A New Stratigraphy for the Pierre Shale at the Cedar Creek Anticline, Montana*

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Abstract

The Cedar Creek Anticline (CCA) is an asymmetrical, plunging, northwest-trending fold at the southwest edge of the Williston Basin. It stretches from the northwest corner of South Dakota through the southwest corner of North Dakota to the Yellowstone River in east central Montana. It is complex and difficult to understand, attributed to several major geological events beginning in the Devonian and culminating in the early to mid-Paleogene. Most of the stratigraphic research at the anticline has been focused on subsurface, petroleum-bearing layers. However, there is also a fascinating surface exposure of Cretaceous Pierre Shale (and layers above) that has attracted research as far back as the 1850s with F. Hayden and others. Although the basic stratigraphy of the Pierre at Red Bird, Wyoming, the CCA, and elsewhere was worked out more than 50 years ago by James Gill, Bill Cobban, Gale Bishop, and others prior to them, many questions and uncertainties have remained due to extensive slumping of the Pierre, variation from site to site, and the paucity of index fossils at key points. We, with early mentorship from Bill Cobban, including in the field, have continued studying the Pierre at the CCA for over 30 years and at more than 120 sites, focused on the northwest fifth of the CCA. Accumulated and recent findings of a sufficient number of critical specimens have permitted us to refine the stratigraphy, including a precise placement of the Campanian-Maastrichtian boundary. The new findings also allow us to more accurately describe the marine paleoenvironments associated with the new stratigraphy and better place this region into the larger context of the Cretaceous Western Interior Seaway. We also comment on the present-day geomorphology of the CCA and how it might have attained its modern form.

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American Museum of Natural History

NDSU NORTH DAKOTA STATE UNIVERSITY

EARLY EARTH ENTERPRISES

Larson PALEONTOLOGY UNLIMITED

AMERICAN MUSEUM OF NATURAL HISTORY

Presented at the AAPG RM Section Annual Meeting, 16 Sept 2019, Cheyenne, WY. This version modified for online publication for clarity, addition of a few narrative statements for context, and to condense series of points from sequential slides to single slides to reduce space.

Disclaimer

Although "new", any given stratigraphy is rarely final but merely the latest step of an ongoing process.

As Cobban et al. (2006) said in the first three words of the introduction to their USGS Zonal Table for the Upper Cretaceous Middle Cenomanian-Maastrichtian of the Western Interior of the United States:

"This **provisional** table ..." (emphasis ours).

Dedication

This presentation is part of a Tribute to Bill Cobban and his Contributions to Stratigraphy. We dedicate this presentation to Bill, who mentored us and assisted us in the field at the Cedar Creek Anticline (CCA), and to Gale Bishop who constructed the foundational stratigraphy of the exposed Pierre Shale at the Cedar Creek Anticline and upon which our work has been based.

Coauthors, left to right: Joyce Grier, Neil Landman, and Tom Linn, in the field at the Cedar Creek Anticline, eastern Montana

Coauthors continued: Neal Larson, Neil Landman, and Joyce Grier (far right) with Bill Cobban (second from right) at USGS facilities, Denver, Colorado. Jim Grier not shown (taking the photos).

Bill Cobban mentoring Joyce and Jim (not shown/taking photos) in the field in Colorado and in his office and collections at the Denver Federal Center in Building 810.

Bill Cobban at the Cedar Creek Anticline, MT, collecting fossils and assisting the Griers. He often combined these trips to the anticline with Montana trout fishing, one of his favorite pastimes.

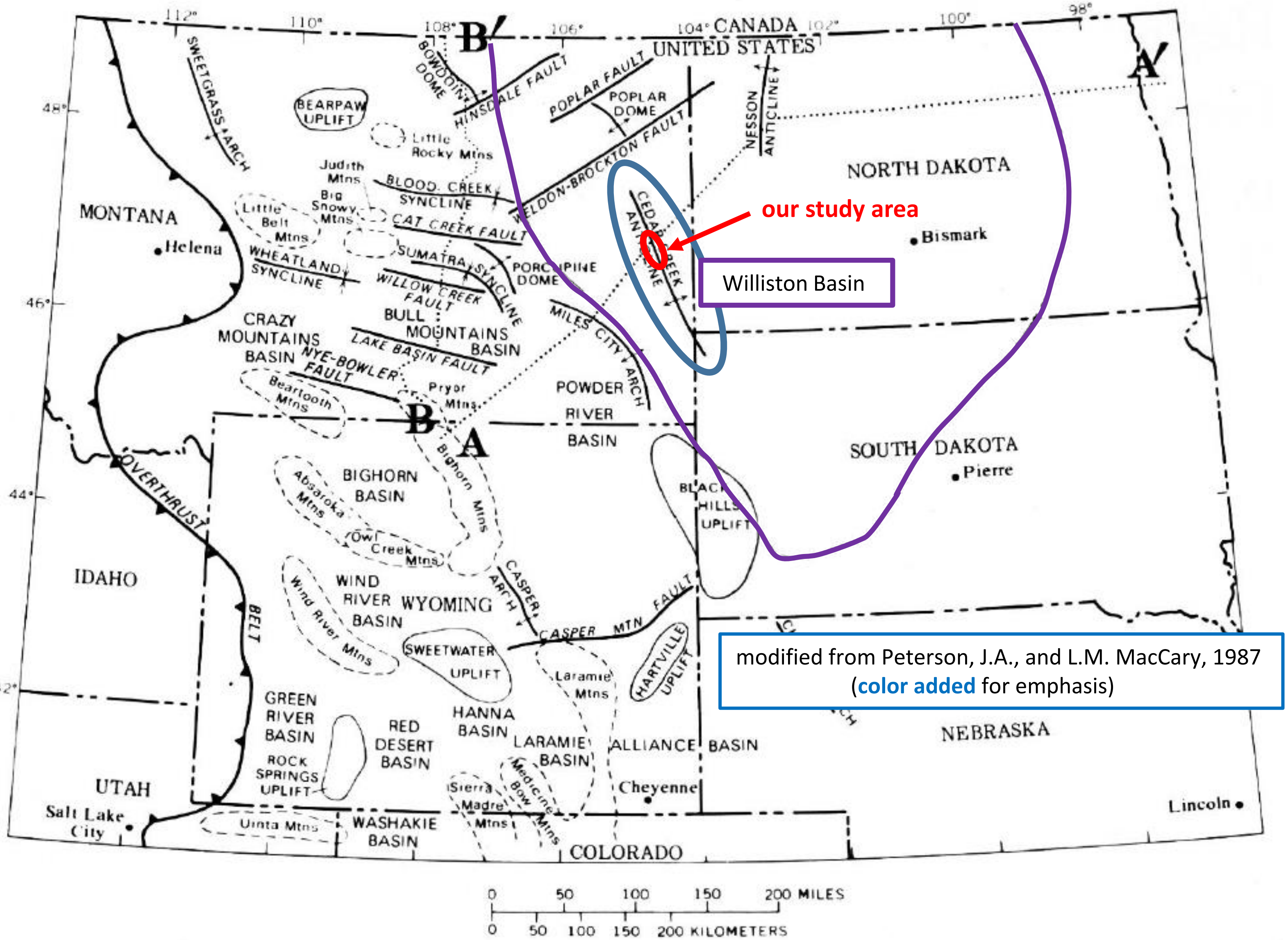
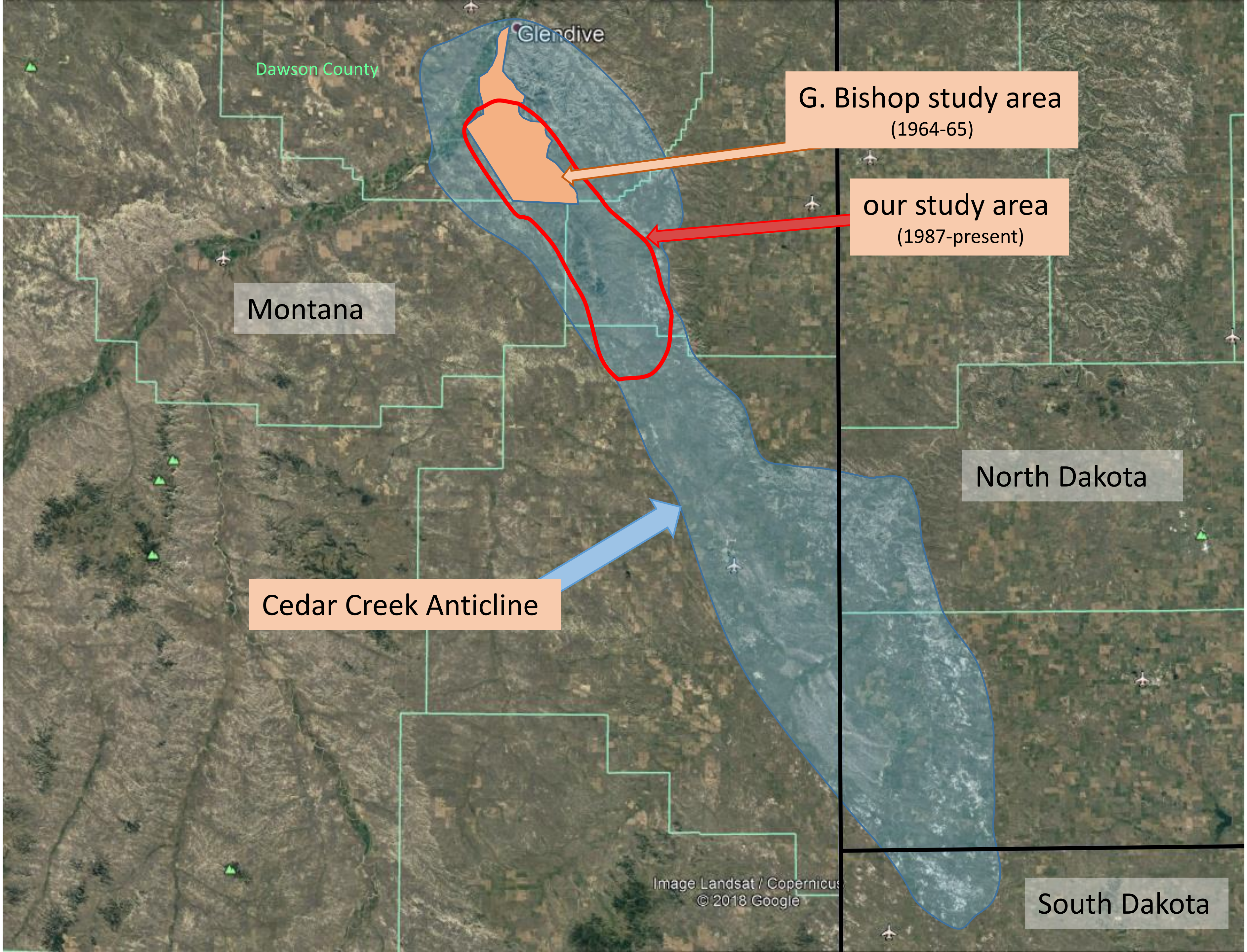
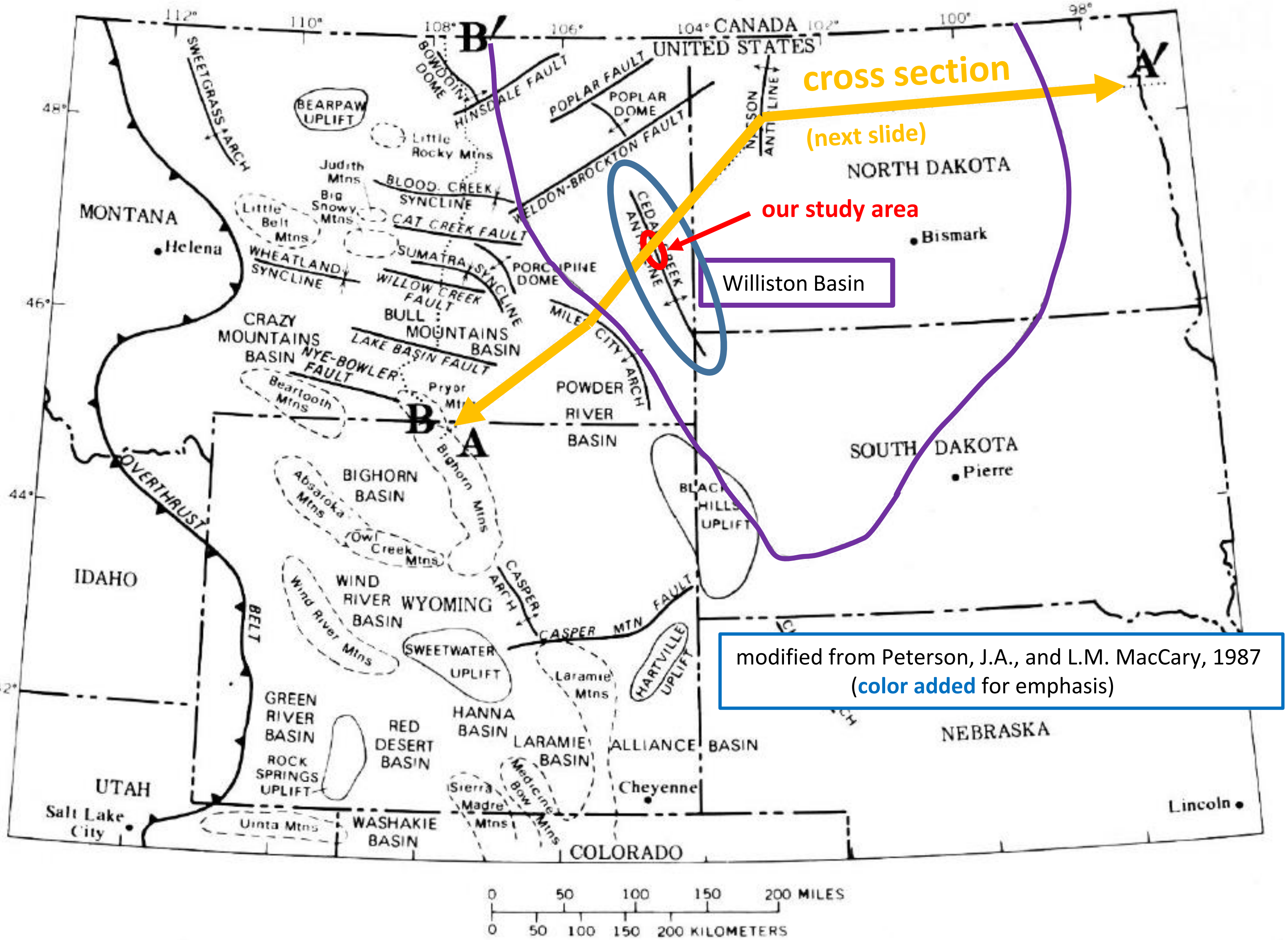


FIGURE 1. Present-day structural features, Western Interior, United States. Lines of cross sections A–A′ and B—B′ of Figures 5 and 8 are shown. Modified after Peterson (1981, 1984b).



