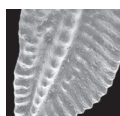


An expanded stratigraphic record of the Devonian–Carboniferous boundary Hangenberg biogeochemical Event from Southeast Iowa (U.S.A.)

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The Devonian–Carboniferous boundary in the type area of the Mississippian subsystem (tri-state area of Iowa, Illinois, and Missouri) has been historically difficult to identify. Many of the localities contain similar lithologies and stratigraphic successions, but chronostratigraphic correlation of seemingly identical lithologies can vary greatly in this interval and frequently this has led to miscorrelation. In particular, the similar lithofacies that comprise the McCroney Formation and Louisiana Formation have been a source of stratigraphic confusion for over 100 years. To investigate the Devonian–Carboniferous boundary interval in the Mississippian type area we selected two localities in southeastern Iowa, the H-28 core from Lee County outside of Keokuk, Iowa, and the Starr’s Cave outcrop located near Burlington, Iowa. In total, 62 conodont samples and 299 carbonate carbon isotope samples were processed for this study and recorded the Hangenberg positive carbon isotope excursion and 25 conodont species, including a diverse assemblage of siphonodellids. The Hangenberg excursion is recorded in over 20 m of strata in southeast Iowa, making this one of the thickest stratigraphic records of this important biogeochemical event yet recovered, and helps to define more clearly the position of the base of the Carboniferous System in the region. These results show that the “McCroney” Fm. at the Starr’s Cave outcrop and the coeval carbonate unit in the H-28 core are both the Louisiana Formation, and calls into question the use of the name McCroney throughout the State of Iowa. • Key words: conodont, carbon isotope, *Siphonodella*, Louisiana Limestone, Devonian–Carboniferous boundary.

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The Devonian–Carboniferous boundary (DCB) interval coincides with a mass extinction on the scale of the ‘Big Five’ (Sepkoski 1996, Kaiser *et al.* 2016) and a major perturbation to the global carbon cycle (Cramer *et al.* 2008, Saltzman & Thomas 2012). The DCB strata of the tri-state area of Missouri, Illinois, and Iowa have been studied for over a century and contain historically important strata for the type Mississippian area including the type area of the lowest Carboniferous North American Kinderhookian Stage (global lower Tournaisian Stage) of the Mississippian Subsystem. The majority of this work occurred more than 50 years ago (*e.g.*, Scott & Collinson 1961) with more recent work limited to the late 1990’s (Chauffe & Nichols 1995, Witzke & Bunker 1996, Chauffe &

Guzman 1997). However, significant problems with unit correlation remain due to long standing nomenclature divides across state boundaries, lack of study, or low-resolution sampling.

Two units of strikingly similar lithologies, the McCroney Formation and the Louisiana Formation, are critical to the placement of the DCB in the tri-state area. These units often occur within a few miles of one another; however, they have never been identified in the same succession, either in outcrop or in the subsurface. Historically, a nearly equal number of publications have considered these units to be equivalent (*e.g.*, Weller 1900, Weller & Sutton 1940, Harris 1947, Stainbrook 1950) as have considered them to be temporally distinct (Keyes 1895, Weller 1906,

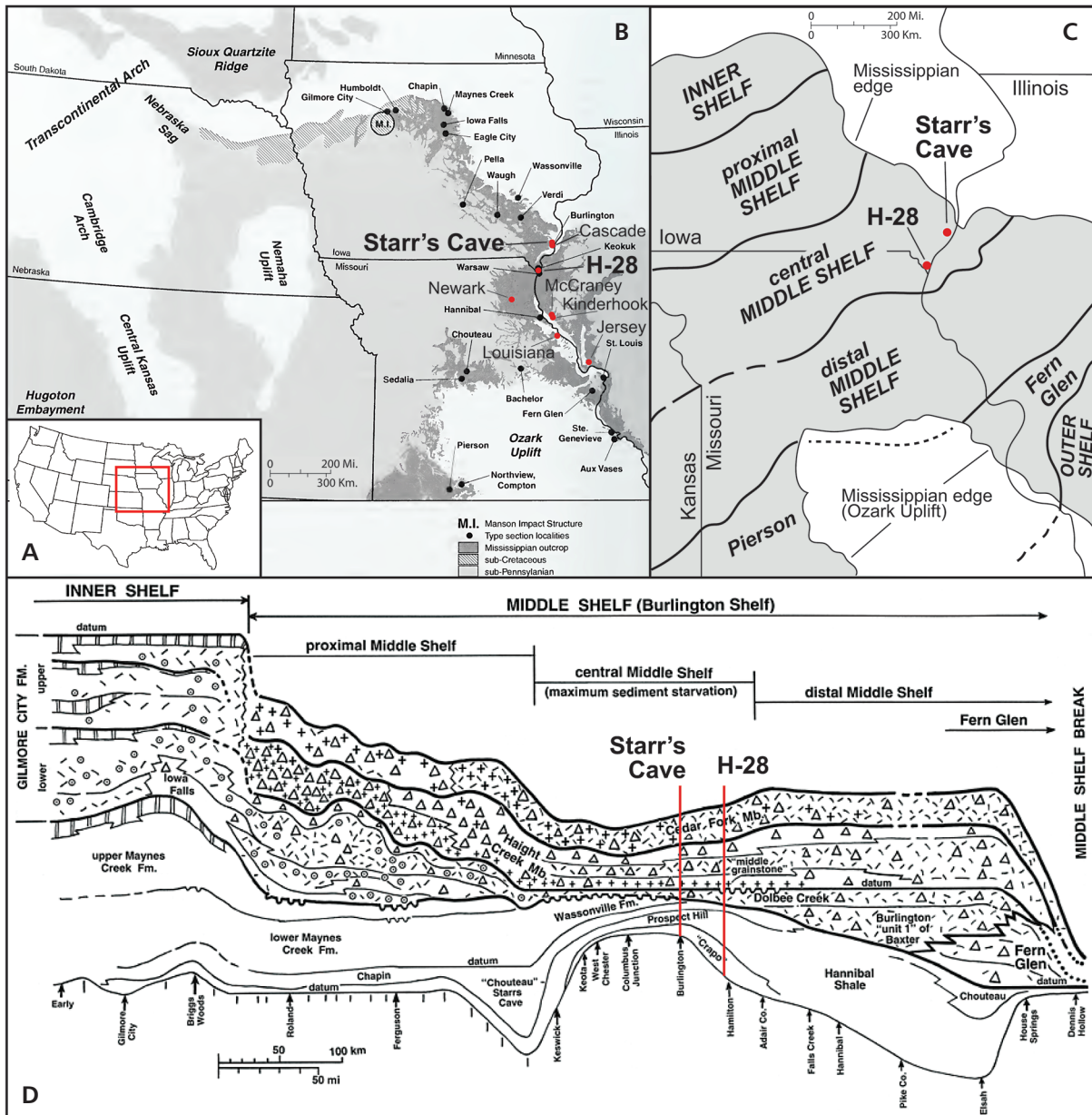


Figure 1. A, B – distribution of Mississippian outcrops in the tri-State area of Missouri, Illinois, and Iowa, including the two locations (H-28 and Starr's Cave) sampled in this study. Other localities shown and discussed in the text include Cascade Station (Cascade), Teneriffe School (Jersey), McCraney North (McCraney), the town of Kinderhook (all from Scott & Collinson, 1961), Fabius River Bridge and Fabius River Cut (Newark) from Chauffe & Guzman (1997), and the town of Louisiana (e.g., Cramer *et al.* 2008). Modified from Witzke & Bunker (2001). • C – paleogeographic reconstruction of the tri-state area during the Mississippian. • D – cross section of Kinderhookian strata spanning northwest to southeast from Early to Dennis Hollow. Sampling localities examined in this study are marked with a red line. B and C modified from Witzke & Bunker (2002).

Moore 1928, Laudon 1931, Williams 1943, Thomas 1949, Workman & Gillette 1956, Scott & Collinson 1961). These different correlation interpretations started in Missouri and Illinois and then later spread into southeastern Iowa when Moore (1928) correlated the basal Mississippian carbonate unit exposed at Burlington, Iowa (IA), with the McCraney Formation. This practice has continued within the State of Iowa into the 21st Century (Witzke *et al.* 1990, Witzke & Bunker 2001).

In the wake of improved conodont biostratigraphic information from the Louisiana and the McCraney in the tri-state area (Chauffe & Nichols 1995, Chauffe & Guzman 1997), and following the preparation of multiple field trip guidebooks to the region (Heckel 2001, Witzke *et al.* 2002), the correlation of these beds in southeast Iowa with the McCraney Formation came into question. Witzke & Bunker (2002) summarized these issues in southeastern Iowa and began using the term “McCraney”

Formation. Here we present integrated high-resolution biochemostratigraphy of conodonts and carbon isotopes from southeastern Iowa to improve our understanding of this unit and its regional correlation. In total, 62 conodont samples and 299 carbon isotope samples were collected and processed that help to improve stratigraphic correlation in the type area of the Mississippian, identify the position of the Hangenberg crisis in Iowa, and demonstrate the likely position of the DCB in type Mississippian strata throughout the region.

Geologic Setting

During the Mississippian, a broad epicontinental sea covered the U.S. Mid-continent and the tri-state area of Iowa, Missouri, and Illinois was located between 10–20° south latitude (e.g., Lane 1978, Witzke & Bunker 1996). The expansive Mississippian carbonate platform known as the Burlington Shelf, transitions to outer shelf and

deeper water deposits towards southern Illinois and southeastern Missouri (Fig. 1). The samples included in this study are from southeastern Iowa within the central middle shelf and include an outcrop at Starr's Cave Park and Preserve north of Burlington, Iowa, and the H-28 core near Keokuk, Iowa. The central middle shelf and sections of study are within the area of maximum sediment starvation across the Burlington Shelf, however, the outcrops in southeastern Iowa are historically important for regional stratigraphy (e.g., Moore 1928, Scott & Collinson 1961).

Mississippian strata increase in thickness from the central middle shelf towards the distal middle shelf (Fig. 2). The two localities studied were the Starr's Cave outcrop north of Burlington, IA and the H-28 core near Keokuk, IA. From Burlington to Keokuk, the lower Mississippian interval expands and doubles in thickness over less than 50 miles. However, the lower Mississippian interval expands even more as you travel southeast into Missouri and Illinois (Fig. 1C).

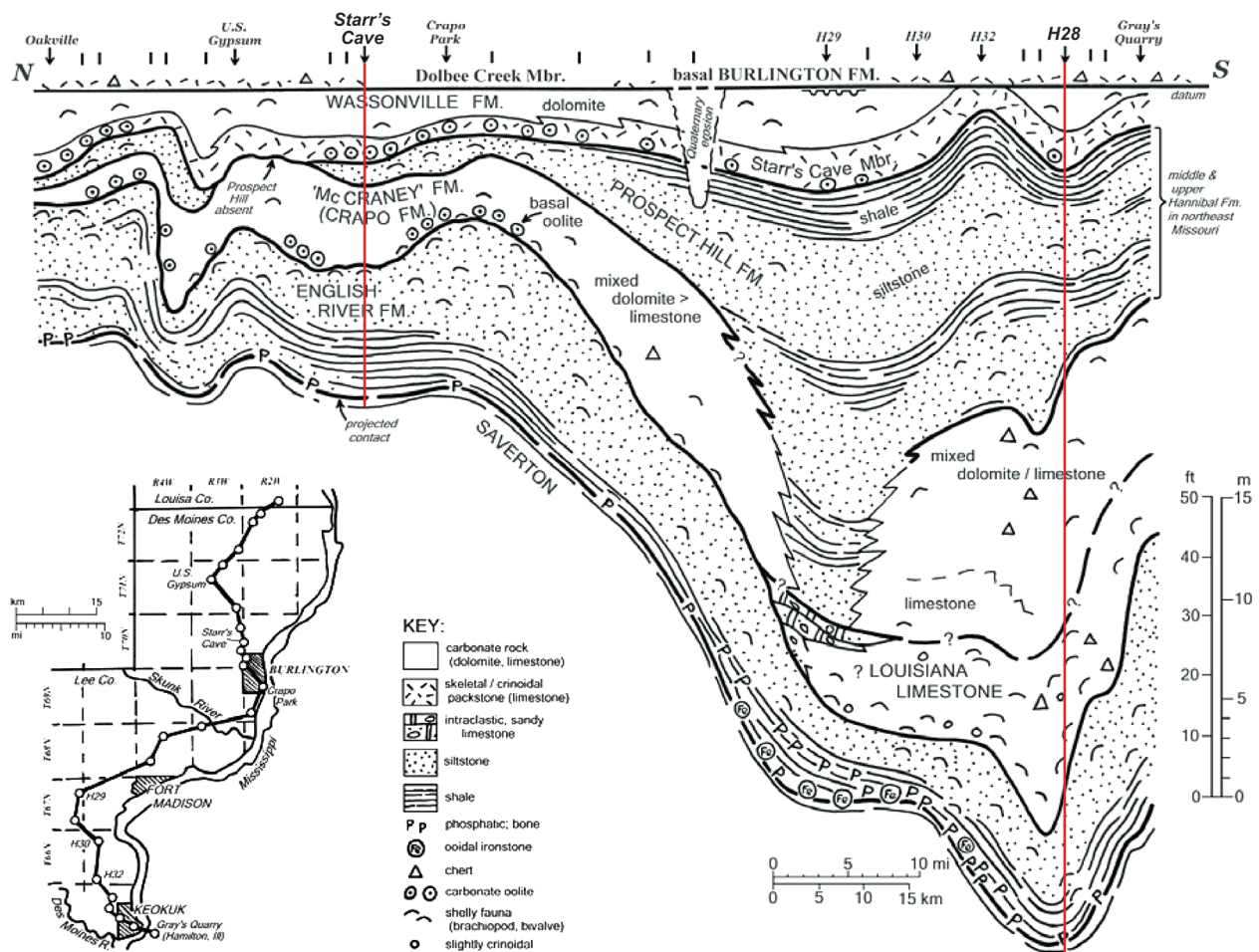


Figure 2. North-south cross section of Kinderhookian stratigraphy through southeastern Iowa illustrating the increase in stratigraphic thickness towards the south. The two locations sampled in this study are designated by red lines. Modified from Witzke & Bunker (2002).

Devonian–Carboniferous boundary

The DCB interval contains one of the largest mass extinctions in Earth history and impacted nearly all marine fauna including conodonts, ammonoids, trilobites, corals, sponges, brachiopods, ostracodes, marine phytoplankton, foraminifera, amphibians, and placoderms (Walliser 1984, 1996; Kaiser *et al.* 2011, 2016). This extinction event, known as the Hangenberg crisis, coincides with the onset one of the largest positive carbon isotope excursions of the Phanerozoic that reaches values greater than +6.0‰ (Cramer *et al.* 2008, Saltzman & Thomas 2012). The stratigraphic record of the tri-state area of the U.S. Mid-continent has been under-evaluated during the past two decades with respect to the global importance of this biogeochemical event.

