionary events: an introduction. Geol. Soc. Lond., Spec. Publ. 423, 1–10.
Bischoff, G., 1957. Die Conodonten-Stratigraphie des rhenoherzynischen Unterkarbons mit Berücksichtigung der Wocklumeria-Stufe und der Devon/Karbon-Grenze. Abhandlungen des Hessischen Landesamtes für Bodenforschung 19 (64 pp.).
Bischoff, G., Ziegler, W., 1957. Die Conodontenchronologie des Mitteldevons und des tiefsten Oberdevons. Abhandlungen des Hessischen Landesamtes für Bodenforschung 22 (136 pp.).
Branson, E.B., Mehl, M.G., 1934a. Conodonts From the Grassy Creek Shale of Missouri. University of Missouri Studies 8, 171-259, pls. 13-21. [imprint 1933].
Branson, E.B., Mehl, M.G., 1934b. Conodonts From the Bushberg Sandstone and Equivalent Formations of Missouri. University of Missouri Studies 8, 265-300, pls. 22-24. [imprint 1933].
Broadhead, R.F., Kepferle, R.C., Potter, P.E., 1982. Stratigraphic and sedimentologic controls of gas in shale–example from Upper Devonian of northern Ohio. AAPG Bull. 66 (1), 10–27.
Bryant, W.L., 1921. The Genesee conodonts, with descriptions of new species. Buffalo Society of Natural Sciences Bulletin 13 (59 pp.).
Cluff, R.M., 1980. Paleoenvironment of the New Albany Shale Group (Devonian-Mississippian) of Illinois. J. Sediment. Res. 50 (3), 767–780.
Conant, L.J., Swanson, V.E., 1961. Chattanooga Shale and Related Rocks of Central Tennessee and Nearby Areas. U.S. Geological Survey Professional Paper 357, (91 pp).
Cooper, C.L., 1931. New conodonts from the Woodford Formation. J. Paleontol. 5, 230–243.
Crick, R.E., Ellwood, B.B., Feist, R., El Hassani, A., Schindler, E., Dreesen, R., Over, D.J., 2002. Magnetostratigraphy susceptability of the Frasnian/Famennian Boundary (Upper Devonian): southern France, Morocco, Belgium, Germany, and Oklahoma (USA). Palaeogeogr. Palaeoclimatol. Palaeoecol. 181 (1–3), 67–90.
Da Silva, A.C., Boulvain, F., 2006. Upper Devonian carbonate platform correlation and sea level variations recorded in magnetic susceptibility. Palaeogeogr. Palaeoclimatol. Palaeoecol. 240, 373–388.
Danielsen, E., Kohn, J., Over, D.J., Schmitz, M., Bundy, K., Ekhoff, J., 2014. Magnetic susceptibility and the Devonian-Carboniferous Boundary in the Exshaw Formation, Rocky Mountains, Alberta, Canada. Geol. Soc. Am. Abstr. Programs 46 (6), 152.
de Witt, W. Jr., 1981. Revision of the aerial extent of the New Albany, Chattanooga, and Ohio shales in Kentucky. In: Roberts, T.G. (Ed.), GSA Cincinnati '81 Guidebooks. Volume II. Economic Geology, Structure. American Geological Institute, pp. 331–334.
Dennison, J.M., Boucot, A.J., 1974. Little War Gap at Clinch Mountain provides standard reference section for Silurian Clinch Sandstone and most nearly complete Devonian section in eastern Tennessee. Southeast. Geol. 16, 79–101.
Droste, J.B., Shaver, R.H., 1986. North Vernon limestone. In: Shaver, R.H., Ault, C.H., Burger, A.M., Carr, D.D., Droste, J.B., Eggert, D.L., Gray, H.H., Harper, D., Hasenmueller, N.R., Hasenmueller, W.A., Horowitz, A.S., Hutchison, H.C., Keith, B.D., Keller, S.J., Patton, J.B., Rexroad, C.B., Wier, C.E. Compendium of Paleozoic Rock-unit Stratigraphy in Indiana–a revision: Indiana Geological Survey Bulletin 59, 103–105.