Glendive
Dawson County
G. Bishop study area
(1964-65)
our study area
(1987-present)
Montana
North Dakota
Cedar Creek Anticline
South Dakota
Image Landsat / Copernicus
© 2018 Google



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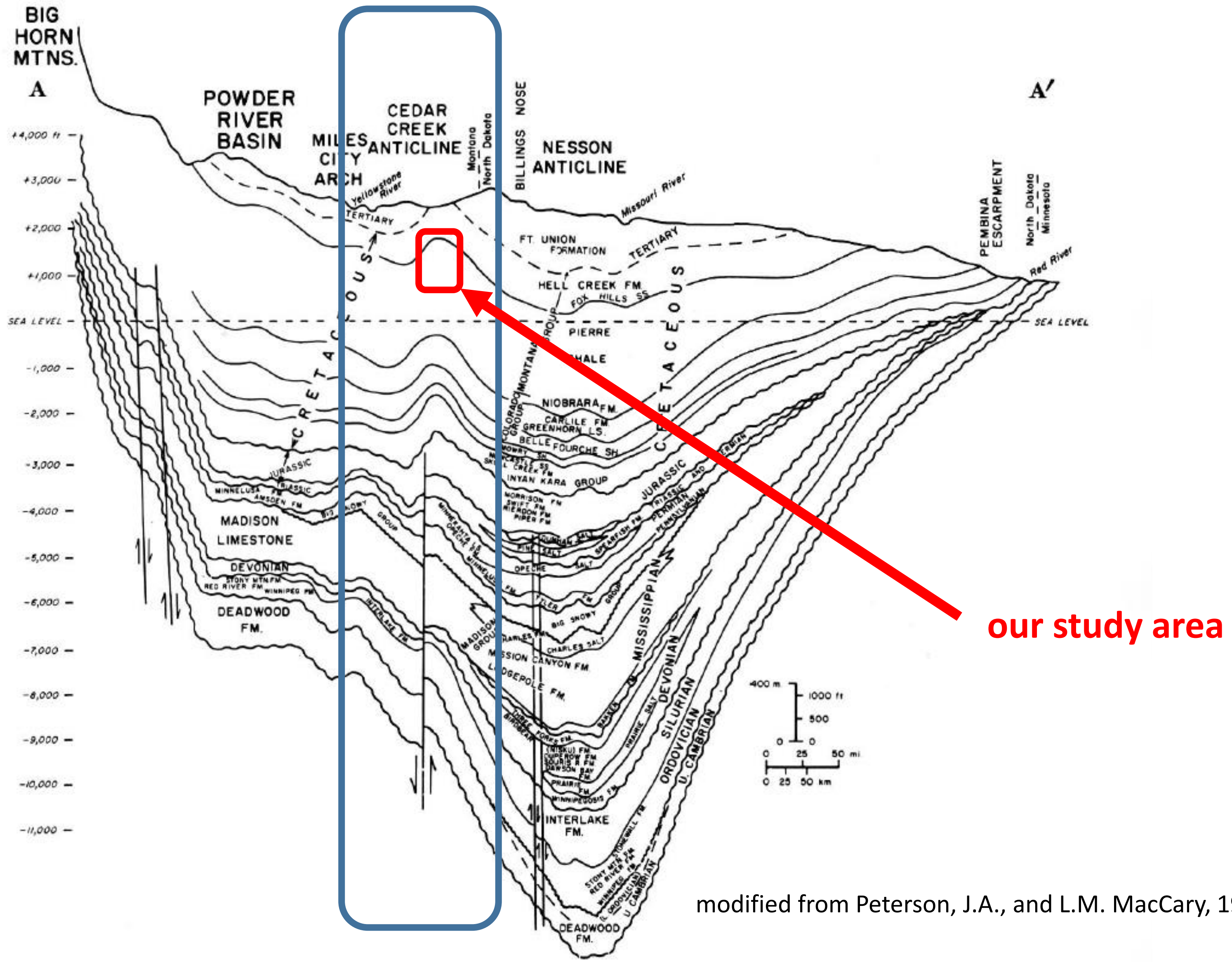
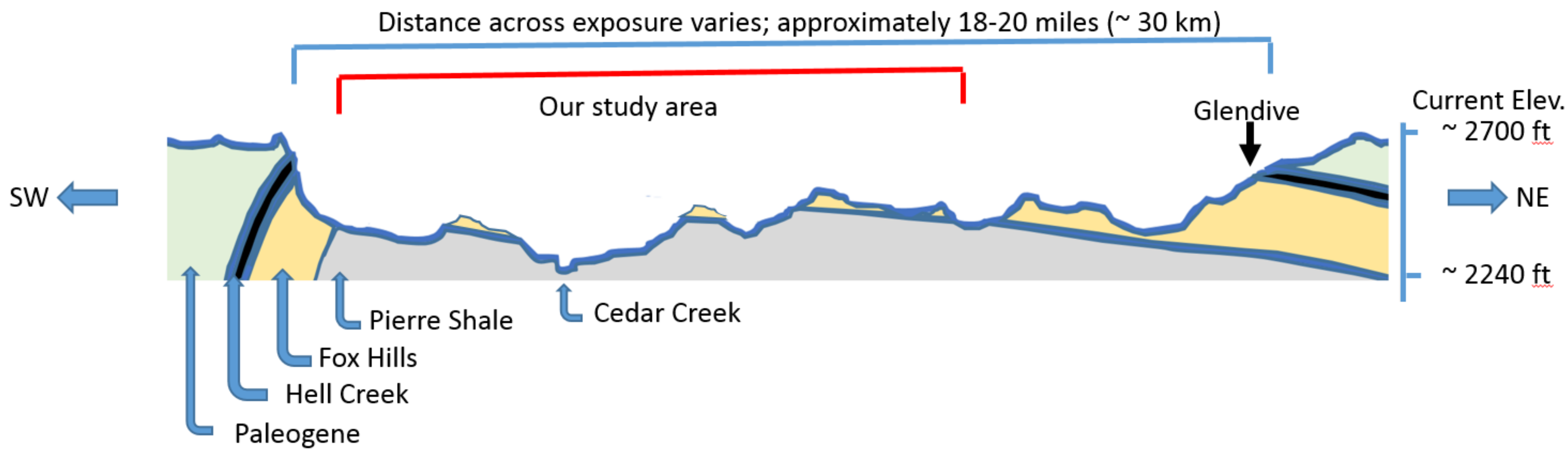


modified from Peterson, J.A., and L.M. MacCary, 1987

FIGURE 5. Generalized west–east structural–stratigraphic cross section A–A′, Bighorn Mountains, Wyoming, to northeastern North Dakota. Line of cross section is shown on Figures 1 and 6.

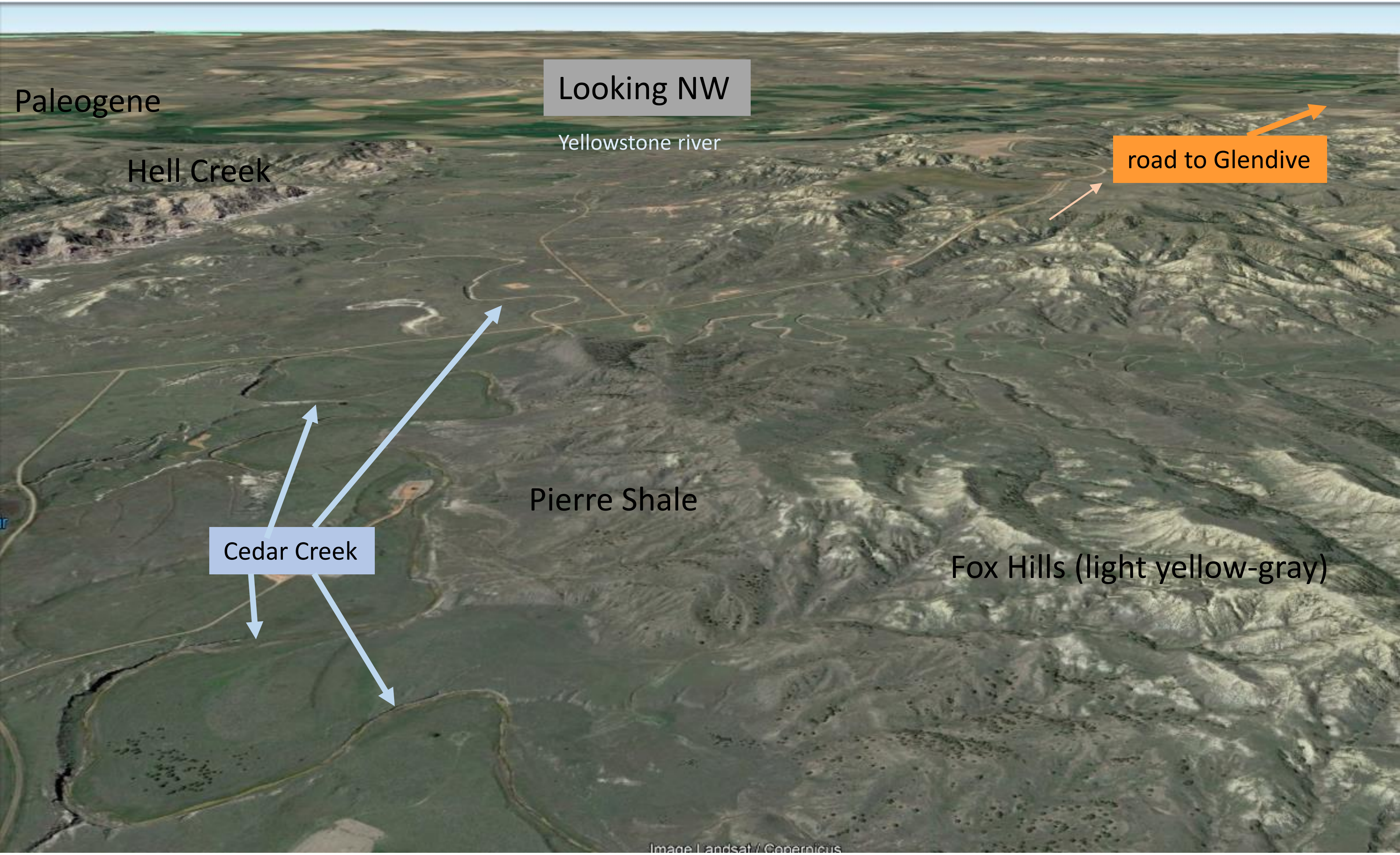
Cedar Creek Anticline cross section, looking from SE towards NW

Heavily eroded with some faulting and much slumping



J.W. Grier

Study area, northwestern portion



(Google Earth tilt view)

Boundary between the Fox Hills and Pierre Shale formations (at the CCA)

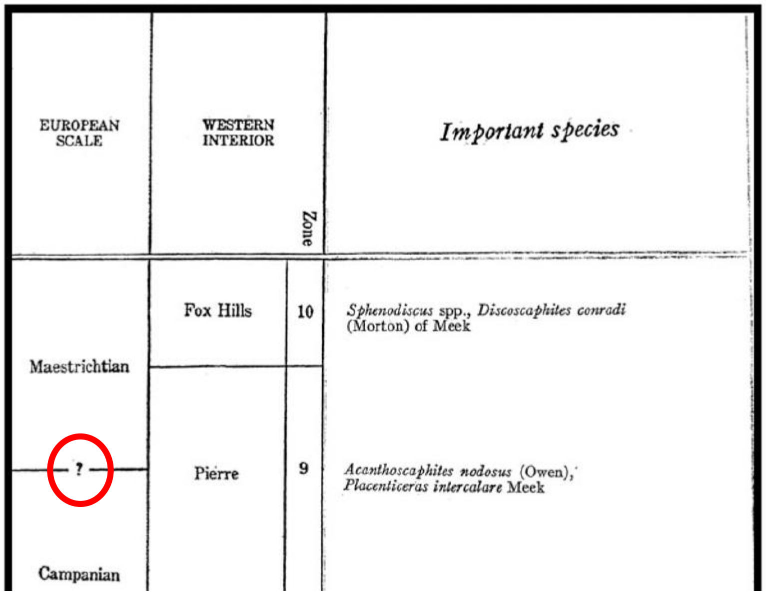
Two ongoing issues for the Western Interior Pierre Shale ammonites in the Upper Campanian and Lower Maastrichtian as exposed at the Cedar Creek Anticline (and elsewhere)

1. Precise identification/location of the Campanian-Maastrichtian boundary has remained unknown

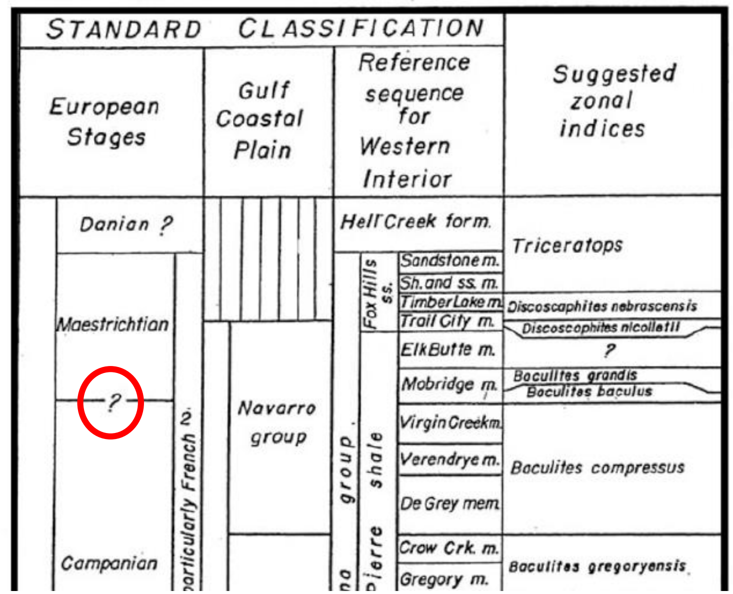
2. *Baculites baculus* – *B. grandis* boundary has been unclear

For examples of the Camp-Maastr boundary problem:

First, what are the index species?



