# Sedimentology of the Belfast Member of the Brassfield Formation (Silurian, western Ohio and northern Kentucky, U.S.A.): Implications for regional sea-level changes and tectonics

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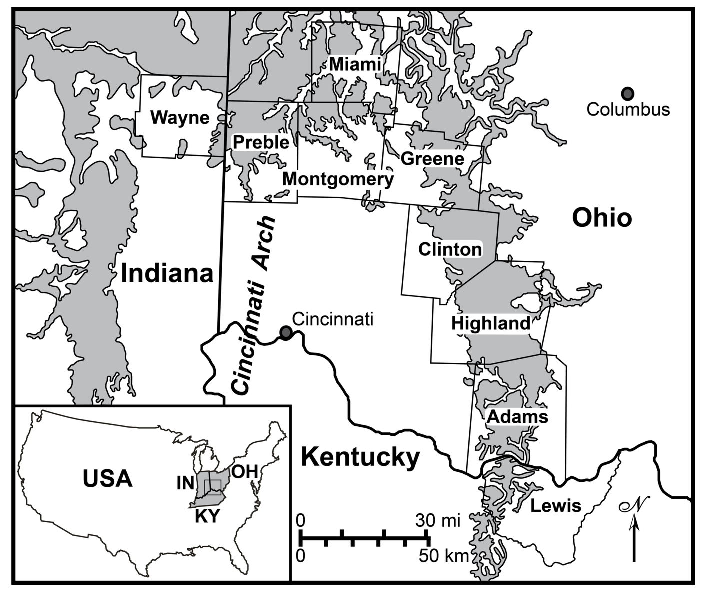
## Abstract

The lowermost Silurian Brassfield Formation, Cincinnati Arch area, records mid-continent deposition on a carbonate ramp that sloped into the Taconic foreland basin. The Brassfield is significant because it represents earliest Silurian deposition in the area resulting from sea-level rise following the late Ordovician glacial maximum, it records the faunal transition from the terminal Ordovician extinction, and its upper part contains tabulate coral-stromatoporoid reefs that are among the oldest Silurian reefs in North America. The lowermost unit of the Brassfield, the Belfast Member, is the focus of this study. Previous interpretations of the Belfast as having been deposited in relatively shallow water (intertidal to shallow subtidal, including lagoonal) associated with the initial early Silurian transgression are equivocal. The Belfast exhibits 3D ripple marks and associated cross laminae, hummocks, hummocky and swaley cross stratification, and planar stratification, with thin interbeds of planar laminated mudstone, all consistent with deposition in an inner shelf-type setting, below fair-weather wave base, but above storm wave base. Trace fossils, including *Chondrites*, *Rosselia*, *Teichichnus*, *Thalassinoides*, and *Palaeophycus*, indicate that during rapid sedimentation associated with storms, organisms adjusted vertically. Under subsequent fair-weather conditions, organisms recolonized upper portions of some beds, while totally bioturbating others. Hence, the Belfast represents relatively deep-water deposition on the Ordovician-Silurian unconformity associated with a relatively rapid sea-level rise. The transition from the Belfast to the overlying Brassfield appears to record a sea-level fall. As such, the Belfast is a low-order sequence not previously recognized. Sea-level changes recorded by the Belfast and overlying Brassfield are consistent with glacio-eustatic variations evident on published sea-level curves. An increase in subsidence also may have contributed to the rapid deepening recorded by the Belfast. Increased subsidence may have been associated with hydrostatic and/or sediment loading, Taconic orogenesis, dynamic subsidence associated with northward directed subduction along the southern margin of Laurentia, or movement on regional structures.

