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Resolving complex stratigraphic architecture across the Burlington shelf and identifying the Devonian-Carboniferous (Hangenberg) and Kinderhookian-Osagean (Tournaisian) boundary biogeochemical events in the type area of the Mississippian subsystem

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ABSTRACT

The tristate area of Iowa, Illinois, and Missouri contains some of the best-exposed Mississippian strata in the world, including the type area for the Mississippian subsystem, across a broad carbonate platform known as the Burlington shelf. Strata have been mapped as thinnest along the central middle shelf and thickening both up-ramp and down-ramp, forming a complex dumbbell-like stratigraphic pattern rather than a simple clinoform geometry thinning into the basin. Additionally, two significant hiatuses at the Devonian-Carboniferous boundary and Kinderhookian-Osagean boundary greatly complicate stratigraphic correlations across the region. As a result, the precise temporal relationships between strata deposited across the region remain uncertain.

Two large biogeochemical events occurred during this interval that provide facies-independent chronostratigraphic tools: the Hangenberg event, which marks the Devonian-Carboniferous boundary, and the Kinderhookian-Osagean boundary event. To target these events, we collected 66 conodont samples and 1005 carbonate carbon isotope samples from three cores and three outcrops and integrated the results with existing data from key facies/depth transitions across the Burlington shelf. Our new data demonstrate a complex relationship among complementary stratigraphic thicknesses, where the Devonian-Carboniferous boundary interval is thin or absent in the up-ramp inner-shelf setting and preserved in a significantly expanded interval in the central to distal middle-shelf deposits of southeast Iowa and northeast Missouri. However, the overlying Kinderhookian-Osagean boundary interval is not preserved in this down-ramp setting but is preserved in significantly expanded strata in the up-ramp inner-shelf setting of central Iowa.

INTRODUCTION

The latest Devonian to Early Mississippian (Famennian to Tournaisian global stages) is a critical time in Earth history marked by significant changes to the ocean-atmosphere-biosphere system because this interval records the onset of the late Paleozoic ice age (Qie et al., 2019; Isbell et al., 2021), a mass extinction (Kaiser et al., 2016), and significant perturbations to the global carbon cycle (e.g., Maharjan et al., 2018; Heath et al., 2021). The first glacial pulses of the late Paleozoic ice age are recorded in the latest Devonian, mid-Tournaisian, and Visean, marking the start of a long-term cooling trend and transition from the greenhouse climate of the Devonian to the icehouse state of the Permian–Carboniferous (Fielding et al., 2008; Lakin et al., 2016; Isbell et al., 2021). The Devonian-Carboniferous boundary is itself marked by the Hangenberg event, a first-order extinction event that affected both marine and terrestrial organisms and was comparable in magnitude to the Frasnian–Famennian extinction (Walliser, 1996; Kaiser et al., 2016). The global carbon cycle of the Early Mississippian was extremely volatile, and two of the largest Phanerozoic positive $\delta^{13}C$ excursions, known as the Hangenberg excursion and Kinderhookian-Osagean boundary excursion, took place within 7 m.y. of each other (ca. 359 Ma to 352 Ma; Cramer and Jarvis, 2020), with peak magnitudes up to +6‰ and +7‰, respectively. While the Hangenberg excursion was clearly linked to an extinction (Kaiser et al., 2016), anoxic event (Paschall et al., 2019; Pisarzowska et al., 2020), and period of enhanced volcanism (Pisarzowska et al., 2020; Rakociński et al., 2020), the driving mechanism(s) behind the Kinderhookian-Osagean boundary excursion is(are) less well understood. The Kinderhookian-Osagean boundary excursion was associated with a period of global cooling recorded in marine $\delta^{18}O$ (Chen et al., 2021), evidence of ocean anoxia (Maharjan et al., 2018; Cheng et al., 2020), and a limited faunal turnover that is largely recorded through an extinction among conodonts and a decrease in foraminiferal diversity (Aretz et al., 2014; Zhuravlev and Plotitsyn, 2022). Combined $\delta^{13}C$, $\delta^{18}O$, and anoxic records in the Early Mississippian have been used to interpret the Kinderhookian-Osagean boundary excursion as representative of a period of enhanced silicate weathering driving primary productivity that led to organic carbon burial and atmospheric CO_2 drawdown, which triggered an initial glacial phase of the late Paleozoic ice age (Chen et al., 2021).

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During the Early Mississippian, much of the North American continent was covered by a broad shallow-water carbonate platform, where depositional centers developed as regionally extensive carbonate shelves, each separated by tectonic highs or intracratonic basins (Lane and De Keyser, 1980; Gutschick et al., 1980; Gutschick and Sandberg, 1983). Along individual shelves, facies belts can be traced laterally across hundreds to thousands of kilometers and contain an abundance of heterotrophic biota, largely lacking the photozoan skeletal reef builders that dominated the Devonian (Lane and De Keyser, 1980; Gutschick and Sandberg, 1983; Copper, 1994; Franseen, 2006). Today, some of the best exposed Lower Mississippian strata in the world are located in the U.S. midcontinent, notably the Iowa, Illinois, and Missouri tristate region, which includes the type area for the regional Kinderhookian Series. Strata were deposited along the Burlington shelf (Fig. 1), a broad carbonate platform that stretched from the tristate area southwestward into southern Missouri, Oklahoma, and Arkansas (Lane and De Keyser, 1980; Gutschick and Sandberg, 1983). Facies along the Burlington shelf are shallowest in north-central Iowa and deepen southeastward into Illinois and Missouri (Fig. 1), before eventually transitioning into basinal facies within the Illinois basin (Lane and De Keyser, 1980; Witzke and Bunker, 2002). Strata are thinnest along the central middle shelf and thicken both updip and downdip into the inner-shelf and distal middle-shelf deposits, respectively (Fig. 1; Witzke and Bunker, 1996, 2002). Further complicating stratigraphic correlations, there is the presence of two disconformities, one at the Devonian-Carboniferous boundary and the other referred to as the sub-Burlington disconformity, a southeastward-expanding hiatal surface that marks the Kinderhookian-Osagean boundary in the tristate and Mississippi River Valley areas (Witzke and Bunker, 2002; Lane and Brenckle, 2005). Given the global importance of these strata as part of the type area of the Mississippian subsystem (e.g., Lane and Brenckle, 2005) and the fact that these strata represent some of the thickest and most continuous records of the Devonian-Carboniferous boundary interval anywhere in the world (e.g., Stolfus et al., 2020; Heath et al., 2021), precise global chronostratigraphic correlation of these strata is critical to evaluate global change during the biogeochemical events that took place at the start of the late Paleozoic ice age.

Here, we present new high-resolution event stratigraphy (Cramer et al., 2015) from integrated conodont biostratigraphy and carbonate carbon isotope chemostratigraphy from the type Mississippian area to constrain regional facies relationships and chronostratigraphic correlations across Iowa, northeast Missouri, and western Illinois. New data are presented from three cores and three outcrops located at key facies and depth transitions across the Burlington shelf, and these results were integrated with previously published data to create a revised chronostratigraphic framework for the region.

GEOLOGIC BACKGROUND

During the Late Devonian to Early Mississippian, the Iowa, Illinois, and Missouri tristate area was located between 15°S and 20°S (Fig. 1; Witzke and Bunker, 1996; Scotese, 2014). Sea level was high, and much of the U.S. midcontinent was covered by a broad epicontinental sea marked by widespread, shallow, mixed carbonate-siliciclastic deposition (Lane and De Keyser, 1980; Witzke and Bunker, 1996). In the tristate area, the siliciclastic-dominated deposits of the Famennian gave way to an expansive carbonate platform known as the Burlington shelf that covered most of the midcontinent during the Mississippian (Witzke et al., 1990; Witzke and Bunker, 2002). A northeast-southwest depositional strike was present on the shelf (Fig. 1), where inner-shelf facies in central Iowa transition to proximal and central middle-shelf facies in southeast Iowa and northern Missouri, distal middle-shelf facies in western Illinois and central Missouri, and eventually outer-shelf and shelf-break facies farther to the southeast (Witzke and Bunker, 2002). Strata are thinnest in the central middle shelf and thicken both northwestward and southeastward as facies transition to the inner-shelf and distal-shelf deposits, respectively, forming a dumbbell-like stratigraphic pattern (Fig. 1). This stratal pattern persisted through successive sea-level cycles and is a prominent feature of the Mississippian stratigraphy of the upper Midwest from the latest Famennian through at least the middle Osagean (Witzke and Bunker, 1996, 2002).

Regional Stratigraphy

In general, the stratigraphy of our study can be divided into three broad geographical regions (Fig. 2), each representing a different depositional regime: (1) the inner shelf of central Iowa, (2) the central middle shelf of southeastern Iowa, and (3) the distal middle shelf to outer shelf of NE Missouri and west-central Illinois. Correlations between these regions are understood in a general sense, but complications arise due to inconsistent naming of units through time, nomenclatural differences across state boundaries, and transitions between facies across depositional environments. We would like to highlight that the results of our current study do not support all of the historical correlations outlined in this section (including Figs. 1 and 2), and our updated interpretations and stratigraphic revisions are discussed in detail later in this article.

In southeastern Iowa, the uppermost Famennian succession consists of the Saverton Shale and the English River Formation (Fig. 2); these successive units are lithologically similar, and both largely consist of green-gray shales and siltstones with the contact between them marked by a prominent oolitic ironstone– and/or phosphate-enriched bed. The name "Maple Mill" has historically been assigned to a variety of Famennian shales and lithostratigraphic units in Iowa and is in need of revision (Witzke and Bunker, 2002). For our current study, we followed the recommendation of Witzke and Bunker (2002) in defining the English River Formation as containing all strata of the transgressive-regressive (T-R) cycle IIf of Johnson et al. (1985), where the base is marked by the phosphatic/ironstone beds, and "Maple Mill" refers to the shaley strata above this bed (Day et al., 2019). As utilized here, the English River Formation consists of the lower green-gray shales of the "Maple Mill" and an upper siltstone-dominated interval; however, this stratigraphic relationship is not always present because the "Maple Mill" and siltstone facies interfinger throughout southeast Iowa. The English River Formation is absent in northeast Missouri and west-central Illinois, and instead the Saverton Shale is the uppermost Famennian unit present in the region (Fig. 2). In central Iowa, Upper Famennian strata consist of the Aplington Dolostone and a thin unnamed shale (Fig. 2). There is no lithologic equivalent of the Aplington Dolostone in southeast Iowa, so the precise stratigraphic correlation across the state is unclear. Often informally referred to as the "Maple Mill," this unnamed shale consists of a lower green-gray shale overlain by a capping siltstone and is likely at least partially equivalent to the "Maple Mill"–English River succession of southeast Iowa (Witzke, 2001; Witzke and Bunker, 2002).

Kinderhookian strata in southeast Iowa include the Louisiana, Prospect Hill, and Wassonville Formations (Fig. 2). The Louisiana Formation, which consists of sublithographic limestones and dolostones, has historically been miscorrelated with lithologically similar units throughout Iowa, Illinois, and Missouri (Witzke and Bunker, 2002). Recent work found that the Louisiana Formation is equivalent to the "McCraney" formation found elsewhere in southeast Iowa (Stolfus et al., 2020), and the revised Devonian-Carboniferous boundary is now placed at the base of the Louisiana Formation, in accordance with the updated international standard (Corradini et al., 2017; Spalletta et al., 2017; Stolfus et al., 2020; Heath et al., 2021). The Prospect Hill Formation

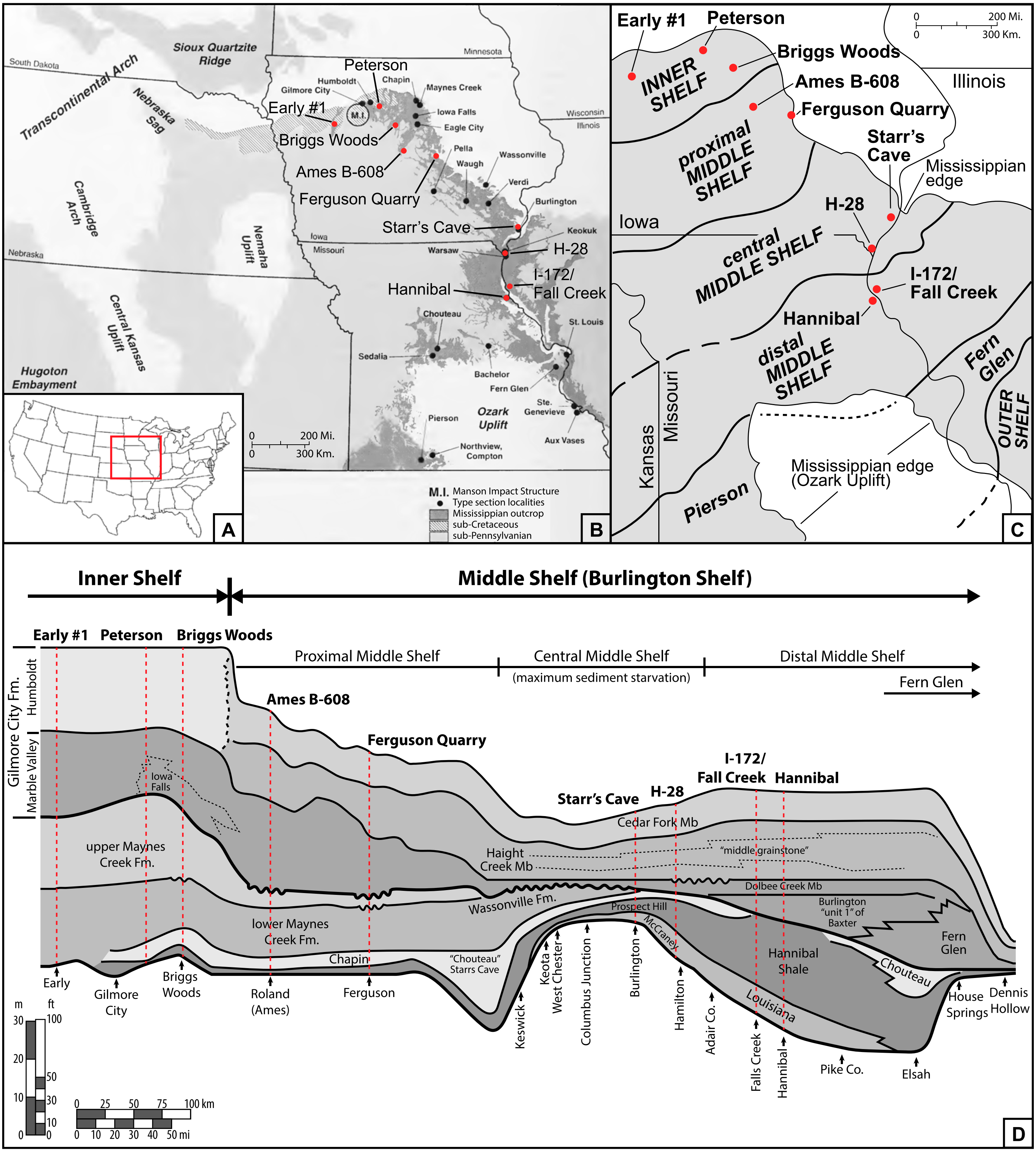


Figure 1. (A) Regional map of the United States highlighting the study area. (B) Distribution of Mississippian outcrops in the tristate area. Red dots indicate locations of cores and outcrops used in this study. (C) Distribution of facies belts during the Early Mississippian. Red dots indicate locations of cores and outcrops used in this study. (D) Cross section of Kinderhookian–Osagean strata spanning northwest to southeast. Red lines indicate locations examined in this study. Parts A–D are all modified after Witzke and Bunker (2002). Note: The regional correlations presented in this figure are representative of historical interpretations. Revised chronostratigraphic correlations are discussed extensively throughout this paper, and our refined regional correlations are presented in Figures 11 and 12.