Stephenson and Reeside 1938, Reeside 1944



Cobban and Reeside 1952

excerpt from Riccardi 1983

CAMPANIAN-MAASTRICHTIAN BOUNDARY

The Bearpaw Formation probably ranges from as low as the Zone of **Didymoceras stevensoni** to as high as the Zone of **Baculites grandis.**

Accepting Jeletzky's (in Cobban and Reeside, 1952, and 1968) positioning of the Campanian-Maastrichtian boundary at the base of the **Baculites baculus** Zone, most of the Bearpaw Formation could be Late Campanian, although the uppermost levels of southern Saskatchewan could be Early Maastrichtian.

Cobban's (see Obradovich and Cobban, 1975; North and Caldwell, 1975a, p. 329) placing of the boundary at the base of the **Baculites reesidei** Zone would imply that the Bearpaw Formation is about equally divided between the latest Campanian and the earliest Maastrichtian. When K-Ar age data on bentonites (see Obradovich and Cobban, 1975, Table 1) are compared with van Hinte's (1976) Cretaceous time scale the boundary should be located between the **Baculites compressus** and the **B. cuneatus** Zones and most of the Bearpaw Formation would be lower Maastrichtian.

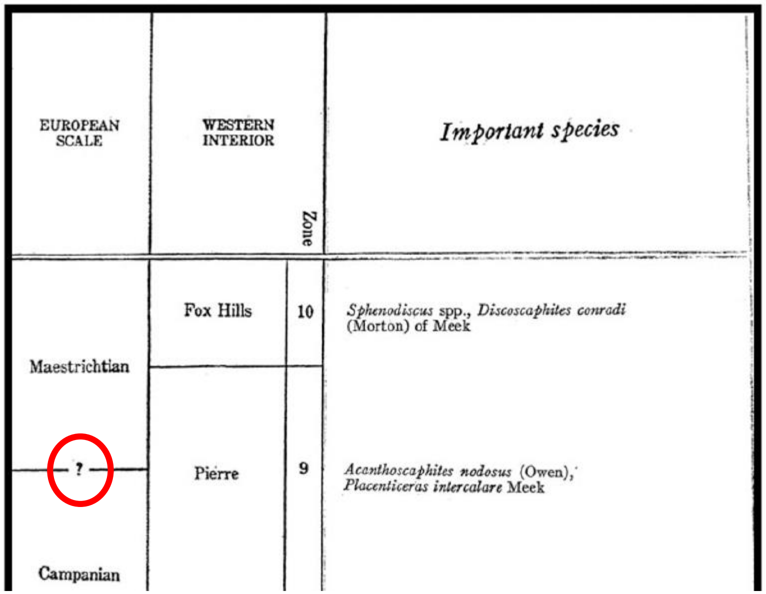
?

All these data indicate that the scaphitids here described probably range in age from the late Campanian to the early Maastrichtian. The apparent relationships and similarities of these specimens with the Eurasian scaphitids also substantiate this age range. A more detailed discussion of the Campanian-Maastrichtian boundary in North America must include all other stratigraphic information available to date, and is beyond the scope of this paper.

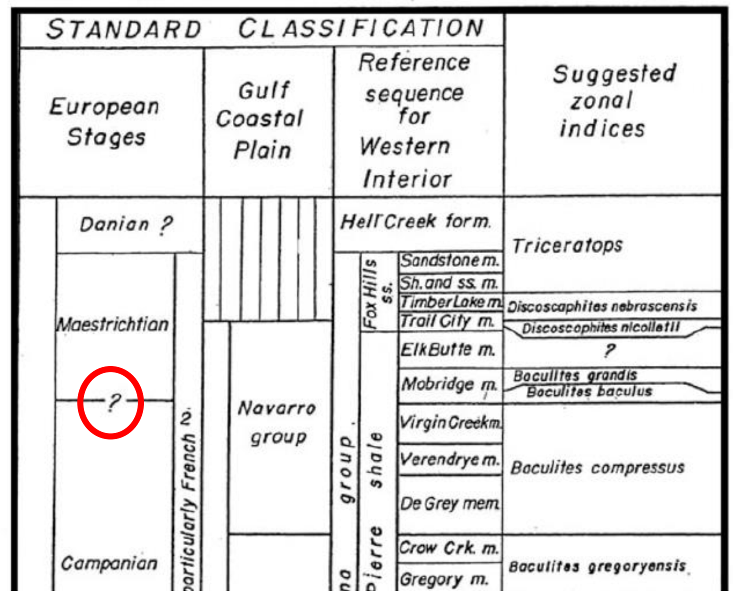
(The Bearpaw formation is equivalent to and lies west and north of the upper part of the Pierre Formation)

For examples of the Camp-Maastr boundary problem:

First, what are the index species?



Stephenson and Reeside 1938, Reeside 1944



Cobban and Reeside 1952

For more examples and discussion, see Cobban et al. 2006

The index-species issue was settled by Gill and Cobban 1966 and Cobban et al. 2006 (next slide).

USGS Open-File Report 2006-1250

Figure 1 A USGS Zonal Table for the Upper Cretaceous Middle Cenomanian - Maastrichtian of the Western Interior of the United States Based on Ammonites, Inoceramids, and Radiometric Ages

William A. Cobban, John D. Obradovich, Ireneusz Walaszcyk, and Kevin C. McKinney

Stages and Substages	[1]Europe	Western Interior Informal Substages	[2]Stage Boundaries Ma	Western Interior Ammonite Taxon Range Zones	Age Ma	Western Interior Inoceramid Interval Zones
			[9]65.5 ± 0.30		[9]65.51 ± 0.10	
Maastrichtian	Upper					
				Jeletzkytes nebrascensis		
				Hoploscaphites nicolletii		
				Hoploscaphites birkelundae		
	Lower			*Baculites clinolobatus*	69.59 ± 0.36	*"Inoceramus" balchii*
				Baculites grandis	70.00 ± 0.45	*Trochoceramus radiosus*
				Baculites baculus		*"Inoceramus" incurvus*
						Endocostea typica
			70.6 ± 0.6			
Campanian	Upper	Upper		*Baculites eliasi*	71.98 ± 0.31	*"Inoceramus" redbirdensis*
				Baculites jenseni		*"Inoceramus" oblongus*
				Baculites reesidei	[11]72.94 ± 0.45	
				Baculites cuneatus		*"Inoceramus" altus*
				Baculites compressus	[8]73.52 ± 0.39	
				Didymoceras cheyennense	74.67 ± 0.15	
				Exiteloceras jenneyi	[8]75.08 ± 0.11	*Sphaeroceramus pertenuiformis*
				Didymoceras stevensoni		
				Didymoceras nebrascense	75.19 ± 0.28	*"Inoceramus" tenuilineatus*
				Baculites scotti	[10]75.56 ± 0.11 75.84 ± 0.26	
				Baculites reduncus		
				Baculites gregoryensis		
				Baculites perplexus		

USGS Open-File Report 2006-1250

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				Baculites grandis	70.00 ± 0.45	*Trochoceramus radiosus*
				Baculites baculus	*	*"Inoceramus" incurvus* *Endocostea typica*
Campanian	[1]Europe	Western Interior Informal Substages	Note: 70.6 ± 0.6			
		Upper		*Baculites eliasi*	71.98 ± 0.31	*"Inoceramus" redbirdensis*
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	Upper			*Baculites scotti*	[10]75.56 ± 0.11 75.84 ± 0.26	
				Baculites reduncus		
				Baculites gregoryensis		
				Baculites perplexus		

*date not shown for *B. baculus*, **also cf. 3 slides below**

BUT, where on the ground is the Camp-Maastr. boundary???

This has been an ongoing puzzle at many places (globally)!

(and ... if, in fact, a distinct boundary
exists ... we'll return to this point later)

Chapter | 27 Cretaceous 807

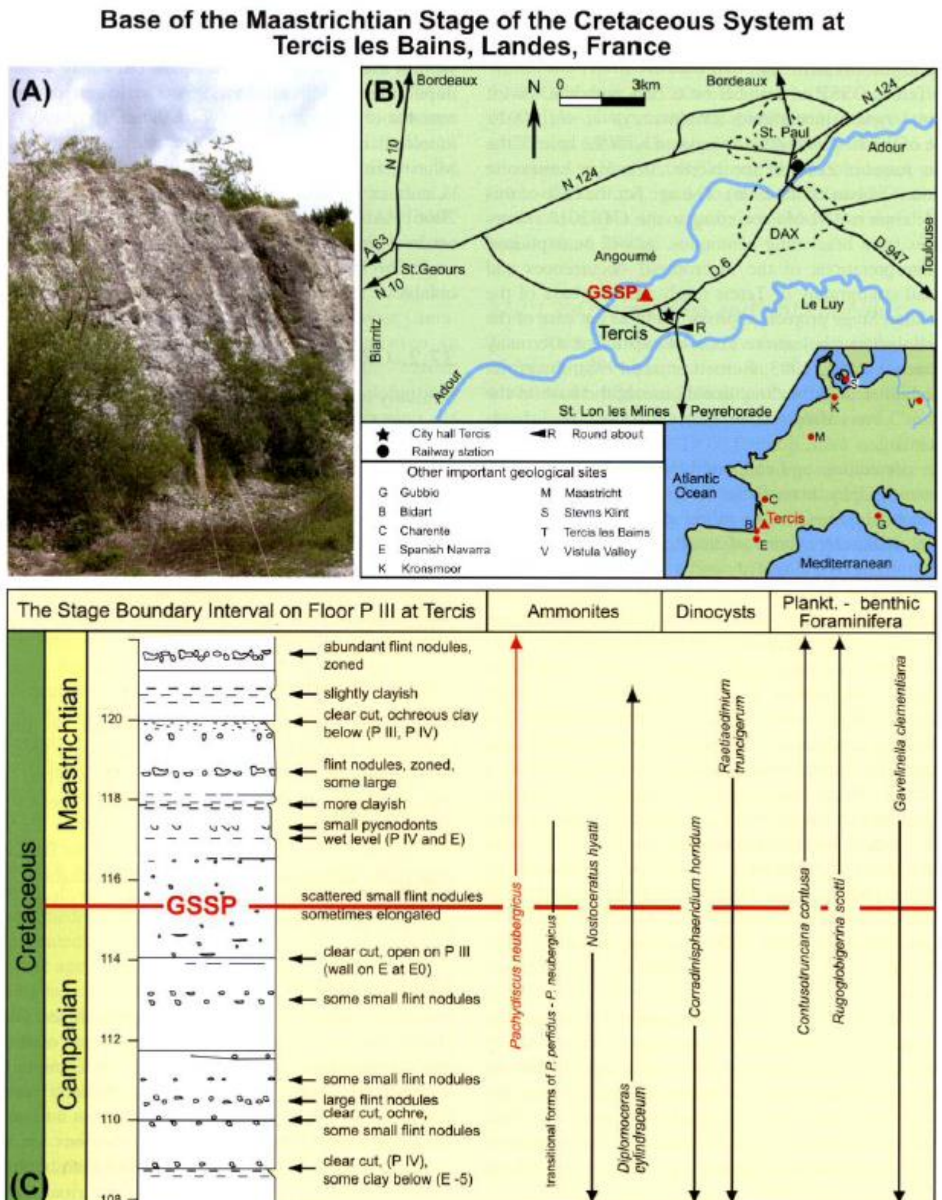


FIGURE 27.5 **GSSP for base of the Maastrichtian Stage at Tercis, France,** is 90 cm below the lowest occurrence of the ammonoid *Pachydiscus neubergicus*. *Photos provided by Andy Gale.*

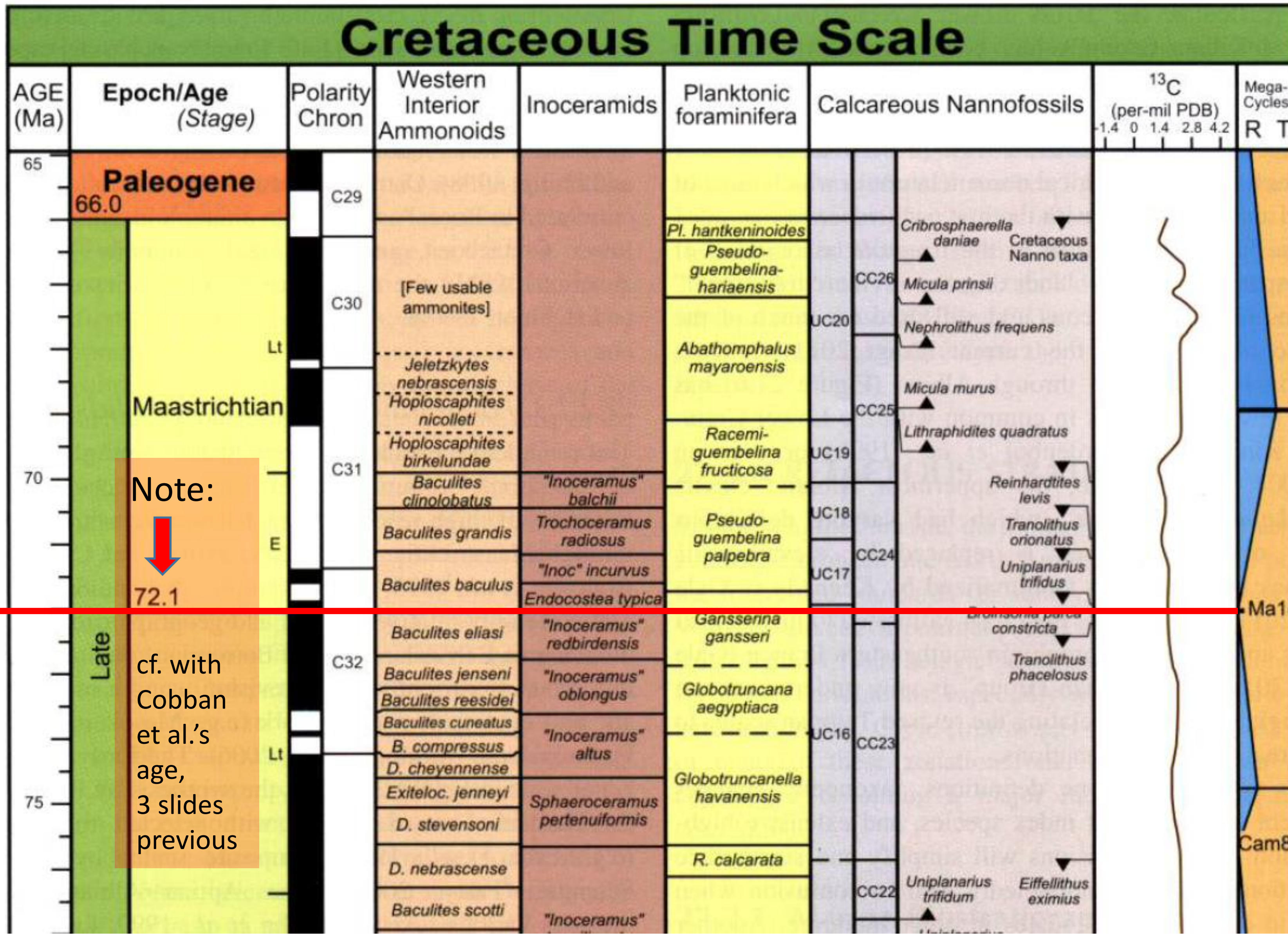
GSSP = Global Boundary Stratotype Section and Point