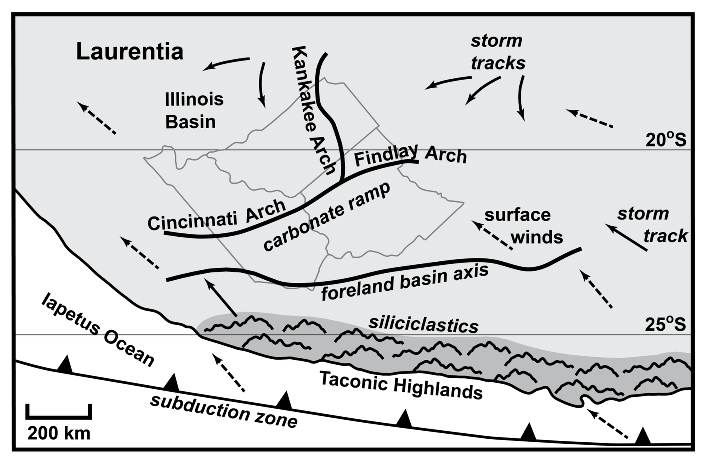
## Location, General Geology, & Geologic Setting




**Regional outcrop map of Silurian rocks** in western Ohio, northeastern Kentucky, and eastern Indiana associated with the Cincinnati Arch. The Belfast Member is exposed throughout the eastern and northern portion of this outcrop belt, but is absent on the far western side of the Cincinnati Arch. Outcrops were studied in the counties shown.

**Generalized stratigraphy** of upper Ordovician and lower Silurian rocks in western Ohio (OH), northeastern Kentucky (KY), and eastern Indiana (IN). The Belfast is Rhuddanian in age, although there is no consensus as to whether it is early, middle to late, or late Rhuddanian. The overlying part of the Brassfield is middle or late Rhuddanian to early or middle Aeronian. The Cherokee Unconformity represents subaerial exposure, weathering, and erosion associated with glacio-eustatic drawdown resulting from the late Ordovician glaciation, and possibly uplift of the proto-Cincinnati Arch. Dates are from the 2017 International Chronostratigraphic Chart.

| Age (Ma) | Period | Epoch | Age | | Unit |
|---|---|---|---|---|---|
| | Silurian | Llandovery | Aeronian | Brassfield Fm. | informal Brassfield subdivisions |
| 440.8 | | | Rhuddanian | | Belfast Member |
| 443.8 | Ordovician | Late | Hirnantian | | Cherokee Unconformity |
| 445.2 | | | Katian | | Drakes Fm. (OH, KY) Whitewater Fm. (IN) |

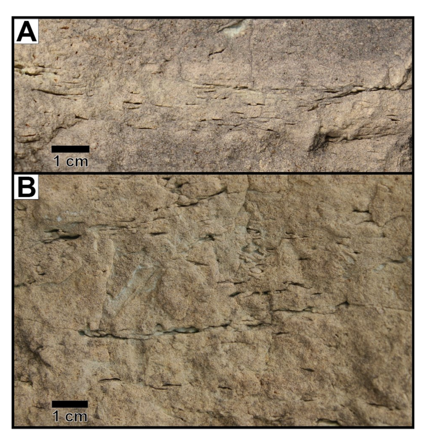



**Paleogeography** of southern Laurentia during the early Silurian showing the study area, major structural features, prevailing winds, and storm tracks. Laurentia was inundated by an **epeiric sea** with the **Taconic highlands** to the south, which formed during the Ordovician in association with the collision of island arcs on the southern margin of Laurentia. In response, a foreland basin formed to the north of the Taconic Mountains. Siliciclastic sediment accumulated in the south side of the basin adjacent to the Taconic highlands. Farther to the north and northwest, a forebulge was produced, the proto-Cincinnati and Findlay Arches. The arches were positive features at the time, though not emergent during deposition of the Belfast. The southeastern flank of the forebulge, on which the study area was located, was a **carbonate ramp** that sloped gently southeastward into the Taconic foreland basin.

During the early Silurian, the study area was located within a **subtropical trade wind belt** dominated by **southeasterlies**. Subtropical **storms and hurricanes** likely tracked along this belt from the north and northeast, and possibly from the southeast. Temperatures in the region at this time were relatively cool, likely on the order of 13°-14°C.
The **South Polar Ice Sheet** of the Hirnantian underwent partial collapse during the latest Ordovician to early Silurian, although the ice sheet was still present through the early Silurian.