Ellwood, B.B., Brett, C.E., MacDonald, W.D., 2007. Magnetostratigraphy susceptibility of the Upper Ordovician Kope Formation, northern Kentucky. Palaeogeogr. Palaeoclimatol. Palaeoecol. 243, 42–54.
Ellwood, B.B., Tomkin, J.H., El Hassani, A., Bultynck, P., Brett, C.E., Schindler, E., Feist, R., Bartholomew, A., 2011. A climate-driven model and development of a floating point time scale for the entire Middle Devonian Givetian stage: a test using magnetostratigraphy susceptibility as a climate proxy. Palaeogeogr. Palaeoclimatol. Palaeoecol. 304, 85–95.
Girard, C., Cornée, J.-J., Corradini, C., Fravalo, A., Feist, R., 2014. Palaeoenvironmental changes at Col des Tribes (Montagne Noire, France), a reference section for the Famennian of north Gondwana-related areas. Geol. Mag. 151, 864–884.
Girard, C., Cornée, J.J., Charruault, A.L., Corradini, C., Weyer, D., Bartzsch, K., Joachimski, M., Feist, R., 2017. Conodont biostratigraphy and palaeoenvironmental trends during the Famennian (Late Devonian) in the Thuringian Buschteich section (Germany). Newsl. Stratigr. 50, 71–89.
Hallam, A., Wignall, P.B., 1999. Mass extinctions and sea-level changes. Earth-Sci. Rev. 48, 217–250.
Hass, W.H., 1956. Age and Correlation of the Chattanooga Shale and Maury Formation. U. S. Geological Survey Professional Paper 286, (47 pp).
Hayes, C.W., 1891. The overthrust faults of the southern Appalachians. Geol. Soc. Am. Bull. 2, 141–154.
Helms, J., 1959. Conodonten aus dem Saalfelder Oberdevon (Thüringen). Geologie 8 (6), 634–677.

Hinde, G.J., 1879. On conodonts from the Chazy and Cincinnati Group of the Cambro-Silurian and from the Hamilton and Genesee shale divisions of the Devonian in Canada and the United States. Geological Society of London Quarterly Journal 35, 351–369.
Hogancamp, N.J., Over, D.J., 2013. The nature, range, and utility of stratigraphic distributions of morphotypes of *Polygnathus linguiformis linguiformis* Hinde, Middle Devonian, northern Appalachian Basin, North America: Part 2 - Systematics. In: Albanesi, G.L., Ortega, G. (Eds.), Conodonts from the Andes. Asociacion Paleontologica Argentina Publicacion Especial No 13. pp. 55–62.
House, M.R., 2002. Strength, timing, setting and cause of mid-Palaeozoic extinctions. Palaeogeogr. Palaeoclimatol. Palaeoecol. 181 (1–3), 5–25.
Howarth, M.K., 1962. The Jet Rock series and the Alum Shale series of the Yorkshire coast. Proc. Yorks. Geol. Soc. 33 (Part 4), 381–421.
Jaminski, J., Algeo, T.J., Maynard, J.B., Hower, J.C., 1998. Climatic origin of dm-scale compositional cyclicity in the Cleveland Member of the Ohio Shale (Upper Devonian), Central Appalachian Basin, USA. In: Schieber, J., Zimmerle, W., Sethi, P.S. (Eds.), Shales and Mudstones. Schweizerbart'sche 1. Stuttgart, Germany, pp. 217–242.
Johnson, J.G., Klapper, G., Sandberg, C.A., 1985. Devonian eustatic fluctuations in Euramerica. Geol. Soc. Am. Bull. 96, 567–587.
Johnson, J.G., Klapper, G., Elrick, M., 1996. Devonian transgressive–regressive cycles and biostratigraphy, northern Antelope Range, Nevada, establishment of reference horizons for global cycles. Palaios 11, 3–14.
Johnston, D.I., Chatterton, B.D.E., 2001. Upper Devonian (Famennian) conodonts of the Palliser Formation and Wabamun Group, Alberta and British Columbia. Canada. Palaeontographica Canadiana 19 (154 pp.).