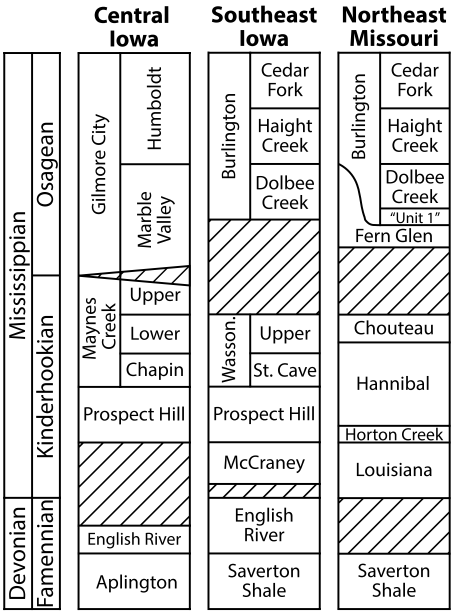


Figure 2. General stratigraphy and nomenclature divisions of our study area. Central Iowa stratigraphy is after Witzke (2001) and Witzke and Bunker (2002), southeast Iowa stratigraphy is after Witzke and Bunker (1996, 2002), and northeast Missouri stratigraphy is after Lane and Brenckle (2005). Note: The regional correlations presented in this figure are representative of historical interpretations. Revised chronostratigraphic correlations are discussed extensively throughout this paper, and our refined regional correlations are presented in Figures 11 and 12.

consists of dolomitic to argillaceous siltstones with common interbeds of green-gray shales, and it sharply overlies the Louisiana Formation through much of southeastern Iowa (Witzke and Bunker, 2002); in regions where the Louisiana strata or "McCraney" equivalent are absent, the Prospect Hill Formation represents the oldest Kinderhookian unit. The Wassonville Formation is a carbonate unit overlying the Prospect Hill Formation, and it represents the uppermost Kinderhookian unit through southeastern Iowa; it is divided into the basal Starr's Cave Member, which is dominated by oolitic packstones and grainstones, and an unnamed upper member, which consists of cherty dolostones interbedded with fossiliferous limestones (Witzke and Bunker, 2002).

The full Kinderhookian succession in northeastern Missouri consists of the Louisiana Formation, Horton Creek Formation, Hannibal Shale, and Chouteau Formation (Fig. 2); however, a continuous sequence is not present, and units are unevenly distributed laterally. The Louisiana Formation in Missouri underlies the Horton Creek Formation or Hannibal Shale and pinches out moving southward (Thompson, 1993). The Horton Creek Formation is a laterally discontinuous oolitic limestone with a poorly known exposure in Missouri (Thompson, 1986). When present, it occurs as thin lenses overlying the Louisiana Formation; however, the Horton Creek Formation was not encountered in our current study. The Hannibal Shale comprises variably calcareous siltstones, shales, and fine-grained sandstones and is widely exposed throughout northeast Missouri (Collinson, 1961; Thompson, 1986). The Hannibal Shale is at least partially correlative with the Prospect Hill Formation in SE Iowa (likely the middle to upper Hannibal units), although precise stratigraphic correlations are not delineated (Fig. 1D; Witzke and Bunker, 2002). Overlying the Hannibal Shale when present, the Chouteau Formation is a finely crystalline silty limestone (Collinson, 1961; Thompson, 1986) that contains a similar faunal assemblage to the Wassonville Formation in SE Iowa (Witzke and Bunker, 2002), although it likely extends slightly younger than the top of the Wassonville Formation (Chauffe and Guzman, 1997); the Chouteau Formation was not encountered in our current study but is best exposed in north-central Missouri.

The Kinderhookian succession in central Iowa consists of a basal siltstone overlain by a thick carbonate package, and it has a history of inconsistent usage of stratigraphic nomenclature. The Prospect Hill Formation represents the base of the Kinderhookian section in the region, and these dolomitic siltstones can be traced regionally into SE Iowa. The base of the Prospect Hill Formation is marked by an irregular disconformity; however, in the past, these beds have been incorrectly assigned to the English River Formation, as the contact is subtle (e.g., Anderson, 1966). The carbonate package consists of alternating beds of limestone and dolostone, with the succession initially named the Hampton Formation and divided into the Chapin, Maynes Creek, Eagle City, and Iowa Falls members (Van Tuyl, 1925; Laudon, 1931). The names "Hampton" and "Eagle City" have been dropped from usage, and the full carbonate succession present between the Prospect Hill Formation and the Kinderhookian-Osagean boundary is now assigned to the Maynes Creek Formation (Fig. 2; Woodson and Bunker, 1989; Witzke, 2001). The Chapin, which was previously assigned formational status, has been relegated to a member within the Maynes Creek Formation, and the Iowa Falls member has since been assigned an Osagean age (Woodson and Bunker, 1989). Following current practice, the Maynes Creek Formation is divided into the basal Chapin Member and unnamed "Lower" and "Upper" members (Fig. 2; Woodson and Bunker, 1989; Witzke, 2001). The Chapin Member consists of fossiliferous oolitic limestones and dolostones and is equivalent to the Starr's Cave Member in SE Iowa (Fig. 1D; Witzke, 2001; Witzke and Bunker, 2002). Both the lower and upper members of the Maynes Creek Formation comprise cherty dolostones, with chert more abundant throughout the lower member relative to the upper member (Woodson and Bunker, 1989; Witzke, 2001). The uppermost beds of the Maynes Creek Formation comprise sublithographic limestones with locally developed stromatolites, which serve as a prominent marker bed across the region (Woodson and Bunker, 1989; Witzke, 2001). The lower Maynes Creek Formation can be correlated to the upper member of the Wassonville Formation; however, there is no clear equivalent to the upper Maynes Creek Formation in SE Iowa (Fig. 1D; Woodson and Bunker, 1989; Witzke, 2001; Witzke and Bunker, 2002).

In both SE Iowa and NE Missouri, the Osagean succession is dominated by the Burlington Formation, a widespread crinoidal limestone that can be traced across the midcontinent from our study area into central Kansas and Oklahoma (Figs. 1 and 2; Lane and De Keyser, 1980; Witzke and Bunker, 2002). The Burlington Formation is divided into the basal Dolbee Creek Member, middle Haight Creek Member, and upper Cedar Fork Member (Witzke and Bunker, 2002). Generally, the Dolbee Creek Member comprises locally dolomitic crinoidal limestones with interbeds of less fossiliferous mudstones. The Haight Creek Member consists of fine-grained dolostones and contains prominent chert nodules and bedded chert throughout; a distinct glauconitic bed marks the base of the member, and an interval of resistant crinoidal limestones, known as the "middle grainstone," is present in the middle of the member, with both horizons providing useful markers for regional correlations (Witzke and Bunker, 2002). The Cedar Fork Member predominantly comprises crinoidal limestones with interbeds of dolostone and chert nodules; locally, the member is glauconite rich, and the upper contact of the member with the overlying Keokuk Formation is marked by a prominent condensed bed enriched in fish bones and shark teeth (Witzke et al., 1990; Witzke and Bunker, 2002). The Burlington Formation is thinnest in SE Iowa and thickens both northwestward into central Iowa and southeastward into Missouri (Fig. 1D; Witzke and Bunker, 2002); in Missouri, a thick accumulation of strata known as "unit 1" of Baxter and Haines (1990) is present below the Dolbee Creek Member, and this unit has no equivalent in SE Iowa (Fig. 1D).

In central Iowa, the Osagean succession is represented by the Gilmore City Formation, a widespread inner-shelf carbonate unit consisting of interfingering dense sublithographic limestones and skeletal-oolitic packstones and grainstones (Brenckle and Groves, 1986; Woodson and Bunker, 1989; Woodson, 1993). The formation is divided into the Marble Valley and Humboldt Members, where the units are separated by a thin bed of peritidal muds (Fig. 2; Woodson, 1993; Witzke, 2001); however, this contact is typically difficult to discern. Locally, the lower portions of the Gilmore City Formation are dolomitized and are often subdivided as the Iowa Falls Member (Van Tuyl, 1925; Laudon, 1931; Woodson and Bunker, 1989); however, biostratigraphy indicates that the "member" actually represents the regional diagenetic overprint of the lower Gilmore City Formation (Brenckle and Groves, 1986; Woodson and Bunker, 1989; Woodson, 1993). Historically, the upper portion of the lower Gilmore City Formation has been correlated to the Dolbee Creek Member, while the upper Gilmore City Formation may correlate with the Haight Creek and Cedar Fork Members (Fig. 1D; Witzke and Bunker, 1996; Witzke and Bunker, 2002), although these correlations are largely conjectural. In central Iowa, a distal expression of the Gilmore City Formation is overlain by part of the Burlington Formation and has been interpreted to represent a transition between inner- and middle-shelf facies belts where the upper Marble Valley Member of the Gilmore City Formation grades into and is overlain by the Haight Creek Member of the Burlington Formation (Witzke and Bunker, 2002). It is difficult to refine this interpretation through biostratigraphy because the Gilmore City Formation is best constrained by foraminifera but sparsely contains conodonts, while, conversely, the Burlington Formation is best constrained by conodonts and sparsely contains foraminifera (Witzke and Bunker, 2002; Lane and Brenckle, 2005). Brachiopods recovered from the Gilmore City Formation are representative of a distinct assemblage that is absent in the Burlington Formation (Carter, 1972, 1987, 1991), although this lack of fauna in the Mississippi River Valley does not preclude a partial relationship between the formations. At most, the Burlington and Gilmore City Formations are only partially correlative, and additional work is needed to resolve formational equivalencies and refine the chronostratigraphic relationships.

Definition of Kinderhookian, Osagean, Tournaisian, and Visean

The Carboniferous System is named for the coal-rich strata in Europe that fueled the industrial revolution (Aretz et al., 2020). Production of coal in regional centers led to the development of three major stratigraphic classifications, originating in Western Europe, Eastern Europe, and North America, respectively (Davydov et al., 2012; Aretz et al., 2020). This initial regional split, along with the complex geological, biological, and climatic histories of the period, led to the Carboniferous having a confusing/complicated stratigraphic and nomenclatural division (Davydov et al., 2012; Aretz et al., 2020). Today, the Carboniferous System is divided into the Mississippian and Pennsylvanian subsystems, with each subsystem divided into an unnamed lower, middle, and upper series; the names "Mississippian" and "Pennsylvanian" were developed through usage in North American strata and were ratified as official subdivisions of the Carboniferous in 2000 (Davydov et al., 2012). The Lower and Middle Mississippian correspond to the Tournaisian and Visean Stages, respectively; originating in Eastern Europe, these names are now applied as the standard global zonation (Aretz et al., 2020).

The Tournaisian global stage is named after the town of Tournai in western Belgium, with the global stratotype section and point (GSSP) located in La Serre, Montagne Noire, France (Paproth et al., 1991). Currently, the base of the Tournaisian (and the Devonian-Carboniferous boundary) is placed at the first appearance datum (FAD) of the conodont *Siphonodella sulcata* (Paproth et al., 1991); however, difficulty with global correlation of the biozone, taxonomic uncertainty within the *Siphonodella* lineage, and stratigraphic uncertainty at the type section have called the placement of this boundary and the utility of the GSSP into question (Kaiser, 2009; Becker et al., 2016; Corradini et al., 2017; Aretz et al., 2020). A joint working group from the international subcommissions on Devonian and Carboniferous stratigraphy has defined a new time-line–based criterion for the placement of the GSSP that includes the base of the *Protognathodus kockeli* conodont zone, the end of the Devonian mass extinction, the start of the Carboniferous radiation, and the top of a major regression (Aretz and Corradini, 2019, 2021). A search for a new GSSP locality is ongoing, but the placement of the GSSP at La Serre remains valid until a new stratigraphic section is selected (Aretz and Corradini, 2021); we note that, following the new boundary criteria, the base of the Tournaisian at La Serre would move downward by 45 cm (Kaiser, 2009; Aretz et al., 2020; Aretz and Corradini, 2021).

The Visean global stage is named after the town of Visé in eastern Belgium, with the historic base of the stage placed at the first black limestone intercalation within the Leffe facies at the Bastion section in the Dinant Basin (Hance et al., 1997; Aretz et al., 2020). Biostratigraphically, this horizon corresponds to the first occurrence of the foraminifera genus *Eoparastaffella*, roughly 1 m below the first occurrence of the conodont *Gnathodus homopunctatus* (Groessens and Noel, 1977; Devuyst et al., 2003). The placement of the GSSP at the Bastion section later came under question, as the first appearance of key fossils occurs diachronously across the basin and was determined to be facies controlled. In addition, the use of an unspecified *Eoparastaffella* sp. as an index fossil was deemed to be unsuitable (Hance et al., 1997; Davydov et al., 2012). No significant faunal turnovers occur in the Tournaisian-Visean boundary interval, so the boundary was redefined to be the first appearance of the foraminifera *Eoparastaffella simplex* within the *Eoparastaffella* lineage (Hance et al., 1997; Devuyst et al., 2003), and this position marks the base of Mississippian foraminifera zone 9 (MFZ9) of Poty et al. (2006). This placement kept the new boundary definition near the original, although the preceding form of *Eoparastaffella* is not present at the Bastion section, so the GSSP was moved to a section near Pengchong village, Guangxi Autonomous Region, South China (Hance et al., 1997; Devuyst et al., 2003; Davydov et al., 2012). At the Pengchong GSSP, the FAD of *Eoparastaffella simplex*, and the base of the Visean, is bracketed by the last appearance datum (LAD) of the conodont *Scaliognathus anchoralis europensis* and the FAD of *Gnathodus homopuctatus* (Hance et al., 1997; Devuyst et al., 2003).