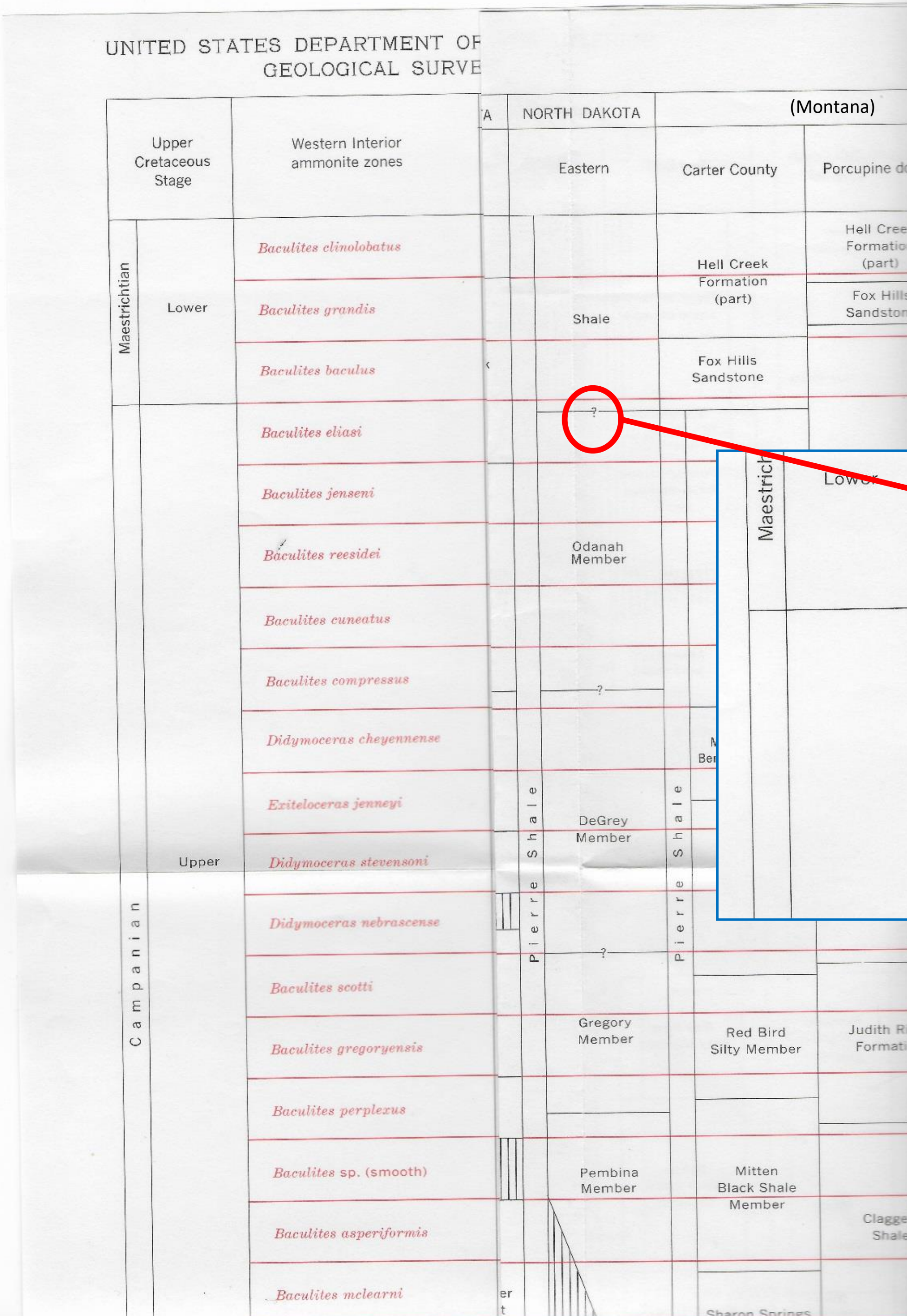
(Ogg et al., Ch. 27, in: Gradstein et al. 2012)

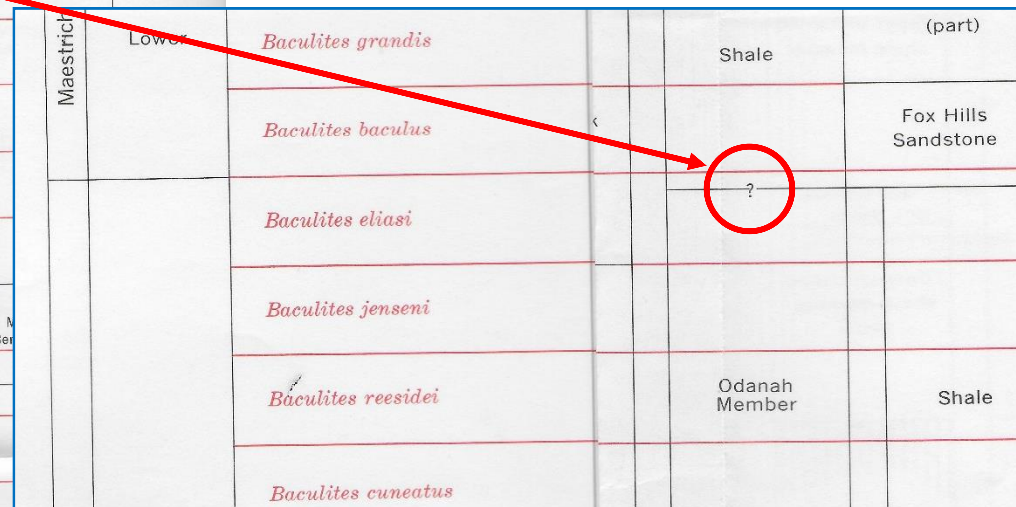
810

(Ogg et al., Ch. 27, in: Gradstein et al. 2012)

The Geologic Time Scale 2012







Gill, J. R. and Cobban, W. A., 1966, The Red Bird section of the Upper Cretaceous Pierre Shale in Wyoming, *with a section on* A new echinoid from the Cretaceous Pierre Shale of eastern Wyoming, by P.M. Kier: U.S. Geological Survey Professional Paper, 393-A, 73p. (Plate 4)

(small portion of a very large, inserted plate [4])

S 1
No. 61

MONTANA BUREAU OF MINES AND GEOLOGY
SPECIAL PUBLICATION 61

GEOLOGY, STRATIGRAPHY, AND BIOSTRATIGRAPHY OF THE NORTH END OF CEDAR CREEK ANTICLINE, DAWSON COUNTY, MONTANA

Gale A. Bishop (1967, 1973)

Although the Cedar Creek anticline, in eastern Montana, has been a productive gas field since 1913 and a productive oil field since 1951, the only detailed geologic map was published by the U.S. Geological Survey in 1934 (Erdmann and Larsen, 1934).

The Pierre Shale has been divided into lithologic members and biostratigraphic zones (Robinson and others, 1959; Gill and Cobban, 1966). The zones are based upon a series of distinguishable ammonites, most of which belong to the genus *Baculites*. Scott and Cobban (1965) illustrated the utility of this zonation in delineating large-scale structures in the Pierre Shale in Colorado. The question partly answered in this paper is whether or not the ammonite zones can be used for detailed mapping.

On the Cedar Creek anticline, strata about 200 feet thick and equivalent to the Kara Bentonitic Member and the overlying unnamed shale member of the Pierre Shale crop out. The rocks contain three biostratigraphic zones, which are (from oldest to youngest): *Baculites eliasi* Cobban Zone, *Baculites baculus* Meek and Hayden Zone, and *Baculites grandis* Hall and Meek Zone.

Specimens of fossils belonging to these taxa were collected and their positions plotted on a map. A composite measured section was compiled from outcrops in the area. Altitudes of collection points were determined by a barometric altimeter. These data were then combined to produce a structure contour map of the top of the *Baculites eliasi* Zone. This mapping was possible for three reasons:

1. The top of the zone carries an accumulation of body-chamber casts of *B. eliasi*, which are easy to find, readily recognizable, and not appreciably displaced by erosion.
2. The top of the zone nearly coincides with a change in the lithology of concretions included in the shale.
3. The 50 feet of beds above the *B. eliasi* zone contain no baculites.

Detailed mapping of the top of the *B. baculus* Zone was not possible, for three reasons:

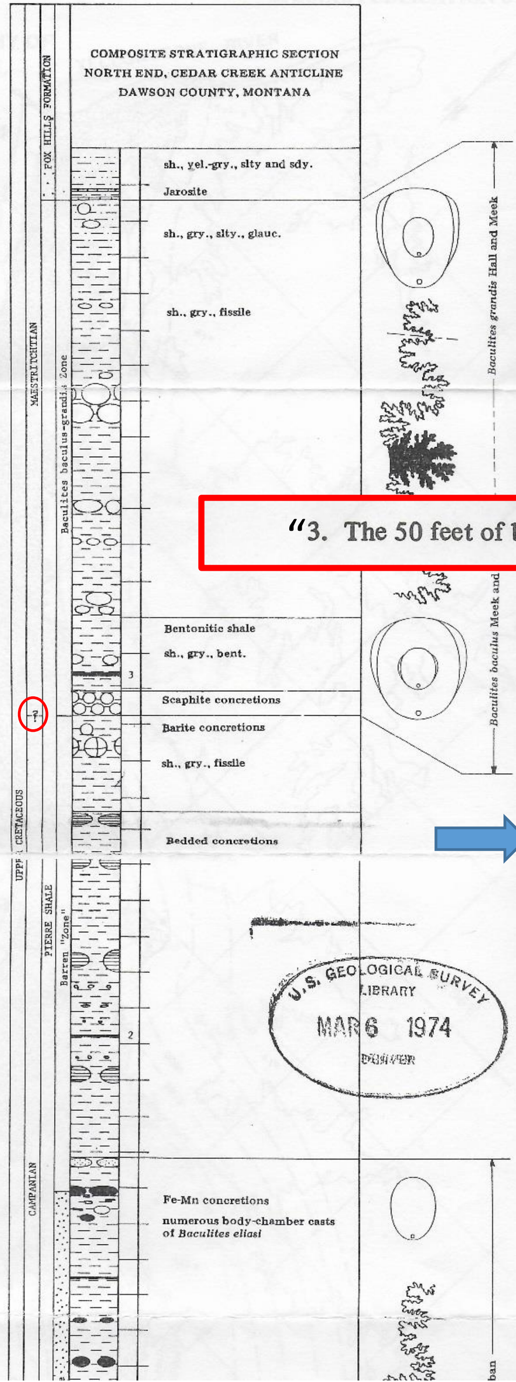
1. Lack of large numbers of individuals.
2. Lack of prominent morphologic difference between *B. baculus* and *B. grandis*.
3. The great amount of slumping in this part of the section.

Detailed mapping of structure using biostratigraphic zones in the Pierre Shale is possible in some circumstances, and generalized structural delineation is possible in any circumstances if the fossils are present. This method of mapping might be applied with some success to previously unmappable expanses of Pierre Shale.

Biostratigraphic mapping in the Pierre Shale is adversely affected by slumping, faulting, mass wasting, and running water, because of transportation of the fossils by these processes. These factors generally do not seem to affect the mapping to any great extent, but could and do affect it locally.

ACKNOWLEDGMENTS

This map is the product of a thesis done under the supervision of Dr. J. C. Mickelson at South Dakota School of Mines and Technology in 1965-1967. The help of the staff of the School of Mines is gratefully acknowledged as is the hospitality of the residents of the map area. Especially helpful were Art and Maxine Anvik of Glendive, Montana.



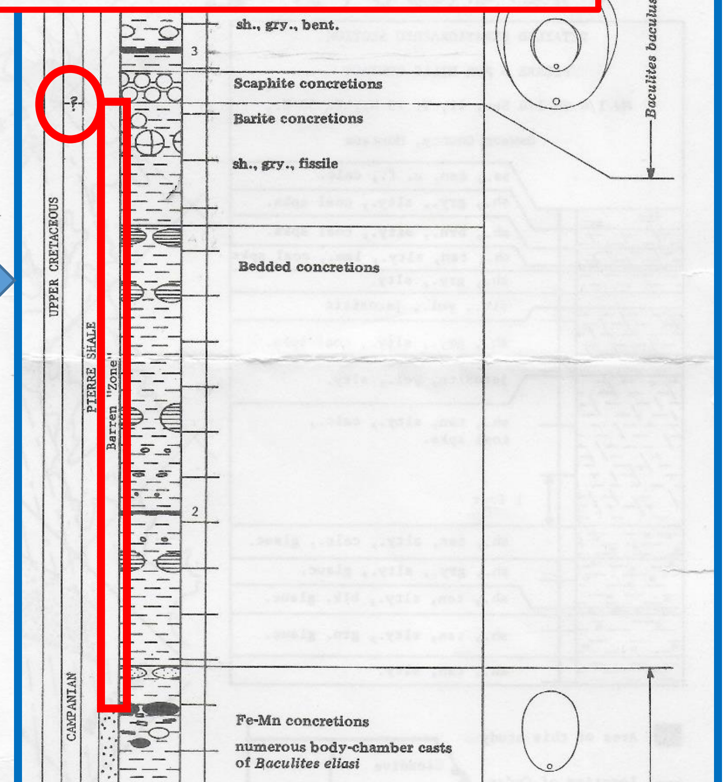
Joyce,

I may have sent you a copy of this publication some time ago. It has a good upper Pierre section.

