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An Expanded Stratigraphic Record of the Devonian-Carboniferous Boundary Hangenberg Biogeochemical Event from Southeast Iowa (U.S.A.)

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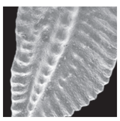

The Devonian–Carboniferous boundary in the type area of the Mississippian subsystem (tri-state area of Iowa, Illinois, and Missouri) has been historically difficult to identify. Many of the localities contain similar lithologies and stratigraphic successions, but chronostratigraphic correlation of seemingly identical lithologies can vary greatly in this interval and frequently this has led to miscorrelation. In particular, the similar lithofacies that comprise the McCraney 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 "McCraney" 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 McCraney 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 McCraney 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,

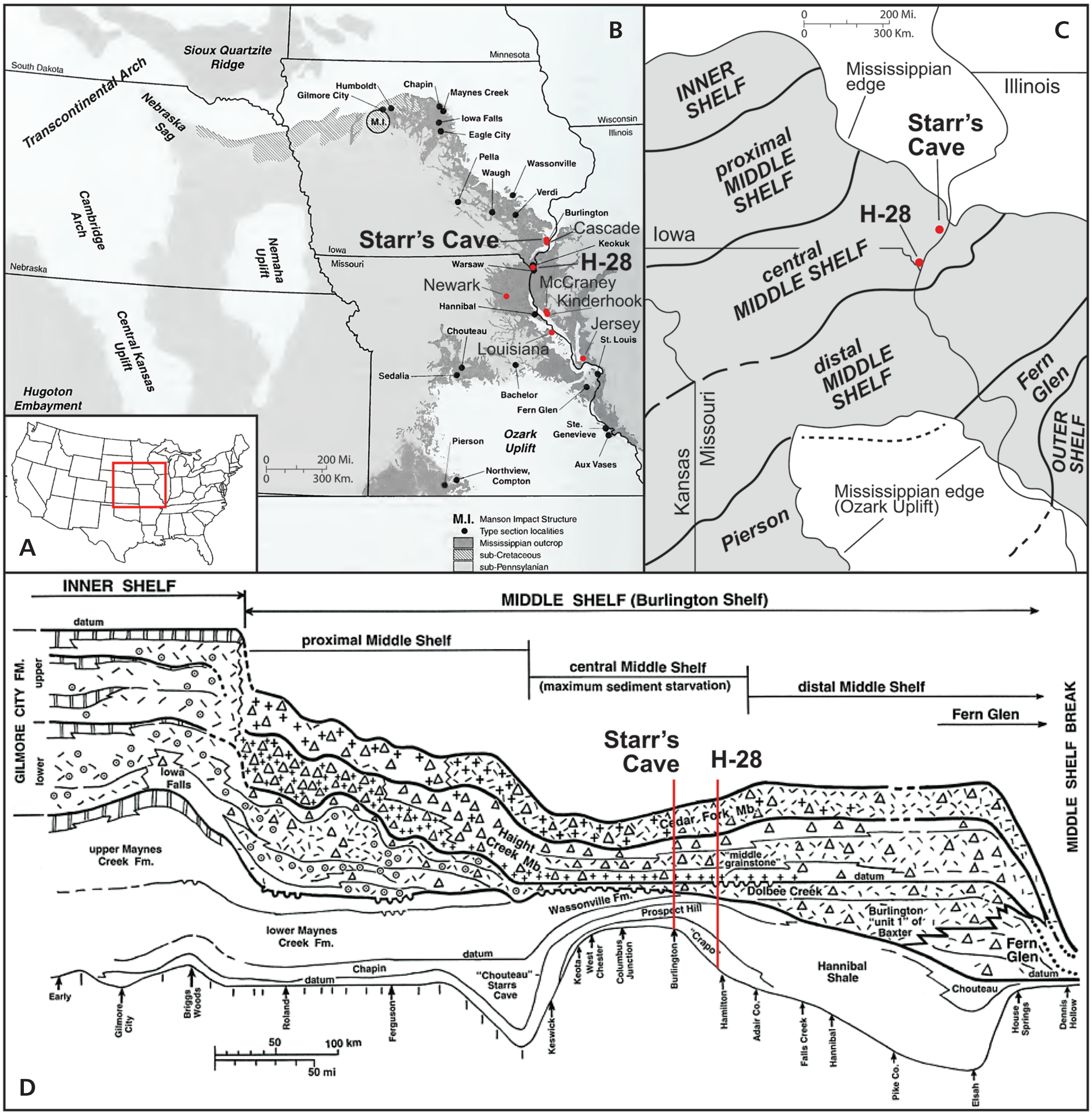


Figure 1. A, B – distribution of Mississippian outcrops in the tri-State area of Missouri, Illinois, and Iowa, including the two locations (H-28 and Starr's Cave) sampled in this study. Other localities shown and discussed in the text include Cascade Station (Cascade), Teneriffe School (Jersey), McCraney 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 – paleoceanographic 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).

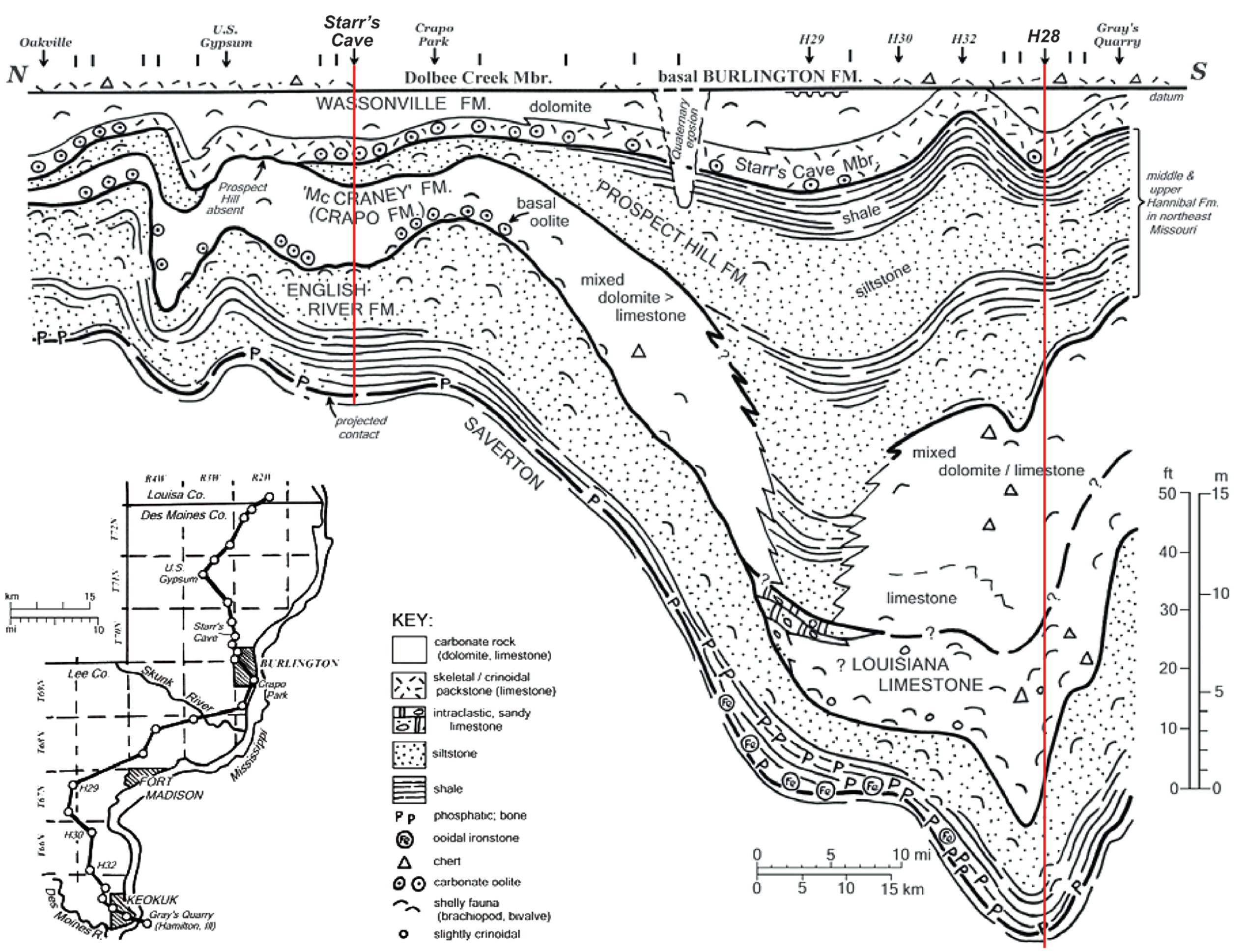


Figure 2. North-south cross section of Kinderhookian stratigraphy through southeastern Iowa illustrating the increase in stratigraphic thickness towards the south. The two locations sampled in this study are designated by red lines. Modified from Witzke & Bunker (2002).

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. Midcontinent 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

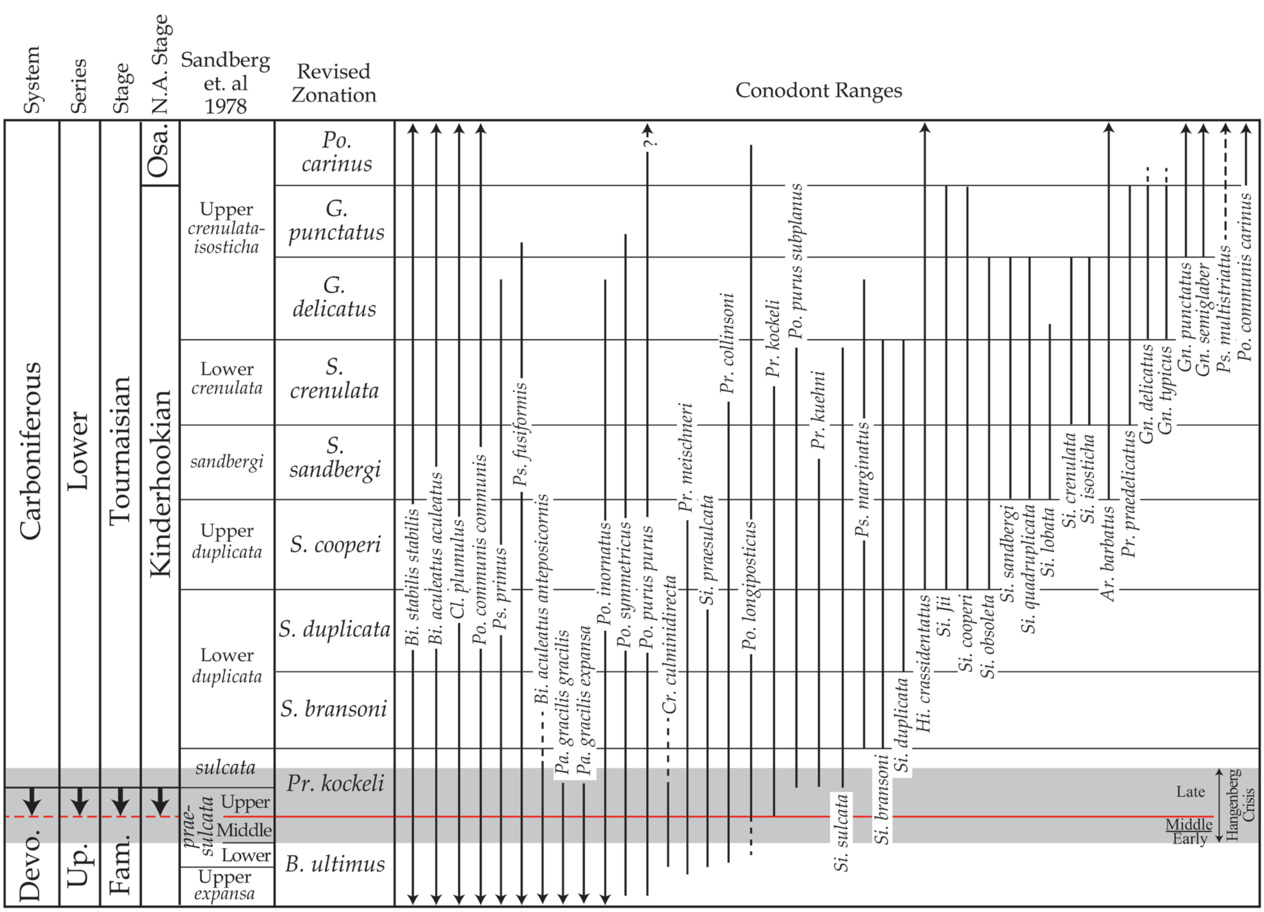


Figure 3. Revised conodont biozonation and range chart for the Kinderhookian. Traditional zonation of Sandberg *et al*. (1978) shown at left with comparison of new zones. New zonation is a composite of Kaiser *et al.* (2009), Spalletta *et al.* (2017), and Zhuravlev & Plotitsyn (2017) and is after Hogancamp *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 Critera (see text). This also fits well with the proposed definition of the end of major regression.

