Direct supplement to:

Climate controlled aggradation and cyclicity ofcontinental siliciclastic sediments in Wolfcampian cyclothems, Permian, Hugoton embayment U.S.A.*

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The following document is a supplement to *Climate controlled aggradation and cyclicity of continental siliciclastic sediments in Wolfcampian cyclothems, Permian, Hugoton embayment U.S.A.* It is not formatted as a standalone paper, but rather is organized in a manner that the material may linked to the manuscript by the reader. Material provided here is inserted into an outline of the manuscript (section and subsection headings).

INTRODUCTION

GEOLOGIC SETTING

Ramp geometry

Present-day structure of Wolfcampian-age rocks (Fig. 1) is a result of Laramide-age eastward tilt and is much different than during deposition. Maximum relief across the ramp in the study area during Wolfcampian deposition is estimated by Dubois (2006) and Dubois *et al.* (2006) as 30 m (100 feet) with a slope of only ~ 0.2 m/km (1.1 ft/mi) on the basis of fauna, paleoshorelines, and isopach maps.
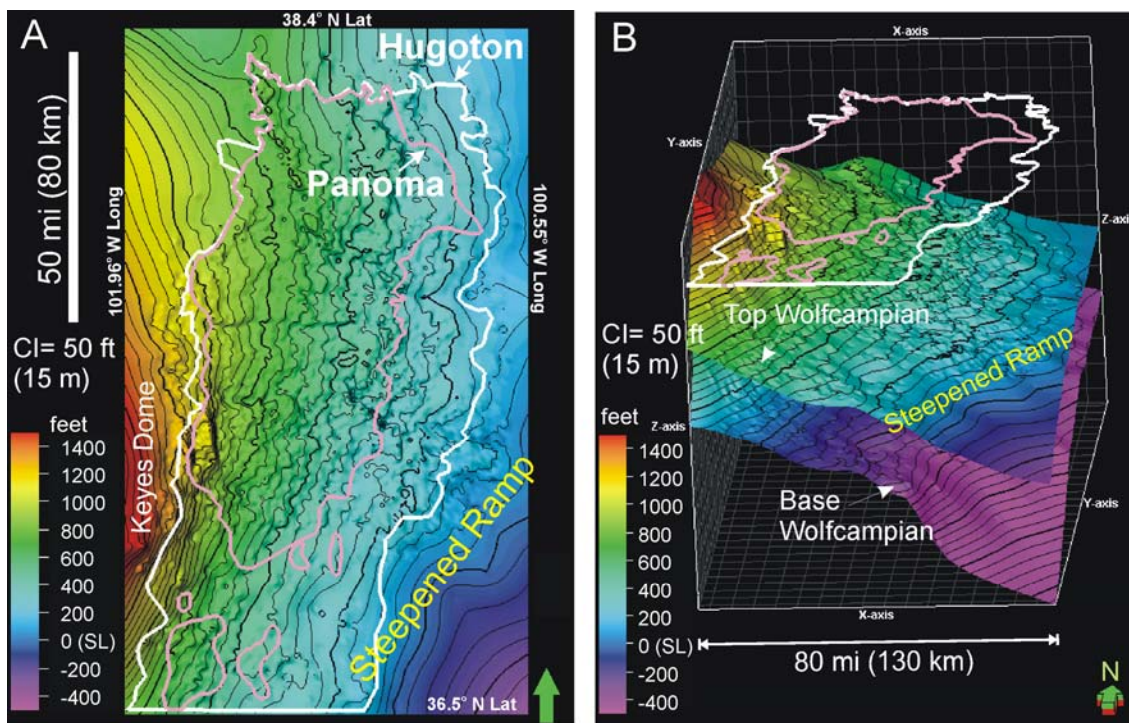

Fig. 1. (A) Study area and boundaries of gas fields. Present-day structure on the top of the Wolfcampian is mostly a function of eastward tilt during the Laramide orogeny. A steepened ramp is at the southeast boundary of the Hugoton field. **(B)** Three-dimensional view of the same area. Present-day structure on the top of the Wolfcampian and a surface near the base of the Wolfcampian are illustrated. The Council Grove surface, not shpown, parallels the top of the Chase (after Dubois *et al.*, 2006).

