CHAPTER 3. DEPOSITIONAL MODEL
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Introduction

Climate, shelf geometry, and glacially forced sea level changes all influenced sediment supply, depositional patterns, accommodation and stabilization of both the marine and continental sediments in the study area. The Hugoton shelf was near the paleo-equator (Figure 3.1) and monsoonal climate conditions are likely to have prevailed at the annual scale (Parrish and Peterson, 1988). Generally arid conditions accompanied glacially induced sea-level lowstands with more humid conditions and high sea level present during interglacial periods (Rankey, 1997; Soreghan, 2002). Prevailing winds are thought to have been from the present-day west during winter and east during summer (Parrish and Peterson, 1988). Extremely low relief enabled rapid migration of the shoreline position and changes in shelf hydrodynamics across the entire study area with only minimal changes in sea level. These conditions set the stage for the vertical succession of lithofacies repeated from one sedimentary cycle to the next as well as remarkable lateral continuity of thin lithofacies units within each cycle.

Shelf Geometry

Technically during Wolfcampian the Hugoton area might be classified as a distally steepened ramp of Read (1985) with the steepening occurring in the southeast portion of the study area (Chapter 2, Figures 2.5 and 2.6). However, for simplicity, we prefer to describe the area with low dip covering most of the study area as shelf and the area of steeper dip, shelf margin. Dubois and Goldstein (2005) estimated the maximum relief across the Kansas portion of the shelf during Council Grove deposition to have been 100 ft (30 m) with a slope of approximately 1 ft/mi (0.18 m/km), a value close to the minimum paleoslope estimated for the Lansing-Kansas City (Pennsylvanian, Missourian) on the Kansas shelf (0.5-1.1 ft/mi, 0.1-0.2 m/km) by Watney et al. (1995).

We do not have a method that provides a precise, irrefutable paleoslope and water depth, but we are reasonably certain of our estimates, at least the Council Grove, for these two important geometric measures. Our estimates are based on three criteria: 1) subsidence history reported in literature, 2) isopachs of relatively large intervals, and 3) location of the updip extent of marine carbonates in combination with updip extent of depth-specific fauna (fusulinids). From earlier work, the Anadarko basin experienced maximum subsidence in Early Pennsylvanian and by Permian subsidence had waned to the point that the entire basin had nearly filled (Kluth and Coney, 1981; Rascoe and Adler, 1983; Kluth, 1986; Perry, 1989). The isopach encompassing most of the Wolfcampian (upper 13 cycles, from the top of the Chase Group to the base of the Grenola Limestone formation in the lower Council Grove Group) thickens only 80 ft (480-560 ft, 146-170m) in 60 mi across the shelf (24m in 100km), a rate of 1.3 ft/mi, 0.24 m/km (Figure 3.2). Any single cycle shows considerable less thickening, but the rate of thickening cannot be considered as equaling slope because the systems were not efficient at filling accommodation space (forced progradation discussed below). Two marine carbonate half-cycles in the middle of the Council Grove (B2_LM and B3_LM) pinch out at or near the west updip margin of the Hugoton field (Figures 3.3 and 3.4, pinning the water depth as zero at that point, and marking the maximum extent of marine flooding on the shelf for those cycles. Other Council Grove cycles thin substantially, especially the B1_LM and B4_LM.

The use of fusulinids as paleo-water-depth indicators in the Pennsylvanian and Permian has been debated extensively. They may live in a wide range of depths and can be easily transported into an even wider range of depths. Mazzulo et al. (1995) provide an overview of the debate and we agree with their assessment that a typical minimum depth for Early Permian fusulinids is approximately 50-60 ft (15-18 m). All Council Grove cycles studied except the Eiss (B3_LM) and Morrill (B4_LM) have thin, distinctive fusulinid-rich intervals that are adjacent to or mark the maximum flooding of their respective marine half-cycles (Figure 3.5). Occurrences in cores studied are usually characterized by an abrupt appearance and disappearance (vertically) of very abundant, large (cm-size) fusulinids, in contrast with occasional scattered individuals, sometimes present in adjacent strata. Boardman and Nestell (1993) and Boardman et al. (1995) place the occurrence of fusulinid biofacies in the transgressive limestone and at the base of the regressive limestone, separated by the deeper-water core shale interval of the idealized Pennsylvanian-Permian cyclothem (Heckel, 1977), placing it approximately in the middle of the relative depth scale for cycles cropping out in eastern Kansas and northeastern Oklahoma. Recognized in this study is the notable absence on the Hugoton shelf of the dark, fissile “core shale” common to Wolfcampian cycles in outcrop (Mazzullo et al., 1995; Boardman and Nestell, 2000), suggesting that water depths on the Hugoton shelf were less than those at the present day outcrop 300 mi (480 km) to the east. The closest equivalent to the typical deep water lithofacies in Hugoton core are dark marine siltstones found near the base of the marine carbonate intervals in four of the 13 cycles studied, the Grenola (C_LM), Funston (A1_LM), Wreford, and Fort Riley. Maximum updip extent of the fusulinid biofacies (Figure 3.3) shows an interesting pattern that is probably related to variability in the amplitude of the oscillating sea level.

Of the seven Council Grove cycles studied, the fusulinid facies extends furthest updip in the two outermost cycles (A1_LM and C_LM), while the B1_LM and B5_LM are downdip and the next cycles towards the center of the Council Grove interval studied. Maximum updip for the fusulinid biofacies in the B2_LM is further southeast and downdip. Neither the B3_LM nor B4_LM have the fusulinid biofacies present in cores studied. If the fusulinid biofacies is assumed to be present in all cycles where water depths exceeded 50-60 ft (15-18 m), then the lack of fusulinids in the cores studied for the B3_LM and B4_LM suggests the water never exceeded that depth in the study area having core data (most of the Hugoton in Kansas and Oklahoma).

Thinning and pinchouts of the Wolfcampian units at the updip margin of the Hugoton are not mechanical in nature as substantial erosion of the upper portion of marine half-cycles is nearly nonexistent in approximately 200 observations of this transition in cores from

29 wells. In the Middleburg (B2_LM) marine carbonate, the maximum extent of the fusulinid facies is approximately 50 mi (80km) from its pinchout (Figure 3.3), suggesting a slope of 1 ft/mi (0.2 m/km), assuming that the minimum water depth for the fusulinid facies is 50 ft (15m). This rate is consistent with rate of thickening in the Wolfcamp (1.3 ft/mi, 0.24 m/km). The other four cycles (A1, B4, B5 and C) do not pinch out in core in the study area but their patterns of fusulinid occurrence fit with lower frequency cyclicity. Considering the three criteria, we believe the slope on the shelf was approximately 1 ft/mi (0.2 m/km) during the deposition of the Council Grove Group. Beyond the shelf break the slope may have increased by 10 times to 10 ft/mi (2 m/km).

Using this reasoning we can estimate the water depths for the Council Grove cycles in the study area. Near, but above, the shelf break in northwest Seward County we estimate water reached a maximum depth of approximately 110 ft (34m) during deposition of the A1_LM and C_LM, 80 ft (24m) for the B1_LM and B5_LM, 50 ft (15m) for the B2_LM and slightly less than 50 ft (<15 m) for the B3_LM and B4_LM. We have not studied the occurrence of fusulinids in the Chase nor have we attempted to estimate water depth. However, the slope is likely to have decreased as subsidence decreased through time as the Anadarko was filling during this period.

Cyclicity

The cyclical nature of the Council Grove and Chase is widely recognized (Siemers and Ahr, 1990; Caldwell, 1991; Mazzulo et al., 1995; Puckette et al., 1995; Olson et al., 1997; Boardman and Nestell, 1993; Boardman and Nestell, 2000; Olszewski and Patzowsky, 2003). Vertical succession of lithofacies in a shoaling upward pattern in both the Council Grove and Chase Groups (Figure 3.6) is a result of depositional environments changing across the shelf in response to rapid sea level fluctuation. In our study, differences in the style (symmetry) and pattern (lithofacies) among the Chase cycles recognized by Olson et al. (1997) are confirmed for the most part. Exceptions are that we observed fine-grained sandstone of marginal-marine origin at both the top and base of the Towanda and Winfield near the updip margin of the field, although it is more common to find the situation as they are depicted elsewhere (sandstone at the base of the Towanda and top of the Winfield). Although similar in many respects, the Council Grove cycles are typically more asymmetric than the Chase cycles and tend to have better-developed, thin, packstone-grainstone lithofacies at the base of the marine half-cycle. Figure 3.7 presents a composite of the vertical distribution of lithofacies from model node wells (Chapter 6) and illustrates the difference in symmetry between a Council Grove and Chase cycle.