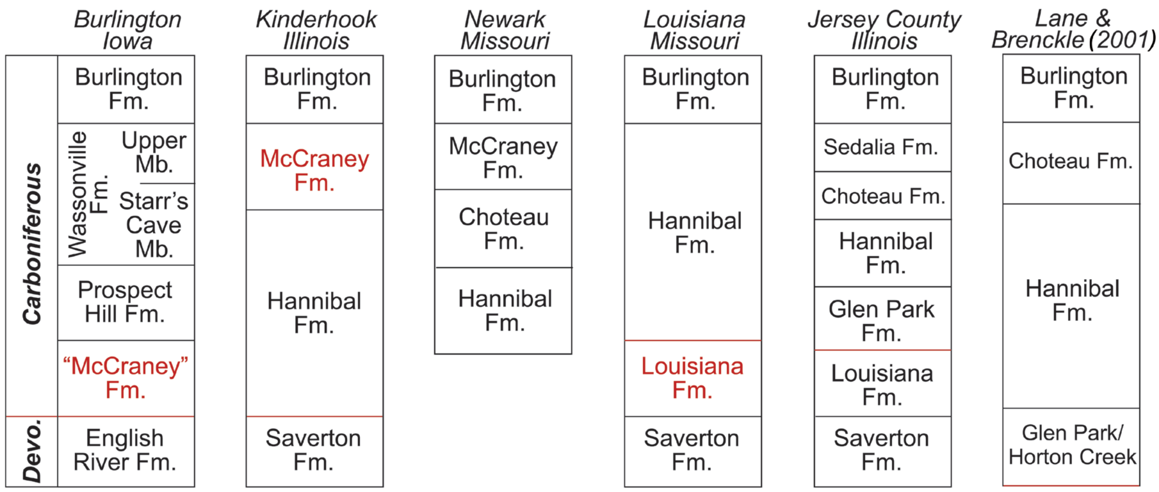


Figure 4. Comparison of Kinderhookian stratigraphic successions in the tri-state area, following Scott & Collison (1961), Chauffe & Guzman (1997), and Lane & Brenckle (2001). Red lines designate traditional placements of the Devonian–Carboniferous boundary in each area.

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 Hogancamp *et al*. (2019). The succession from *S. bransoni* 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 Hogancamp *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 chronostratigraphic 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 ($\delta^{13}C_{carb}$) chemostratigraphy. For chemostratigraphy, the H-28 core was sampled at one foot (0.30 m) intervals and the Starr's Cave outcrop at 10cm 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	$\delta^{13}C_{carb}$	$\delta^{18}O$	Formation	Member
153	3.91	–4.11	Burlington	Cedar Fork
154	3.98	–3.86	Burlington	Cedar Fork
154.8	3.94	–3.86	Burlington	Cedar Fork
156	3.91	–4.81	Burlington	Cedar Fork
156.6	3.83	–5.18	Burlington	Cedar Fork
158	3.45	–4.49	Burlington	Cedar Fork
159	3.47	–4.27	Burlington	Cedar Fork
160	3.92	–5.04	Burlington	Cedar Fork
162	3.74	–5.24	Burlington	Haight Creek
163	3.86	–4.86	Burlington	Haight Creek
164	3.66	–5.48	Burlington	Haight Creek
165	3.58	–5.46	Burlington	Haight Creek
166	3.77	–5.11	Burlington	Haight Creek
167	3.74	–4.87	Burlington	Haight Creek
168	3.73	–4.78	Burlington	Haight Creek
169	3.67	–5.21	Burlington	Haight Creek
171	2.86	–5.63	Burlington	Haight Creek
172	2.96	–5.19	Burlington	Haight Creek
173	3.45	–4.66	Burlington	Haight Creek
173.8	3.20	–4.89	Burlington	Haight Creek
175	3.55	–4.15	Burlington	Haight Creek
176	3.55	–4.06	Burlington	Haight Creek
176.7	3.69	–5.09	Burlington	Haight Creek
178	3.08	–5.26	Burlington	Haight Creek
179	2.97	–4.81	Burlington	Haight Creek
180	3.00	–4.85	Burlington	Haight Creek
181	2.92	–5.25	Burlington	Haight Creek
182	3.22	–4.59	Burlington	Haight Creek
183	2.98	–5.19	Burlington	Haight Creek
184	3.45	–2.52	Burlington	Haight Creek
184.6	3.46	–3.98	Burlington	Haight Creek
186	3.46	–2.37	Burlington	Haight Creek
186.8	3.44	–2.16	Burlington	Haight Creek
188	3.43	–1.91	Burlington	Haight Creek
189	3.41	–4.65	Burlington	Haight Creek
190	3.25	–2.31	Burlington	Haight Creek
191	3.43	–2.10	Burlington	Haight Creek
192	3.42	–1.52	Burlington	Haight Creek
193	2.65	–4.29	Burlington	Haight Creek
193.3	2.12	–4.44	Burlington	Haight Creek
195	2.98	–4.80	Burlington	Dolbee Creek
196	2.40	–4.53	Burlington	Dolbee Creek
197	2.91	–5.35	Burlington	Dolbee Creek
198	2.88	–4.77	Burlington	Dolbee Creek
199	2.95	–4.67	Burlington	Dolbee Creek
200	3.14	–3.07	Burlington	Dolbee Creek
201	3.05	–4.23	Burlington	Dolbee Creek
202	3.07	–4.06	Burlington	Dolbee Creek
203	3.12	–4.11	Burlington	Dolbee Creek
204	3.07	–4.17	Burlington	Dolbee Creek
205	3.11	–3.97	Burlington	Dolbee Creek
206	3.10	–4.32	Burlington	Dolbee Creek
207	3.00	–4.31	Burlington	Dolbee Creek
208	3.12	–4.43	Burlington	Dolbee Creek
209	3.04	–4.75	Burlington	Dolbee Creek
210	3.00	–4.61	Burlington	Dolbee Creek
211	3.61	–4.88	Wassonville	Upper Mb.
212	3.52	–5.12	Wassonville	Upper Mb.
213	3.65	–4.86	Wassonville	Upper Mb.
214	3.36	–4.46	Wassonville	Upper Mb.
215	3.21	–4.97	Wassonville	Upper Mb.
216	3.12	–3.75	Wassonville	Upper Mb.
217	3.28	–5.02	Wassonville	Upper Mb.
218	2.93	–5.52	Wassonville	Upper Mb.
219	2.59	–5.86	Wassonville	Upper Mb.
220	2.62	–5.83	Wassonville	Upper Mb.
221	2.65	–5.71	Wassonville	Upper Mb.
221.5	2.91	–4.40	Wassonville	Upper Mb.
222	3.10	–3.25	Wassonville	Upper Mb.
222.5	2.51	–5.80	Wassonville	Upper Mb.
223	2.78	–5.63	Wassonville	Starr's Cave
223.5	2.75	–5.58	Wassonville	Starr's Cave
224	2.92	–5.40	Wassonville	Starr's Cave
224.5	2.73	–5.67	Wassonville	Starr's Cave
224.8	2.23	–5.39	Wassonville	Starr's Cave
225	2.67	–1.25	Wassonville	Starr's Cave
225.5	2.49	–4.82	Prospect Hill	
226	2.72	–1.50	Prospect Hill	
226.5	2.24	–7.96	Prospect Hill	
227	2.63	–2.33	Prospect Hill	
228	2.41	–0.88	Prospect Hill	
229	1.87	–1.88	Prospect Hill	
230	1.67	–2.22	Prospect Hill	
231	3.00	–1.25	Prospect Hill	
232	2.91	–1.37	Prospect Hill	
233	2.97	–1.75	Prospect Hill	
234	3.15	–1.92	Prospect Hill	
235	2.90	–2.64	Prospect Hill	

Table 1. Continued.

Decimal Feet	$\delta^{13}C_{carb}$	$\delta^{18}O$	Formation	Member
236	2.97	–2.18	Prospect Hill	
237	3.01	–2.28	Prospect Hill	
238	2.91	–2.70	Prospect Hill	
239	2.40	–4.22	Prospect Hill	
240	2.98	–3.02	Prospect Hill	
241	2.92	–4.35	Prospect Hill	
242	1.28	–4.19	Prospect Hill	
243	1.82	–3.58	Prospect Hill	
244	1.09	–4.28	Prospect Hill	
245	2.38	–4.09	Prospect Hill	
246	2.55	–3.43	Prospect Hill	
247	2.51	–3.30	Prospect Hill	
248	2.53	–4.52	Prospect Hill	
249	2.11	–3.88	Prospect Hill	
250	2.21	–4.41	Prospect Hill	
251	1.96	–3.19	Prospect Hill	
252	2.74	–2.30	Prospect Hill	
253	1.34	–2.94	Prospect Hill	
254	1.83	–2.38	Prospect Hill	
255	2.70	–1.48	Prospect Hill	
256	3.55	–1.09	Prospect Hill	
257	3.69	–1.80	Prospect Hill	
257.8	4.28	–3.58	Louisiana	
258	4.55	–4.74	Louisiana	
259	4.74	–4.93	Louisiana	
260	4.64	–5.14	Louisiana	
260.9	4.66	–4.89	Louisiana	
262	5.04	–4.76	Louisiana	
263	5.00	–5.09	Louisiana	
264	5.49	–4.76	Louisiana	
265	4.98	–4.89	Louisiana	
266	5.47	–4.87	Louisiana	
267	5.53	–4.79	Louisiana	
268	5.73	–4.84	Louisiana	
269	5.71	–4.91	Louisiana	
270	5.40	–5.15	Louisiana	
271	5.94	–4.87	Louisiana	
272	5.27	–4.31	Louisiana	
273	5.48	–4.60	Louisiana	
274	6.00	–4.98	Louisiana	
275	5.65	–5.12	Louisiana	
276	5.82	–4.99	Louisiana	
277	5.84	–4.87	Louisiana	
278	5.86	–4.94	Louisiana	
279	5.82	–4.52	Louisiana	
280	5.79	–4.12	Louisiana	
281	5.76	–5.03	Louisiana	
282	5.65	–5.14	Louisiana	
283	5.61	–5.23	Louisiana	
284	5.63	–5.34	Louisiana	
285	5.95	–4.36	Louisiana	
286	5.65	–5.13	Louisiana	
287	5.67	–4.90	Louisiana	
288	5.42	–5.57	Louisiana	