The Global Boundary Stratotype Section and Point (GSSP) of the base of the Carboniferous System is located at La Serre, Montagne Noire, France, and was chosen to coincide with the first appearance datum (FAD) of the

conodont *Siphonodella sulcata*, which marks the base of the eponymous biozone (Paproth *et al.* 1991, Davydov *et al.* 2012). The base of the *S. sulcata* Zone occurs towards the end of the Hangenberg crisis, significantly above the onset of the Hangenberg positive carbon isotope excursion. The base of this zone has been notoriously difficult to correlate to global stratigraphy due in part to taxonomic uncertainty around the marker species (Kaiser & Becker 2007, Kaiser & Corradini 2008, Kaiser 2009, Davydov *et al.* 2012, Becker *et al.* 2016). As a result, this boundary is currently under review by a working group from the international subcommissions on Devonian and Carboniferous stratigraphy and there are several proposed biostratigraphic positions for the future base of the Carboniferous System (Becker *et al.* 2016, Corradini *et al.* 2017). All of the proposed revisions place the base of the Carboniferous lower, and the clearest conodont-based position is the base of the *Protognathodus kockeli* Zone (Becker *et al.* 2016, Spalletta *et al.* 2017, Corradini *et al.* 2017), although the full “Montpellier Criteria” for

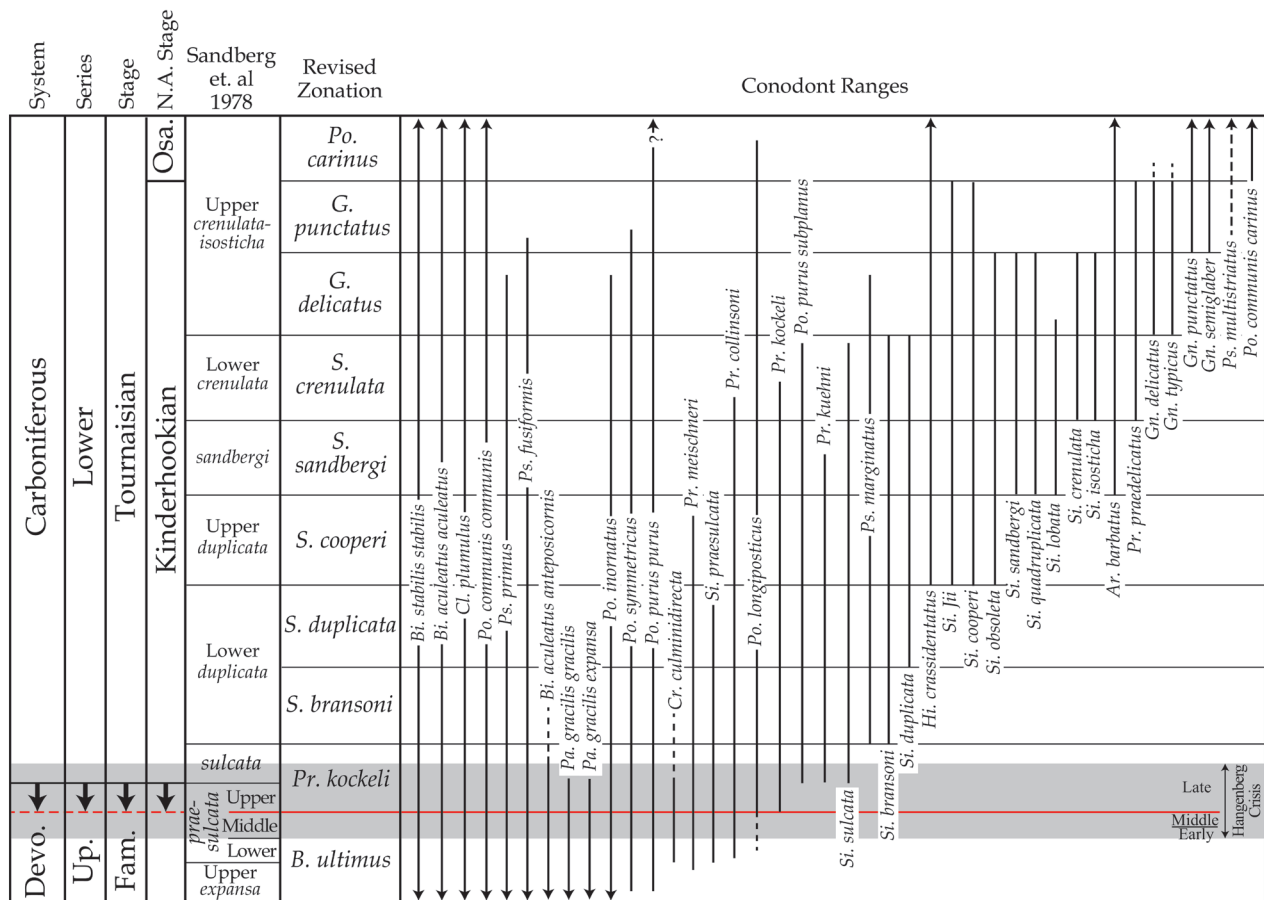


Figure 3. Revised conodont biozonation and range chart for the Kinderhookian. Traditional zonation of Sandberg *et al.* (1978) shown at left with comparison of new zones. New zonation is a composite of Kaiser *et al.* (2009), Spalletta *et al.* (2017), and Zhuravlev & Plotitsyn (2017) and is after Hogancamp *et al.* (2019). The dashed line corresponds to the base of the *Protognathodus kockeli* Zone, indicating the likely position of the Devonian–Carboniferous boundary according to the Montpellier Criteria (see text). This also fits well with the proposed definition of the end of major regression.

	Burlington Iowa	Kinderhook Illinois	Newark Missouri	Louisiana Missouri	Jersey County Illinois	Lane & Brenckle (2001)
Carboniferous	Burlington Fm.	Burlington Fm.	Burlington Fm.	Burlington Fm.	Burlington Fm.	Burlington Fm.
	Wassonville Fm. Upper Mb. Starr's Cave Mb.	McCraney Fm.	McCraney Fm.		Sedalia Fm.	Choteau Fm.
	Prospect Hill Fm.	Hannibal Fm.	Choteau Fm.	Hannibal Fm.	Choteau Fm.	
	"McCraney" Fm.		Hannibal Fm.		Hannibal Fm.	Hannibal Fm.
Devo.	English River Fm.	Saverton Fm.		Louisiana Fm. Saverton Fm.	Glen Park Fm. Louisiana Fm. Saverton Fm.	Glen Park/ Horton Creek

Figure 4. Comparison of Kinderhookian stratigraphic successions in the tri-state area, following Scott & Collison (1961), Chauffe & Guzman (1997), and Lane & Brenckle (2001). Red lines designate traditional placements of the Devonian–Carboniferous boundary in each area.

a revised placement of the base Carboniferous GSSP include the base of the *P. kockeli* Zone, the beginning of post-extinction radiation, the top of major regression, and the end of mass extinction. Throughout this study the potential new placement (based herein upon the *P. kockeli* Zone and the top of major regression) is used for placement of the base Carboniferous System in our two studied sections (Fig. 3).

Here, we utilize a revised conodont biozonation that closely follows Kaiser *et al.* (2009) for the Kinderhookian, Zhuravlev & Plotitsyn (2017) for the uppermost Kinderhookian–lowest Osagean, and Spalletta *et al.* (2017) for the DCB, with the following comments and changes. A complete discussion of the revisions to the Kinderhookian conodont biozonation utilized herein can be found in Hogan-camp *et al.* (2019). The succession from *S. bransonii* to *S. sandbergi* is identical to Kaiser *et al.* (2009) with the exception of the *Siphonodella cooperi* Zone. As noted by Becker *et al.* (2016) the name *Siphonodella hassi* was rejected due to homonymy and replaced with *Siphonodella jii*. However, the designation of *S. hassi* by Ji (1985) was an invalid junior synonym of *Siphonodella cooperi hassi* (Thompson & Fellows, 1970). What was not discussed by Becker *et al.* (2016) was that many specimens originally designated as *S. cooperi hassi* were later synonymized with *S. isosticha* by Klapper & Phillip (1971). As a result, the name *hassi* has now been applied to a variety of species in the literature that range nearly the entire Kinderhookian from what was the Upper *duplicata* Zone to the *isosticha*–Upper *crenulata* Zone of Sandberg *et al.* (1978). It is for this reason that we choose not to use either *hassi* or *jii* as a zonal designation but rather the comparatively taxonomically stable species *S. cooperi* as the name-bearer for the zone (see Hogan-camp *et al.* 2019).

Mississippi Valley stratigraphy

The stratigraphy in the tri-state area is diverse with an abundance of different lithologies and stratigraphic units. The two units of primary interest for the placement of the DCB in the tri-state area are the McCraney Fm., which resides above the current boundary placement in the region and the Louisiana Fm., which lies below the current boundary placement in the region. These units bear a striking resemblance to each other with a unique lithology of gray to brown, sublithographic limestone with silty dolomite partings that break in subconchoidal fractures (Chauffe & Guzman 1997, Witzke 2002). Due to this striking lithologic similarity and a lack or low abundance of fossils from this facies, the McCraney Fm. and the Louisiana Fm. have been generally correlated based on lithology alone.

The unique facies of the Louisiana and McCraney formations occur at different positions with respect to the Hannibal and Prospect Hill formations (Fig. 4). The Louisiana Formation in Louisiana, MO, and Jersey County, IL, is below the Hannibal, whereas sections containing the McCraney in Newark, MO and the type section in Kinderhook, IL, place the McCraney above the Hannibal. A similar facies relationship to sections in Louisiana, MO and Jersey County, IL, can be seen in Burlington, IA, where the "McCraney" lies below the Prospect Hill, and overlays the uppermost Famennian English River Formation. Witzke (2002) proposed the idea that the "McCraney" at the Starr's Cave outcrop near Burlington, IA was miscorrelated originally by Moore (1928) and then by all subsequent workers (e.g., Witzke *et al.* 1990, Witzke & Bunker 2001). Here, we provide new conodont and biostratigraphic evidence for the chrono-stratigraphic correlation of the "McCraney" in southeast

Iowa that has significant implications for the placement of the DCB throughout the type Mississippian tri-state area.

Methods

We sampled the H-28 core and the Starr's Cave outcrop for conodont biostratigraphy and carbonate carbon isotope

($\delta^{13}\text{C}_{\text{carb}}$) chemostratigraphy. For chemostratigraphy, the H-28 core was sampled at one foot (0.30 m) intervals and the Starr's Cave outcrop at 10 cm intervals using drills fitted with tungsten-carbide tile bits with a preference for fine-grained carbonates (*e.g.*, Saltzman *et al.* 2002). Samples were analyzed at the Keck Paleoenvironmental and Environmental Stable Isotope Laboratory (KPESIL) at the University of Kansas where powdered sample was

Table 1. Stable isotope data from H-28 Core, Lee County, IA.

Decimal Feet	$\delta^{13}\text{C}_{\text{carb}}$	$\delta^{18}\text{O}$	Formation	Member	Decimal Feet	$\delta^{13}\text{C}_{\text{carb}}$	$\delta^{18}\text{O}$	Formation	Member
153	3.91	-4.11	Burlington	Cedar Fork	199	2.95	-4.67	Burlington	Dolbee Creek
154	3.98	-3.86	Burlington	Cedar Fork	200	3.14	-3.07	Burlington	Dolbee Creek
154.8	3.94	-3.86	Burlington	Cedar Fork	201	3.05	-4.23	Burlington	Dolbee Creek
156	3.91	-4.81	Burlington	Cedar Fork	202	3.07	-4.06	Burlington	Dolbee Creek
156.6	3.83	-5.18	Burlington	Cedar Fork	203	3.12	-4.11	Burlington	Dolbee Creek
158	3.45	-4.49	Burlington	Cedar Fork	204	3.07	-4.17	Burlington	Dolbee Creek
159	3.47	-4.27	Burlington	Cedar Fork	205	3.11	-3.97	Burlington	Dolbee Creek
160	3.92	-5.04	Burlington	Cedar Fork	206	3.10	-4.32	Burlington	Dolbee Creek
162	3.74	-5.24	Burlington	Haight Creek	207	3.00	-4.31	Burlington	Dolbee Creek
163	3.86	-4.86	Burlington	Haight Creek	208	3.12	-4.43	Burlington	Dolbee Creek
164	3.66	-5.48	Burlington	Haight Creek	209	3.04	-4.75	Burlington	Dolbee Creek
165	3.58	-5.46	Burlington	Haight Creek	210	3.00	-4.61	Burlington	Dolbee Creek
166	3.77	-5.11	Burlington	Haight Creek	211	3.61	-4.88	Wassonville	Upper Mb.
167	3.74	-4.87	Burlington	Haight Creek	212	3.52	-5.12	Wassonville	Upper Mb.
168	3.73	-4.78	Burlington	Haight Creek	213	3.65	-4.86	Wassonville	Upper Mb.
169	3.67	-5.21	Burlington	Haight Creek	214	3.36	-4.46	Wassonville	Upper Mb.
171	2.86	-5.63	Burlington	Haight Creek	215	3.21	-4.97	Wassonville	Upper Mb.
172	2.96	-5.19	Burlington	Haight Creek	216	3.12	-3.75	Wassonville	Upper Mb.
173	3.45	-4.66	Burlington	Haight Creek	217	3.28	-5.02	Wassonville	Upper Mb.
173.8	3.20	-4.89	Burlington	Haight Creek	218	2.93	-5.52	Wassonville	Upper Mb.
175	3.55	-4.15	Burlington	Haight Creek	219	2.59	-5.86	Wassonville	Upper Mb.
176	3.55	-4.06	Burlington	Haight Creek	220	2.62	-5.83	Wassonville	Upper Mb.
176.7	3.69	-5.09	Burlington	Haight Creek	221	2.65	-5.71	Wassonville	Upper Mb.
178	3.08	-5.26	Burlington	Haight Creek	221.5	2.91	-4.40	Wassonville	Upper Mb.
179	2.97	-4.81	Burlington	Haight Creek	222	3.10	-3.25	Wassonville	Upper Mb.
180	3.00	-4.85	Burlington	Haight Creek	222.5	2.51	-5.80	Wassonville	Upper Mb.
181	2.92	-5.25	Burlington	Haight Creek	223	2.78	-5.63	Wassonville	Starr's Cave
182	3.22	-4.59	Burlington	Haight Creek	223.5	2.75	-5.58	Wassonville	Starr's Cave
183	2.98	-5.19	Burlington	Haight Creek	224	2.92	-5.40	Wassonville	Starr's Cave
184	3.45	-2.52	Burlington	Haight Creek	224.5	2.73	-5.67	Wassonville	Starr's Cave
184.6	3.46	-3.98	Burlington	Haight Creek	224.8	2.23	-5.39	Wassonville	Starr's Cave
186	3.46	-2.37	Burlington	Haight Creek	225	2.67	-1.25	Wassonville	Starr's Cave
186.8	3.44	-2.16	Burlington	Haight Creek	225.5	2.49	-4.82	Prospect Hill	
188	3.43	-1.91	Burlington	Haight Creek	226	2.72	-1.50	Prospect Hill	
189	3.41	-4.65	Burlington	Haight Creek	226.5	2.24	-7.96	Prospect Hill	
190	3.25	-2.31	Burlington	Haight Creek	227	2.63	-2.33	Prospect Hill	
191	3.43	-2.10	Burlington	Haight Creek	228	2.41	-0.88	Prospect Hill	
192	3.42	-1.52	Burlington	Haight Creek	229	1.87	-1.88	Prospect Hill	
193	2.65	-4.29	Burlington	Haight Creek	230	1.67	-2.22	Prospect Hill	
193.3	2.12	-4.44	Burlington	Haight Creek	231	3.00	-1.25	Prospect Hill	
195	2.98	-4.80	Burlington	Dolbee Creek	232	2.91	-1.37	Prospect Hill	
196	2.40	-4.53	Burlington	Dolbee Creek	233	2.97	-1.75	Prospect Hill	
197	2.91	-5.35	Burlington	Dolbee Creek	234	3.15	-1.92	Prospect Hill	
198	2.88	-4.77	Burlington	Dolbee Creek	235	2.90	-2.64	Prospect Hill	

Table 1. Continued.

