COMPARATIVE ANALYSIS OF STATISTICAL REGIONALIZATION AND COMPUTER CORRELATION IN SOUTHWEST KANSAS

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SUMMARY

Machine assisted stratigraphic correlation of gamma ray logs of 24 wells resulted in a 220 mile (354 km) cross-section through the Upper Pennsylvanian spanning an area from west-central to southwestern Kansas. The section crosses a carbonate-dominated shelf that extends into a siliciclastic basin at the northern end of a flysch foredeep extending off the Ouachita Mountains. The high resolution lithostratigraphic correlations show better than ever before several shifted episodes of carbonate bank building abruptly downlapping into shales and forming interbeds with shales basinward. Furthermore clastics thin and become shalier away from the foreland. Internal variation in temporarily distinct stratigraphic events correspond well with homogeneous zones that are based on regionalized classification of stratal thicknesses. The geometry of homogeneous zones represent regions of varying sediment accumulation and related thickness and composition resulting from changing subsidence, elevation and sea level history, and sediment supply.

PROBLEMS AND OBJECTIVES

The Upper Pennsylvanian carbonate to siliciclastic, shelf-to-basin transition along the northern border of the Anadarko and Arkoma Basins (Figure 1) is defined by a series of abrupt terminations of carbonate and siliciclastic lithofacies. The carbonate-dominated to mixed carbonate-siliciclastic shelf covering much of Kansas changes southward to a siliciclastic-dominated basin. Beyond correlation of marker beds consisting of thin condensed sections (marine shales), detailed correlation of these transitions has been attempted and questioned for many years. Similar transitions are found in many other shelf-to-basin transitions worldwide and results here may be useful in conducting refined basin analyses in these other regions.

Specific objectives addressed in this investigation include: 1) delineation of high-frequency, temporally distinct strata and their stacking patterns in order to interpret relative sea level history along the shelf margin; 2) definition of consistent, reliable high-resolution correlations of strata including internal correlations of thicker regressive strata in order to delineate heretofore unrealized internal geometries at a regional scale; 3) presentation of refined interpretations of the shelf and comparison to previous results using statistical regionalization (Watney et al., 1997); and 4) validation of the correlation procedure (CORRELATOR) for use in analysis of high-frequency Pennsylvanian cycles.

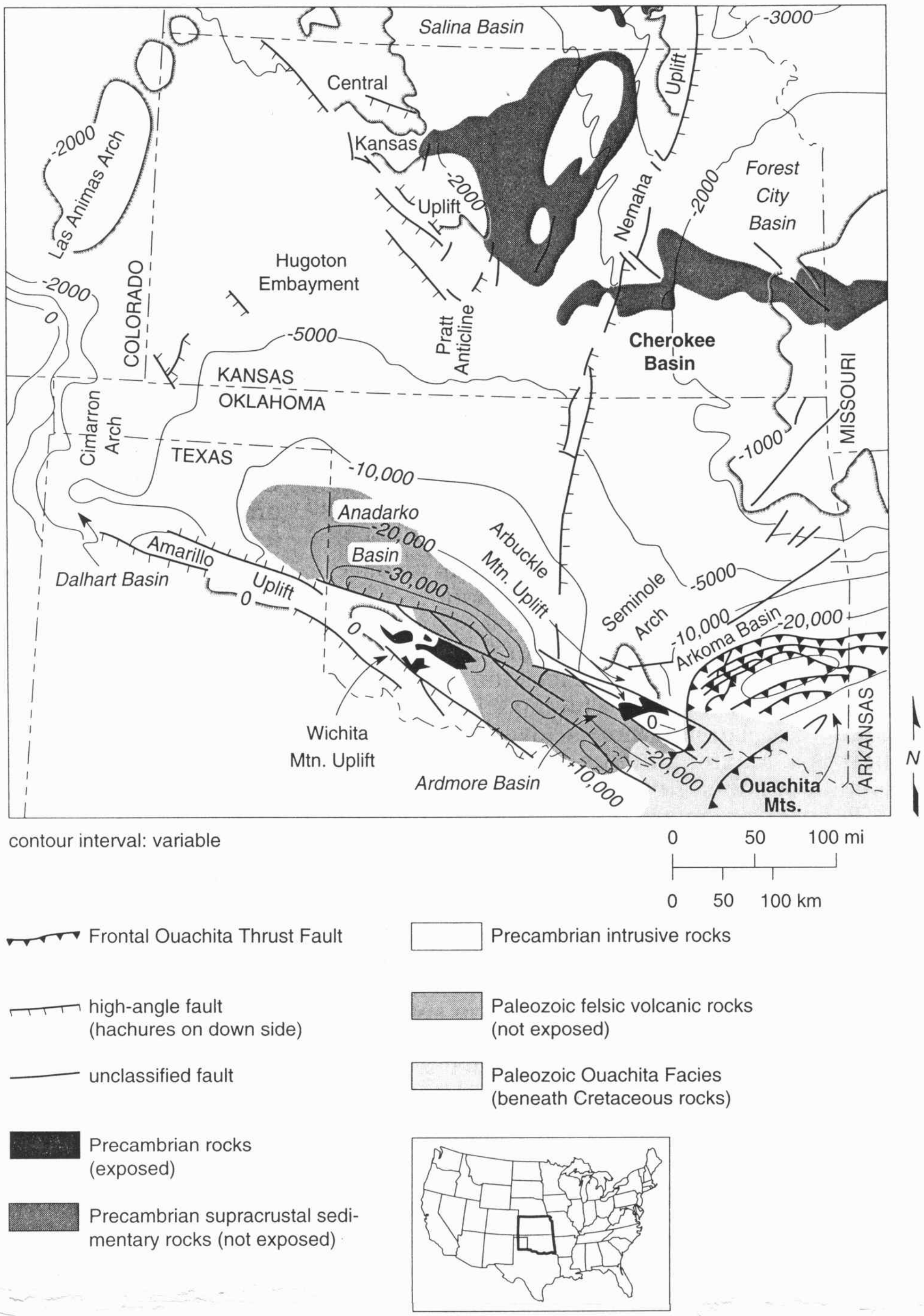

Figure 1. Geology of the American Mid-Continent (After Förster et al., 1998).