Klapper, G., 1989. The Montagne Noire Frasnian (Upper Devonian) conodont succession. In: McMillan, N.J., Embry, A.E., Glass, D.J. (Eds.), Devonian of the World. Calgary, Canadian Society of Petroleum Geologists, Memoir 14, v. 3, 449–468. [imprint 1988].
Klapper, G., 1997. Graphic correlation of Frasnian (Upper Devonian) sequences in Montagne Noire, France, and western Canada. In: Klapper, G., Murphy, M.A., Talent, J.A. (Eds.), Paleozoic Sequence Stratigraphy, Biostratigraphy, and Biogeography: Studies in Honor of J. Granville ("Jess") Johnson. Geological Society of America Special Paper 321, 113–129.
Klapper, G., 2007. Frasnian (Upper Devonian) conodont succession at Horse Spring and correlative sections. Canning Basin, Western Australia: Journal of Paleontology 81, 513–537.
Klapper, G., Foster Jr., C.T., 1993. Shape analysis of Frasnian species of the Late Devonian conodont genus *Palmatolepis*. The Paleontological Society Memoir 32 (35 pp.).
Klapper, G., Kirchgasser, W.T., 2016. Frasnian Late Devonian conodont biostratigraphy in New York: graphic correlation and taxonomy. J. Paleontol. 90, 525–554.
Kodama, K.P., Anastasio, D.J., Newton, M.L., Pares, J.M., Hinnov, L.A., 2010. High-resolution rock magnetic cyclostratigraphy in an Eocene flysch, Spanish Pyrenees. Geochemistry, Geophysics, Geosystems 11, Q0AA07, doi:https://doi.org/10.1029/2010GC003069.
Kronberg, P., Pilger, A., Scherp, A., Ziegler, W., 1960. Spuren altvariscischer Bewegungen im nordöstlichen Teil des Rheinischen Schiefergebirges. Fortschritte in der Geologie von Rheinland und Westfalen 3 (1) (46 pp.).
Müller, K.J., 1956. Zur Kenntnis der Conodonten-Faunen des europäischen Devons, 1. Die Gattung *Palmatolepis*. Abhandlungen der Senckenbergischen Naturforschenden Gesellschaft 494 (70 pp.).
Müller, K.J., Müller, E.M., 1957. Early Upper Devonian (Independence) conodonts from Iowa, part 1. J. Paleontol. 31, 1069–1108.
Nuttall, B.C., 2013. Middle and Late Devonian New Albany Shale in the Kentucky Geological Survey Marvin Blan No. 1 Well, Hancock County, Kentucky. Kentucky Geological Survey Report of Investigations 17. Series XII (72 pp.).
Over, D.J., 1997. Conodont biostratigraphy of the Java Formation (Upper Devonian) and the Frasnian-Famennian boundary in western New York State. In: Klapper, G., Murphy, M.A., Talent, J.A. (Eds.), Paleozoic Sequence Stratigraphy, Biostratigraphy, and Biogeography: Studies in Honor of J. Granville ("Jess") Johnson. Geological Society of America Special Paper 321, 161–177.
Over, D.J., 2002. The Frasnian-Famennian Boundary in the Appalachian Basin, Michigan Basin, Illinois Basin, and southern continental margin, central and eastern United States. Palaeogeogr. Palaeoclimatol. Palaeoecol. 181, 153–170.
Over, D.J., 2007. Conodont biostratigraphy of the Chattanooga Shale, Middle and Upper Devonian, southern Appalachian Basin, eastern United States. J. Paleontol. 81, 1194–1217.
Over, D.J., Ruppel, S.C., 2012. Woodford conodonts and biostratigraphy (Upper Devonian – Carboniferous) in the subsurface of eastern New Mexico and Texas. Stratigraphy 8, 271–280.
Over, D.J., Grimson, M., Barrick, J.E., 1991. Scanning electron microscope inverse imaging technique for positive image photomicrographs of microfossil molds. J. Paleontol. 65, 1013–1014.
Over, D.J., Lazar, R., Baird, G.C., Schieber, J., Ettensohn, F.R., 2009. *Protosalvinia* Dawson and associated conodonts of the Upper *trachytera* Zone, Famennian, Upper Devonian, in the eastern United States. J. Paleontol. 83, 70–79.