Decimal Feet	$\delta^{13}\text{C}_{\text{carb}}$	$\delta^{18}\text{O}$	Formation	Member	Decimal Feet	$\delta^{13}\text{C}_{\text{carb}}$	$\delta^{18}\text{O}$	Formation	Member
236	2.97	−2.18	Prospect Hill		289	5.62	−5.41	Louisiana	
237	3.01	−2.28	Prospect Hill		290	5.26	−5.57	Louisiana	
238	2.91	−2.70	Prospect Hill		291	5.80	−4.51	Louisiana	
239	2.40	−4.22	Prospect Hill		292	5.73	−5.13	Louisiana	
240	2.98	−3.02	Prospect Hill		293	5.97	−4.84	Louisiana	
241	2.92	−4.35	Prospect Hill		294	5.54	−5.28	Louisiana	
242	1.28	−4.19	Prospect Hill		295	5.60	−5.33	Louisiana	
243	1.82	−3.58	Prospect Hill		296	5.60	−5.02	Louisiana	
244	1.09	−4.28	Prospect Hill		297	5.78	−4.84	Louisiana	
245	2.38	−4.09	Prospect Hill		298	5.67	−4.68	Louisiana	
246	2.55	−3.43	Prospect Hill		299	5.81	−4.36	Louisiana	
247	2.51	−3.30	Prospect Hill		300	5.76	−4.30	Louisiana	
248	2.53	−4.52	Prospect Hill		301	5.55	−5.24	Louisiana	
249	2.11	−3.88	Prospect Hill		302	5.97	−4.38	Louisiana	
250	2.21	−4.41	Prospect Hill		302.8	5.46	−5.52	Louisiana	
251	1.96	−3.19	Prospect Hill		303.9	5.58	−4.96	Louisiana	
252	2.74	−2.30	Prospect Hill		304.9	5.62	−5.18	Louisiana	
253	1.34	−2.94	Prospect Hill		306.2	5.87	−4.65	Louisiana	
254	1.83	−2.38	Prospect Hill		307	5.92	−4.00	Louisiana	
255	2.70	−1.48	Prospect Hill		308	5.38	−5.40	Louisiana	
256	3.55	−1.09	Prospect Hill		309	5.83	−4.68	Louisiana	
257	3.69	−1.80	Prospect Hill		310	5.69	−4.91	Louisiana	
257.8	4.28	−3.58	Louisiana		311	5.55	−3.91	Louisiana	
258	4.55	−4.74	Louisiana		312	5.37	−5.15	Louisiana	
259	4.74	−4.93	Louisiana		313	5.63	−4.48	Louisiana	
260	4.64	−5.14	Louisiana		314	5.65	−4.46	Louisiana	
260.9	4.66	−4.89	Louisiana		315	5.31	−4.33	Louisiana	
262	5.04	−4.76	Louisiana		316	5.43	−4.60	Louisiana	
263	5.00	−5.09	Louisiana		317	5.20	−4.44	Louisiana	
264	5.49	−4.76	Louisiana		318	5.28	−4.26	Louisiana	
265	4.98	−4.89	Louisiana		319	5.21	−4.28	Louisiana	
266	5.47	−4.87	Louisiana		320	5.06	−4.13	Louisiana	
267	5.53	−4.79	Louisiana		321	4.91	−4.24	Louisiana	
268	5.73	−4.84	Louisiana		322	4.60	−4.16	Louisiana	
269	5.71	−4.91	Louisiana		323	3.18	−4.49	Louisiana	
270	5.40	−5.15	Louisiana		324	2.67	−3.72	Louisiana	
271	5.94	−4.87	Louisiana		325	3.09	−2.80	Louisiana	
272	5.27	−4.31	Louisiana		326	1.92	−2.41	English River	
273	5.48	−4.60	Louisiana		327	2.29	−2.13	English River	
274	6.00	−4.98	Louisiana		328	2.01	−2.05	English River	
275	5.65	−5.12	Louisiana		329	1.24	−2.71	English River	
276	5.82	−4.99	Louisiana		330	1.58	−1.95	English River	
277	5.84	−4.87	Louisiana		331	1.72	−2.00	English River	
278	5.86	−4.94	Louisiana		332	1.70	−2.01	English River	
279	5.82	−4.52	Louisiana		333.2	1.46	−2.41	English River	
280	5.79	−4.12	Louisiana		334	1.89	−1.86	English River	
281	5.76	−5.03	Louisiana		335	1.73	−2.36	English River	
282	5.65	−5.14	Louisiana		336	0.21	−3.66	English River	
283	5.61	−5.23	Louisiana		337	−0.24	−4.47	English River	
284	5.63	−5.34	Louisiana		338	0.28	−3.58	English River	
285	5.95	−4.36	Louisiana		339	0.54	−3.77	English River	
286	5.65	−5.13	Louisiana		340	1.03	−2.82	English River	
287	5.67	−4.90	Louisiana		340.6	0.45	−3.67	English River	
288	5.42	−5.57	Louisiana		341.9	0.85	−1.76	English River	

Table 2. Stable isotope data from Starr's Cave, Burlington, IA.

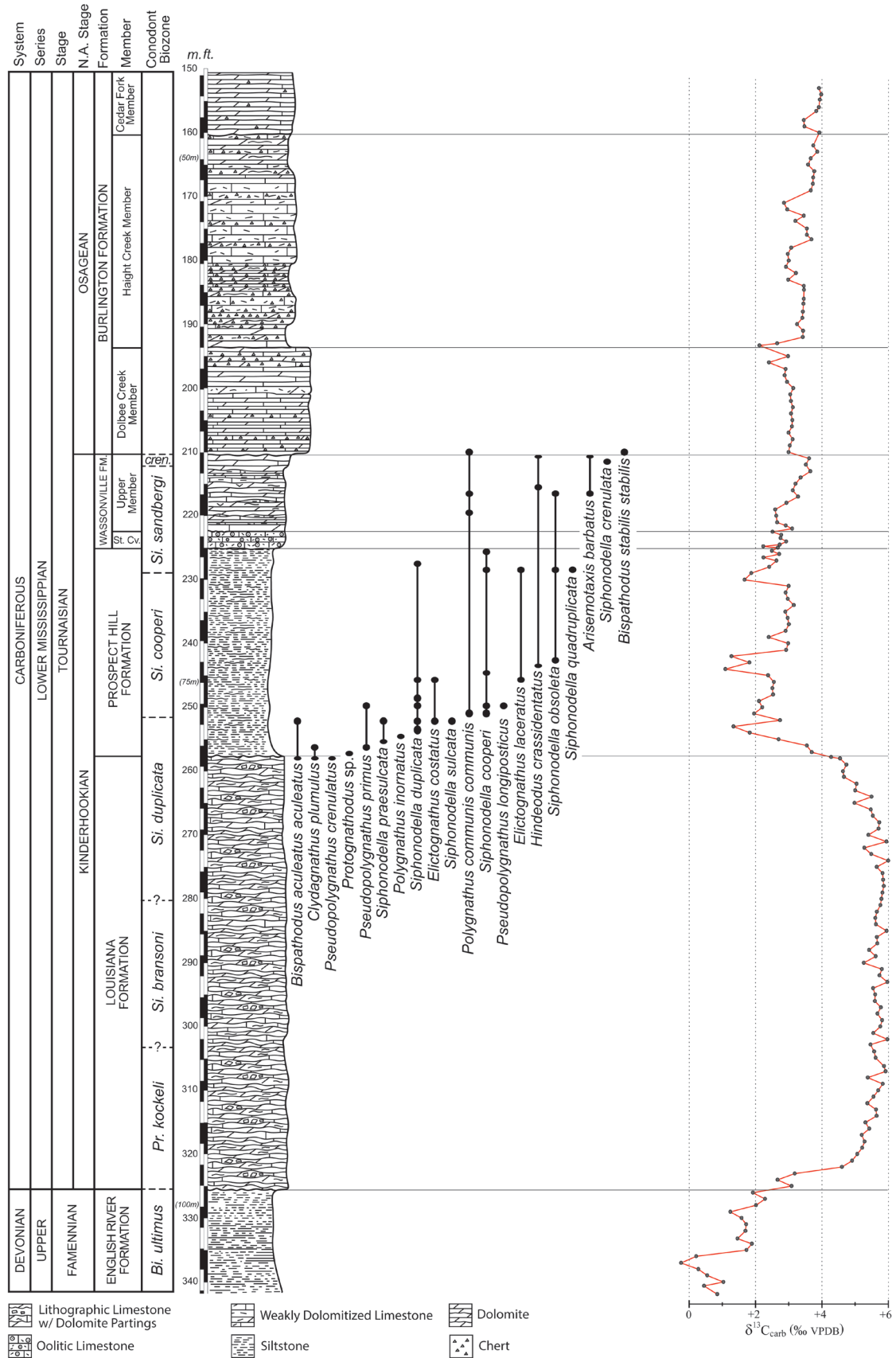
Meters	$\delta^{13}\text{C}_{\text{carb}}$	$\delta^{18}\text{O}$	Formation	Member	Meters	$\delta^{13}\text{C}_{\text{carb}}$	$\delta^{18}\text{O}$	Formation	Member
7.0	1.57	-1.84	Wassonville	Upper Mb.	2.5	2.15	-4.50	"McCraney"	
6.9	1.12	-2.02	Wassonville	Upper Mb.	2.4	2.26	-4.74	"McCraney"	
6.8	0.20	-4.98	Wassonville	Upper Mb.	2.3	2.05	-4.70	"McCraney"	
6.7	0.55	-1.93	Wassonville	Upper Mb.	2.2	2.35	-4.58	"McCraney"	
6.6	2.08	-0.93	Wassonville	Upper Mb.	2.1	2.52	-4.51	"McCraney"	
6.5	1.61	-2.60	Wassonville	Upper Mb.	2.0	2.46	-4.57	"McCraney"	
6.4	0.98	-4.86	Wassonville	Upper Mb.	1.9	2.51	-4.65	"McCraney"	
6.3	0.75	-4.43	Wassonville	Upper Mb.	1.8	2.19	-4.67	"McCraney"	
6.2	1.10	-4.34	Wassonville	Starr's Cave	1.7	2.23	-4.59	"McCraney"	
6.1	0.42	-5.25	Wassonville	Starr's Cave	1.6	2.80	-4.44	"McCraney"	
6.0	0.85	-4.54	Wassonville	Starr's Cave	1.5	2.87	-4.51	"McCraney"	
5.9	1.16	-4.36	Wassonville	Starr's Cave	1.4	1.83	-4.16	"McCraney"	
5.8	0.87	-4.70	Wassonville	Starr's Cave	1.3	2.79	-4.39	"McCraney"	
5.7	1.38	-3.89	Wassonville	Starr's Cave	1.2	3.27	-4.62	"McCraney"	
5.6	1.21	-4.16	Wassonville	Starr's Cave	1.1	2.81	-4.42	"McCraney"	
5.5	0.93	-4.57	Wassonville	Starr's Cave	1.0	3.02	-4.44	"McCraney"	
5.4	2.52	-0.80	Prospect Hill		0.9	3.46	-4.42	"McCraney"	
5.3	2.24	-1.42	Prospect Hill		0.8	3.13	-4.49	"McCraney"	
5.2	1.57	-2.41	Prospect Hill		0.7	3.10	-4.52	"McCraney"	
5.1	1.48	-1.77	Prospect Hill		0.6	3.56	-4.56	"McCraney"	
5.0	1.34	-2.04	Prospect Hill		0.5	2.38	-4.75	"McCraney"	
4.9	2.02	-1.18	Prospect Hill		0.4	2.63	-4.38	"McCraney"	
4.8	1.52	-1.50	Prospect Hill		0.3	2.16	-4.27	"McCraney"	
4.7	1.64	-2.71	Prospect Hill		0.2	2.32	-4.70	"McCraney"	
4.6	1.52	-1.76	Prospect Hill		0.1	-0.02	-12.45	"McCraney"	
4.5	1.16	-1.41	Prospect Hill		0.0	1.19	-5.00	English River	
4.4	1.48	-1.29	Prospect Hill		-0.1	1.62	-1.80	English River	
4.3	1.90	-1.10	Prospect Hill		-0.2	1.55	-1.88	English River	
4.2	-0.16	-2.57	Prospect Hill		-0.3	2.48	-0.96	English River	
4.1	3.41	-0.51	Prospect Hill		-0.4	1.63	-1.63	English River	
4.0	-0.05	-2.20	Prospect Hill		-0.5	2.17	-0.82	English River	
3.5	4.71	-0.03	"McCraney"		-0.6	1.85	-1.06	English River	
3.4	1.04	-3.63	"McCraney"		-0.7	2.00	-0.81	English River	
3.3	4.92	0.46	"McCraney"		-0.8	2.08	-0.92	English River	
3.2	2.73	-1.20	"McCraney"		-0.9	2.06	-0.84	English River	
3.1	3.70	-0.37	"McCraney"		-1.0	2.04	-0.90	English River	
3.0	1.64	-4.34	"McCraney"		-1.1	1.81	-0.96	English River	
2.9	1.73	-4.40	"McCraney"		-1.2	0.94	-1.00	English River	
2.8	2.17	-4.61	"McCraney"		-1.3	-0.39	-3.05	English River	
2.7	2.35	-4.55	"McCraney"		-1.4	1.23	-0.62	English River	
2.6	2.11	-4.64	"McCraney"		-1.5	0.60	-2.56	English River	

reacted with 100% phosphoric acid with density >1.9 (Wachter Hayes 1985) with a KIEL Carbonate Device connected to a ThermoFinnigan MAT 253 isotope ratio mass spectrometer. Isotopic values were calibrated to VPDB using NBS-18 and NBS-19 as primary standards, and daily performance was monitored with laboratory (secondary) standards TSF-1, SIGMA CALCITE, and 88b

Dolomite analyzed at the beginning, middle, and end of each 40 sample queue. Precision was better than 0.10‰ for both carbon and oxygen isotopes.

