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The Global Boundary Stratotype Section and Point for the base of the Turonian Stage of the Cretaceous: Pueblo, Colorado, U.S.A.

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Following the recommendation of the International Commission on Stratigraphy (16 votes Yes [94%], 1 abstention, 2 votes not received), the Global boundary Stratotype Section and Point (GSSP) for the base of the Turonian Stage of the Cretaceous System is defined as the base of bed 86 of the Bridge Creek Limestone Member of the Greenhorn Limestone Formation at the western end of the Denver and Rio Grande Railroad cut near the north boundary of the Pueblo Reservoir State Park Recreation Area, west of Pueblo, Colorado, USA. This GSSP horizon is also exposed and protected in the adjacent state recreation area. It coincides with the first occurrence of the ammonite *Watinoceras devonense*, is in the middle of a global positive excursion in Carbon-13 isotopes, and is bracketed by widespread bentonites that have yielded ages of 93 to 93.5 Ma.

Introduction

The present document defining a Global boundary Stratotype Section and Point (GSSP) for the base of the Turonian Stage of the Upper Cretaceous arises from the recommendations of the Turonian Working Group of the Subcommittee on Cretaceous Stratigraphy at its meetings during the Second International Symposium on Cretaceous Stage Boundaries held in Brussels from September 8–16 1995. A report of the conclusions of the Turonian Working Party was provided by Bengtson (compiler) (1996). The proposal was subsequently submitted to the International Commission on Stratigraphy, which voted Yes 16 votes (94%), with one abstention and two votes not received. The International Union of Geological Sciences was requested to ratify this decision; the proposal was finally ratified in September 2003.

Historical Background

When Alcide d'Orbigny began to divide the Upper Cretaceous into stages, he at first recognized only two, the Turonian below, and the Senonian above (1843, pp. 403–406). With respect to the Turonian, his words are: “je propose de designer à l'avenir l'étage qui m'occupe sous le nom de terrain TURONIEN, de la ville de Tours (Turones) ou de la Touraine (*Turonia*), situées sur ces terrains” (1842, p. 404), defining the Turonian as equivalent to the Craie Chloritée, Craie tuffeau, Glauconie crayeuse, Grès Vert Supérieur etc.,

and taking the name from Touraine (Roman Turonia). Six years later he realised that two distinct ammonite and rudistid faunas were present and restricted the term to beds corresponding to his third zone of rudists, yielding “*Ammonites Lewesiensis*, *peramplus*, *Vielbancii*, *Woollgari*, *Fleuriausianus*, *Deverianus*” etc. (d'Orbigny, 1851, p.270), stating “le plus beau type Côtier était très prononcé dans tout la Touraine”.

In the second volume of the *Prodrome* (1850) d'Origny listed 809 species as characteristic of the Cenomanian and 366 as characteristic of the Turonian. In the *Cours Elementaire* (d'Origny, 1852) there is the most complete statement of the Cenomanian and Turonian stages. The origin of the names is explained, faunal characteristics are defined, and type areas are indicated, as are other regions or successions where rocks of comparable age are known. Most significantly, the area between Saumur and Montrichard is stated to be the type area. Although d'Origny did not define the Cenomanian-Turonian boundary in unmistakable terms and there are conflicting data in the *Prodrome* and *Cours Elementaire*, he regarded *Metoicoceras* [*Ammonites*] *geslinianum*, *Actinocamax plenus* (Blainville) (= *Belemnitella vera* d'Origny non Miller) and *Terebratella carantonensis* as Cenomanian, and *Lewesiceras* [*Ammonites*] *peramplus* (Mantell), *L.* [*Ammonites*] *lewesiense* Mantell and *Inoceramus labiatus* (= *Inoceramus problematicus* d'Origny) as Turonian.

The definition of the boundary between Cenomanian and Turonian Stages should, as far as possible, follow d'Origny's views. Wright & Kennedy (1981, p.126) reviewed this historical evidence, in the context of an ammonite zonal scheme as follows:

LOWER TURONIAN	<i>Mammites nodosoides</i> Zone <i>Watinoceras coloradoense</i> Zone
UPPER CENOMANIAN (part)	<i>Neocardioceras juddii</i> Zone <i>Metoicoceras geslinianum</i> Zone

They concluded that although d'Origny did not define the Cenomanian-Turonian boundary in unmistakable terms, and although there are conflicting data in the *Prodrome* (d'Origny, 1850) and *Cours Elementaire* (d'Origny, 1852) (conflicts stressed by Hancock, 1984, p.124), there is an argument that the *Metoicoceras geslinianum* Zone as used by Wright & Kennedy is Cenomanian and the *Mammites nodosoides* Zone as used by Wright & Kennedy is Turonian (other, earlier definitions have regarded the *nodosoides* Zone as including horizons as low as *geslinianum* Zone).

The interval spanning *geslinianum* to *nodosoides* Zones of Wright & Kennedy encompasses most of the proposed markers noted by Birkelund et al. (1984) in their summary following the 1983 Copenhagen Meeting, which were:

(a) Base of the *Metoicoceras geslinianum* ammonite Zone, or slightly later appearance of the ammonite *Euomphaloceras septemseriatum*.

* With contributions by P. Dodsworth, W.P. Elder, A.S. Gale, G.R. Scott, J.M. Hancock, S. Voigt and J.I. Kirkland

- (b) Base of the *Pseudaspidoceras flexuosum* ammonite Zone (or better the appearance of some vascoceratid ammonite, possibly *Vascoceras proprium*).
- (c) "The appearance of the [ammonite] Assemblage Zone of *Watinoceras coloradoense* is the definition that has been most used by ammonite workers in Europe during the last few years. This level is close to proposal (b) above. However, the nominate subspecies is absent in Europe, and the base of the zone is drawn at a lower level than the base of the zone of the same name in the USA (see Cobban this volume), this lower level probably corresponds to the base of the *P. flexuosum* Zone". (Birkelund et al., 1984, p. 12).
- (d) Definition on the basis of the *Mytiloides* inoceramid bivalve lineage.
- (e) The appearance of a flood of *Mytiloides* at the base of the assemblage zone of *Mammites nodosoides*.
- (f) Appearance of the coccolith *Quadrum gartneri* in the ammonite zone of *Neocardioceras juddii*.
- (g) The extinction of the planktic foraminiferan genus *Rotalipora* in the *Metoicoceras geslinianum* Zone.
- (h) The appearance of the planktic foraminifer *Whiteinella archaeocretacea*.
- (i) The appearance of the distinctive Turonian planktic foraminifer *Praeglobotruncana helvetica*.

Their only mention of anoxia at this level is the observation that "the distinctive anoxic event of Schlanger & Jenkyns (1976) has recently been shown by Hart & Bigg (1981) to fall within the *W. archaeocretacea* Zone".

The conclusion of Birkelund et al. was as follows:

"Conclusion

Boundary level: The boundary at the base of the Pseudaspidoceras flexuosum Zone gained some support. In the present volume it is recommended in papers by Cobban and by Kennedy. However, P. flexuosum has a restricted geographical distribution.

Important support for that boundary is the widespread appearance of early Mytiloides as represented by M. opalensis sensu Kauffman at the same level, an event which can be traced in both Tethyan and Boreal regions (recommended by Hancock, this volume).

The appearance of Quadrum gartneri immediately below, in the Neocardioceras juddii Zone and the extinction of Rotalipora in the Metoicoceras geslinianum Zone further below are world-wide markers."

The Copenhagen Meeting stimulated work on the Cenomanian-Turonian boundary, such that it is now recognised as an interval in which a major oceanic anoxic event occurred, and during which a phase of mass extinction is claimed. Work on ammonite and inoceramid bivalve faunas in the U.S. Western Interior has produced great refinement of the ammonite and inoceramid zonation across the boundary interval, while biostratigraphic, isotopic, geochemical and radiometric analysis on the section at Pueblo in Colorado (Figure 1) and its correlatives led to the proposal of the section as a candidate stratotype for the Cenomanian-Turonian boundary.