In contrast to the now-standard usage of boundary stratotypes to define GSSPs, the Mississippian and its subdivisions in North America were defined based on the unit-stratotype concept and type areas, where the type area for the Mississippian is the exposures along the Mississippi River between Burlington, Iowa, and southern Illinois (Collinson, et al., 1979; Lane and Brenckle, 2005). The Kinderhookian regional series was named for outcrops near the town of Kinderhook, Pike County, Illinois, and was originally defined to include all strata between the Louisiana Limestone and the Burlington Formation (Collinson, 1961; Lane and Brenckle, 2005). The McCraney North section near Kinderhook is generally treated as the main reference section, and outcrops at Crapo Park in Burlington, Iowa, are considered as the alternative type section (Keyes, 1941; Collinson, 1961; Lane and Brenckle, 2005). Regionally, biostratigraphic data placed the base of the Kinderhookian at the FAD of the conodonts *Siphonodella sulcata* and *Protognathodus kuehni* within the Horton Creek Formation (Collinson, 1961). Recent work would move the base of

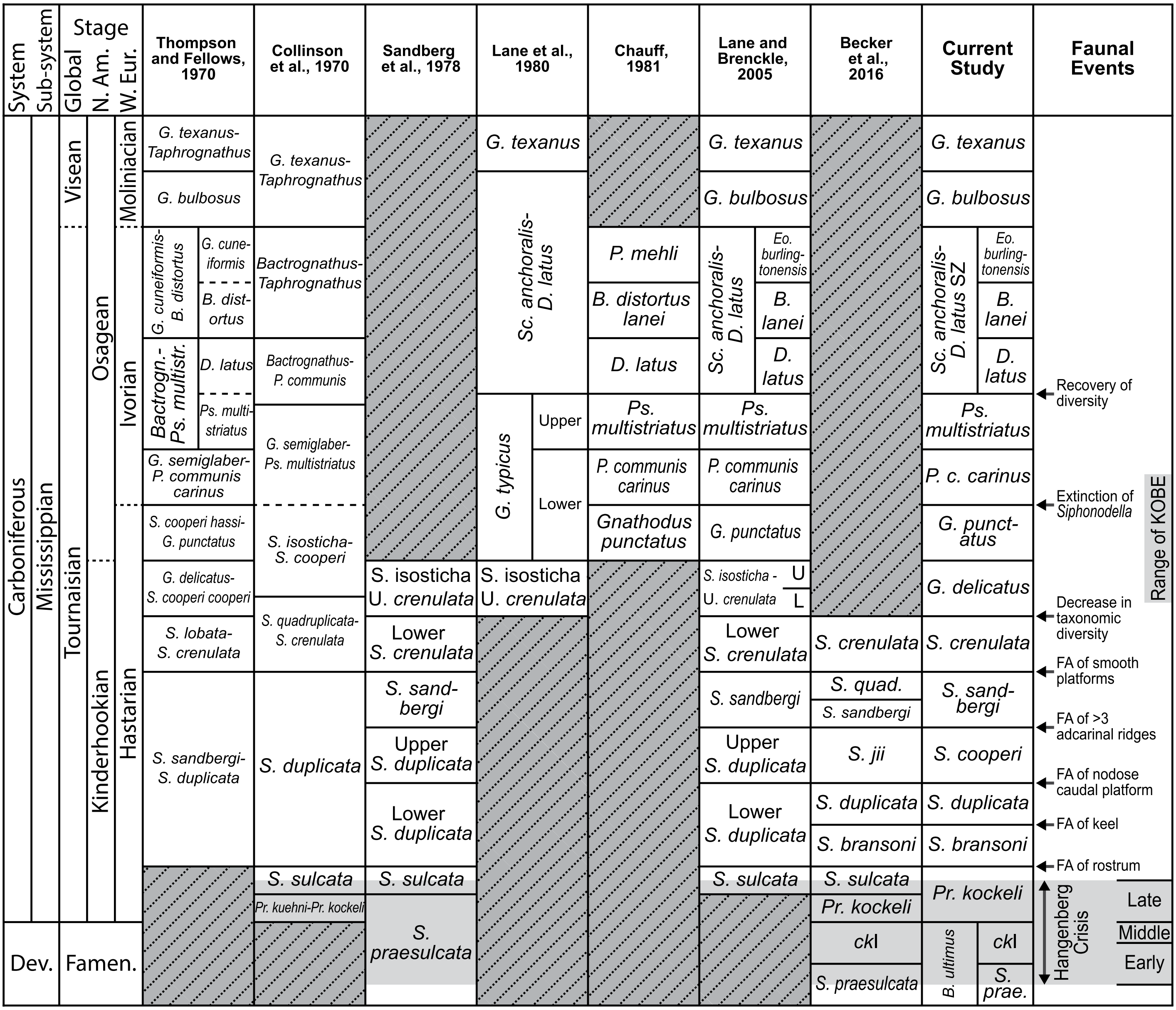


Figure 3. Conodont zonations for the U.S. midcontinent from 1970 to present. Note: Becker et al. (2016) represents the revised international zonation for the Devonian-Carboniferous boundary. Faunal events are after Sandberg et al. (1978), Hogancamp et al. (2019), and Zhuravlev and Plotitsyn (2022). *B.—Bactrognathus*; *ck*I—*Bispathodus costatus–Protognathodus kockeli* Interregnum; *D.—Doliognathus*; Dev.—Devonian; *Eo.—Eotaphrus*; FA—first appearance; Fam.—Famennian; *G.—Gnathodus*; KOBE—Kinderhookian-Osagean boundary excursion; L—lower; N. Am.—North America; *P.—Polygnathus*; *Pr.—Protognathodus*; *Ps.—Pseudopolygnathus*; *S.—Siphonodella*; *Sc.—Scaliognathus*; SZ—superzone; U—upper; W. Eur.—Western Europe.

the Kinderhookian to the first occurrence (FAD) of the *Pr. kockeli* conodont zone (Fig. 3) at the base of the Louisiana Formation, in line with the revised global conodont zonations (see discussion in Stolfus et al., 2020).

The Osagean regional series was named after the exposures along the Osage River in St. Clair County, central Missouri (Williams, 1891), considerably removed from the classical exposures along the Mississippi River Valley. No type section was designated in the original definition, and the exposures described by Williams (1891) all belong to the Burlington Formation (Kaiser, 1950; Thompson, 1986). The concept and use of the Osagean Series have grown and have been primarily based upon the better-known strata of the Mississippi River Valley (i.e., Burlington Formation). However, a significant unconformity between the Burlington/Fern Glen/Meppen units and the clearly Kinderhookian underlying strata throughout the Mississippi River Valley of the Iowa, Illinois, Missouri tristate area removes several conodont zones across the Kinderhookian-Osagean boundary, which limits our ability to precisely define the chronostratigraphic placement of the base of the Osagean in the U.S. midcontinent. The original Missouri reference area remains critically important to the definition of the Osagean series, and the outcrops around the town of Osceola, Missouri, currently serve as the main reference sections (Thompson, 1986; Lane et al., 2005). Throughout central and southwestern Missouri, the base of the Osagean has traditionally been placed at the base of the Pierson Formation (e.g., Thompson, 1986).

Partly due to difficulties with biostratigraphic correlation between the base of the Pierson Formation in central and southwestern Missouri and the base of the Meppen/Fern Glen/Burlington units in the Mississippi River Valley of the tristate area, two schools of thought have developed regarding the biostratigraphic placement of the Kinderhookian-Osagean boundary. The lowest Osagean strata of the Mississippi River Valley, the Meppen and Fern Glen Formations, belong to the *Polygnathus communis carinus* zone (Fig. 3), whereas the base of the Pierson Formation is within the underlying *Gnathodus delicatus* zone (Thompson and Fellows, 1970; Thompson, 1986; Lane and Brenckle, 2005). These two positions, base *delicatus* and base *carinus*, both persist in the literature, and here we chose to follow the position advocated by Lane and Brenckle (2005) for the base of the *punctatus* zone. The base of the Pierson Formation appears to lie within the *punctatus* zone, below the first appearance of *P. c. carinus* (Lane and Brenckle, 2005), and therefore, it is a better approximation of the base of the Osagean regional series. Within the Mississippi River Valley, the Osagean regional stage has historically included all strata between the base of the Meppen Limestone or Fern Glen Formation and the top of the lower Warsaw Formation (Kammer et al., 1990; Lane et al., 2005).

The regional Kinderhookian and Osagean Stages correspond to the global Tournaisian Stage and lower part of the Visean Stage; however, a precise correlation of the base of the Visean Stage into type Mississippian area remains unclear. Historically, the base of the Visean Stage has been correlated to a range of strata in the Mississippian type area from as low as the base of the Burlington/Fern Glen Formation to as high as the Keokuk-Warsaw formational contact (e.g., Witzke and Bunker, 2002; Lane and Brenckle, 2005). Key fossils from the Visean GSSP, including the foraminiferal lineage of *Eoparastaffella* and the conodont *Scaliognathus anchoralis europensis*, are not known in North America (Lane and Brenckle, 2005; Sevastopulo and Devuyst, 2005; Barrick et al., 2022). *Scaliognathus anchoralis anchoralis*, a descendent of *Sc. a. europensis*, has been recovered from the Mississippi Valley region and was used by Brenckle et al. (2005) to place the Tournaisian-Visean boundary within the Fern Glen Formation, corresponding to the *Doliognathus latus* zone of Lane and Brenckle (2005); however, this placement was called into question because it is inconsistent with European conodont occurrences, which suggest that the boundary could occur no lower than the *Gnathodus bulbosus* zone (Sevastopulo and Devuyst, 2005). *Gnathodus homopunctatus*, which occurs just above the GSSP level at the Visean type section, was recovered in Oklahoma from a stratigraphic level equivalent to the *Gnathodus texanus* zone (Godwin et al., 2020; Barrick et al., 2022). Although the exact position remains unclear, the Tournaisian-Visean boundary in the Mississippian type area appears to now be restricted to a position no lower than the base of the Cedar Fork Member of the Burlington Formation and no higher

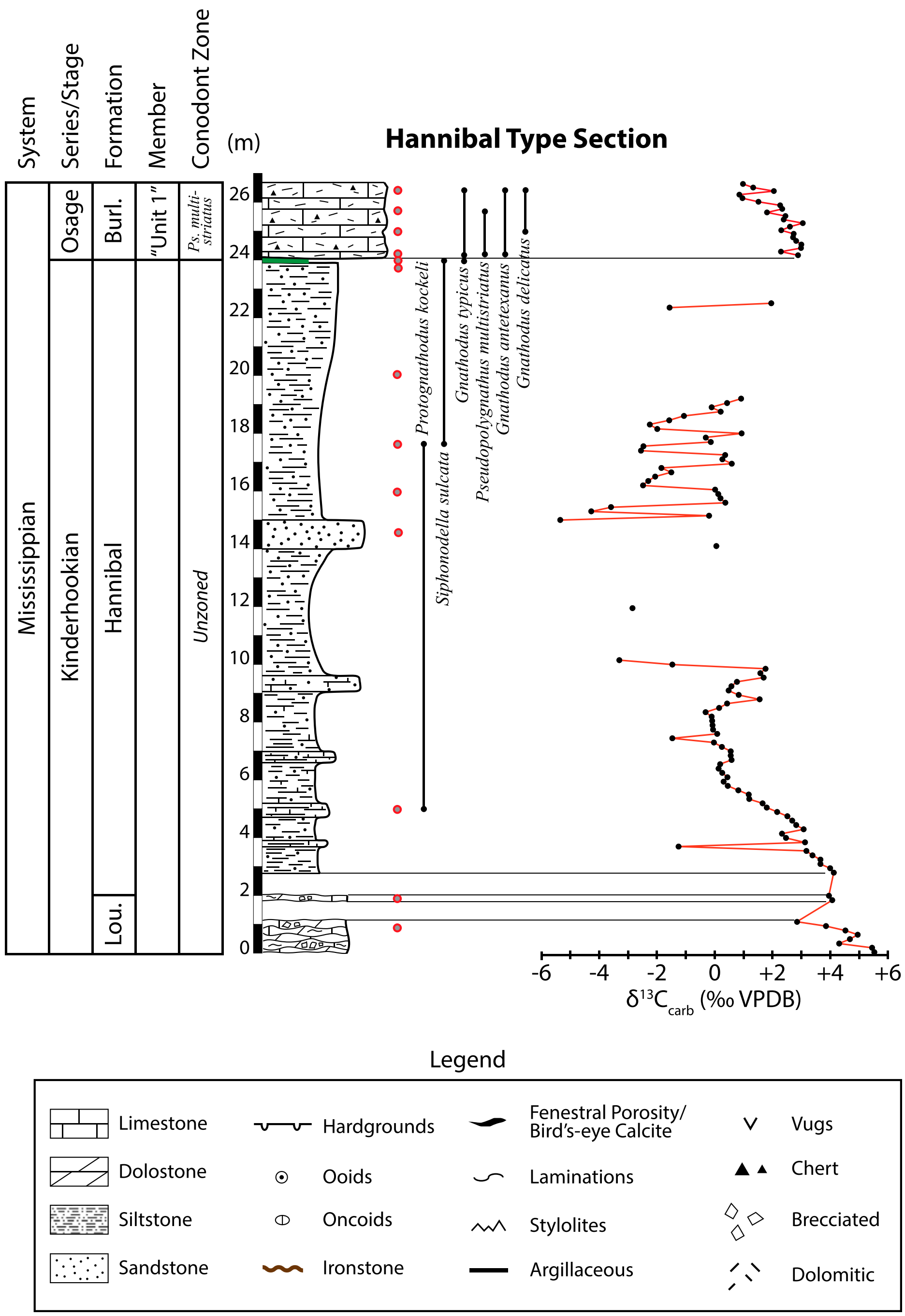


Figure 4. Stratigraphic column and conodont zonation for the Hannibal type section. Red dots next to the lithologic column represent horizons where conodont samples were collected; however, not all samples yielded specimens. Burl.—Burlington; Lou—Louisiana; *Ps.—Pseudopolygnathus*; VPDB—Vienna Peedee belemnite.