Both the H-28 Core and the Starr's Cave outcrop were sampled for conodont biostratigraphy. Continuous samples (50 total) were taken every foot (0.30 m) to as small as every three inches (7.5 cm) from the H-28 Core,

Figure 5. Conodont biostratigraphy and carbon isotope chemostratigraphy of the H-28 core from Burlington, Iowa. Conodont occurrences are represented by small circles. The red dashed line is a proposed position of the Devonian–Carboniferous boundary at the base of the *Protognathodus kockeli* Zone. Note the use of Louisiana Fm. in the core. Previously this strata in Iowa had been referred to as "McCraney".



from the top of the Louisiana Limestone to the top of the Wassonville Fm. sampling the entire core over this interval. Not all samples yielded conodonts, and those that did yield identifiable specimens are shown in Fig. 5. The Starr's Cave outcrop was similarly sampled at 30–40 cm resolution. Conodont samples were dissolved in a 10% double-buffered formic acid solution (Jeppsson & Anehus 1995). Residues were sieved through 1,000 and 63 micron sieves, and the 63-micron fraction was subjected to heavy liquid separation using lithium metatungstate at 2.83–2.84 g/mL. Conodonts were then picked under a microscope and photographed using a Cannon 60D camera with a StackShot platform and Zerene image-stacking software for regular-light images before being gold coated and imaged in a Hitachi S-3400N Scanning Electron Microscope. All conodont samples illustrated here, as well as additional material not imaged, are housed at the University of Iowa Paleontology Repository with accession numbers SUI 148219–SUI 148368.

Results

H-28 Core

The H-28 core (Iowa Geological Survey WNumber 27539) is located in southeastern Iowa, south of the city of Burlington, at 40.408131° N, 91.417870° W. The sampled section spans 190 feet (58 m) and contains the English River, Louisiana, Prospect Hill, Wassonville, and Burlington formations. Two hundred seventeen carbon isotope samples were taken at mostly one-foot intervals (0.30 m) and 50 conodont samples were taken from the top of the Louisiana through Wassonville formations every 12 inches (30 cm) with some samples every three inches (7.5 cm) for continuous sampling of the entire core in this interval. Carbonate carbon isotope ($\delta^{13}\text{C}_{\text{carb}}$) values ranged from -0.05‰ to $+6.0\text{‰}$ (Fig. 5) and the data are presented in Tab. 1. This includes the Hangenberg positive isotope excursion, which occurs from the upper English River Fm. to the lowermost Prospect Hill Fm. Peak values of $+6\text{‰}$ occur throughout the Louisiana Formation. Conodont samples returned a diverse *Siphonodella* fauna. Biostratigraphically important specimens include *Siphonodella praesulcata*, *S. sulcata*, *S. duplicata*, *S. cooperi*, *S. obsoleta*, and *Hindeodus crassidentatus* in the Prospect Hill Fm. and *S. quadruplicata*, *Arisemotaxis barbatus*, and *S. crenulata* in the Wassonville Formation (Figs 6–10, 12).

Starr's Cave

The Starr's Cave locality is located in Starr's Cave Park and Preserve, north of the city of Burlington, Des Moines

County, at 40.851537° N, 91.136000° W (Fig. 11). The section was sampled from the base of the English River Fm. into the Upper Member of the Wassonville Fm. Conodont samples were taken at roughly 30–40 cm intervals and 82 carbon isotope samples were taken at 10 cm resolution. Carbonate carbon isotope ($\delta^{13}\text{C}_{\text{carb}}$) data ranged from -0.5‰ to $+5\text{‰}$ with peak values occurring near the top of the "McCraney" Fm. (Fig. 13) and the data are presented in Tab. 2. Conodont samples returned a diverse conodont fauna many of which are from the Prospect Hill Fm. Biostratigraphically important specimens include *Siphonodella duplicata*, *S. quadruplicata*, *S. cooperi*, *S. sulcata*, *S. obsoleta*, and *S. sandbergi* (Figs 14–17).

Discussion

The data recovered by this study provide important new information regarding the distinction between the Louisiana and McCraney formations in southeastern Iowa. Below we summarize the chronostratigraphic information available for these units in their type areas and compare them to the new data provided from southeastern Iowa.

Conodont biostratigraphic and chemostratigraphic data unequivocally demonstrate the chronostratigraphic position of the Louisiana Formation in its type area. Conodonts from the Louisiana in its type area include *Protognathodus kockeli*, *P. collinsoni*, *P. meischneri*, and *Cryptotaxis culminidirecta* (Scott & Collinson 1961, Straka 1968, Chauffe & Nichols 1995). Several of these species were originally identified as belonging to the genus *Gnathodus* and these misidentifications suggested an earliest Mississippian (Kinderhookian) origin for the genus that was not supported anywhere else in the world. To clarify these identifications, we re-illustrate the specimens in question here in Fig. 18. Scott & Collinson (1961) provided a species list of specimens recovered from the Louisiana Limestone that included *Gnathodus* cf. *G. commutatus* (Scott & Collinson 1961, p. 113). Later in the plate caption to their plate 1 (p. 137) they refer two specimens to *Gnathodus commutatus*, shown in our Fig. 18 with their original figure designation as image 23, 25, and 26. These two specimens clearly belong to two species of *Protognathodus*, with 23 and 25 re-identified herein as oral and basal views of *P. collinsoni*, and image 26 re-identified herein as *P. meischneri*. Image 28 was originally identified as belonging to *Gnathodus kockeli*, now *P. kockeli* (see Corradini *et al.* 2011). All of these specimens are from the Louisiana Limestone at Teneriffe School, Jersey County, Illinois. Straka (1968) also reported a single Kinderhookian occurrence of *Gnathodus* in Iowa. His specimen, from the Wassonville Formation at the Maple Mill Locality, Washington

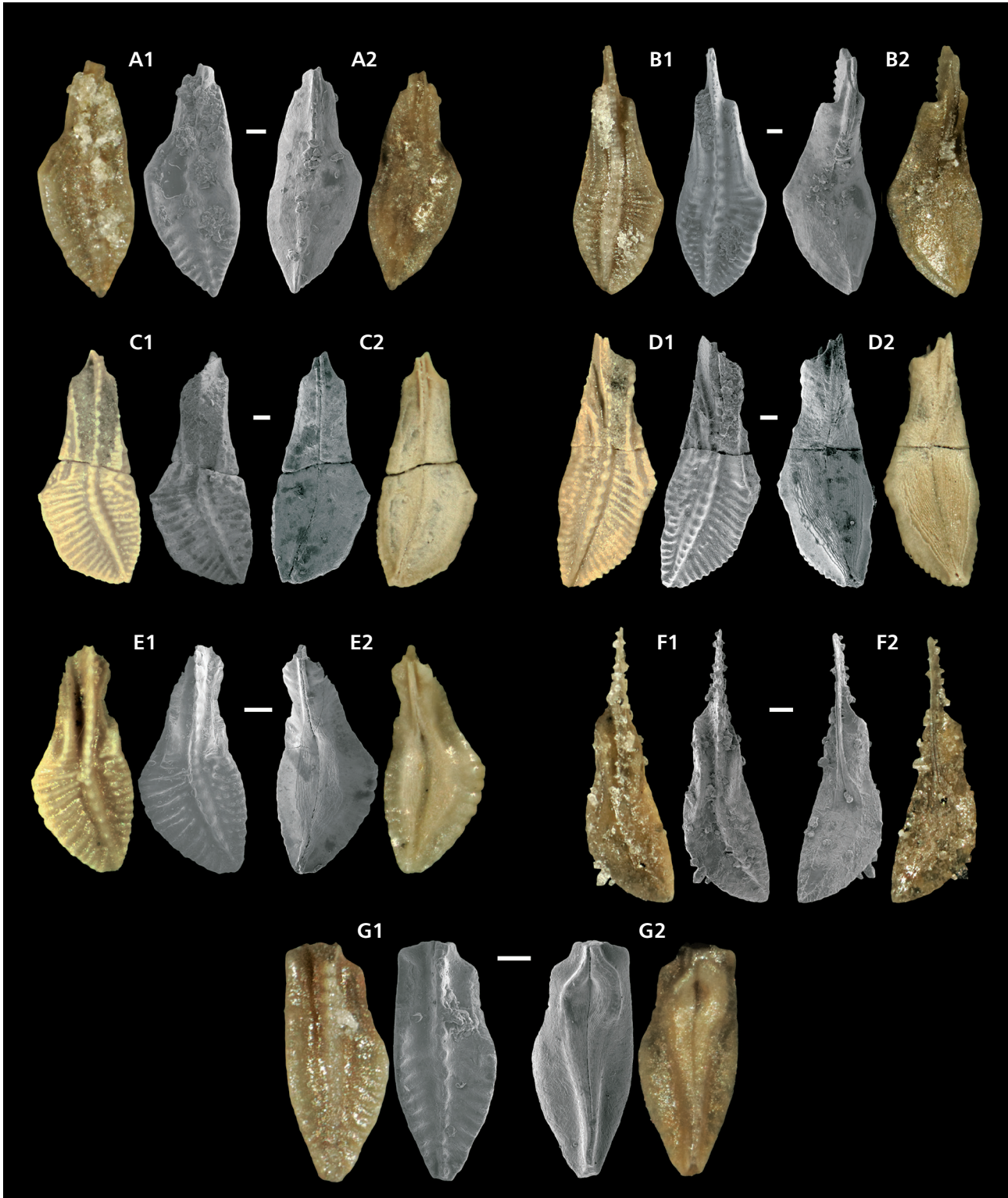


Figure 6. Conodonts from the H-28 Core. • A, C – *Siphonodella duplicata* (Branson & Mehl, 1934a); A – sinistral P_1 element, oral view (A1), aboral view (A2), Prospect Hill Fm., 252'11"–254'3", SUI 148219; C – sinistral P_1 element, oral view (C1), aboral view (C2), Prospect Hill Fm., 248'0"–249'2", SUI 148220. • B, D – *Siphonodella cooperi* Hass, 1959; B – dextral P_1 element, oral view (B1), aboral view (B2), Prospect Hill Fm., 249'2"–250'2", SUI 148221; D – dextral P_1 element, oral view (D1), aboral view (D2), Prospect Hill Fm., 224'11"–226'0", SUI 148222. • E – *Siphonodella crenulata* (Cooper, 1939); sinistral P_1 element, oral view (E1), aboral view (E2), Upper Member, Wassonville Fm., 211'0"–212'0", SUI 148223. • F – *Siphonodella obsoleta* Hass, 1959; sinistral P_1 element oral view (F1), aboral view (F2), Upper Member, Wassonville Fm., 216'0"–217'0", SUI 148224. • G – *Pseudopolygnathus* sp., dextral P_1 element, oral view (A1), aboral view (A2), Prospect Hill Fm., 250'2"–251'7", SUI 148225.



Figure 7. Conodonts from the H-28 Core. • A – *Siphonodella praesulcata* Sandberg *et al.*, 1972; sinistral P₁ element, oral view (A1), aboral view (A2), Prospect Hill Fm., 255°0'–255°9", SUI 148226. • B, C – *Siphonodella duplicata* (Branson & Mehl, 1934a); B – dextral P₁ element, oral view (B1), aboral view (B2), Prospect Hill Fm., 249°2'–250°2", SUI 148227; C – sinistral P₁ element, oral view (C1), aboral view (C2), Prospect Hill Fm., 245°2'–246°1", SUI 148228. • D – *Siphonodella ?quadruplicata* (Branson & Mehl, 1934a); sinistral P₁ element, oral view (D1), aboral view (D2), Prospect Hill Fm., 228°0'–229°0", SUI 148229. • E – *Siphonodella obsoleta* Hass, 1959; sinistral P₁ element, oral view (E1), aboral view (E2), Prospect Hill Fm., 242°1'–243°1", SUI 148230. • F – *Siphonodella sulcata* (Huddle, 1934); sinistral P₁ element, oral view (F1), aboral view (F2), Prospect Hill Fm., 251°7'–252°10", SUI 14823. • G – gen. et sp. indet.; ?P₁ element, oral view (G1), aboral view (G2), Upper Member, Wassonville Fm., 212°0'–213°0", SUI 148232.