The Global boundary Stratotype Section and Point for the base of the Turonian Stage

The section at Pueblo (Figures 1, 2; Tables 1, 2) was known to Stanton (1894), was mapped by Scott (1964, 1970) and ammonite faunas documented by Cobban & Scott (1973), Cobban (1985), Elder (1985), Kennedy & Cobban (1991) and Kennedy et al. (1999, 2000). Inoceramid bivalves are documented by Kennedy & Cobban (1991), Elder (1991) and Walaszczyk & Cobban in Kennedy et al., 2000; planktic foraminifera by Eicher & Diner (1985), Leckie (1985),

Keller & Pardo (2004), and Keller et al. (2004); calcareous nannofossils by Watkins (1985) and Bralower (1988); dinoflagellates by Dodsworth (2000); stable isotopes by Pratt (1981, 1983, 1984, 1985), Pratt et al. (1993), Pratt & Threlkeld, (1984), Keller & Pardo (2004), Keller et al. (2004), and Gale et al. (2005); iridium anomalies by Orth et al. (1988); and numerical dating of bentonites in correlative sections by Obradovich (1993) and Kowallis et al. (1995). Elder

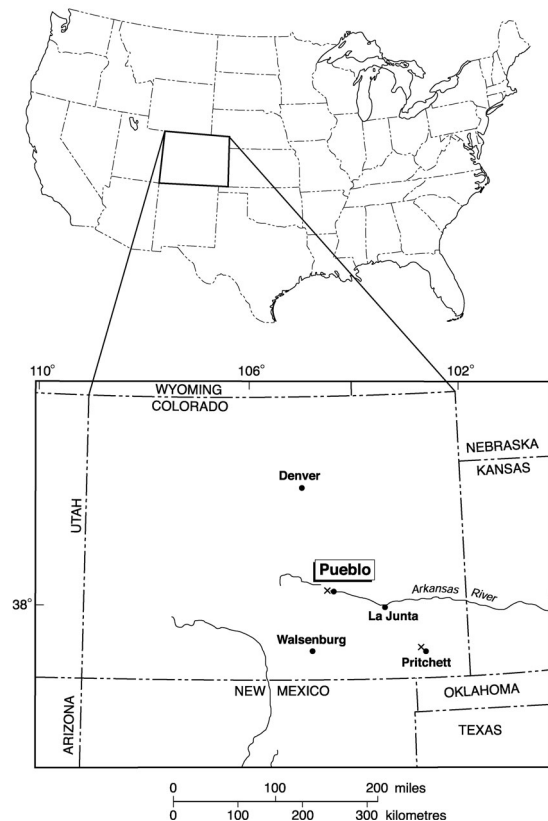


Figure 1 The location of Pueblo, Colorado, in the U.S. Western Interior.

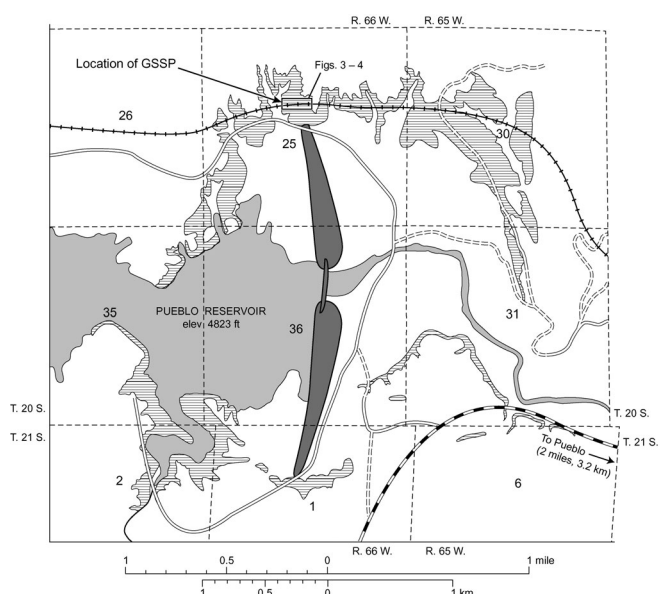


Figure 2 Geological sketch map of the area around the Pueblo Reservoir. The Global boundary Stratotype Section and Point for the base of the Turonian Stage is situated within the box marking the position of Figures 3–4 (based on Scott, 1964). Horizontal pattern shows outcrop of Greenhorn Limestone.

(1985, 1987), Harries & Kauffman (1990), Harries (1993) and Keller & Pardo (2004) discuss extinctions across the interval, and there is much valuable and additional information in Pratt, Kauffman & Zelt (1985).

The outcrop succession at Pueblo shows no obvious signs of condensation or non-sequence across the boundary interval and consists of diagenetically modified limestone-marl Milankovitch cycles, individual limestone and marl beds of which can be correlated across tens of thousands of square kilometres in the U.S. Western Interior (e.g. Hattin, 1971, 1975).

The section at the Rock Canyon anticline lies west of Pueblo, where the Arkansas River cuts through the Cretaceous section (Figures 1, 2). As Kennedy & Cobban (1991, p.10) note, the construction of a dam on the Arkansas River and subsequent development of a State Park (the Pueblo Reservoir Recreation Area) provide easy vehicular access, and although fossil collecting without permit is not possible from natural outcrops in the State Park (permission from bona fide workers will not normally be refused), relocation of the adjacent Denver and Rio Grande Western Railroad has exposed several kilometres of fresh cuts through the Bridge Creek Member of the Greenhorn Limestone.

Location

The GSSP (Figures 3–4) is located at the western end of the cuts on the Denver and Rio Grande Western Railroad, north of Pueblo Reservoir, west of Pueblo, Colorado, where the Arkansas River cuts through the Rock Canyon anticline (Figures 1, 2). The area is semi-arid, with little vegetation cover, and there are semi-continuous exposures throughout most of the outcrop indicated in Figure 2. These outcrops form an arcuate belt several kilometers long mostly in secs. 25, 35, and 36 of T. 20S., R. 66W., and secs. 30 and 31, T. 20S., R. 65W., Northwest Pueblo 7¹/₂ minute quadrangle, scale 1:24,000, and lie within Townships 20 and 21 South, Ranges 65 and 66 west, latitude 38° North, longitude 104° 30' West.

Access

Following the damming of the Arkansas River, the resultant reservoir has become the focus of the Pueblo State Recreation Area. Vehicular access is now possible by tarmac road, by taking State Highway 96 west from the center of Pueblo. Within the State Recreation Area, permission must be obtained prior to sampling by contacting the Rangers at the Park headquarters. All reasonable requests will be granted. Roads within the State Recreation Area are all tarmac. Figures 3, 4 show the GSSP, and there are further outcrops extending along the several kilometers of cut of the railroad immediately north of the State Recreation Area.

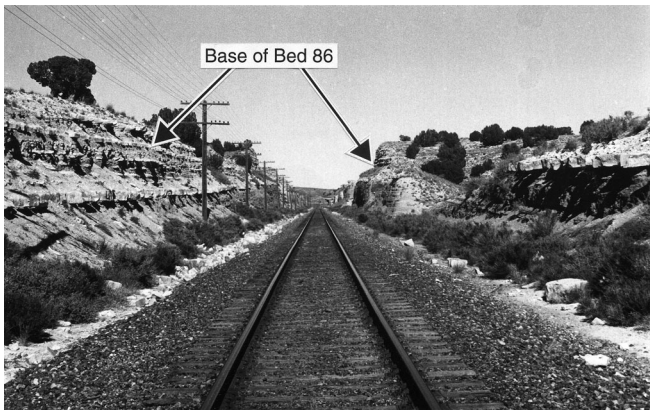


Figure 3 The GSSP for the base of the Turonian Stage. Cut at the western end of the Denver and Rio Grande Western Railroad at the north boundary of the Pueblo Reservoir State Recreation Area; see Figure 2 for location. The base of the Turonian Stage is drawn at the base of Bed 86 of the Bridge Creek Member of the Greenhorn Limestone.

Description of the GSSP

Table 1 is a detailed lithological log of the interval that encompasses the base of the Turonian Stage, which is within the Bridge Creek Member of the Greenhorn Limestone (Figure 5). Table 2 puts this unit in its regional lithostratigraphic context.

Figure 5 provides a summary lithostratigraphic section, with the base of the Turonian Stage indicated, as well as key bed-by-bed ammonite records.

Figure 8 gives data on the distribution of the inoceramid bivalves, key secondary markers in the boundary interval, following the taxonomic revision by Walaszczyk & Cobban *in* Kennedy et al. (2000).

As can be seen from Figures 3, 4, the basic succession within the Bridge Creek Member is of alternations of limestone and shale; the alternations are in part primary in origin, accentuated by diagenetic redistribution of carbonate. Much of the sequence is bioturbated, with laminated and sublaminated units. Petrographically, the limestones are fossiliferous biomicrites.

The alternations in the Bridge Creek are climatically driven (Milankovitch) cycles, and individual beds are of wide geographical extent. Hattin (1971) was the first to demonstrate their wide distribution, and this work was extended by Elder (1985, 1987), Elder & Kirkland (1985), and others. Individual marker beds can be traced for hundreds of kilometers away from Pueblo, into Kansas, New Mexico, Utah, and Arizona. The Bridge Creek Member is also characterized by the presence of bentonites, and several of these have been traced for equally long distances (Elder, 1988). Detailed descriptions of the lithostratigraphy of the Pueblo sequence are to be found in Scott (1964), Cobban & Scott (1973), and in the many papers edited by Pratt, Kauffman & Zelt (1985).