Ovnatanova, N.S., 1976. Novye pozdnedevonskie konodonty Russkoy Platformy. Paleontologicheskiy Zhurnal 1976 (2), 106–115.
Robinson, S., 1993. Lithostratigraphic applications for magnetic susceptibility logging of deep-sea sediment cores, examples from ODP Leg 115. Geol. Soc. Spec. Publ. 70, 65–98.
Sandberg, C.A., 1976. Conodont biofacies of late Devonian *Polygnathus styriacus* Zone in western United States. In: Barnes, C.R. (Ed.), Conodont Paleoecology. Geological Association of Canada, Special Paper No. 15, pp. 171–86.
Sandberg, C.A., Ziegler, W., Leuteritz, K., Brill, S.M., 1978. Phylogeny, speciation and zonation of *Siphonodella* (Conodonta, Upper Devonian and Lower Carboniferous). Newsl. Stratigr. 7, 102–120.
Sandberg, C.A., Ziegler, W., Bultynck, P., 1989. New standard conodont zones and early *Ancyrodella* phylogeny across Middle-Upper Devonian boundary. Courier Forschungsinstitut Senckenberg 110, 195–230.
Sandberg, C.A., Morrow, J.R., Ziegler, W., 2002. Late Devonian sea-level changes, catastrophic events, and mass extinctions. In: Koeberl, C., MacLeod, K.G. (Eds.), Catastrophic Events and Mass Extinctions: Impacts and Beyond: Boulder, Colorado, Geological Society of America Special Paper. 356. pp. 473–487.
Sannemann, D., 1955. Oberdevonische Conodonten (to IIalpha). Senckenbergiana lethaia 36, 123–156.
Schieber, J., 1998a. Developing a sequence stratigraphic framework for the Late Devonian Chattanooga Shale of the southeastern US: relevance for the Bakken Shale. In: Christopher, J.E., Gilboy, C.F., Paterson, D.F., Bend, S.L. (Eds.), Eighth International Williston Basin Symposium, Saskatchewan Geological Society. Special Publication No 13. pp. 58–68.
Schieber, J., 1998b. Deposition of Mudstones and Shales: Overview, Problems, and Challenges. In: Schieber, J., Zimmerle, W., Sethi, P. (Eds.), Shales and Mudstones (vol. 1): Basin Studies, Sedimentology and Paleontology. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart.
Schieber, J., 1998c. Sedimentary features indicating erosion, condensation, and hiatuses in the Chattanooga Shale of Central Tennessee: relevance for sedimentary and stratigraphic evolution. In: Schieber, J., Zimmerle, W., Sethi, P. (Eds.), Shales and Mudstones (vol. 1): Basin Studies, Sedimentology and Paleontology. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, pp. 187–215.
Schieber, J., 2004. Connecting the dots: sequence stratigraphic correlation in Devonian black shales of the eastern U.S. and relationship to global sealevel variations. In: Schieber, J., Lazar, R. (Eds.), Devonian Black Shales of the Eastern U.S. Indiana Geological Survey Open-File Study 04-05, 80–82.
Schieber, J., Over, D.J., 2005. Sedimentary fill of the Late Devonian Flynn Creek Crater: a hard target marine impact In: Over, D.J., Morrow, J.R., Wignall, P.B. (Eds.), Understanding Late Devonian and Permian-Triassic Biotic and Climatic Events: Towards an Integrated Approach: Developments in Palaeontology and Stratigraphy. Elsevier, pp. 51-69.
Schindler, E., 1990. Die Kellwasser-Krise (hohe Frasne-Stufe, Ober-Devon). Göttinger Arbeiten zur Geologie und Paläontologie 46 (115 pp.).
Schülke, I., 1995. Evolutive Prozesse bei *Palmatolepis* in der frühen Famenne-Stufe (Conodonta, Ober - Devon). Göttinger Arbeiten zur Geologie und Paläontologie 67 (108 pp.).
Spalletta, C., Perri, M.C., Over, D.J., Corradini, C., 2017. Famennian (Upper Devonian) conodont zonation: revised global standard. Bull. Geosci. 92, 31–57.