## Previous Interpretations of the Belfast

**The Belfast previously has been interpreted as representing relatively shallow water deposition**, from intertidal to shallow subtidal, including lagoonal, associated with early Silurian transgression. The Brassfield overlying the Belfast has been interpreted as representing progressively deeper water deposition, from near or above fair-weather wave base, upsection to below fair-weather wave base. Hence, the transition from the Belfast to the overlying Brassfield has been interpreted as recording a sea-level rise. Many of the previous interpretations of the Belfast, perhaps biased by its positon above an unconformity and characteristics of the overlying Brassfield indicative of progressive deepening upsection, were based on reports of shallow-water features such as mudcracks, gypsum casts, algal laminites, and birdseye structures. **However**, the identifications of these sedimentary structures are **either suspect or equivocal, and unpublished** (reported in M.S. theses and Ph.D. dissertations). It is likely that all of these **features** have been **misinterpreted**, most being confused with various effects of bioturbation (e.g., presumed algal structures), weathering, and compaction (see example to right). Mudcracks were only reported in one study (an M.S. thesis), from one outcrop, with no photo documentation. Furthermore, a study that used palynomorphs as proxies for Silurian benthic assemblages and water depth estimates is riddled with assumptions and inferences, and is suspect. Additionally, studies indicate that abundance of palynomorphs versus depth relationships only hold for water depth changes well over an order of magnitude, an unlikely scenario for the mid-continental, early Silurian epeiric sea.

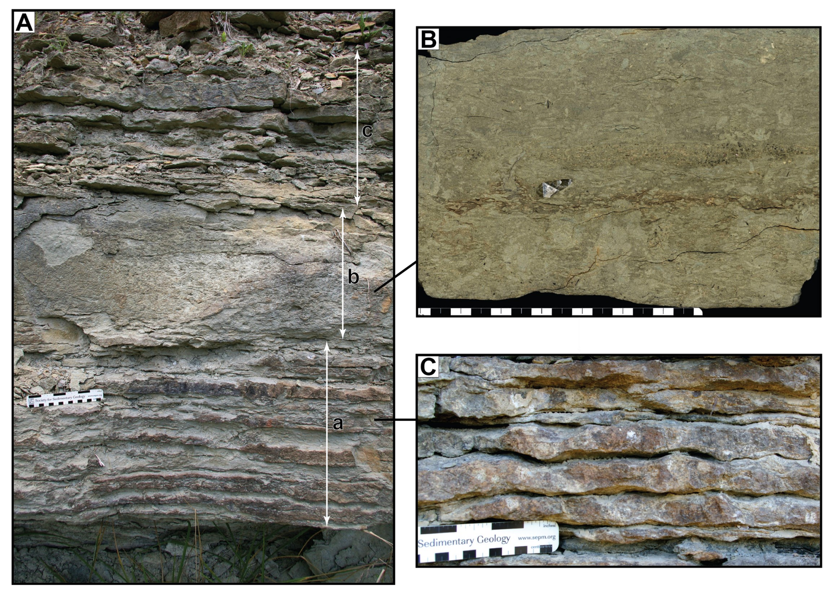



**Compacted *Chondrites* and *Palaeophycus* burrows** within the Belfast which are preferentially weathering, producing small, oblong, horizontally oriented voids. Some previous workers may have mistaken such voids for gypsum casts or birdseye structures. **A)** A zone of burrows aligned parallel to bedding.
**B)** More dispersed burrows.