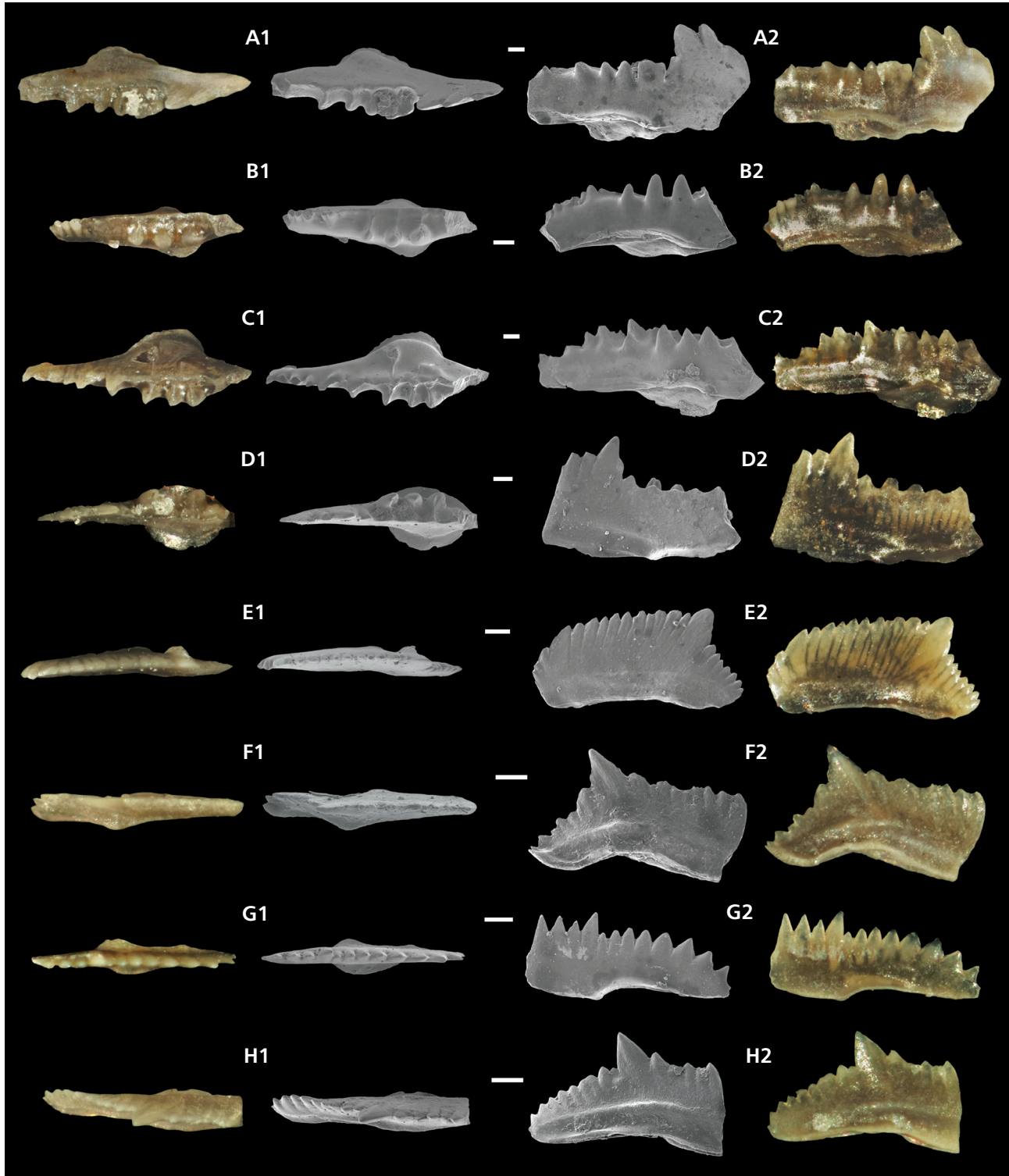


Figure 8. Conodonts from the H-28 Core. • A, D – *Clydagnathus plumulus* (Rhodes *et al.*, 1969); A – sinistral P_1 element, oral view (A1), caudal view (A2), Louisiana Fm., 257'8"–258'2", SUI 148233; D – sinistral P_1 element, oral view (D1), rostral view (D2), Prospect Hill Fm., 255'9"–256'10", SUI 148234. • B, C – *Bispathodus aculeatus aculeatus* (Branson & Mehl, 1934b); B – sinistral P_1 element, oral view (B1), caudal view (B2), Louisiana Fm., 257'8"–258'2", SUI 148235; C – sinistral P_1 element, oral view (C1), caudal view (C2), Louisiana Fm., 257'8"–258'2", SUI 148236. • E – *Elicognathus costatus* (Branson & Mehl, 1934a); E – dextral P_2 element, oral view (E1), caudal view (E2), Prospect Hill Fm., 245'2"–246'1", SUI 148237. • F, H – *Elicognathus laceratus* (Branson & Mehl, 1934a); F – dextral P_2 element, oral view (F1), rostral view (F2), Prospect Hill Fm., 245'2"–246'1", SUI 148238; H – dextral P_2 element, oral view (H1), rostral view (H2), Prospect Hill Fm., 228'0"–229'0", SUI 148239. • G – *Hindeodus crassidentatus* (Branson & Mehl, 1934a), dextral P_2 element, oral view (G1), caudal view (G2), Prospect Hill Fm., 243'1"–243'9", SUI 148240

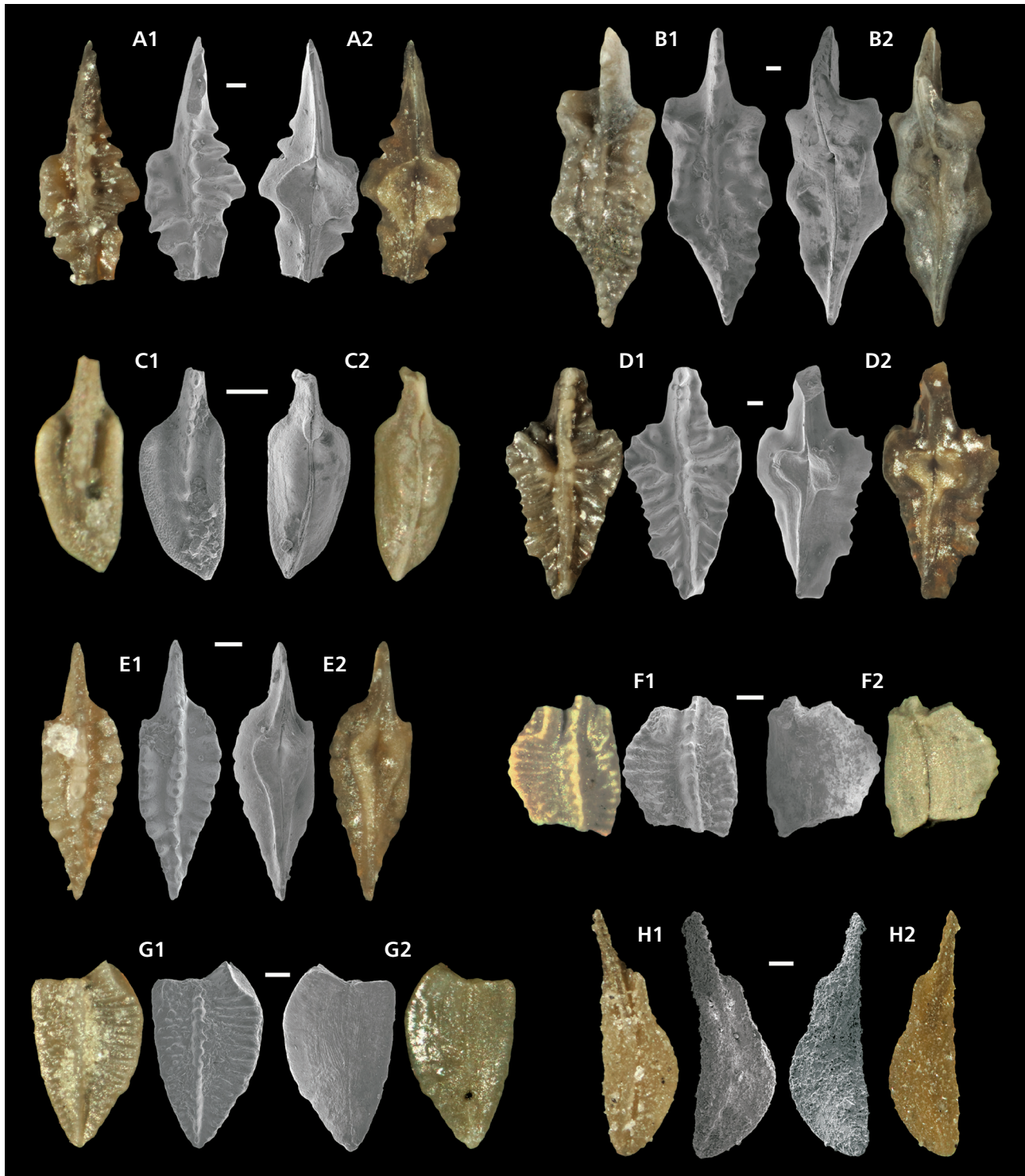


Figure 9. Conodonts from the H-28 Core. • A, D – *Pseudopolygnathus primus* Branson & Mehl, 1934a; A – sinistral P_1 element, oral view (A1), aboral view (A2), Prospect Hill Fm., 255°9'–256°10', SUI 148241; D – sinistral P_1 element, oral view (D1), aboral view (D2), Prospect Hill Fm., 249°2'–250°2', SUI 148242. • B – *Pseudopolygnathus crenulatus* Branson & Mehl, 1934a; sinistral P_1 element, oral view (B1), aboral view (B2), Louisiana Fm., 257°8'–258°2', SUI 148243. • C – *Polygnathus communis communis* (Branson & Mehl, 1934a); sinistral P_1 element, oral view (C1), aboral view (C2), Prospect Hill Fm., 250°2'–251°7', SUI 148244. • E – *Polygnathus longiposticus* Branson & Mehl, 1934a; extral P_1 element, oral view (E1), aboral view (E2), Prospect Hill Fm., 249°2'–250°2', SUI 148245. • F – *Siphonodella* sp., sinistral P_1 element, oral view (F1), aboral view (F2), Prospect Hill Fm., 241°5'–242°0', SUI 148246. • G – *Siphonodella cooperi* Hass, 1959, dextral P_1 element, oral view (G1), aboral view (G2), Prospect Hill Fm., 228°0'–229°0', SUI 148247. • H – *Siphonodella* sp. – dextral P_1 element, oral view (H1), aboral view (H2), Prospect Hill Fm., 220°0'–221°0', SUI 148248.

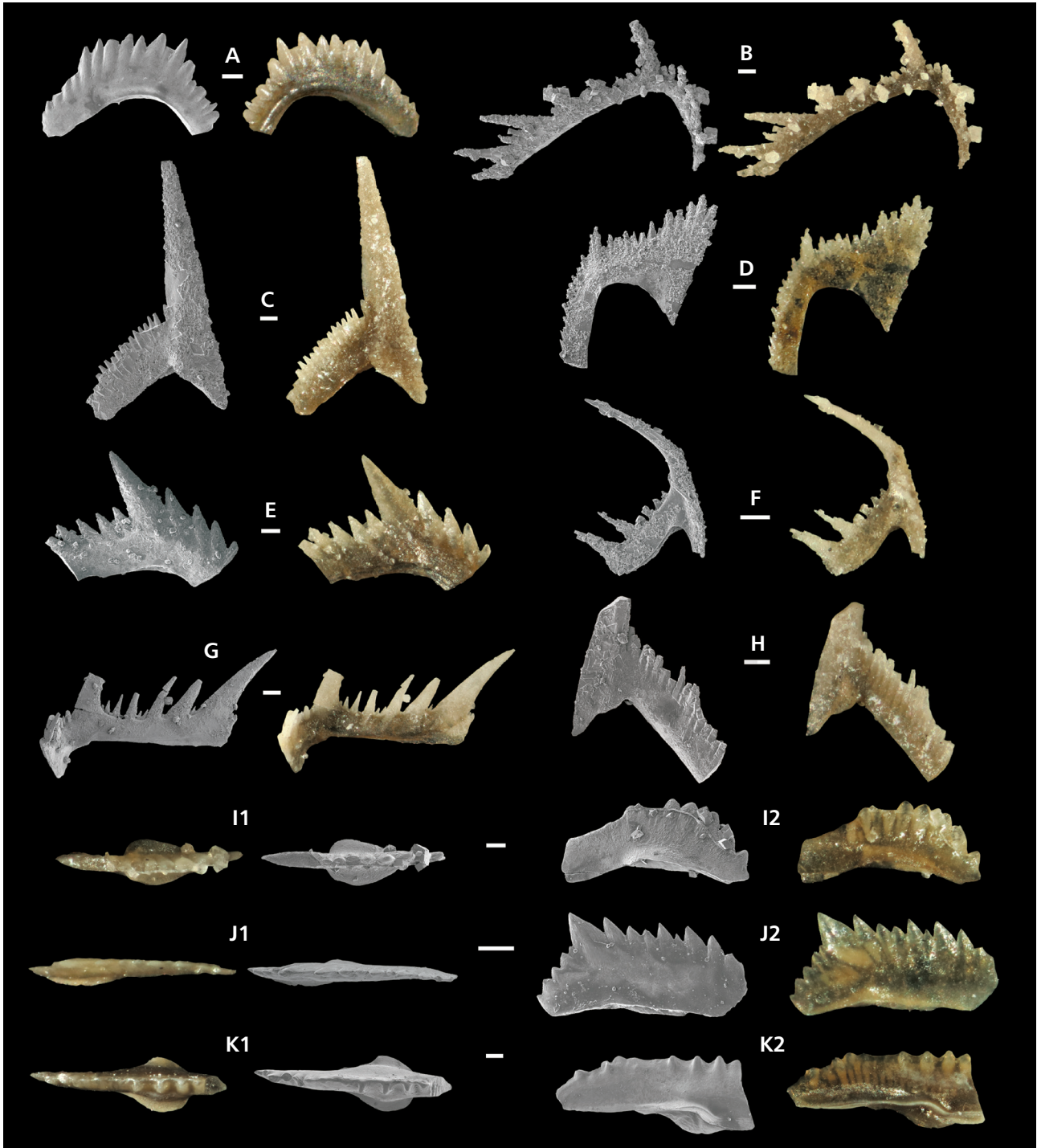
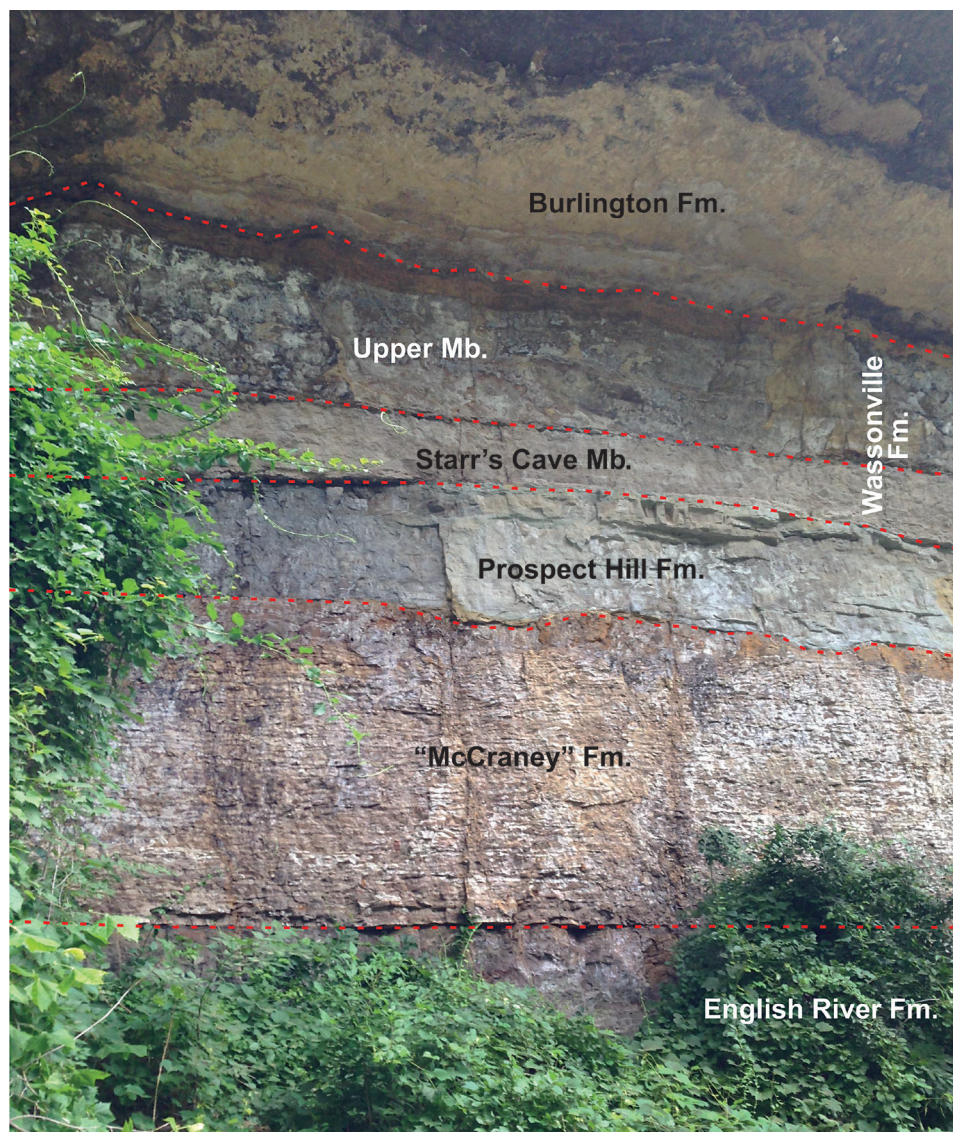


