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PETROLEUM RESERVOIR CHARACTERIZATION OF
UPPER PENNSYLVANIAN CYCLIC CARBONATES
IN THE HUGOTON EMBAYMENT
Short Course and Workshop

presented by

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Short Course and Workshop

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ATTACHMENT:

Black-line copies of maps and cross sections for work sessions

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Notes to Accompany Short Course:

Petroleum Reservoir Characterization of Upper Pennsylvanian Cyclic Carbonates in the Hugoton Embayment

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Outline of Presentation:

1. Introduction to study area and depositional model for the Kansas City Group.
2. Structural-depositional framework of Hugoton Embayment/evaluation of structural trends.
3. Significant statistics on petroleum production in Kansas.
4. Examples of rocks as components of cyclothems and integration with wireline log signatures.
5. Regional mapping of cyclothems for reservoir assessment.
6. Factors in prospect development.

INTRODUCTION

Cyclothems characterize the Mid Carboniferous through early Permian stratigraphic succession in Midcontinent of North America and other sites world-wide.

Repetitive sequences of lithofacies are common, widespread, and relatively constant in thickness on the craton. It is not unusual to be able trace beds less than 3 m thick over 450 km along outcrop.

Objective of this presentation is to address the character of these cyclothems and significance toward reservoir distribution, with new insights provided by regional correlation and analysis of 4 Missourian cyclothems. Correlation of cyclothems and regionally significant internal divisions of these cyclothems is based on extensive 3-D network of subsurface data covering >70,000 Km^2 (30,000 mi^2).

Specific objectives of study:

1) examine effects of configuration of the shelf on the nature of 4 cyclothems;
2) evaluate evidence for sea level change;
3) attempt to estimate the contribution of the potential causes of cyclicity: sea level change, tectonism, and sedimentation process itself;

4) identify factors responsible for accumulation of hydrocarbons in these carbonate reservoirs, establishing and evaluating productive trends or fairways and models for reservoir development.

Western Kansas and Hugoton Embayment was part of broad shelf bordering the Anadarko basin during much of the late Paleozoic, including the Missourian. Sampling in this study was sufficient to describe activity of subtle tectonic elements on this shelf and varying depositional setting of each cyclothem.

Flexure and subsidence of Missourian shelf in western Kansas was concurrent with rapid subsidence in the adjacent Anadarko basin. Local episodic movement on the shelf influenced the lithofacies distribution in each cyclothem, but the objective was to evaluate how much.

However, local tectonism does not account for the shelf-wide repeating patterns of lithofacies. Perhaps tectonism related to orogeny, sea level oscillation, or shifting of sedimentary environments were responsible for the cyclicity.

*Figure 1--Study area in western Kansas

47 counties, 30,000 mi^2 (77,000 sq. km); NW trending Central Kansas uplift (CKU) and Cambridge arch (CA); Major tectonism associated with these uplifts occurred in Late Mississippian-Early Pennsylvanian; Site of previous uplift during early Paleozoic; Uplift produced only 100's feet of relief, much less than block faulting and thrusting in nearby orogenic systems to south (Amarillo-Wichita-Arbuckles).

*Figure 2 -- core and log control

2300 well logs through Kansas City Group, one well per 34 km^2 or one well every 5.8 km (3.5 mi); Series of maps produced with data from these wells.

37 cores of portions of four cycle interval--slabbed and thin sections taken; Described carbonates using Dunham classification:

<10% grains in micrite matrix: lime mudstone
>10% grains in micrite-supported matrix: Wackestone
grain-supported framework but significant micrite matrix: packstone
micrite free and grain supported: grainstone.

Staining done with ALR-S and K-ferrocyanide; Fossil fragments abundant in these limestones.

Computer data base: includes name, location, 26 stratigraphic variables; Use Fortran programs for data entry, edit, and plotting (SURFACE II); Convert latitude-longitude coordinates to X-Y Lambert conformal conic projection; Conduct error analysis to check data on well with nearest neighbors; Display equipment includes line printer, flat-bed plotter, and color graphics terminal. Combine data with test and production information for productivity evaluation. Database management could be handled by appropriate microcomputer.

Statistical analysis: used trend surface analysis to assist in characterizing configuration of shelf and identification of local anomalies.

*Figure 3--Stratigraphic nomenclature and equivalency with informal subsurface units

<u>Nomenclature</u>

Missourian of Upper Pennsylvanian, Kansas City Group; A time nearing maximum inundation of the shelf by long-term rise in sea level that began during early Pennsylvanian time; Carbonate-dominated succession in Kansas; Each cycle is comprised of transgressive-regressive assemblage.

*Figure 4--Table of lithofacies comprising cyclothems in Kansas City Group in western Kansas

Subsurface: H, I, J, K cycles

Lower (transgressive) carbonate (base of cycle) (thin)

Lower (marine, core) shale (thin, but commonly with distinctive high GR)

Upper (regressive) carbonate--main petroleum reservoir, shallowing upward (thickest)

Upper (regressive) shale (top of cycle) (intermediate and variable in thickness)

PROBLEMS ASSOCIATED WITH CONCEPT OF CYCLOTHEMS

1) true repetition -- repetition of similar environments on shelf do not necessarily produce exactly the same lithologies; recurring environments with certain periodicity?
2) allocyclic vs. autocyclic processes possibly responsible for cyclothems

Common conclusion of most workers that slight changes in sea level caused a great migration of strandline over craton during the Pennsylvanian. However, Heckel's (1977) quasi-estuarine circulation model which requires relatively deep water places a need for greater change in water depth well beyond typical thickness of cycle (<60 ft., 20 m). Late Paleozoic cyclic sedimentation is not simply the result of sediment progradation. Cyclothems here generally very thin, widely distributed successions of contrasting lithologies separated by sharp contacts which suggest more than simple aggradation of sediment over shallow platform. Terrigenous clastic influx is only of minor significance in western Kansas, unlike southeastern Kansas and eastern Oklahoma during Late Pennsylvanian.

Wanless and Shepherd (1936): presented a climatic model for generating cyclothems which is much discussed today; Called on repeated glaciation in Gondwanaland to produce global variations in sea level; For 20 years following publication of their paper these conclusion were viewed with considerable doubt due to insufficient record of glaciation in time and space to account for some 160 cyclothems recognized in the Late Paleozoic stratigraphic column.

Some workers called on oscillating tectonism (Weller, 1956) that affected uplift of the source of terrigenous clastics. Swann (1964) invoked a precipitation cycle causing a variation in stream discharge which affected their capability of transporting terrigenous detritus. George (1978) used a combination of eustacy and tectonics to explain sedimentary succession in British Dinantian (same interval studied by Ramsbottom (1979). Heckel (1977) revitalized the idea that continental glaciation was the cause for eustatic change in sea level which produced a marked contrast in successive depositional environments over wide region. (Change in sea level appears to have been significantly greater than entire thickness of stratigraphic interval of individual cycle).

Ultimate proof would be to find regionally correlative cycles that transcend depositional systems and represent regular periodic or episodic events. This would require an interregional mechanism independent of sedimentation or local tectonics.

Significant recent advances in understanding causes of eustatic sea level change and response in sedimentary record (particularly during last 150 m.y. interval) have occurred.

Plate Tectonics and Continental Glaciation, Climate Changes

Donovan and Jones (1979) -- Short term but significant effects on sea level caused by glaciation; Pleistocene glaciation produced 100-150 m change in sea level at a rate of approximately 1 cm/year. Sea floor spreading in contrast, causes sea level to change around 1 cm/1000 years with maximum of 300 m change. Cyclothem lasted approximately ~400,000 years with an estimated change in sea level probably less than 100 m.

Crowell (1978) use plate tectonics to explain why continental glaciation occurred during Late Paleozoic:

1) huge continent, Gondwana, over South Pole
2) during a time of intermediate sea level

Fisher (1980) distinguishes between "ice-house state" (O-state) vs. "greenhouse state" (G-state) climate regimes; Berger--proposed that there is an inherent instability during changing sea level and at low sea level with oscillations in climate during these being the norm rather than the exception.

*Figure 5--Sea level (coastal onlap) curve of Vail et al. and Wise

*Figure 6--Carbonate isotope fluctuation in Cenozoic deep sea sediments

RECOGNITION OF SEA LEVEL CHANGE IN SEDIMENTARY RECORD

Nature of periodicity of Pleistocene glaciation and resultant transgressions and regressions is well documented by analysis of __ O^{18} and __C^{13} in nano-plankton from deep sea cores. Processes that be surmised here are thought to be transferable to the late Paleozoic.

Variations in eccentricity of earth's orbit could have provided 400,000 year periodicity compared to 100,000 of Pleistocene.

Study of Pleistocene coastal sedimentary record have been important in inferring to what extent process of sea level change had on these sedimentary successions. If glaciation was an important factor in generation of cyclothems then there should be similarities to the Pleistocene, e.g., Frasier's (1974) study on Gulf Coast (sequence model).

Evans (1979): Provided evidence of sea level change in Quaternary sedimentary records in area lacking significant influx of terrigenous detritus resulting in predictable sedimentary sequences.

1) rapid inundation of shelf;
2) followed by condensed interval; e.g., diastem or hardground, accumulation of glauconite, phosphorite, carbonate debris representing high sea level stand (perhaps stagnation of tidal circulation).
3) Thicker, more rapidly deposited sediment heralding onset of regressive coastal sedimentation. But rapid influx of sediment also during slow transgression resulting in progradation, e.g., Mississippi River prograded 20 km/1000 years in last 5000 years during sea level rise.
4) Slow, stepwise fall in sea level during regression (slow, intermittent ice buildup) producing barrier bars, lagoonal and delta-plain deposits across coasts and shelves along Gulf and Atlantic. Isotopic shifts in oxygen 18 in nano-plankton from deep sea sediments suggests that intermittent fall in sea level occurred at rate that was slower than transgression. Intermittent stillstands produced prolonged development of shoreline deposits like barrier islands, offshore bars, carbonate banks, etc. which are common in the Quaternary sedimentation record.
5) Evans (1979) notes that even loose and friable sediment are typically not eroded away during subaerial exposure at a time of lowered sea level, e.g., coastal buildups of sand which later became coastal hills during subaerial exposure still maintain this depositional relief.
6) Weathered oxidized surfaces (paleosol) separate these sedimentary sequences. Form upper boundary to this period of sedimentation.