## Belfast Sedimentology

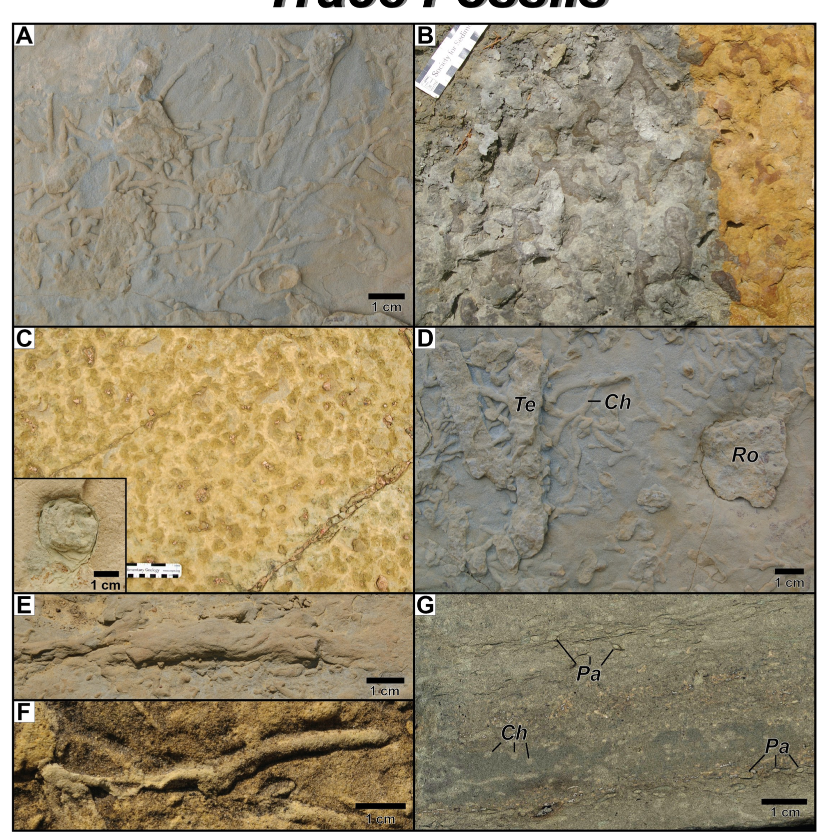
The Belfast consists of argillaceous to silty dolostones containing sand-size skeletal fragments and sparse glauconite pellets. From southwestern Ohio, it thins to the west into Indiana and to the south-southwest where it eventually pinches out on the Cincinnati Arch. A thin lag consisting of quartz grains, reworked Ordovician fossils and clasts, phosphorite, and glauconite occurs locally near its base. ***Interpretation of primary sedimentary structures (below):*** 3D ripples form under relatively vigorous oscillatory (wave-generated) flows or combined oscillatory and unidirectional currents. 3D asymmetric ripples form exclusively under combined flows. Such flows have a dominant oscillatory component with a relatively small unidirectional component. Hummocks and hummocky & swaley cross stratification is generally believed to form under oscillatory flows beneath large waves (with large orbital velocities) with a relatively minor unidirectional component. Such conditions generally have been attributed to shelf environments below fair-weather wave base, but above storm wave base. Planar stratification forms by deposition associated with upper-stage plane beds. Such conditions may be produced by purely unidirectional or oscillatory flows, or by combined flows. The common occurrence of planar stratification in the Belfast with hummocky and swaley cross stratification suggests that it was produced under combined flows and possibly intense oscillatory flow. Thin, interbedded, laminated carbonate mudstones represent settling of suspended sediment under waning flow conditions following the deposition of planar stratification, hummocky and swaley cross stratification, and 3D ripples.