The boundary level: primary and secondary biostratigraphic markers

The boundary level is taken at the base of bed 86 of the section (Figure 5). This bed is indicated in Figures 3, 4. It is most easily recognized in the field by working up from the lowest, and very prominent limestone of the Bridge Creek Member: Bed 63, and there is a prominent yellow-weathering bentonite (bed 88) 50.4 cm above the top of bed 86. The base of bed 86 corresponds to the first occurrence of the ammonite *Watinoceras devonense* (Wright & Kennedy, 1981) in the section; the characteristic ammonite fauna of bed 86 is shown in Figure 6.

Apart from its occurrence at Pueblo, *Watinoceras devonense* also occurs elsewhere in bed 86 in Colorado, and in Southern England. There are also a series of secondary biostratigraphic markers for the basal boundary level in the Pueblo section; these are indicated in Figure 9. The ammonite, inoceramid bivalve, and dinoflagellate

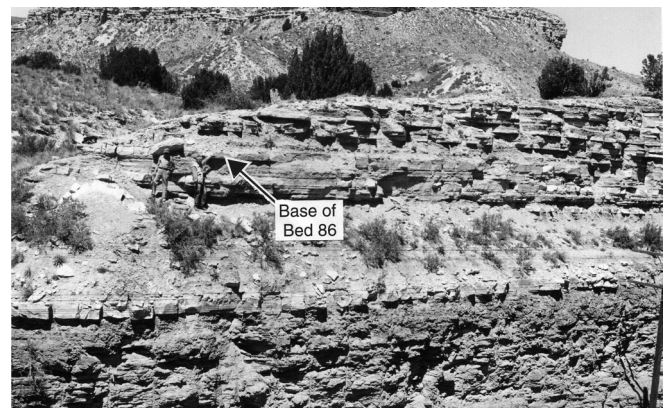


Figure 4 The GSSP for the base of the Turonian Stage. Cut on the north side of the Denver and Rio Grande Western Railroad (detail of Figure 3). The base of the Turonian Stage is drawn at the base of bed 86 of the Bridge Creek Member of the Greenhorn Limestone.

Table 1 Principal reference section of Bridge Creek Member of the Greenhorn Limestone measured on Rock Canyon anticline in the NW1/4NE1/4 sec. 31, T. 20 S., R. 65 W., and in the SW1/4 and NW1/4NW1/4 sec. 30. T. 20 S., R. 65 W. Pueblo County, Colorado: from Cobban and Scott, 1973 with inoceramid names updated.

Bridge Creek Member of the Greenhorn Limestone		Ft	in	(cm)
150	Calcarenite, shaly to platy; contains some fragments of <i>Mytiloides</i> and <i>Collignoniceras woollgari</i> -----		4	(10.2)
149	Shale, calcareous, soft -----		5	(12.7)
148	Bentonite -----		0.5	(1.3)
147	Shale, calcareous, soft -----		3	(7.6)
146	Shale, calcareous; contains numerous hard thin partings of calcarenite. Contains some fragments of <i>Mytiloides</i> -----	1	3	(38)
145	Shale, calcareous, soft; contains a few thin partings of calcarenite -----		5.5	(14)
144	Bentonite -----		0.5	(1.3)
143	Shale, calcareous, hard -----		4	(10.2)
142	Bentonite, orange-brown, limonitic -----		2	(5.1)
141	Shale, calcareous, hard and soft -----		3	(7.6)
140	Bentonite, yellowish-orange; contains selenite crystals -----		1.5	(3.8)
139	Shale, calcareous, hard, platy -----		5	(12.7)
138	Shale, calcareous, soft -----		11	(28)
137	Limestone, shaly; contains fragments of <i>Ostrea</i> and <i>Mytiloides</i> -----		2	(5.1)
136	Shale, calcareous, soft -----		4	(10.2)
135	Limestone, light-gray, shaly ----- USGS D3985 and D3986: <i>Mytiloides subhercynicus</i> (Seitz), <i>Collignoniceras woollgari</i> (Mantell)		5	(12.7)
134	Shale, gray, calcareous -----		6	(15.2)
133	Limestone, gray, shaly; top has worm burrows. Contains <i>Mytiloides subhercynicus</i> (Seitz) -----		5	(12.7)
132	Shale, gray, calcareous; contains three hard beds -----	3	7	(109.2)
131	Shale; medium gray where fresh, orange brown where weathered, soft, calcareous; contains very thin partings of harder shale and calcarenite ----- USGS D3983 at top: <i>Baculites</i> cf. <i>B. yokoyamai</i> Tokunaga and Shimizu, <i>Collignoniceras woollgari</i> (Mantell)	5	0	(152.4)
130	Bentonite, orange-brown -----		2	(5.1)
129	Shale, calcareous, soft -----	1	5	(43.2)
128	Bentonite -----		0.5	(1.3)
127	Shale, calcareous, soft -----		7.5	(19.1)
126	Shale, calcareous; contains thin hard partings of calcarenite and hard shale -----	2	11	(88.9)
125	Bentonite -----		0.5	(1.3)
124	Shale, calcareous, soft -----		3.5	(8.9)
123	Calcarenite, shaly; contains fragments of <i>Inoceramus</i> -----		7	(17.8)
122	Limestone, light-gray, massive, chalky -----		3.5	(8.9)
121	Shale, calcareous, soft -----	1	2	(35.6)
120	Limestone, gray, hard, irregularly bedded. Forms top of bluff locally ----- USGS D3982: <i>Mytiloides mytiloides</i> (Mantell), <i>Morrowites wingi</i> (Morrow)		5	(12.7)
119	Shale, gray, calcareous ----- Limestone, gray, hard, irregularly bedded. Commonly forms top of bluff ----- USGS D3981: <i>Mytiloides mytiloides</i> (Mantell), <i>Baculites</i> cf. <i>B. yokoyamai</i> Tokunaga and Shimizu, <i>Morrowites wingi</i> (Morrow)		8	(20.3)
118	Shale, gray, calcareous -----		8	(20.3)
117	Limestone, gray, hard, irregularly bedded. Contains <i>Mytiloides mytiloides</i> (Mantell) -----		9	(22.9)
116	Shale, gray, calcareous -----		7	(17.8)
115	Bentonite, yellowish-orange -----		10	(25.4)
114	Limestone, gray, hard, irregularly bedded. Contains well-preserved fossils ----- USGS D3980: <i>Mytiloides mytiloides</i> (Mantell), <i>M. ganuzai</i> Lopez, <i>M. goppelnensis</i> (Badillet and Sornay), <i>Baculites</i> cf. <i>B. yokoyamai</i> Tokunaga and Shimizu		3	(7.6)
113	Shale, gray, calcareous -----		4	(10.2)
112	Bentonite -----		9	(22.9)
111	Shale, gray, calcareous -----		1	(2.5)
110	Limestone, gray, shaly. Contains <i>Mytiloides</i> sp. -----	1	1	(33)
109	Shale, gray, calcareous -----		3	(7.6)
108	Limestone, gray, shaly. <i>M. mytiloides</i> (Mantell), <i>M. goppelnensis</i> (Badillet and Sornay), -----		5	(12.7)
107	Shale, gray, calcareous -----		2.5	(6.4)
106	Limestone, gray, hard, massive to shaly. Fragments of <i>Puebloites</i> rather common ----- USGS D3979: <i>Mytiloides kossmati</i> (Heinz), <i>M. labiatus</i> (Schlotheim), <i>Puebloites greenhornensis</i> Cobban and Scott, <i>Tragodesmoceras bassi</i> Morrow sp., <i>Kamerunoceras puebloense</i> , <i>Morrowites wingi</i> (Morrow), <i>Choffaticeras pavillieri</i> (Pervin-quièrè)-----	1	7	(48.3)
105	Shale, gray, calcareous -----		6	(15.2)
104	Limestone, gray, shaly, platy; contains baculites -----		9	(22.9)
103	Shale, gray, calcareous; middle is harder and in part a shaly limestone that contains abundant pelagic Foraminifera and some flattened baculites -----		6	(15.2)
102	Limestone, gray, hard, somewhat shaly; contains pyrite in places ----- USGS D3978: <i>Mytiloides kossmati</i> (Heinz), <i>Watinoceras coloradoense</i> Henderson?, <i>Mammites</i> sp., <i>Choffaticeras</i> sp., <i>M. labiatus</i> (Schlotheim)	1	5	(43.2)
101	Shale, gray, calcareous -----		6	(15.2)