Internal, high-resolution correlations are critical to advance interpretations of any strata being studied. This is a fundamental task and problem in stratigraphy. Routine correlations of strata that are below resolution of seismic imaging methods have been left primarily to manual procedures including correlation of wireline geophysical logs. This is time consuming and the approach sometimes lacks consistency as different workers examine information. Resolving geometries of temporally distinct strata consistently and easily are key to solving many of the problems in sequence stratigraphic interpretation and in generating predictive stratigraphic models quantitative or conceptual. Moreover, the effective and efficient utilization of well logs for this purpose will be crucial for the success of this endeavor since they usually supply the 3-D information base from which geometries are derived.

Well recognized Pennsylvanian cyclothemic-scale genetic stratigraphic units on the Kansas shelf are relatively thin (few meters to 10s of meters), but widespread. Areal extent of internal, high-frequency and meter-scale beds (approximately 5th order, <100 ky) are basically unknown at this point except locally as revealed in petroleum reservoir field and near-surface examinations or limited surface studies (e. g. French and Watney, 1993; Felton and Heckel, 1996). Km-scale, high-resolution techniques in stratigraphy offer much potential to add to our understanding, provided that the techniques can expeditiously and consistently extend local correlations to a regional scale. This is also an essential goal of sequence stratigraphy.

Continuously recorded digital wireline log data are very abundant in Kansas, offering the potential to be an excellent source for regional, three-dimensional quantitative representation of Pennsylvanian stratigraphy. Automated methods are requisite to expeditious handling of these well log data. The opportunity to examine log correlations in three dimensions will also help to refine our understanding of processes that were responsible for observed strata architecture, namely eustacy, subsidence, and sediment supply. The distinction of these processes is an important academic problem, but is also consequential in developing quantitative sedimentologic and stratigraphic models for use in prediction. The purely descriptive information that could be provided in a 3-D, high-resolution correlation would be very useful in reexploring Kansas mature oil and gas producing province to find remaining anomalies. The advent of an automated correlation procedure could vastly change industry's risk and margin in delimiting stratigraphic anomalies and finding remaining oil and gas resources in Kansas. Again, this approach may have important ramifications in other mature areas or those that will be reaching maturity. The only prerequisite is digital wireline log information.

PREVIOUS WORK

Thickness and lithofacies of Upper Pennsylvanian high-resolution genetic stratigraphic units (GSUs) have been used to infer a detailed regional paleogeographic evolution of the Kansas shelf (Watney et al. 1995). In excess of 3000 wells were used to map thicknesses of GSUs. Cores and surface exposures were used to characterize component beds and facies comprising these stratigraphic units and to develop correlations with wireline log response. Datums were correlated manually among these wells to develop a data base consisting of structure, interval thicknesses, porosity development in regressive carbonates, and gamma ray deflections of condensed sections. Resulting maps revealed changing shelf configuration as an apparent response to differential subsidence, sediment supply and eustacy. Two-dimensional simulation modeling utilizing these variables reproduced overall observed stratal stacking pattern.

A cycle hierarchy was also recognized for Middle and Upper Pennsylvanian strata in which 5 to 7 successive GSUs form more coherent strata packages called genetic sets (GSs) (Watney et al., 1995). GSs closely correspond to formal stratigraphic groups- Excello GS and Marmaton Group, Nuyaka Creek GS and Pleasanton and most of Kansas City Group, and Muncie Creek GS and upper Kansas City, Lansing, and Douglas Groups.

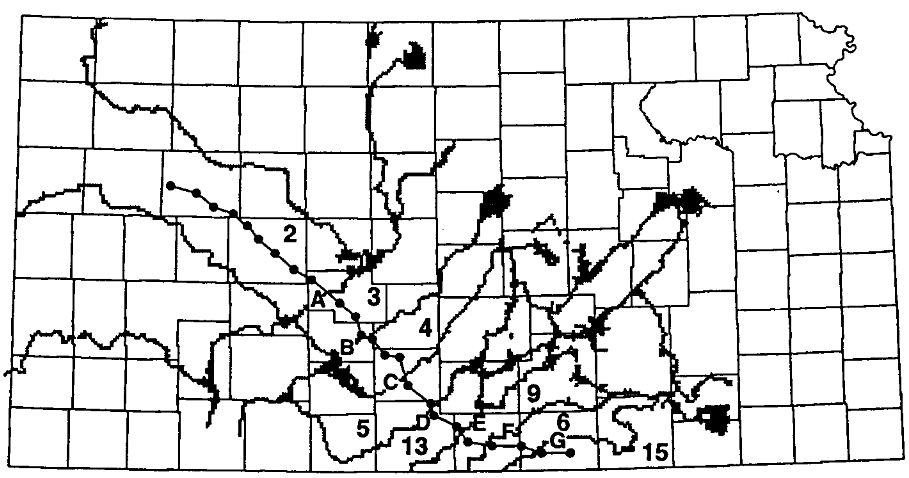

Figure 2. Sediment accumulation boundaries based on statistical regionalization (After Watney et al., 1997).

Regionalized classification was used to describe coherent spatial variation in thicknesses of four GSUs and two GSs (Watney et al., 1997). Fifteen km-scale sediment accumulation regions (SARs) were recognized on the Kansas shelf (Figure 2). Regionalized classification is a statistical procedure previously described by Harff and Davis (1990) that divides an area into regions that are as homogeneous as possible while as distinct as possible from other regions. Average thicknesses of these regions and associated inferred subsidence represented, suggest breakup of the Kansas shelf with increasing subsidence southward (basinward). Regions roughly correlate with basement geology and potential fields variations (Watney et al., in press). During this episode of sedimentation, the Kansas shelf apparently was fragmented along basement-related weaknesses during basin development to the south. Generally, increasing subsidence rates occurred southward, changing abruptly in rates between basement blocks leading to changes in elevation. Elevation changes were sufficiently great along the southern shelf to greatly reduce carbonate accumulation due to excessive water depths. Subsidence continued without sedimentation until clastic influx or carbonate progradational episodes again reached this location. Locations of carbonate shelf margin represent fringe of basin at that time, however ephemeral or long lasting it was. Shelf margin closely coincides with region boundaries and basement heterogeneity and point toward subsidence variation as important and critical control in sediment distribution (Watney et al., in press).