We resisted the temptation to place the sedimentary record of the Chase and Council Grove in a sequence-stratigraphic framework (Van Wagoner et al., 1988), mainly because it was not necessary for building the Hugoton geomodel. Intervals were defined within a simple cyclic rather than a sequence stratigraphic framework. Existing formation or member tops are half-cycle boundaries between marine and continental intervals and represent a sequence boundary and flooding surface. Because the transgressive system tract (flooding surface to maximum flooding) is relatively thin and consistent in the majority of the cycles, little is gained by correlation of an additional surface for sequence-stratigraphic classification. Readers interested in Wolfcamp sequence stratigraphy in the Anadarko basin are referred to works by Boardman et al. (1995), Mazzulo et al. (1995), Boardman and Nestell (2000), Miller and West (1998), and Olszewski and Patzowsky (2003).

Boardman and Nestell (2000) recognized three orders of depositional sequences in the Council Grove and placed Goldhammer et al. (1993) time scales on them (3^{rd} order, 1-10 Ma; 4^{th} order, 0.1-1 Ma; and 5^{th} order, 0.01-0.1 Ma). We recognize the same orders of frequency, but prefer to refer to them as depositional cycles. The seven marine-continental cycles we describe in the Council Grove (Figure 1.4, Chapter 1) correspond to the upper six of their nine 4^{th} order depositional sequences. We interpret their Beattie 4^{th} order sequence as two 4^{th} order cycles, the Morrill (B4_LM) and Cottonwood (B5_LM). If we accept Boardman and Nestell's (2000) nine 4^{th} order depositional sequences and our six 4^{th} order cycles for the Chase, the Wolfcamp has 15 4^{th} order cycles. Ross and Ross (1988) Permian cycle chart suggests the Wolfcamp lasted 11.5 my (274.5-286 Ma), an average of 0.8 Ma per cycle, the upper end of the range for a Goldhammer et al. (1993) 4^{th} order cycle. Higher order cyclicity (fifth) is recognized in the Funston (A1_LM) and Grenola (C_LM), where lithofacies and associated fauna indicate two flooding events that are traceable in core and on wireline logs throughout the study area (see Figure 3.4).

Patterns through time (multi-cycles) and space of the position of the maximum flood shoreline, maximum extent of certain biofacies (fusulinids in the Council Grove), gross thickness of the marine half-cycles, and lithofacies distribution are overwhelming evidence for lower-order cyclicity (third). The Hugoton geomodel provides us with an unprecedented view of the entire Wolfcamp volume in 3D over an extremely large area (10,000 square mi, 26,000 km square). The model facilitates the study of sedimentary response to two related variables, sea level oscillation and climate (glaciation) without the overprint of tectonics, during a period when the earth was transitioning from icehouse to greenhouse conditions. Figure 3.3 demonstrates systematic shifts in the fusulinid biofacies and shoreline about a pivot point, the middle of the seven Council Grove cycles studied (B3_LM). The same pattern is illustrated in a vertical slice through the geomodel (Figure 3.4) with the shoreline extent at a minimum in the middle of the Council Grove. In the context of glacial-eustatic cycles and a stable shallow shelf, gross thickness of marine carbonate can be considered a proxy for submergence time and water depth. The thinnest marine half-cycle of the seven studied for the Council Grove is the middle cycle, Eiss (B3_LM). Adjacent cycles increase in thickness with the A1_LM and C_LM (first and seventh cycles) being the thickest (also see Figure 1.4, Chapter 1). In the Council Grove, lithofacies patterns, notably the transition from grain-supported textures (basinward) to mud-supported (landward) on the Hugoton shelf (Figure 3.9), exhibit patterns consistent with other indicators for higher-order cyclicity in the Council Grove. Connected volumes in depicted in 2-D maps in Figure 3.9 are volumes of cells in the Hugoton 3-D cellular model that have the same properties defined by filter ranges. This type of illustration does not show thickness (number of cells vertically), but serves to illustrate overall distribution trends. The 15 largest volumes of connected cells with lithofacies defined as packstone-grainstone (lithofacies 7) having > 10% porosity (six of seven marine half-cycles). A higher porosity limit of 14% for the B5_LM was used because the connected volumes for >10% are extremely large for that interval and do not illustrate the general trend as well. The updip extent of grain-supported texture (packstone-grainstone) within marine half-cycles serves as proxies for bathymetry on the shallow shelf, and parallels the trends established for the extent of the fusulinid biofacies (Figure 3.3), for the most part. Carbonate rocks with mud-supported textures deposited in a quiet lagoonal setting dominate updip from the packstone-grainstone lithofacies geobodies (connected volumes). Packstone-grainstone lithofacies has its furthest landward excursion in the A1_LM and C_LM (maximum-flooding cycles) and it's shortest in the B3_LM (minimum-flooding cycles). Shelfward extent of packstone-grainstone lithofacies in the marine intervals B1, B2, B4, and B5 are intermediate to the end members.

Our observations are consistent with the work by Olsen et al. (1997), where they place a maximum-flooding cycle in the lower Council Grove and in the Fort Riley (Chase) and infer that the E Lime (Eiss, B3_LM by our nomenclature) is a minimum-flooding cycle (Figure 3.8). We agree that the Fort Riley is likely the "deepest" cycle in the Chase and that water depths generally decreased in successive cycles. However, whether the cycle-stacking pattern is progradational is debatable and deserves further study. It is conjecture at present, but we propose that changes in climate and sea level oscillation amplitude and/or frequency during the transition from icehouse to greenhouse are responsible for differences between Council Grove and Chase cycles. Shifts in control variables likely influenced sediment type and supply (more marine siliciclastics upward) and duration of marine flooding on the shelf and may be the reason Chase marine intervals are significantly thicker. Decreased frequency (slower cycle oscillation) would tend to support a "normal" progradation, or possibly aggradation, rather than "forced" regression interpretation for individual Chase cycles above the Fort Riley (further discussion below). Chase cycles above the Fort Riley (Towanda, Winfield and Krider) appear to be an aggradational cycle set, or possibly retrogradational (back-stepping lithofacies in Figure 3.4). Again, more study is needed. The immediate superior Herington cycle marks a fundamental shift from mixed carbonate-siliciclastic cycles to Leonardian mixed siliciclastic-evaporite rocks that are the top seal for the Hugoton reservoir system (Garlough and Taylor, 1941; Mason, 1968; Pippin, 1970; Parham and Campbell, 1993).

Idealized models

Idealized depositional models for the Council Grove (Figure 3.4) and Chase (Figure 3.5) are similar, but differences exist due to gradual changes in climate, ambient sea level position, and sea level fluctuation rate. Differences may be related to a shift from more icehouse to more greenhouse conditions in the Permian (Parrish, 1995; Olszewski and Patzkowsky, 2003). For all studied Council Grove cycles, the entire Hugoton shelf was above sea level during maximum lowstand. Continental redbed siliciclastics accumulated, were stabilized by vegetation, and built relief preferentially near the field's west updip margin (Dubois and Goldstein, 2005). Accommodation for the carbonate sediments of the overlying marine half-cycle was reduced, leading to non-deposition, or pinchouts, of several marine intervals in the Council Grove at that position.

At the end of each lowstand, a relatively rapid sea-level rise resulted in deposition of a thin (1-4 ft, 0.3-1.2 m) transgressive carbonate-siliciclastic interval at the base of each marine half-cycle. Only in the Funston (A1-LM) and Neva (C-LM) cycles are well-developed marine siliciclastics (shaly siltstone) deposited during maximum flooding. After maximum flooding, shallowing accompanied by conditions that fostered increased carbonate production resulted in a shoaling-upward lithofacies-stacking pattern. A fall in absolute sea level caused progradation of broad facies belts (e.g., carbonate-sand shoals) resulting in laterally extensive lithofacies bodies. The primary evidence for progradation being forced by sea level fall rather than due to excess sediment influx relative to accommodation space (definition of forced regression by Posamentier et al., 1992) is in the vertical succession and relative thickness of depositional facies. Relatively deep-water facies (maximum flooding), recognized by darker color; normal-marine faunal assemblage, including thin-shelled brachiopods, crinoids, fenestrate bryozoan; mud supported texture; and elevated concentrations of siliciclastic silt and clay (Olson et al., 1997), were deposited well below wave base, probably in a few 10's of meters of water. The complete succession of facies above the maximum-flooding interval passes through subtidal, peritidal, supratidal and, ultimately, continental depositional environments in as little as 3 m (Council Grove Group cycles) to a maximum of 15 m (Chase Group cycles). Aggradation by carbonate production was outpaced by absolute sea level fall, especially in the Council Grove. The Chase marine carbonate half-cycles are up to several times thicker than those of the Council Grove, and progradation of lithofacies by carbonate sediment production exceeding subsidence may have occurred.