Figure 10. Conodonts from the H-28 Core. • A – *Protognathodus* sp., sinistral P₂ element, rostral view on left (SEM), caudal view on right (plain light), Prospect Hill Fm., 256°10'–257°8", SUI 148249. • B – gen. et sp. indet., sinistral ?S₃ element, adaxial view, Upper Member, Wassonville Fm., 216°0'–217°0", SUI 148250. • C, H – *Arisemotaxis barbatus* (Branson & Mehl, 1934a); C – dextral M element, dorsal view, Upper Member, Wassonville Fm., 216°0'–217°0", SUI 148251; H – sinistral M element, dorsal view, Upper Member, Wassonville Fm., 210°5'–211°0", SUI 148252. • D – *Siphonodella* sp., sinistral S₂ element, adaxial view, Upper Member, Wassonville Fm., 216°0'–217°0", SUI 148253. • E–G – *Hindeodus crassidentatus* (Branson & Mehl, 1934a); E – dextral P₂ element, caudal view, Upper Member, Wassonville Fm., 210°5'–211°0", SUI 148254; F – dextral S₂ element, adaxial view, Upper Member, Wassonville Fm., 215°0'–216°0", SUI 148255; G – dextral S₃ element, adaxial view, Upper Member, Wassonville Fm., 210°5'–211°0", SUI 148256. • I – *Bispathodus stabilis stabilis* (Branson & Mehl, 1934b), sinistral P₁ element, oral view (I1), rostral view (I2), Dolbee Creek Member, Burlington Fm., 209°6'–210°5", SUI 148257. • J – *Elictoognathus costatus* (Branson & Mehl, 1934a), sinistral P₂ element, oral view (J1), caudal view (J2), Prospect Hill Fm., 251°7'–252°10", SUI 148258. • K – *Bispathodus aculeatus aculeatus* (Branson & Mehl, 1934b), sinistral P₁ element, oral view (K1), caudal view (K2), Prospect Hill Fm., 251°7'–252°10", SUI 148259.

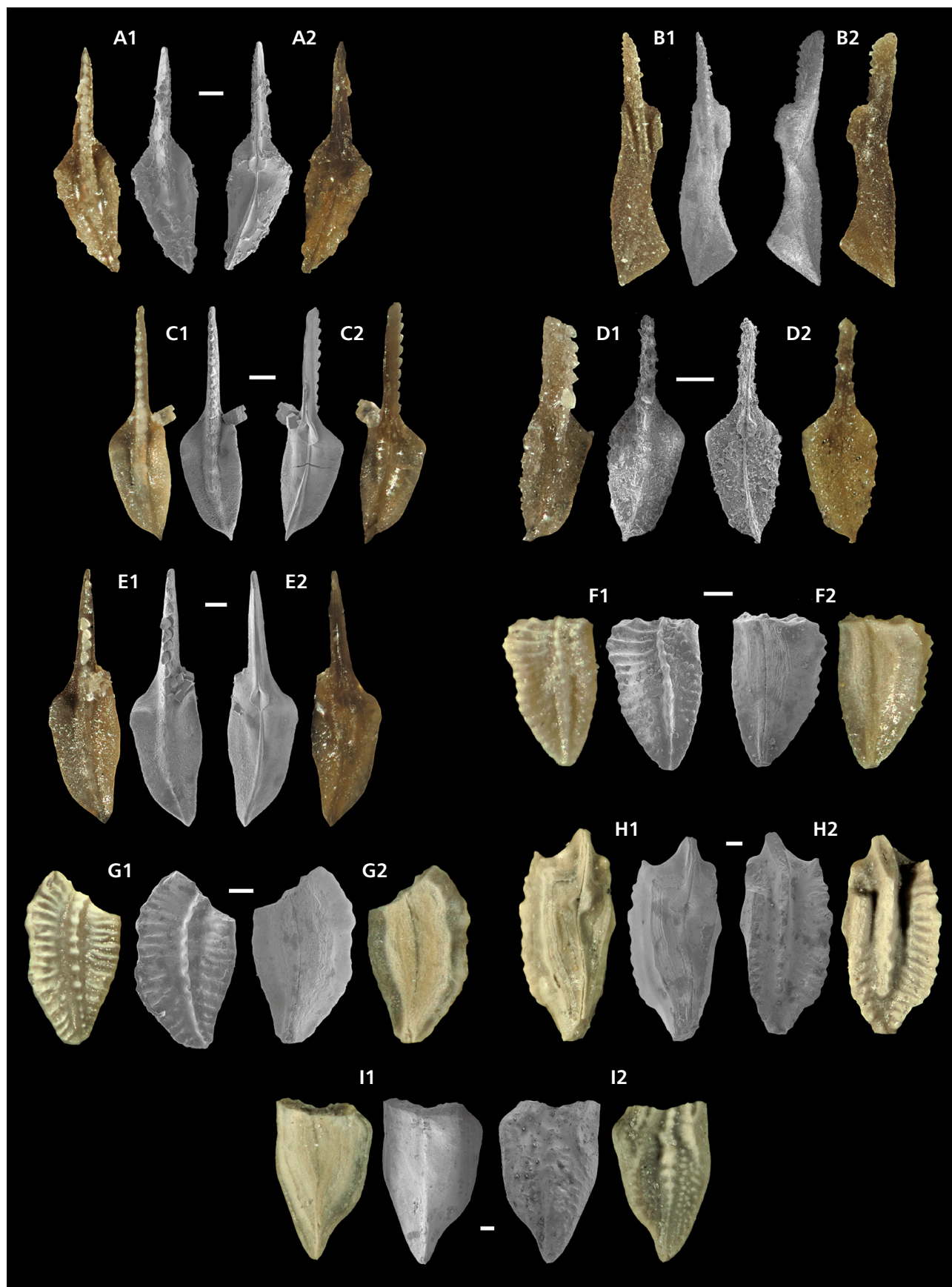
Figure 11. Field photograph of the Starr's Cave Outcrop at Starr's Cave Park in Des Moines County, IA. Formations and unit members are labeled. The red dashed lines indicate the boundary between members or formations.



County, Iowa, was originally identified as *Gnathodus delicatus*. This specimen (spec. 11, pl. 7, Straka 1968) is housed at the University of Iowa Paleontology Repository as SUI #125484 and was re-examined by the authors. The specimen clearly has a single node on each side of the platform and is best identified as *P. collinsoni*. Taken together, these re-identifications of reports of *Gnathodus*

in Kinderhookian strata of the tri-state area, and the data presented from the Louisiana Limestone by Chauffé & Nichols (1995), demonstrate that the entire succession of *Protognathodus*, including the base of the *P. kockeli* Zone, occurs within the DCB interval in the tri-state area and that the first occurrence of *P. kockeli* is no lower than the base of the Louisiana Limestone.

Figure 12. Conodonts from the H-28 Core. • A, C–E – *Polygnathus communis communis* (Branson & Mehl, 1934a); A – sinistral P₁ element, oral view (A1), aboral view (A2), Upper Member, Wassonville Fm., 219'0"–220'0", SUI 148260; C – sinistral P₁ element, oral view (C1), aboral view (C2), Dolbee Creek Member, Burlington Fm., 209'6"–210'5", SUI 148261; D – dextral P₁ element, oral view (D1), aboral view (D2), Upper Member, Wassonville Fm., 216'0"–217'0", SUI 148262; E – sinistral P₁ element, oral view (E1), aboral view (E2), Dolbee Creek Member, Burlington Fm., 209'6"–210'5", SUI 148263. • B – *Siphonodella* sp., dextral P₁ element, oral view (B1), aboral view (B2), Upper Member, Wassonville Fm., 216'0"–217'0", SUI 148264. • F – *Siphonodella ?cooperi* Hass, 1959; sinistral P₁ element, oral view (F1), aboral view (F2), Prospect Hill Fm., 244'3"–245'0", SUI 148265. • G – *Siphonodella duplicata* (Branson & Mehl, 1934a); sinistral P₁ element, oral view (G1), aboral view (G2), Prospect Hill Fm., 227'0"–228'0", SUI 148266. • H – *Polygnathus inornatus* E.R. Branson, 1934; dextral P₁ element, aboral view (H1), oral view (H2), Prospect Hill Fm., 254'3"–255'0", SUI 148267. • I – *Siphonodella obsoleta* Hass, 1959, sinistral P₁ element, aboral view (I1), oral view (I2), Prospect Hill Fm., 227'0"–228'0", SUI 148268.



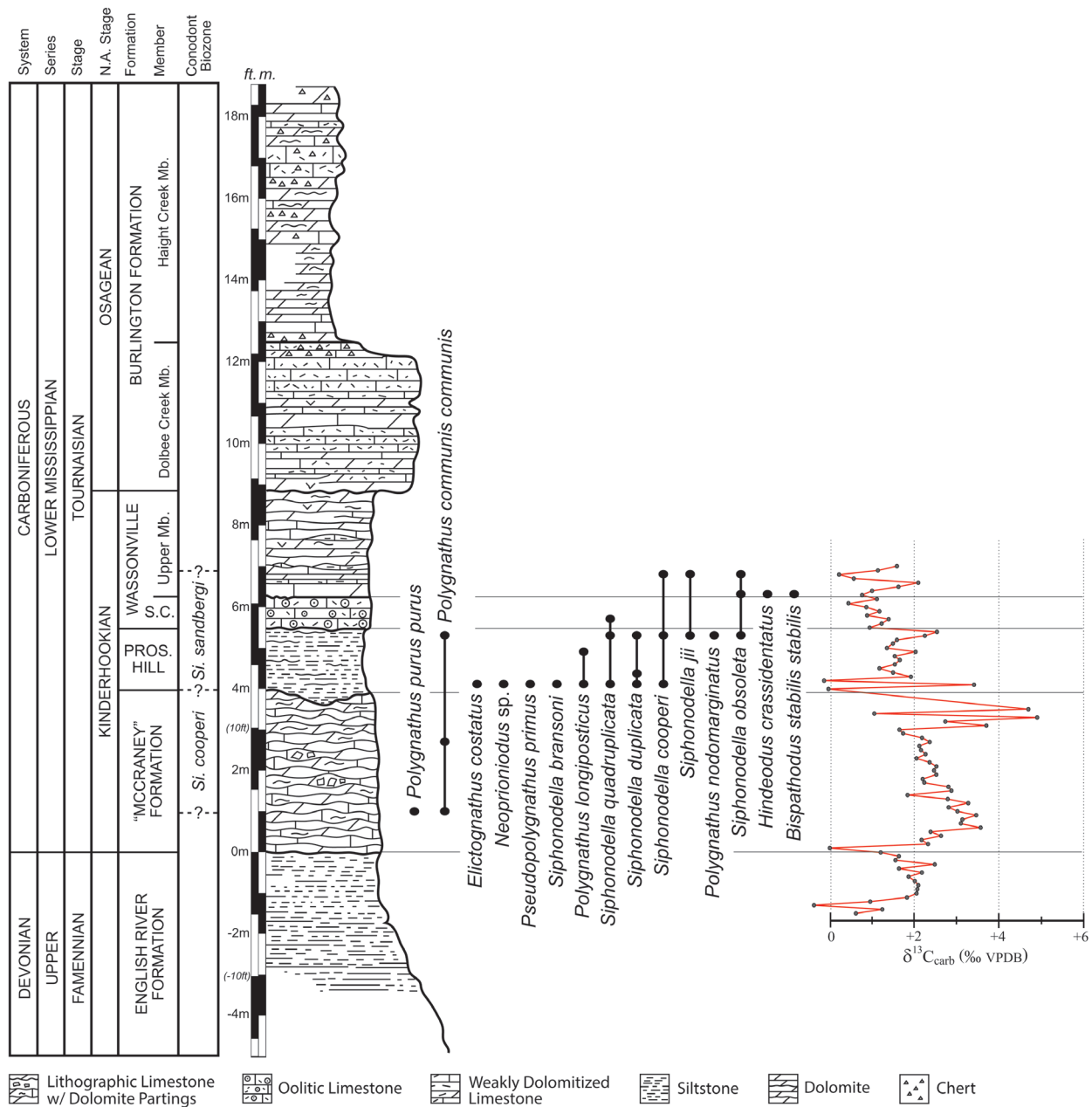


Figure 13. Conodont biostratigraphy and carbon isotope chemostratigraphy of the Starr's Cave Outcrop in Des Moines County, Iowa. Conodont occurrences are represented by small circles.