The question remained about validation of the regions. Watney et al. (in press) examine the use of color log imaging based on manual stratigraphic correlation at the GSU level and above and correlation of regions with gravity and magnetic potential fields. The conclusion was that the regions do correspond with significant changes in stratigraphy and inferred lithofacies. Regions also correlate to changes in potential fields along with basement geology and strongly suggest that basement reactivation contributed to the development of these regions. The question still remained regarding the first scale changes only obtained by smaller scale high-resolution correlation.

Twenty-four wells along the same line of section used in Watney et al. (in press) was used to conduct the automated wireline log (natural gamma ray) correlation of this current study (Table 1). Thus, a nearly direct comparison can be made of the results of manual and automated correlation. Furthermore, the increased resolution within the GSUs using the automated technique can be assessed. The correlated section was expanded to also include the Shawnee Group, thus extending the interpretation to another set of genetic stratigraphic units.

METHODOLOGY

Wireline logs were digitized at a sampling interval of 0.5 ft (15 cm). The natural gamma ray curve was digitized and normalized to a shale baseline and a clean, shale-free lithology either sandstone or carbonate unit. The shale baseline was assigned 1 and the clean lithology was assigned zero. While the normalizing resulted in a log response was consistent between wells for use in CORRELATOR, this eliminated the high gamma ray spikes often associated with condensed sections (black marine shales) of the GSUs. The focus of the autocorrelation is to decipher pattern internal to these GSUs, particularly the thicker intervals of shale and carbonate. For details on the mathematics of the methodology, see Olea (1994).

Rendition of CORRELATOR results can be in color or black and white. For the shale variation cross-sections, the hotter the color, the cleaner the rock; for the black and white figures included in the report, the more black the color, the lower the rock shale content. Intervals that are white represent no correlation between wells for that segment. These gaps serve well in outlining correlations between wells.

Table 1. The northwest-southeast Kansas data set.

	Well	Location	County
1.	Wycoff Brothers No. 1 Eklna	C SE NW sec 27, T 13 S, R 30 W	Gove
2.	Tidewater Oil Co. R. D. No. 1 Adams	C NW NW sec 8, T 14S, R 27W	Gove
3.	D. C. Slawson Corp. No. 1 Curtis "L"	SE NE NE sec 31, T 15S, R 26W	Gove
4.	Trans-Era Petr., Inc. No. 1 Huxman	SE SE SW sec 14, T 16S, R 25W	Ness
5.	Bearmore Drilling Co. No. 1 Ummel	C NW NE sec 11, T 17S, R 24W	Ness
6.	George P. Vye Co. No. 1 Antenan	SW SW NW sec 9, T 18S, R 23W	Ness
7.	Rains & Williamson No. 1 Bondurant	C SW SE sec 25, T 18S, R 23W	Ness
8.	Cities Service Oil Co. No. 1 Sears "A"	C SE NW sec 6, T 20S, R 21W	Ness
9.	Mull Drilling Co. No. 1 Lipp	C SW NE sec 24, T 21S, R 20W	Pawnee
10.	Ambassador Oil Corp. No. 1 Dahlquist	SW SE NE sec 10, T 23S, R 18W	Pawnee
11.	F. G. Holl Co. No.8-13 Hawley	NE NE NE sec 13, T24S, R 17W	Edwards
12.	Southland Royalty Co. No. 4 Lamb	C NE sec 36, T25S, R 16W	Edwards
13.	Texas Energy Inc. No.1-21 Smith	SE SE SW sec 21, T26S, R 15W	Pratt
14.	Texas Energy Inc. No. 1-16 Clarkland	NW NW NW sec 16, T27S, R 14W	Pratt
15.	Phelps Dodge Fuel Dev. No. 22-3-3 Green	SW SE NW sec 2, T 28S, R 13W	Pratt
16.	Abercrombie Drilling Co. No. 1 Wray	SE SW SE sec 20, T 29S, R 12 W	Pratt
17.	Texas Nat. Gas & Oil Co.No. 1 Poland	SW SE NW sec 22, T 30S, R 11W	Barber
18.	Tennessee Gas & Oil No. 1 Mc Reynolds	SW SW NW sec 32, T31S, R 10W	Barber
19.	Hummon OIl Co. No. 1 Yocam	C SE SW sec 13, T 32S, R 9W	Harper
20.	Aurora Gasoline Co. No. 1 Miller	SE SE NE sec 11, T33S, R8W	Harper
21.	National oil Co. No. 2 Pulliam	NE NE NW sec 1, T 34S, R 6W	Harper
22.	Mack Energy Co. No. 2 Misak	NE SE NW sec 6, T 34S, R 4W	Sumner
23.	Forney Oil Co. No. 1-20 Subera	NW SE SW sec 20, T 34S, R 3 W	Sumner
24.	Annaco Inc. No. 1-A Schmidt	C SW SW sec 17, T 34S, R 2W	Sumner

Several displays were prepared to provide an assortment of perspectives. Figure 3 and Plate 1 are structural cross-sections with a sea-level datum; Figures 4 and 5 and Plates 2 and 3 have a top of Heebner Shale datum; and Plate 4 has a top of Topeka Limestone datum.