Sure enjoyed talking to you.

Bill

"3. The 50 feet of beds above the *B. eliasi* zone contain no baculites."



Our studies (Joyce & Jim Grier, Tom Linn, Neal Larson, and Neil Landman) at CCA

- 32 years, since 1987
- over 120 site locations
- Methods, in brief: numerous trips of several days each, 1-4 trips per year, ground searches and curated collections (mostly deposited at AMNH, some at Smithsonian, and elsewhere), measurements by tape, Jacob sticks, GPS, plus reference photography. For details, see publications:

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Landman, N.H., W.J. Kennedy, N.L. Larson, J.C. Grier, J.W. Grier, and T. Linn. 2019. Description of two species of Hoploscaphites (Ammonoidea: Ancyloceratina) from the Upper Cretaceous (Lower Maastrichtian) of the U.S. Western Interior. Bulletin of the American Museum of Natural History. No. 427, 72 pp. 38 fig., 4 tables.

A **MAJOR** issue at the Cedar Creek Anticline: **slumping**! (including slumps during our 32 years in the field)

Quote from Bill Cobban during one of his visits to the area with Joyce and Jim, "Doesn't all that slumping make you feel uncomfortable?!"

Our studies (Joyce & Jim Grier, Tom Linn, Neal Larson, and Neil Landman) at CCA

- 32 years, since 1987
- over 120 site locations
- Methods, in brief: numerous trips of several days each, 1-4 trips per year, ground searches and curated collections (mostly deposited at AMNH, some at Smithsonian, and elsewhere), measurements by tape, Jacob sticks, GPS, plus reference photography. For details, see publications:

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- **Composite section** with **measurements <u>only within</u> given slumps, and with common landmark references (not just “bottom-up”), then stitched together to create the composite.**

NEW FINDINGS

(with stratigraphic interpretations based on Cobban et al. 2006)

Stages and Substages		2Stage Boundaries Ma	Western Interior Ammonite Taxon Range Zones	Age Ma	Western Interior Inoceramid Interval Zones
		[9]65.5 ± 0.30		[9]65.51 ± 0.10	
Maastrichtian	Upper				
			Jeletzkytes nebrascensis		
			Hoploscaphites nicolletii		
			Hoploscaphites birkelundae		
	Lower		*Baculites clinolobatus*	69.59 ± 0.36	*"Inoceramus" balchii*
			Baculites grandis	70.00 ± 0.45	*Trochoceramus radiosus*
			Baculites baculus		*"Inoceramus" incurvus*
					Endocostea typica
		70.6 ± 0.6			
Campanian	[1]Europe / Western Interior Informal Substages		*Baculites eliasi*	71.98 ± 0.31	(*"Inoceramus" redbirdensis*)*
			Baculites jenseni		*"Inoceramus" oblongus*
			Baculites reesidei	[11]72.94 ± 0.45	
			Baculites cuneatus		

- Several *B. grandis*
- Lots of *B. baculus*, including 5 now down into the sandy-bedded concretion zone
- Lots of *B. eliasi*, including a small number up just below (within 0.5m of) the sandy-bedded zone *(Note: we have not found *"I." redbirdensis* in the *B. eliasi* zone at the CCA)
- One (published, pictured) *Trochoceramus radiosus* plus more suspected
- Lots of *Endocostea typica*, including at least 4 in the sandy-bedded concretion zone

Examples:

Stages and Substages			[2]Stage Boundaries Ma	Western Interior Ammonite Taxon Range Zones
			[9]65.5 ± 0.30	
Maastrichtian	Upper			
				Jeletzkytes nebrascensis
				Hoploscaphites nicolletii
				Hoploscaphites birkelundae
	Lower			*Baculites clinolobatus*
				Baculites grandis
				Baculites baculus
			70.6 ± 0.6	
Campanian	[1]Europe	Western Interior Informal Substages		*Baculites eliasi*
				Baculites jenseni
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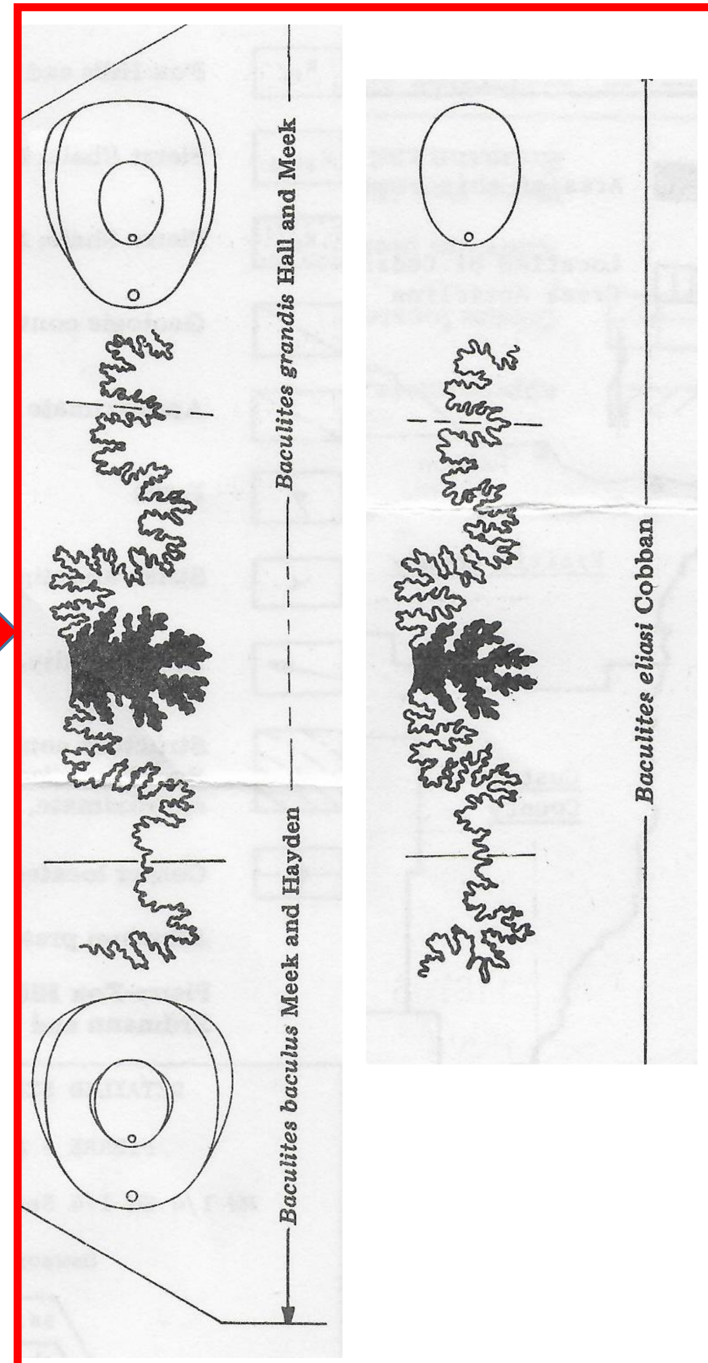
				Baculites cuneatus



Outlines and sutures from Bishop 1973, after Scott and Cobban 1965

Examples:

Stages and Substages			[2]Stage Boundaries Ma	Western Interior Ammonite Taxon Range Zones	Age Ma	Western Interior Inoceramid Interval Zones
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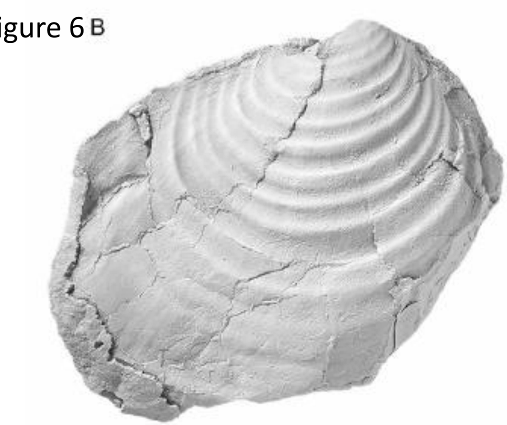
Landman et al. 2019. Figure 6 B



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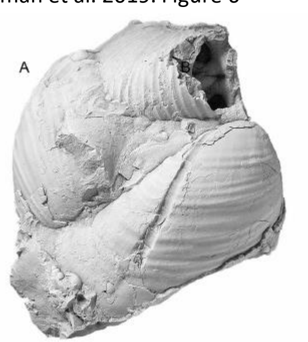
				Baculites cuneatus		

Landman et al. 2019. Figure 6



In sandy bedded concretion at CM boundary

Showing prominent sulcus

Examples:

Stages and Substages		[2]Stage Boundaries Ma	Western Interior Ammonite Taxon Range Zones	Age Ma	Western Interior Inoceramid Interval Zones
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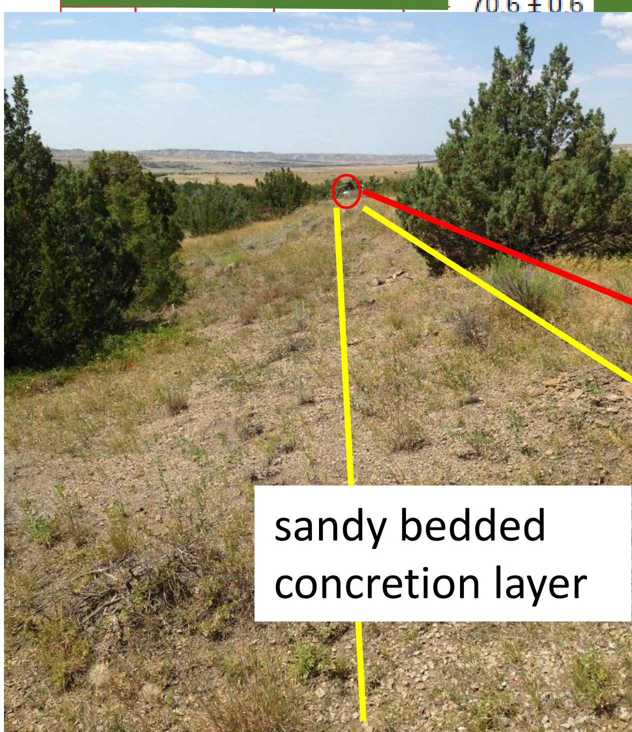

Examples:

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				Baculites cuneatus

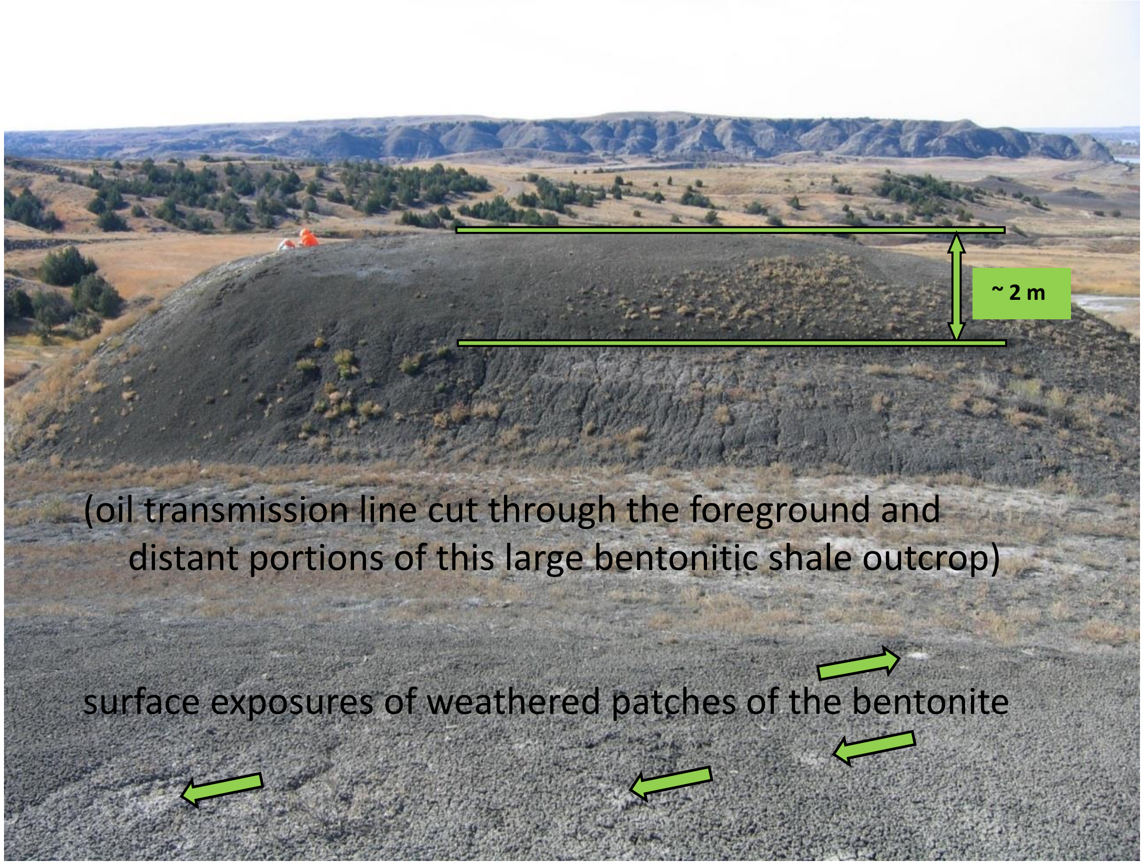
est. ~ 2 ft below sandy bedded concretion layer

Plus a few other stratigraphic tweaks based on our findings and experience at the CCA:

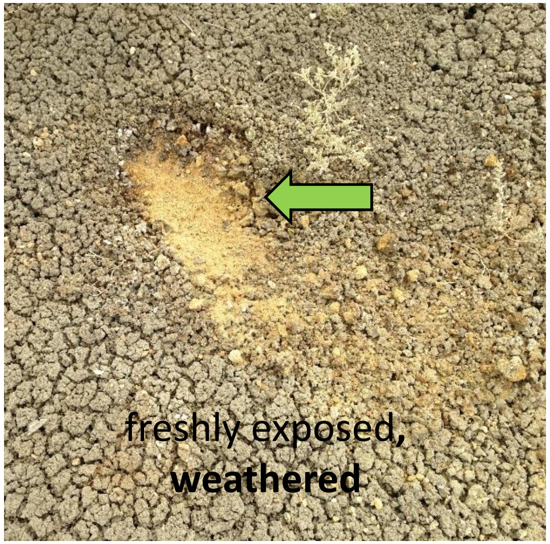
- There appears to be only one sandy-bedded concretion layer, at least only one major one ... with a possible second, minor one, or else the minor one we have seen might be a slump artifact.