100	Shale, gray, calcareous -----	8	(20.3)
99	Limestone, gray, shaly -----	2	(5.1)
98	Shale, gray, calcareous -----	10	(25.4)
	Limestone, gray, hard, irregularly bedded; contains horizontal burrows and here and there grayish-green patches and films of montmorillonitic clay that contains small amounts of quartz and pyrite -----		
	USGS D3977: <i>Mytiloides kossmati</i> (Heinz), <i>M. puebloensis</i> , <i>M. goppelnensis</i> , <i>M. labiatus</i> , <i>Ostrea</i> sp., <i>Puebloites spiralis</i> Cobban and Scott, <i>Watinoceras coloradoense</i> (Henderson), <i>W. reesidei</i> Warren?, <i>Vascoceras (Greenhornoceras) birchbyi</i> Cobban and Scott, <i>Fagesia</i> sp.		
97	Shale, gray, calcareous -----		
96	Limestone, gray, shaly -----	6	(15.2)
95	Shale, gray, calcareous -----	9	(22.9)
94	Limestone, gray, shaly -----	3	(7.6)
93	Shale, gray, calcareous -----	2	(5.1)
92	Bentonite -----	2	(5.1)
91	Limestone, gray, hard, massive; weathers yellowish gray; contains numerous horizontal burrows filled with limonitic marl that give rock a mottled appearance -----	2	(5.1)
	USGS D3976: <i>Mytiloides puebloensis</i> , <i>M. kossmati</i> , <i>M. hattini</i> , <i>Ostrea</i> sp., <i>Baculites</i> cf. <i>B. yokoyamai</i> Tokunaga and Shimizu, <i>Puebloites</i> sp.	0.5	(1.3)
90	Shale, gray, calcareous -----		
89	Bentonite -----	5	(12.7)
88	Shale, gray, calcareous -----	10	(25.4)
87	Limestone, gray, hard; largely massive but upper few inches shaly; contains abundant pelagic Foraminifera and some mollusks -----	0.5	(1.3)
	USGS D3975: <i>Mytiloides hattini</i> Elder, <i>M. puebloensis</i> , <i>Puebloites?</i> sp., <i>Kanaboceras</i> sp., <i>Anisoceras</i> sp.	1	8 (50.8)
BASE TURONIAN			
86	Shale, gray, calcareous -----		
85	Limestone, gray, hard, massive; contains small pyritic spots and abundant pelagic Foraminifera, <i>Inoceramus pictus</i> -----	11	(27.9)
84	Shale, gray, calcareous -----	2	1 (63.5)
83	Bentonite, rusty -----	9	(22.9)
82	Shale, gray, calcareous -----	1	8 (50.8)
81	Bentonite, orange-gray -----	1	(2.5)
80	Limestone, gray, hard, massive. Contains a few <i>Inoceramus pictus</i> -----	3	(7.6)
79	Shale, gray, calcareous -----	6	(15.2)
78	Limestone, gray, nodular, hard, extremely irregular in thickness (3-6 in.); weathers light tan. Fossils sparse -----	6	(15.2)
	USGS D3974: <i>Sciponoceras</i> sp., <i>Euomphaloceras septemseriatum</i> (Cragin), <i>Worthoceras gibbosum</i> Moreman	2	0 (61)
77	Shale, gray, calcareous -----		
76	Limestone, gray, nodular, concretionary (commonly lensing out); may be as thick as 2 in (5.8 cm) -----	6	(15.2)
75	Shale, gray, calcareous -----	3	(7.6)
74	Limestone, gray, nodular, rather soft and unbedded; contains burrows as much as 1 in. in diameter. Thickness ranges from 3 to 6 in; USGS D4444: Echinoid, <i>Inoceramus pictus</i> Sowerby, <i>Sciponoceras gracile</i> (Shumard), <i>Camptonectes</i> sp., <i>Pseudocalycoceras</i> sp., <i>Euomphaloceras septemseriatum</i> (Cragin) -----	1	(2.5)
		7	(17.8)
73	Shale, gray, calcareous -----		
72	Bentonite -----	5	(12.7)
71	Shale, gray, calcareous -----	4	(10.2)
70	Bentonite, yellowish-orange, limonitic -----	1	(2.5)
69	Shale, gray, calcareous -----	2	(5.1)
68	Limestone, gray, hard, nodular, concretionary -----	7	(17.8)
	USGS D3973 and D6472: <i>Holaster feralis</i> Cooke, <i>Camptonectes</i> sp., Gastropods (sparse), <i>Hemiptychoceras reesidei</i> Cobban and Scott, <i>Sciponoceras gracile</i> (Shumard), <i>Allocrioceras annulatum</i> (Shumard), <i>Puebloites corrugatus</i> (Stanton), <i>Pseudocalycoceras angolaense</i> (Spath), <i>Euomphaloceras septemseriatum</i> (Cragin), <i>Metoicoceras geslinianum</i> (d'Orbigny)	9	(22.9)
67	Shale, gray, calcareous -----	6	(15.2)
66	Limestone, gray -----	6	(15.2)
65	Shale, gray, calcareous -----	2	(5.1)
64	Limestone, gray, hard, massive; weathers light gray and forms conspicuous ledge -----	3	(7.6)
63	USGS D3972 and D6473: <i>Inoceramus pictus</i> Sowerby, <i>Calycoceras</i> cf. <i>C. naviculare</i> (Mantell), <i>Metoicoceras</i> sp.	1	6 (45.7)
Total Bridge Creek Member (rounded) -----			
		57	0 17.4 meters

records from the sequence are not in dispute. There are, in contrast, differences in the planktic foraminiferan record between the results of Eicher & Diner (1985) and Leckie (1985), which we incorporated in the original submission and those in Keller & Pardo (2004) and Keller et al. (2004), and records in Caron et al. (in press). The latter also differ from those in Keller & Pardo (2004) and Keller et al. (2004). We are unable to resolve these differences, and in consequence retain our original conclusions, pending resolution of disparities in the planktic foraminiferan record in subsequent publications.

On this basis, the sequence of secondary markers, from lowest to highest, is:

1. The last occurrence of *Rotalipora greenhornensis* (Morrow) and *Rotalipora deekei* in the top 25 cm of the Hartland Shale, below Bed 63 of the Bridge Creek Member.
2. The first occurrence of the ammonite *Metoicoceras geslinianum* (d'Orbigny) at the base of bed 63, and last occurrence in bed 67 (geographic range: Wyoming, Montana, Utah, Colorado, Kansas, Arizona, New Mexico, and Texas in the United States; Mexico, southern England, France, Spain, Germany, Czech Republic, Iran (?), Angola, Nigeria, and, possibly, Morocco).
3. The last occurrence of *Rotalipora cushmani* (Morrow) in the thin bentonite layer 15 cm above the top of Bed 63.

Table 2 The Graneros Shale to Carlile Shale west of Pueblo, Colorado (modified after Scott, 1964).

Formation	Member	Thickness and lithology
Carlile Shale	Juana Lopez	0-0.6m (2ft) fetid calcarenite (dark shale)
	Codell Sst	9.15m (30ft) cliff forming sandstone
	Blue Hill Shell	30.8m (101 ft) dark grey, hard to soft blocky shale; sandy in upper half, with two layers of large septarian concretions
Greenhorn Limestone	Fairport Chalky Shale	30.2m (99 ft) grey to yellowish-brown soft bentonitic platy calcareous shale
	Bridcreek Limestone	15.8m (52ft) hard, grey, shaley weathering limestones, interbedded with soft calcareous shale and bentonite
	Hartland Shale	18m (59 ft) dark grey calcareous shales with thin layers of calcarenite and bentonite
	Lincoln Limestone	11.6 m (38 ft) grey limestone-shale alternations with bentonites
Graneros Shale		31.4 m (103 ft) dark-grey fissile soft to medium-hard non-calcareous shale with numerous bentonites

- The first occurrence of the ammonite *Euomphaloceras septemseriatum* (Cragin) is bed 67 and last occurrence in bed 77 (geographic range: Wyoming, Montana, Utah, Colorado, Kansas, Oklahoma, Arizona, New Mexico, and Texas in the United States; Mexico, southern England, France, Germany, Nigeria, Angola, Japan).
- The last occurrence of *Globigerinella bentonensis* (Morrow) near the base of Bed 68, 66 cm above the top of limestone Bed 63, and 40 cm above the last occurrence of *R. cushmani*.
- The *Heterohelix* shift in Bed 78, which marks dominance (~80%) of this low oxygen tolerant taxon and signals anoxic conditions. To date the *Heterohelix* shift has also been recognized in southern England, France and Tunisia.
- The first occurrence of the ammonite *Neocardioceras juddii* (Barrois & Guerne) in bed 79, and its last occurrence in bed 84 (geographic range: Montana, Colorado, Utah, New Mexico, Arizona, southern England, France, Germany, Czech Republic).
- The last occurrence of the bivalve *Inoceramus pictus* J. de C. Sowerby in bed 84 (geographic range: Wyoming, Montana, Utah, Colorado, Kansas, Oklahoma, Arizona, New Mexico, and Texas in the United States, England, France, Germany, Poland, Czech Republic, Russia, Kazakhstan, Madagascar).
- The first occurrence of the bivalve *Mytiloides hattini* Elder (Figure 7. 6–8, 10–15) in the top-most part of bed 84, and last occurrence in the lower part of Bed 99 (geographic range: Colorado, Kansas, Utah, and Arizona in the United States; Southern England, France, Spain, Portugal, Germany, Kazakhstan, Russia).
- The last occurrence of the nannofossil *Microstaurus chiastius* between beds 85 and 88.
- The primary marker: the first occurrence of the ammonite *Watinoceras devonense* Wright & Kennedy, 1981, in bed 86.
- The first occurrence of the bivalve *Mytiloides puebloensis* Walaszczyk and Cobban in bed 86, and last occurrence in bed 105 (geographic distribution Colorado, Kansas, New Mexico in the United States; Portugal).