STRATIGRAPHY

Genetic stratigraphic units (GSUs) in the Lower Virgilian and Missourian Shawnee, Lansing and Kansas City Groups each contain a condensed section, a thin marine shale that generally exhibits elevated natural gamma radiation. These shales, although thin (approximately 1 m), are very widespread and are most easily manually correlated from well log to well log across the shelf, in spite of considerable variations in lithofacies of adjoining strata (Figure 3). The GSUs also contain a thin (less than 1 m) flooding unit identifying the base of the GSU, and immediately underlying the condensed section. A regressive unit, the thickest (10 to 30 m) component of the GSU consists primarily of carbonate and shale units with occasional sandstones. Paleosols and evidence of subaerial exposure also typify the GSUs on the Kansas shelf. These exposure events are interdispersed through usually the upper portions of the regressive unit. The number and duration of exposure events becomes more frequent northward on the Kansas shelf (landward) away from the active foreland basin areas—Anadarko and Arkoma Basins in

Oklahoma and Arkansas (Watney et al., 1995). However, on the higher shelf areas, exposure surfaces merge (converge) landward in thinner carbonate-dominated units as thickness of stratal units and inferred sedimentation decrease (Watney et al., 1995).

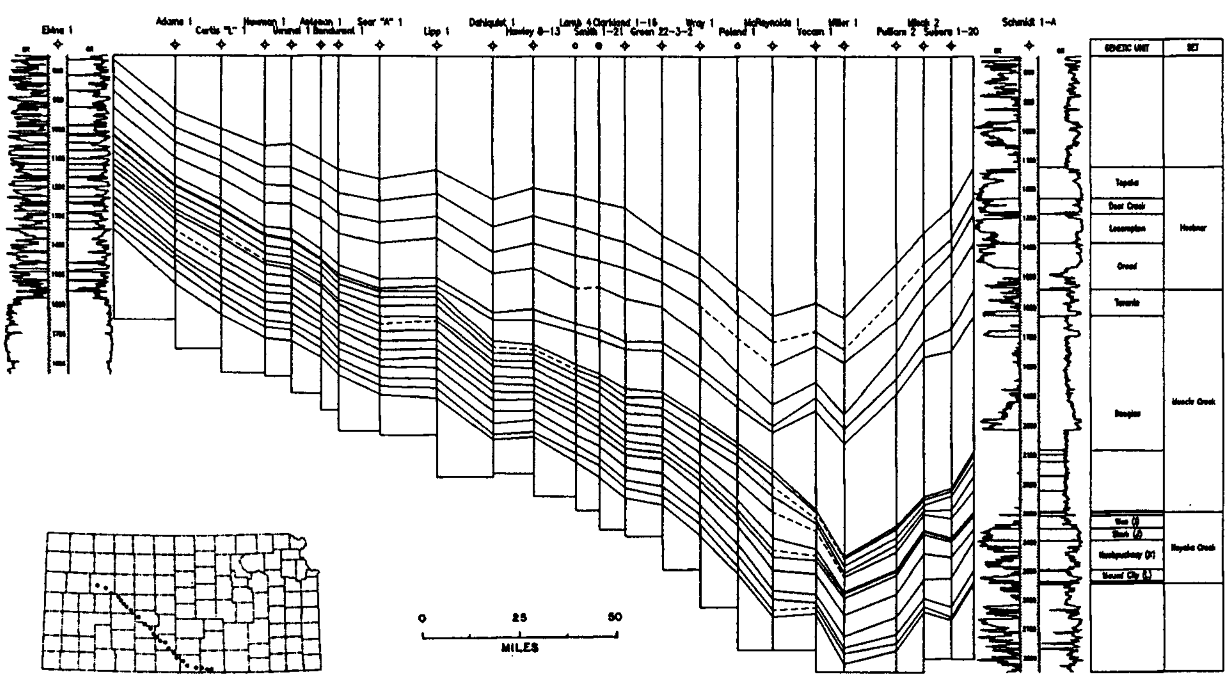

Figure 3. Structural cross-section based on interpretation of all lithostratigraphic correlations established for wells denoted by solid dots in Kansas index map. Vertical exaggeration is 400 times.

Larger scale geometries of these strata, similar to what is observed here, have been characterized via outcrop and near-surface cored and logged analog sites in southeastern Kansas (Watney et al., 1989; Watney et al., 1995). These sites exhibit two types of carbonate-dominated shelf margins including a longer-term sediment-starved carbonate margin involving several GSUs. The other type involves reciprocal carbonate and siliciclastic accumulation involving episodic siliciclastic influx that fills space in front of the carbonate margin during each GSU after carbonates are deposited. This siliciclastic sedimentation is termed reciprocal as it came after the carbonate during an inferred time of lower sea level conditions. This reciprocal sedimentation was probably accomplished, in part, by sediment bypassing across the carbonate shelf during lowstand conditions. Another viable source would be the Ouachita Mountains to the southeast (Watney et al., 1995). Whether a clastics shelf margin was reciprocal or long-term probably depended on the elevation difference between the shelf margin and basin floor, absolute elevation of the shelf margin (which would affect carbonate accumulation rate), and proximity to clastic sediment supply (so as to reach the distal shelf in time frame of the fall in sea level. Higher rates of relative sea level rise and lower rates of sediment supply appear to be associated with the initiation of long-term genetic sets resulting in backstepping stratal geometries (Watney et al., in press).

RESULTS

The Heebner Shale is a GS boundary situated above the Nuyaka Creek and the Muncie Creek GSs and below the Heebner GS (Figure 4 and 5, full-cross section in two parts).