Sedimentary cycles and regional setting

DATA AND METHODS

Core slabs were examined at half-foot intervals using a high power binocular scope and translucent grain size comparator to estimate grain size. In unpolished core slabs, grains are not cut and the depth of field is such that entire grain width can be observed, at least in these very

fine-grained rocks. Grain size estimates in core were validated by subjective observations in 101 thin sections, but not by point counts, understanding that the cross sectional area is narrower than the actual diameter. This is less of a problem with these very fine grained rocks than with coarser material.

A handful of quantitative grain-size data from thin section and X-ray diffraction (XRD) was made available to the study (Table 1). The grain size data, although very limited, helps to validate the work we performed with binocular microscopes on core and petrographic work 101 thin sections.

XRD data, although very limited, also provides support for our observations and conclusions. The first five samples are arkose and subarkose with low clay content, consistant with a loess interpretation. The balance of the samples are from marine carbonate intervals. They exhibit very low siliciclcastic content (quartz) supporting our observations in core and our conclusions that very little loess was delivered to the ramp during relative high sea level (interglacial periods).

Well	Depth (ft)	Zone	Mean Grain Size (mm)	Lithofacies	Qtz	Ksp	Plag	Cal	Dol	Anh	Clay	Total	Grain Density	Classification
Youngren	2794	A1SH	0.08	VFG Sand	59	20	7	4	0	6	4	100	2.65	Arkose
Youngren	2794	A1SH	0.098	VFG Sand	61	8	6	8	0	14	3	100	2.68	Subarkose
Youngren	2803	A1SH	0.058	Crs Silt	64	8	7	13	2	0	6	100	2.65	Subarkose
Youngren	2805	A1SH	0.06	Crs Silt	73	0	8	7	3	0	9	100	2.66	Subarkose
Youngren	2926	B4SH	0.58	Crs Silt	74	0	5	0	14	0	7	100	2.68	Subarkose
Youngren	2870	B1LM		Pkst-Grnst	3	0	0	74	0	23	0	100	2.76	
Youngren	2879	B1LM		Wkst	1	0	0	99	0	0	0	100	2.71	
Youngren	2896	B2LM		Pkst-Grnst	3	0	0	97	0	0	0	100	2.71	
Youngren	2898	B2LM		Pkst-Grnst	12	0	0	88	0	0	0	100	2.7	
Youngren	2917	B3LM		Pkst-Grnst	3	0	0	97	0	0	0	100	2.71	
Youngren	2918	B3LM		Pkst-Grnst	7	0	0	90	0	3	0	100	2.71	
Youngren	2932	B4LM		Pkst-Grnst	2	0	0	95	0	3	0	100	2.72	
Youngren	2952	B5LM		Wkst	6	0	0	78	16	0	0	100	2.73	
Youngren	2952	B5LM		Wkst	1	0	0	98	1	0	0	100	2.71	
Flower	2877	B1LM		Pkst-Grnst	3	0	0	95	2	0	0	100	2.71	
Flower	2891	B2LM		Pkst-Grnst	1	0	0	79	0	20	0	100	2.75	
Flower	2933	B4LM		Pkst-Grnst	3	0	0	97	0	0	0	100	2.71	
Flower	2950	B5LM		PA-Baff	0	0	0	100	0	0	0	100	2.71	

Table 1. Mineralogy from whole-core samples by X-ray diffraction (weight %). Continental siliciclastic rocks are shown at the top (A1SH and B1SH). Mean siliciclastic (quartz) volume in 13 marine carbonate samples is 3.5%. Data courtesy of Anadarko Petroleum Corporation (prepared by Reservoirs, Inc., unpublished data). Abbreviations include: Qtz, quartz,; Ksp, K-feldspar; Plag, plagioclase; Cal, calcite; Dol, dolomite; Anh, anhydrite; Clay, total clay; VFG Sand, very-fine-grained sandstone; Crs Silt, coarse-grained siltstone; Wkst, wackestone; Pkst-Grnst, packstone-grainstone; and PA-Baff, phylloid-algal bafflestone.