Decimal Feet	$\delta^{13}C_{carb}$	$\delta^{18}O$	Formation	Member
289	5.62	–5.41	Louisiana	
290	5.26	–5.57	Louisiana	
291	5.80	–4.51	Louisiana	
292	5.73	–5.13	Louisiana	
293	5.97	–4.84	Louisiana	
294	5.54	–5.28	Louisiana	
295	5.60	–5.33	Louisiana	
296	5.60	–5.02	Louisiana	
297	5.78	–4.84	Louisiana	
298	5.67	–4.68	Louisiana	
299	5.81	–4.36	Louisiana	
300	5.76	–4.30	Louisiana	
301	5.55	–5.24	Louisiana	
302	5.97	–4.38	Louisiana	
302.8	5.46	–5.52	Louisiana	
303.9	5.58	–4.96	Louisiana	
304.9	5.62	–5.18	Louisiana	
306.2	5.87	–4.65	Louisiana	
307	5.92	–4.00	Louisiana	
308	5.38	–5.40	Louisiana	
309	5.83	–4.68	Louisiana	
310	5.69	–4.91	Louisiana	
311	5.55	–3.91	Louisiana	
312	5.37	–5.15	Louisiana	
313	5.63	–4.48	Louisiana	
314	5.65	–4.46	Louisiana	
315	5.31	–4.33	Louisiana	
316	5.43	–4.60	Louisiana	
317	5.20	–4.44	Louisiana	
318	5.28	–4.26	Louisiana	
319	5.21	–4.28	Louisiana	
320	5.06	–4.13	Louisiana	
321	4.91	–4.24	Louisiana	
322	4.60	–4.16	Louisiana	
323	3.18	–4.49	Louisiana	
324	2.67	–3.72	Louisiana	
325	3.09	–2.80	Louisiana	
326	1.92	–2.41	English River	
327	2.29	–2.13	English River	
328	2.01	–2.05	English River	
329	1.24	–2.71	English River	
330	1.58	–1.95	English River	
331	1.72	–2.00	English River	
332	1.70	–2.01	English River	
333.2	1.46	–2.41	English River	
334	1.89	–1.86	English River	
335	1.73	–2.36	English River	
336	0.21	–3.66	English River	
337	–0.24	–4.47	English River	
338	0.28	–3.58	English River	
339	0.54	–3.77	English River	
340	1.03	–2.82	English River	
340.6	0.45	–3.67	English River	
341.9	0.85	–1.76	English River	

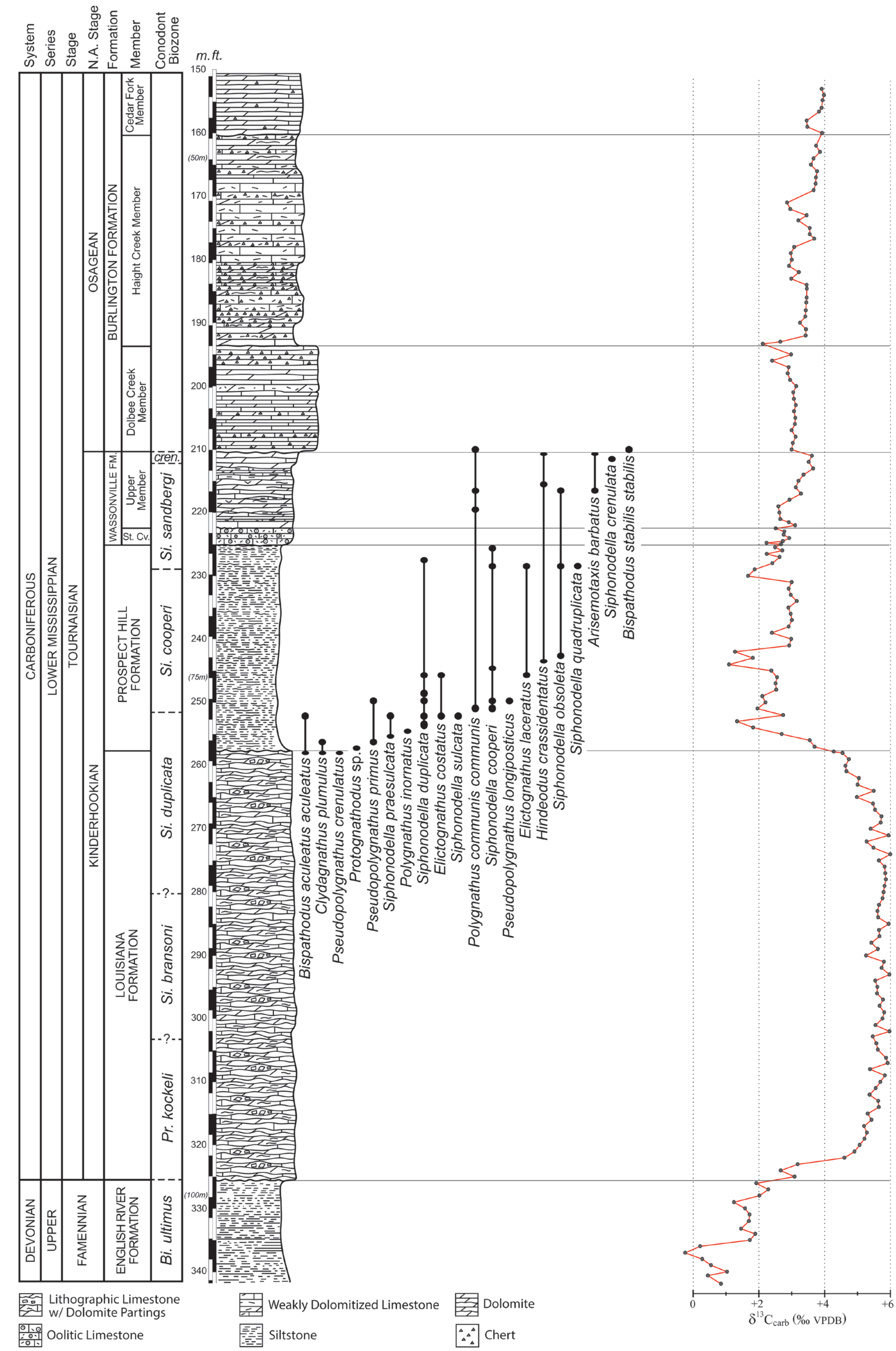
Table 2. Stable isotope data from Starr's Cave, Burlington, IA.

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


System
Series
Stage
N.A. Stage
Formation
Member
Conodont Biozone
m.ft.
CARBONIFEROUS
LOWER MISSISSIPPIAN
TOURNAISIAN
OSAGEAN
KINDERHOOKIAN
BURLINGTON FORMATION
Cedar Fork Member
Haight Creek Member
Dolbee Creek Member
WASSONVILLE FM.
Upper Member
St. Cv.
PROSPECT HILL FORMATION
LOUISIANA FORMATION
DEVONIAN
UPPER
FAMENNIAN
ENGLISH RIVER FORMATION
cren.
Si. sandbergi
Si. cooperi
Si. duplicata
Si. bransoni
Pr. kockeli
Bi. ultimus
(50m)
(75m)
(100m)
Bispathodus aculeatus aculeatus
Clydagnathus plumulus
Pseudopolygnathus crenulatus
Protognathodus sp.
Pseudopolygnathus primus
Siphonodella praesulcata
Polygnathus inornatus
Siphonodella duplicata
Elictognathus costatus
Siphonodella sulcata
Polygnathus communis communis
Siphonodella cooperi
Pseudopolygnathus longiposticus
Elictognathus laceratus
Hindeodus crassidentatus
Siphonodella obsoleta
Siphonodella quadruplicata
Arisemotaxis barbatus
Siphonodella crenulata
Bispathodus stabilis stabilis
Lithographic Limestone w/ Dolomite Partings
Oolitic Limestone
Weakly Dolomitized Limestone
Siltstone
Dolomite
Chert
δ13Ccarb (‰ VPDB)

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 ($\delta^{13}C_{carb}$) values ranged from −0.05‰ to +6.0‰ (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‰ 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 10cm resolution. Carbonate carbon isotope ($\delta^{13}C_{carb}$) data ranged from −0.5‰ to +5‰ 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

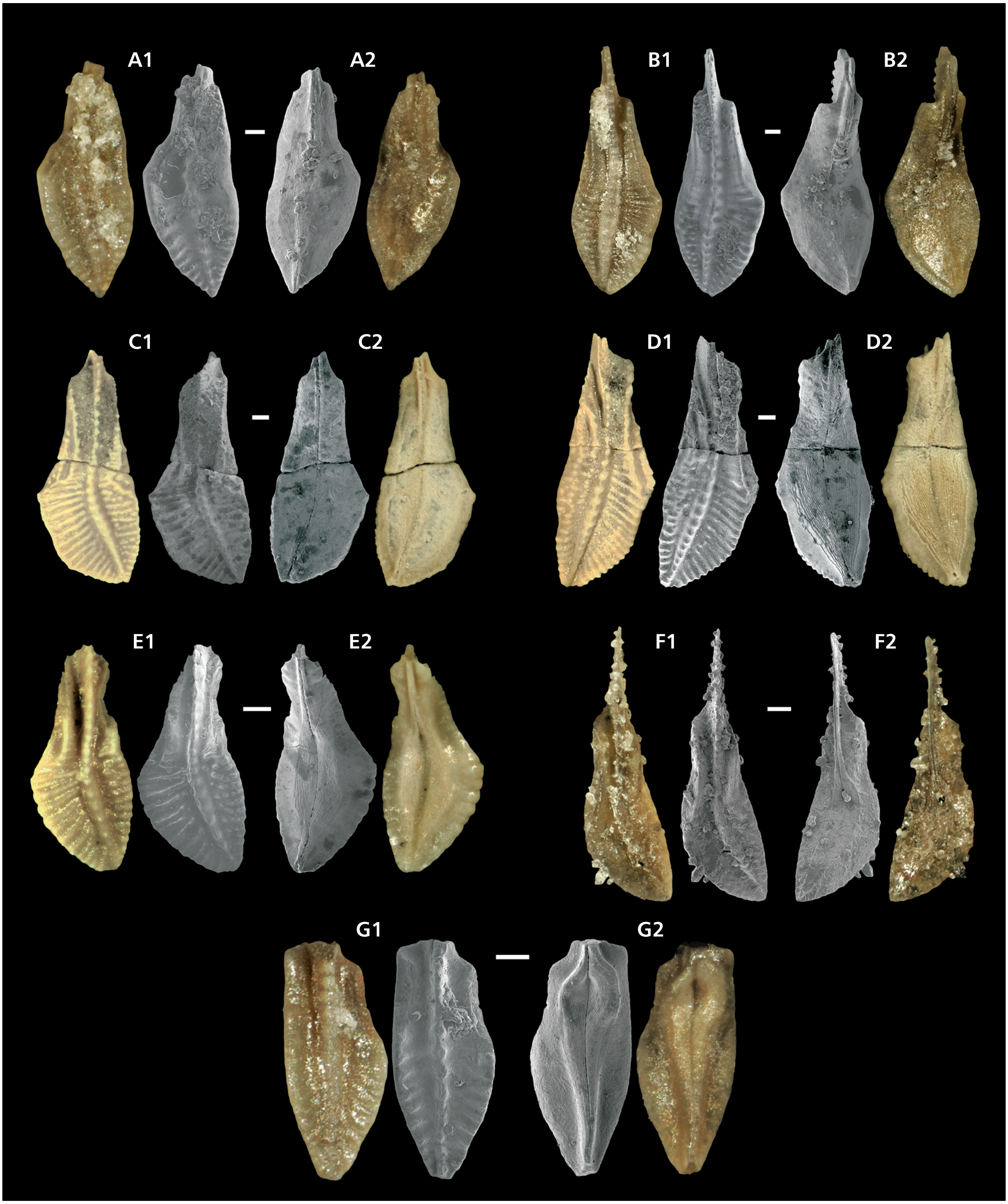


Figure 6. Conodonts from the H-28 Core. • A, C – *Siphonodella duplicata* (Branson & Mehl, 1934a); A – sinistral P_1 element, oral view (A1), aboral view (A2), Prospect Hill Fm., 252'11"–254'3", SUI 148219; C – sinistral P_1 element, oral view (C1), aboral view (C2), Prospect Hill Fm., 248'0"–249'2", 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.