Together 1) stratal contacts, 2) geometry of sedimentary units, and 3) recognition of nearly isochronous bedding surfaces (transgression over an exposure surface) permit construction of comprehensive stratigraphic model. In chronostratigraphy this sedimentation would qualify as being referred to as "event" or "sequence" strata), see Frasier (1974).
The evolution of sedimentary processes within these sequences can be highly variable, e.g., terrigenous clastic or carbonate, high energy or low energy, fast or slow sediment accumulation, etc., but boundaries representing a hiatus in sediment accumulation define and isolate these products (sequence model).

In order to accomplish conclusive identification of auto cyclicity: use 3-dimensional, regionally-correlated data; Need to look large scale down to microscopic scale to interpret internal processes.

POTENTIAL FOR UNDERSTANDING CYCLOTHEMS IN STUDY AREA

Late Pennsylvanian Missourian sediments are unmistakably repetitive as they occur elsewhere with similar characteristics: Paradox basin, Midland basin, Colorado Plateau, Appalachian coal basin, Novia Scotia, Northwest Europe, and Russian platform. These sequences are comprised of carbonates, terrigenous clastics, evaporites, and mixtures. Thickness of these cycles are similar and estimated duration is comparable. A dozen alternating carbonates and clastics comprise the Lansing and KC Groups.

Eustatic sea level was slowly rising and the submergence of the craton was underway during Pennsylvanian.

Study area in western Kansas: a stable shelf during the Missourian following pronounced tectonism in early Pennsylvanian (Central Kansas uplift-CKU, Cambridge arch-CA, Nemaha uplift-NU). It provided a unique opportunity to study succession in 3-D: 1) gradual lateral variation in composition to cyclothems; and 2) predominance of carbonates that are sensitive to diagenesis and provide record of events of late stage of cycles; 3) assess epeirogenic movement on sedimentation over uplift and shelf--interval of strata noticeably thin over earlier uplift.

REVIEW TECTONIC DEVELOPMENT--FOCUS ON KANSAS SHELF

*Figure 7--Paleozoic interior basins (Lidiak)

Western Kansas-- area during Pennsylvanian was the shelfward extension of Anadarko basin, a "hybrid" foreland basin and reactivated, downdropped aulacogen. The Anadarko and Arkoma basins are immediately north of a tectonic suture formed by collision of Laurasia and leading plate boundary of Gondwana. Plate collision climaxed along Ouachita segment in Late Mississippian to Early Pennsylvanian with thrusting and uplifting of core region and downwarping of foreland basins. Concurrent movement of intracratonic uplifts (CKU, CA, Nemaha) and adjacent basins occurred with the deformation of the plate margin.

Kluth and Coney (1981): Proposed that an evolving stress pattern in the interior of the craton developed as the orogenic system migrated to south-west. Reactivation of the basement occurred on craton during this time along pre-existing weaknesses. Research on tectonism along convergent plate boundary indicates that even if tectonism was episodic, it would be too long in duration to have been the cause for cyclothem development. One major result of appears to be clear distinction between lengths of tectonic deformation and estimated duration of cyclothemic sedimentation, e.g., compare approximately 400,000 year duration of cyclothems with typical several m.y. long tectonic episodes along convergent plate boundaries, which are also generally non periodic. Another component in the evaluation of structure is the recurrence of structural deformation and the effect of epeirogenic deformation on sedimentation.

Fath (1920): Described the origin of the granite ridge (Nemaha uplift) in northern midcontinent. Nemaha uplift is located along postulated series of faults or other weaknesses (Berendsen and Blair, in press). Fath concluded that vertical movement in Late Paleozoic occurred as faulting along these existing weaknesses.

Morgan (1932) named the Central Kansas Uplift (CKU). Trends on the CKU appear to follow Precambrian geophysical trends. Timing according to Morgan (1932) was related to Appalachian folding event.

Powers (1925) described spasmatic movement of local uplifts occurred throughout the Pennsylvanian and Permian in western Kansas. Successive rejuviation of buried hills occurred in a process he described as plains-type folding. (i.e., ideas on subject are not new). Shelf is site of recurrent structural deformation of thin sedimentary veneer.

*Figure 8--paleogeographic map of western Midcontinent

Kansas: broad shelf; Compare the study area in western Kansas with the outcrop belt in southeastern Kansas; thinning in northwest; Anadarko basin underwent rapid subsidence resulting in the development of an abrupt shelf margin built by reciprocal sedimentation; Northeastern shelf margin of the Anadarko basin was estimated to have presented up to 450 m (1200 ft.) relief (Kumar and Slatt, 1984) across which periodic influx of terrigenous detritus alternated with carbonate deposition; Anadarko basin was then a sediment trap, not a source of sediment and blocked clastic influx from the southeast from the Ouachitas into western Kansas; Apron of coarse arkosic detritus was located adjacent to the Amarillo-Wichita-Arbuckle trend and Ancestral Rockies; keep in mind low latitude (tropical) setting of the Midcontinent.

--Lane (1979): study area along northern shelf margin of Anadarko in Missourian-Virgillian strata; Noted oolitic and phylloid algal-rich carbonates comprising massive limestone along shelf margin; Slope estimated only 1 degree, but relief estimated at ~120 m; Allodapic skeletal and oolitic debris comprise submarine fans at toe of slope; Contracts with terrigenous clastics in submarine fans to east and south in areas of study by Kumar and Slatt (1984), and Galloway et al. (1976); Periodic development of coralgal-capped phylloid algal carbonate banks also noted along southern Anadarko basin (Dutton, 1982, Becker, 1977).

--(General observation) While Permo-Penn. time occupy only 23% of Paleozoic time, this stratigraphic interval averages 45 to 75 percent of entire sedimentary column preserved in Kansas; Pennsylvanian strata onlap onto eroded terrain, locally resting on Precambrian schist, granite, and quartzite on CKU (Walters, 1946), 36 percent of OOIP in Kansas from Pennsylvanian reservoirs (5.8 billion bbls.); Over half of latest oil discoveries in Kansas from Pennsylvanian reservoirs; 75% of these are from Marmaton and Lansing-Kansas City.

*Figure 9--A-A' SW to NE strat. cross section.

H, I, J, K-Zones; 410 km long; GR, N, LL; Top of displayed log interval from 4200 ft. (1260 m) to 3200 ft. (960 m) below the surface; Note scale and vertical exaggeration: 500 X.

*Figure 10--Index map for cross sections B and C; structure X-Section C-C'.

*Figure 11--C-C' strat. section, 3800 ft. (1140 m) below surface.

*Figure 12--B-B' strat. and structure cross section.

*Figure 13--Data sheet.

*Figure 14--Isopach base K-Zone to base of Pennsylvanian.

Note: Thickness vary from 0 over the CKU to 410 m in extreme southwest; Lower surface is regional unconformity; Progressive onlap through Pennsylvanian; L-KC deposited some 20 m.y. after major uplift. Thinning in eastern part of mapped area reflect NW-SE uplift of CKU; CKU is site of earlier uplift; A NW-SE oriented embayment to west received sediment in early Penn. (Morrow) in SW Kansas, paralleling the ancestral uplift; Little thrusting occurred in Wichitas during earliest Pennsylvanian and accordingly little indication here that there was concurrent parallel west-east oriented subsidence along this shelf in Kansas [Atokan represent first period of major thrusting].

*Figure 15--Isopach top H to base K (H, I, J, K), 3 m shaded intervals, black area >55 m thickness.

Thickness of interval vary from 60 ft (18.3 m) to over 250 ft. (76.2 m). Rate of thickening <2 ft/mi. (0.38 m/km) over 225 km distance or average 0.5 ft/mi. thickening for each of four cyclothems.

Differential subsidence across shelf during accumulation of 4 cyclothems was low in any event; Gradual syndepositional structural movement cause regional thinning, for example, over CKU because very thin beds can be traced over structure; Minimum paleoslope ~0.5 ft/mi., constrained by the rate of regional thickening; Will suggest later that the slope of this shelf was probably not constant during the deposition of each the cyclothems--i.e., the configuration of this shelf had a very important influence on nature of carbonate deposition and petroleum reservoir distribution.

Significant thinning: on this map along 2 centers: Cambridge arch (CA) and Rush Rib (under 60 ft. thick), coinciding closely, but not exactly with earlier tectonic uplifts.

Notice more E-W strike in southern region of this isopach than isopach of earlier interval (lower Pennsylvanian)--appear to reflect time of increased subsidence in Anadarko basin and thrusting of Amarillo-Wichita-Arbuckle; As a consequence active tectonism and subsidence of shelf; positive in SW suggested by thinning (growth of Los Animas and Cimmaron Arch which bisects depositional trend of Morrow and is now an important oil province for Morrow).

*Figure 16--Top Stone Corral to top H-Zone, 60 m shading.

Thickening to south toward Anadarko continued in this interval; Reflected in facies in L. Permian as well as U. Penn.; Apparent shifting of structural activity to west particularly in association with Los Animas Arch by E. Permian.

Slight epeirogenic movement significantly affected depositional environments.

*Figure 17 and 18--Configuration of Precambrian surface in western Kansas.

*Figure 19--Structure contour top K-Zone; 50 ft. (15 m) C.I., dashed lines are structural lineaments; Map represents sum of post-depositional deformation; Most pronounced deformation over CA; Lineaments oriented both NW and NE. Structure cross-cuts isopach trends.

*Figure 20--Oil and gas fields producing from L-KC.

Majority of production found to date is structurally controlled.