CORE LITHOFACIES AND DEPOSITIONAL ENVIRONMENTS

Main core lithofacies

Core fine- to medium-grained siltstone

Core coarse-grained siltstone

Unbranched, variably oriented, backfilled meniscate burrows,0.5-1 cm in diameter, with circular to elliptical cross sections are noted in several cores but are less common than in core very fine-grained sandstone. Measured lengths on core slabs are commonly >5 cm, although true burrow lengths are difficult to estimate due to variable orientation and core dimension constraints. On the basis of burrow morphology and size they are identified as adhesive meniscate burrows (AMB) and assigned to Naktodemasis isp. (Smith et al. 2008; Counts & Hasiotis, 2009). Burrows are distinctive due to color differences (selective iron depletion), or are recognized by a mottled texture in core or subtle grain arrangement in thin section (manuscript Fig. 6B, Fig. 6C, and Fig. 7). AMB commonly have crosscutting relationships with rhizoliths indicating the AMB and pedogenic features are contemporaneous. Fig. 2 (below) is an additional example of AMB.
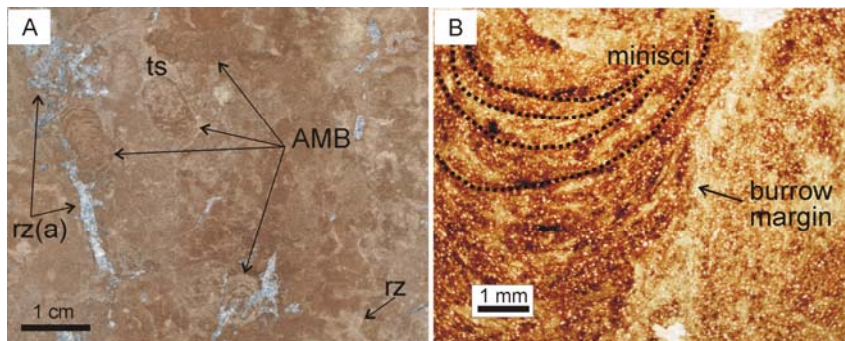

Fig. 2. Examples of *Naktodemasis* in core coarse-grained siltstone (well: Cross H Cattle; depth: 792 m (2600 ft); zone: A1SH; Speiser Shale). **(A)** Core slab is heavily burrowed. Arrows indicate several well-defined *Naktodemasis*. Most other mottling due to *Naktodemasis* combined with rhizohaloes. Rhizohaloes filled with silt (rz) or later anhydrite (rz(a)). *Naktodemasis* in thin section (ts). **(B)** In thin section photomicrograph (diffused transmitted light), thin, subparallel menisci-bound back fill packets of *Naktodemasis*.

Core very fine-grained sandstone

Interpretation of main lithofacies

Depositional environment

Climate signal

    Seasonality

    Long-term moisture variability

Lesser core lithofacies

Core gray muddy siltstone-laminated

Core gray muddy siltstone-blocky

Core primary evaporite

Core laminated sandstone and siltstone

Core nodular carbonate mudstone

GEOMODEL LITHOFACIES IN THREE-DIMENSIONAL MODEL

Relation of core lithofacies to geomodel lithofacies

Geomodel lithofacies architecture

Carbonate and siliciclastic strata are cyclically interbedded, however, siliciclastic strata clearly dominate the inner ramp position and marine carbonates dominate basinward of mid ramp (Fig. 3). Contour maps in Figs. 3 and 4 are based on data from 1139 wells that penetrated the complete Council Grove interval. Council Grove is thinnest at a mid ramp position (70 m, 230 ft), exceeds 85 m (280 ft) in the inner ramp (northwest), and thickens dramatically to 107 m (350 ft) in the outer ramp and steepened ramp (southeast) (Fig. 3A). Net siliciclastic thickness, the sum of silciclastic intervals in all seven cyclothems, ranges from 73 to12 m (240-40 ft) from northwest to southeast across the study area (Fig. 3B). Net carbonate thickness, the sum of carbonate intervals in all seven cyclothems, ranges from 76 to15 m (50-250 ft) from northwest to southeast across the study area (Fig. 3C). N/G ratio (net siliciclastic/gross interval) demonstrates that 80% of the Council Grove is siliciclastic in the northwest and 80% is marine carbonate to the southeast (Fig. 3D).

Siliciclastic grains tend to decrease in size toward the southeast (Figs. 4, 5). Grain-size distribution for Blue Rapids Shale (B1SH) is representative of trends observed in all cyclothems studied. Blue Rapids Shale is thickest in the west and northwest (Fig. 4A) where geomodel very fine-grained sandstone dominates (Fig. 4B). N/G ratios (lithofacies thickness/overall interval thickness) demonstrate the trend of coarse-to-fine grain size from west-northwest to east-southeast. N/G geomodel very fine-grained sandstone is highest in the west and northwest (Fig. 4C). N/G geomodel coarse-grained siltstone is highest in a mid ramp position (Fig. 4D). N/G geomodel fine- to medium-grained siltstone is highest in the southeast (Fig. 4E). Geomodel very fine-grained sandstone dominates the siliciclastic intervals near the inner portion of the ramp in four of the seven cyclothems (Figs. 5 and 6). Shaded portions of cross sections in Fig. 5 are areas

of lower node-well density. Aberrations in vertical or lateral lithofacies distribution as compared to un-shaded areas of higher density may be a function of the stochastic simulation process that populates areas between node wells constrained by variograms (see Dubois *et al.*, 2006). Un-shaded areas are considered more accurate representations than shaded areas.