With continued sea level fall, continental sabkha, coastal plain and savannah environments followed the retreating shoreline and covered the carbonate surface. Evidence for prolonged direct subaerial exposure and erosion of the carbonate surface is absent in all seven Council Grove cycles in the nine cores examined. Instead of calcretes, microkarst, erosion, or other indicators of prolonged exposure in the upper portion of the marine carbonate, there is a vertical succession of lithofacies that suggests continuous sedimentation that accompanied a sea level fall and withdrawal: subtidal carbonate, tidal-flat carbonate, red siltstone and muddy siltstone with anhydrite (sabkha), and finally red siltstone with paleosols (coastal plain or savannah).

Although Chase deposition was similarly influenced by absolute sea level, it differs from the Council Grove in significant ways. During Chase lowstand, the lateral extent of subaerial exposure on the shelf was generally more limited, and in some “continental” intervals, tidal-flat siltstone and very fine-grained sandstone is prevalent, particularly in positions lower on the shelf. Fine-grained eolian sandstone present in nearly all continental half-cycles in the Council Grove is nearly absent in the Chase. Marine transgressions in the Chase generally extended further landward than they did during Council Grove deposition with marine sediments extending beyond the updip margin of the field in all six cycles, whereas they pinch out in four of the seven Council Grove cycles studied. During the maximum highstand and the subsequent fall in sea level, carbonate sand shoals of the Chase tend to be coarser grained. Constituents include bioclasts and occasionally ooids, rather than oncoids and peloids (in the Council Grove), indicating more open-marine conditions. Another significant difference between the Chase and Council Grove is the presence of fine-grained sandstone deposited in tidal flat and marginal marine settings at either the top, base, or top and base of all cycles above the Fort Riley in the northwest portion of the of the field (Winters et al., 2005).

In all Chase or Council Grove intervals, the nature of the lithofacies present in a succession is a function of the position on the shelf: the further west and updip, the greater the volume of siliciclastics, whether in the marine or continental setting. Marine carbonate tends to be muddier to the west and northwest, and grain-supported carbonate tends to be finer towards the west with the dominant grains being hardened pellets (round, very fine-grained, micritic) and peloids (subrounded, fine-grained, micritic) rather than oncoids, bioclasts, or ooids (found in upper Chase only). Marine environments become more restricted in a westerly direction and rocks with normal-marine assemblages are absent in most of the Council Grove cycles at or near the west margin of the field. Both the Chase and Council Grove cycles exhibit gradual changes through time that may be related to third-order cyclicity (Boardman and Nestell, 2000) and the overall shift from icehouse to greenhouse conditions that began in Late Pennsylvanian and continued until the end of glacial conditions in the Permian (Parrish, 1995). Most likely as a consequence of the climate-change trend, Chase marine-carbonate intervals tend to be 3-5 times thicker than their Council Grove counterparts, at least in the Crouse through Cottonwood interval (B1-LM – B5-LM) on the Hugoton shelf.

Geology of the updip field margin

See: Dubois, M. K., and Goldstein, R.H., 2005, Accommodation model for Wolfcamp (Permian) redbeds at the updip margin of North America's largest onshore gas field (abs.): Proceedings American Association of Petroleum Geologists 2005 Annual Convention, June 19-21, Calgary, Alberta, Canada, and Kansas Geological Survey Open-file Report 2005-25, http://www.kgs.ku.edu/PRS/AAPG2005/2005-25/index.html (accessed March 20, 2007)

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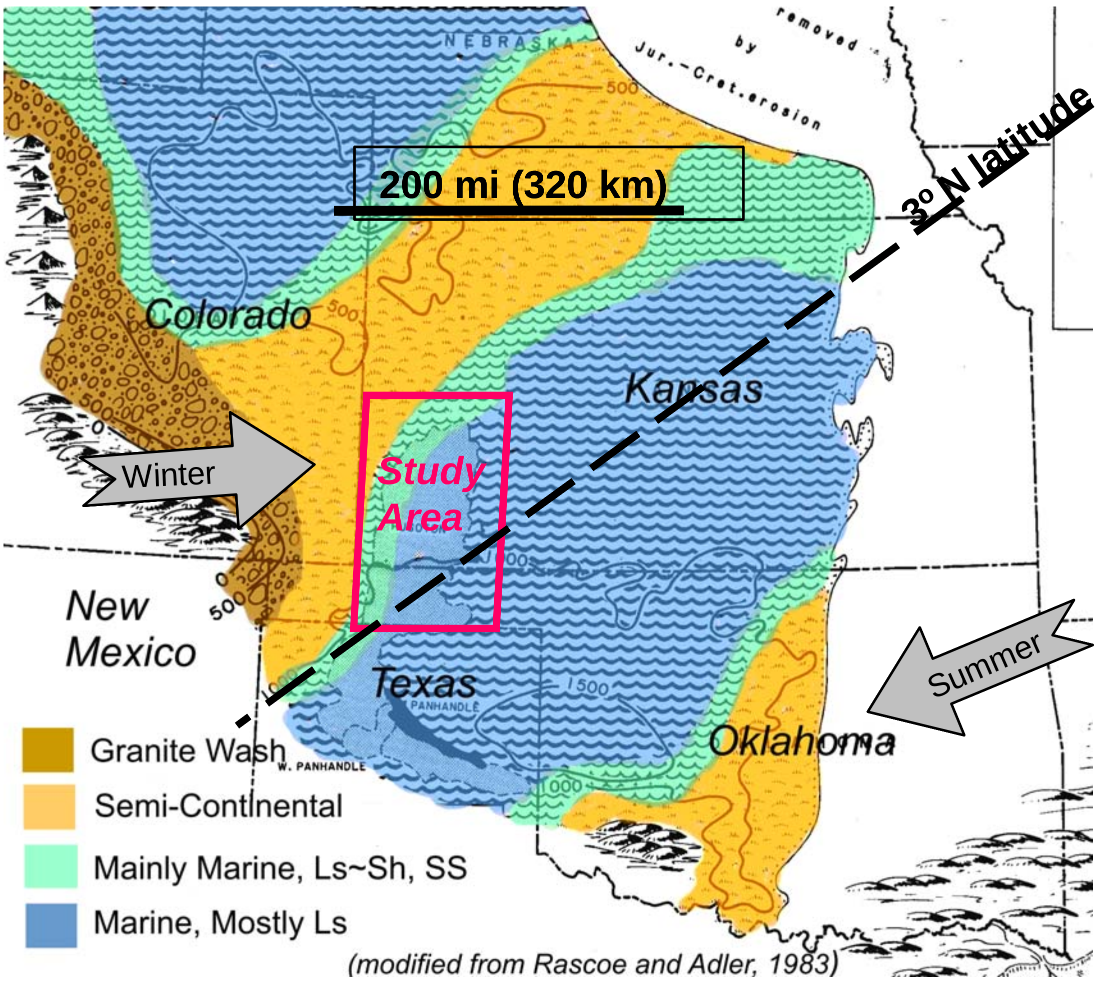

Figure 3.1. Distribution of major lithofacies in the midcontinent during the late Wolfcampian (after Rascoe, 1968; Rascoe and Adler, 1983). Approximate paleo-latitude was 3 degrees north (Scotese, 2004). Prevailing wind directions are from Parrish and Peterson, 1988.