*Figure 21--3-rd order trend residual structure K-Zone

*Figure 22--trend order plot vs. goodness of fit

Trend surface mapping: means of partitioning local and regional elements of map; Remove regional dip to emphasize local structural anomalies.

Use polynomial trend fitting program of SURFACE II, select order to use empirically, optimizing lowest order to preserve both regional and local variation (sum of squares due to regression divided by total sum of squares to calculate goodness of fit); Sum of squares of regression: departure of regression surface from original data; Total sum of squares: sum of variation of the data set.

3rd-order trend surface explains more than 90% of original variation; Higher orders contribute only small increments to this fit.

Finer details of residual map correspond closely with Precambrian surface, e.g., Rush Rib, also magnetic anomaly, perhaps intermittent, local, structural reactivation; Also note that CKU outline closely corresponds with concentration of positive anomalies; Regional dip reversal occurs over CKU on horizon of K-Zone; Also predominantly a positive area following deposition; Favorable site for oil entrapment.

Interval thickness of 4 cycles -- produce regionally uniform patterns; Paleohighs and breaks are perhaps revealed by such a map and, in turn, may give us clues about slope and influence on sedimentation; Isopach of individual cyclothem would reflect changes of shelf configuration during each cyclothem; Technique helpful in assessing relationship of structure on sedimentation, i.e., paleotopography: Help to explain locations of carbonate banks and shoals, terrig. clastic deltas, offshore bars, etc.

<u>Evidence for Recurrent Structural Activity in Western Kansas</u>:

Similarity in structure and isopach maps of many intervals suggest episodic movement of structures that follow a template defined by underlying basement rocks; During Late Paleozoic: nearby Ouachita orogeny probably provided the driving force for epeirogenic deformation.

Weaknesses in basement include faults, fractures, and discontinuities; Use gravity and magnetic patterns to assist in interpreting trends and patterns some which may be related to discontinuities in Precambrian crust.

*Figure 23--Dutch major geophysical trends in Precambrian.

Kansas: dominated by NW and NE trends; Also coincide with dominant joint trends; 3 distinct Precambrian terranes; Older orogenic terranes probably formed by continental accretion paralleling ancient Precambrian continental margin. These are cut by younger CNARS (Central North American Rift System).

Geophysical trends correlate with geology of Precambrian; Also some correlation to present structural trends.

*Figure 24--pole correction map of total magnetic field intensity for western Kansas.

Distortion caused by earth's magnetic field is calculated and subtracted from original map of total magnetic field intensity.

Low frequency NW trends probably represent deep-seated structure of Precambrian; Two prominent terranes are distinguished by heavy line; Hatured lines are major basement faults; Southern half of CA-CKU nearly parallels the magnetic anomaly map.

*Figure 25--2nd vertical derivative map of total magnetic field intensity for state.

Second vertical derivative map of the total magnetic field; Dark intensity areas on map are where changes in magnetic field are the greatest. Areas of high contrast probably represent steep contacts between rocks of contrasting magnetization (faulting or intrusion); This filtering enhances the short subparallel NE trending linears probably associated with the shallow basement CNARS. This is a 1.1 billion year old graben/horst system.

*Figure 26--Precambrian terranes in Kansas.

The areas of attenuated magnetic signature are interpreted to denote thick, Precambrian sedimentary strata filling the rift; Note: 1) edge of rift basin defined by the attenuated signature coincides with the SE termination of CKU, 2) the southern CKU is sliced by NE-trending linear magnetic anomalies, which coincide with terminations of local NW-trending anticlines on the CKU; 3) Pratt anticline parallels the NE trending magnetic lineaments; 4) most structure and isopach maps have local anomalies that parallel the northeasterly trend located on the east side of mapped area overlying the rift. A west-northwesterly trend dominates the area west of the CKU.

[Oil and Gas Production Data Insert]

*Figure 27--Structure contour map of Swope Ls. in Collier Flats field.

*Figure 28--Isopotential map of Swope Ls. in Collier Flats field.

Overview of cyclothem concept

*Figure 29--Basic Kansas cyclothem of Heckel (1977).

*Figure 30--Detailed sea level curve of Middle and Upper Pennsylvanian strata in the Midcontinent outcrop (Heckel, 1985).

*Figure 31--Patterns of atmospheric circulation during Late Pennsylvanian.

*Figure 32--Paleography during maximum transgression.

CYCLOTHEMS AND STRATIGRAPHIC SUCCESSION

*Figure 33--Gamma ray neutron wireline log display and lithologies of cycles H, I, J, K.

H, I,J,K; Marine and non-marine divisions, based on cyclothem concept (genetic).

*Table 2 -- Components of cyclothem

4 members, "Kansas Cyclothem" of Heckel, carbonate-dominated, to understand reservoir unit (upper limestone) important to know characteristics of rest of cycle.

Upper shale = regressive shale

Upper carbonate = regressive carbonate

Lower shale = marine shale

Lower carbonate = transgressive carbonate

TRANSGRESSIVE CARBONATE

Thin, but widespread, generally less than <1.5 m thick; Sharp basal contact; Deepening of water upwards in deposit; Evidence of minor erosion common below lower contact; Common to have clasts incorporated in base; Sharp contrast in depositional environment with onset of new cycle; Locally sandy carbonate or coarsening-upward sandstone capped by brachiopod-crinoid coquina (to 3 m thick) which is locally productive; Oolitic (9 m thick) bars are developed over upthrown block of prominent basement fault in Ellsworth County and are oil productive (Hopkins, 1977).

Examples of Transgressive Carbonate

Findlay +120 m (J) -- Sharp contact of limestone with shale of underlying cycle; Diverse marine skeletal debris in quartz siltstone matrix; Underlying shale appears to be nonmarine; Evidence of desiccation and subaerial exposure and not fossiliferous; Carbonate clasts are caliche.

Findlay 1120 m (3742.5 ft.) (J) -- Thin section of same samples of transgressive carbonate -- algal-coated skeletal carbonate grains in silty matrix; Deposited in moderate energy in shallow water (densely packed).

Ainsworth 900 m (2986 ft.) (J) -- Reworked carbonate clasts at base of transgressive carbonate; Rounded clasts with mixed lithologies in shaley, fossiliferous carbonate matrix.

Ainsworth 870 m (2914.5 ft.) (G) -- Transgressive limestone, but at top of interval -- lower-energy environment, with open marine fauna indicates deepening of water as shelf was submerged; Some organic matter preserved in carbonate matrix; Pyrite is also common; Commonly darker colored carbonate; White dots here are crinoid oscicles.

Depositional Environment of Transgressive Carbonate

Thickness:length ratio exceeds 5 X 10^5; Widespread marine unit overlying non marine stratum; Short duration for transgression affecting large area of shelf; Speed of transgression very fast, i.e., not related to tectonics; Rapid transition from restricted to normal marine environments; Commonly high energy at base to subtidal, quiet water accumulation in upper portion.

Diagenesis of Transgressive Carbonate

Slow grain-to-grain compaction in absence of early cementation; Unstable grains have been neomorphosed in absence of leaching; Fine crystalline pyrite common and preservation of flecks of organic matter--suggest low oxygen condition late during transgression (Heckel, 1983).

MARINE SHALE

Important and controversial lithofacies; Green or olive to gray-green, massive, silty or clay-rich to gray or black, carbonaceous, fissile clay shales; Black shale separated by gray shale from adjoining lithofacies; Green and gray fossilif. is open marine with common to abundant benthic organisms while black shales contain nektonic and nektobenthonic organisms, few benthic, if any, and abundant pelagic organisms.

Unusual abundance of conodonts, fish debris, but lack common marine invertebrates in black shales.

Moreover, black shales commonly contain non-skeletal phosphorite, pyrite, and large amounts of finely comminuted organic matter; Minor elements in elevated concentrations are well documented in literature; these shales are typically described as fissile, non-burrowed, and hard.

Black shale grade laterally to dark gray and gray and locally thin significantly over paleohighs; Phosphate nodules from mm to cm-sized--correlates with high levels of organic matter and pyrite.

Non skeletal PO_4--apatite, commonly with preserved, abundant and diverse radiolarians and nautiloids and fish debris; Kidder (1983) interpreted PO_4 as precipitation from interstitial water unto radiolarian tests displacing sediment; Source of PO_4--planktonic organisms, fecal material, or perhaps solution and suspension from river water; Similarity of these to modern phosphorites suggest slow deposition, predominantly marine derived.

In study area the marine shale generally averages 0.6 m thick or less, but up to 6 m on northern shelf; Pinches out locally over CKU on a surface that appears to represent a lag concentration.

Depositional Environment of Marine Shale--Lower Shelf

Notably different depositional conditions compared to adjacent lithofacies and characterized by rapid transition to adjacent lithofacies; Marine shale represents lowest energy, probably deepest water conditions; Restricted, anoxic or dysaerobic conditions common and widespread during accumulation of this shale.

Evidence for low rate of accumulation: 1) abundant phosphate; 2) concentration of normally sparse fossils; 3) concentration of organic matter; 4) horizontally-oriented clay mineral plates in face-to-face contact--called parallel horizontal bedding of Potter et al. (1980) interpreted to have resulted from episodic suspension sedimentation in still water in absence of bioturbation.

River water is commonly laden with suspended clay-sized particles which upon mixing with sea water, produce flocs or aggregates of hundreds of randomly oriented clay-sized particles (Gibbs, 1983); In contrast, Reineck and Singh (1975) describe single-grain sedimentation, resulting from very slow accumulation when low density suspended particles are too distant from each other to come in contact with one another in the water column; Overburden and compaction alone have been shown to not be sufficient to orient clay flakes from originally flocculated condition. Thus, the horizontally-oriented state of the clay is thought to be due to extremely slow rates of accumulation.

Examples of Core Shale

Reese F-5, 1011 m (J) -- Gray green shale with carbonate mottling, diversely fossiliferous, marine deposit, carbonate mottles are burrows.

Denker (K) -- Dark gray to gray shale with many marine fossils.