  In all of our years and experience, we have only been able to verify one sandy-bedded concretion layer for certain. It is distinct. That also makes sense if it’s at a stage boundary (Campanian-Maastrichtian).

- The bentonite layer at the base of the prominent 2 m thick layer of bentonitic shale described by Bishop (1967, 1973) appears to be in error. We have found it (consistently) at the top of the bentonitic shale, not the bottom.



Bentonite layer at the <u>top</u> of the prominent layer of bentonitic shale



Plus a few other stratification tweaks based on our findings and experience at the CCA:

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- The bentonite layer at the base of the prominent 2 m thick layer of bentonitic shale described by Bishop (1967, 1973) appears to be in error. We have found it (consistently) at the top of the bentonitic shale, not the bottom.

- Presence of **cold methane seeps**: 5 discovered so far, at the sandy-bedded concretion layer, and the highest occurrence of such deposits in the U.S. Western Interior


2nd vent
main vent
First methane seep site discovered at the CCA

AMNH field crew discussing a methane seep (arrow) and Joyce instructing on identifying the associated fossils

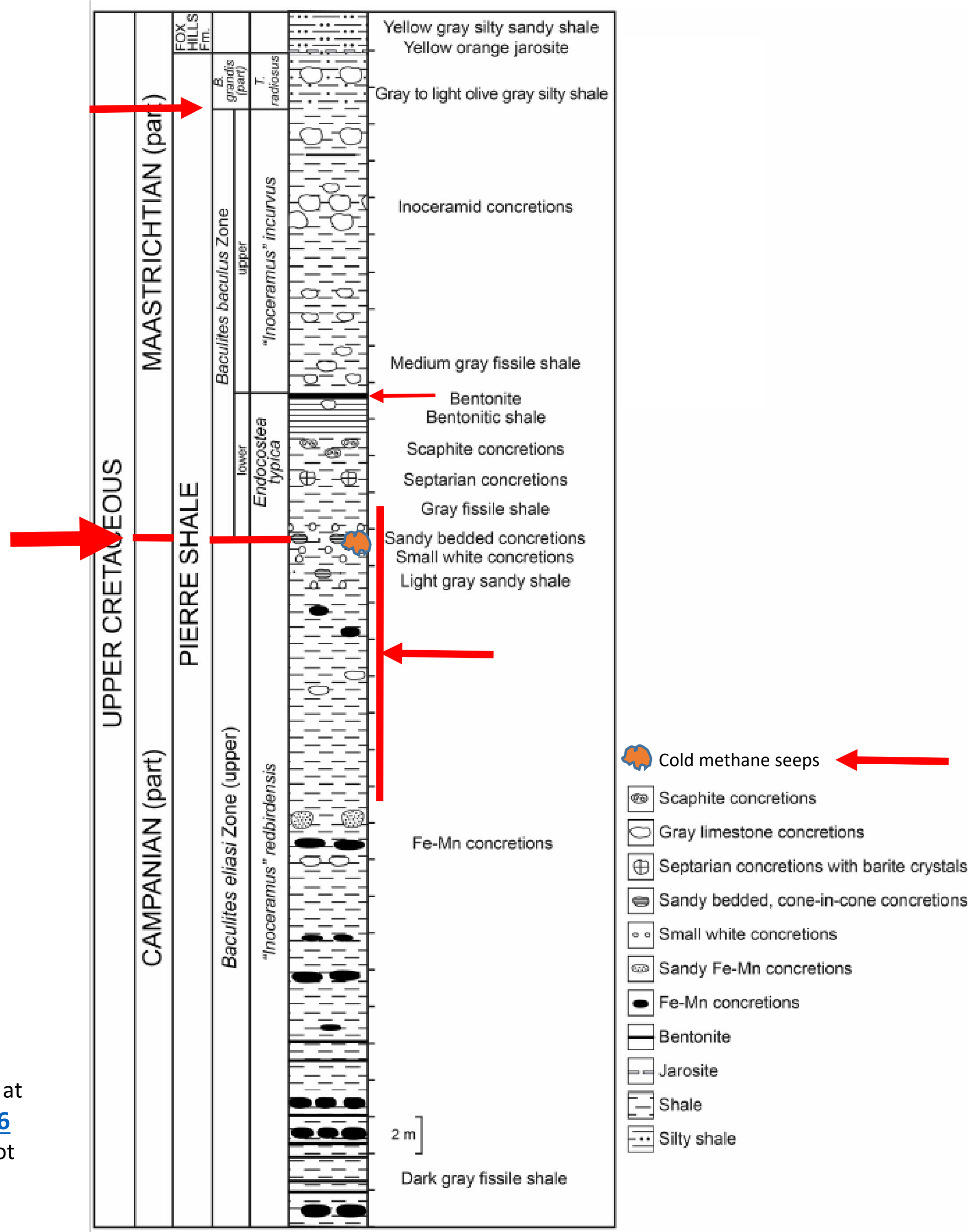
"Chimney" from a large methane seep where the surrounding, sloped ground has eroded away.


Typical sponge-like methane seep carbonates
at the Cedar Creek Anticline

A small methane seep site with only a few methane seep carbonates

RESULTS

Our new, latest stratigraphy for the Cedar Creek Anticline, NW area



→ = main points of revision from previously published stratigraphies (Bishop 1967, 1973, and our previous pubs.*)

* The most recent published stratigraphy can be found at http://digitallibrary.amnh.org/handle/2246/6926 (page 8, Figure 4; methane seeps mentioned in text, not on figure)

Discussion and Conclusions

1. The Campanian-Maastrichtian “Boundary”, including comparisons with the Red Bird Section in Wyoming and generally (globally)

2. Likely and/or possible causes of the current exposure of the Cedar Creek Anticline

Recap and important notes:

- Gill and Cobban (1966) did not find a distinct CM boundary and marked the possible boundary (their Plate 4) with question marks, a wavy line (for Kansas), and uncertainties. At their Red Bird section their closest samples for *B. baculus* (or *E. typica*) and *B. eliasi* (localities D1970-71 and D1969 respectively [e.g., Plate 2]) were about 30 ft apart vertically.

- Bishop (1967, 1973) described a "barren zone" with some, but few, fauna, and he found no *Baculites* in that 50 ft part of the section.

- In the "barren zone" we have found a few other fauna (as did Bishop) and (unlike Bishop) a (very) small number of *Baculites* (both *B. baculus* and *B. eliasi*, as discussed), despite many years in the field and with some intensive and extensive searching in that zone.

- (New) One or more disconformity issues ... following slides

Chapter 6

Stratigraphic Unconformities: Review of the Concept and Examples from the Middle-Upper Paleozoic

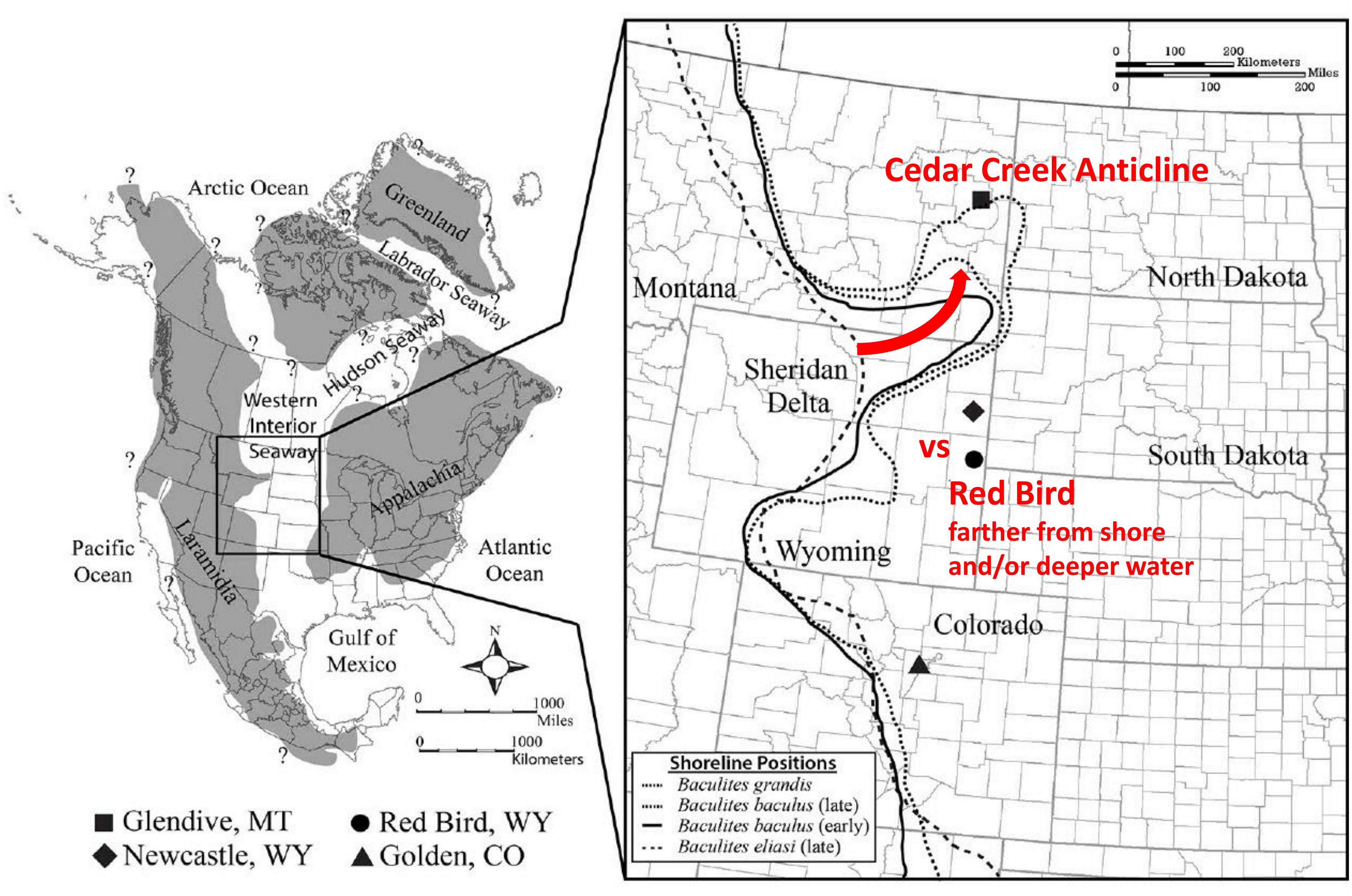
Pavel Kabanov

Additional information is available at the end of the chapter

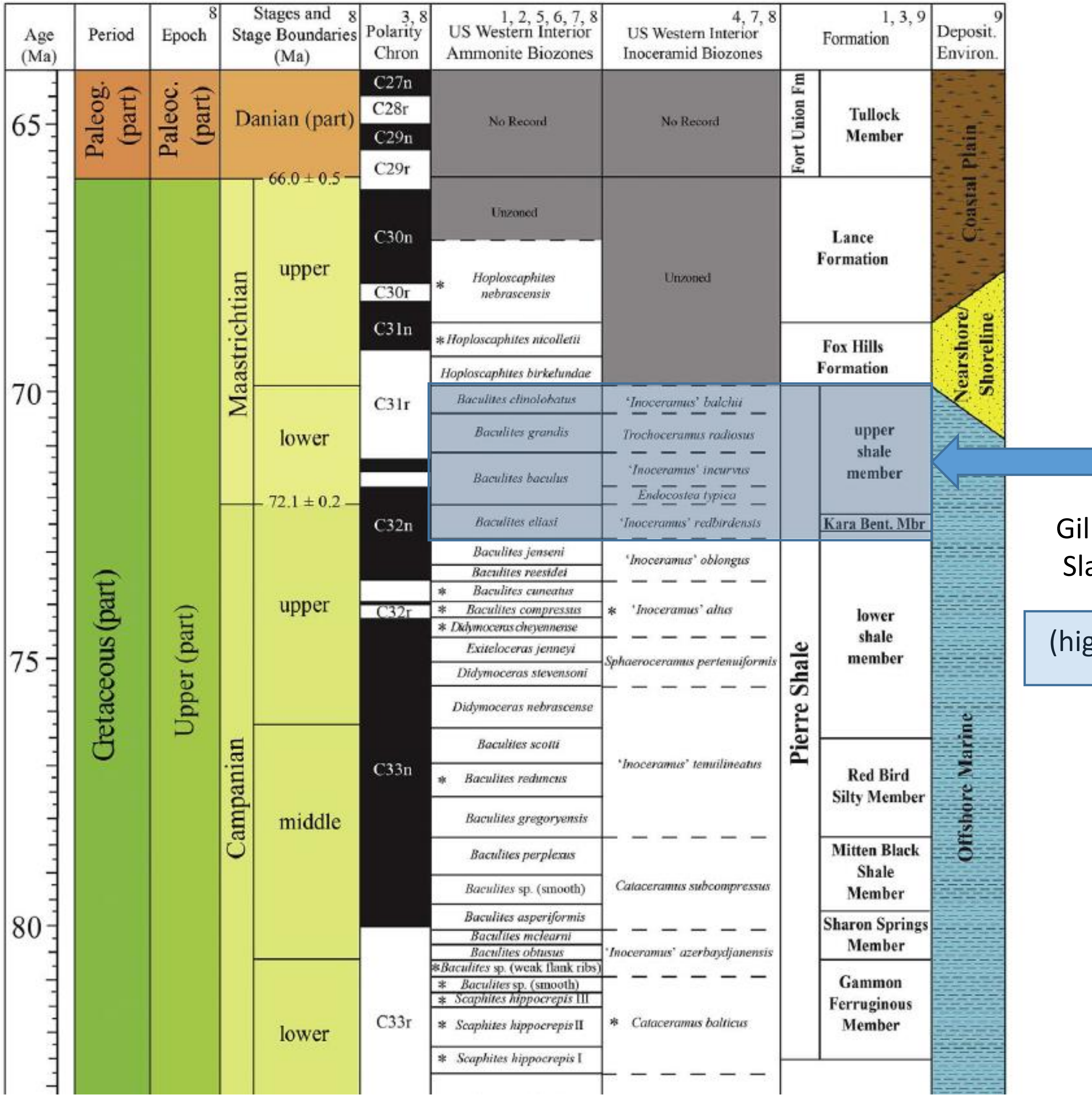
http://dx.doi.org/10.5772/intechopen.70373 (2017)