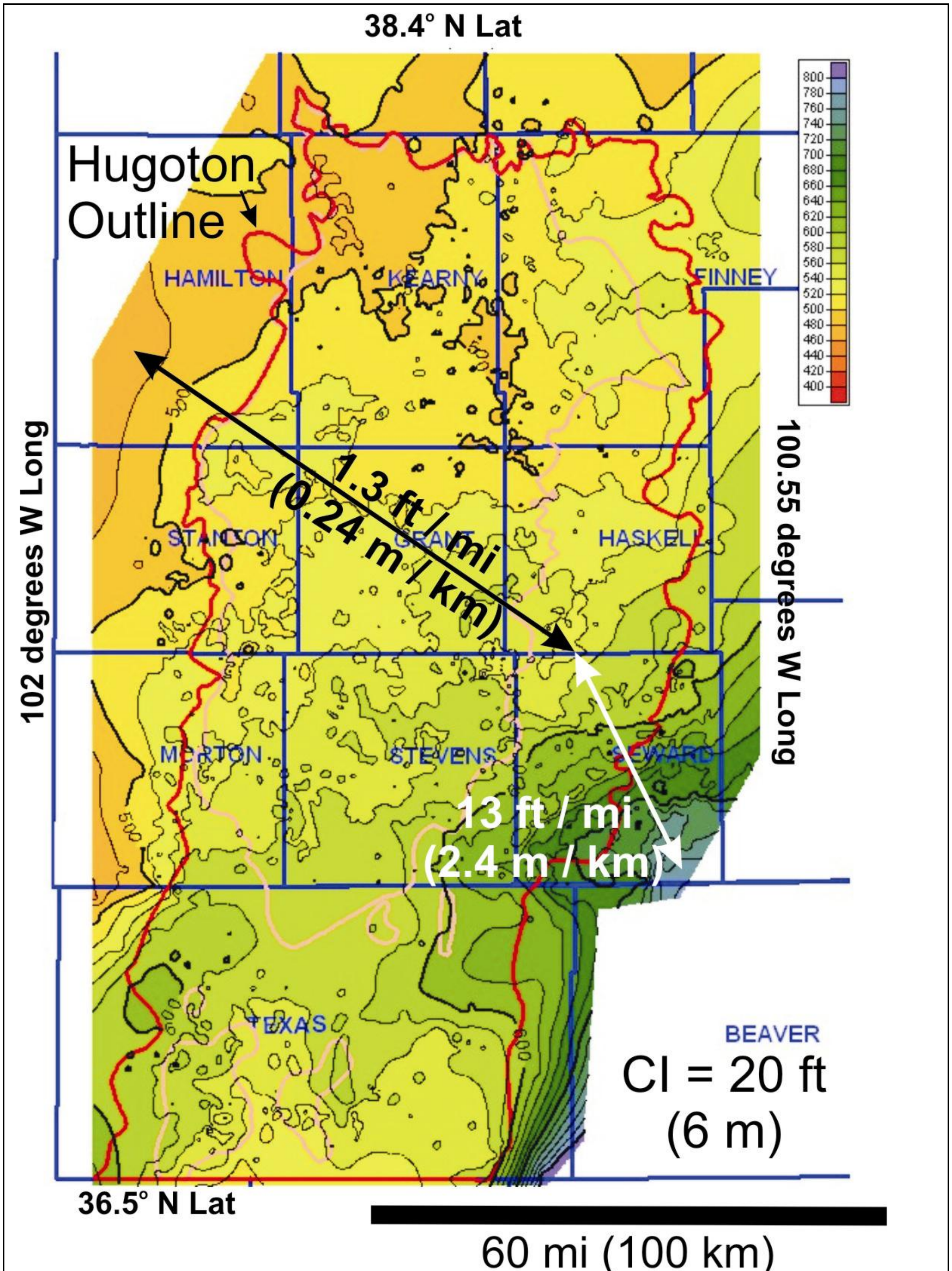

Figure 3.2. Isopach of the Wolfcampian (top of Chase Group to base of Grenola Limestone, Council Grove Group). Wolfcampian rate of thickening increases by a factor

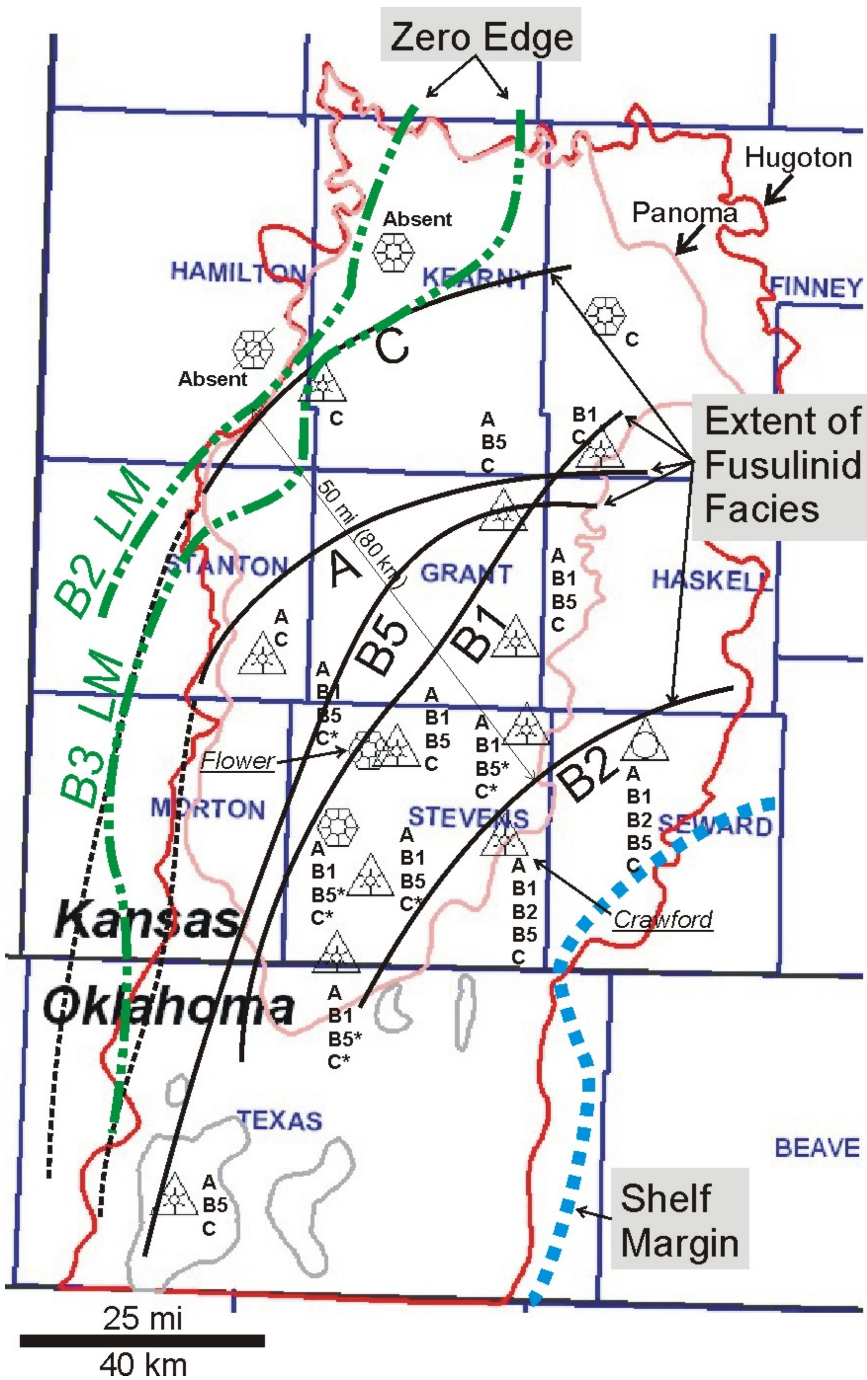
Zero Edge
Hugoton
Panoma
Absent
HAMILTON
KEARNY
FINNEY
Absent
C
Extent of Fusulinid Facies
B2 LM
B3 LM
STANTON
A
50 mi (80 km)
GRANT
B5
B1
HASKELL
Flower
MORTON
STEVENS
B2
SEWARD
Crawford
Kansas
Oklahoma
TEXAS
BEAVE
Shelf Margin
25 mi
40 km

Figure 3.3 Study area showing updip limit of B2_LM and B3_LM (zero edge) and updip extent of fusulinid biofacies in five of seven Council Grove cycles (not present in B3_LM and B4_LM). Occurrence of fusulinid biofacies in core is indicated by Council Grove cycle letter code adjacent to 17 wells in study. Asterisk (*) means interval was not cored but fusulinid biofacies is assumed to be present. No core was available below the shelf margin.