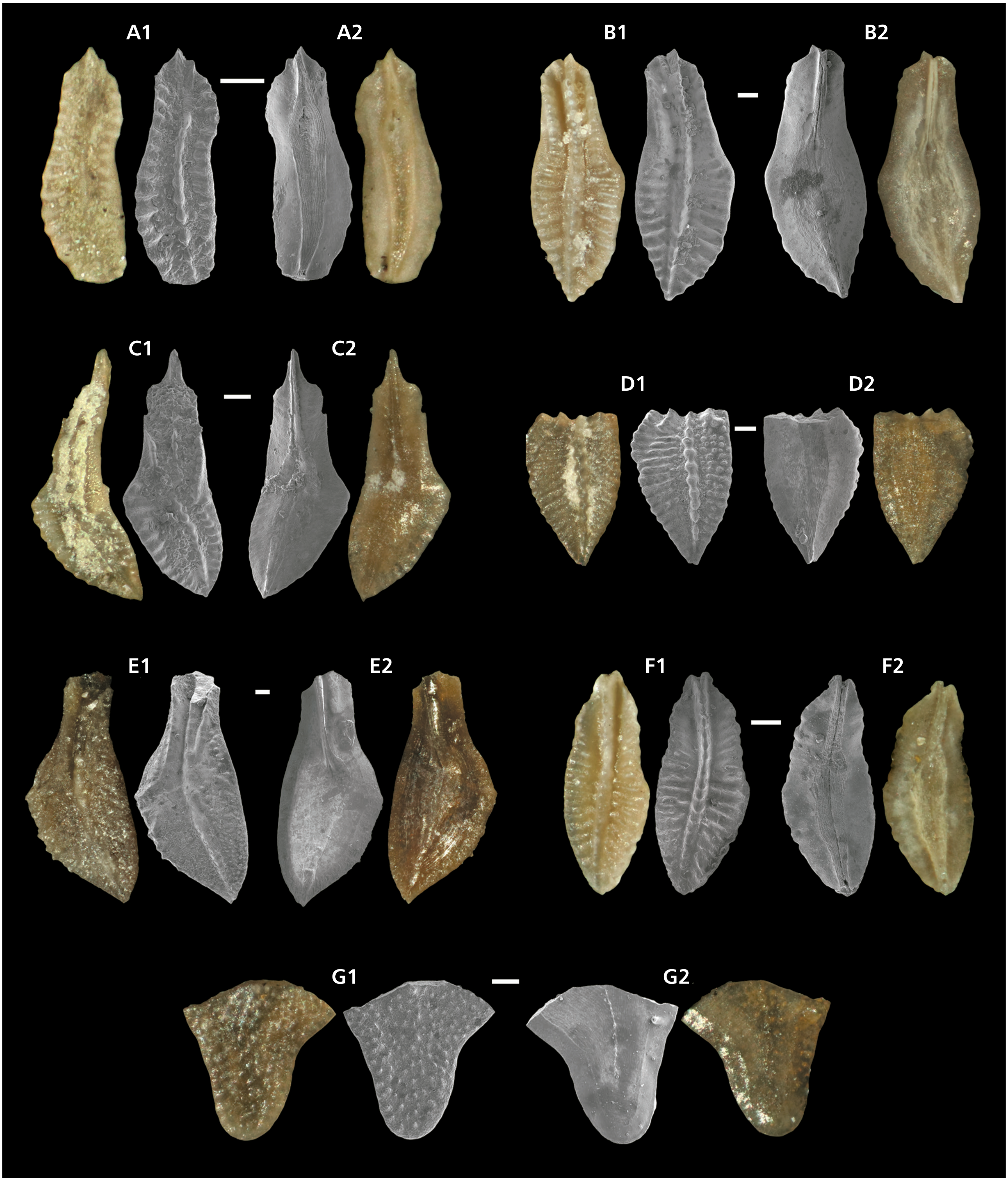


Figure 7. Conodonts from the H-28 Core. • A – *Siphonodella praesulcata* Sandberg *et al.*, 1972; sinistral P_1 element, oral view (A1), aboral view (A2), Prospect Hill Fm., 255'0"–255'9", SUI 148226. • B, C – *Siphonodella duplicata* (Branson & Mehl, 1934a); B – dextral P_1 element, oral view (B1), aboral view (B2), Prospect Hill Fm., 249'2"–250'2", SUI 148227; C – sinistral P_1 element, oral view (C1), aboral view (C2), Prospect Hill Fm., 245'2"–246'1", SUI 148228. • D – *Siphonodella ?quadruplicata* (Branson & Mehl, 1934a); sinistral P_1 element, oral view (D1), aboral view (D2), Prospect Hill Fm., 228'0"–229'0", SUI 148229. • E – *Siphonodella obsoleta* Hass, 1959; sinistral P_1 element, oral view (E1), aboral view (E2), Prospect Hill Fm., 242'1"–243'1", SUI 148230. • F – *Siphonodella sulcata* (Huddle, 1934); sinistral P_1 element, oral view (F1), aboral view (F2), Prospect Hill Fm., 251'7"–252'10", SUI 14823. • G – gen. et sp. indet.; ?P_1 element, oral view (G1), aboral view (G2), Upper Member, Wassonville Fm., 212'0"–213'0", SUI 148232.

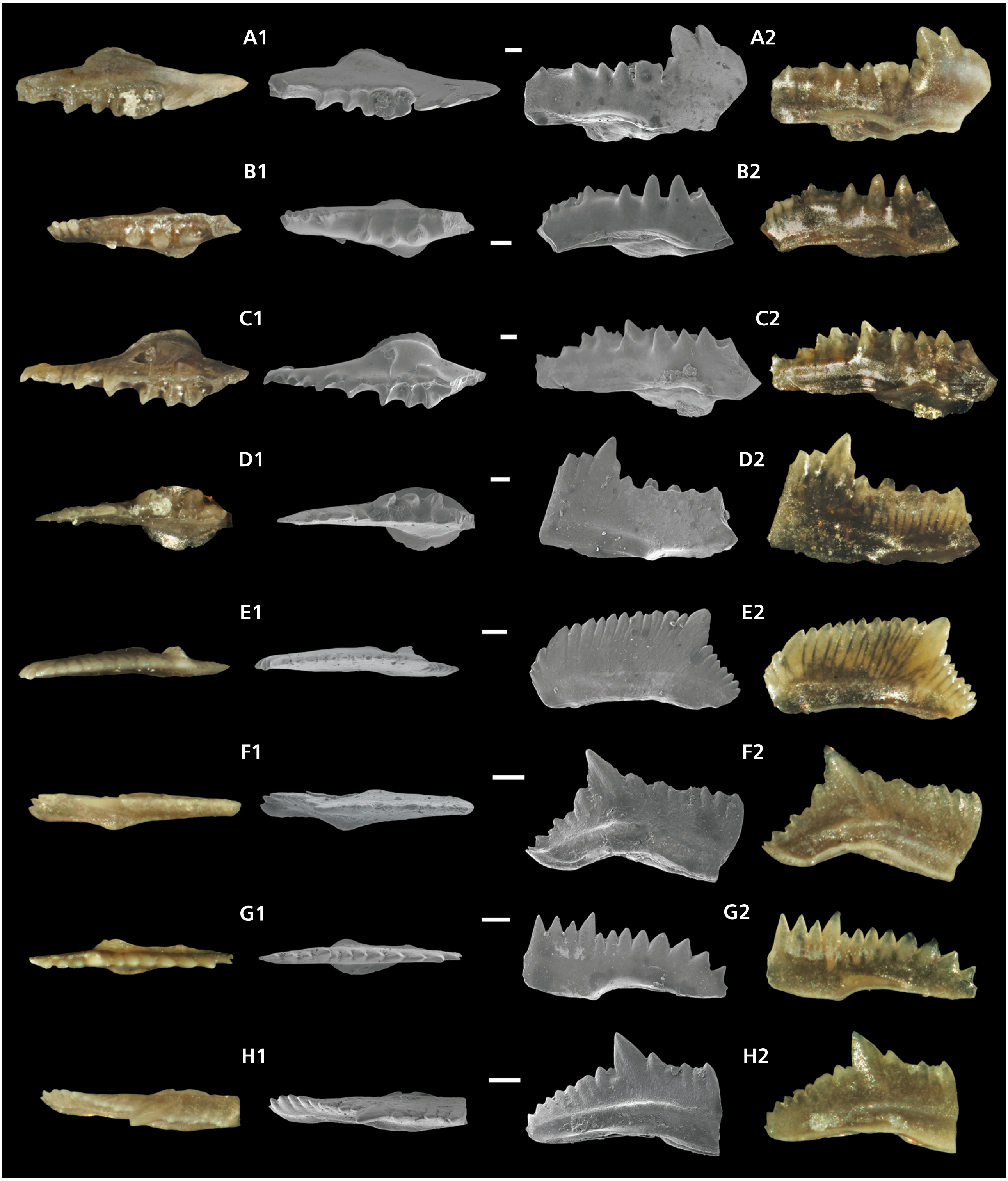


Figure 8. Conodonts from the H-28 Core. • A, D – *Clydagnathus plumulus* (Rhodes *et al.*, 1969); A – sinistral P_1 element, oral view (A1), caudal view (A2), Louisiana Fm., 257'8"–258'2", SUI 148233; D – sinistral P_1 element, oral view (D1), rostral view (D2), Prospect Hill Fm., 255'9"–256'10", SUI 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 – *Elictognathus 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 – *Elictognathus 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