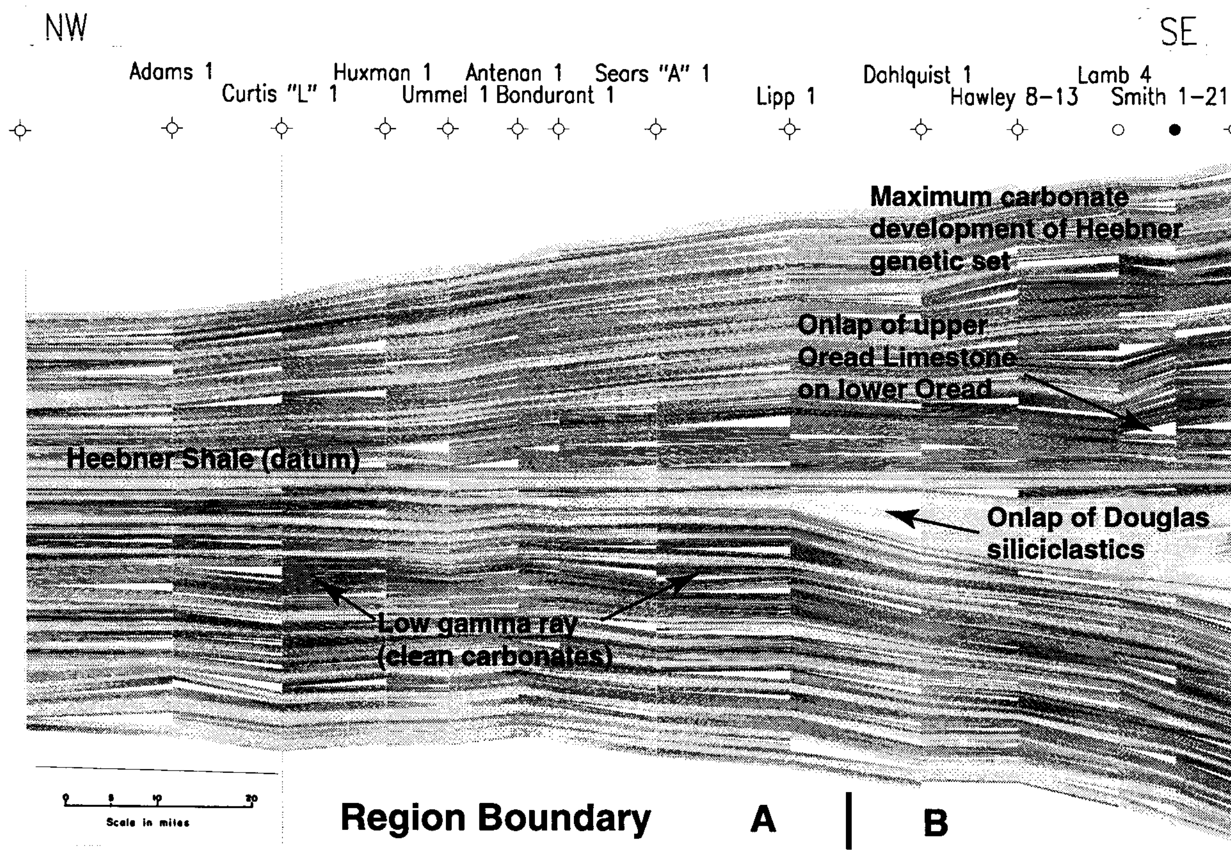

Figure 4. Northwestern end of lithostratigraphic cross-section. Vertical exaggeration is 400 times.

The Heebner Shale represents a high frequency marine inundation of the Kansas shelf at which time carbonate production was temporarily interrupted and clastic supply was drastically diminished. The inundation extended well beyond the borders of present Kansas well unto the craton and has been attributed to continental glaciation. Most GSUs are associated with these thin, extensive shales, whose characteristics depend on shelf position and sea level history. As with other larger-scale genetic sets, they are initiated with the development of condensed sections that belong to particular GSUs. The Heebner Shale represents an important shift in the stratigraphic pattern, thus serving as a genetic set boundary.