The Louisiana Limestone in its type area of eastern Missouri contains $\delta^{13}\text{C}_{\text{carb}}$ values greater than +6‰ (Cramer *et al.* 2008) indicative of the Hangenberg positive carbon isotope excursion (Kaiser *et al.* 2016). Therefore, the combined conodont and carbon isotope biochemostratigraphic data clearly demonstrate that the Louisiana Fm. in its type area records the Hangenberg Crisis, the Hangenberg positive carbon isotope excursion, and is at least in part within the *P. kockeli* conodont

Zone (Kaiser 2005, 2009; Cramer *et al.* 2008; Becker *et al.* 2016; Kaiser *et al.* 2016; Fig. 3 herein). In its type area the Louisiana Formation is typically devoid of siphonodellids, and is consistently overlain by the Hannibal Formation.

Samples from the McCraney Formation at its type locality in Kinderhook, Illinois has not produced conodont specimens. Most recently, Chauffe & Guzman (1997) sampled the type section of the McCraney at McCraney



Figure 14. Conodonts from the Starr’s Cave Outcrop. • A, C – *Polygnathus longiposticus* Branson & Mehl, 1934a; A – [?] dextral P₁ element, oral view (A1), aboral view (A2), “McCraney” Fm., 0.9–1.1 m, SUI 148269; C – dextral P₁ element, oral view (C1), aboral view (C2), Prospect Hill Fm., 4.8–5.0 m, SUI 148270. • B, D, E – *Polygnathus communis communis* (Branson & Mehl, 1934a); B – sinistral P₁ element, oral view (B1), aboral view (B2), “McCraney” Fm., 2.6–2.8 m, SUI 148271; D – dextral P₁ element, oral view (D1), aboral view (D2), Prospect Hill Fm., 5.2–5.4 m, SUI 148272; E – sinistral P₁ element, oral view (E1), aboral view (E2), “McCraney” Fm., 0.9–1.1 m, SUI 148273. • F – *Polygnathus purus purus* (Voges, 1959), dextral P₁ element, oral view (F1), aboral view (F2), “McCraney” Fm., 0.9–1.1 m, SUI 148274. • G – *Siphonodella bransoni* Ji, 1985; sinistral P₁ element, oral view (G1), aboral view (G2), Prospect Hill Fm., 4.0–4.2 m, SUI 148275. • H – *Polygnathus nodomarginatus* E.R. Branson in Branson & Mehl, 1934a; dextral P₁ element) oral view (H1), aboral view (H2), “McCraney” Fm., 2.6–2.8 m, SUI 148276. • I – sinistral P₁ element, oral view (I1), aboral view (I2), Prospect Hill Fm., 5.2–5.4 m, SUI 148277.

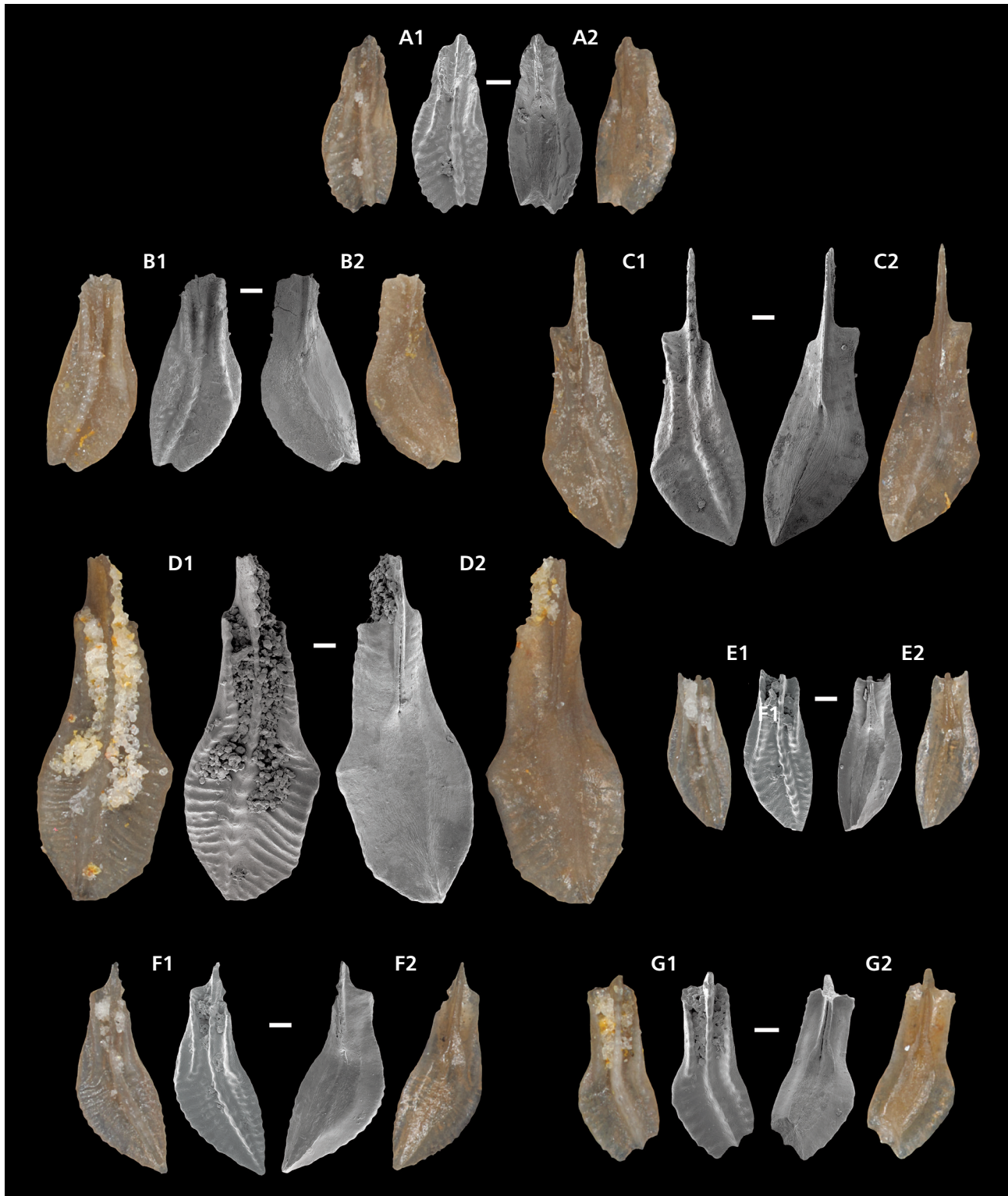


Figure 15. Conodonts from the Starr's Cave Outcrop. • A, E, G – *Siphonodella cooperi* Hass, 1959; A – sinistral P₁ element, oral view (A1), aboral view (A2), Prospect Hill Fm., 5.2–5.4 m, SUI 148278; E – sinistral P₁ element, oral view (E1), aboral view (E2), Prospect Hill Fm., 5.2–5.4 m, SUI 148279; G – sinistral P₁ element, oral view (G1), aboral view (G2), Prospect Hill Fm., 4.0–4.2 m, SUI 148280. • B, C – *Siphonodella obsoleta* Hass, 1959; B – dextral P₁ element, oral view (B1), aboral view (B2), Upper Member, Wassonville Fm., 6.2–6.4 m, SUI 148281; C – sinistral P₁ element, oral view (C1), aboral view (C2), Upper Member, Wassonville Fm., 6.7–6.8 m, SUI 148282. • D – *Siphonodella duplicata* (Branson & Mehl, 1934a); dextral P₁ element, oral view (D1), aboral view (D2), Prospect Hill Fm., 4.0–4.2 m, SUI 148283. • F – *Siphonodella jui* Becker *et al.*, 2016; sinistral P₁ element, oral view (F1), aboral view (F2), Prospect Hill Fm., 5.2–5.4 m, SUI 148284.

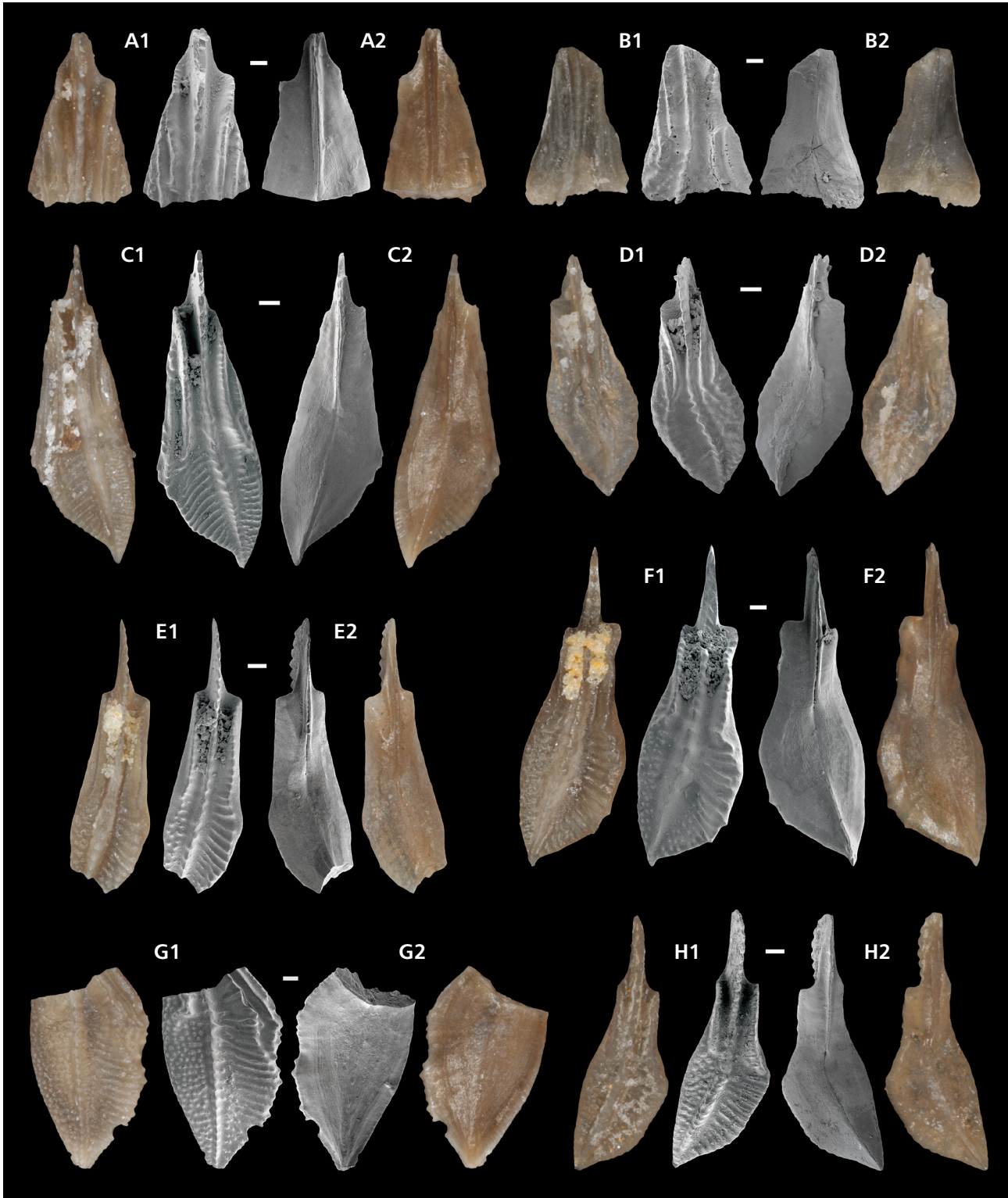


Figure 16. Conodonts from the Starr's Cave Outcrop. • A–D – *Siphonodella quadruplicata* (Branson & Mehl, 1934a); A – [?] sinistral P_1 element, oral view (A1), aboral view (A2), Prospect Hill Fm., 5.2–5.4 m, SUI 148285; B – dextral P_1 element, oral view (B1), aboral view (B2), Starr's Cave Member, Wassonville Fm., 5.6–5.8 m, SUI 148286; C – sinistral P_1 element, oral view (C1), aboral view (C2), Prospect Hill Fm., 5.2–5.4 m, SUI 148287; D – sinistral P_1 element, oral view (D1), aboral view (D2), Prospect Hill Fm., 5.2–5.4 m, SUI 148288. • E–H – *Siphonodella cooperi* Hass, 1959; E – dextral P_1 element, oral view (E1), aboral view (E2), Prospect Hill Fm., 4.0–4.2 m, SUI 148289; F – dextral P_1 element, oral view (F1), aboral view (F2), Prospect Hill Fm., 4.0–4.2 m, SUI 148290; G – [?] dextral P_1 element, oral view (G1), aboral view (G2), Prospect Hill Fm., 5.2–5.4 m, SUI 148291; H – dextral P_1 element, oral view (H1), aboral view (H2), Upper Member, Wassonville Fm., 6.7–6.9 m, SUI 148292.