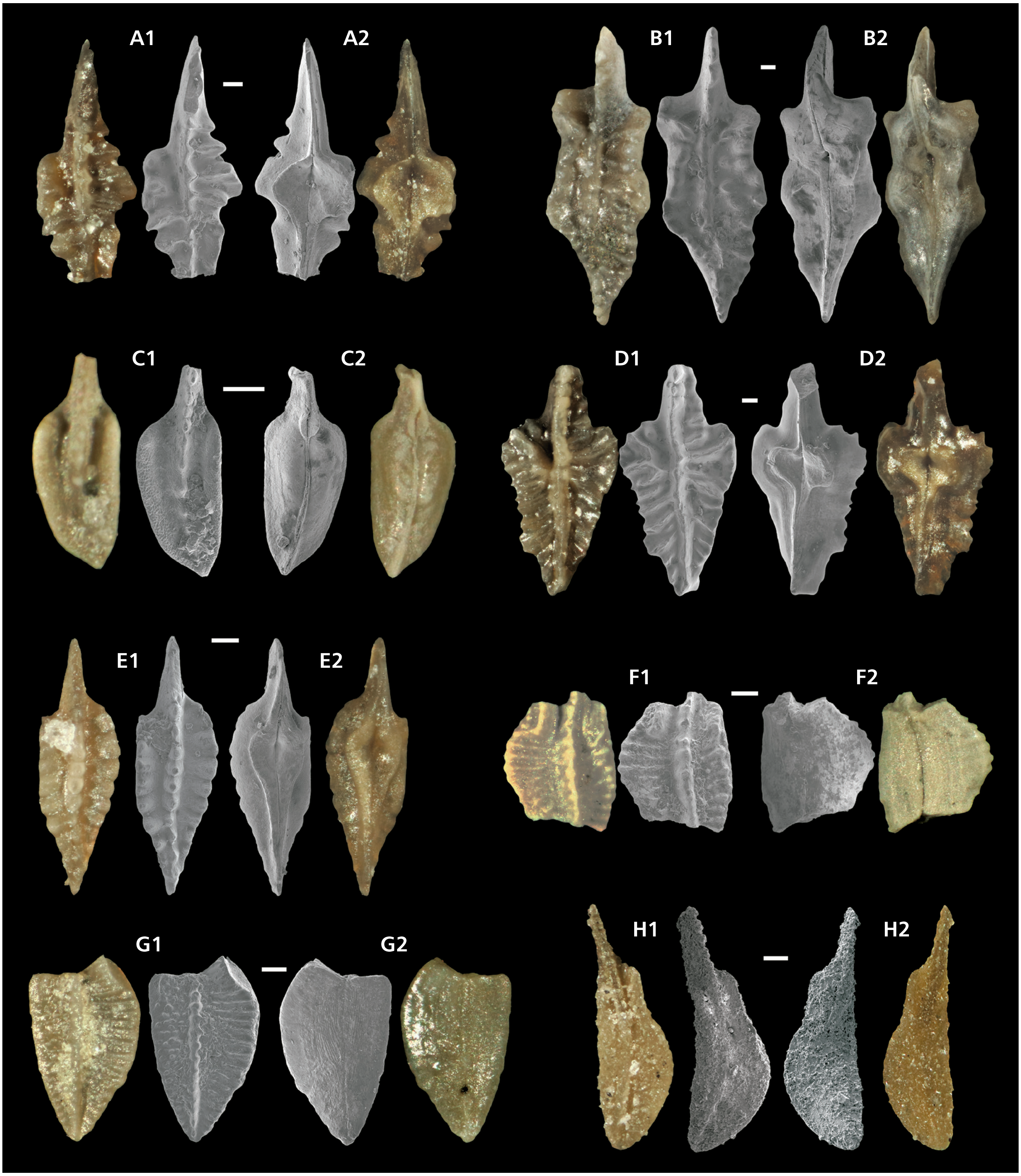


Figure 9. Conodonts from the H-28 Core. • A, D – *Pseudopolygnathus primus* Branson & Mehl, 1934a; A – sinistral P_1 element, oral view (A1), aboral view (A2), Prospect Hill Fm., 255’9”–256’10”, SUI 148241; D – sinistral P_1 element, oral view (D1), aboral view (D2), Prospect Hill Fm., 249’2”–250’2”, 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.

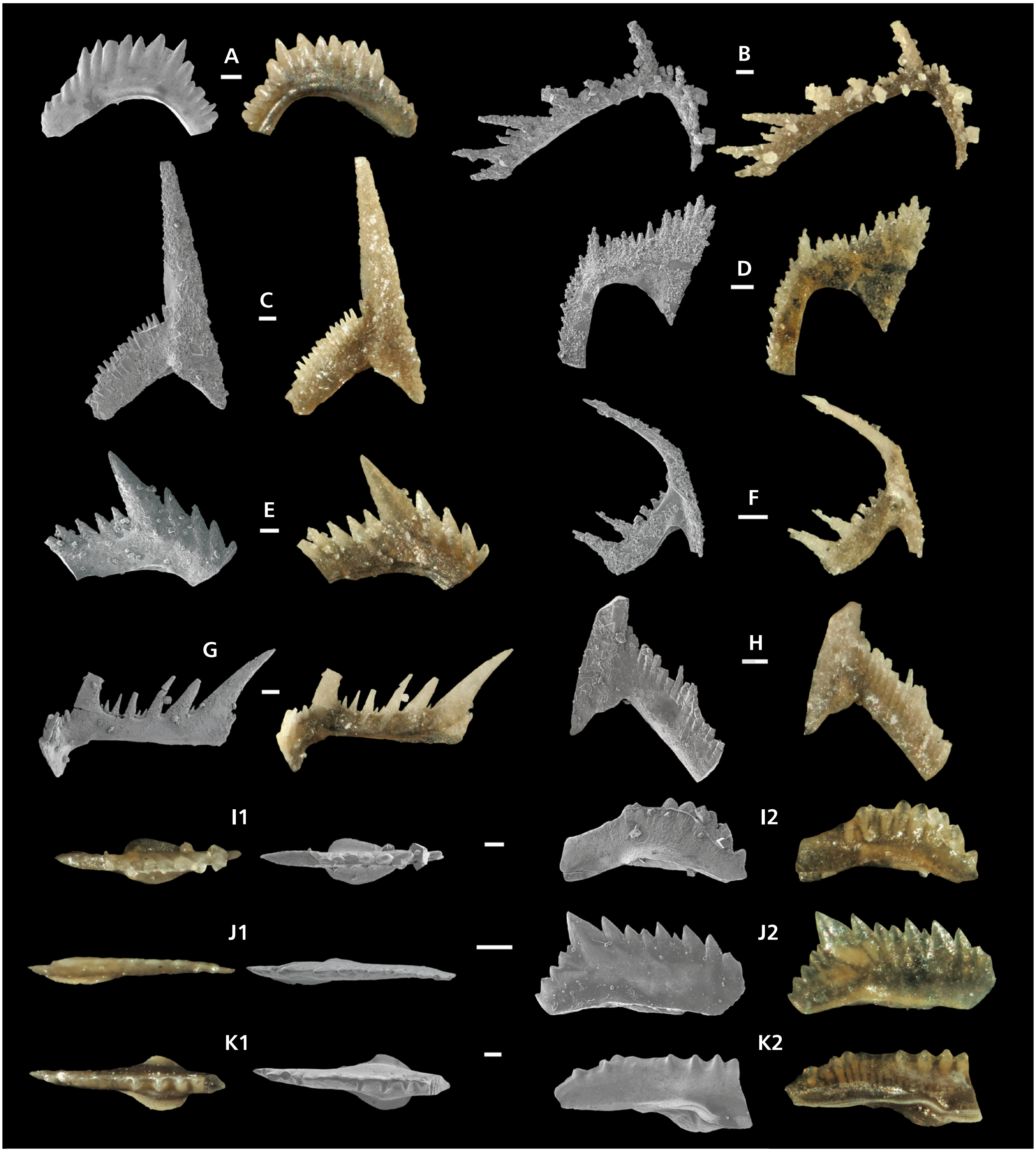


Figure 10. Conodonts from the H-28 Core. • A – *Protognathodus* sp., sinistral P_2 element, rostral view on left (SEM), caudal view on right (plain light), Prospect Hill Fm., 256’10”–257’8”, SUI 148249. • B – gen. et sp. indet., sinistral ?S_3 element, adaxial view, Upper Member, Wassonville Fm., 216’0”–217’0”, 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 S_2 element, adaxial view, Upper Member, Wassonville Fm., 216’0”–217’0”, SUI 148253. • E–G – *Hindeodus crassidentatus* (Branson & Mehl, 1934a); E – dextral P_2 element, caudal view, Upper Member, Wassonville Fm., 210’5”–211’0”, SUI 148254; F – dextral S_2 element, adaxial view, Upper Member, Wassonville Fm., 215’0”–216’0”, SUI 148255; G – dextral S_3 element, adaxial view, Upper Member, Wassonville Fm., 210’5”–211’0”, SUI 148256. • I – *Bispathodus stabilis stabilis* (Branson & Mehl, 1934b), sinistral P_1 element, oral view (I1), rostral view (I2), Dolbee Creek Member, Burlington Fm., 209’6”–210’5”, SUI 148257. • J – *Elictognathus costatus* (Branson & Mehl, 1934a), sinistral P_2 element, oral view (J1), caudal view (J2), Prospect Hill Fm., 251’7”–252’10”, SUI 148258. • K – *Bispathodus aculeatus aculeatus* (Branson & Mehl, 1934b), sinistral P_1 element, oral view (K1), caudal view (K2), Prospect Hill Fm., 251’7”–252’10”, SUI 148259.