Figure 5. Conodonts recovered from the Peterson #1 core and the I-172, Fall Creek, and Hannibal type sections. All images are from a scanning electron microscope (SEM), and the scale bar is 100 µm for each specimen. (A) *Polygnathus communis communis* Branson and Mehl, 1934; dextral P_1 element, oral view, I-172 section, Dolbee Creek Member, Burlington Formation, 0.5–0.6 m. Note: the morphology of this element is atypical. (B) *Polygnathus communis communis* Branson and Mehl, 1934; sinistral P_1 element, oral view, I-172 section, Dolbee Creek Member, Burlington Formation, 1.0–1.15 m. Note: the morphology of this element is atypical. (C) *Polygnathus communis carinus* Hass, 1959; sinistral P_1 element, oral view, Fall Creek section, "unit 1" of Baxter, Burlington Formation, 1.0–1.1 m. (D) *Polygnathus communis carinus* Hass, 1959; sinistral P_1 element, oral view, Fall Creek section, "unit 1" of Baxter, Burlington Formation, 1.0–1.1 m. (E) *Siphonodella sulcata* (Huddle, 1934); sinistral P_1 element, E1 oral view, E2 aboral view, Hannibal type section, Hannibal Formation, 17.65–17.75 m. (F) *Siphonodella sulcata* (Huddle, 1934); dextral P_1 element, F1 oral view, F2 aboral view, Hannibal type section, Hannibal Formation, 17.65–17.75 m. (G) *Siphonodella sulcata* (Huddle, 1934); sinistral P_1 element, G1 oral view, G2 aboral view, Hannibal type section, Hannibal-Burlington contact, 23.9–24.1 m. (H) *Siphonodella obsoleta* Hass, 1959; sinistral P_1 element, oral view, Peterson #1 core, Lower Member, Maynes Creek Formation, 259′4″–260′1″. (I) *Siphonodella cooperi* Hass, 1959; sinistral P_1 element, oral view, Peterson #1 core, Lower Member, Maynes Creek Formation, 259′4″–260′1″. (J) *Siphonodella isosticha* (Cooper, 1939); sinistral P_1 element, oral view, Peterson #1 core, Lower Member, Maynes Creek Formation, 243′9″–245′0″. (K) *Siphonodella isosticha* (Cooper, 1939); dextral P_1 element, oral view, Peterson #1 core, Lower Member, Maynes Creek Formation, 243′9″–245′0″. (L) *Siphonodella* sp.; sinistral P_1 element, oral view, Peterson #1 core, Lower Member, Maynes Creek Formation, 226′9″–228′0″. (M) *Siphonodella* sp.; dextral P_1 element, oral view, Peterson #1 core, Lower Member, Maynes Creek Formation, 259′4″–260′1″. (N) *Siphonodella isosticha* (Cooper, 1939); dextral P_1 element, oral view, Peterson #1 core, Lower Member, Maynes Creek Formation, 226′9″–228′0″. (O) *Siphonodella isosticha*? (Cooper, 1939); sinistral P_1 element, oral view, Peterson #1 core, Upper Member, Maynes Creek Formation, 176′7″–177′6″. (P) *Pseudopolygnathus multistriatus* Mehl and Thomas 1947; see synonymy of Thompson (1967); sinistral? P_1 element, oral view, I-172 section, Dolbee Creek Member, Burlington Formation, 2.9–3.1 m. (Q) *Pseudopolygnathus multistriatus* Mehl and Thomas 1947; see synonymy of Thompson (1967); dextral? P_1 element, oral view, I-172 section, Dolbee Creek Member, Burlington Formation, 2.9–3.1 m. (R) *Pseudopolygnathus multistriatus* Mehl and Thomas 1947; see synonymy of Thompson (1967); dextral P_1 element, oral view, Hannibal type section, "unit 1" of Baxter, Burlington Formation, 25.5–25.8 m. (S) *Pseudopolygnathus multistriatus* Mehl and Thomas 1947; see synonymy of Thompson (1967); sinistral P_1 element, oral view, Hannibal type section, "unit 1" of Baxter, Burlington Formation, 25.5–25.8 m. (T) *Bactrognathus hamatus* Branson and Mehl, 1941; dextral P_1 element, oral view, I-172 section, Dolbee Creek Member, Burlington Formation, 3.4–3.6 m. (U) *Bactrognathus excavatus* Branson and Mehl, 1941; sinistral P_1 element, oral view, I-172 section, Haight Creek Member, Burlington Formation, 5.4–5.55 m. (V) *Bactrognathus excavatus* Branson and Mehl, 1941; dextral P_1 element, oral view, I-172 section, Haight Creek Member, Burlington Formation, 5.4–5.55 m. (W) *Bactrognathus distortus lanei* Chauffe, 1981; dextral? P_1 element, oral view, I-172 section, Haight Creek Member, Burlington Formation, 5.4–5.55 m. (X) *Bactrognathus distortus lanei* Chauffe, 1981; sinistral? P_1 element, oral view, I-172 section, Haight Creek Member, Burlington Formation, 5.4–5.55 m. (Y) *Doliognathus latus* Branson and Mehl, 1941; sinistral P_1 element, oral view, I-172 section, Haight Creek Member, Burlington Formation, 7.0–7.3 m. (Z) *Eotaphrus burlingtonensis* Collinson and Norby, 1973, as reported by Pierce and Langenheim (1974); sinistral P_1 element, oral view, I-172 section, Haight Creek Member, Burlington Formation, 12.0–12.3 m. (AA) *Eotaphrus burlingtonensis* Collinson and Norby, 1973, as reported by Pierce and Langenheim (1974); dextral P_1 element, oral view, I-172 section, Haight Creek Member, Burlington Formation, 15.9–16.1 m. (BB) *Eotaphrus burlingtonensis* Collinson and Norby, 1973, as reported by Pierce and Langenheim (1974); dextral P_1 element, oral view, I-172 section, Haight Creek Member, Burlington Formation, 19.0–19.2 m. For reference: 250 ft = 76.2 m.

than the Burlington-Keokuk formational contact (Witzke and Bunker, 2002; Lane and Brenckle, 2005), primarily based upon the presence of the conodonts *Gnathodus bulbosus*, *G. texanus*, and *Taphrognathus varians* in the lowermost Keokuk Formation.

Conodont Zonation

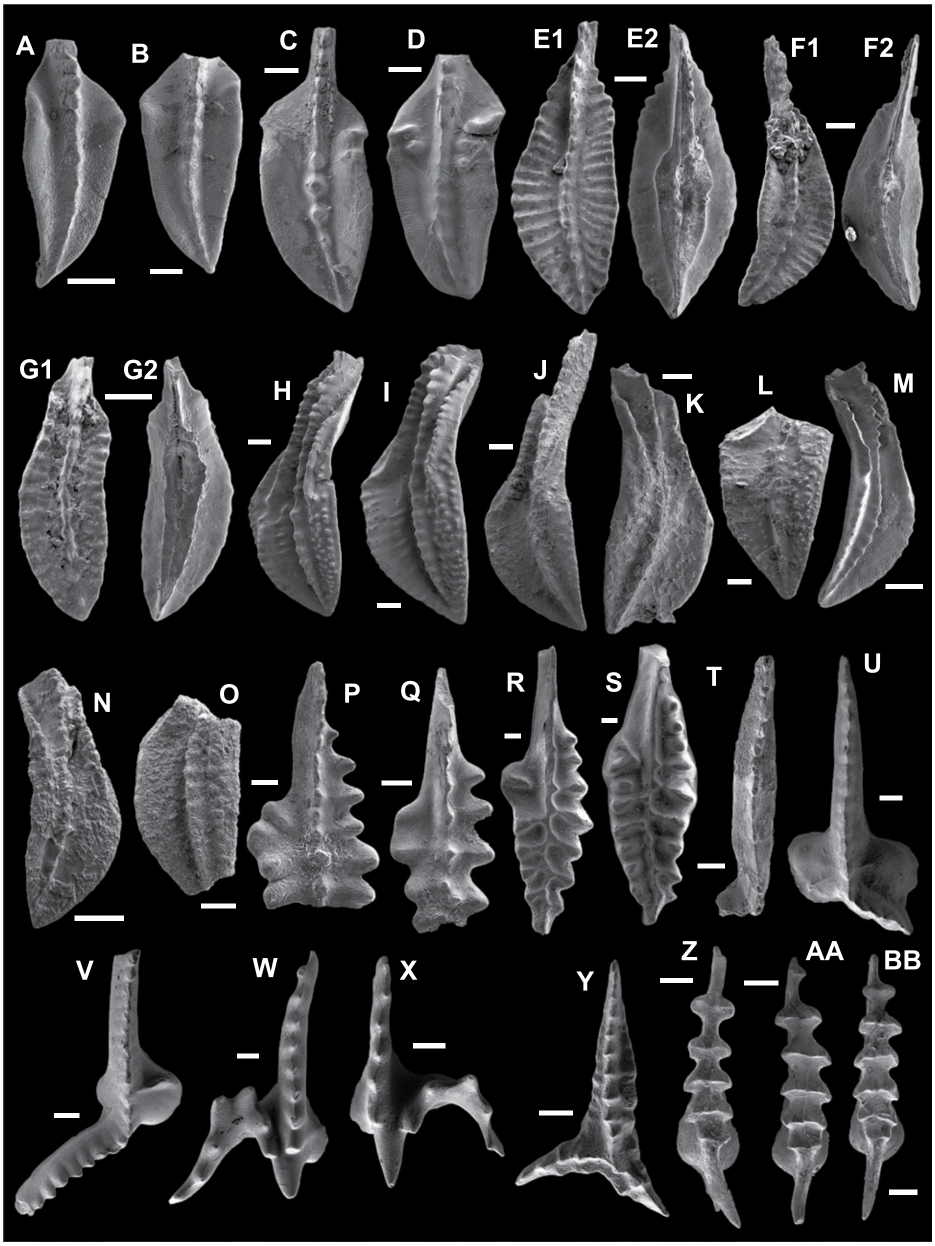
Various conodont zonations have been developed for Early Mississippian strata over the past 50 yr that create a complex and confusing terminology (Fig. 3). Here, we utilized a conodont zonation that closely follows Stolfus et al. (2020) for the Kinderhookian and Lane and Brenckle (2005) for the Osagean. Stolfus et al. (2020) combined zones from Kaiser et al. (2016) for the Kinderhookian, Zhuravlev and Plotitsyn (2017) for the uppermost Kinderhookian to lowest Osagean, and Spalletta et al. (2017) for the Devonian-Carboniferous boundary interval (for a complete discussion of zonal revisions, see Hogancamp et al., 2019; Stolfus et al., 2020). In our usage (Fig. 3), we followed Lane and Brenckle (2005) and placed the Kinderhookian-Osagean boundary at base of the *G. punctatus* zone. It is important to note that the base of the *Gnathodus typicus* zone of Lane et al. (1980) corresponds to the base of the *G. punctatus* zone of Lane and Brenckle (2005).

Carbon Isotope Stratigraphy

The Kinderhookian-Osagean boundary $\delta^{13}C_{carb}$ excursion is a useful chronostratigraphic marker for the Kinderhookian-Osagean boundary interval and has been identified as a major perturbation to the global carbon cycle from sections around the globe (e.g., Mii et al., 1999; Saltzman, 2003; Saltzman et al., 2004; Maharjan et al., 2018; Oehlert et al., 2019; Zhuravlev et al., 2020). Most of these studies utilized the Lane et al. (1980) conodont zonation for comparison, and the onset of the excursion clearly begins during the range of the genus *Siphonodella* (e.g., Saltzman et al., 2004), and the base of the *G. typicus* zone occurs during the excursion near peak values (e.g., Maharjan et al., 2018). Therefore, if the base of the *G. typicus* zone of Lane et al. (1980) corresponds with the base of the *G. punctatus* zone of the revised zonation, as suggested by Lane and Brenckle (2005), then the Kinderhookian-Osagean boundary excursion straddles the Kinderhookian-Osagean boundary.

METHODS

This study integrates new data from three cores and three outcrops with previously published data from three cores and one outcrop across Iowa, Missouri, and Illinois. The Briggs Woods and Ames B-608 cores were sampled for $\delta^{13}C_{carb}$ chemostratigraphy, while the Peterson core was sampled for conodont biostratigraphy; the general stratigraphy from cores Early #1 and Ferguson Quarry was examined and



can be found in Figure S1 of the Supplemental Material[1]. Key outcrops in the Mississippi River Valley were sampled for $\delta^{13}C_{carb}$ chemostratigraphy and conodont biostratigraphy concurrently, including outcrops along Interstate 172 and Fall Creek State Park in Illinois, and the type section of the Hannibal Shale along Missouri Route 79 in Hannibal, Missouri. Additional conodont and $\delta^{13}C$ data from Stolfus et al. (2020) for the H-28 core and outcrops at Starr's Cave Park were integrated with our new data to expand our stratigraphic framework.

For $\delta^{13}C_{carb}$ analysis, a bulk-rock sampling procedure was used to produce a continuous high-resolution chemostratigraphic record through the studied succession. Samples were generally collected at a 30 cm interval; however, in stratigraphic intervals expected to record $\delta^{13}C$ excursions, the sampling resolution was increased to 10 cm. For each sample, the finest available carbonate material from freshly cut and cleaned surfaces was selected and drilled using a handheld drill and tungsten-carbide bit; careful consideration was taken to avoid contamination from biological components, obvious postdepositional cements, and/or secondary mineralization. Sample analysis was performed at the Keck Paleoenvironmental and Environmental Stable Isotope Laboratory (KPESIL) at the University of Kansas. Carbonate powder was reacted with 100% phosphoric acid with density >1.9 (Wachter and Hayes, 1985) and analyzed on a ThermoFinnigan MAT 253 stable isotope ratio mass spectrometer coupled with a Kiel IV carbonate device. Isotopic values were calibrated using the international standards NBS-18 and NBS-19, and daily instrument performance was monitored with laboratory standards TSF-1, SIGMA CALCITE, and 88b Dolomite analyzed at the beginning, middle, and end of each 40 sample queue. Results are reported in per mil notation (‰) measured against the Vienna Peedee belemnite (VPDB) standard, with an analytical precision of ±0.1‰ for both C and O.

At most study localities, conodont samples were collected at 1–2 m resolution, with higher-resolution sampling (≤0.5 m) conducted at expected inflections in the $\delta^{13}C_{carb}$ profile or at sequence boundaries. For each sample, ~6 kg aliquots of rock were digested in a double-buffered formic acid solution using the technique of Jeppsson and Anehus (1995). Residues were sieved through 1000, 125, and 63 μm sieves, and the 125 μm fraction was subjected to heavy liquid separation using lithium metatungstate at 2.84–2.85 g/mL. Conodonts were handpicked under a microscope before selected specimens were coated in gold and imaged using a Hitachi S-3400N scanning electron microscope. All conodont samples illustrated here, as well as nonimaged specimens used in this study, are housed at the University of Iowa Palaeontology Repository.

RESULTS

Hannibal Type Section

The type section for the Hannibal Shale is located along Missouri Route 79, southeast of Hannibal Missouri at 39.70°N, 91.35°W. The outcrop was sampled from the lowest accessible beds of the Louisiana Formation to the highest accessible beds of the Burlington Formation, for a total of ~27 m. Notably at this locality, the contact between the Hannibal and Burlington formations is marked by a thin gummy green shale, a feature not exposed at other outcrops in the region. Strata of the Burlington Formation at this locality belongs to "unit 1" of Baxter and Haines (1990), an interval that occurs below the Dolbee Creek Member. When possible, conodont samples were collected every ~3 m in the Hannibal Shale and every meter in the Burling-

[1]Supplemental Material. Figure S1: Stratigraphic columns for the Hills Chemical (Early #1) and Ferguson Quarry sections used for stratigraphic correlations. Table S1: Data table of all carbon isotope data produced in this study. Please visit https://doi.org/10.1130/GSAB.S.24011463 to access the supplemental material, and contact editing@geosociety.org with any questions.