B2LM and B3LM (Beneath B2SH and B3SH) pinch out in the inner ramp position and other marine intervals also thin westward. Thinning and pinching out coincides with thickening in underlying siliciclastic intervals. The datum selected in Fig. 5 (top of B4LM) helps illustrate relief built by deposition of siliciclastic strata, primarily geomodel very fine-grained sandstone and geomodel coarse siltstone. Council Grove is thinnest at the mid ramp position. Geomodel very fine-grained sandstone lithofacies dominates siliciclastic intervals in the up-dip position. It occurs as expansive, 30-50+ km wide, relatively thin (2-4 m) deposits, stratigraphically near the middle of the siliciclastic intervals. Down dip, geomodel very fine-grained sandstone is less common, and geomodel coarse-grained siltstone dominates the middle of the intervals. Geomodel fine- to medium-grained siltstone is commonly restricted to the upper and lower portions of the intervals in this region.

Connected volume views, generated in Petrel^{TM}, are views of geomodel cells that are in contact with one another having the same lithofacies in the cellular model and are particularly useful in illustrating the large scale geometry of the geomodel very fine-grained sandstone (Fig. 6). The model volumes depicted were filtered to show the ten largest connected volumes. Where present, sandstone bodies extend over large areas and mostly lack linear, elongate, or other shapes that would suggest deposition by channelized water. They do not exhibit clear onlapping or offlapping relationships, however, internal geometries are difficult to image at the scale at which the model was run.
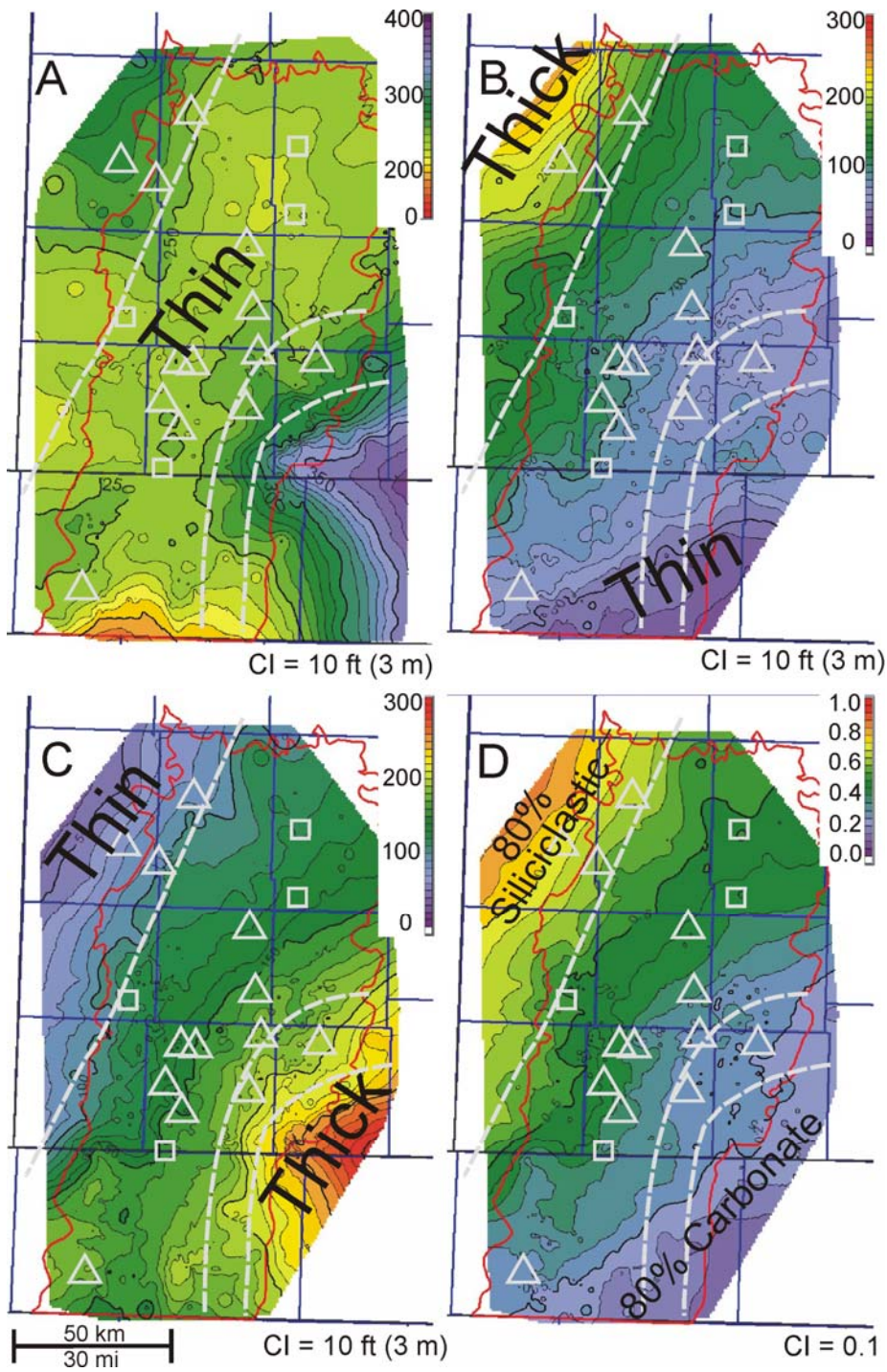