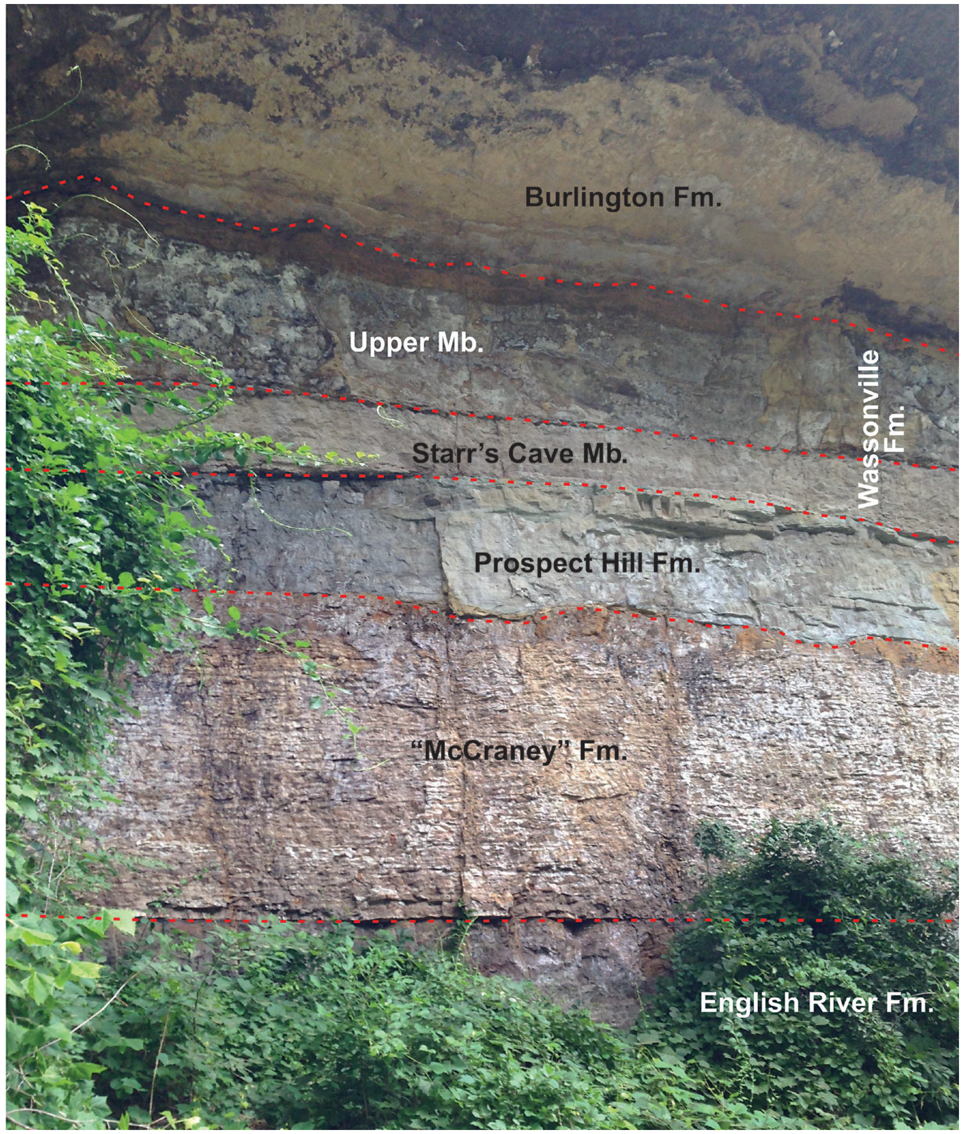
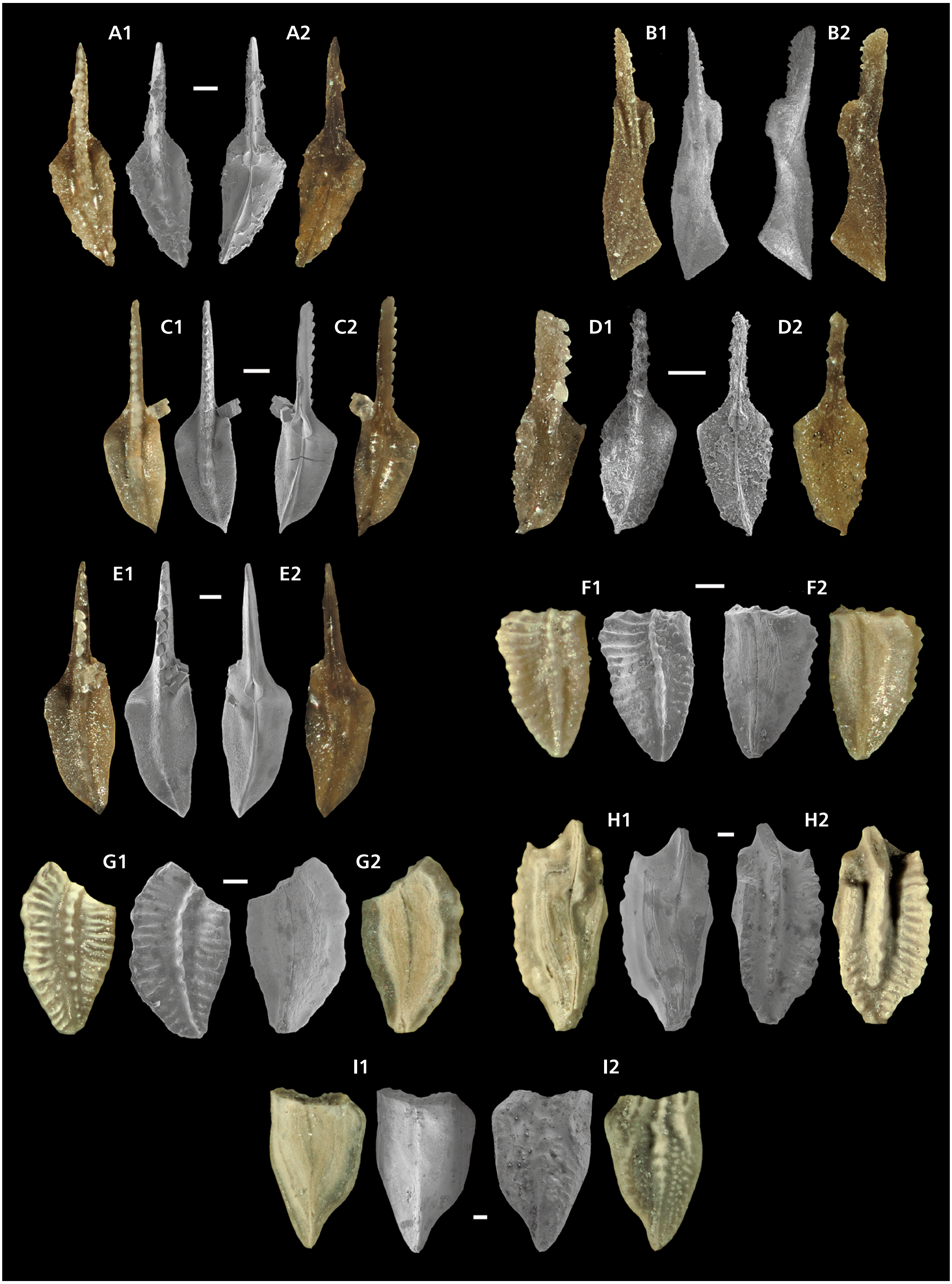


Figure 11. Field photograph of the Starr's Cave Outcrop at Starr's Cave Park in Des Moines County, IA. Formations and unit members are labeled. The red dashed lines indicate the boundary between members or formations.

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 Chauffe & 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 P_1 element, oral view (A1), aboral view (A2), Upper Member, Wassonville Fm., 219'0"–220'0", SUI 148260; C – sinistral P_1 element, oral view (C1), aboral view (C2), Dolbee Creek Member, Burlington Fm., 209'6"–210'5", SUI 148261; D – dextral P_1 element, oral view (D1), aboral view (D2), Upper Member, Wassonville Fm., 216'0"–217'0", SUI 148262; E – sinistral P_1 element, oral view (E1), aboral view (E2), Dolbee Creek Member, Burlington Fm., 209'6"–210'5", SUI 148263. • B – *Siphonodella* sp., dextral P_1 element, oral view (B1), aboral view (B2), Upper Member, Wassonville Fm., 216'0"–217'0", SUI 148264. • F – *Siphonodella ?cooperi* Hass, 1959; sinistral P_1 element, oral view (F1), aboral view (F2), Prospect Hill Fm., 244'3"–245'0", SUI 148265. • G – *Siphonodella duplicata* (Branson & Mehl, 1934a); sinistral P_1 element, oral view (G1), aboral view (G2), Prospect Hill Fm., 227'0"–228'0", SUI 148266. • H – *Polygnathus inornatus* E.R. Branson, 1934; dextral P_1 element, aboral view (H1), oral view (H2), Prospect Hill Fm., 254'3"–255'0", SUI 148267.• I – *Siphonodella obsoleta* Hass, 1959, sinistral P_1 element, aboral view (I1), oral view (I2), Prospect Hill Fm., 227'0"–228'0", SUI 148268.


A1
A2
B1
B2
C1
C2
D1
D2
E1
E2
F1
F2
G1
G2
H1
H2
I1
I2

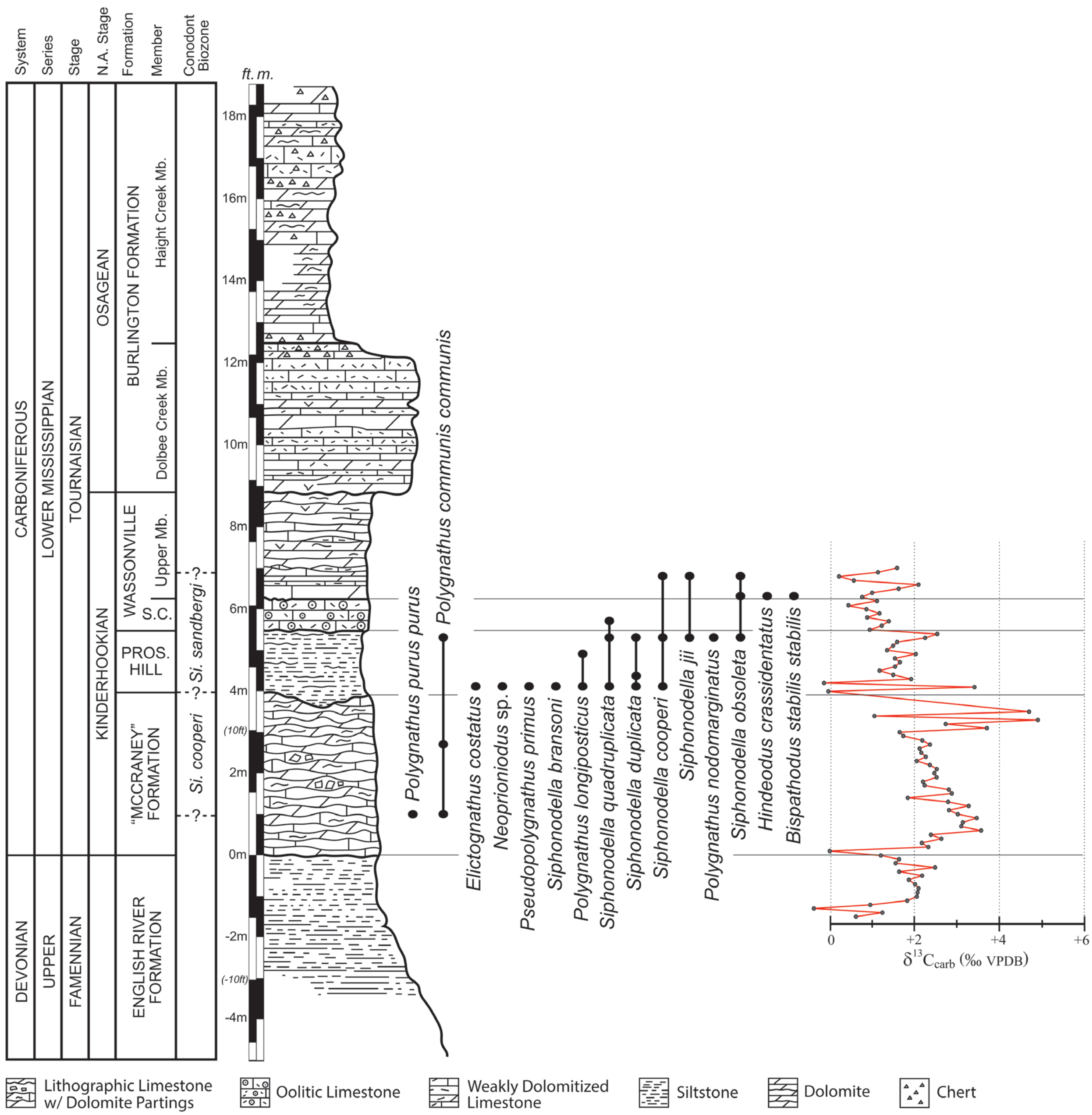


Figure 13. Conodont biostratigraphy and carbon isotope chemostratigraphy of the Starr's Cave Outcrop in Des Moines County, Iowa. Conodont occurrences are represented by small circles.