Strapoc, D., Mastalerz, M., Schimmelmann, A., Drobniak, A., Hasenmueller, N.R., 2010. Geochemical constraints on the origin and volume of gas in the New Albany Shale (Devonian–Mississippian), eastern Illinois Basin. AAPG Bull. 94 (11), 1713–1740.
Trabucho-Alexandre, João, 2015. More gaps than shale: erosion of mud and its effect on preserved geochemical and palaeobiological signals. In: Smith, D.G., Bailey, R.J., Burgess, P.M., Fraser, A.J. (Eds.), Strata and Time: Probing the Gaps in Our Understanding. Geological Society, London, pp. 251–270.
Tuskes, K., Over, D.J., Hartvigsen, G., Schmitz, M., Davydov, V., 2014. Orbital cyclostratigraphy within the Late Devonian Kellwasser crisis indicated by magnetic susceptibility in western New York State – preliminary results. Geol. Soc. Am. Abstr. Programs 46 (6), 774.
Ulrich, E.O., Bassler, R.S., 1926. A classification of the toothlike fossils, conodonts, with descriptions of American Devonian and Mississippian species. United States National Museum Proceedings 68 (12) (63 pp.).
Walliser, O., Bultynck, P., 2011. Extinctions, survival and innovations of conodont species during the Kačák Episode (Eifelian-Givetian) in south-eastern Morocco. Bull. Inst. R. Sci. Nat. Belg. Sci. Terre 81, 5–25.
Whalen, M.T., Day, J.E., 2008. Magnetic susceptibility, biostratigraphy, and sequence stratigraphy: insights into Devonian carbonate platform development and basin infilling, Western Alberta. In: Lukasik, J., Simo, J.A. (Eds.), Papers on Phanerozoic Reef Carbonates in Honor of Wolfgang Schlager. SEPM Special Publication 89. pp. 291–314.
Whalen, M.T., Day, J.E., 2010. Cross-basin variations in magnetic susceptibility influenced by changing sea level, paleogeography, and paleoclimate: Upper Devonian, Western Canada sedimentary basin. J. Sediment. Res. 80, 1109–1127.
Youngquist, W.L., 1945. Upper Devonian conodonts from the Independence Shale(?) of Iowa. J. Paleontol. 19, 335–367.
Ziegler, W., 1962. Taxonomie und Phylogenie Oberdevonischer Conodonten und ihre stratigraphische Bedeutung. Abhandlungen des Hessischen Landesamtes fiir Bodenforschung 38 (166 pp.).
Ziegler, W., 1965. Eine Verfeinerung der Conodontengliederung an der Grenze Mittel-/Oberdevon. Fortschritte in der Geologie von Rheinland und Westfalen 9, 647–676.
Ziegler, W., Huddle, J.W., 1969. Die *Palmatolepis glabra* - Gruppe (Conodonta) nach der Revision der Typen von Ulrich & Bassler durch J.W. Huddle. Fortschritte in der Geologie von Rheinland und Westfalen 16, 377–386.
Ziegler, W., Klapper, G., 1982. The *disparilis* conodont Zone, the proposed level for the Middle–Upper Devonian boundary. Courier Forschungsinstitut Senckenberg 55, 463–492.
Ziegler, W., Sandberg, C.A., 1984. *Palmatolepis*-based revision of upper part of standard Late Devonian conodont zonation. In: Clark, D.L. (Ed.), Conodont Biofacies and Provincialism. Geological Society of America Special Paper 196. pp. 179–194.
Ziegler, W., Sandberg, C.A., 1990. The Late Devonian Standard Conodont Zonation. Courier Forschungsinstitut Senckenberg 121 (115 pp.).
Ziegler, W., Klapper, G., Lindström, M., 1964. The validity of the name *Polygnathus* (Conodonta, Devonian and lower Carboniferous). J. Paleontol. 38, 421–423.
Ziegler, W., Klapper, G., Johnson, J.G., 1976. Revision and subdivision of the *varcus* - Zone (Conodonts, Middle-?Upper Devonian) in Europe and North America. Geol. Palaeontol. 10, 109–140.