### *Typical Section of the Belfast*



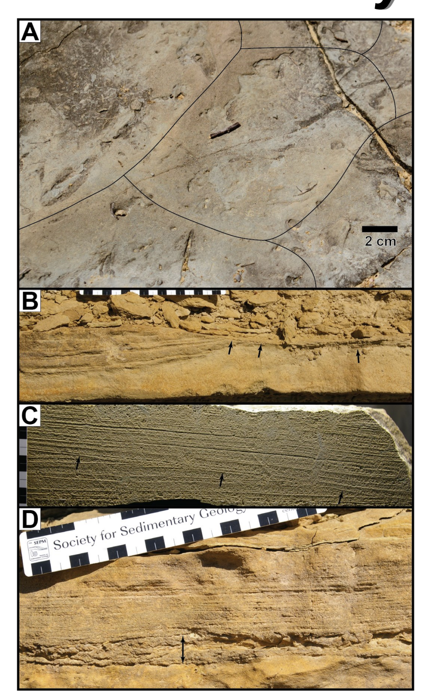

**A) A section typical of the Belfast** in central & northern Adams County and Highland County, Ohio. In this outcrop, the Belfast consists of (bottom to top) ~70 cm of centimeter-scale beds exhibiting **3D symmetric ripple cross laminae** and **laminated carbonate mudstone** (a), ~40 cm of a more massive, highly bioturbated carbonate (b), overlain by ~50 cm of more centimeter-scale beds exhibiting 3D symmetric ripple cross laminae and laminated carbonate mudstone (c). **B)** Polished slab of the middle bed, (b) in (A), showing **extensive bioturbation**, primarily due to *Chondrites*, which has nearly obliterated primary sedimentary structures. **C)** Close-up view of beds typical of (a) and (c) in (A). Scales in (A) and (C) in centimeters (lower) and inches (upper). Scale in (B) in centimeters.

### *Trace Fossils*

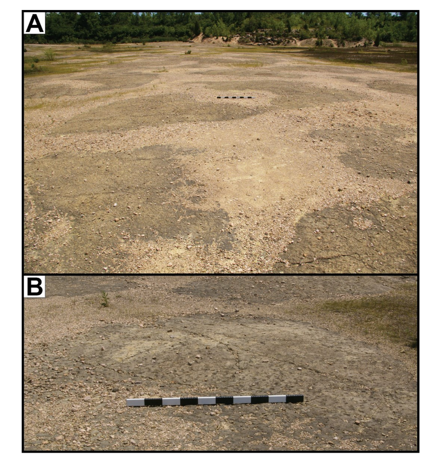



**Trace fossils** common within the Belfast. **A) *Chondrites***, plan view. **B) *Thalassinoides***, plan view. Scale in centimeters (lower) and inches (upper). **C) *Rosselia***, plan view. Scale in centimeters (lower) and inches (upper). Inset is close-up, plan view of an individual *Rosselia* burrow exhibiting characteristic internal layering. **D) *Teichichnus* (*Te*), *Chondrites* (*Ch*)**, and ***Rosselia* (*Ro*)**, plan view. **E) *Teichichnus***, plan view, exhibiting characteristic internal layering. **F) *Palaeophycus***, plan view. **G)** Polished slab showing side views of ***Palaeophycus* (*Pa*)** and ***Chondrites* (*Ch*)**.

### *Primary Sedimentary Structures*




**Sedimentary structures** common within the Belfast. **A)** Plan view of **3D symmetric ripple marks** (lines accent crestlines).
**B) and C) Swaley cross stratification.** Arrows indicate truncation surface of overlying trough, or swale. **D) Planar stratification** with a layer of coarse-grained skeletal fragments near the base of the bed (indicated with vertical, double arrow). Scales in B-D in centimeters.




Bedding plane exposure of **hummocks** in Oakes Quarry, Greene County, Ohio. The small pits on the bedding surface are *Rosselia* burrows. **A)** Recent sediment has accumulated in most hummock troughs, accenting their crests. **B)** Close-up view of an individual hummock.
In both photos, meter stick for scale.

### *Synthesis*

The primary sedimentary structures, and the type and distribution of trace fossils, indicate that the **Belfast was deposited in association with storms in an inner shelf-type setting, below fair-weather wave base, but above storm wave base**. This is consistent with the study area being located within a subtropical trade wind belt along which subtropical storms and hurricanes likely tracked from the north and northeast, and possibly from the southeast. Storms generated strong oscillatory currents, some with superimposed unidirectional currents, which eroded underlying beds and subsequently produced 3D ripples, hummocks, and upper-stage plane beds. During rapid sedimentation associated with the storms, organisms adjusted vertically. Under fair-weather conditions following storms, settling of suspended sediment formed planar laminae and organisms recolonized upper portions of some beds, while totally bioturbating others. The characteristics exhibited by the Belfast are very similar to other Ordovician and Silurian storm beds of the mid-continental U.S.A. and elsewhere in North America.