The Louisiana Limestone in its type area of eastern Missouri contains $\delta^{13}C_{carb}$ 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

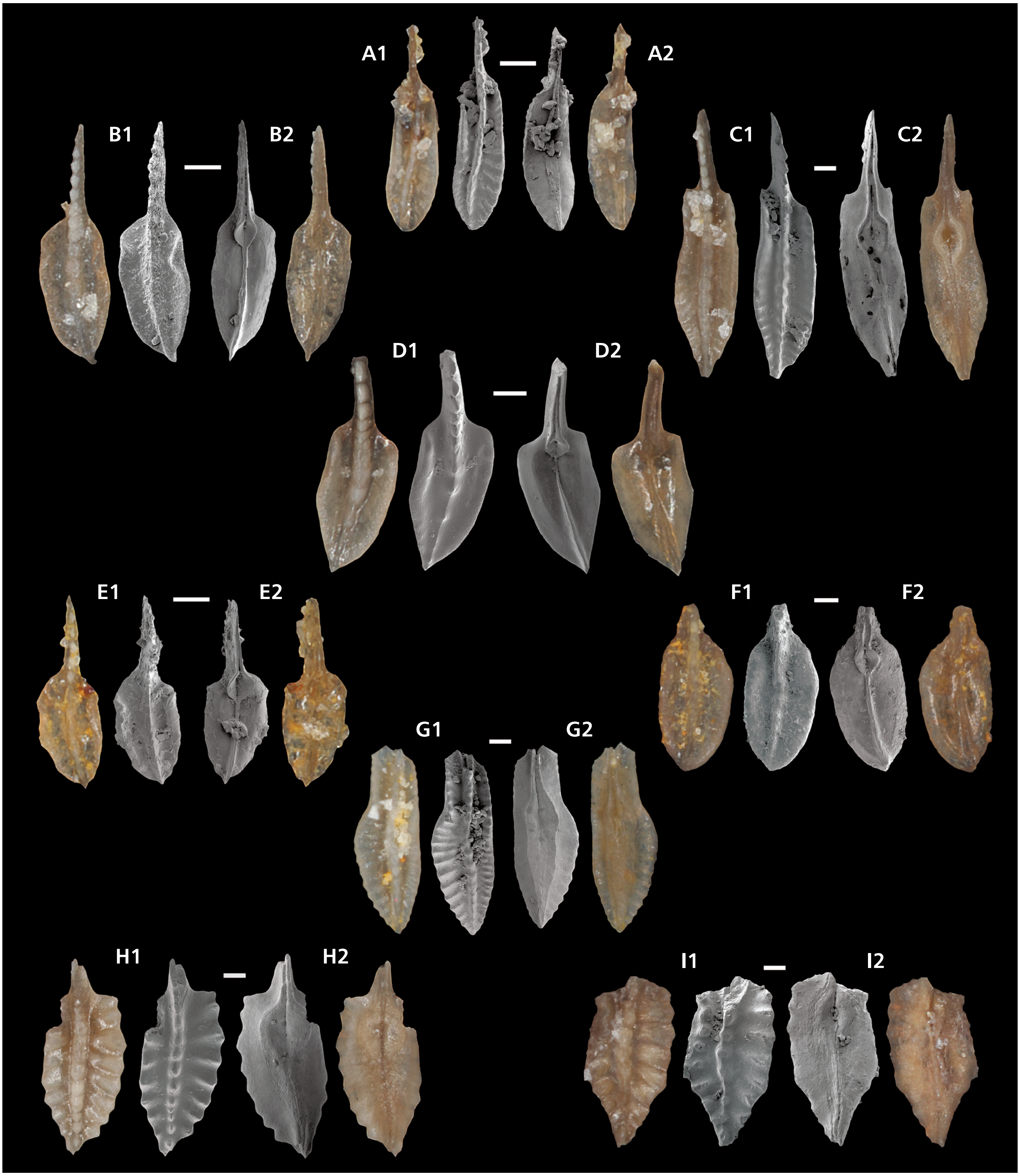


Figure 14. Conodonts from the Starr's Cave Outcrop. • A, C – *Polygnathus longiposticus* Branson & Mehl, 1934a; A – [?] dextral P_1 element, oral view (A1), aboral view (A2), "McCraney" Fm., 0.9–1.1 m, SUI 148269; C – dextral P_1 element, oral view (C1), aboral view (C2), Prospect Hill Fm., 4.8–5.0 m, SUI 148270. • B, D, E – *Polygnathus communis communis* (Branson & Mehl, 1934a); B – sinistral P_1 element, oral view (B1), aboral view (B2), "McCraney" Fm., 2.6–2.8 m, SUI 148271; D – dextral P_1 element, oral view (D1), aboral view (D2), Prospect Hill Fm., 5.2–5.4 m, SUI 148272; E – sinistral P_1 element, oral view (E1), aboral view (E2), "McCraney Fm., 0.9–1.1 m, SUI 148273. • F – *Polygnathus purus purus* (Voges, 1959), dextral P_1 element, oral view (F1), aboral view (F2), "McCraney" Fm., 0.9–1.1 m, SUI 148274. • G – *Siphonodella bransoni* Ji, 1985; sinistral P_1 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 P_1 element) oral view (H1), aboral view (H2), "McCraney" Fm., 2.6–2.8 m, SUI 148276. • I – sinistral P_1 element, oral view (D1), aboral view (D2), Prospect Hill Fm., 5.2–5.4 m, SUI 148277.

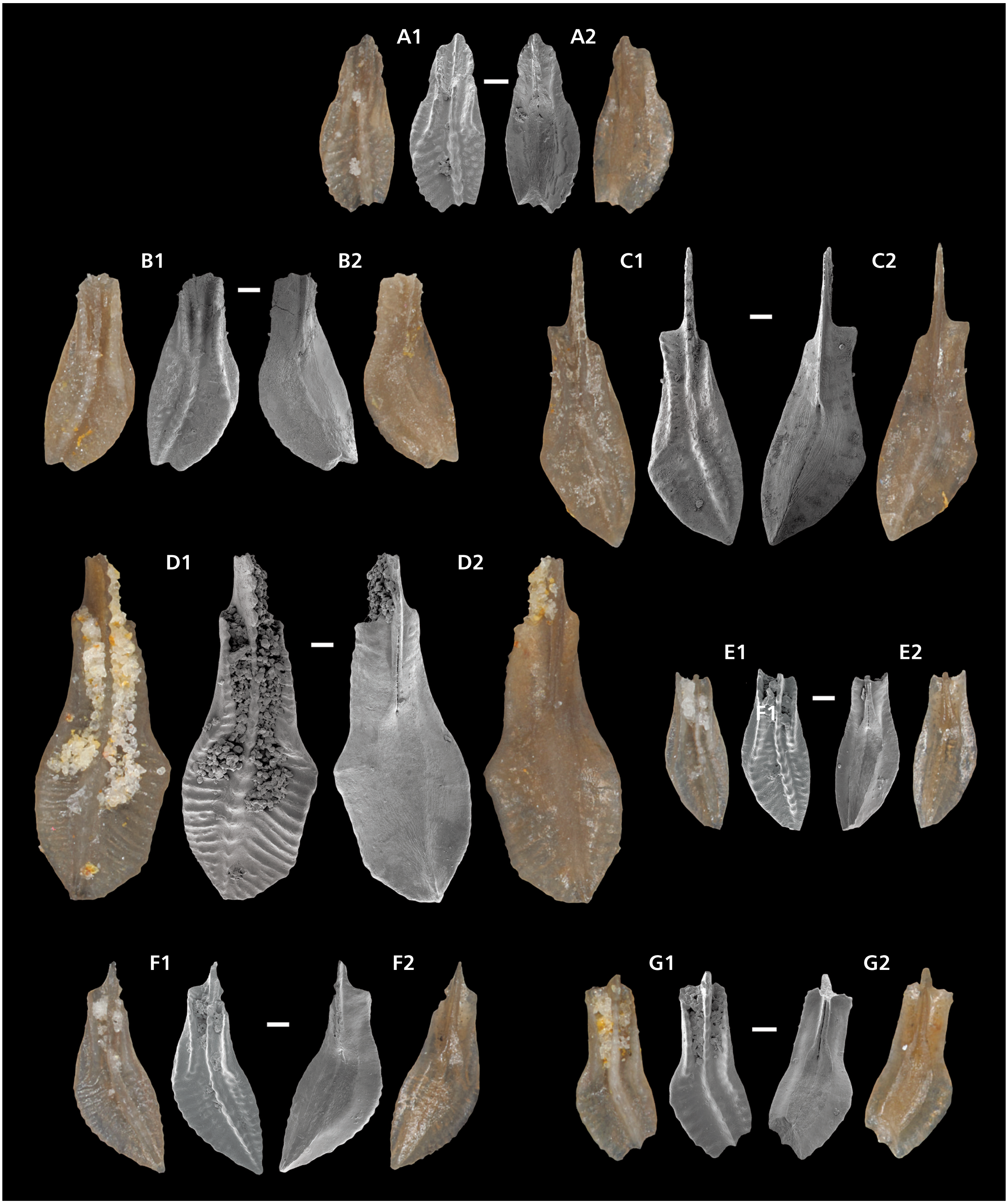


Figure 15. Conodonts from the Starr's Cave Outcrop. • A, E, G – *Siphonodella cooperi* Hass, 1959; A – sinistral P_1 element, oral view (A1), aboral view (A2), Prospect Hill Fm., 5.2–5.4 m, SUI 148278; E – sinistral P_1 element, oral view (E1), aboral view (E2), Prospect Hill Fm., 5.2–5.4 m, SUI 148279; G – sinistral P_1 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 P_1 element, oral view (B1), aboral view (B2), Upper Member, Wassonville Fm., 6.2–6.4 m, SUI 148281; C – sinistral P_1 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 P_1 element, oral view (D1), aboral view (D2), Prospect Hill Fm., 4.0–4.2 m, SUI 148283. • F – *Siphonodella jii* Becker *et al*., 2016; sinistral P_1 element, oral view (F1), aboral view (F2), Prospect Hill Fm., 5.2–5.4 m, SUI 148284.