Ohlson (G) -- Black shale, few visible fossils, gray shale burrows.

Conover (K) -- Black shale with no visible fossils.

Other Evidence for Water Depths During Deposition of Black Shale

1) Stagnation due to limited circulation on the sea floor in the interior regions of the shelves -- poor circulation and resultant stagnation.
2) Warm tropical climate would induce thermal stratification with elevated temperatures in surface layers (Black Sea Model); Thermally stratified lakes in East Africa have thermocline developed near 70-100 m below surface, but fluctuate.
3) Large volumes of freshwater carry suspended organic matter could be dispersed over the shelf and settle into stagnant areas and remove or significantly lower the oxygen content.
4) Geochemical Trends: Expect areas of upwelling to be richest in organic matter and minor elements; but increase of organic content inland; Molybdenum (Mo) over 1160 parts per million and zinc high concentrations in central craton in a Des Moines age black shale; Phosphate, uranium, organic matter and other trace metals in the same shale are about twice the levels in the eastern craton compared to samples of the same zone in the western midcontinent; Phosphate content correlates with the uranium content.
5) Phosphate may be derived from river water, but studies of modern rivers however indicate amount of phosphate average around 10X greater in marginal ocean settings and areas of upwelling.

6) Average hydrocarbon yield (extract able organic matter divided by total organic carbon) is higher in the western Midcontinent than in the eastern belt--in general, hydrocarbons would be evolved in greater concentrations from marine organic matter unless terrestrial matter was lipid rich -- such as from algae. Organic matter in much of the craton may have an important terrestrial component and would be expected to increase eastward.

Pelagic sedimentation--no specific depth connotation, only open marine; exclude marginal marine; >50 m water depth to insure exclusion of strong wave and light influence and preclude growth of most shallow-marine carbonate flora and fauna (Scholle and Arthur, and Ekdale, 1984).

Pelagic sedimentation is characterized by slow grain-by-grain setting of material biochemically produced in surface water; However, in Paleozoic "starved-basin facies," little evidence of calcareous microplankton (diatums, coccoliths) such as in Cenozoic, mainly organic walled, phosphatic, or siliceous varieties (radiolarians, conodonts) and ammonites, nautiloids.

Recognition of pelagic conditions during accumulation of marine shale: 1) no planktonic forams or diatoms in Paleozoic, but radiolarians and other plankton and nektons, e.g., conodonts in generally great abundance; 2) condensed interval; 3) hardgrounds--bored, encrusted, lithified; 4) fine-grained and great lateral extent; 5) mm-rhythmic bedding; 6) skolithos and zoophycos burrows; 7) gradual lateral facies transitions.

REGRESSIVE CARBONATE

Greatest diversity in thickness, depositional environments, and diagenesis; Shallowing-upwards sequence from open marine to restricted marine; Gradational base with marine shale, with interval of gradation markedly extended along periphery of shelf where clastic influx was more significant.

Lower part of the regressive carbonate--diversely fossiliferous, tan to gray, burrowed wackestone with brachiopods, crinoids, fusulinids, corals, peleoypods, tubular and encrusting forams, bryozoa; Phylloid algae are locally abundant where important components of broad, low relief carbonate buildups (H-Zone).

Eugonophyllum is the dominant alga, originally aragonite and easily dissolved.

Examples of Lower Portion of Upper Carbonate

Dorr (H) -- Burrowed wackestone with diverse fossils, wispy shale laminations.

Ainsworth (G) -- Brown slightly shaley micrite rich, diversely fossiliferous (lower energy, open marine).

Findlay (J) -- Clean micritic carbonate alternating with thin layers of shale.

Findlay (J) -- Thin section, diversely fossilif. (note trilobite fragment).

(1) Burrowing pervasive on northern shelf in light-colored wackestone while on the southern shelf--less frequent burrowing and more rhythmic-bedded dark shale in darker, (2) less fossiliferous carbonate matrix; (3) Occasionally higher GR carbonate on south coincide with units with greater concentration of dispersed organic matter; (4) GR spectralog reveals higher concentration of uranium; (5) Also quartz silt concentration is greater in south and also extreme north; (6) Concentrations of fossil debris and zones of pyrite-rich shale suggest periods of decreased sedimentation on southern shelf. Recurring, episodic, dysaerobic bottom conditions.

Heckel (1977) noted lack of micritization of grains in lower portion of upper carbonate; Concluded too deep for proliferation of blue green or green algae (~100 m); However endolithic fungal borings down to nearly 800 m in modern ocean; Unabraided skeletal fragments still indicate deep water.

I-Zone: unusual in that (1) shallow water indicators throughout cyclothem along entire northern shelf; (2) Regressive carbonate pinches out along northern border in relatively thin upper shale; (3) Pinchout of carbonate not because overwhelmed by terrigenous detritus; (4) Prominent paleosol seen in core on northern shelf in interval of red shale where marine portion of I-Zone should be; Suggest slow sediment accumulation during emergence of northern shelf; Marine I-Zone to south and exposure to north support regional slope to shelf.

Upper Part of Regressive Carbonate

Lighter colored, thickest lithofacies, shallow water conditions, high and low energy, but much variability; limited fauna: mudstones with high spired gastropod, concentrations of ostracods, tubular forams, small bivalves; peloids, laminations, mudcracks, fenestral fabric is common, algal stromatolites; On upper shelf grainstones more commonly lightly coated bioclasts (0.5 to 2 m in thickness); Grains are generally poorly preserved, usually micritized or dissolved.

Environments interpreted to be shallow or restricted (shelf, bay, lagoon), intertidal, and supratidal--a complex facies mozaic (unlike terrigenous). No significant influx of terrigenous detritus during this time in contrast to southeast Kansas.

Environmental conditions represented:

Restricted: impoverished fauna, low biotic productivity, low diversity, abundant mud, abundant burrows; suggesting slow-water circulation, abnormal salinity, depleted nutrients, temperature extremes, slow sedimentation.

Intertidal: laminations, fenestrae, oncolites, mud cracks, vertical burrows, intraclasts.

Supratidal: stromatolites, mud cracks, flat-pebble conglomerate, intra-stratal dolomite, evaporites, horizontal laminations (no burrows).

Shallow-water mozaic sedimentation, diachronous across an inclined slope; Early diagenesis is variable but pronounced, varying according to position on shelf, from oldest on north to youngest on south; Slope perhaps inclined 0.5 ft/mi. (0.1 m/km) minimum; Shallow water deposits comprise thin veneer only several meters thick at most locations perhaps limited by restriction of time that shelf is occupied by shallow water conditions; Model is important in developing concept for reservoir trends on shelf; Need to reconstruct shelf configuration and go through development of cycle. Use abundant wireline logs to piece lithofacies together. Noted differences in character of cycles exist in this area.

Generally thicker or greater proportion of grainstones over CA and CKU than NW shelf; Local paleohighs are sites where concentrations of grainstones occurred (Watney, 1980).

Oolites dominate upper portion of upper carbonate across southern shelf in 3 of the 4 cycles studied; Thickness in south exceeds that of entire cycle on northern shelf; Must reflect change in shelf setting. Use regional maps to aid in interpretation.

General limited thickness but extreme areal extent of shallowest water facies; Abrupt transition from subtidal, open marine deposits to shallow-water sediments suggest shallowing developed independent of sedimentation, i.e., not simply progradation and aggradation of shelf.

Examples of upper portion of regressive carbonate:

Nicholson (D) -- Light colored micrite with restricted fauna.

Rathe (D) -- Burrow mottled, very silty wackestone, sparsely fossiliferous, scattered brachiopods and crinoids.

Ohlson (J) -- Laminated limestone with intervals of fenestral fabric; some of voids filled with internal sediment and quartz silt.

Dorr (H) -- Algal stromatolite.

Ainsworth (H) -- Birdseye structure, irregular fractures, brown altered rim around fractures and vugs, internal quartz sediment.

Bartosovsky (H) -- Thin section vuggy, clotted, pelloidal lime mudstone, unfossiliferous.

Stegman (K) -- Base of skeletal grainstone with patches of oil saturation sharp basal contact.

Conover (K) -- Cross stratified oolite.

Litsey (K) -- Oolitic grainstone with molds of oolite cemented, partial dissolution and collapse of cement and molds of ooids.

Findlay (J) -- Significant dissolution of a lime wackestone with infiltration of internal sediment--green silty shale, altered oil stained rim around voids.

Findlay (J) -- Unfossiliferous mudstone cut by vertical oriented voids filled by green shale, also fracturing of carbonate. (.3 meters above last sample).

Dorr (J) -- In situ breccia of pelloidal mudstone, originally mudcracked and probably ripped up.

Riedel -- Similar to previous slide with fitted clasts of lime mudstone infilled by shale.

Diagenesis of Regressive Carbonate

Early freshwater diagenesis is very important in porosity development and porosity occlusion; Is critical to development of oil and gas reservoirs in LKC. Later stage dissolution may be locally important. Also fracturing.

*Dissolution of unstable grains and skeletal material, particularly:

phylloid algae

oolite

bioclasts

Provide secondary porosity; dissolved carbonate may also occlude what was once primary porosity: intergranular or framework; Relative significance of fabric selective late stage dissolution has yet to be demonstrated.

Examples shown in slides:

Prentice -- Subaerial crust -- brown, wavy laminated accretionary micrite lying on skeletal packstone; Voids are fenestral like and interpreted as root casts.

Prentice -- Thin section of crust -- crinkly laminated, microcrystalline calcite with rounded, vertically oriented voids interpreted as root casts.

Miller Z-1 -- Thin section -- horizontal fracture filled with rounded clasts of wall rock carbonate; Some clasts are coated; Edge of fracture is encrusted with brown microcrystalline micrite (caliche).

Beauchamp (H) -- Thin section, packstone or grainstone; Grains are solution pitted and coated by brown, dense micritic cement followed by fine calcite spar; Some of dense micritic cement has pendant shape and distribution (hanging beneath grains). Pore system described as rectilinear.