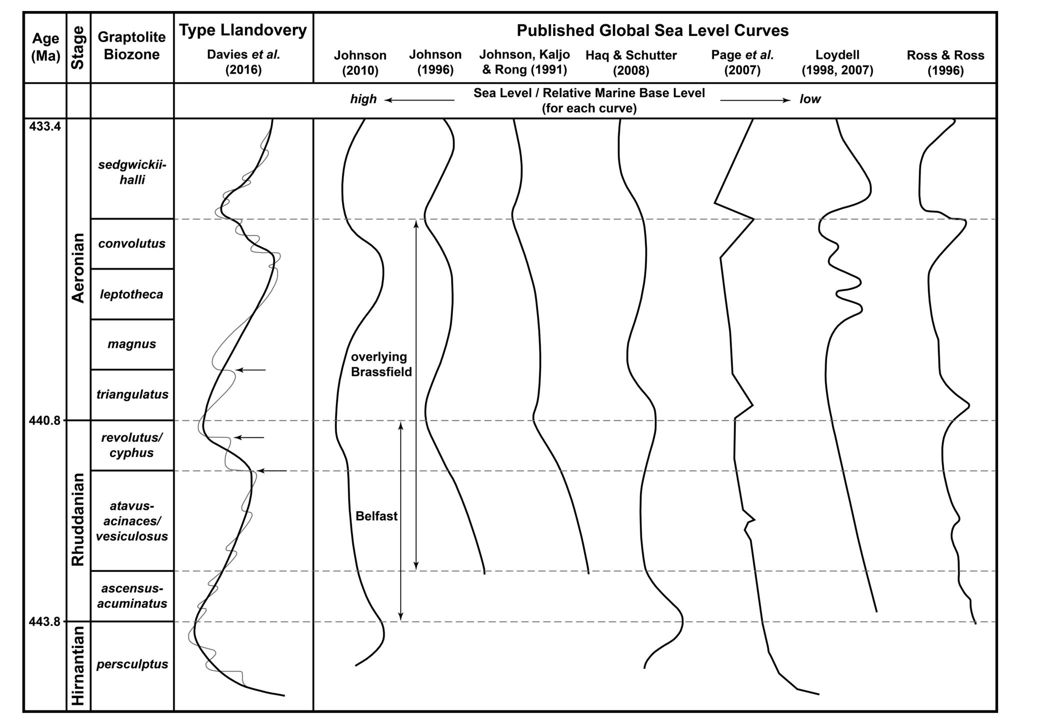

**Polished slabs showing typical characteristics of Belfast beds**. Individual beds, each representing a depositional event, are indicated with a vertical, double arrow (cg, coarse-grained sediment; rz, recolonization zone). The dominant trace fossil, particularly in recolonization zones, is *Chondrites* (*Ch*; some representative examples are labelled). Several representative examples of *Teichichnus* (*Te*), *Palaeophycus* (*Pa*), and *Rosselia* (*Ro*) also are labelled. **(A)-(C)** exhibit swaley cross stratification. **(D) and (E)** are from beds which exhibited 3D symmetric ripples in plan view. **(F)** exhibits planar stratification overlain by swaley cross stratification (partial view).
All scales in centimeters.

## Discussion & Implications

**The Belfast represents relatively deep-water deposition on the Ordovician-Silurian unconformity**, which developed primarily under subaerial conditions. Such a condition generally requires a rapid rise in regional sea level which may be facilitated by a rapid rise in eustatic sea level, tectonic subsidence, and transgression across an area of low slope.