Figure 6. Conodonts recovered from the I-172, Fall Creek, and Hannibal type sections. All images are from a scanning electron microscope (SEM), and the scale bar is 100 µm for each specimen. (A) *Protognathodus kockeli* (Bischoff, 1957); dextral P_1 element, oral view, Hannibal type section, Hannibal Formation, 4.8–5.0 m. (B) *Protognathodus kockeli* (Bischoff, 1957); sinistral P_1 element, oral view, Hannibal type section, Hannibal Formation, 17.65–17.75 m. Note: the morphology of this element is atypical. (C) *Gnathodus semiglaber* Bischoff, 1957; sinistral P_1 element, oral view, Fall Creek section, "unit 1" of Baxter, Burlington Formation, 1.0–1.1 m. (D) *Gnathodus semiglaber* Bischoff, 1957; sinistral P_1 element, oral view, I-172 section, Dolbee Creek Member, Burlington Formation, 3.4–3.6 m. (E) *Gnathodus semiglaber* Bischoff, 1957; sinistral P_1 element, oral view, Fall Creek section, "unit 1" of Baxter, Burlington Formation, 3.8–4.0 m. (F) *Gnathodus antetexanus* Rexroad and Scott, 1964; dextral P_1 element, oral view, Hannibal type section, "unit 1" of Baxter, Burlington Formation, 26.4–26.7 m. (G) *Gnathodus antetexanus* Rexroad and Scott, 1964; sinistral P_1 element, oral view, I-172 section, Dolbee Creek Member, Burlington Formation, 2.9–3.1 m. (H) *Gnathodus antetexanus* Rexroad and Scott, 1964; sinistral P_1 element, oral view, Hannibal type section, "unit 1" of Baxter, Burlington Formation, 24.1–24.4 m. (I) *Gnathodus antetexanus* Rexroad and Scott, 1964; dextral P_1 element, oral view, Hannibal type section, "unit 1" of Baxter, Burlington Formation, 24.1–24.4 m. (J) *Gnathodus antetexanus* Rexroad and Scott, 1964; sinistral P_1 element, oral view, Hannibal type section, "unit 1" of Baxter, Burlington Formation, 26.4–26.7 m. (K) *Gnathodus antetexanus* Rexroad and Scott, 1964; dextral P_1 element, oral view, I-172 section, Dolbee Creek Member, Burlington Formation, 2.4–2.6 m. (L) *Gnathodus typicus* Cooper, 1939; dextral P_1 element, oral view, Hannibal type section, Hannibal-Burlington contact, 23.9–24.1 m. (M) *Gnathodus typicus* Cooper, 1939; dextral P_1 element, oral view, Hannibal type section, "unit 1" of Baxter, Burlington Formation, 24.1–24.4 m. (N) *Gnathodus typicus* Cooper, 1939; dextral P_1 element, oral view, Hannibal type section, "unit 1" of Baxter, Burlington Formation, 24.1–24.4 m. (O) *Gnathodus typicus* Cooper, 1939; dextral P_1 element, oral view, Fall Creek section, "unit 1" of Baxter, Burlington Formation, 3.8–4.0 m. (P) *Gnathodus typicus* Cooper, 1939; sinistral P_1 element, oral view, I-172 section, Dolbee Creek Member, Burlington Formation, 4.9–5.1 m. (Q) *Gnathodus typicus* Cooper, 1939; sinistral P_1 element, oral view, I-172 section, Dolbee Creek Member, Burlington Formation, 4.5–4.65 m. (R) *Gnathodus typicus* Cooper, 1939; dextral P_1 element, oral view, I-172 section, Haight Creek Member, Burlington Formation, 6.0–6.15 m. (S) *Gnathodus typicus* Cooper, 1939; dextral P_1 element, oral view, I-172 section, Haight Creek Member, Burlington Formation, 6.0–6.15 m. (T) *Polygnathus mehli* Thompson, 1967; P_1 element, oral view, I-172 section, Cedar Fork Member, Burlington Formation, 22.9–23.1 m. (U) *Gnathodus delicatus* Branson and Mehl, 1938; dextral P_1 element, oral view, I-172 section, Dolbee Creek Member, Burlington Formation, 4.9–5.1 m. (V) *Gnathodus delicatus* Branson and Mehl, 1938; dextral P_1 element, oral view, I-172 section, Dolbee Creek Member, Burlington Formation, 4.9–5.1 m. (W) *Gnathodus delicatus* Branson and Mehl, 1938; dextral P_1 element, oral view, I-172 section, Haight Creek Member, Burlington Formation, 7.0–7.3 m. (X) *Gnathodus delicatus* Branson and Mehl, 1938; dextral P_1 element, oral view, I-172 section, Haight Creek Member, Burlington Formation, 10.0–10.2 m. (Y) *Gnathodus delicatus* Branson and Mehl, 1938; dextral P_1 element, oral view, Hannibal type section, "unit 1" of Baxter, Burlington Formation, 24.8–25.1 m. (Z) *Gnathodus delicatus* Branson and Mehl, 1938; dextral P_1 element, oral view, Hannibal type section, "unit 1" of Baxter, Burlington Formation, 26.4–26.7 m.

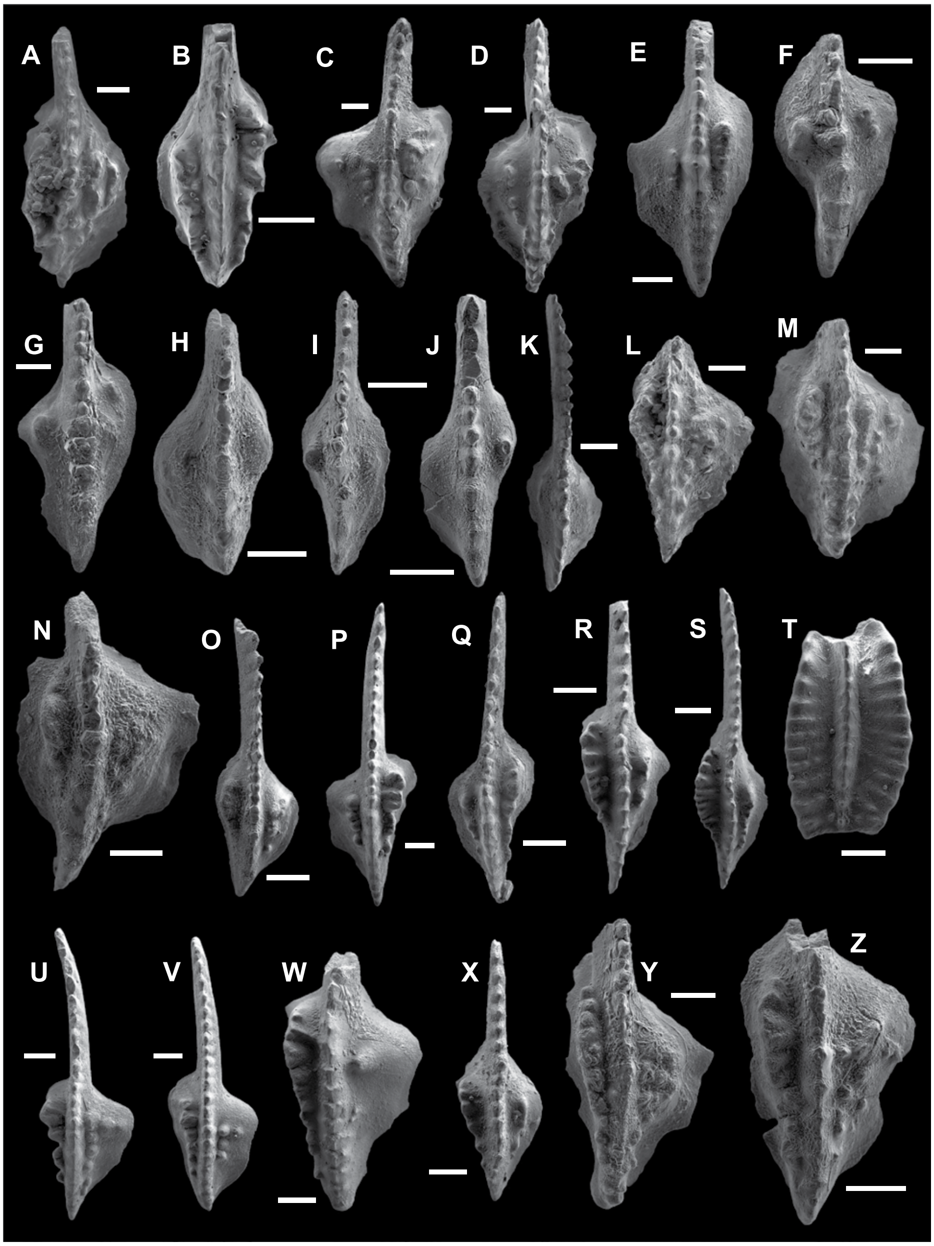
ton Formation, whereas carbon isotope samples were collected every 15 cm through both formations; however, recessive weathering of the outcrop and accumulations of scree near the middle (10–15 m) and the top (20–23 m) of the section made sampling difficult in these intervals. Strata in these two intervals were carbonate poor, and as a result, conodont samples collected between 10 m and 15 m and 20 m to 23 m did not break down, and many of the isotope samples did not yield sufficient carbonate material for analysis. In total, 13 conodont samples were processed, and 131 carbon isotope samples were analyzed. In the section, $\delta^{13}C_{carb}$ values ranged from −5.52‰ to +5.46‰, with peak values occurring in the lowest sampled beds of the Louisiana Formation (Fig. 4). Elevated $\delta^{13}C_{carb}$ values in the Louisiana Formation record the tail end of the Hangenberg excursion, with the falling limb extending into the lower 4 m of the Hannibal Formation (Fig. 4). Biostratigraphically significant conodonts included *Pr. kockeli* and *Siphonodella sulcata* from the Hannibal Formation, *S. sulcata* and *Gnathodus typicus* from the gummy green shale horizon, and *Pseudopolygnathus multisriatus*, *G. typicus*, *Gnathodus antetexanus*, and *G. delicatus* from "unit 1" of the Burlington Formation (Figs. 5 and 6).

Interstate 172

One of the best exposures of the Burlington Formation in the tristate area is located in a road cut on Interstate 172, roughly 20 km south of the city of Quincy, in Adams County, Illinois (39.79°N, 91.31°W). This is one of the most complete nonquarry sections of the formation, as all three members are present and clearly identifiable across 24 m of strata. We collected a total of 30 conodont samples at 0.5 m resolution in the Dolbee Creek Member and at 1 m resolution in the Haight Creek and Cedar Fork Members, as well as 77 carbon isotope samples at 30 cm resolution through the full outcrop. The $\delta^{13}C_{carb}$ values ranged from −4.87‰ to +4.00‰ but generally fluctuated around +3‰ through most of the outcrop (Fig. 7). In the upper half of the Haight Creek Member, $\delta^{13}C_{carb}$ values were highly irregular and varied by as much as ±6‰ between successive data points. Conodont samples returned a diverse faunal assemblage from all three members (Figs. 5 and 6). Biostratigraphically important species included *Polygnathus communis communis*, *Ps. multisriatus*, *G. antetexanus*, *Gnathodus commutatus commutatus*, *Bactrognathus hamatus*, *Gnathodus semiglaber*, and *G. typicus* in the Dolbee Creek Member, *G. typicus*, *G. delicatus*, *Bactrognathus excavatus*, *Bactrognathus distortus lanei*, *Doliognathus latus*, and *Eotaphrus burlingtonensis* in the Haight Creek Member, and *Polygnathus mehli* in the Cedar Fork Member. Irregular $\delta^{13}C_{carb}$ values in the upper Haight Creek Member were coincident with an increase in conodont alteration indices (CAI) values and a change in lithology where strata are more pervasively dolomitized, and chert is more abundant. Notably, within a few meters, CAI values increase from 2 to 5 and are sustained across this 8 m interval. In the Cedar Fork Member, CAI values abruptly return to 2, coincident with the interval where $\delta^{13}C_{carb}$ values return to a baseline of +3‰.

Fall Creek

Located ~1 km southeast of the Interstate 172 section, the Fall Creek Scenic Overlook Park is in Adams County, Illinois (39.79°N, 91.30°W). Here, the uppermost beds of the Hannibal Formation and the lower Burlington Formation are exposed along a stream bed, including ~4 m of "unit 1" of Baxter and Haines (1990) present below the base of the Dolbee Creek Member (Fig. 7). Conodont samples were collected across the Hannibal-Burlington formational



contact and near the top of the Dolbee Creek Member to correlate this section to the nearby Interstate 172 strata. Biostratigraphically significant species recovered included *Po. communis carinus*, *G. semiglaber*, *G. typicus*, and *G. antetexanus* in "unit 1" and *G. typicus* in the Dolbee Creek Member (Figs. 5 and 6).

Ames B-608 Core

The Ames B-608 core (Iowa Geological Survey W# 30842) was drilled within the city limits of Ames, Iowa, at 42.02°N, 93.62°W. We sampled ~210 ft (~64 m) of strata spanning the English River, Prospect Hill, Maynes Creek, Gilmore City, and Burlington Formations. All three members of the Burlington Formation are present and overlie the Gilmore City Formation in this core, a stratigraphic relationship not seen elsewhere in our study (Fig. 8); the Burlington–Gilmore City formational contact is marked by a thin, well-developed hardground. In total, 232 carbon isotope samples were collected at a resolution of every 3 in. (~7.5 cm) through the English River Formation, every 6 in. (~15 cm) through the Prospect Hill Formation and Chapin Member, and every 1 ft (~30 cm) through the Maynes Creek and Gilmore City Formations. Through most of the core, $\delta^{13}C_{carb}$ values ranged from −0.25‰ to +5.30‰; however, within the Prospect Hill Formation, $\delta^{13}C_{carb}$ values were significantly lighter and ranged between −2.10‰ and −3.66‰ (Fig. 8). The Kinderhookian-Osagean boundary excursion is recorded here and has a rising limb within the lower Gilmore City Formation before reaching peak values of +5‰ near the Marble Valley–Humboldt member contact; the falling limb of the excursion is present within the Humboldt Member, and $\delta^{13}C_{carb}$ values appear to return to baseline before the hardground that marks the contact with the Burlington Formation. The Hangenberg excursion is not recorded in this core, and the Devonian-Mississippian boundary is marked by a thin, irregular oolitic ironstone bed present at the base of the Prospect Hill Formation.

Briggs Woods Core

The Briggs Woods core (Iowa Geological Survey W# 50000) was drilled on the outskirts of Webster City, Iowa, at 42.44°N, 93.80°W. The sampled section spans 271 ft (~83 m) of strata across the Aplington, English River, Prospect Hill, Maynes Creek, and Gilmore City Formations. In total, 565 carbon isotope samples were collected from the core, generally at a 6 in. interval (~15 cm); the sampling resolution was increased to 3 in. (~7.5 cm) in condensed strata and expanded to 1 ft (~30 cm) in the upper portion of the core. In general, $\delta^{13}C_{carb}$ values ranged between +0.06‰ and +6.29‰, with one anomalously negative data point present in the English River Formation (Fig. 9). The Kinderhookian-Osagean boundary excursion is present here and begins near the base of the Gilmore City Formation and rises to peak values of +6‰ around the contact between the Marble Valley and Humboldt Members; the falling limb of the excursion is present in the upper Humboldt Member, as $\delta^{13}C_{carb}$ values decrease and return to baseline near the top of the sampled strata. The Hangenberg excursion is absent in this core, and the base of the Prospect Hill Formation comprises a thin oolitic ironstone bed, which marks the Devonian-Mississippian boundary.