- The first occurrence of the planktic foraminifer *Helvetoglobotruncana helvetica* (Bolli) in bed 89. (*H. prae-helvetica-helvetica* transitional forms occur in beds 85 and 87).
- The first occurrence of the bivalve *Mytiloides kossmati* (Heinz) in bed 90, and last occurrence in bed 105 (geographic distribution: Colorado, Utah, in the United States, Germany, Russia, Kazakhstan, Madagascar and Japan).
- The first occurrence of the ammonite *Mammites nodosoides* (Schlüter) in bed 101, and its last occurrence in bed 118 (geographic distribution: Montana, Wyoming, Utah, Colorado, South Dakota, Arizona, Kansas, New Mexico, Texas, in the United States; Mexico, England, France, Spain, Germany, the Czech Republic, Romania, Kazakhstan, Iran (?), Lebanon, Israel, Algeria, Tunisia, Morocco(?), Angola, Nigeria, Madagascar, Colombia, Venezuela, Peru, Brazil).
- The first occurrence of the bivalve *Mytiloides mytiloides* (Mantell) in bed 105 (geographic distribution: Montana, Wyoming, South Dakota, Kansas, Oklahoma, Colorado, Utah, Arizona, and New Mexico in the United States; Europe, Western Asia, Madagascar, Japan).
- Dodsworth (2000) has recently documented the dinoflagellate cyst biostratigraphy across the Cenomanian-Turonian boundary in the Pueblo section, and noted the disappearance of consistent/common *Litosphaeridium siphoniphorum* (Cookson and Eisenack) Davey and Williams in bed 73.
- The first occurrence of *Heterosphaeridium difficile* (Manum and Cookson) loannides in bed 95. These events have been correlated inter-regionally.

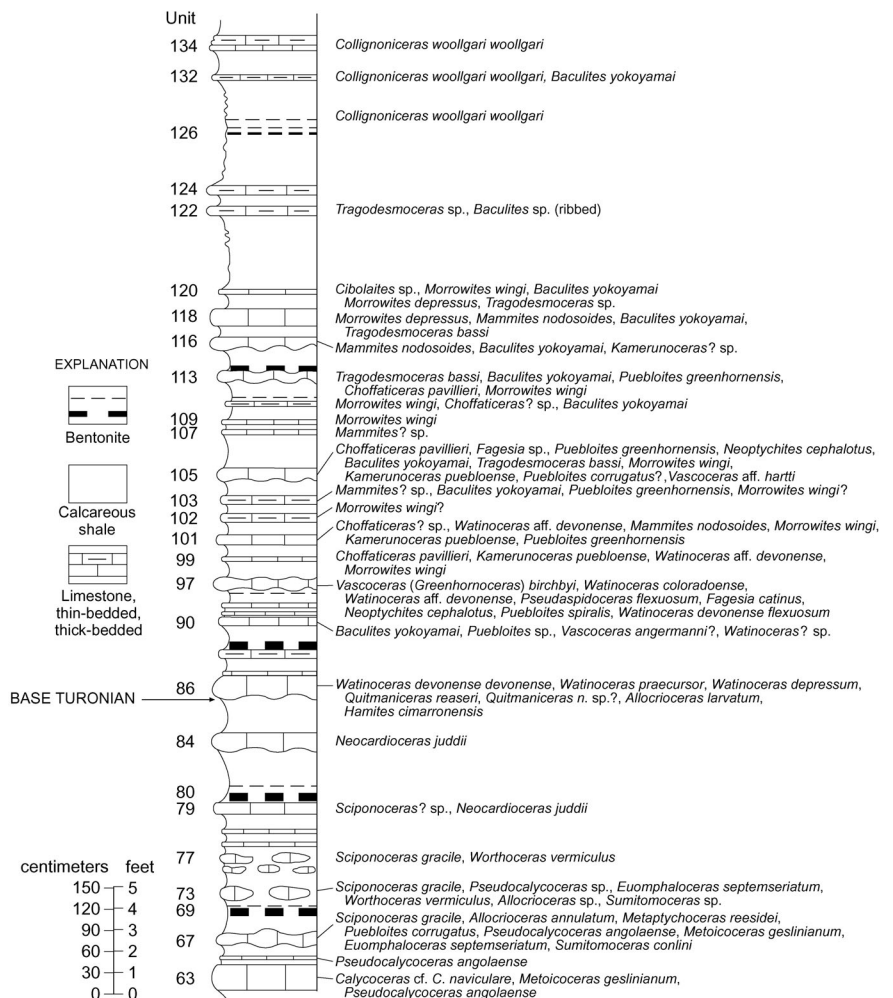


Figure 5 Lithological succession in the Bridge Creek Member of the Greenhorn Limestone on the north side of Pueblo Reservoir State Recreation Area, in sec. 25, T. 20S., R. 66W., with principal ammonite occurrences marked. The base of the Turonian Stage is drawn at the base of bed 86 (modified after Cobban & Kennedy, 1991).