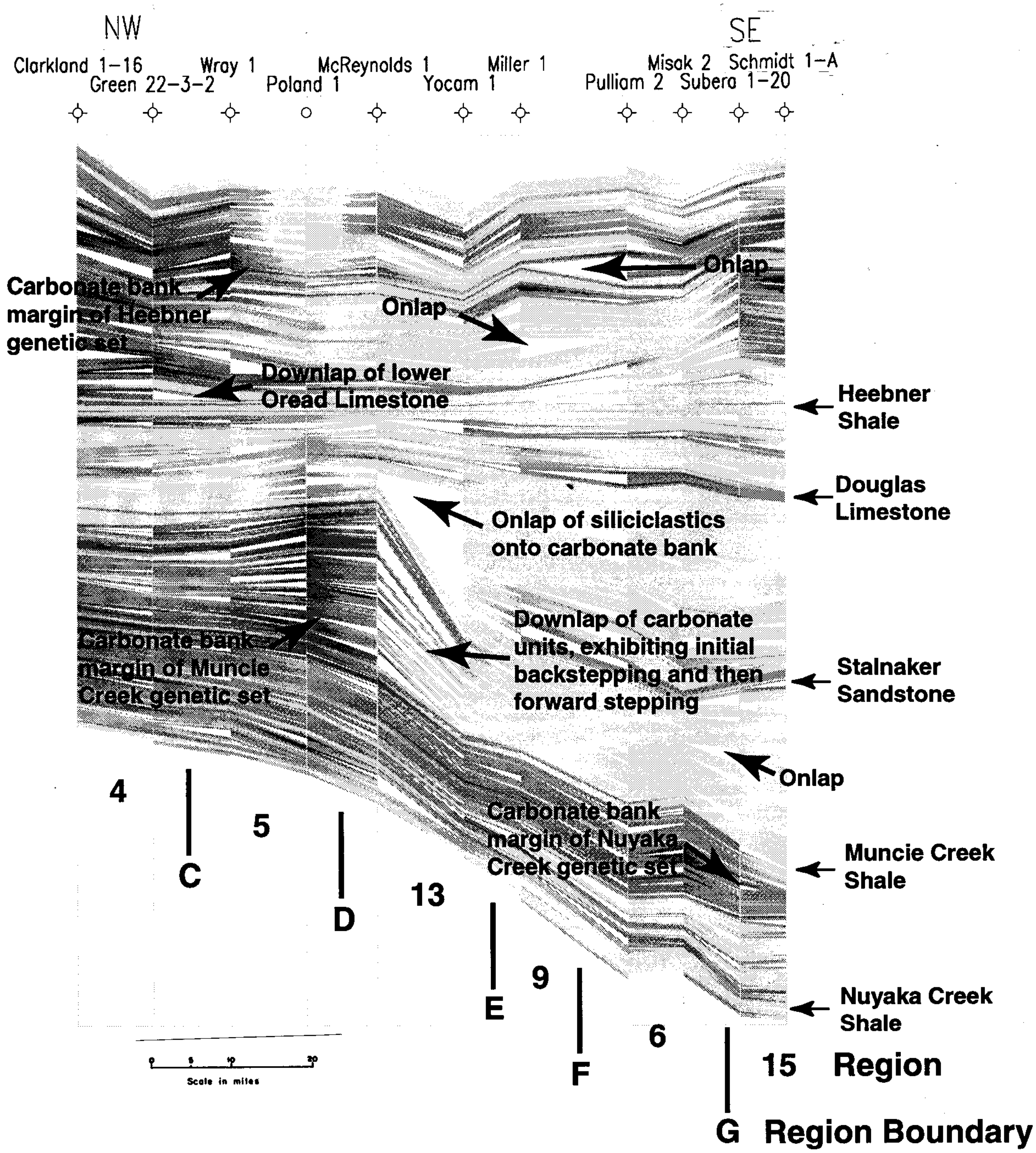

Figure 5. Southeastern end of lithostratigraphic cross-section. Vertical exaggeration is 400 times.

The northwest to southeast cross section is 220 mile (354 km) long crossing the carbonate-dominated Upper Pennsylvanian shelf and extending into the siliciclastic-dominated basin. The basin lies at the northern end of a flysch dominated foredeep extending off of the Ouachita Mountains (Figure 1). The section includes strata ranging from 600 ft (183 m) thick at the northwest end to nearly 1500 ft (457 m) thick on the southeast end. Note that current day structural is higher on the southern end of cross-section reflecting approach to the Nemaha uplift. This uplift although expressed in present day structure apparently was not active or was greatly diminished by subsidence during much of this episode of sedimentation. Later uplift reestablished this overall positive feature whose history extends prior to sedimentation of this interval.

Uplift or reduced subsidence may have begun as early as in the lower Shawnee Group, after accumulation of the Heebner Shale, as reflected by redevelopment of carbonates along the southern portion of the cross-section. The middle of the cross-section is within the Sedgwick basin, the structural extension of the Anadarko basin. Here the basinal shales continued to be deposited until late in the Shawnee Group. The Oread Limestone and succeeding limestones in the most of the Shawnee Group downlap within the lower reaches of the Sedgwick basin, suggesting that the area was an embayment, an extension of the Anadarko Basin. Probable increased subsidence lead to non-deposition (drowning) of the Oread in this area. The resurgence of the Nemaha Uplift as a positive feature is an indication of differential structural basement reactivation. This southern boundary of the apparent reorganized Sedgwick basin immediately above the Heebner Shale correspond with region boundary "G" in Figure 5.

Nuyaka Creek Genetic Set

Large-scale changes in the genetic sets (GSs) are quite apparent. The Nuyaka Creek GS consists of carbonate-dominated GSUs across the entire cross section except for the last well on the southeast side. This southeasterly well contains mixed sandstone and shale that were apparently deposited reciprocally with the adjacent carbonate units on the shelf. This geometry is very similar to that observed in the near-surface study with clastic sedimentation in the basin following carbonate deposition on the shelf at the GSU level (Watney et al., 1989; 1995). Note that the carbonate shelf margin of the Nuyaka Creek GS thickens and then thins abruptly immediately northwest of the carbonate bank margin. The thick carbonate is immediately northwest of the region boundary labeled G defined from the regionalized study (Watney et al., 1997).

The Nuyaka Creek GS also exhibits carbonate units with low gamma radiation (depicted in the figure by dark gray to black tone). These cleaner, low gamma ray carbonates are focused at several locations on the shelf. Clean carbonates often are associated with porosity and potential reservoir development (Watney, French, and Guy, 1996). Sites of clean carbonate also correlate with sites immediately north (shelfward) of southerly increases in overall stratal thickness. Several of these locations are at or close to region boundaries, e.g., upsides of A, B, E, and G boundaries. These boundaries apparently reflect the flexure of the shelf and suggest differential subsidence/uplift such that southern edges of the block immediately north of the region of boundaries were higher and suited for more sustained or enhanced carbonate accumulation in locally shallower conditions proximal to deeper water (Baars and Watney, 1991).

Overall the Nuyaka Creek GS is shalier illustrated as lighter tones in Figure 5) in the lower basinward location. Near-surface and outcrop studies indicate that increases in shale and reduced carbonate result from downlapping of shelf carbonates in lower GSUs at locations higher on the shelf followed by onlapping of lowstand clastics (Watney et al., 1989). These geometries are also suggested by CORRELATOR in this cross section. White triangles that show no correlation suggest landward onlap of shales (indicated by light gray shades) and basinward downlap of carbonates (dark gray) (Figure 5). In contrast, on the landward side (right-hand) of the cross-section (Figure 5), lower GSUs of the Nuyaka Creek GS generally have lower gamma-ray and are predominantly carbonate, while upper GSUs in Nuyaka Creek genetic set contain greater proportions of shale. Furthermore, as upper GSUs are traced basinward, the overall gamma-ray values decrease (cleaner, less shaly carbonates) and the carbonates themselves thicken. These upper-thickened carbonate-dominated GSUs extend basinward out over the more clastic dominated lower GSUs (Figure 5). This all suggests that the carbonate-dominated facies tract initially shifted landward in the lower GSUs, then shifted basinward in the upper GSUs of the Nuyaka Creek genetic set. This includes pronounced, local thickening of carbonates in several GSUs in the lower shelf. Location of thickened carbonate units are constrained by region boundaries, but this may be expected because thickness was a criteria used to classify the region. What is confirmed here is that clean carbonates accompanies this thickening. These sites are optimal for development of petroleum reservoirs. A breaking in slope on the shelf margin lead to ramp development and associated carbonate buildups.

Muncie Creek Genetic Set

The lower portion of the Muncie Creek genetic set, a carbonate-dominated interval, shows a pronounced carbonate margin developed between region boundaries D and E. A 250 ft (76 m) carbonate bank abruptly terminates at this location during accumulation of the carbonate bank. CORRELATOR is not forced or constrained to follow individual GSUs in this transition. What is correlated by CORRELATOR suggests that each carbonate-dominated GSU (intermediate gray and dark gray units) downlaps onto shales, proximal to the edge of the carbonate bank margin. This downlap is also indicated by the series of wedges (triangles) with the sharp narrow apex pointed downdip and basinward (Figure 5).