Stegman (L) -- Top zone, subaerial crust.

Ohlson (H) -- Diagenetic calcite, dense brown caliche clasts in chalky white calcite; Also caliche matrix precipitated during expansion or swelling of original carbonate fabric with precipitation of chalky calcite in expanded framework. (Displacive growth, circumgranular and intragranular cracking, dissolution of quartz grains).

Rathe (G) -- Mixed-pebble carbonate conglomerate in red, silty-shale matrix; White, powdery micritic calcite surrounds clasts-caliche.

Ohlson (H) -- Unfossiliferous lime mudstone cut by root casts.

Denker (H) -- Top, grade downward to fitted clasts (*in situ* breccia) with solution rounding, shale infiltration.

Palmer (J) -- Thin section of wall of fissure in carbonate filled with wall rock debris; notice unweathered limestone with fusulinid.

Palmer (J) -- Thin section, within fissure of previous slide, corroded grains of skeletal carbonate covered by brown dense micritic carbonate.

Blair (K) -- 4mm across base, alizerin-red-K ferro stain, blue plastic impregnation; dissolved ooids or replaced with fine blocky, low Fe calcite suggesting cementation undersaturated meteoric waters; oolites common along southern shelf.

Conover (K) -- Fine blocky calcite cement, dolospar as void fill and replacement. Syntaxial overgrowths of calcite.

Nicholson (D) -- Overpacked bioclastic packstone, many molds, darkened solution embayed edges.

Prentice (G) -- Exterior core with large vugs.

Repeated subaerial exposure of tops of each upper carbonates noted; defined by carbonate crusts, paleosols with calichification with root casts, freshwater vadose features.

<u>Spacial variation in diagenetic overprinting in regressive carbonate</u>: (1) Irregular micritic cements, (2) caliche-like fine-crystalline calcite cements, (3) irregular, menisus, pendant, blocky, and sparry crystalline cements; (4) Diagenetic breccias and conglomerates restricted to northern shelf and locally over CA and CKU; (5) Oxidation and red-colored silicification.

Pervasive dissolution of ooids to produce <u>oomoldic porosity</u> with local cementation of primary pore space.

Solution fissures: to 6m below surface of upper carbonate filled with red-brown, silty shale and carbonate debris. Channeling and Karst in north.

Local anhydrite lenses and caliche-like patches in red shales along northern shelf.

Net effect of subaerial exposure and freshwater percolation: 1) leaching of grains, and matrix, 2) recrystallization of micrite; 3) disturbance of original depo. fabric by vugs, solution cavities; 4) still best continuous porosity in grain-supported textures, i.e., important to identify nature of depositional environment.

More intense diagenesis over CKU and CA; CKU is a site without significant shale infiltration to occlude pores: Abundant in situ breccias, solution channels, nontectonic fractures on CKU; Suggest that this location on shelf was <u>more positive</u>.

Less intense diagenesis to south, still subaerial exposure in south with thin crusts and attendant dissolution, root penetrations, calichification, and rectilinear, micritic cement.

<u>Calichification Associated with Regressive Carbonate</u>

Examples:
*Ohlson 3097.5

Nodular-chalky caliche carbonate exhibiting top H-Zone.

1) displacive growth of finely crystalline diagenetic calicite;

2) circumgranular and intragranular cracking;

3) dissolution of quartz grains, little if any original depo. fabric preserved.

*Wertz

Circumgranular cracking in thin section, 4 mm unstained plane-polarized; All of example shown is diagenetic calicite (micro crystalline and spar); Circumgranular cracking in a clotted texture; Part and parcel of soil formation during extended weathering in semi-arid environment (evap >pptn.).

*Palmer 10

Clasts of wall rock debris settled in vertical cavity, interpreted as a solution pipe, lined with caliche crust (brown, clotted, microcrystalline calcite).

*Prentice

Laminated and pisolitic caliche crust.

Crusts common: early lithification and better chance of preservation vs. soft caliche or soil.

Also dolomitization and intense recrystallization (mottling) important on southern shelf: mixing of waters, greater hydrologic circulation due to extensive oolite development.

REGRESSIVE SHALE

Relatively thin (<9 m) except in NW and extreme SW; Continental deposit here, but marginal, marine deltaic sedimentation was common in eastern Kansas.

Typically, only a veneer of shale present; Thickness slowly decreases southward.

Passively fills depositional and structurally-formed paleotography; Red-brown argillaceous siltstone on north to green and gray silty shale to south; Soil development is common; Caliche mottling abundant on north associated with preservation of root casts, oxidation, and anastomosing shrinkage cracks, circumgranular cracks; Some root casts have oriented-clay skins (cutans).

<u>Examples of Regressive Shale</u>

LKC strat column

Bartosovsky (J) -- Color-mottled, silty shale; Nodules are micritic carbonate caliche nodules; Fractures, vertical fissures lined with caliche, and root casts are abundant.

Bartosovsky (J) -- Vertical tubes filled with softer shale.

Reese F-5 (K) -- Red-brown, oxidized, silty shale with caliche nodules.

Wertz (D) -- Thin section. Clotted fabric within caliche nodule with clast-like areas surrounded by sparry calcite (circumgranular cracking). Shades of darkening indicating periods of calcite precipitation, development by displacive growth of microcrystalline calcite.

Bartosovsky -- Thin section. Caliche nodule within quartz silt matrix, dissolution of quartz grains and precipitation of sparry calcite.

Bart -- Thin section. Root casts surrounded by micritic caliche calcite.

Regressive shale succeeded regressive carbonate in subaerial setting rather than concurrent deposition; Thinning over CKU suggests that this location was an elevated portion of shelf as previous evidence indicate.

Depositional model--Irwin

Wilson model of carbonate shelf

Black and white photos in these notes:

*Figure 34--Lower portion of upper carbonate on southern shelf.

*Figure 35--High-energy grainstone facies in the upper portion of upper carbonate

*Figure 36--High-energy facies in the upper regressive carbonate.

*Figure 37--Restricted marine, shallow water facies, with low faunal diversity.

*Figure 38--Carbonate cements

*Figure 39--Fracturing

*Figure 40--Evidence of subaerial exposure in regressive shale.

Petroleum Geology LKC production map for Kansas

L-KC major contributor to oil and gas production in Nebraska, Kansas, and Panhandles of Oklahoma and Texas; Ultimate recovery from Pennsylvanian rocks in Midcontinent 8.8 billion bbls. (1.26 billion metric tons), 3.79 of which from giant fields (>100 million bbls.), 2.7 billion from significant fields (25-100 million bbls.); one-fourth ultimate oil production estimated will come from smaller fields.

Hall-Gurney discovered in 1931 now occupying Russell and Barton counties, Kansas; The only giant oil field in Kansas producing primarily from L-KC; 139 million bbls. produced.

OOIP (Pennsylvanian reservoirs)	= 5.75 billion (.82 billion metric tons)
Ultimate oil production from (Pennsylvanian reservoirs)	= 2 billion (.29 billion metric tons)

All field OOIP = 16 billion (36 % Penn Co_3)

All field ultimate = 5.1 billion (39% Penn Co_3)

Recent discoveries in LKC 50-300 BOPD (7-43 metric tons per day)

Frequency distribution of field size (# wells) versus numbers of fields; 8 divisions of study area; include median field size ranging from 2 wells to 5; productive surface area ranging from 0.41 percent to 14 percent in each area.

CKU one of most densely drilled and most active province in U.S.; Very mature; Distribution of field sizes in this area approximate hyperbolic distribution; Less defined distribution in developing areas like western Kansas.

*Table 4 (not included) -- Field data of selected reservoirs

Selected field data on LKC reservoirs; Arbitrary on what is available from published literature; Recovery factors complicated by some commingled production; certain wells in Gove and Trego County produce as much as 150,000 bbls. over 15 year average lifetime; Production in excess of 10,000 bbls. per day was common early in history of larger fields on CKU: only when encountered high porosity and fracturing, with long oil column.

Primary reservoir drive: water and pressure depletion with gas cap to south.

2ndary recovery by waterflooding in these reservoirs can come close to doubling the primary production; Significantly reduced sweep efficiency in many reservoirs due to highly discontinuous porosity.

--Carbon dioxide injection: (miscible flood) are a possibility for these carbonate reservoirs; Miscibility pressures shown experimentally to be 1200 to 1500 psi and are within range of original reservoir conditions.

Nearly half of original oil in place may still be in reservoir after primary and secondary recovery methods; Incremental recovery from tertiary methods like carbon dioxide have been 15% of the original oil in place; Feasibility studies need to be done; Knowledge of the geology of these reservoirs is essential.

Over 1/3 of all oil discoveries from LKC in boom period in 1981, 1982; small fields, stratigraphic component increasingly important.

Collier Flats field

Recent example of successful drilling, 54 wells have produced in excess of million bbls. from single zone in LKC, the K-Zone; IP of wells commonly exceeded 100 BOPD; Southerly plunging anticline; Dry hole updip where porosity pinchout occurs.

Western Kansas; Limited structure closure, areal restriction of porosity; Many small single payfields are common; However still potential for multipay; e.g., Cahoj disc. 1959 produced over 6.9 million bbls. from 2.8 wells from all zones; Field located on prominent dome with demonstrable paleo relief during deposition (Watney, 1980).

Exploration philosophy: think subtle, combination structure-stratigraphic traps; Lithofacies distribution is an important part of porosity distribution. Development of models to classify reservoir systems based on lithology, pore types--primary and secondary, geometry of reservoir quality rock.

Integration of Lithofacies and Wireline Logs

Log response generally not unique because bulk composition of rock can vary considerably. Wireline logs respond to change in lithology, pore volume, and composition of fluid in pores.

Modern logs standardized and calibrated; Some more sensitive to lithology; measure new properties of rock and therefore more directly applicable to interpretation of physical and chemical nature of rocks because of characteristic responses.