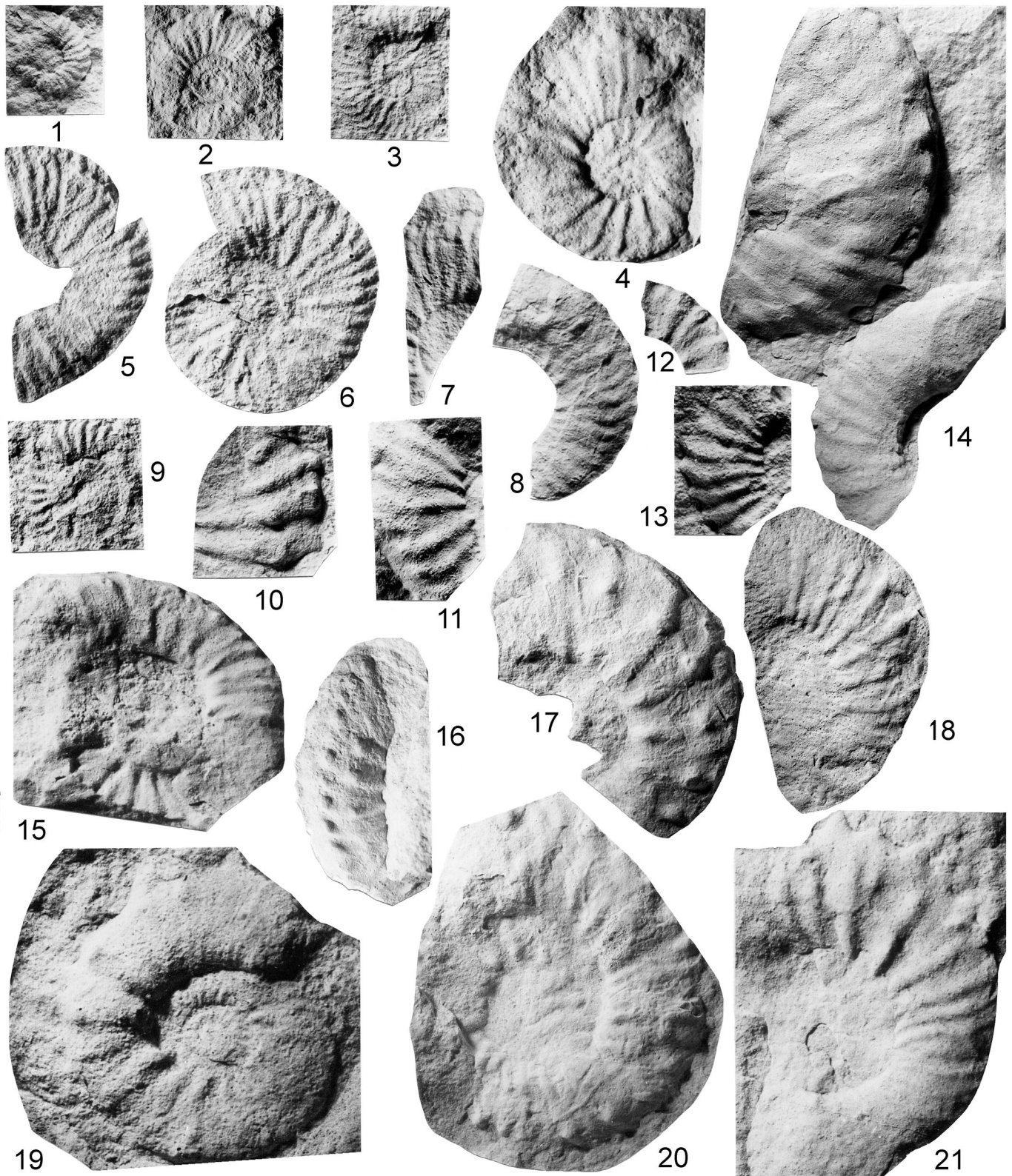


Figure 6 Ammonites from the *Watinoceras devonense* Zone fauna of bed 86 of the Bridge Creek Member of the Greenhorn Limestone. 1-4, 14-18, 20, 21. *Watinoceras praecursor* Wright & Kennedy, 1981. 1, USNM 441443, from locality D12715. 2, USNM 441441, from locality D12715. A latex cast. 3, USNM 441440, from locality D12715. A latex cast. 4, USNM 460750, from locality D12715. A latex cast. 14, USNM 460735, from locality D13246. 15, 16, USNM 460736, from locality D13246. 17, USNM 441438, from locality D6123. 18, USNM 442106, from locality D3975. A latex cast. 20, USNM 441442, from locality D12460. A latex cast. 21, USNM 460737, from locality D13246. 5-7, 12, *Watinoceras devonense devonense* Wright & Kennedy, 1981. 5, 6, USNM 441445, from locality D3975. Figure 5 is latex cast. 7, USNM 441447, from locality D3975. 12, USNM 441446, from locality D10176. 9-11, 13, 19, *Watinoceras depressum* Wright & Kennedy, 1981. 9, USNM 441450, from locality D12715. 10, USNM 441452, from locality D12715. 11, USNM 441451, from locality D12715. 13, USNM 441448, from locality D12715. 19, USNM 460749, from locality D12715. 8, *Quitmaniceras reaseri* Powell, 1963, USNM 441468, from locality D12715. All figures are original size.

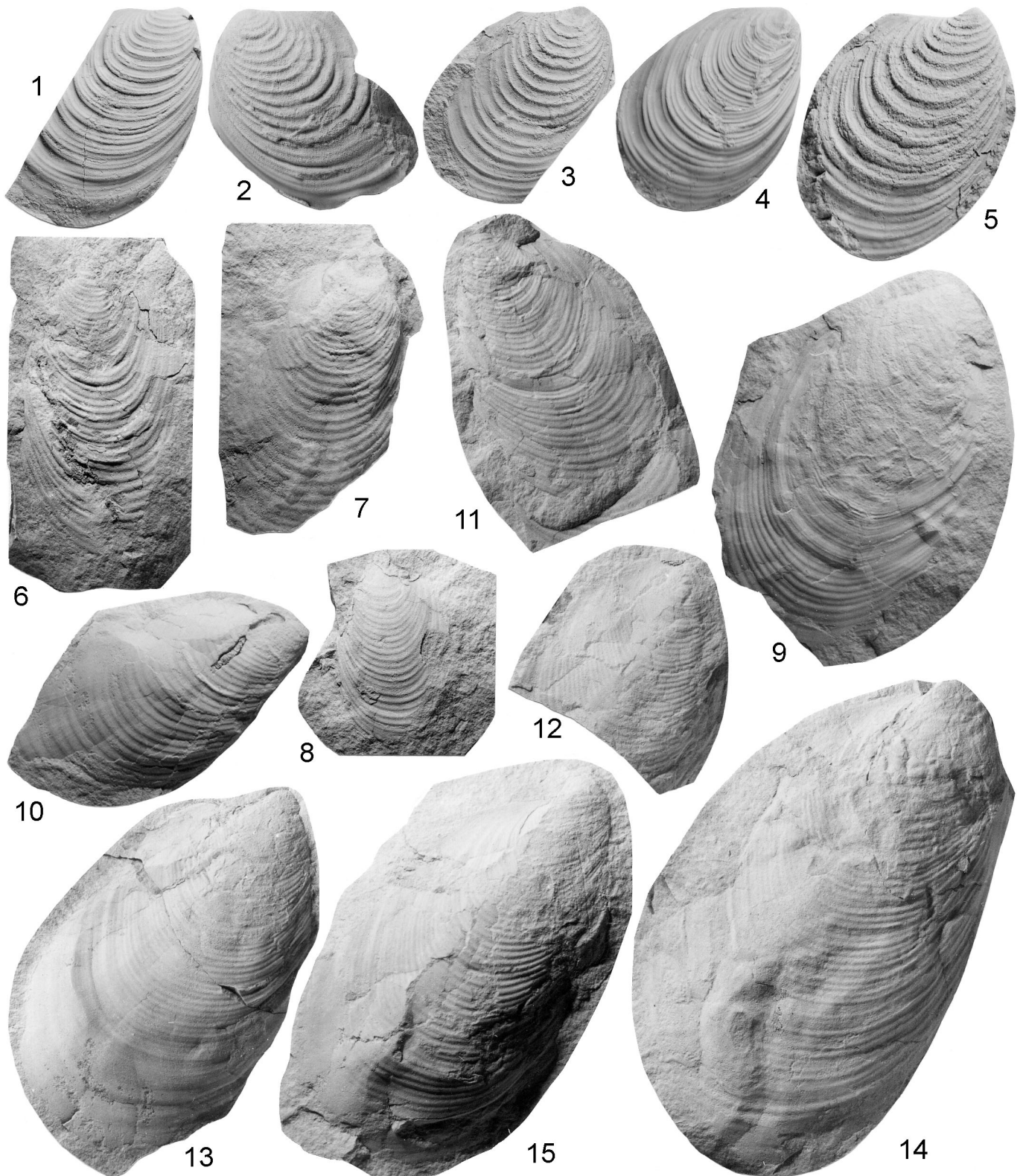


Figure 7 Mytiloides species that are key secondary markers for the base of the Turonian Stage in the Pueblo section. 1, 4–5, Lower Turonian *Mytiloides puebloensis* Walaszczyk and Cobban. 2–3, *M. goppelnensis* (Badillet and Sornay) from bed 97 of the Bridge Creek Member of the Greenhorn Limestone at USGS Mesozoic locality D6147, NW¹/₄, NW¹/₄, sec. 1, and NE¹/₄, NE¹/₄ sec. 2, T. 21S., R. 66W., Pueblo, Colorado. 1, USNM 441477; 2, USNM 441480; 3, USNM 441479; 4, USNM 441476; 5, USNM 441478. 6–8, 10–15, Lower Turonian *Mytiloides hattini* Elder. 9, *M. puebloensis* Walaszczyk and Cobban, from bed 86 of the Bridge Creek Member of the Greenhorn Limestone. 6, USNM 441470; 7, USNM 441469; 8, USNM 441471, all from USGS Mesozoic locality D3975, SW¹/₄, sec. 30, T. 20S., R. 65W., Pueblo County, Colorado. 9, USNM 507293; 13, USNM 507298; 15, USNM 507299, all from USGS Mesozoic locality D12460; 10, USNM 507294; 11, USNM 507295; 12, USNM 507296; 14, USNM 507752; from USGS Mesozoic locality D10176, in the center of sec. 25, T. 20S., R. 66W., Pueblo County, Colorado. All figures are original size.