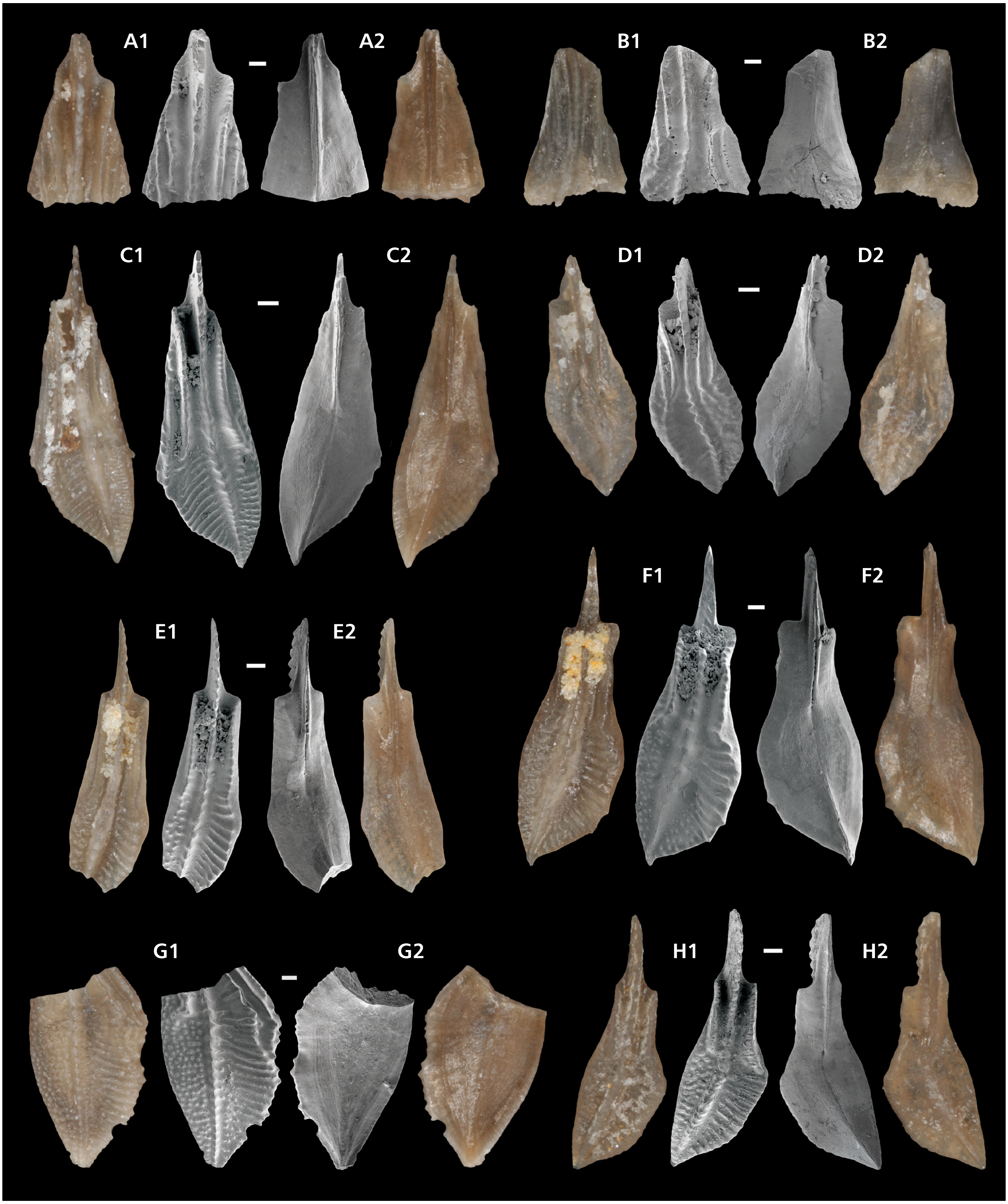


Figure 16. Conodonts from the Starr's Cave Outcrop. • A–D – *Siphonodella quadruplicata* (Branson & Mehl, 1934a); A – [?] sinistral P_1 element, oral view (A1), aboral view (A2), Prospect Hill Fm., 5.2–5.4 m, SUI 148285; B – dextral P_1 element, oral view (B1), aboral view (B2), Starr's Cave Member, Wassonville Fm., 5.6–5.8m, 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.

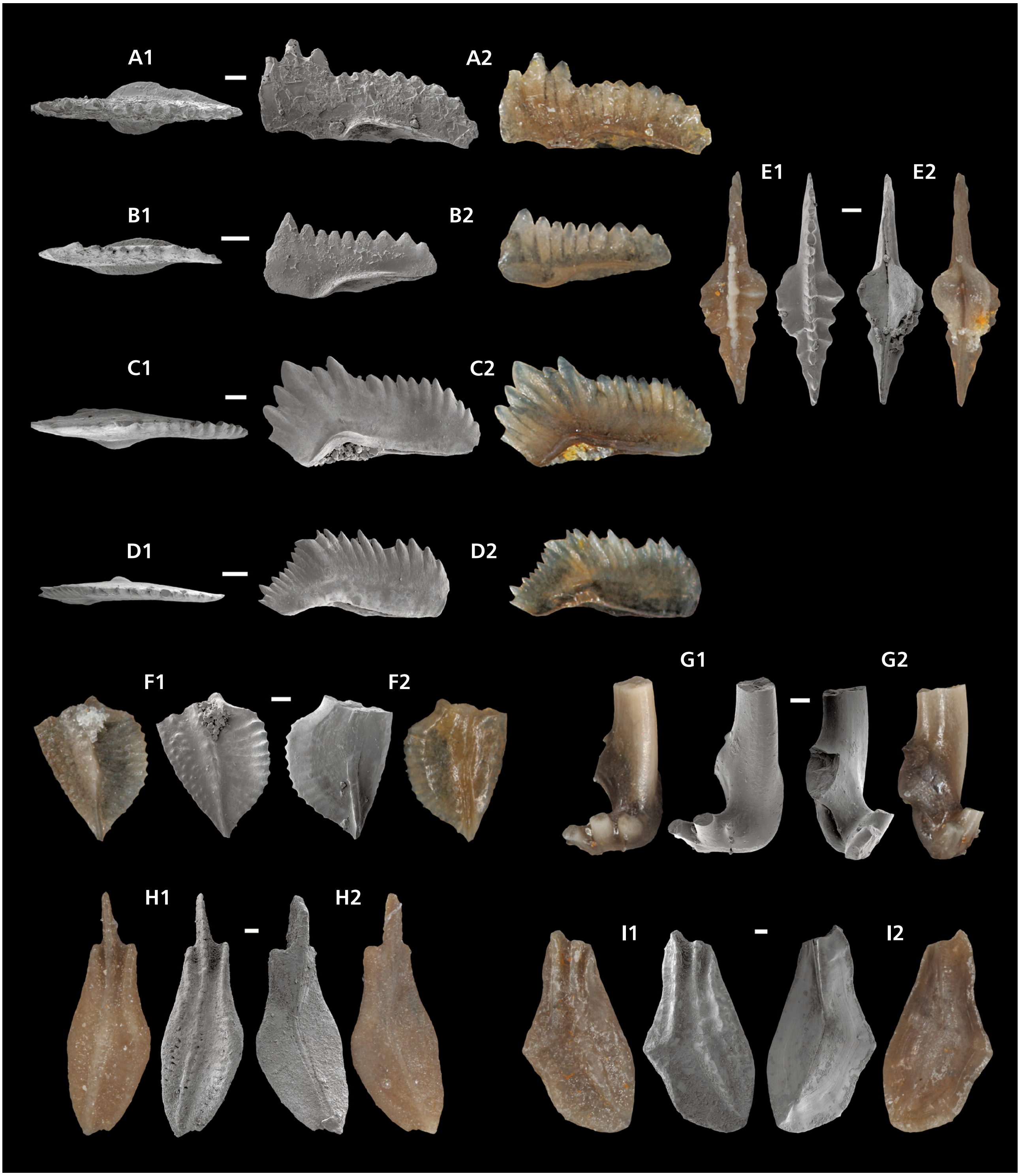


Figure 17. Conodonts from the Starr's Cave Outcrop. • A – *Hindeodus crassidentatus* (Branson & Mehl, 1934a); dextral P_1 element, oral view (A1), caudal view (A2), Upper Member, Wassonville Fm., 6.2–6.4 m, SUI 148293. • B – *Bispathodus stabilis stabilis* (Branson & Mehl, 1934b); dextral P_1 element, 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 P_2 element, oral view (C1), caudal view (C2), Prospect Hill Fm., 4.0–4.2 m, SUI 148295; D – sinistral P_2 element, oral view (D1), caudal view (D2), Prospect Hill Fm., 4.0–4.2 m, SUI 148296. • E – *Pseudopolygnathus primus* Branson & Mehl, 1934a; ?sinistral P_1 element, oral view (E1), aboral view (E2), Prospect Hill Fm., 4.0–4.2 m, SUI 148297. • F–I – *Siphonodella* sp.; F – dextral P_1 element, oral view (F1), aboral view (F2), Prospect Hill Fm., 4.8–5.0 m, SUI 148298; H – dextral P_1 element, oral view (H1), aboral view (H2), Upper Member, Wassonville Fm., 6.2–6.4 m, SUI 148299; I – sinistral P_1 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 praedelicatus*, 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*

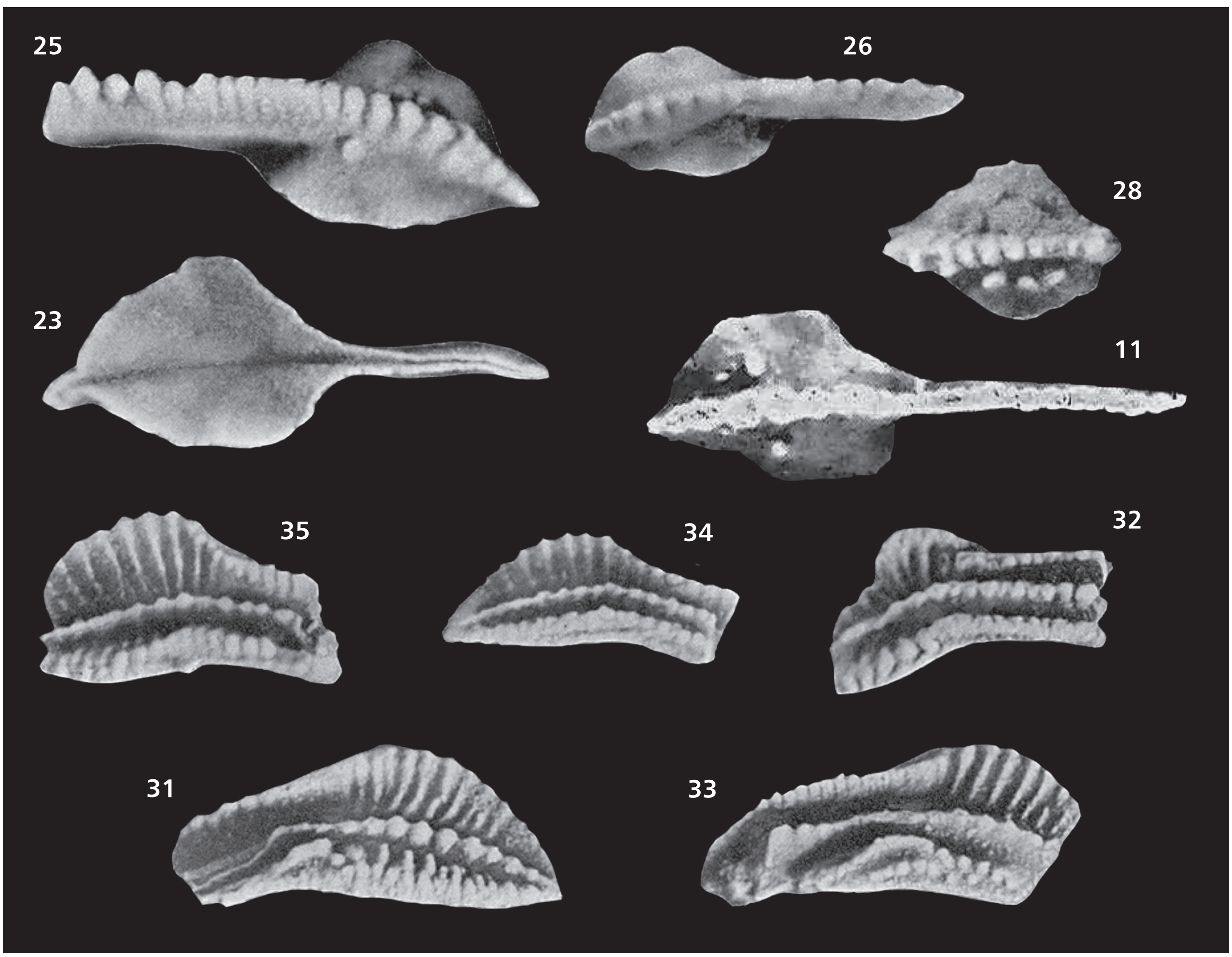


Figure 18. Re-illustrations of images from Scott & Collinson (1961) and Straka (1968). Specimen numbers are the original designations from the original authors. Specimens 23, 25, 26, and 28 are from Scott & Collinson (1961, pl. 1), images are 40x, and all specimens are from the Teneriffe School Section, 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 $\delta^{13}C$ 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 (Chauffe & 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 $\delta^{13}C_{carb}$ 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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