Peterson Core

The Peterson core (Iowa Geological Survey W# 11749) was drilled near Thor, Iowa, at 42.63°N, 94.02°W. We sampled ~150 ft (~46 m) of strata for conodont biostratigraphy across the Maynes Creek, Prospect Hill, and English River Formations, generally at a 5 ft (~1.5 m) resolution for a total of 16 samples (Fig. 10). The top of the cored interval begins within the upper Maynes Creek Formation and does not represent the formational contact; in the subsurface, the contact with the overlying Gilmore City Formation occurs at depth of ~120 ft

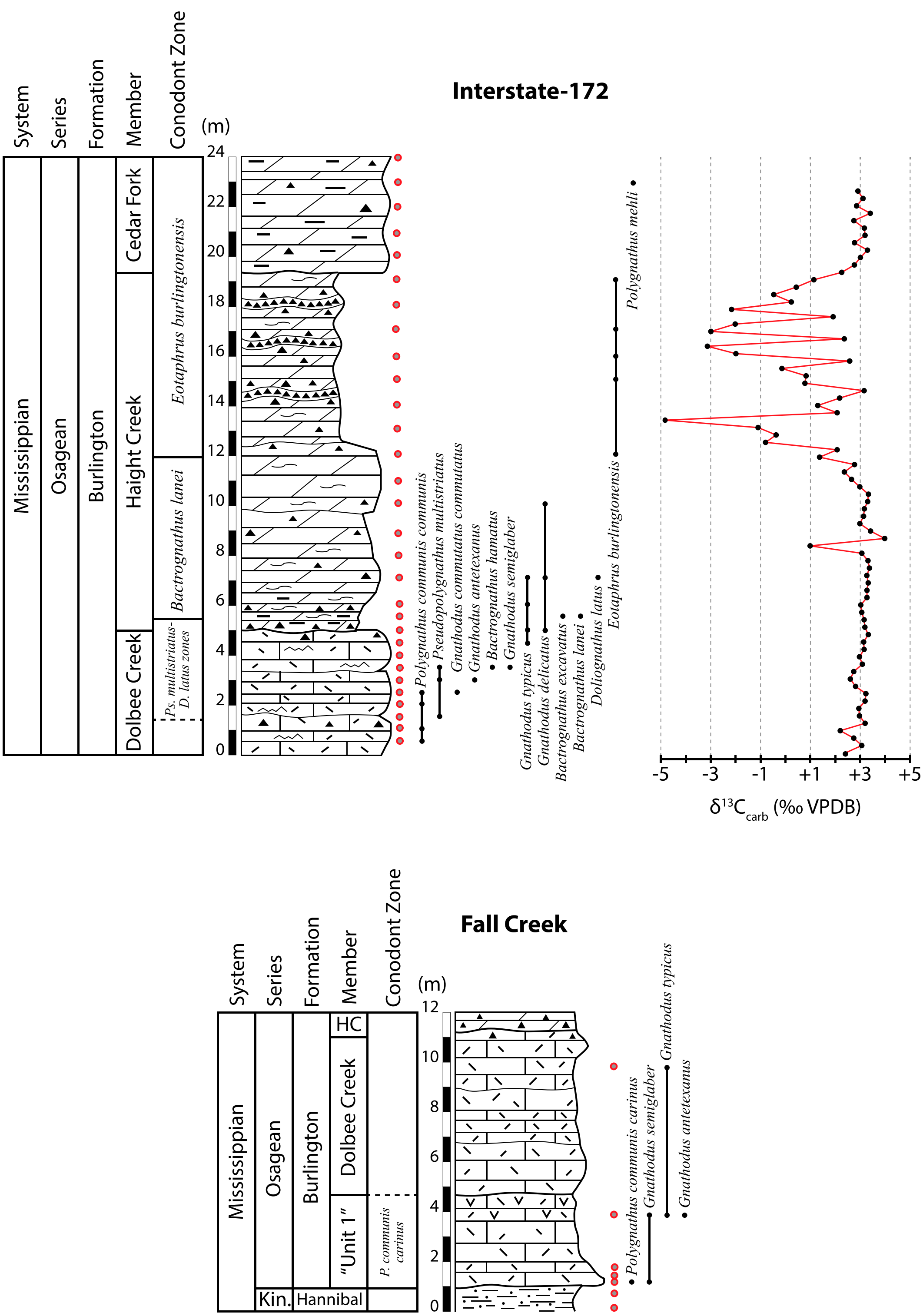


Figure 7. Stratigraphic columns and conodont zonation for the Interstate-172 and Fall Creek sections. Red dots next to the lithologic column represent horizons where conodont samples were collected; however, not all samples yielded specimens. Irregular $\delta^{13}C$ pattern in the upper Haight Creek Member corresponds to an increase in conodont alteration indices values and a change in lithology where strata become more pervasively dolomitized and chert rich. See Figure 4 for legend. *D.*—*Doliognathus*; HC—Haight Creek; Kin.—Kinderhookian; *P.*—*Polygnathus*; *Ps.*—*Pseudopolygnathus*; VPDB—Vienna Peedee belemnite.

(~37 m). Samples yielded an abundance of conodonts belonging to the genus *Siphonodella*, including *Siphonodella quadruplicata*, *Siphonodella cooperi*, and *Siphonodella obsoleta* in the Prospect Hill Formation, and *S. cooperi*, *S. obsoleta*, and *Siphonodella isosticha* in the Maynes Creek Formation (Fig. 5).

DISCUSSION

A stratigraphic cross section that extends from central Iowa to southeast Iowa to northeast Missouri is presented in Figure 11. All outcrops and cores discussed in this study (Figs. 4 and 7–10) were included and integrated with lithostratigraphic data from the Early #1 core and Ferguson Quarry sections (Fig. S1 [see footnote 1]), as well as the Starr's Cave outcrop and H-28 core from Stolfus et al. (2020). The integrated conodont and carbon isotope biochemostratigraphy presented here provides new insights into the chronostratigraphic correlation of strata across

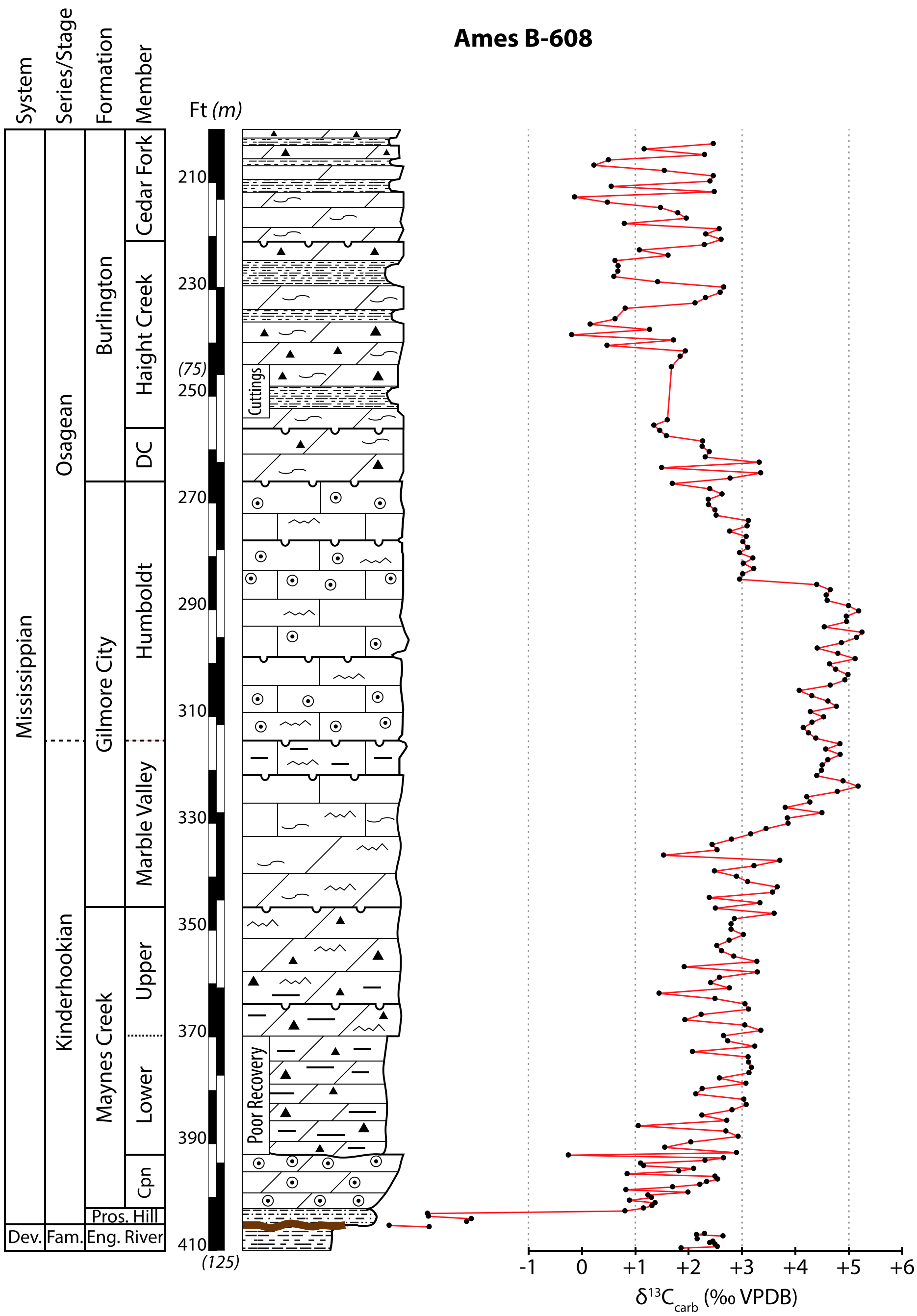


Figure 8. Stratigraphic column for the Ames B-608 core. See Figure 4 for legend. Cpn—Chapin; DC—Dolbee Creek; Dev.—Devonian; Eng. River—English River; Fam.—Famennian; Pros. Hill—Prospect Hill; VPDB—Vienna Peedee belemnite.

the Burlington shelf (Fig. 11) and revises the historical correlations of the Gilmore City and Burlington Formations (Figs. 1 and 2). Three general stratigraphic trends can be identified across the study area: (1) a northwestward thinning of lower Kinderhookian strata, (2) a northwestward thickening of upper Kinderhookian and lower Osagean strata along the Kinderhookian-Osagean boundary, and (3) a concomitant southeastward expansion of the Kinderhookian-Osagean boundary unconformity across the proximal and central middle shelf (Fig. 11).

Lower Kinderhookian Strata and the Hangenberg Excursion

The Hangenberg excursion is recorded at the Hannibal type section, in the H-28 core, and at the Starr's Cave section. At the Hannibal type section, the Hangenberg excursion is present within the Louisiana Formation and the lower few meters of the Hannibal shale (Fig. 4); additionally, ∼10 mi (∼16 km) southeast along Missouri Route 79, the excursion is recorded across 8 m of the Louisiana Formation present below our section (Cramer et al., 2008). In the H-28 core, an expanded section of the Hangenberg excursion is recorded and covers the *Pr. kockeli*, *Siphonodella bransoni*, and *Siphonodella duplicata* conodont zones, whereas at Starr's Cave, the "McCraney" section contains a partial record of the descending limb of the Hangenberg excursion within the *S. cooperi* zone (Stolfus et al., 2020). At the Hannibal type section, not enough diagnostic conodonts were recovered in our study to provide a zonation for the outcrop; however, the presence of the end of the Hangenberg excursion in the basal beds of the Hannibal Shale indicates the base of the formation likely lies within the *S. duplicata* zone at this outcrop, as it does in the H-28 core. Elsewhere in Missouri, conodonts ranging from the *S. bransoni* up to the *Siphonodella crenulata* zones have been recovered from the Hannibal Shale (Collinson et al., 1970; Sandberg et al., 1978; Lane and Brenckle, 2005). As the interval thins northwestward, the Prospect Hill Formation has yielded conodonts from the *S. duplicata*, *S. cooperi*, and *Siphonodella sandbergi* zones in the H-28 core (Stolfus et al., 2020) but gets progressively younger to the northwest and only yielded conodonts from the *S. sandbergi* zone at both Starr's Cave and the Peterson core (Fig. 10).

Across the study area, the base of the Kinderhookian (i.e., the Devonian-Carboniferous boundary) is marked by a northwestward-expanding hiatal surface (Fig. 12). No record of the Hangenberg excursion was identified in central Iowa, and the four lowest Kinderhookian conodont zones are missing throughout the inner shelf of central Iowa, all of the proximal middle shelf, and the much of the central middle shelf where the oldest Kinderhookian conodonts recovered are from the *S. sandbergi* zone. The lowermost Kinderhookian stratum in central Iowa is a thin oolitic ironstone at the base of the Prospect Hill Formation, which was likely deposited as a transgressional lag. Lower Kinderhookian strata expand rapidly into southeasternmost Iowa and northeastern Missouri (Figs. 11 and 12). The preservation of Devonian-Carboniferous boundary strata and the Hangenberg excursion only in down-ramp settings from the central middle shelf and basinward corresponds well with the global eustatic sea-level reconstructions of this interval, wherein the Devonian-Carboniferous

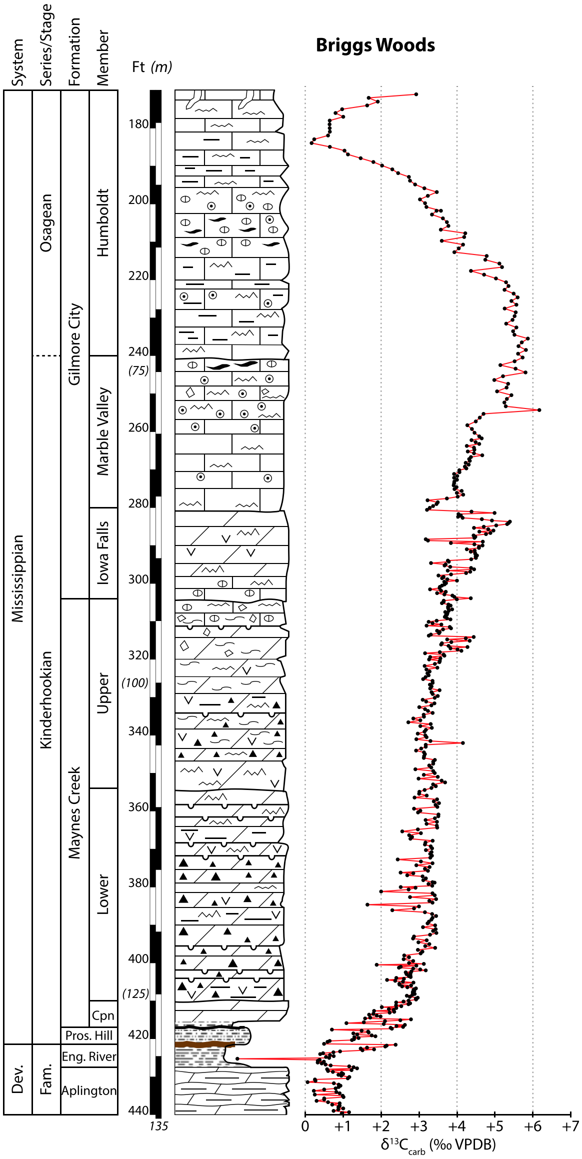


Figure 9. Stratigraphic column for the Briggs Woods core. See Figure 4 for legend. Cpn—Chapin; Dev.—Devonian; Eng. River—English River; Fam.—Famennian; Pros. Hill—Prospect Hill; VPDB—Vienna Peedee belemnite.

boundary is marked by a general regression (e.g., Becker et al., 2016; Kaiser et al., 2016), which helps to explain the preservation of this interval only in the most distal settings of our study area.