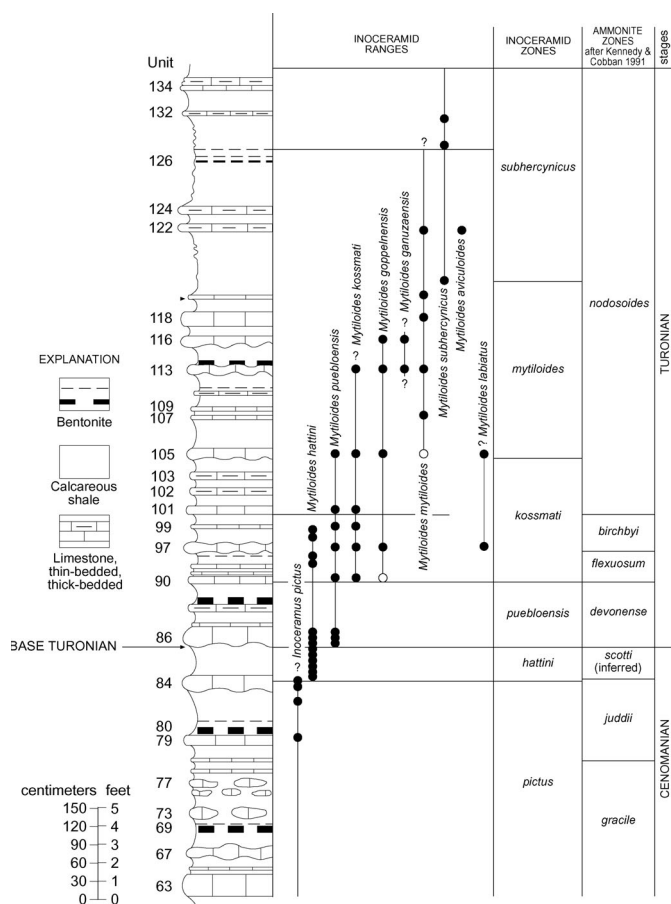


Figure 8 Lithological succession in the Bridge Creek Member of the Greenhorn Limestone on the north side of the Pueblo Reservoir State Recreation area, in sec. 25, T. 20S., R. 65W., with ranges of key inoceramid bivalves and zonation by Walaszczyk & Cobban in Kennedy et al. (2000); ammonite zones after Kennedy & Cobban (1991).

Stable isotope stratigraphy of the boundary interval

It is now well-established that the Cenomanian-Turonian boundary interval was characterized by abnormally high rates of burial of organic carbon in the marine realm, leading to a positive (heavy) carbon isotope excursion in the marine carbonate record that defines what has become known as an Oceanic Anoxic Event (OAEII) (Schlanger & Jenkyns, 1976; Jenkyns, 1980; Schlanger et al., 1987; Scholle & Arthur, 1980; Tsikos et al., 2004).

This anoxic event and corresponding positive (heavy) excursion in carbon stable isotope excursion was first demonstrated in the Pueblo sequence by analysis of a core drilled within the Pueblo Recreation area in the NW1/4 NW1/4 NE1/4 Sec. 31, T. 20S., R. 65W. (Figure 2), and comprehensively documented by Pratt (1981, 1983, 1984, 1985) and discussed by Pratt, Kauffman & Elder (1983), Pratt & Threlkeld (1984), Elder (1985, 1987), Arthur, Dean and Pratt (1988), Gale et al. (1993), Accarie et al. (1996) and others. High resolution carbon isotope analysis was recently conducted on the planktic foraminifer *Hedbergella planispira* (Keller et al., 2004).

$\delta^{13}\text{C}_{\text{org}}$ (PDB) data published in Gale et al. (2005) are plotted against the log of the Cenomanian-Turonian boundary interval in Figure 10. It will be seen that the base of bed 86 falls immediately below the third positive peak in the curve.

It is now known that expanded Cenomanian-Turonian boundary sections in pelagic facies in other parts of the Western Interior (e.g. Pratt, 1985; Pratt, Arthur, Dean & Scholle, 1993), in southern England (Gale et al., 1993; Paul et al., 1999; Keller et al., 2001;

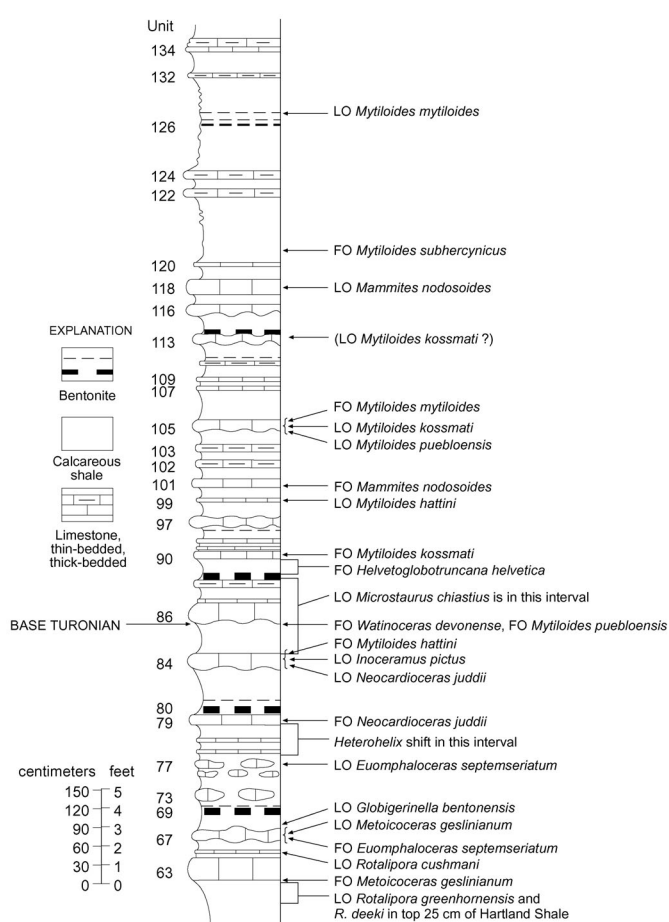


Figure 9 The primary and secondary markers for the base of the Turonian Stage, plotted on the outcrop section of the GSSP in the cut at the western end of the Denver and Rio Grande Western Railway north of the Pueblo State Reservoir Recreation Area. LO = last occurrence ; FO = first occurrence.

Tsikos et al., 2004), northern Spain (Paul et al., 1994), northern Tunisia (Accarie et al., 1996) and Japan (Hagesawa, 1995) preserve similarly ornate excursion, and that peaks and troughs in the curve can be correlated between sections (Gale et al., 1993). This is demonstrated in Figure 10, which compares the curve from Pueblo with that from Eastbourne, Sussex, England (after Gale et al., 2005).

Radioisotopic dating of the boundary interval

No less than four prominent bentonites occur in the boundary interval, as well as a number of minor bentonitic levels. Integration of biostratigraphy, lithostratigraphy and chemostratigraphy show these bentonites to be widely recognisable throughout the U.S. Western Interior. We have failed to obtain satisfactory dates from the Pueblo section where the bentonites are thin and weathered, but correlative bentonites in Arizona and Nebraska have provided $^{40}\text{Ar}/^{39}\text{Ar}$ ages that can be tied to the coeval bentonites in the Pueblo section; identifying numbers in parentheses correspond to those in Obradovich (1993). From oldest to youngest:

(22) Marker bed BM5, 0.9 m bentonite, 5.7 m above base of Mancos Shale (lower calcareous shale member), Lohali Point, Black Mesa, NE Arizona (Kirkland, 1991, 1996), corresponding to bed 64 at Pueblo. 93.90 ± 0.72 Ma.

(21) Marker bed BM6, 22.5 cm bentonite 6.8 m above base of Mancos Shale (lower calcareous shale member), Lohali Point, Black Mesa, NE Arizona (Kirkland, 1991, 1996), corresponding to bed 69 at Pueblo. 93.49 ± 0.89 Ma.

- (20) Bentonite in upper third of *Neocardioceras juddii* Zone in sec. 33, T. 31N., R. 20W., Rocky Point Quadrangle, San Juan County, New Mexico, correlated with bed 80 at Pueblo. 93.78 ± 0.49 Ma; 93.59 ± 0.58 Ma.
- (20) Bentonite in Greenhorn Limestone Member, corresponding to HL3 marker bed of Hattin (1975) and Bed 80 at Pueblo; Alexandria Quadrangle, Little Blue River, in NE1/4 Sec. 5, T. 2N., R. 1N, Thayer County, Nebraska. 93.30 ± 0.4 Ma.
- (19) Marker bed BM15, 0.6 m bentonite, 6.4 m above base of Mancos Shale (lower calcareous shale member), Lohali Point, Black Mesa, NE Arizona (Kirkland, 1991, 1996), corresponding to bed 88 at Pueblo. 93.25 ± 0.5 Ma.
- (18) Marker bed BM17, 0.16 m bentonite, 25 m above base of Mancos Shale (lower calcareous shale member), Lohali Point, Black Mesa, NE Arizona (Kirkland, 1991, 1996), corresponding to bed 96 at Pueblo. 93.40 ± 0.63 Ma.

These radiometric dates are plotted onto Figure 10.