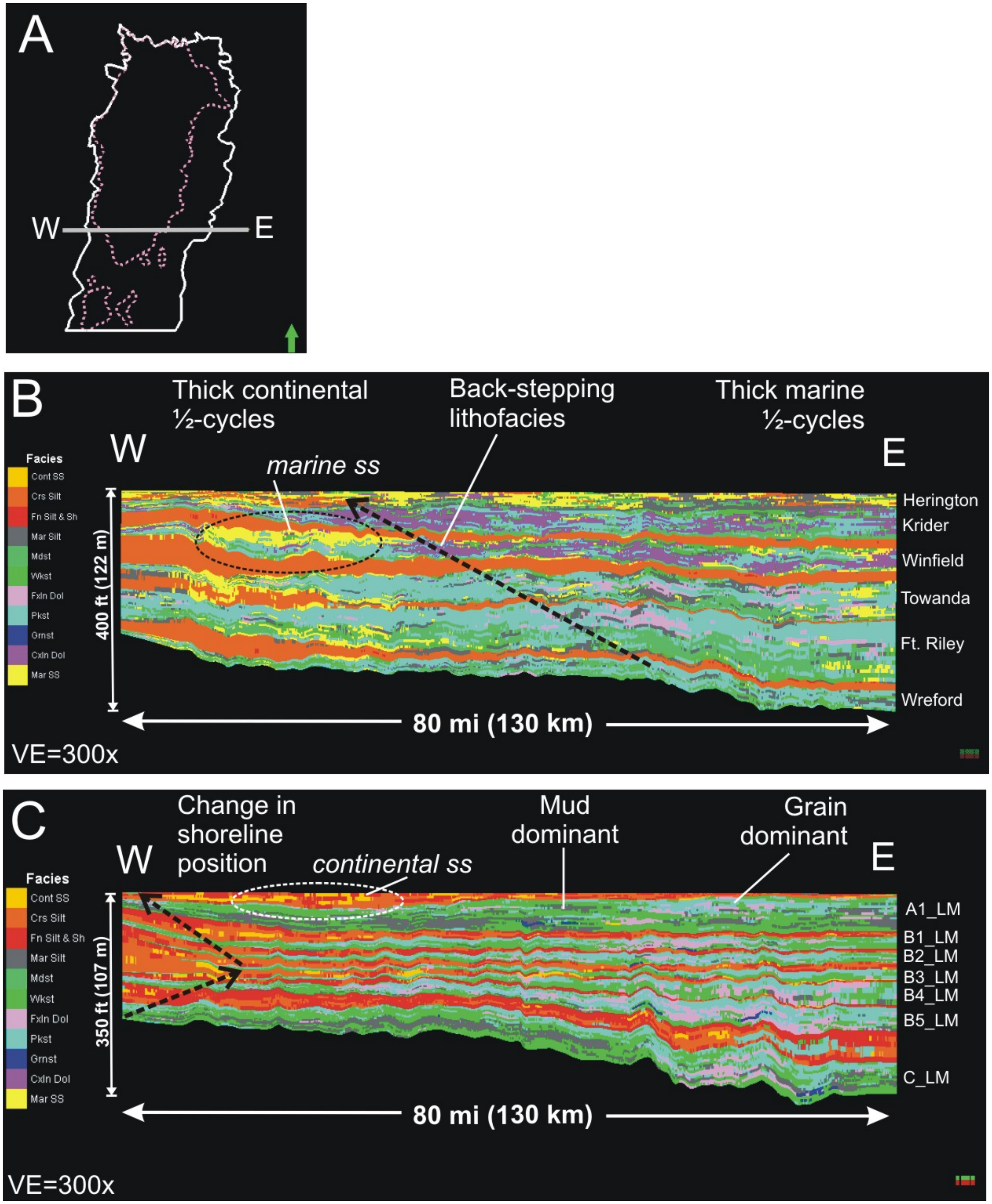
A
W
E
B
Thick continental
½-cycles
Back-stepping
lithofacies
Thick marine
½-cycles
W
E
marine ss
Facies
Cont SS
Crs Silt
Fn Silt & Sh
Mar Silt
Mdst
Wkst
Fxln Dol
Pkst
Grnst
Cxln Dol
Mar SS
400 ft (122 m)
Herington
Krider
Winfield
Towanda
Ft. Riley
Wreford
80 mi (130 km)
VE=300x
C
Change in
shoreline
position
Mud
dominant
Grain
dominant
W
E
continental ss
Facies
Cont SS
Crs Silt
Fn Silt & Sh
Mar Silt
Mdst
Wkst
Fxln Dol
Pkst
Grnst
Cxln Dol
Mar SS
350 ft (107 m)
A1_LM
B1_LM
B2_LM
B3_LM
B4_LM
B5_LM
C_LM
80 mi (130 km)
VE=300x

Figure 3.4. Lithofacies in stratigraphic cross sections across the Hugoton shelf (A) for the Chase (B) and Council Grove (C). Cross sections are 10-15 degrees from being dip sections and are hung on the top of the Chase (B) and the Council Grove (C). Some key observations can be made: 1) In both the Chase and Council Grove, continental half-cycles (yellow-orange to red lithofacies) are thickest at the west field margin and thin basinward (southeasterly). The pattern for the marine half-cycles is the opposite and, somewhat reciprocal relationship with the continental half-cycles. 2) Back-stepping pattern in lithofacies distribution from one marine cycle to the next in the Chase. 3) Middle three Council Grove marine half-cycles "pinch out" near the west field margin, marking paleo-shorelines. 4) Trend in carbonate-rock texture from mud dominated (landward) to grain dominated (basinward), especially in the Council Grove. Large-scale sedimentation patterns and distribution of resultant lithofacies (at the cycle scale) are largely a function of the position on the shelf and reflect the interaction of shelf geometry, sea level, and, possibly, the proximity to siliciclastic sources. Lithofacies distribution and cycle-stacking patterns at larger scales may be a function of lower-order cyclicity and a shift from icehouse to green-house conditions (upward) during the Lower Permian.
(Version Geomod 3)

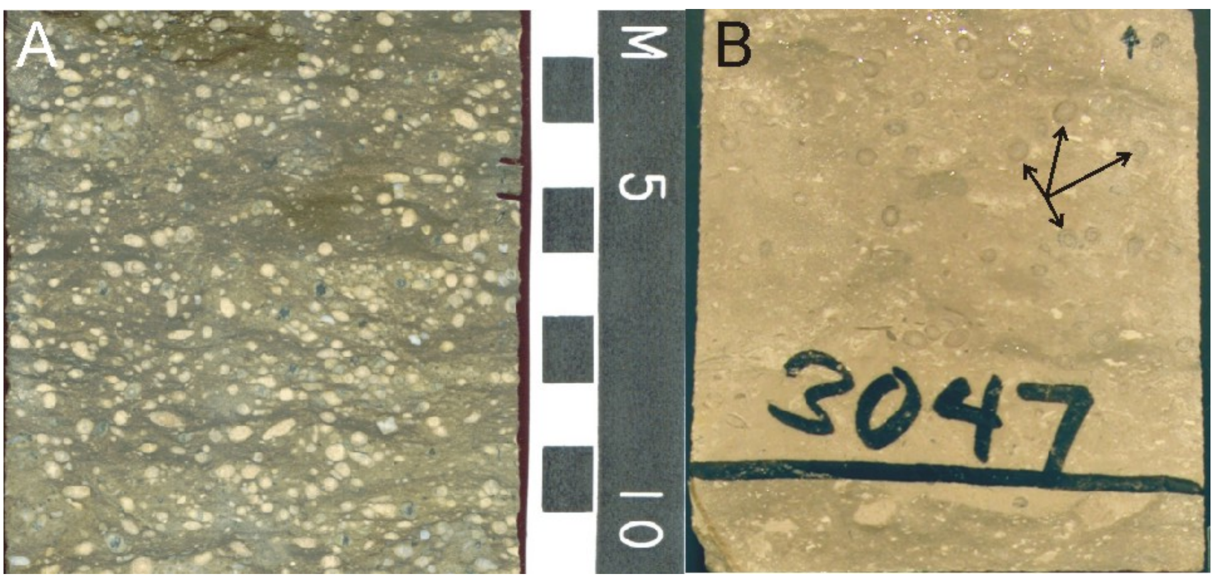

Figure 3.5. Fusulinid biofacies in core slabs. **A)** Extremely abundant in fusulinid (white)-dominated silty wackestone (upper part of transgressive limestone, subjacent to maximum flooding, in Funston, A1_LM, Flower A1 well). **B)** Scattered in fusulinid (gray) -mixed skeletal wackestone (maximum flooding in Crouse, B2_LM, Crawford 2 well). Well locations are shown in Figure 3.3.