Note that the downlap surfaces of the lower GSUs at the edge of the carbonate shelf first migrate landward then basinward suggesting that the backstepping that began at the base of the Muncie Creek GS continued, but at a reduced level. The position of this carbonate margin represents a landward retreat of 50 miles (83 km) of the carbonate bank margin associated with the underlying Nuyaka Creek genetic set. The maximum backstepping is near the Argentine and Farley Limestone GSUs. These GSU are represented by the farthest landward (northward) migration of the carbonate banks in the eastern Kansas outcrop belt where Argentine bank margins terminate just south of Kansas City (Watney et al., 1989). The Stanton GSU in contrast has migrated 100 mi (160 km) southward along the outcrop to near the

Oklahoma line. Comparable positions of bank margins in this cross section being discussed are only a few miles apart. This contrast in distance between bank margins is probably due to differences in elevation and slope of the respective shelves (higher elevation with more favorable condition to laterally accrete toward the basin). This difference can probably be attributed to subsidence variation (higher in western Kansas leading to lower elevation) and clastic sedimentation (nearly lacking on the shelf in western Kansas leading to carbonates alone contributing to filling sediment accommodation space).

The lower carbonate-dominated portion of the Muncie Creek GS exhibits several sites of particularly clean carbonate development (low gamma-ray), most translating from one GSU to the next. Some of the sites of clean carbonate also extend down into the Nuyaka Creek GS. In contrast, shales interbedded within these carbonates are generally thicker along the landward northern border suggesting proximity to a landward clastic source.

The high-resolution correlations by CORRELATOR between the edge of the carbonate bank and the basinal shales suggest approximately 100 ft (30 m) of shale was deposited over the flooding (drowning) surface at the base of the Muncie Creek genetic set during accumulation of the carbonate bank.

The Stalnaker Sandstone lies outboard (basinward) from the Lower Muncie Creek GS carbonate bank (Figure 5). The landward edge of the Stalnaker Sandstone is situated immediately southeast of the F region boundary. A large triangle of no correlation is interestingly sited immediately landward from this sandstone (Figure 5). The lowest position of this triangle is situated at the base of the sandstone in a basinward position at the edge of the E region boundary. The highest point of the triangle is located 200 ft (61 m) above the top of Stalnaker Sandstone. The basin shales and sandstone are indicated here to onlap the northwest (landward) side within this triangle of no correlation.

The stratigraphic position of the highest apex of the no correlation triangle situated updip from the Stalnaker Sandstone corresponds to an interval in the Douglas Group above the Haskell Limestone in the upper Douglas Group. A significant paleosol (vertisol) representing considerable time is developed above the Amazonia Limestone in the Upper Douglas Group (Joeckel, 1994; Joeckel, 1995; Feldman, Archer, and Joeckel, 1995). Feldman et al. (1995) place their Ireland Sequence boundary at this position. This highest onlap point suggests that the timing of the Stalnaker Sandstone is equivalent to that stratigraphic position on the shelf. Some have previously suggested that the Stalnaker Sandstone and the Tonganoxie Sandstone are nearly temporally equivalent (Winchell, 1957; Archer, Lanier, and Feldman, 1994). The correlation in the paper suggests that the equivalent, at least at this position on the shelf in south-central Kansas, is the Ireland Sandstone above the Tonganoxie Sandstone.

The Stalnaker Sandstone probably represents a lowstand deposit consisting of clastic sediment that bypassed both the shelf on the north and the area to the south comprising a flysch deltaic and turbidite system originating from the Ouachita Mountains. The Stalnaker Sandstone has been described as a deltaic deposit (Walton and Griffith, 1985), also suggesting shallowing conditions in keeping with a lowstand interpretation. It is inferred here that the maximum depth of the incised valleys being described on the shelf for the Tonganoxie and Ireland Sandstones (135 ft., 41 m, Feldman et al., 1995) is within the height of the triangle, approximately 250 ft (76 m). This is comparable to depth of incisement of 120 ft (40 m) recorded on the upper shelf such as in the outcrops near Kansas City (Beaty et al., 1998). The nickpoint that led to valley formation began in the shelf margin and migrated landward through the upper portion of the shelf. The nickpoint migrated beyond the Kansas City area 100 miles (160 km) north of the Stanton bank margin in southeastern Kansas, over the time span of a GSU, between 100 to 500 ky.

Correlations in the upper portion of the Muncie Creek GS indicate continuation of an overall onlap that began following low stand in sea level associated with the Stalnaker Sandstone. The Douglas Limestone is developed in a basinward position. Earlier interpretations of manually correlated logs suggest toplap (Watney et al., in press). However, the white "no correlation" interval within this limestone suggests at least internal onlap, but continued correlation of this interval well up onto the shelf suggests that there is no toplap.

It has been suggested that the Douglas Limestone correlates with the Amazonia Limestone on the shelf which is a thin, discontinuous marine limestone that was severely subaerially exposed (Stephens and Watney, 1991). It probably represents a marine cycle with limited shelf inundation, analogous to the overlying Toronto Limestone indicating lower relative sea level during its deposition. The shales that bound the Douglas and Toronto Limestones thicken basinward suggesting overall lateral accretion of sediment toward the basin.

The thick upper Muncie Creek clastic-dominated interval in the basinward side diminishes to simply a thin shale on the upper, northwestern end of the cross section, not unlike surrounding regressive shale units. This is a clear indication of the loss of sediment accommodation space, in this case due to gain in elevation of the shelf, probably due to decreased subsidence with increasing distance from the foreland basin tectonism.

Heebner Genetic Set

The Leavenworth Limestone and the Heebner Shale are located at the base of the Heebner genetic set. The Heebner genetic set represents another modification in shelf and basin stratal geometries. A carbonate bank margin is reestablished in this genetic set situated approximately 25 mi (40 km) landward from the preceding carbonate margin. This edge is located at region boundary D (Figure 2). Maximum thickness of the carbonate shelf of the Heebner genetic set (450 ft, 136 m thick) is developed slightly landward of this margin, immediately basinward of boundary B. While this stratigraphic interval was not used to determine the region boundaries, the boundaries still are important loci for stratigraphic and facies change.