Fig. 3. Summary maps for the upper seven Council Grove cyclothems (Speiser Shale through the Grenola Limestone). **(A)** Gross thickness for the seven cyclothems. **(B)** Net siliciclastic thickness map—sum of siliciclastic thickness in seven cyclothems. **(C)** Net marine carbonate thickness map—sum of marine carbonate in seven cyclothems. **(D)** Net-to-gross ratio (net siliciclastic/gross interval).
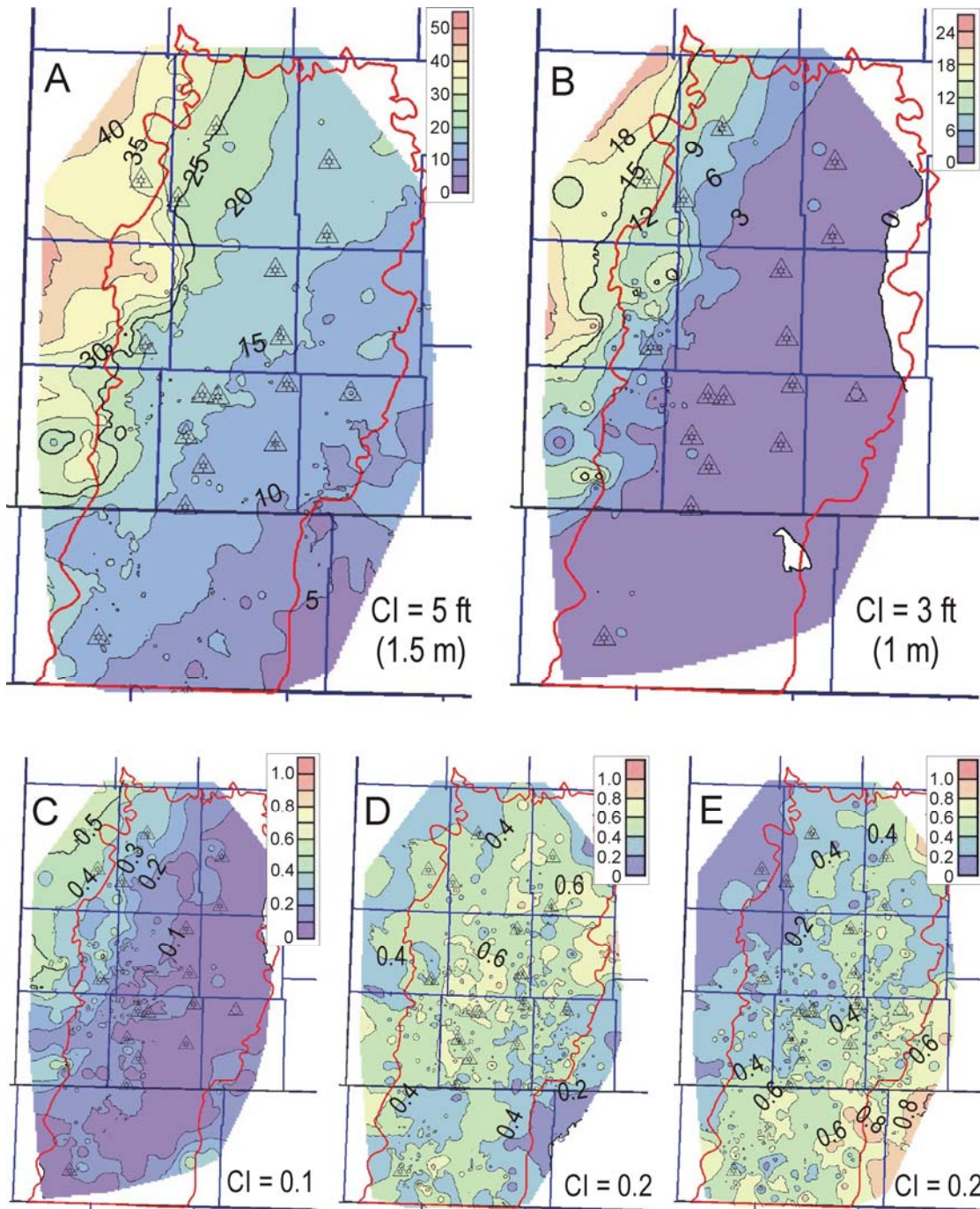
Fig. 4. Blue Rapids Shale (B1SH) summary maps. **(A)** Gross interval thickness. **(B)** Net sandstone thickness. **(C)** Net-to-gross geomodel very fine-grained sandstone (lithofacies thickness/overall interval thickness). **(D)** Net-to-gross geomodel coarse-grained siltstone. **(E)** Net-to-gross geomodel fine- to medium-grained siltstone.
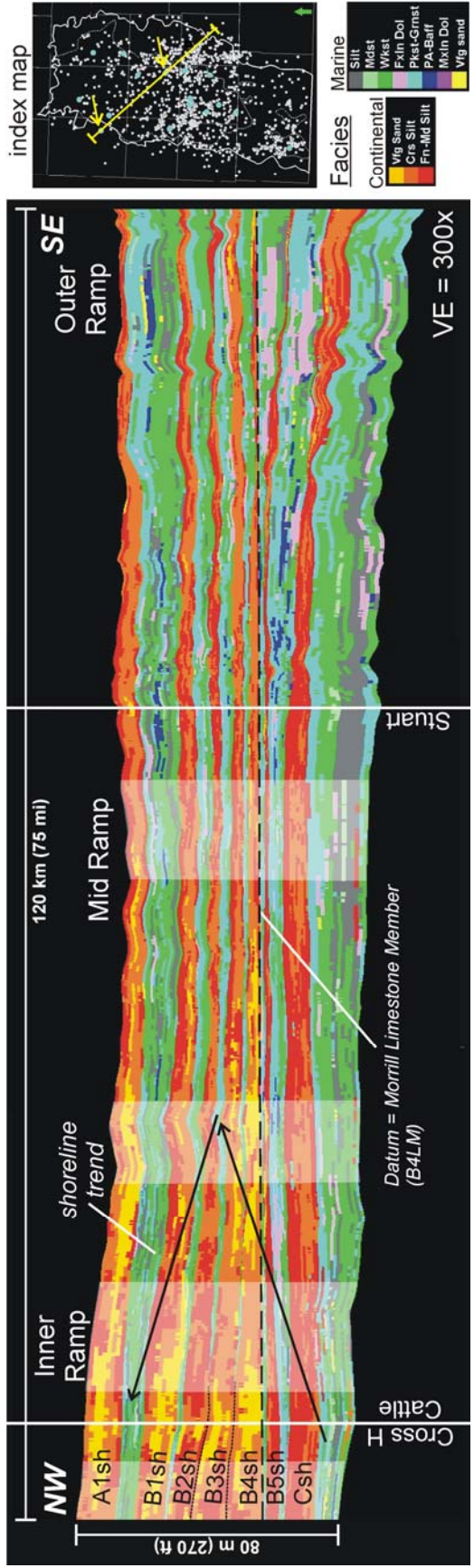
Facies