Abstract

Only about 10% of geologic time is imprinted in sedimentary strata and the rest is hidden in non-depositional or erosional surfaces called unconformities. Stratigraphic unconformities (disconformities) are principal bounding surfaces in sequence stratigraphy, which a geologist would easily identify in the outcrop but frequently overlook in the subsurface unless core is available. The proportion of disconformities that are misidentified or overlooked in subsurface stratigraphy is quite large, which puts a warning sign on simplistic sequence stratigraphic models. The amount of time imprinted in disconformities can be evaluated using relative weathering maturity of the subaerial profile, cyclostratigraphic calibration, absolute dating, and biostratigraphy. However, using biostratigraphy



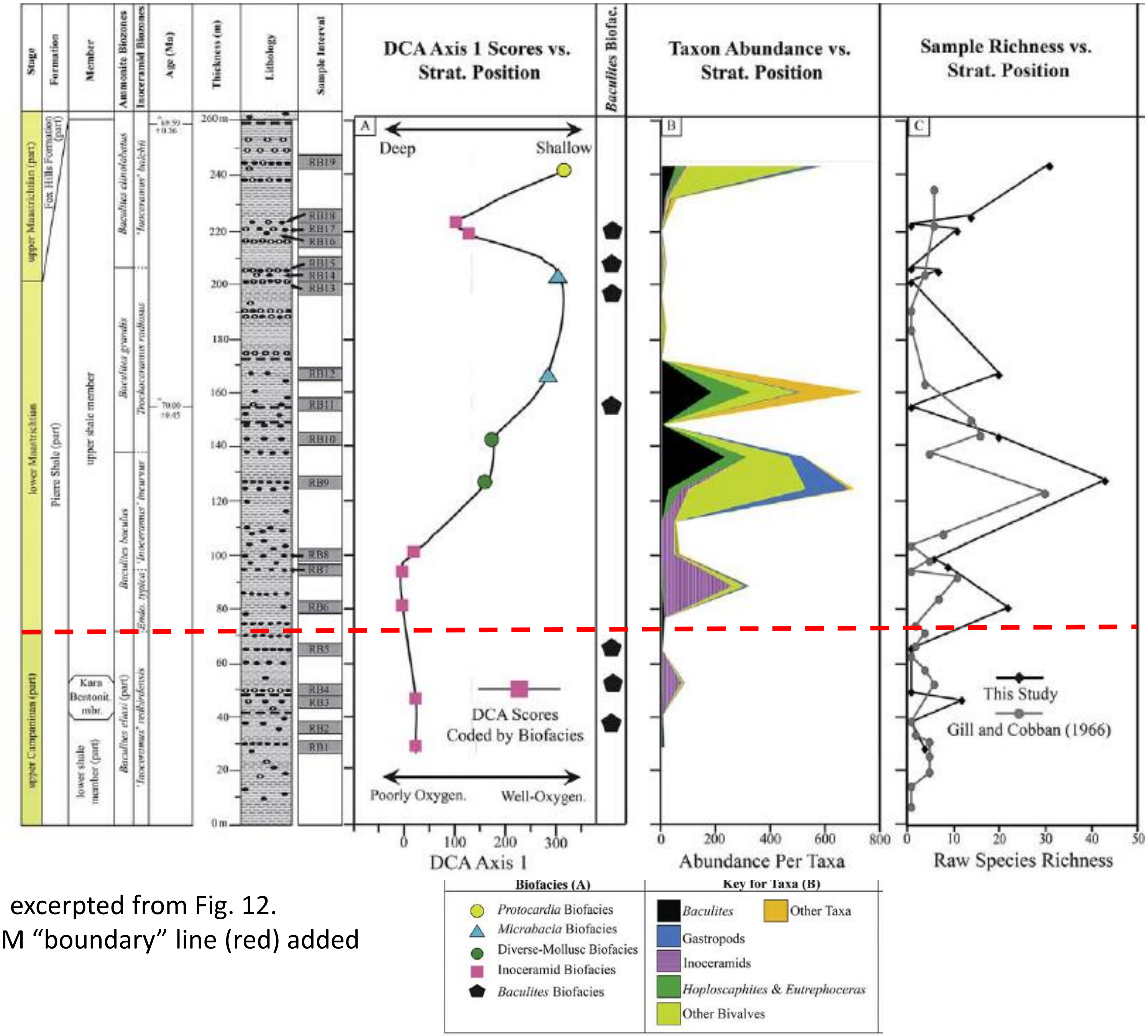
modified from Landman et al. 2016, 2019, and based on several previous iterations including Gill and Cobban 1973 and Slattery et al. 2015, 2018



Red Bird

Gill and Cobban, Slattery et al.

(highlight added)



excerpted from Fig. 12.
with CM “boundary” line (red) added

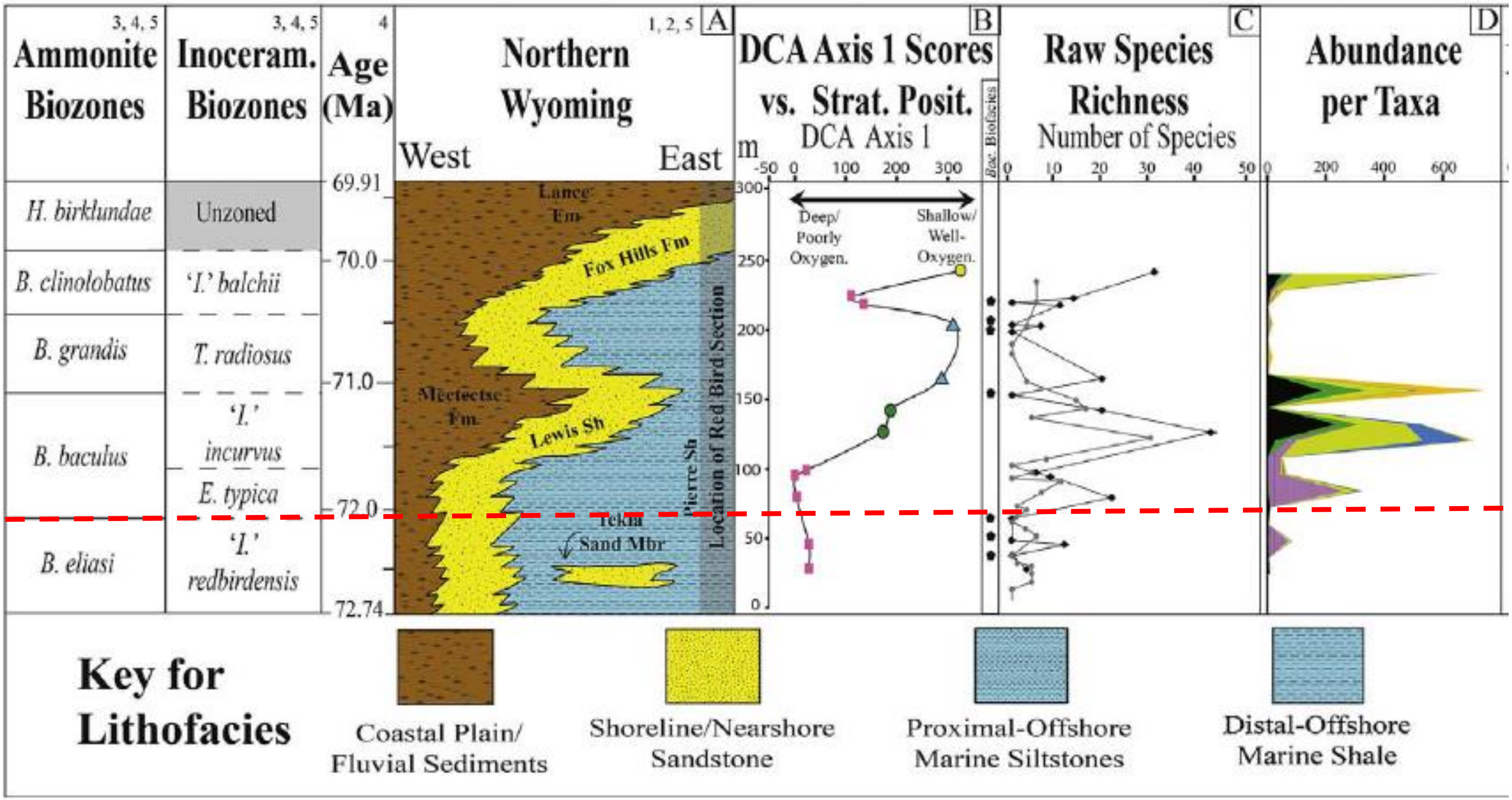


Fig. 13. Comparison among lithofacies patterns in northcentral Wyoming (A), stratigraphically plotted DCA axis 1 scores and biofacies (B), raw species richness trends (C), abundance patterns (D), as well as relative life-habit patterns (E) (Compiled from: [1]Gill and Cobban, 1973; [2]Krystinik and DeJarnett, 1995; [3]Cobban et al., 2006; [4]Ogg and Hinnov, 2012; and [5]Lynds and Slattery, 2017). Coding for biofacies, raw species richness trends, abundance plot, and relative life-habit plot shown in Fig. 12.

excerpted from Fig. 13. with CM "boundary" line (red) added

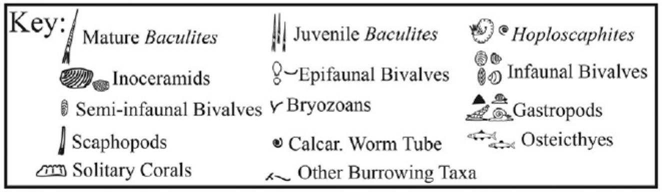


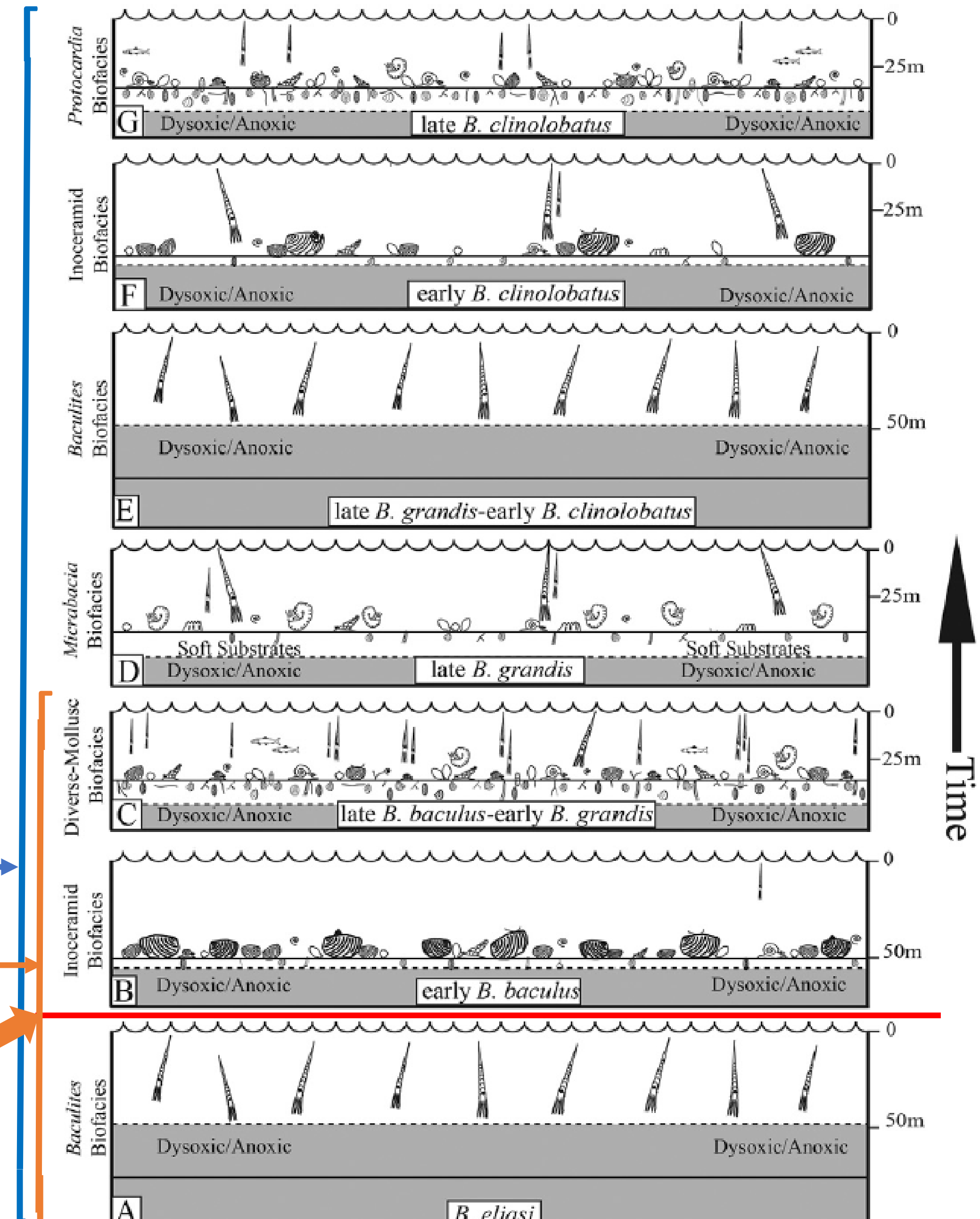
Fig. 14. Biofacies and reconstructed water-column conditions during the study interval at Red Bird, Wyoming. A) *Baculites* biofacies, deepest water conditions. B) Inoceramid biofacies, relatively deep-water conditions. C) *Diverse-mollusc* biofacies, shallow-water conditions. D) *Micrabacia* biofacies, mid-depth conditions. E) *Baculites* biofacies, deepest water conditions. F) Inoceramid biofacies, relatively deep-water conditions. G) *Protocardia* biofacies, shallow-water conditions. Note: depths depicted in the figure are estimated; actual depths of the WIS remain unresolved.