The Oread Limestone, which includes the limestone member superjacent to the Heebner shale, thickens southward across the shelf. High-resolution correlation using CORRELATOR indicates that the lower portion of this limestone thins markedly on the lower shelf while the upper Oread Limestone thickens immediately basinward from this position. Correlations further indicate that the upper Oread Limestone onlaps the lower interval suggesting a basinward shift of the upper Oread Limestone, perhaps related to a relative fall in sea level.

The line of section crosses two opposing carbonate bank margins in the mid and upper portion of the Heebner genetic set, one on the northwestern side and the other on the eastern side. The intervening area is dominated by shale, coinciding with the location of the Sedgwick Basin. The eastern carbonate bank is located at the western edge of the Nemaha Uplift east of region boundary G. The stratal geometries suggest that the elevation of the southeastern location of the section near the Nemaha Uplift was high enough to reestablish a carbonate bank, not previously developed since the Middle Pennsylvanian Marmaton Group. In contrast, a shale-filled basin developed between these carbonate banks had previously been part of the carbonate shelf during deposition of the underlying Muncie Creek genetic set. This suggests some reorganization in the subsidence pattern around different structural/basement blocks. High-resolution correlation of the associated shelf carbonates and basinal shales in the upper Heebner genetic set show abundant evidence for downlapping carbonates and onlapping shales (Figure 5).

DISCUSSION

Analysis of the cross-section illustrates that there is a regional pattern to the stacking of GSUs within a genetic set, backstepping followed by forward stepping consistent with marine inundation due to sea level rise followed by forward stepping due to either still stand or more slowly falling relative to sea level. The latter interpretation is consistent with a relative rise and fall in sea level inferred from examination of the thorium/uranium ratios.

Coupled with this stratal variation is a redox trend formed by a combination of paleosols and lower regressive carbonates in the Nuyaka Creek genetic set. Th/U ratios through this interval show consistent patterns of abrupt reduction in both lithofacies followed by a gradual increase in oxidation. This correspondence to stratal pattern suggests that the Th/U ratio represents a proxy to marine inundation, more reducing more greater inundation (Watney et al., 1995).

The stratal coherency in this genetic set is maintained out of the plane of this cross-section and beyond this region of the shelf. This organized rise and fall of multiple high frequency GSUs has been previously suggested as a global eustatic process responsible for third-order cycles (Mitchum and Van Wagoner, 1991). This stratal coherency was also recognized in rocks slightly older (Atokan) than this in the immediate area (Youle, Watney, and Lambert, 1994). This apparent organization of relative sea level history in different basins and tectonic settings at different times suggests that this third-order cyclicity is due to eustacy. Local conditions, namely elevation of the shelf defining what part of the sea level history is seen, sediment supply determining how fast accommodating space is filled, and tectonics/subsidence helping define local topography and elevations. In this case, a fragmenting, subsiding shelf apparently offered many opportunities for carbonate building and drowning, and clastic influx subtle and possible obscured by later structural movement. Some order is apparent, namely:

(1) location of fragmentation on the shelf is closely linked to basement heterogeneity (Watney et al., in press), as revealed by gravity and magnetics.

(2) organized third-order and fourth-order marine cycles affecting likelihood of varying sites of the shelf to be loci of carbonate buildups.

The fragmentation of the shelf is closely tied to orogenesis and strength of far-field stress, e. g. mountain building and subsiding of the foredeep in Ouachita system. Different periods of geologic time will have changes on stress fields, for example, development of the Cretaceous interior seaway.

Secondly, the subtle changes in topography and slope due to changes in sedimentation and subsidence coupled with residence time of sea level dictated the location of carbonate buildups or fairways for clastic sedimentation. Sediment accommodation is extremely variable in a stratigraphic succession that undergoes wide excursions in sea level change, estimated at 100m fluctuations in GSU, well beyond thickness of GSU units. Shelf is inundated and shelf is exposed episodically and carbonate buildup requires residence time in order for sediments to be significant. Residence time is as important as water depth to permit sediment to accumulate. Locus for these sites of optimum sediment accumulation whether carbonates or clastics is closely tied to tracking these "stands" of the sea level along strike, temporarily distinct, analogous to tracing a bathtub ring at a common elevation. Favorable orientations and configurations shelf will result in similar stratigraphy and possibly lithofacies. High resolution stratigraphic correlation is essential to recognizing these events and tools are needed to quickly decipher the stratigraphic/lithologic changes.

There is a certain level of prediction that appears possible to isolate stratigraphic intervals, lithofacies, and shelf locations that contain favorable conditions for petroleum reservoir development. Efforts are needed to (1) access digital wireline log data, (2) image and correlate, (3) filter on features significant to reservoir development, and (4) model quantitatively through automated techniques.

CONCLUSIONS

In summary, the following geologic events and processes have been either confirmed, better understood, or discovered through the machine lithostratigraphic correlation of gamma ray logs of 24 wells through the Upper Pennsylvanian in an area from west-central to southwestern Kansas:

1. Established correlations within individual GSUs, thick shales, and transitions between successions of carbonates to shales suggesting temporal correlations (more consistent than manual attempts);
2. Recognition of rarely recognized stratal geometries within GSUs on the craton including downlapping and laterally accreting carbonate strata onto a maximum flooding surface/condensed section (Plattsmouth Limestone unto Heebner Shale);
3. Isolated stratigraphic intervals between wells that could not be autocorrelated, providing precise sites where probable onlap or downlap occurred (not reliably done manually in any consistent way, unless have core, high resolution seismic data, or complete surface exposure);
4. Helped to confirm the presence of genetic sets utilizing a combination of detailed correlations and gamma ray variation; and
5. Corroborate existence of stratigraphically distinct regions on the shelf through recognition of corresponding changes in stratal composition.

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