Continental
- Vfg Sand
- Crs Silt
- Fn-Md Silt

Marine
- Silt
- Mdst
- Wkst
- Fxln Dol
- Pkst-Grnst
- PA-Baff
- Mxln Dol
- Vfg sand

index map

NW

SE

Outer Ramp

Mid Ramp

Inner Ramp

VE = 300x

120 km (75 mi)

80 m (270 ft)

shoreline trend

Datum = Morrill Limestone Member (B4LM)

Stuart

Cattle

Cross H

A1sh
B1sh
B2sh
B3sh
B4sh
B5sh
Csh

Fig. 5. (prior page) Stratigraphic cross section of the Council Grove (vertical slice from a cellular geomodel built with Petrel[TM]) with the datum being the top of the B4LM. Section is approximately perpendicular to depositional strike and cuts two of the core wells, shown by arrows on index map and named on cross section. Siliciclastic (continental) rocks represented by warmer colors. Gray-shaded areas indicate low well density where unusual lithofacies geometries are likely aberrations of the stochastic simulation process during model construction. Lithofacies abbreviations: Vfg sand, geomodel very-fine grained sandstone; Crs silt, geomodel coarse-grained siltstone; FnMd silt, geomodel fine- to medium-grained siltstone; Silt, siltstone; Mdst, carbonate mudstone; Fxln Dol, fine-crystalline dolomite; Wkst, wackestone; Pkst-Grnst, packstone-grainstone; PA-Baff, phylloid algal bafflestone; and Mxln Dol, medium-crystalline moldic dolomite.
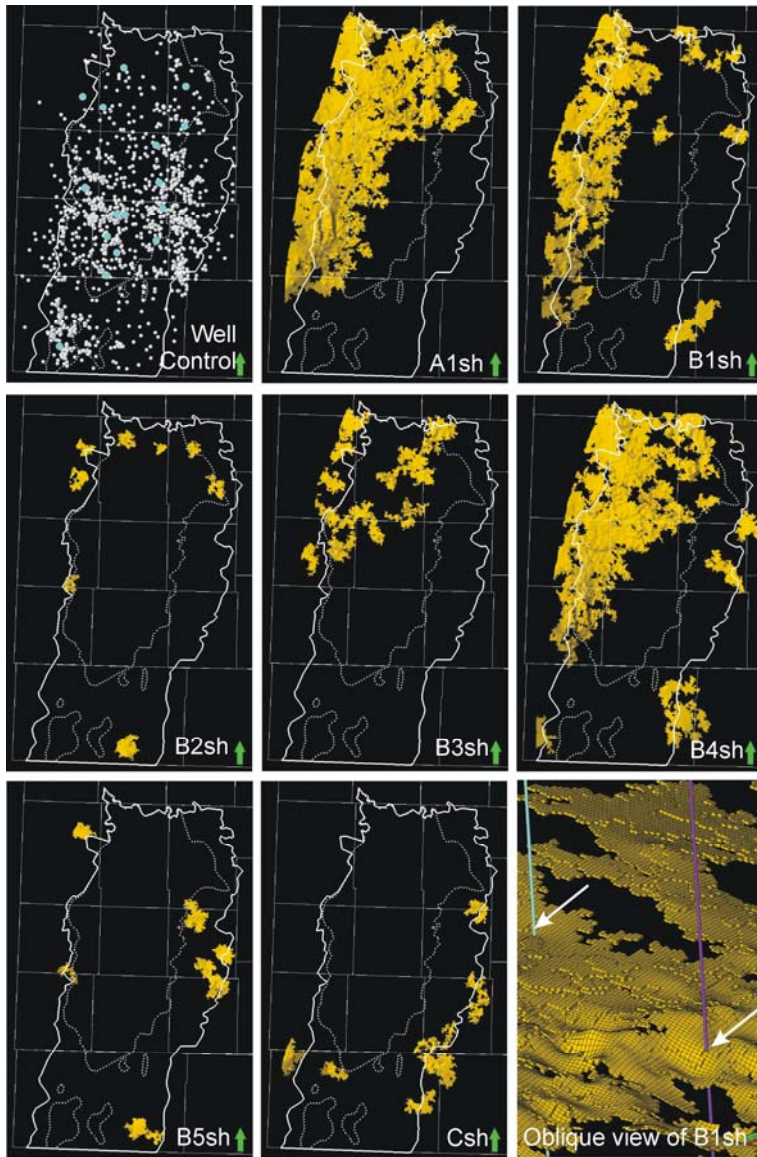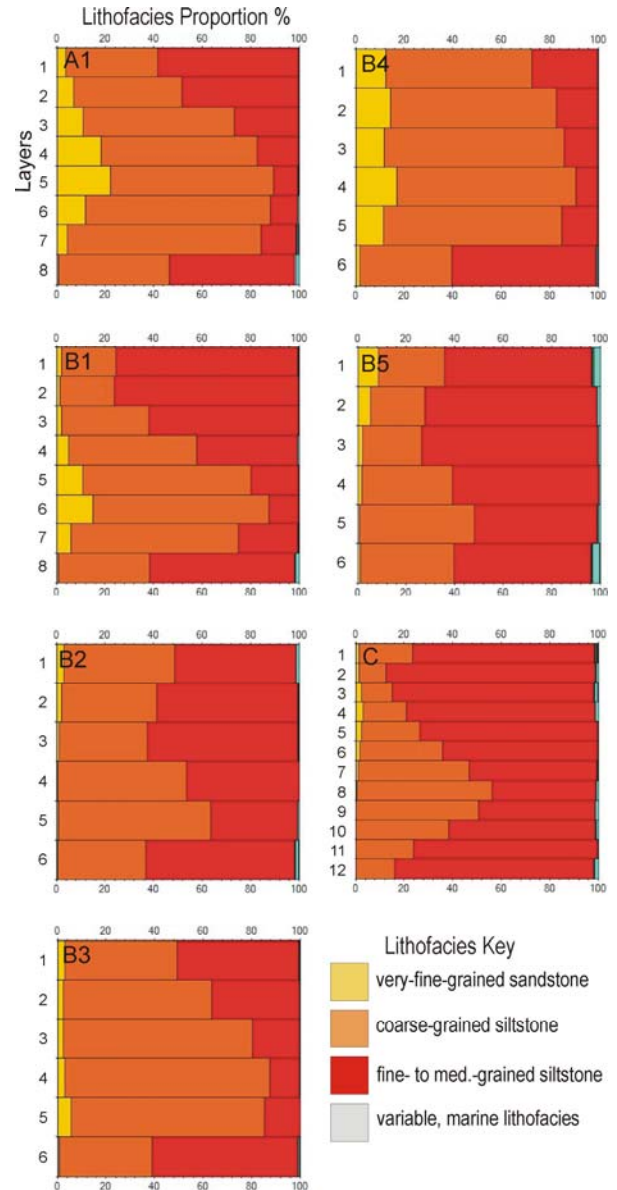