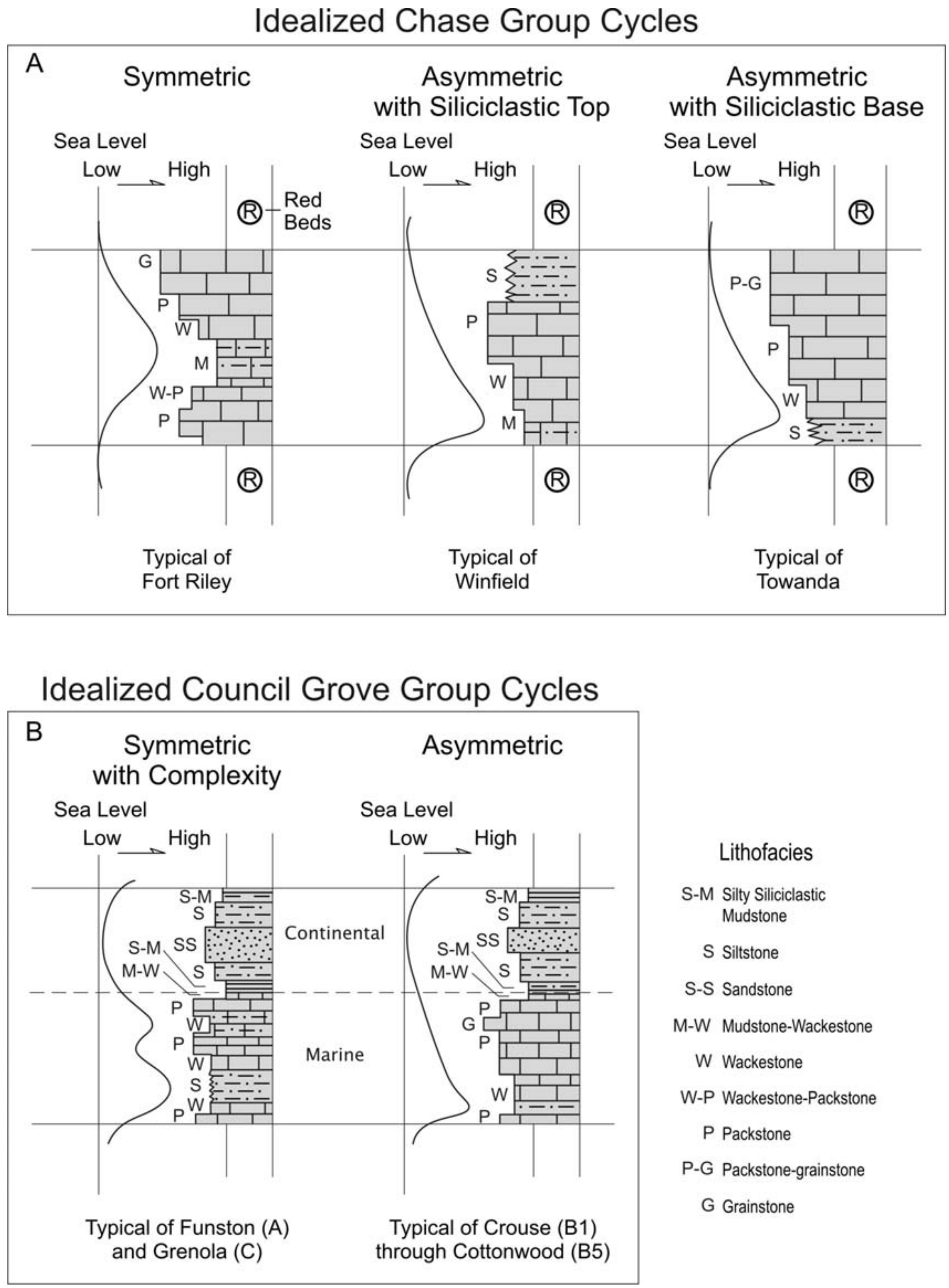

Figure 3.6. Idealized Chase and Council Grove Groups cycles. Chase cycles are from Olson et al., 1997, used with permission from the AAPG, and our Council Grove cycles are similarly formatted. One exception is that we extend the cycle and approximate sea level curve through the continental half-cycle based on earlier work (Dubois and Goldstein, 2005). Five "cycle types" are distinguished on the basis of lithofacies-stacking pattern and inferred relative sea level curve.

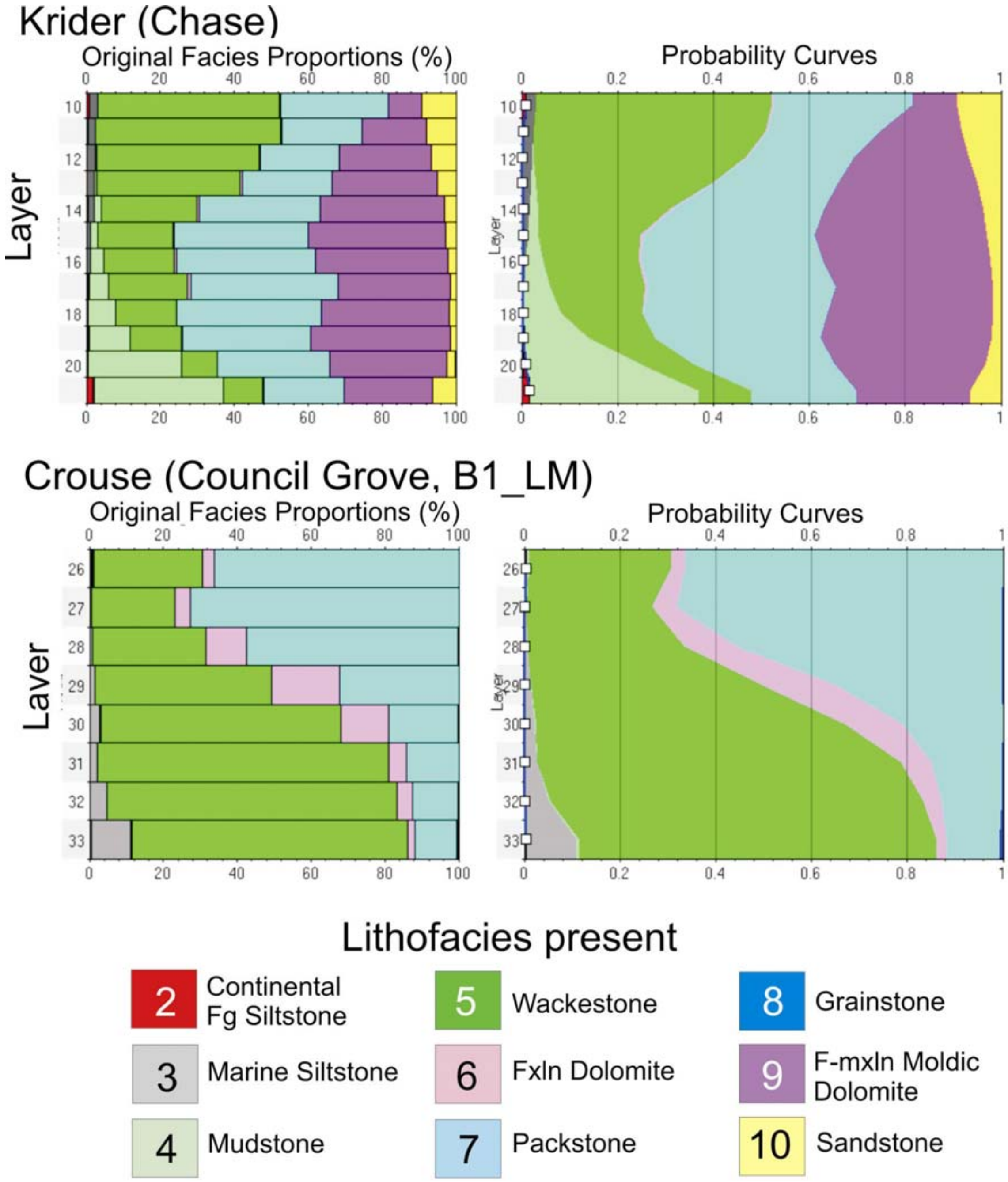

Figure 3.7. Vertical histograms showing the average relative distribution of lithofacies in two Wolfcampian marine half-cycles from wells having predicted lithofacies data (node wells). Data for the Crouse (B1_LM), Council Grove Group, are from 1146 wells and for the Krider, Chase Group, are from 1069 wells. Histograms and probabilities demonstrate the difference in symmetry in vertical lithofacies distribution between the Chase and Council Grove. Probability distributions were used to condition lithofacies modeling by sequential-indicator simulation between node wells. Layer annotations refer to layering within the half-cycle respective models (discussed later). Abbreviated are fine-grained (Fg), fine-crystalline (Fxln), and fine- to medium-crystalline (F-mxln). *(from version Geomod3)*