Well logs have been crux of exploration program in western Kansas since the 1940's: porosity, detection of hydrocarbons, lithology; most effective and economic suite: GR (gamma ray), N (neutron), R (guard, lateralog, focused induction).

Identify lithology when tied frequency to core, i.e., limestone, shale, sandstone.

X-plots of wells to compare wells in different areas or reveal vertical trends in a cyclothem.

Figure 41--GR-N, Bierig well; SW margin of study; readings at one foot increments over K-Zone; cuttings description.

Area of clastic influx, thin mudstone-wackestone, regressive shale and marine shale not distinguishable (intermediate GR-N); frequency plot of GR values sampled on per foot basis expressed as normalized percent--bimodal with small peak for limited clean carbonate.

Similar to wells on NW shelf--low GR marine shale, thick regressive shale, and thin regressive carbonate; Clustered points more characteristic of terrigenous influx.

Figure 42--GR-N cross plot.

*Hughes well in Thomas County, NW Kansas.

Note wide spread of GR frequency plot ranging from clean carbonate to marine shale; Marine shale above 160 API units, is dark gray shale.

Circular pattern of lithofacies succession on GR-N cross plot; Significant spread between the lithofacies; Suggest significant differences in environment on shelf.

Figure 43--GR-N cross plot in oolitic bearing cycle on southern shelf (Lee well).

Can distinguish 4 components of cyclothem on wireline log for reasons previously described (Watney, 1979).

[Please note that the following figures (3-16) are only references to a publication and are not presented included in notes.]

Figure 3, p. 82, Watney, 1979--Index map

Figure 4, p. 85, Watney, 1979--Conceptual strat. cross section, NW Kansas-SW Nebraska.

Figure 5, p. 86, Watney, 1979--N-S lithofacies X-Section with wireline logs.

Figure 6, p. 87, Watney, 1979--GR-N X-plot of representative, inner shelf well, 6 cyclothems carbonates distinct from shales.

Figure 7, p. 88, Watney, 1979--GR-N X-plot; landward position

Same 6 cyclothems, no dark shale but have spread between limestone and shale, i.e., carbonate is relatively pure.

Figure 8, p. 89, Watney, 1979--GR-N X-plot northwest shelf, off CA.

Area of more clastic influx; Substantial decrease in contrast between marine and regressive shale (composition, oxidized); Regressive carbonates less pure--more silt and shale intercolations and dispersed, also infiltration of shale into pore space; Nearshore marine carbonate and continental shales with decreased difference, eventually converge and distinctive log signatures are lost.

Figure 9, p. 90, Watney, 1979--Shale: carbonate ratio map of G-Zone, clastic domination in northwest; gradient steeps in NW sector.

Figure 10, p. 91, Watney, 1979--Max. GR deflection in marine shale of G-Zone.

Peak reaches plateau at just over 200 API units; minimum, shale base line around 80 API units (GR floor for shale), which is same as regressive shale; Therefore essentially loose distinction between two shales in northern region.

Figure 11, p. 92, Watney, 1979--X-ray diffraction major peak heights for selected minerals distinguished as to marine or regressive shales; Quartz and feldspar peaks constantly greater for regressive shales; 100 A peak of mica and illite also usually higher in regressive shales; muscovite more abundant in regressive shale.

Calcite and dolomite generally higher in marine shale; also clay fraction greater in marine shale.

In average dark shales uranium context vary from 3-250 ppm; Heebner shale 30-50 ppm; average shale 3.7 ppm uranium with range of 1-13 ppm.

Lower regressive carbonate -- elevated GR thought due to uranium found in dispersed organic matter; Shale fraction generally not great enough to account for GR level; Organic matter is observed in thin section in these carbonates.

Figure 16, p. 97, Watney, 1979--X-plot of G-Zone with phylloid algae.

Mapping with Wireline Logs in K-Zone

Use available cores (framework) to ID lithofacies and translate to wireline logs. Well density in this study averages 1 well per 34 km^2 or every 5.8 km (2300 wells).

Objective of mapping:

1) Define the configuration of shelf.
2) Determine the effects that the shelf configuration had on lithofacies distribution.
3) Define patterns and trends on maps to help interpolate very limited lithofacies data and relate to reservoir development.
4) Evaluate possible causes of cyclicity.

<u>Marine Interval Isopach</u>

Figure 44--Marine interval isopach of K-Zone.

Thickness of marine shale is generally insignificant, compared to thickness of regressive carbonate. Exception to this is in extreme NW and SW mapped area where influx of terrigenous detritus occurred. Carbonate buildups resulted from accumulation of grainstone (high energy), or mudbank consisting of lime mud trapped by organisms like phylloid algae (e.g., Watney, 1980; Ebanks and Watney, 1985).

Grainstone can also occupy pre-existing bathymetric low or alternately, along bathymetric highs without significant addition to thickness. For example, grains such as oolite could be formed on positive and reworked into adjacent lows.

Identify favorable reservoir rock most rapidly assessed by magnitude and kind of porosity. Need to know depositional environment (facies) and extent of diagenesis and their relationship to porosity in order to identify parameters to map and predict reservoir development.

Best reservoir quality in LKC most commonly associated with rocks deposited originally in high energy environments. Grain support provides rigid architecture and network that assists in perculation of undersaturated waters and leaching of grains and mud.

Thick mudbanks are possible sites for early leaching by meteoric water as shelf becomes emergent or constrains flow of undersaturated subsurface waters.

Marine interval isopach map regionally thickens southward or basinward and suggests differential subsidence increased to south. Sedimentary facies and diagenesis do vary across shelf sympathetic to this trend and suggest differential relief during deposition of the cyclothem.

Trends on map of marine interval of K-Zone, lowermost cycle studied:

1) thickening along arcuate trend, concave to west; 32 km wide which runs 240 km from Wallace County to Stanton County;
2) thick lobate volume in Haskell County;
3) elongate multilobed area extending W-NW to E-SE;
4) narrow N-S trending lobe in Rice and Reno counties;
5) generally a marked regional southward thickening south of 35-40 foot contours.

Note, all significant local anomalies occur in the southern region. Marine interval is thin over the northern shelf and along the CKU (outline).

*Figure 45--Thickness of porous carbonate

Map depicts thickness of porous carbonate above 8 percent porosity. Pore space above 8 percent is generally permeable (>0.4 md). Another method is to use the porosity feet map. Both are good indices of favorable reservoir rock except for: 1) oomoldic carbonate rock, commonly low permeability, but high porosity (>20%); 2) porosity in fractured carbonate rock (permeable even below 8%).

Porosity is commonly restricted to upper portion of regressive carbonate. May want to map porosity distribution in upper and lower intervals of this carbonate.

Close correspondence with marine interval thickness:

1) lobate pattern in SW 16-24 km wide;
2) belt of multilobed porous carbonate development along 240 km line extending from NW to SE; Closely coincides with 35-foot isopach of marine interval thickness;
3) substantial porosity development in excess of 8m in southwest; Area is immediately south of site of local thinning; Area of thinning also thin on marine interval isopach map; Porosity and interval thickness vary closely across shelf; Both are thin across northern shelf.

Figure 46--marine interval percentage

Regressive shale at top of K-Zone typically has many characteristics of soil development. Watney (1980) illustrated that the unit characteristically thins over paleohighs in NW KS and SW Neb. Paleotopography was created because of buildup of underlying carbonate or structural growth. The regressive shale was interpreted to passively fill in and diminish this relief. Regionally, the regressive shale: 1) thins dramatically to the south; 2) thins over the CKU; 3) on the southern shelf it reaches the minimum detection limit on wireline log (1-2 ft.); 4) local lobe of thickened regressive sh. in the SW mapped area coincide with a thinning of the marine interval isopach and thickness map of porous carbonate.

Regional distribution of the regressive shale forms a broad apron of terrigenous detritus thickening toward source area in the north. Regressive shale is up to 3 m thick in areas with mapped values here of <70%.

Mapped values here of >90% typify southern shelf. Map reveals an arcuate buildup of carbonate in the southwest. Southern CKU also is an area of >90% marine interval, i.e., very thin regressive shale. An area of maximum thinning of marine interval occurs in Barton and Rush counties over a feature called the Rush Rib. It is a Precambrian horst where the Kansas City Group rests directly on Precambrian. The area is thought to lack terrigenous detritus because of its topographic relief.

Figure 47--Maximum GR map

GR values >160 API units are associated with black shales. Those shales rich in certain organic matter, also have elevated GR values thought to be related to uranium (Watney, 1979)

In the northern study area the GR values of the regressive shale and marine shale vary between 70-100 (low values, average for non-organic rich shale).

Many areas on the CKU are sites of low GR values in marine shale. Thickness of shale under 0.5 m would fall below resolution of GR tool--including some areas on uplift. Cores however confirm change of black shale to non black facies over crest of CKU and pinchout of marine shale altogether.

Sites of low GR values on CKU are also locations of (1) thin marine interval, (2) regressive shale, and (3) thin overall Kansas City interval.

CA and Pratt Anticline are also location so flow GR values. GR values are also low in SW KS, but marine interval here is thicker. This thickening in the local SW area appears to be primarily due to an increase in terrigenous clastics, suggesting that this area was likely positive location on shelf.

Cimmaron Arch immediately off the map to the west may have extended eastward into the mapped area during the deposition of this cyclothem. The map of maximum GR may reflect (a) circulation near sea floor during deposition of the marine shale, (b) rate of sedimentation, or (c) level of anoxic bottom conditions. Most significantly, the mapped distribution may be a function of bathymetry which affected the (1) degree, (2) frequency, and (3) duration of anoxic conditions.

Only 6 m of thinning of the marine interval is noted over the CKU. This probably represents minimum relief, but appears to have been enough to affect the level of anoxic conditions or current action which may have winnowed shale from these paleohighs.

Figure 48--Percentage thickness of K-Zone in four cycle package.

1) In excess of 35% around arc in southwest Kansas (around positive area);
2) also high percentages in south-central; and
3) along N-S trend in southeastern mapped area.