Fig. 14. with CM "boundary" line (red) and Red Bird vs. Cedar Creek Anticline brackets (blue vs orange, respectively) added

Red Bird

Cedar Creek Anticline

shallow zone and disconformity



Our current interpretations ...

- The Campanian-Maastrichtian stage change is perhaps best viewed as a relatively gradual transition without distinct boundaries, with the best (resolution and accuracy) understanding of the actual situation being that seen by Gill and Cobban (1966) and Slattery et al. (2018) at the Red Bird Section in Wyoming – farther from shore/deeper water than the Cedar Creek Anticline at the time.

- During the (relatively gradual) transition, marine environmental conditions were likely less favorable (cooler? ... from depth and/or climatic changes) for organisms, including Baculites and inoceramids, and there were many fewer of them present (hence, many fewer fossils during that time period).

- The case of the distinct boundary at the Cedar Creek Anticline in our study area, thus, most likely represents a local disconformity. (The same probably can also be said for the GSSP for the Maastrichtian in Tercis, France.)

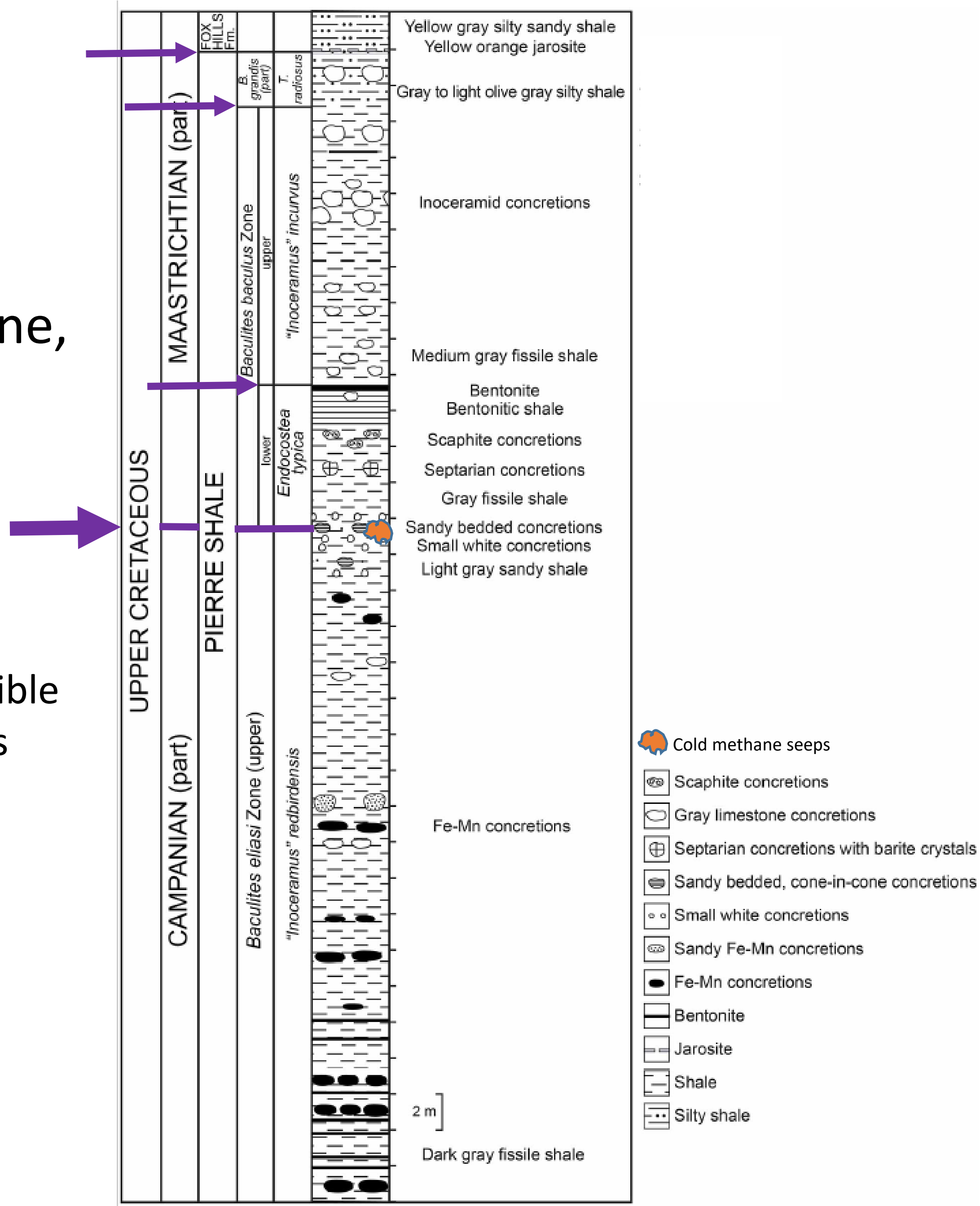
- CM boundaries found elsewhere in the Western Interior Seaway (or elsewhere in the world for that matter) most likely depend on the local situations, thus, vary from place to place -- which has led to much of the confusion surrounding the CM boundary.

Our current interpretations ... (cont.)

- Searching for stage boundaries can represent a wild goose-chase, with the position of the goose in time depending on the locality!

- Additionally, we now believe, based on the biostratigraphy and lithofacies, that there are probably at least four disconformities in the Pierre Shale of our study area.

Our new, latest stratigraphy for the Cedar Creek Anticline, NW area

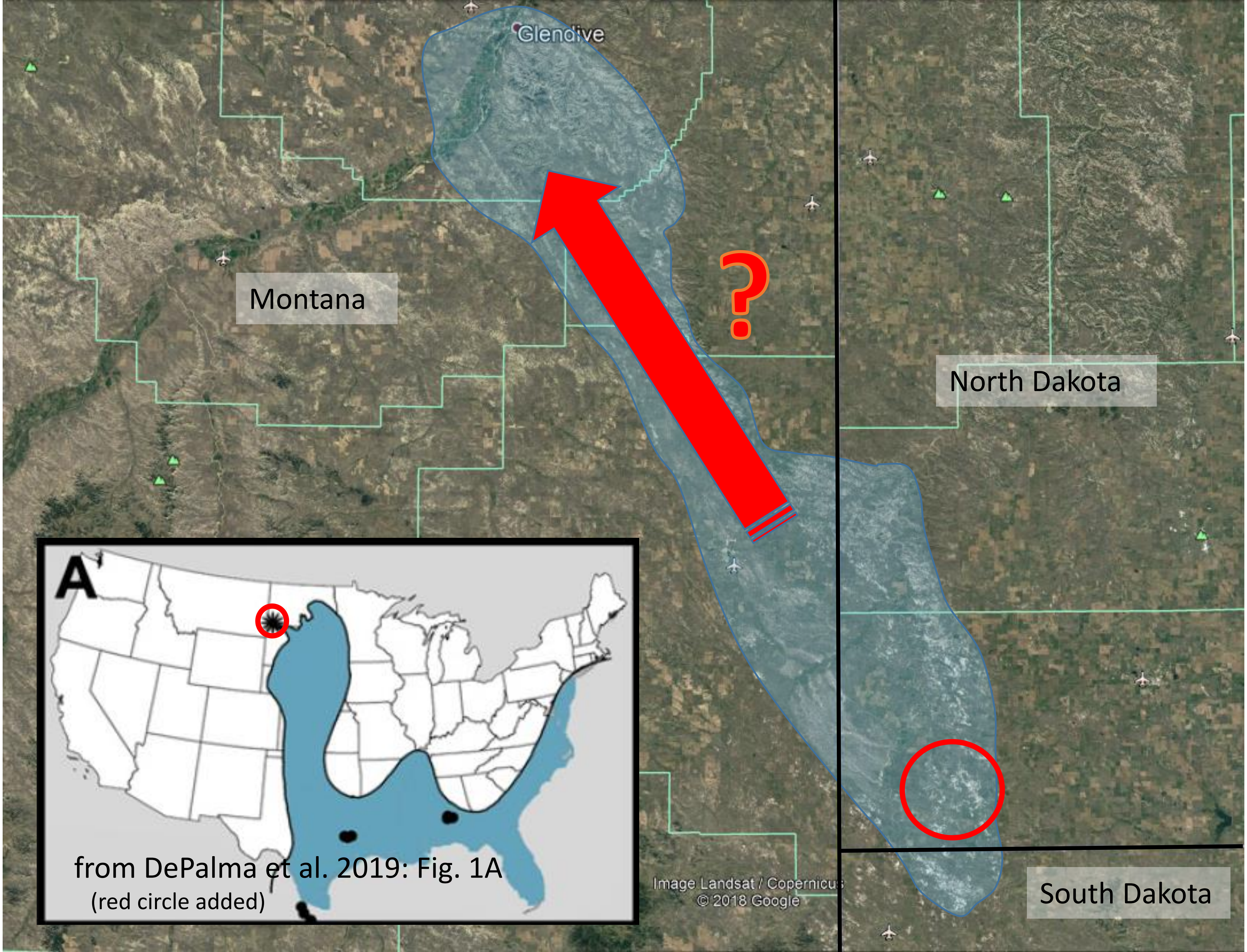


= likely or possible disconformities

Likely and possible cause(s) of the present-day exposure of the CCA in our study area

1. Numerous faulting events from the Paleozoic into the Paleogene
2. Erosion ...
   A. Weaknesses/openings in the strata (from the bending of the anticline which make the strata more vulnerable to erosion)
   B. Presence of soft sediment, particularly the Pierre Shale
   C. Long time periods of accumulated stream erosion with numerous knick points
3. Slumping

4. (speculative) Seismic surge/sloshing blowout from the KPg Chicxulub event ... as proposed by DePalma et al. (PNAS, 2019) for the “Tanis” site nearby in North Dakota at the southeast edge of the CCA



Glendive
Montana
?
North Dakota
South Dakota
A
Image Landsat / Copernicus
© 2018 Google
from DePalma et al. 2019: Fig. 1A
(red circle added)

Acknowledgements

USGS -- Bill Cobban

NDSU

- D. Schwert
- A. Ashworth
- L. Tacket
- D. Grier

Early Earth Enterprises

- J. Linn
- A. Linn

Larson Paleontology

- B. Larson
- L. Larson

AMNH

- S. Thurston
- S. Klofak (deceased)
- M. Slovacek
- B. Hussaini
- M. Conway
- K. Sarg

Assistance in the field

- **Bill Cobban**
- J. Petersen
- S. Klofak (deceased)
- J.K. Cochran
- K.F. Grier
- L. Larson
- Many undergrad and grad students, post-docs, and colleagues on annual Landman field trips

Funding

N.D. Newell Fund

personal funds of J.C. & J.W. Grier, T. & J. Linn, and N. & B. Larson

Landowners

B. Blankenship ***land sold, no longer accessible**

(anonymous landowners) ***see appendix**

Cedar Creek Grazing Association ***highly restricted access**

BLM ***now somewhat restricted ...**

state of Montana ***now somewhat restricted ...**

***details in APPENDIX re. collecting**

SEE FOLLOWING PAGES

Appendix: land access, collecting, and related matters

- ## Know before you go!

  Thanks in part to a few careless, property-abusing/-damaging, unscrupulous, and excessive individuals and rock clubs (plus some game hunters and off-road vehiclers), much of the Cedar Creek Anticline is now closed or moderately to highly restricted to access.

  - Most private property is now completely off limits unless you have previous, long-term relationships with the owners.
  - The Cedar Creek Grazing Association land, once freely open with permission (including oral), is now <u>highly</u> restricted – with written permission for a fee of $100 per day per person, or, without permission, law enforcement will be called.
  - Federal and state property is being watched and somewhat restricted depending on the nature of the access; some activities are limited or prohibited.

Appendix: land access, collecting, and related matters

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  Thus, you MUST AT ALL TIMES know where you are and who owns the property, have permission/permits where required, act responsibly, and follow the rules!

Appendix: land access, collecting, and related matters

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  Thanks in part to a few careless, property-abusing/-damaging, unscrupulous, and excessive individuals and rock clubs (plus some game hunters and off-road vehiclers), much of the Cedar Creek Anticline is now closed or moderately to highly restricted to access.

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  - The Cedar Creek Grazing Association land, once freely open with permission (including oral), is now highly restricted – with written permission for a fee of $100 per day per person, or, without permission, law enforcement will be called.
  - Federal and state property is being watched and somewhat restricted depending on the nature of the access; some activities are limited or prohibited.

  Thus, you MUST AT ALL TIMES know where you are and who owns the property, have permission/permits where required, act responsibly, and follow the rules!

- ## Don't burn the place down!

  - **NO SMOKING**
  - **Consciously avoid parking where vehicle catalytic converters could contact vegetation**


OK
no
vegetation

Appendix: land access, collecting, and related matters

- **Know before you go!**

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- **Respect all property and minimize signs of presence, including no litter, no driving off the roads, etc.**

A common landowner pet peeve: broken concretions left laying around
(despite the fact that there are many naturally eroded and broken ones laying around the landscape)

We've heard them. Thus, we recommend and try to do ourselves:

BEFORE – excavated, with a deep hole, broken concretion fragments, and samples in bags

AFTER – hole filled in and smoothed over

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Note: The region has been heavily collected for decades by many individuals and groups including researchers (including us), class field trips, rock clubs, and commercial collectors. There is now much less material than formerly.