On the basis of these data, Obradovich (1993) dated the Cenomanian-Turonian boundary at 93.3 ± 0.2 Ma; note that dates around the boundary level are not without problems, as discussed by Obradovich. Kowallis et al. (1995) dated the boundary at 93.1 ± 0.3 Ma.

Conclusions

The proposed Global Boundary Stratotype Section and Point for the base of the Turonian Stage near Pueblo, Colorado fulfils the following requirements set out by Remane et al. (1996):

- Exposures extend over an adequate thickness, and the boundary is well defined by both primary and secondary (auxiliary) biostratigraphic markers.
- The Pueblo section can be traced laterally over several kilometers distance.
- The pelagic, climatically driven, rhythmically bedded Milankovitch sequence shows no evidence for gaps or for condensation in the proximity of the proposed boundary. (Meyers, Sageman & Hinnov, 2001) analysed the sequence in the No. 1 Portland core numerically, and concluded that there is a hiatus in the lower part of bed 78, of an estimated 25,000 years duration. These authors noted that this proposed hiatus is not readily apparent in the core, or at outcrop in the Pueblo area. The proposed hiatus lies in the lower part of a shale unit, within the *Neocardioceras juddii* Zone, and well below the GSSP at the base of bed 86. It does not compromise the GSSP. Meyers et. al found no other evidence for hiatus within the sequence.
- The rate of sedimentation is sufficiently high that the successive biostratigraphic and isotopic events used as secondary markers are clearly separated.
- There is no syndimentary or tectonic disturbance in the boundary interval.
- Neither metamorphic nor strong diagenetic alteration of the boundary sequence has occurred.
- There is a well-preserved abundant and diverse fossil record across the boundary interval, with key markers for uppermost Cenomanian and Lower Turonian intercontinental biostratigraphic correlation: ammonites, inoceramid bivalves, planktic forams, dinoflagellates, and nannofossils well-represented.

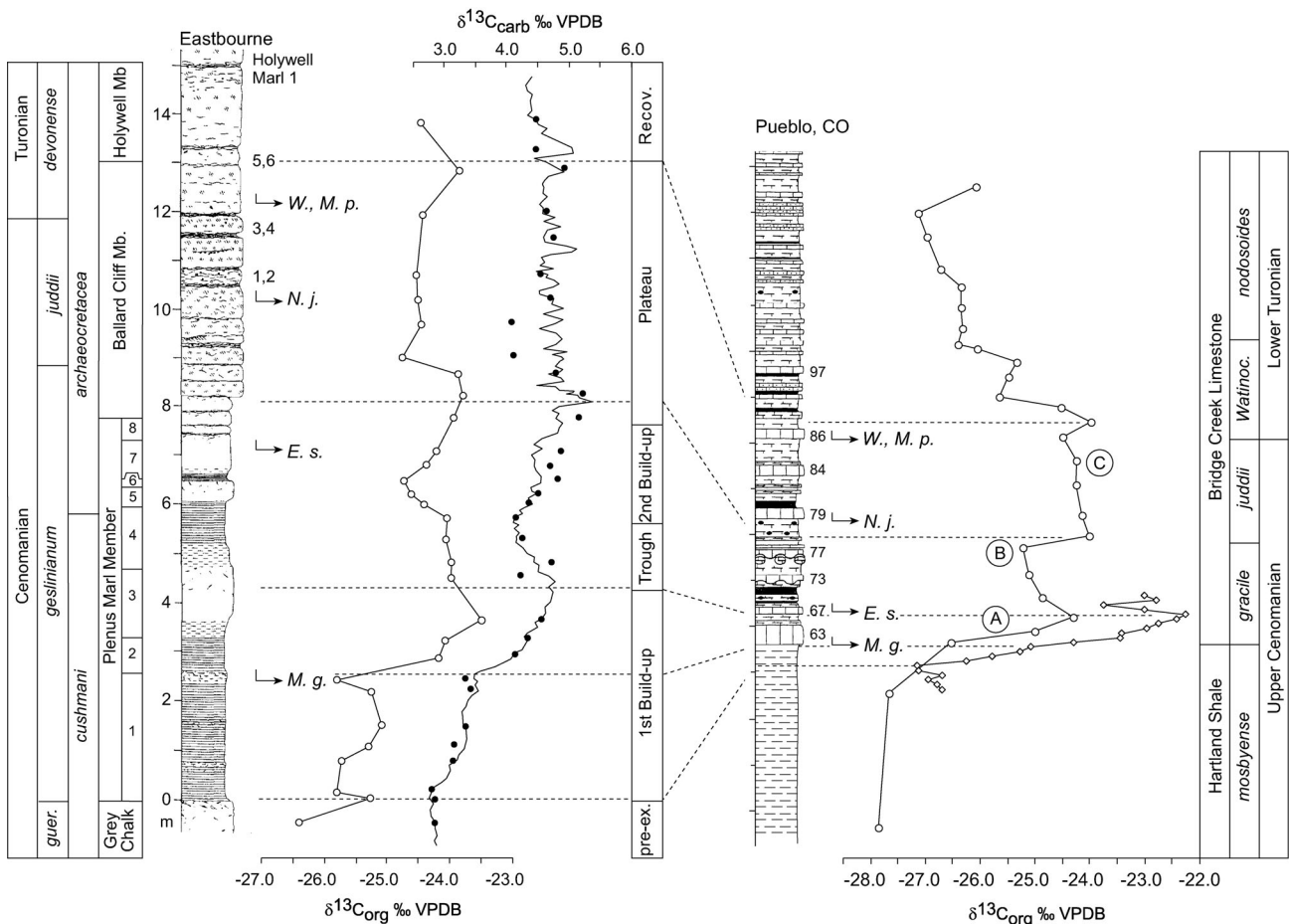


Figure 10 Stable isotope curves and correlation of the Cenomanian-Turonian boundary interval at Pueblo, Colorado and Eastbourne, Sussex, from Gale et al. (2005). The carbon isotope stratigraphy is based on Pratt & Threlked and Gale et al. Macrofossil markers are: *M.g.* – first occurrence of the ammonite *Metoicoceras geslinianum*; *E.s.* – first occurrence of the ammonite *Euomphaloceras septemseriatum*; *N.j.* – first occurrence of the ammonite *Neocardioceras juddii*; *W., M.p.* – first occurrence of the ammonites *Watinoceras spp.*, and the bivalve *Mytiloides puebloensis*. $^{40}\text{Ar}/^{39}\text{Ar}$ ages for correlative bentonites that straddle the base of the Turonian elsewhere in the U.S. Western Interior, from Obradovich (1993) are: Bed 80: 93.3 ± 0.4 Ma, 93.59 ± 0.58 Ma; Bed 88: 93.25 ± 0.55 Ma.

- There are no prominent facies changes across the boundary levels other than the hemipelagic limestone/marl alternations typical of rhythmically bedded Milankovitch sequences.
- The offshore pelagic Milankovitch facies is ideal for long-distance lithostratigraphic correlation, and this is enhanced by the presence of bentonite horizons.
- The presence of bentonites straddling the boundary level provides a theoretical basis for direct numerical calibration of the boundary. This has not been achieved at Pueblo owing to the thinness of the bentonite beds, but coeval bentonites elsewhere in the U.S. Western Interior allow indirect dating of the base of the Turonian Stage.
- We have no information on the magnetostratigraphy of the sequence, although it is well-known that the Turonian Stage falls within the Cretaceous Quiet Interval.
- The $\delta^{13}\text{C}$ excursion across the Cenomanian-Turonian boundary interval has been recognized on a near world-wide basis in both continental and oceanic contexts. The $\delta^{13}\text{C}_{\text{org}}$ (PDB) profile of the section including the GSSP for the base of the Turonian is ornate, with well-defined peaks and troughs that can be precisely located with respect to no less than 15 secondary biostratigraphic markers. The curve for an expanded Cenomanian-Turonian boundary interval in pelagic chalk facies at Eastbourne, Sussex, England, more than 8000 km east of the GSSP has a similarly ornate profile, and secondary biostratigraphic marker events occur in both sections in the same relative order, and in the same relative position to the peaks and troughs in the $\delta^{13}\text{C}_{\text{org}}$ (PDB) curves, indicating that biostratigraphic and isotopic markers were synchronous in the two widely separated locations (Gale et al., 1993, 2005).

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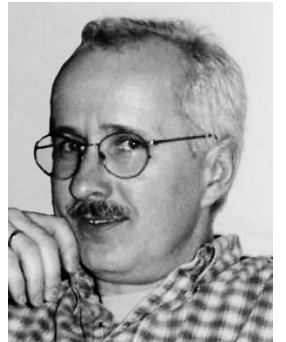
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