Trends of greater interval percent in SW correspond to greater thicknesses of porous regressive carbonate (Figure 32). Implied here that depositional relief apparently affects thickness of succeeding cycles (compensation).

<u>Summary</u>

Regional thinning of marine interval supported by lithologic data as positive shelf locations; Other maps also support this interpretation.

Subdivisions of shelf:

1) Shelf: broad, gentle subsidence during K-Zone;
2) positive areas: less subsidence;
3) areas of flexure--areas of greater subsidence and tilting along southern shelf.

Positive: CKU-CA, southwest; flexure: southern shelf area, facies.

<u>Integrate with Rock Descriptions</u>

<u>Upper regressive carbonate</u>: Most change is expected in this interval because of shallow water environment in which it was deposited.

(A) Greater restricted shallow water facies exist on northern shelf and on CA and CKU. (B) More than half of the carbonate in these locations are intertidal and supratidal varying from low to high-energy deposits. (C) Thick oolitic grainstone are common in southwestern wells while thin, (D) abraided bioclastic grainstone are locally developed on northern shelf.

Figure 49--Index map locating core-log examples.

Figure 50 a and b--Combined wireline log and core description and interpretation (including Dorr, Thompson, and Lemon wells).

Dorr well, poorly sorted, heavily micritized grainstone, few concentric lamination.

Gamma ray, neutron logs lithologic column, environmental interpretation ranging from open marine, stagnant marine, slightly restricted, restricted, very restricted, nonmarine.

*Figure 51--Core description of 2-D Stegman well

*Figure 52--Core description of 4 Litsey well

*Figure 53--Core description of #6 Lemon (from Lemon Ranch-Collier Flats field in Commanche County, Kansas)

*Figure 54--Legend for Figures 51 to 53.

Note expression of oolite on wireline log (Figure 50e). Formation and accumulation of oolite required persistent tidal action in shallow water (<2 or 3m). The oolite is recognizable on wireline logs as very clean and porous (>15%) intervals. Thicker porous carbonate near top of regressive carbonate is generally oolite along central and southern shelf.

Northern shelf is a broad platform with a low paleoslope which dampened most of the current action; Predominant current activity probably resulted from episodic local storms which winnowed fines. Only significant paleohighs apparently had sufficient relief on northern shelf to locally produce oolitic grainstone (Jenning Anticline).

Southern shelf apparently was a steeper shelf according to interpretation of isopach maps. Abrupt thickening of porous carbonate occurs along the northern edge of southern shelf. Samples along this trend indicate oolitic grainstone correspond with abrupt thickening from cores and cuttings that are available. Break in slope apparently was the focus for currents and waves during late regression.

Southwest positive is rimmed by unusually thick oolitic grainstone where perhaps the greater slope developed in proximity to the southern, open marine shelf margin.

Figure 55--Hand contoured version, thickness of porous carbonate.

Reveals trends not recognized by computer contouring. Observe the lobate forms (6-19m maximum thickness 2 to 8 km long--8 to 16 km wide); Lobes extend northward where they pinchout along flexure or hinge on the shelf. Lobes are thought to be analogous to modern prograding spillover lobes of oolite developing along coast and worked landward by storms in the Bahamas; However, these are 5X larger then modern examples.

These modern deposits of oolite developed on a platform edge facing the open ocean. In this ancient example, storm surges pushed ooids northward or landward. As sea level dropped, the shoreline retreated southward across shelf. The oolite formation required proximity to good circulation with significant wave energy.

How long did it take for the oolite shoals to develop: the cycle is estimated to average around 400,000 years in length; Oolite formation during latest regression perhaps took only 5% of this time or ~20,000 years, comparable to the time taken by the Pleistocene age Miami oolite to develop in southern Florida. The Miami oolite is also similar in size to this deposit.

Oolite prograded to the south with time and is therefore oldest on northern side. Oolite accumulation probably occurred while a great part of the northern shelf was exposed.

Figure 56--S-N lithofacies cross section of K-Zone, 350 km, exaggerated.

Sequence of events in formation of cyclothem: widespread <u>transgressive</u> limestone deposition with little reworking of underlying sediment, locally sandy. <u>Black shale</u> accumulation in south and central (a reflection of slow accumulation under anoxic conditions); Perhaps marine shale reflect pelagic accumulation (>50 m water depth over much of shelf). <u>Dark silty poorly fossiliferous--lower regressive carbonate on southern shelf</u> began carbonate accumulation following marine shale; During late regression the upper shelf was exposed while ooid accumulation occurred in south. Limited influx of terrigenous detritus occurred on northern shelf during latest regression. Local channeling and solution of carbonates occurred on upper shelf (DuBois, 1979; 1985).

480 km long N-S tranverse across Neb-KS shelf; assume simple ramp model (0.5 ft/mi. paleoslope to south or 0.1 m/km based on average rate of thickening of isopach maps of marine intervals). 48 m in relief (minimum) across shelf less the amount of aggradation estimated at 9m leaving 39 m minimum change in sea level. Then consider maximum water depths to establish anoxic conditions on the shelf and amount of fall in sea level to permit extended exposure of shelf.

*Figure 57--Chronostratigraphic cross section

Cyclothem duration approximately 400,000 years; Erosional boundaries are isolated deposit in time. Also rapid transgression which define boundaries of sequences (hiatal surface, climate change surface). Sequences comparable to Frasier (1974) Quaternary sequences except these formed on carbonate-dominated shelf.

*Figure 58--Frasier (1974) time-depositional model for terrigenous clastic coastal sedimentation.

Structural Implications of Mapping

Paleohighs coincide with earlier, prominent tectonic uplifts and secondary trends, e.g., zone of flexure.

Origin of locations of flexure: Tectonic stress created by subsiding Anadarko basin probably related to thrusting of Wichita-Arbuckle Mountains (several m.y. long episodes); Location of flexure perhaps related to structural grain in Precambrian revealed by filtered magnetics intensity map (west of CKU have dominant NW trend).

Nature and significance of SW positive area: Later in Permian the SW positive became an important area of uplift, while earlier pre-upper Pennsylvanian activity was insignificant. Upper Pennsylvanian uplift was precursor to later structural activity.

In contrast, dominate NE trend in southeastern mapped area coincides with magnetic linears associated with CNARS. This NE trend cross-cuts older Precambrian grain almost at right angles. CNARS trend is younger and perhaps less well healed and weaker than older trend. Also inherent nature of rift includes complex faulting.

Compare K-Zone with J-, I-, and H-Zones

Intercyclothem variation--Changes in shelf configuration

*Plates 3, 4, 5 (J, I, H) (See display)

Use polynomial trend surface modeling of thickness of marine interval for 4 cyclothems to summarize changes in lithofacies between cyclothems (Watney, 1985--see paper for maps).

J and K-Zones both have extensive areas of oolite development on southern shelf. I and H are notably different, where H-Zone has widespread accumulations of micrite, particularly mud banks.

Marine interval is a good map to summarize changes between zones because it: 1) depicts structural changes on shelf and 2) local variations in carbonate accumulation.

Best statistical fit using lowest order, residuals allow focus on local anomalies.

Goodness of fit, R^2 == (sum of squares residual/sum of squares total) *100 (%).

Skewness, third moment about mean, M_3 = (X-X) X-3

Plot of goodness of fit, versus order of trend for H, I, J, K Zones.

4 and 5th order surfaces fits somewhat poorer for K then I or J. H-Zone is least well fit by surfaces (all cases below goodness of fit of 50%), i.e., because surface is more complicated.

Skewness of Residuals (SLIDE ONLY)

At higher orders, the skewness of residuals is appreciably reduced for H, J, I while skewness increases with trend order for the K-Zone (positive skewness is an asymmetrical plot of the frequency of residuals with more positive deviations than negative). In order to optimize the statistical fit would have to minimize this skewness, but we are also interested in preserving the geological significance of the residuals.

4th-order trend surfaces was chosen to represent all 4 cycles. This order generally provides the best.

K-Zone 4th order trend surface (SLIDE ONLY)

Line of flexure interpreted at 35 foot (10 m) separating two areas of contrasting rates of thickening. Oolite is developed south of this line. Rate of thickening (north) = 2.4 m/51 km = 0.05 m/km. Rate of thickening on southern shelf = .07 m/km slightly greater than to north.

K-Zone 4th order trend surface residual (SLIDE ONLY)

Note the SW positive anomaly associated with adjacent oolite shoals interpreted to surround it. This feature probably accounts for the positive skewness. Note the very thick anomalous strata which are adjacent to the southern flanks of the CKU. Also note the Rush Rib is the site of very thin marine interval as previously described. Notice the NW-SE trend in the western mapped area and the NE-SW trend in the southeastern mapped region.

Top J-Base J isopach (5 - 27 meters) (SLIDE ONLY)

J-Zone 4th order trend surface (SLIDE ONLY)

Broadened region of thinning occurs over northern area compared to the underlying K-Zone which extends significantly west of CKU. More pronounced thinning is noted over the CA than in the K-Zone. More uniform southward thinning is apparent in J than the K with no notable thinning in SW. 35 to 40 foot contours identify the northern limit of rapid change in thickness which is comparable to the position K-Zone, but displaced southward slightly. Rate thickening on northern shelf = 2.1 m/50 km = 0.04 m/km. Rate thickening on southern shelf = 8.4 m/50 km = 0.17 m/km, which is greatest rate of regional thickening recorded in four successive depositional sequences.

A Greater amount of oolite is developed across the southern shelf in the J-Zone than in any of the other cycles studied.

General comments about J-Zone: (1) Depositional grain of the J-Zone is more W-E than K-Zone; 2) dip more perpendicular to shelf margin; 3) SW positive is now an insignificant structure; 4) more extensive higher energy conditions expected across shelf in the northern region during deposition of the J-Zone due to the greater inclination of the shelf. More E-W oriented trends in response to southward flexing of shelf.

N-S trend in southeast.

*4th order trend residual of thickness J-Zone marine interval isopach.