Kinderhookian-Osagean Boundary Interval and the Kinderhookian-Osagean Boundary Excursion

The Kinderhookian-Osagean boundary interval is missing in the most distal portions of our study area, and it is a well-documented disconformity throughout the classical Mississippi River Valley type area (e.g., Thompson and Fellows, 1970; Witzke and Bunker, 1996; Witzke and Bunker, 2002; Lane and Brenckle, 2005). Within the central middle shelf of southeast Iowa, the transgressive carbonate package above the Prospect Hill Formation begins with the Starr's Cave Member of the Wassonville Formation. Across the inner shelf and proximal middle shelf of central Iowa, the Chapin Member of the Maynes Creek Formation is the transgressive carbonate above the thin Prospect Hill. Conodonts from the Chapin Member and lower Maynes Creek Formation in the Peterson core (Fig. 10) and from the Starr's Cave Member and Wassonville Formation at the Starr's Cave outcrop and H-28 core (Stolfus et al., 2020) demonstrate that the base of this carbonate package occurs within the *S. sandbergi* zone. This carbonate package is dramatically truncated below (typically along a hardground) the Burlington Formation (Witzke and Bunker, 1996, 2002), and the truncation is most severe within the central middle shelf of southeastern Iowa, where the uppermost beds of the Wassonville Formation barely extend into the *Siphonodella crenulata* zone (e.g., H-28 core; Stolfus et al., 2020), and the overlying unit is the Dolbee Creek Member of the Burlington Formation, which is not known to be any older than the *Ps. multistriatus* zone (e.g., Lane and Brenckle, 2005). In this central middle-shelf position, the disconformity is at its regionally most extensive and removes three entire conodont zones (*G. delicatus*, *G. punctatus*, *P. c. carinus*) and part of at least one other (*S. crenulata*). As one may expect, this gap is partially filled in down ramp, as the Chouteau Formation in eastern Missouri and western Illinois (Collinson et al., 1970; Chauffe and Guzman, 1997) contains *Siphonodella isosticha*, *G. delicatus*, and other early *Gnathodus* specimens and ranges at least as high as the *G. delicatus* zone, while the overlying Meppen and Fern Glen units, as well as Burlington "unit 1 of Baxter" (Baxter and Haines, 1990; Witzke and Bunker, 1996; Fig. 7), contain conodonts indicating the *P. c. carinus* zone below the oldest Dolbee Creek Member of the Burlington Formation (Lane and Brenckle, 2005; Fall Creek outcrop herein). Unfortunately, no carbon isotope data are available from these down-ramp sections, and it remains unclear if any of the Kinderhookian-Osagean boundary excursion is preserved in these strata.

The most perplexing part of the Early Mississippian stratigraphic succession of the region is the fact that this gap at the Kinderhookian-Osagean boundary is also infilled in the up-ramp direction (e.g., Witzke, and Bunker, 2002) with extremely thick carbonate strata of the upper Maynes Creek and overlying Gilmore City Formations in the proximal middle shelf and inner shelf (Fig. 13; Ferguson, Ames B-608, Briggs Woods, Peterson, and Early #1 sections). The Kinderhookian-Osagean boundary excursion was recorded in the skeletal-oolitic packstones and grainstones of the Gilmore City Formation in the Briggs Woods and Ames B-608 cores (Figs. 8 and 9). However, no biostratigraphy samples were collected from the formation in the present study, and conodont yields in this formation have been notoriously poor because the formation was deposited in a shallow peritidal environment. A few conodonts have been recovered from the lowermost 4 m of the Gilmore City Formation, which yielded *Siphonodella* sp. (including cf. *S. isosticha* and a single *S. obsoleta*). This indicates that the base of the lower Gilmore City Formation is no older than the *G. delicatus* zone (Hughes, 1977; Woodson et al., 1989; Witzke and Bunker, 2002).

Most of the global records of the Kinderhookian-Osagean boundary excursion that also

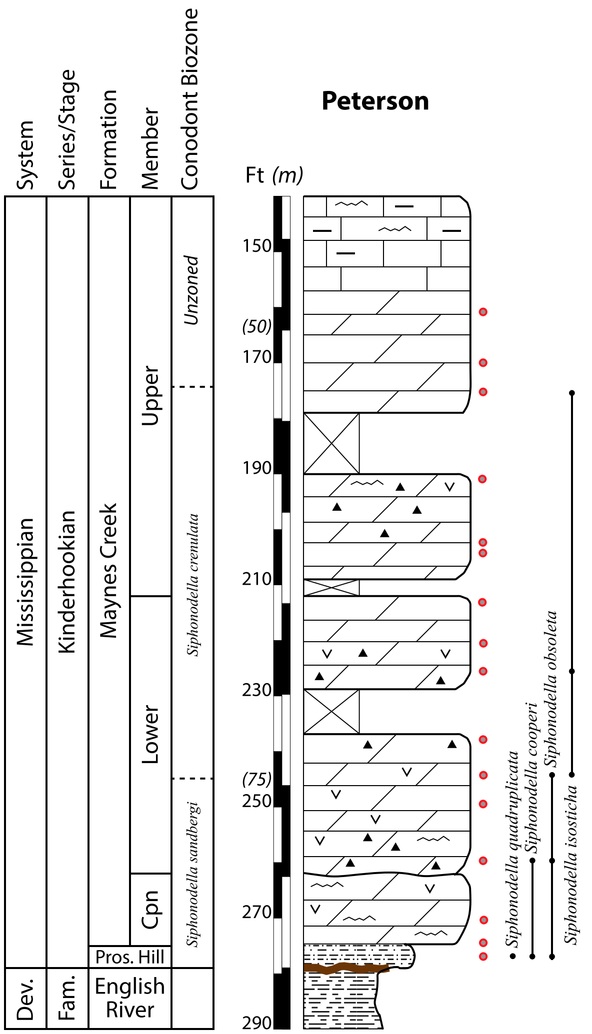


Figure 10. Stratigraphic column and conodont zonation for the Peterson core. Red dots next to the lithologic column represent horizons where conodont samples were collected; however, not all samples yielded specimens. See Figure 4 for legend. Cpn—Chapin; Dev.—Devonian; Fam.—Famennian; Pros. Hill—Prospect Hill.

contain conodont control utilized the conodont zonation of Lane et al. (1980) and demonstrate that the excursion begins within the upper Kinderhookian *isosticha*–upper *crenulata* zone (our *G. delicatus* zone), persists at or near peak values into the *G. typicus* zone (Fig. 3; our *G. punctatus* zone; Lane and Brenckle, 2005), and ends shortly after the first occurrence of *P. c. carinus* (e.g., Saltzman et al., 2004; Maharjan et al., 2018). Specifically, the excursion clearly begins within the range of the genus *Siphonodella* and ends just beyond the first occurrence of *P. c. carinus* and therefore ranges from the *G. delicatus* zone to within the *P. c. carinus* zone. In both the Briggs Woods and Ames B-608 cores, the excursion begins within the lower Gilmore City Formation, reaches peak values near the Marble Valley–Humboldt member (i.e., lower-upper Gilmore City Formation) contact, and persists into the Humboldt Member of the upper Gilmore City Formation. The Marble Valley–Humboldt contact is marked by hardgrounds in Ames B-608 and a hiatal surface in Briggs Woods (Figs. 8 and 9) and likely represents a sediment-starved flooding surface. Based on the record of the Kinderhookian-Osagean boundary excursion in these cores, the Gilmore City Formation likely spans the *G. delicatus* to *P. c. carinus* conodont zones (Fig. 12), with the Kinderhookian-Osagean boundary (base *G. punctatus* zone) present at, or near, the Marble Valley–Humboldt Member (lower-upper Gilmore City Formation) contact. The Gilmore City Formation has long been thought to be laterally equivalent to the Burlington Formation (Figs. 1 and 2). Instead, the identification of the Kinderhookian-Osagean boundary excursion in the Gilmore City Formation demonstrates that most, if not all, of the formation sits chronostratigraphically below the Dolbee Creek Member of the Burlington Formation (Fig. 12).

The fact that the Gilmore City Formation represents a chronostratigraphic interval not preserved in the classical Mississippi River Valley area is not a new insight (e.g., Witzke and Bunker, 1996), and biostratigraphic tools other than conodonts have suggested this in the past. For example, in a series of publications, Carter (1972, 1987, 1991) demonstrated that the Gilmore City Formation contained a brachiopod fauna (his *Calvustrigis rutherfordi* zone) that was absent in the Mississippi River Valley and that predated the earliest Osagean and postdated the latest Kinderhookian in the type Mississippian area. Foraminifera also corroborate the identification of the positive carbon isotope excursion in the Gilmore City Formation as the Kinderhookian-Osagean boundary excursion, and the presence of tuberculate foraminifera in the Marble Valley and Humboldt Members of the Gilmore City Formation (Brenckle and Groves, 1986; Woodson, 1993; Lane and Brenckle, 2005) is useful for comparison to the classical European type area of the Tournaisian global stage in Belgium (Poty et al., 2006, 2014).

The foraminifera zonation of Devuyst and Hance in Poty et al. (2006) demonstrated that the first tuberculate endothyrid foraminifera entered at the base of their MFZ4, which in the Tournaisian type area occurs at the base of the Hun Member of the Yvoir Limestone (Poty et al., 2014) and co-occurs with the last of the siphonodellid conodonts (*S. obsoleta*) as well as the first of the gnathodids (*G. delicatus* and *G. punctatus*) in the lower part of the zone. The base of MFZ4 corresponds with the base of the "Zone of Tuberculate Foraminifera (ZTF)" of Brenckle and Groves (1986), and the carbon isotope data of Saltzman et al. (2004) showed that this position in Belgium occurs during the rising limb of the onset of the Kinderhookian-Osagean boundary excursion. Several biostratigraphically useful foraminifera have been recovered from the Gilmore City Formation, including *Granuliferella latispiralis*, *Palaeospiroplectamina tchernyshinensis*, *Granuliferelloides nalivkini*, *Spinochernella brencklei*, and the tuberculate species *Tuberendothrya tuberculata* (Brenckle and Groves, 1986; Woodson, 1993; Lane and Brenckle, 2005), the latter three of which first occur at the base of MFZ4, and *G. latispiralis* first occurs at the base of MFZ5. Therefore, the base of the MFZ4 is within the Marble Valley Member of the lower Gilmore City Formation, while the base of MFZ5 lies within the Humboldt Member of the upper Gilmore City Formation (Brenckle and Groves, 1986; Woodson, 1993; Lane and Brenckle, 2005). In Belgium, the conodont *P. c. carinus* zone, and therefore the base of the *P. c. carinus* zone, first occurs in the upper part of MFZ4 and extends into MFZ5 (Poty et al., 2014), where the end of the Kinderhookian-Osagean boundary excursion appears to be restricted within this interval (Saltzman et al., 2004). Therefore, the foraminifera biostratigra-

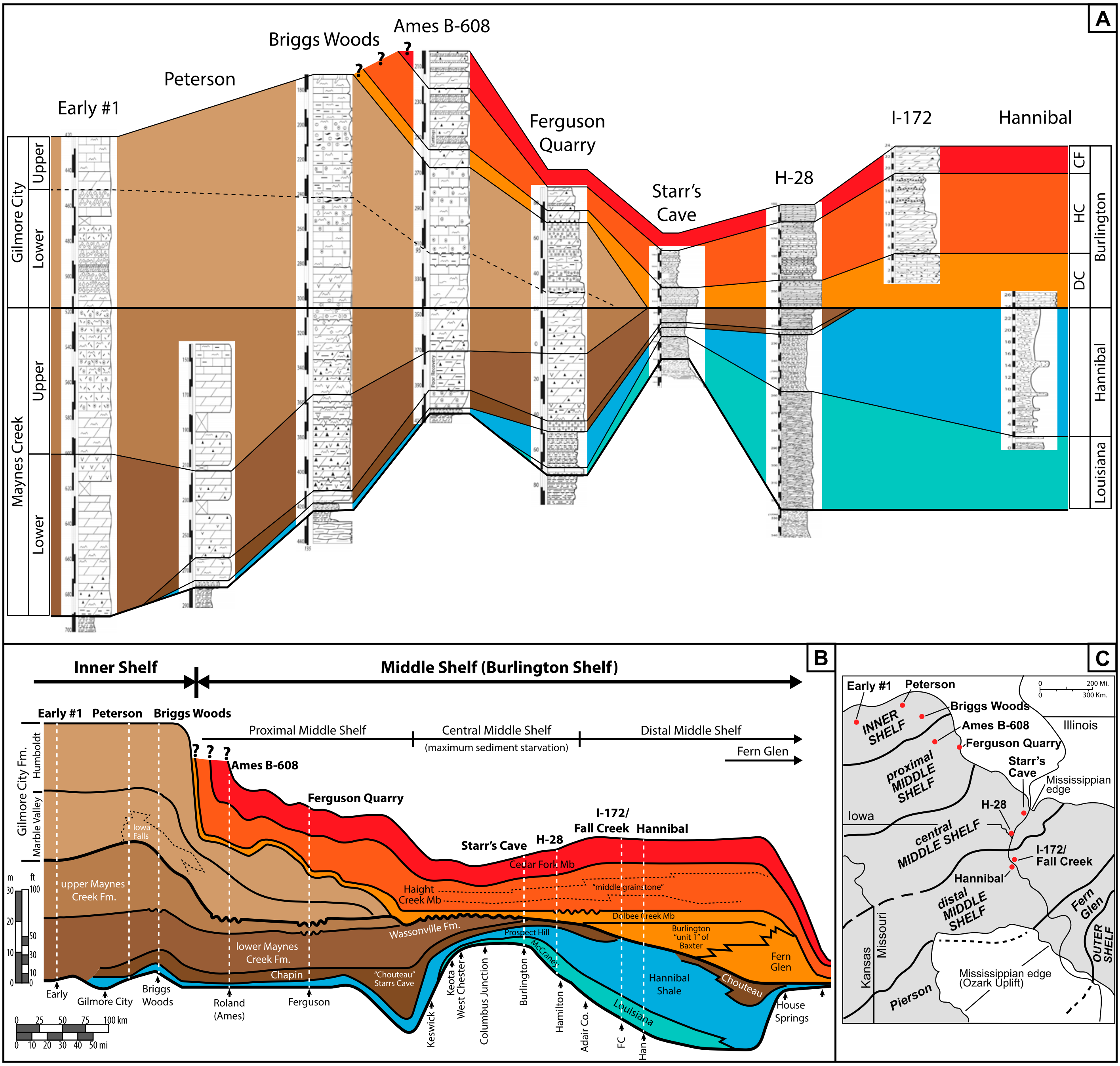


Figure 11. (A) Northwest-southeast stratigraphic correlation from central Iowa to Missouri. Colors are organized by depositional sequences discussed in text. (B) Revised correlation across the tristate area. (C) Distribution of Early Mississippian facies belts and localities used in the correlations. Parts B and C are modified after Witzke and Bunker (2002). See Figure 4 for legend. CF—Cedar Fork; DC—Dolbee Creek; FC—Fall Creek; HC—Haight Creek.

phy (MFZ4 and MFZ5) provides further support for a correlation of the Gilmore City Formation to an interval from the *G. delicatus* zone to the *P. c. carinus* zone as suggested above.