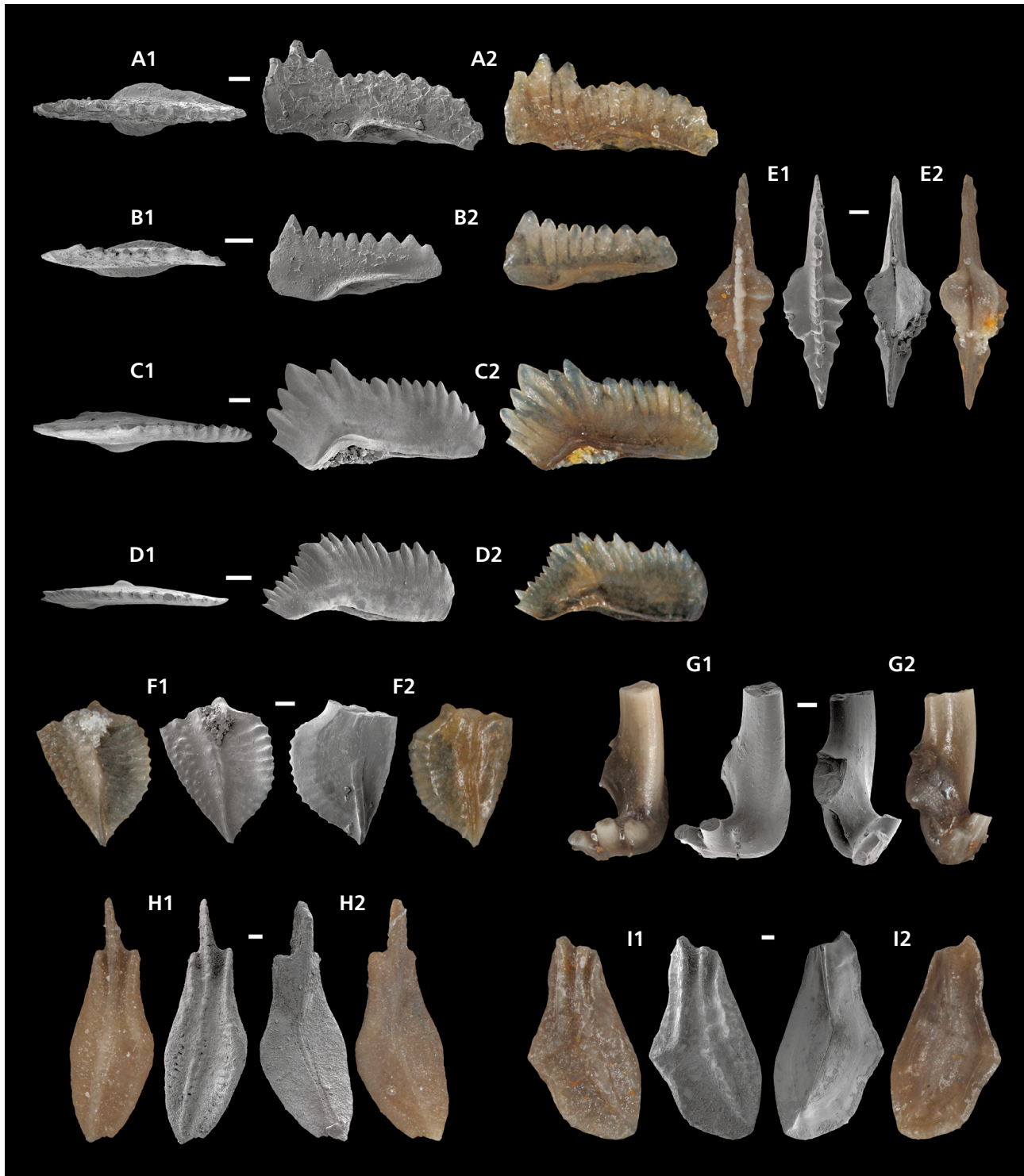


Figure 17. Conodonts from the Starr's Cave Outcrop. • A – *Hindeodus crassidentatus* (Branson & Mehl, 1934a); dextral P₁ element, oral view (A1), caudal view (A2), Upper Member, Wassonville Fm., 6.2–6.4 m, SUI 148293. • B – *Bispathodus stabilis stabilis* (Branson & Mehl, 1934b); dextral P₁ element, oral view (B1), caudal view (B2), Upper Member, Wassonville Fm., 6.2–6.4 m, SUI 148294. • C, D – *Elictognathus costatus* (Branson & Mehl, 1934a); C – sinistral P₂ element, oral view (C1), caudal view (C2), Prospect Hill Fm., 4.0–4.2 m, SUI 148295; D – sinistral P₂ element, oral view (D1), caudal view (D2), Prospect Hill Fm., 4.0–4.2 m, SUI 148296. • E – *Pseudopolygnathus primus* Branson & Mehl, 1934a; ?sinistral P₁ element, oral view (E1), aboral view (E2), Prospect Hill Fm., 4.0–4.2 m, SUI 148297. • F–I – *Siphonodella* sp.; F – dextral P₁ element, oral view (F1), aboral view (F2), Prospect Hill Fm., 4.8–5.0 m, SUI 148298; H – dextral P₁ element, oral view (H1), aboral view (H2), Upper Member, Wassonville Fm., 6.2–6.4 m, SUI 148299; I – sinistral P₁ element, oral view (I1), aboral view (I2), Upper Member, Wassonville Fm., 6.7–6.9 m, SUI 148300. • G – *Neoprioniodus* sp., Prospect Hill Fm., 4.0–4.2 m, SUI 148301.

North and recovered no conodonts from 25 kg of sample. No other conodont data have been published from the McCraney Formation at McCraney North (see discussion in Chauffe & Guzman 1997). Conodonts recovered from the underlying Hannibal Formation at McCraney North include *Elictognathus laceratus*, *Siphonodella duplicata*, and *S. cooperi*, indicating a position no lower than the *S. cooperi* Zone for the base of the type McCraney. Across the river in Newark, Missouri (Fig. 1B), the McCraney Formation is in a stratigraphic position above the Choteau Formation (Fig. 4), is at the top of the Kinderhookian sequence, and contains the conodonts *Siphonodella crenulata*, *Arismotaxis barbatus*, *Protognathodus prae-*

delicatus, and *Gnathodus* aff. *G. punctatus* (Chauffe & Guzman 1997). Collectively, these demonstrate a significantly higher chronostratigraphic position than the Louisiana Formation in each of their type areas. Therefore, in this area of Missouri, the McCraney is latest Kinderhookian in age and does not correlate to any known portion of the Louisiana.

The H-28 core contains the entirety of the Hangenberg positive carbon isotope excursion including both the ascending and descending limbs (Fig. 5). The Hangenberg positive carbon isotope excursion (Kaiser 2005; Kaiser et al. 2006, 2008, 2016; Becker et al. 2016) begins in the uppermost *Bispathodus ultimus* Zone (Middle *praesulcata*

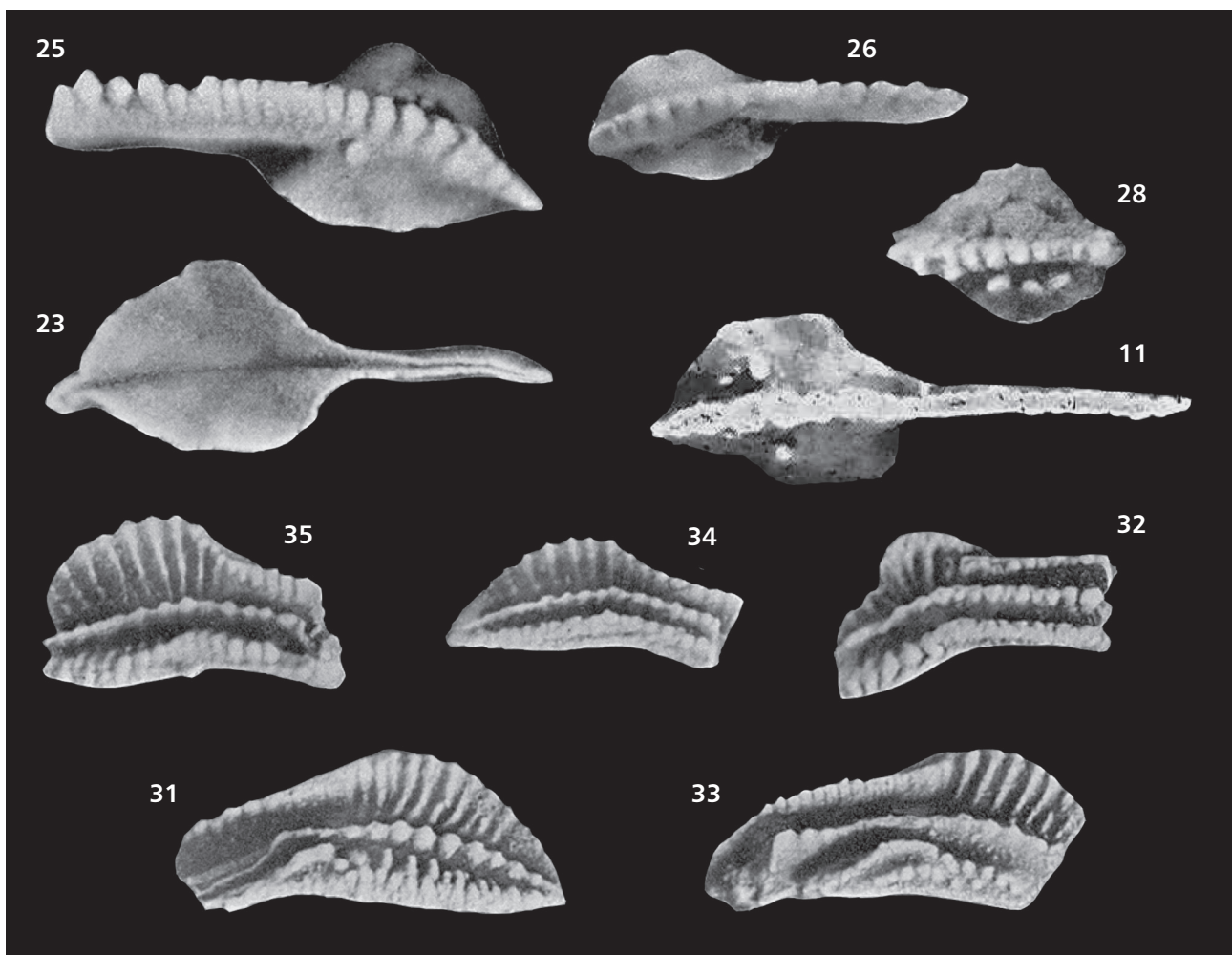


Figure 18. Re-illustrations of images from Scott & Collinson (1961) and Straka (1968). Specimen numbers are the original designations from the original authors. Specimens 23, 25, 26, and 28 are from Scott & Collinson (1961, pl. 1), images are 40x, and all specimens are from the Teneriffe School Section, Jersey County, Illinois. Specimens 31–35 are from Scott & Collinson (1961, pl. 2), images are 40x, and all specimens are from Cascade Station, Burlington, Iowa. Specimen 11 is from Strata (1968, pl. 7), and image is 58x. • 11, 23, 25 – *Protognathodus collinsoni* Ziegler, 1969; 11 – sinistral P_1 element, oral view, Wassonville Fm., SUI 125484; 23 – dextral P_1 element, oral view, Louisiana Fm.; 25 – dextral P_1 element, basal view, Louisiana Fm.. • 26 – *Protognathodus meischneri* Ziegler, 1969; sinistral P_1 element, oral view, Louisiana Fm. • 28 – *Protognathodus kockeli* (Bischoff, 1957), ?sinistral P_1 element, oral view, Louisiana Fm.. • 31, 32, 34, 35 – *Siphonodella duplicata* (Branson & Mehl, 1934a), “McCraney” Fm.; 31 – [?] dextral P_1 element, oral view; 32 – sinistral P_1 element, oral view; 34 – sinistral P_1 element, oral view; 35 – sinistral P_1 element, oral view. • 33 – *Siphonodella cooperi* Hass, 1959; dextral P_1 element, oral view, “McCraney” Fm.

Zone), and extends at least into the uppermost part of the *P. kockeli* Zone (*sulcata* Zone). The recognition of the onset of the Hangenberg excursion allowed us to tentatively place the *B. ultimus* and *P. kockeli* Zones in the core, and they fit well with the sequence of siphonodellids recovered from the Prospect Hill. Therefore, we can confidently say that the Hangenberg positive carbon isotope excursion is recorded by the upper English River and Louisiana formations in the H-28 core.

The chronostratigraphic correlation of the end of the Hangenberg excursion remains enigmatic. The presence of *S. cooperi* Zone and *S. sandbergi* Zone conodonts in the Prospect Hill Fm. in H-28 core agrees well with prior biostratigraphy of the Prospect Hill in Iowa (Straka 1968), and requires that the interval from the *P. kockeli* Zone at least through the *S. duplicata* Zone be present in the Louisiana Fm. of the core. Similarly, the presence of both *S. duplicata* and *S. cooperi* in the “McCraney” within the city of Burlington (Cascade Station Section, Scott & Collinson 1961, see below and Fig. 18) support elevated carbon isotope values at least into the *S. duplicata* Zone in the region.

The succession at Starr’s Cave contains an identical stratigraphic succession as the H-28 core that includes the English River, “McCraney”, Prospect Hill, Starr’s Cave, Wassonville, and Burlington formations. The only difference in the stratigraphic succession between this locality and H-28 core is that the carbonate unit between the Prospect Hill and English River formations is named “McCraney” instead of Louisiana. This carbonate unit at Starr’s Cave records $\delta^{13}\text{C}$ values greater than +5.0‰ (Fig. 13), which likely indicates a position somewhere within the Hangenberg carbon isotope excursion interval. Scott & Collinson (1961) recovered conodonts from the “McCraney” at Cascade Station [<10 miles (16km) from Starr’s Cave] within the city of Burlington, and they are re-illustrated here in Fig. 18 using their original specimen numbers from the original plates. Whereas they originally identified all of these specimens as *S. cooperi*, with the exception of specimen 32 as *S. duplicata*, we suggest that only specimen 33 has a demonstrably nodose interior platform and suggest that all specimens should be designated *S. duplicata*, with the exception being specimen 33 as *S. cooperi*. All five of these specimens were recovered from an interval “three to six feet above the base of the Louisiana” (Scott & Collinson 1961, p. 119). Conodonts recovered from the Prospect Hill at Starr’s Cave demonstrate a position within the *S. sandbergi* Zone which matches perfectly with the identification of *S. duplicata* and *S. cooperi* in the “McCraney” by Scott & Collinson (1961). This position of the “McCraney” in Burlington Iowa (*S. duplicata* and *S. cooperi*), is considerably below the McCraney at Newark, Missouri (Chauffé & Guzman 1997), and matches well the upper

portion of the Louisiana in the H-28 core (compare Figs 5 and 13). Therefore, the unit referred to as “McCraney” at Starr’s Cave is more likely correctly identified as the upper Louisiana Fm., even if it does not represent the entire Louisiana Fm. preserved in the H-28 core.

Conclusions

The H-28 core and Starr’s Cave outcrop were examined using integrated conodont biostratigraphy and carbon isotope chemostratigraphy. These analyses resulted in the detection of the Hangenberg positive carbon isotope excursion and returned a diverse fauna of siphonodellids. Combined with data from the type areas in Missouri and Illinois we can conclude that the carbonate unit beneath the Prospect Hill Formation in the H-28 core is undoubtedly the Louisiana Formation, not the “McCraney”. Similarly, the carbonate unit below the prospect Hill Formation referred to as the “McCraney” at Starr’s Cave is likely the upper part of the Louisiana. This calls into question whether or not the name McCraney should be applied to any stratigraphic units in the State of Iowa.

The combined data presented herein demonstrate that the Devonian–Carboniferous boundary interval is contained in an extremely expanded section in the type Mississippian tri-state area of Iowa, Missouri, and Illinois. Whereas most sections in the world where the Hangenberg positive carbon isotope excursion has been recovered contain a few meters of elevated positive $\delta^{13}\text{C}_{\text{carb}}$ values, the tri-state area of the upper Mississippi Valley has nearly 20 meters of this critical interval in the co-evolution of ocean-atmosphere-biosphere Earth system. Furthermore, the comparatively carbonate-rich succession of the tri-state area allows for more complete and detailed carbon isotope chemostratigraphy and conodont biostratigraphy than many other regions in the world. Collectively, this study demonstrates the importance of this part of the U.S. Mid-continent to any potential re-evaluation of the base Carboniferous GSSP and choice of combined biological and chemical markers for global chronostratigraphic correlation.

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