Local thicks (oolite) in J offset those in K, compensating and probably filling in bottom relief. This is more evidence that transgression did little major modification to earlier deposits, i.e., must have been fast. Enos and Perkins (1979) describe relict Pleistocene topography which is common along shelf margin of South Florida. There may be an analogous situation here. The transgressive deposit of the Holocene sequence is relatively thin and commonly was deposited in a high energy environment.

*Plate 3 (display): Maps of J-Zone

Maximum Gamma radiation in marine shale: Similar locations of minimum GR to K-Zone (<160).

Very low GR levels recorded over Rush Rib, an area also with a thin marine interval. Elevated GR values noted in structural sag between CA and CKU. Variability of GR appears to be more than depth related: perhaps variation in bottom circulation, presence of local depressions on sea floor, availability of organic matter.

Percent marine interval thickness in J-Zone: position of CKU appears to have restricted thickness of terrigenous clastics due to topographic relief; a separate lobe of terrigenous sedimentation appears to originate from SW.

Porous carbonate in J-Zone: southern shelf in excess of 3 m thick; J-Zone comprises >40% and 50% of entire 4 cyclothem interval in Ford and Clark counties. Significant accumulation of carbonate and also probably important in progradation of shelf margin to south.

Figure 59--Index map for logs and mapped area, J-Zone oolite shoals.

Figure 60--Wireline logs 1 and 2 on index map.

Figure 61--Wireline logs 3 and 4 on index map.

Figure 62--Hand contoured J-Zone porous carbonate.

Figure 63--Perspective diagram of thickness of porous carbonate of J-Zone in outlined area.

More northward finger-like projections of porous carbonate similar to K-Zone; Oolite indicated from cutting sample is facies in which porosity is developed.

Top-base H-Zone isopach-Zone trend surface

H-Zone 4th order trend surface (SLIDE ONLY)

Youngest cyclothem which is characterized by 1) marked change in the configuration of the shelf; with much less range in thickness, -17 ft. (5.1 m) (up to 10 meters thick) versus 15 to 24 m in other cycles; 2) no southward thickening, 3) no significant oolitic facies in south; 4) broad thick in west central mapped area (160 km X 80 km) with up to 12 m of carbonate. Rate of thickening of upper shelf is 0.36 m/50 km = only 0.007 m/km (flat). Rate of thickening of lower shelf in SW is same as north. In extreme SE the rate of thickening is 0.06 m/km, which is perhaps the only location in the mapped area of the H-Zone that can be considered a shelf flexure.

H-Zone 4th order trend surface residual (SLIDE ONLY)

Dominate NW-SE trend to residuals is similar to other cycles, but significant thickened carbonate in west-central which probably accounts for such poor fit of polynomial trend surface in H-Zone. Thickened complex is micrite-dominated carbonate.

SW positive appears to have been active again and perhaps provided (1) southern barrier to currents and waves generated in the south. The (2) relatively level protected area to the NE became the site for a large complex of micrite-dominated carbonate buildups during mid-regression.

The (3) less inclined slope and general stability of shelf (quiescence of tectonic activity?) appears to have produced a low energy shelf setting, at least relative to the earlier cycles. Perhaps more rapid regression occurred limiting the time when shoreline could rework the shelf and deposit significant accumulations of grainstone.

(4) Extended pronounced thinning also noted in SE margin of CKU extending southward off the mapped area. Progressive southeastward migration of positive area through period of four cyclothems. Most rapid change began during deposition of I-Zone.

On maximum GR map of marine shale the gamma ray readings are generally lower in the H-Zone than the J and K, particularly over CKU. Level of inundation of the sea may have been slightly less (which would correlate with overall thinner interval than J and K). CA not as positive, i.e., the GR values are not markedly low. High GR in area of carbonate buildup in west-central mapped area suggests a slightly lower region of the shelf and site of accumulation of organic matter. Later, during regression, this area became a protected area for proliferation of phylloid algae and development of carbonate mounds.

Regressive shale is more uniformly distributed across the shelf as one might anticipate on a flatter shelf. Shale is thinnest: 1) east central CKU; 2) Pratt anticline; 3) SE portion of SW positive; 4) where thick marine interval in Scott County.

% contribution of H-Zone to 4 cycle interval: CA interpreted to have not been as positive as supported above: H-Zone occupies >40% of 4 cycle interval in Graham County, compared to less than 20% to total four cyclothem interval in southern shelf.

Cores indicate sediments are predominantly open marine in NW. Greater proportion of interval is comprised of restricted marine deposits in SE suggesting area was most positive (#3 Denker is most restricted).

Differential relief across the shelf changed gradually and produced secondary, albeit important effects on sedimentation patterns. This is not revealed or suggested by studying gross interval isopach of four cyclothems.

Summary--Intercyclical Variation, Causes and Effects

1) Differential structural movement of shelf occurred as it tilted and subsided in conjunction with downwarping of Anadarko basin.
2) Formation of 1st- and 2nd-order structural activity (uplifts and flexure lines) appear to be related to basement heterogeneity and weakness indicated by a) sites of ancestral uplift, b) faulting, c) geophysical anomalies. Isopach mapping important to identify timing with respect to sedimentation and oil migration.
3) Precambrian is segmented into geologic terranes, each with varying physical strength, i.e., rigidity, encouraging propensity to operate independently. Some blocks are strong, unitized and generally positive while others are weak and possibly fractured or faulted.
4) Mechanical integrity, orientation and location, sense and direction of forces define extent of movement of these blocks.
5) Evolution of a single tectonic event causes variation in stress.

6) Oscillation (up and down movement) of shelf-wide structural deformation is not demonstrated, i.e., did not cause the change in sea level needed to produce cyclothems; Shelf was dominated by varying degrees of subsidence during successive cyclothems.
7) Western Kansas and northern shelf of the Anadarko basin during late Pennsylvanian was a southward tilted ramp modified by local, resistant, positive elements. Subtle ridges, domes, and flexures significantly affected sedimentation and diagenesis. Porosity distribution is linked closely with grain-supported rocks which either provide the primary porosity or avenues for fluid migration to create secondary porosity. Late stage dissolution may also be focused along these structures.

CONCLUSIONS:

1) Pennsylvanian and Permian sedimentation on H.A. North American craton is repetitive generally an alternation between marine and non marine conditions in both clastic and carbonate rocks.
2) Sedimentary sequences begin with a thin transgressive facies followed by considerably thicker regressive deposits. The sequences in clastic deltaic succession **are commonly** obscured by downcutting of the younger deposits into the older extensive areas of deposition with slow subsidence.
3) Maximum transgression is frequently marked by thin black shale accumulation. Fossils, phosphate, clay texture suggest that the deposition of the black shale was very slow and water was relatively deep (pelagic) and anoxic (without oxygen). Some deposits of black shale are basin wide and preliminary work has provided correlations into other regions and basins. These black shales owe their color to the abundance of organic matter which is commonly oil-prone. However, the level of thermal maturation of these Upper Pennsylvanian shales is low and appear to be oil or gas generative in southern Kansas and Oklahoma.
4) The later stages of development of these cyclothems are usually characterized by terrestrial, subaerially exposed conditions. If the environment is favorable a thin soil can be formed. These deposits appear to be extensive, yet their recognition is difficult. These surfaces conveniently form sequence boundaries.

5) The characteristics of Pennsylvanian cyclothems strongly suggests that interbasinal processes are active in the formation of these deposits, namely eustatic sea level change.

Holocene Analog to Western Kansas Carbonate Shelf

Ramp model, Arabian Gulf (Wilson and Jordan, 1983)

Arabian Gulf is a shallow inland sea, low latitude, clear water. The Great Pearl Bank is 150 X 100 km. The entire Arabia Gulf covers 1000 km X 350 km, a shallow shelf ranging from 20 to 80 deep.

Floor of much of the Gulf was laid bare by Late Pleistocene sea level lowering. Exposure resulted in karst drainage and formation of terraces and cuestas. The slope in the Gulf is 0.5 m/km vs. an estimated 1 m/km in Western Kansas. Local highs on the sea floor are sites with shoal-water, bioclastic grainstones many now in relatively many deep waters. Below ~50 m are dark argillaceous carbonate mudstones and wackestones. While in shallow water molluscan wackestones and packstones are accumulating.

Average Holocene thickness: only 2m, but only relative short time has passed (~5000 years) since last sea level rise.

Barrier islands have formed along Trucial coast an area with a steeper coast. Here bioclastic carbonate sands are flanked by oolitic sands forming beaches and aeolian dunes, some up to 20 m high. If the slope is great enough, oolites are likely to form along the shoreline. During gradual lowering of sea, then oolites prograde across shelf.

Another possible analog to western Kansas carbonate shelf--Yuccatan shelf (Sellwood, 1979).

Yuccatan shelf located 20-23 degrees N in Gulf of Mexico. It is a peninsula comprised of a low undulating karstic plain without surface drainage. The shelf covers 34,000 km^2 (similar in size to western Kansas), which has a thin veneer of modern sediments covering relict Pleistocene deposits. This shelf is 160 to 290 km wide, and is now 82 to 315 m below sea level.

Salient aspects about geologic history: 1) terraces cut into shelf during Holocene rise in sea level; 2) open to influence of ocean; 30 cm tide; 3) coastal dune ridges parallel wave dominated shell beach. Inner shelf is composed of mollusc-rich skeletal sand and coquinas (modern accumulation). Outer shelf consists of a veneer of relict ooid, peloids, intraclasts of underlying unit (little modern sedimentation). Shelf below 90 m is composed of primarily planktonic forams (pelagic environment in oxygenated water column).

The Wisconsin low stand (glaciation), a paleo shoreline is marked by a dune ridge at 130 meters below present sea level with a karst plain developed landward. Ooid-pellet calcarenites were generated seaward of the series of conical karst rims (paleohigh).

Basically the Yuccatan shelf is a simple ramp where high energy reaches the shoreline. Shoreline migrated as sea level varied during the Quaternary.