### *Sea-Level Changes*

The transition from the Belfast to the overlying Brassfield appears to record a sea-level fall. As such, **the Belfast is a low-order sequence not previously recognized**. Deposition of the Belfast likely was associated with the transgression produced by the collapse of the Hirnantian South Polar Ice Sheet seen on most sea-level curves through the Rhuddanian. The most rapid flooding depicted on the sea level curves (particularly the high order Type Llandovery curve) occurred during the late Rhuddanian. A late Rhuddanian age for the Belfast would be consistent with this rapid sea-level rise. A prominent unconformity within the upper part of the overlying Brassfield may be associated with the early *convolutus*, high order sea-level low. As such, the shallowing from the Belfast to the overlying Brassfield, and subsequent progressive deepening upsection to the unconformity within the upper Brassfield may correspond to the lower order fluctuations for the late Rhuddanian-early Aeronian seen on the Type Llandovery curve (a South Polar ice mass likely was still in place during the Rhuddanian). If the Belfast is early or middle Rhuddanian, and the remainder of the Brassfield is late Rhuddanian or late Rhuddanian to early Aeronian, the Belfast may reflect deposition associated with the high order transgression seen on most other curves, with the overlying Brassfield reflecting the lower order fluctuations depicted on the Type Llandovery curve.




Late Ordovician-early Silurian base-level curves of Davies et al. (2016) for the Type Llandovery section (U.K., Wales), other select, commonly cited global sea-level curves, and the ranges of possible ages for the Belfast and overlying Brassfield (vertical, double arrows). The Belfast may be early, middle to late, or late Rhuddanian. The overlying Brassfield may be middle or late Rhuddanian to early or middle Aeronian. Horizontal arrows highlight low order (small amplitude, high frequency), apparently eustatic, sea-level rises which may have influenced deposition of the Belfast and overlying Brassfield. Graptolite zones for the U.K. and elsewhere are from Davies et al. (2016) and Cramer et al. (2011). Dates are from the 2017 International Chronostratigraphic Chart, v. 2017/02 (Cohen et al., 2013, updated).

### *Tectonics*

Although the rapid deepening recorded by the Belfast may be purely eustatic, **an increase in tectonic subsidence also may have been a contributing process**. Goodman (1992) conducted a backstripping subsidence analysis on the Paleozoic section in eastern Kentucky. Results indicated increased tectonic subsidence associated with the Taconic and Salinic orogenies, but showed no increase in subsidence during Brassfield deposition. However, if carbonate production rates were low during deposition of the Belfast, a possibility given the rapid sea-level rise, an increase in tectonic subsidence would not be detected by his analysis. Heidlauf et al.'s (1986) subsidence analysis of the Illinois Basin (to the west of the Cincinnati Arch) showed an increase in subsidence in the early Silurian which they attributed to thermal subsidence. However, the interpretation of a thermal driving mechanism for this subsidence is suspect. Given knowledge of the formation of arches in the region and possible processes associated with the formation of the Illinois Basin, the increase in subsidence may be linked to tectonism along the southern margin of Laurentia. Hence, it is possible that the study area underwent a related increase in subsidence. There also is some indication that subsidence associated with the Taconic orogeny may have persisted into the early Silurian. Additionally, the initiation of northward directed subduction in the early Silurian may have induced a component of dynamic subsidence associated with viscous mantle corner flow in the asthenosphere (vis-à-vis dynamic topography). This process could have potentially caused flexure of the Laurentian plate downward to the southeast. The result would have been more rapid regional deepening than that of eustatic sea-level rise alone. It is also possible that movement on structures in the region, as documented for the upper Brassfield and overlying rocks, may have contributed to increased subsidence and rapid deepening. Such movements may reflect the far-field influences of events at the southern plate margin of Laurentia or could have been induced by hydrostatic loading. The above scenarios, though speculative, may warrant further investigation as more data become available regarding the timing, nature, and magnitude of tectonic events along the southern margin of Laurentia and their influence on the craton of eastern North America.