It should be noted, however, that above this interval (MFZ4 and MFZ5), the zonation in Poty et al. (2006) is difficult to align with the conodont biostratigraphy of the U.S. midcontinent. There are no zonally diagnostic foraminifera of MFZ5 known from the Burlington Formation in the Mississippian type area, and the first diagnostic MFZ6 genera, *Endothyra* and *Tetrataxis*, do not occur until the uppermost Cedar Fork Member and the lowermost Keokuk Formation, respectively (Lane and Brenckle, 2005). The first occurrence of *Tetrataxis* defines the base of MFZ6 (Poty et al., 2006), which co-occurs with the base of the *anchoralis-latus* conodont zone (*Sc. anchoralis–D. latus* superzone herein; Fig. 3) in Belgium (Poty et al., 2014), and the base of the Visean global stage is marked by the base of MFZ9 and the base of the *G. homopunctatus* conodont zone (Poty et al., 2014). Throughout

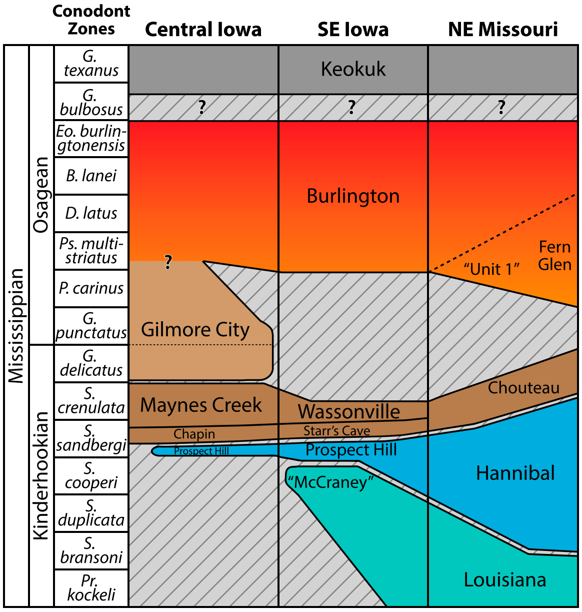


Figure 12. Chronostratigraphic chart for the Lower Mississippian strata across the Burlington shelf. Conodont zonation follows our zonation in Figure 3. *B.*—*Bactrognathus*; *D.*—*Doliognathus*; *Eo.*—*Eotaphrus*; *G.*—*Gnathodus*; *P.*—*Polygnathus*; *Pr.*—*Protognathodus*; *Ps.*—*Pseudopolygnathus*; *S.*—*Siphonodella*.

our study area, the base of the *Sc. anchoralis–D. latus* superzone occurs low within the Burlington Formation near the base of the Haight Creek Member (e.g., I-172 outcrop herein; Lane and Brenckle, 2005), and the first Visean conodonts (e.g., *G. texanus* and *T. varians*) occur at or near the base of the Keokuk Formation, roughly coincident with the advent of MFZ6 taxa.

Burlington Formation and the Sub-Burlington Disconformity

The Gilmore City and Burlington Formations have long been thought to be at least partially correlative units, representing coeval inner-shelf and middle-shelf facies, respectively (Witzke and Bunker, 1996; Witzke and Bunker, 2002). The Dolbee Creek Member was correlated to the uppermost interval of the Marble Valley Member, while the Haight Creek and Cedar Fork Members were correlated to the Humboldt Member (Fig. 1). Our new $\delta^{13}C$ chemostratigraphic data demonstrate that the formations are not equivalent, as the Kinderhookian-Osagean boundary excursion does not extend into the Burlington Formation in the Ames B-608 core, nor was the excursion recorded in the H-28 core or I-172 section. The Gilmore City Formation likely spans the *G. delicatus* to *P. c. carinus* conodont zones, while conodonts recovered from the Burlington Formation at I-172 span the *Ps. multistriatus* to *Eo. burlingtonensis* zones (Fig. 7); rather than being partially correlative units, the majority of the Burlington Formation above "Unit 1 of Baxter" appears to be younger than the Gilmore City Formation (Figs. 11 and 12). In both the Briggs Woods and Ames B-608 cores, the Kinderhookian-Osagean boundary excursion ends within the upper Gilmore City Formation as $\delta^{13}C$ values return to a baseline before the contact with overlying strata (Figs. 8 and 9). It is possible that this postexcursion interval of uppermost Gilmore City strata in central Iowa extends into the *Ps. multistriatus* zone and may be coeval with part of the lowermost Burlington Formation in southeast Iowa (Fig. 12). However, additional biostratigraphic work will need to be completed in central Iowa to refine this contact and confirm the age of the uppermost Gilmore City Formation. Conodonts recovered from "Unit 1 of Baxter" are within the *Ps. multistriatus* zone at the Hannibal type section (Fig. 4) and may be as low as the *P. c. carinus* zone at Fall Creek (Fig. 7), an interval slightly older than strata sampled at the I-172 section. Farther southeast of our study area, the Burlington Formation grades laterally into and is underlain by strata of the Fern Glen and Meppen Formations as the middle shelf break is approached (Witzke and Bunker, 2002). Conodonts from the Fern Glen and Meppen type sections are at least as old as the *P. c. carinus* zone (Thompson and Fellows, 1970; Thompson, 1975; Lane and Brenckle, 2005) and are older than the base of the Dolbee Creek Member farther up ramp in the central middle shelf.

The new high-resolution chronostratigraphic data presented here demonstrate a disconformity at the Kinderhookian-Osagean boundary that shows a perplexing geometry across the Burlington shelf, where it is largest (>3 conodont zones) in the central middle shelf, smaller (~1 conodont zone) down ramp in the distal middle shelf, and smallest (<<1 conodont zone) in the most up-ramp, inner-shelf setting. Witzke and Bunker (2002) discussed this atypical geometry, and the new data presented here only compound the issue, making the extent of discrepancies in the duration of the disconformity more severe. As they pointed out, the three possible explanations are tectonic, subaerial exposure/erosion, and submarine erosion/nondeposition. Tectonic flexure would appear unlikely for two reasons. First, the timing would require a NE-SW–trending fold to develop in the middle Kinderhookian above the Hangenberg excursion, persist only through the Kinderhookian-Osagean boundary, and then subside back to essentially pre–middle Kinderhookian level all within 3 m.y. (Aretz et al., 2020). Second, there are no concomitant facies changes that would suggest shoreline depositional environments in the central middle-shelf area during this time. All of the shallowest strata during the Kinderhookian-Osagean boundary interval are in the northwest part of the study area (i.e., central Iowa) where mudcracks, peritidal carbonates, and stromatolites all indicate a shoreline to the northwest of the inner shelf in central Iowa.

If subaerial exposure and erosion were the primary drivers of this disconformity, one would expect the greatest amount of erosion to have occurred in the shallowest settings (i.e., inner shelf) because it would have been exposed the greatest amount of time during regression, yet this is not what is seen. Finally, we are left with the option of submarine erosion or nondeposition during the Kinderhookian-Osagean boundary interval across the central middle shelf, which seems to be the only justifiable conclusion for the data presented here. This could have resulted from sediment starvation of the central middle shelf, storm reworking/winnowing/erosion of this area, or geochemical/biological consumption of these strata. The widespread presence of submarine hardgrounds at this position across the central middle shelf provides additional support for this interpretation and suggests that this is most likely a sedimentologic/oceanographic/geochemical feature of the Burlington shelf rather than a tectonic or eustatic feature. Ultimately, this realization demonstrates that the geometry of the Burlington shelf is much more complex than simple clinoforms across the region, and significant chronostratigraphic assessment must be performed prior to any regional sequence stratigraphic analysis.

CONCLUSIONS

The integrated conodont and carbon isotope biochemostratigraphy presented in this

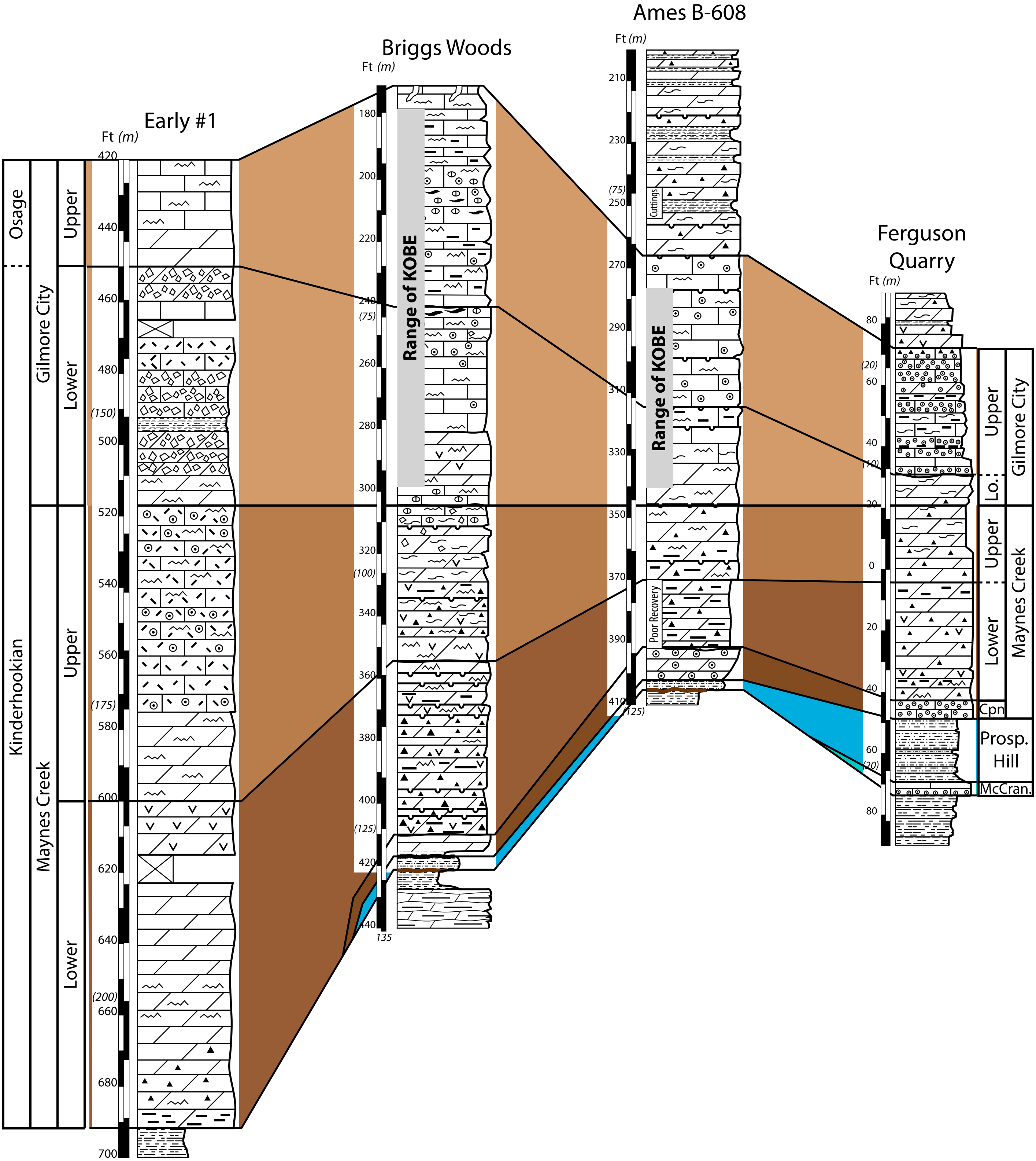


Figure 13. Correlation of the Gilmore City Formation in central Iowa. Note the general thinning of the Kinderhookian-Osagean boundary excursion (KOBE) and Gilmore City Formation from left to right. See Figure 4 for legend. Colors follow formations as presented in Figures 11 and 12. See Figure 11 for core locations. Cpn—Chapin; McCran—McCraney; Pros. Hill—Prospect Hill.

study provides new insight into the correlation of strata across the Burlington shelf and the chronostratigraphic relationships between inner-shelf facies in central Iowa and the distal middle-shelf facies of the Iowa, Illinois, and Missouri tristate area. An expanded record of lower Kinderhookian strata is present in the distal middle-shelf facies of the tristate area; however, the Kinderhookian-Osagean boundary is marked by an unconformity across the rest of the shelf. In the most distal settings of our study area, the Hangenberg excursion is recorded within the Louisiana Formation and lowermost Hannibal Shale, reaching peak values approaching +6‰. No record of the Kinderhookian-Osagean boundary excursion was identified in the central or distal middle shelf, and much of the uppermost Kinderhookian and lower Osagean interval is absent due to the presence of the sub-Burlington disconformity. Conversely, strata of the inner-shelf and proximal middle-shelf facies of central Iowa preserve an expanded record of the Kinderhookian-Osagean boundary, whereas the base of the Kinderhookian is marked by an unconformity. No record of the Hangenberg excursion was identified in the region, and the oldest preserved Kinderhookian strata are from the *S. sandbergi* conodont zone in the Prospect Hill Formation. The Kinderhookian-Osagean boundary excursion is recorded within the Gilmore City Formation, reaching peak values of +6‰ near the Marble Valley–Humboldt Member contact.

Our new high-resolution chronostratigraphic correlations reveal important stratigraphic trends along the Burlington shelf. While previously thought to be partly correlative units, most, if not all, of the Gilmore City Formation can now be shown to be older than the Burlington Formation. The magnitude of the sub-Burlington disconformity in the tristate area is greater than previously thought, and the full interval of time represented by the Gilmore City Formation appears to be absent in southeast Iowa. The sub-Burlington disconformity is greatest in the central middle shelf and dramatically decreases in magnitude in the up-ramp direction into the inner-shelf facies of central Iowa. The disconformity also decreases in magnitude when transitioning southeastward into the distal middle-shelf deposits of Missouri and Illinois. However, a portion of upper Kinderhookian and lower Osagean strata is likely still missing, and it remains unclear if the Kinderhookian-Osagean boundary interval is preserved in the outermost portions of the distal middle-shelf and middle shelf-break strata of the Chouteau, Meppen, and Fern Glen Formations.

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