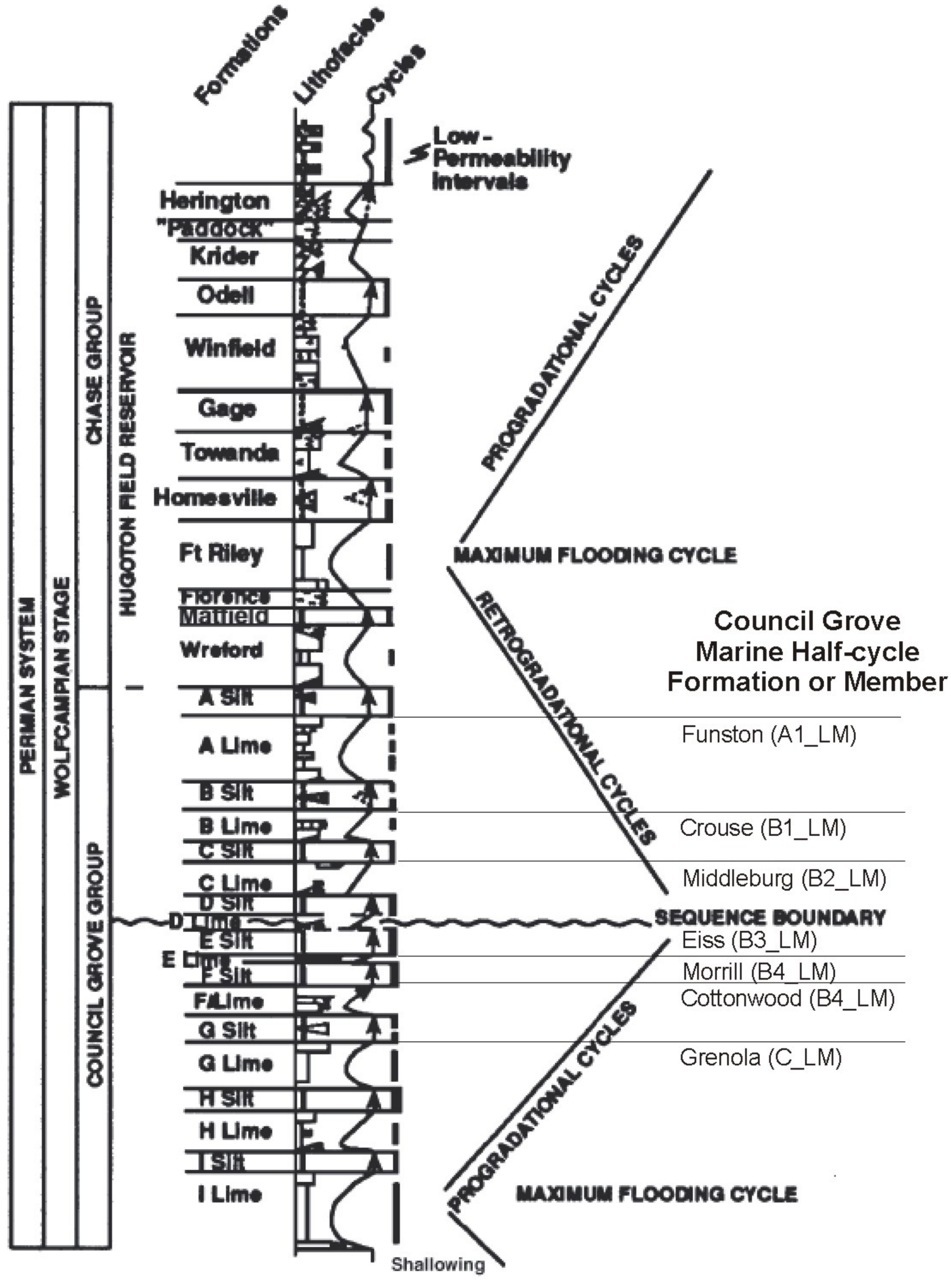

Figure 3.8. Chase and Council Grove Groups depositional cycles and sequence stratigraphy (after Olson et al., 1997). Informal stratigraphic nomenclature used in this paper is shown on the right. Their sequence boundary may be that of a super sequence. We agree with their sea-level curve symmetry, interpretation that the Council Grove cycles were progradational and then retrogradational, and position of maximum flooding, but suggest that Chase-cycle stacking above the Fort Riley may be aggradational at least through the Krider.

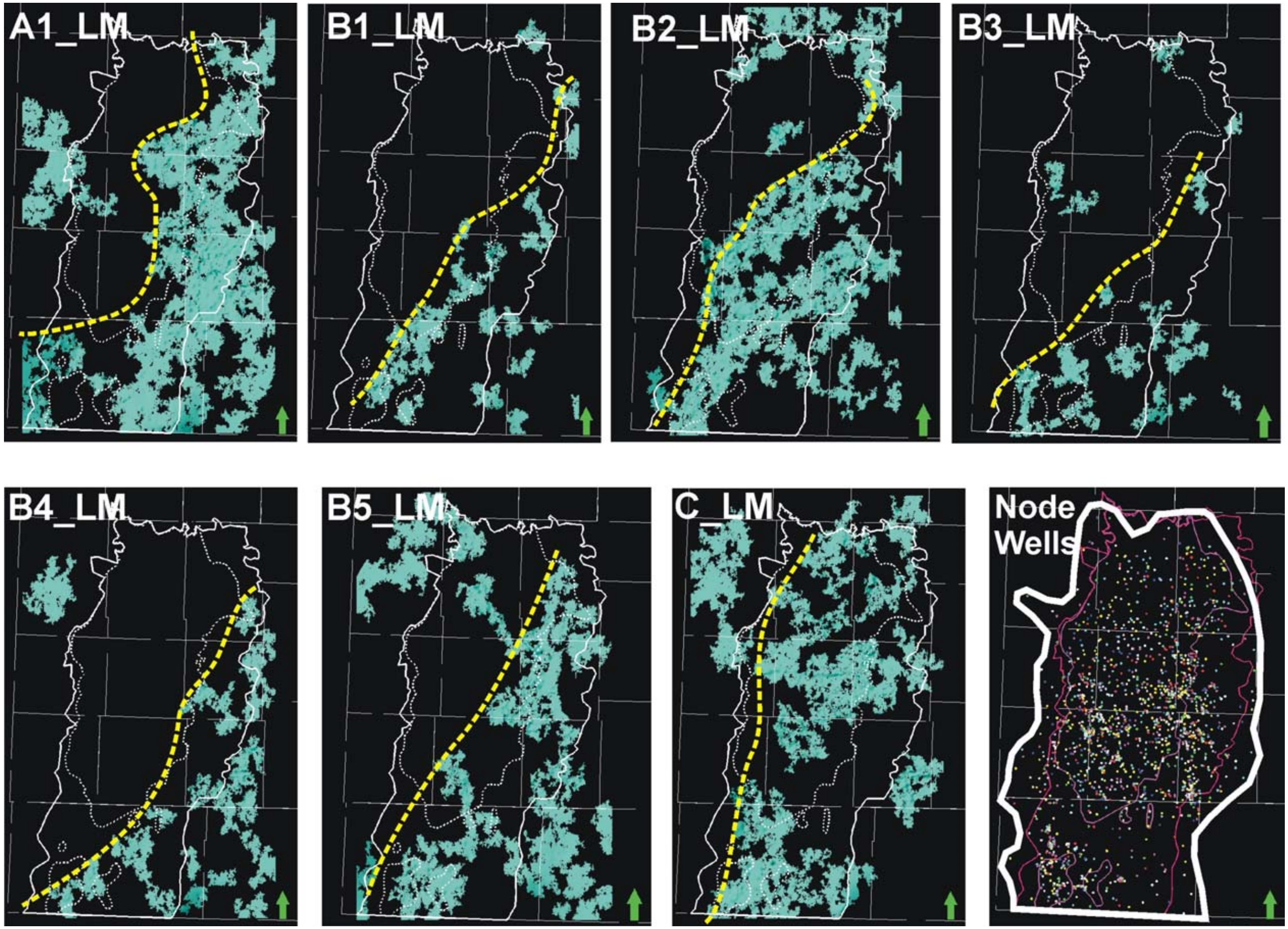

Figure 3.9. Distribution of packstone-grainstone lithofacies (L7) for Council Grove marine intervals. Illustrated are 2-D map views of the 15 largest connected 3-D volumes from the Hugoton cellular geo-model for L7 cells having greater than 10% porosity, except in the B5_LM where 14% was the lower cutoff. Areas outside node well control may be ignored. Dashed line highlights the approximate updip limit for the larger grain-supported marine carbonate geobodies. *(Model version Geomod 4-3).*