Fig. 6. Two-dimensional view of three-dimensional connected volumes (CV) for geomodel very fine-grained sandstone derived from cellular geomodel. Illustrated in upper left is well control, 1234 wells with lithofacies predicted by neural networks (white) and 17 with lithofacies from core (blue). Ten largest CV for each siliciclastic interval studied are shown. Oblique view (lower right) looking to northwest shows part of B1SH CV cells, which have XY dimensions of 200 m (660 ft) and Z of approximately 0.6 m (2 ft). Two wells with arrows are the most northwestern wells with core. Vertical exaggeration is 100X. Data in fringe areas have been clipped (not shown) because they are less reliable where well control is sparse.

DISTRIBUTION OF LITHOFACIES

Vertical succession of core lithofacies

An ordered succession of lithofacies is presented in the manuscript on the basis of core lithofacies, but is also supported by geomodel statistics. Although only three lithofacies are defined in the geomodel, these three lithofacies directly correlate to 84% of core lithofacies. In the geomodel, finer-grained siliciclastic strata generally dominates at the base of the siliciclastic intervals, immediately above shallowing-upward carbonate strata, and at the top of the siliciclastic intervals immediately below the carbonate intervals (Fig. 7). Coarser grained siliciclastic components, very-fine-grained sandstone and coarse-grained siltstone, are most common near the stratigraphic center in six of the seven siliciclastic intervals. Thus, an ordered, vertical succession of geomodel lithofacies, coarser towards the middle and finer at the top and base, is supported by model statistics.

Fig. 7. Geomodel lithofacies proportions in siliciclastic intervals (ratio of given lithofacies volume to entire model volume for a given layer). In general, coarsest lithofacies occur towards the middle and finer lithofacies are at the top and base of the intervals.

Core lithofacies across the ramp

DISCUSSION

Climate linkage to glacial-eustasy and controls on sedimentation

Integrated climatic-eustatic-depositional model

Aggradation and accommodation

CONCLUSIONS

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