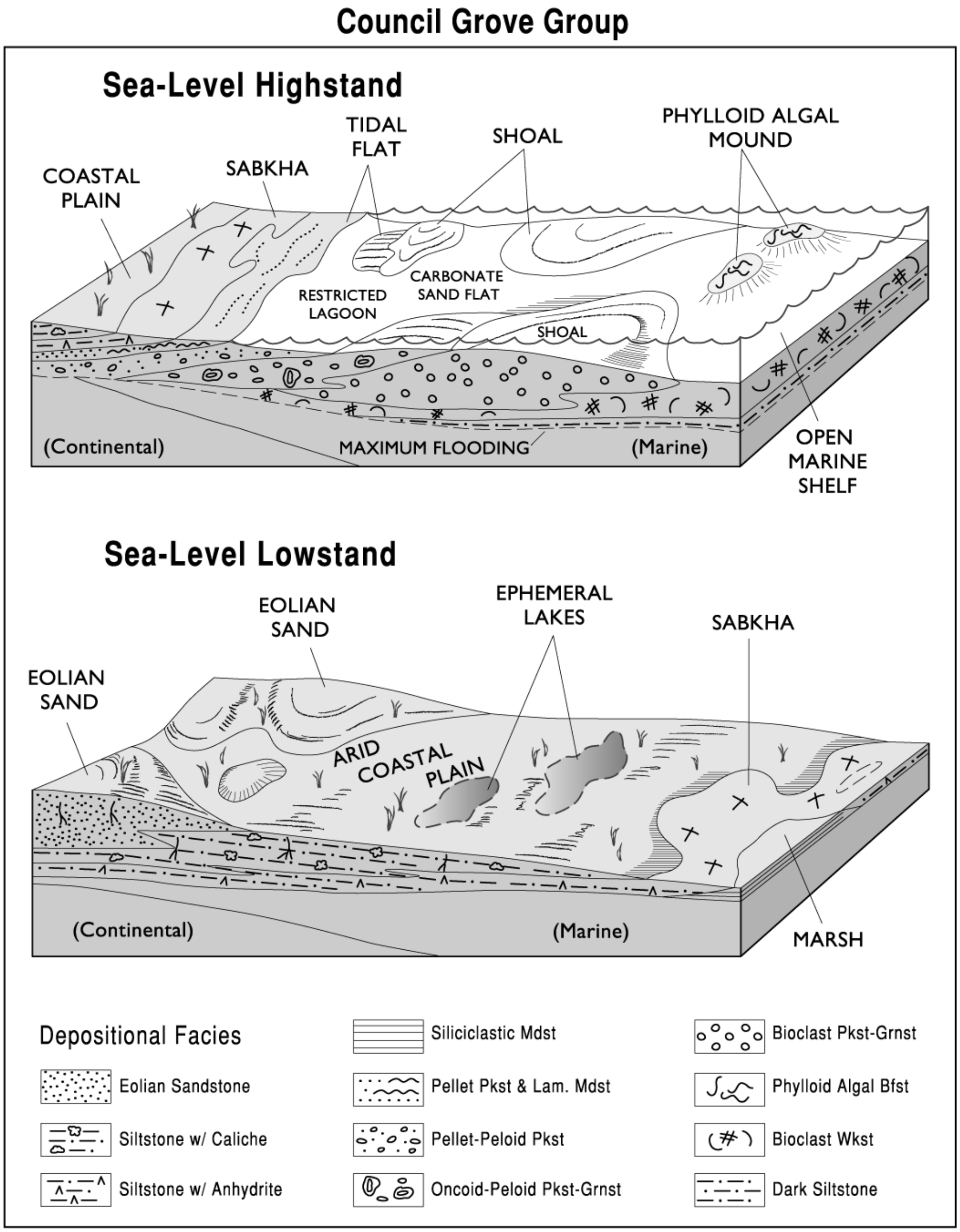

Figure 3.10. Idealized depositional models for the Council Grove showing the distribution of dominant lithofacies on the Hugoton shelf. Depicted are approximate depositional environments and associated lithofacies for “typical” Council Grove cycles at maximum sea-level lowstand and during the falling sea level stage of the marine highstand.

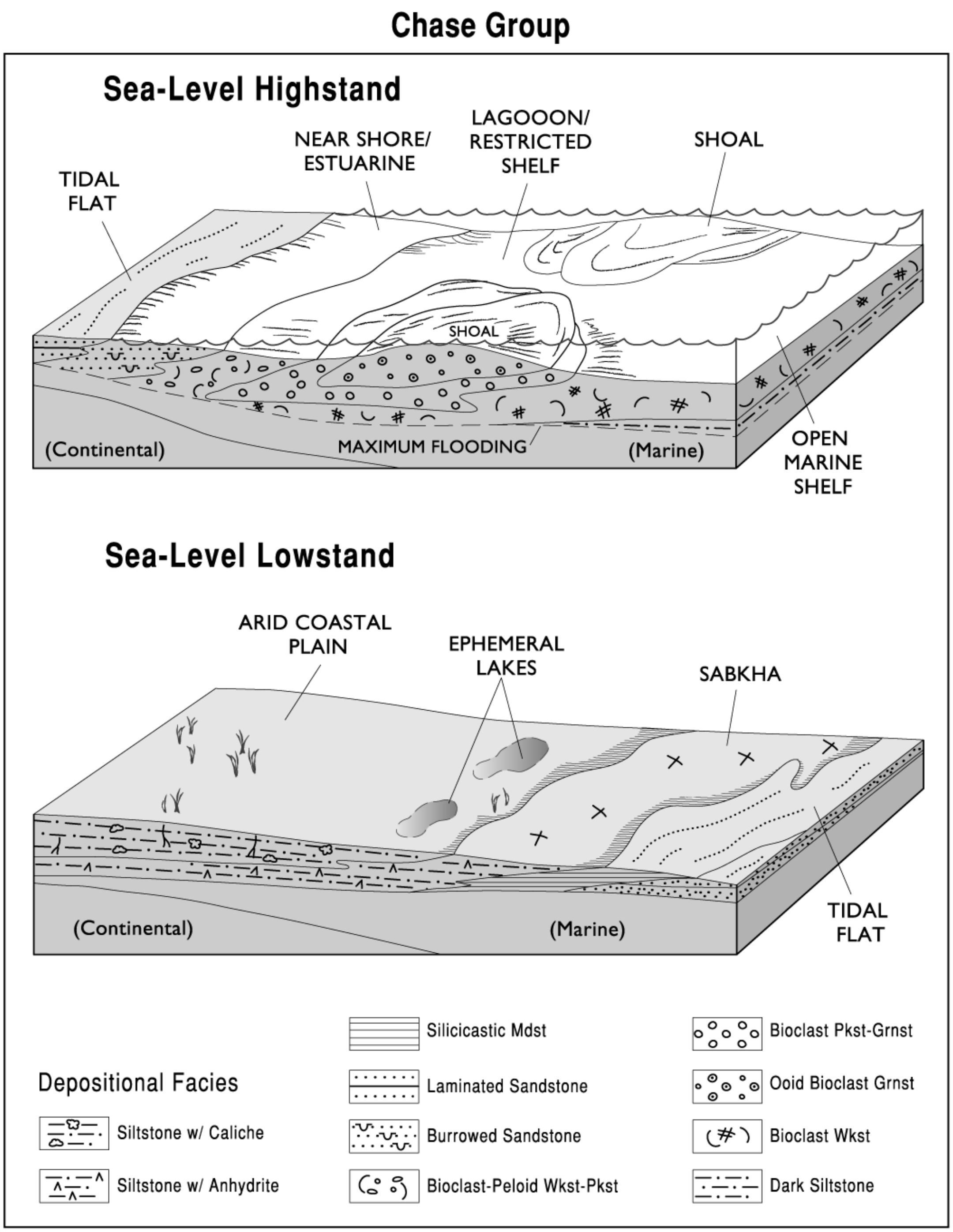

Figure 3.11. Idealized depositional models for the Chase showing the distribution of dominant lithofacies on the Hugoton shelf. Depicted are approximate depositional environments and associated lithofacies for “typical” Chase cycles at maximum sea-level lowstand and during the falling sea level stage of the marine highstand.