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INTRODUCTION

North American Pennsylvanian strata were deposited during extremely high magnitude, short duration relative sea-level oscillations (e.g. Heckel, 1977). Vast areas of the North American craton were exposed during relative lowstands of sea level and then submerged during subsequent transgressions (Fig. 1). Most previous stratigraphic studies of these Pennsylvanian strata have primarily focused on the laterally extensive marine highstand units for correlation (Heckel, 1977, 1994; Klein, 1993; Watney *et al.*, 1995). In these studies, the ideal Kansas cyclothem contains a thin, widespread, black, organic-rich shale (core shale) that is interpreted to have been deposited during maximum transgression (see Heckel, 1994 for a comprehensive review of this model). The focus on the marine facies in these studies is a natural consequence of the extensive continuity of these facies and the relative lack of lithologic variability. In addition, the core shales are radioactive and easily recognized and correlated with natural gamma ray wireline well logs. The application of sequence stratigraphy concepts to these strata has been recently attempted by some workers in which each cyclothem is interpreted to represent a single depositional sequence (e.g. Heckel, 1994; Heckel *et al.*, 1998).

Our study focuses on using widespread unconformities that formed during relative lowstands of sea level as sequence boundaries within the Pennsylvanian section. These sequence boundaries (*sensu* Mitchum *et al.*, 1977) are manifest as widespread paleosols and incised valleys. We believe our approach to sequence-stratigraphic study of these strata is important because some recent studies have shown that cyclothems may contain multiple sequence boundaries suggesting depositional sequences do not necessarily coincide with cyclothems (e.g. Gómez-Pérez *et al.*, 1997; Carr *et al.*, 1995; Watney *et al.*, 1995). Also, the recognition of sequence boundaries is critical to successful paleogeographic reconstructions and for delineating petroleum reservoirs. Reconstructions based on units bounded by flooding surfaces may be difficult to interpret because the stratal units include genetically unrelated strata that were deposited above and below sequence boundaries.

Our study has revealed a wide range of expression of sequence boundaries and types of associated incised valleys. There does not seem to be a relationship between the types of boundaries and positions of the lowstand or highstand shorelines. For most of these cycles the study area was far from both shorelines. Likewise differences in substrate cannot account for the range of expression of the sequence boundaries. The most likely explanation of the observations is that climate varied from cycle to cycle and caused differences in the types of paleosols the formed and the types of incised valleys.

Below we document eight successive sequence boundaries of upper Missourian to lower Virgilian (Pennsylvanian) cyclothems along the outcrop belt from southeastern Kansas to southwestern Iowa and adjacent portions of Nebraska (Fig. 2, 3). This outcrop belt is generally parallel to depositional dip and thus offers a shelf-to-basin transect. The study interval includes both carbonate and siliciclastic dominated cyclothems. In the northern area, the sequences are thin and dominated by limestone alternating with paleosols. To the south, the same sequences thicken dramatically and thick siliciclastic facies dominate the section. These units have been described by many workers, and we do not intend to redescribe all of the facies that occur within this interval. Instead, we

will focus on the character of the sequence boundaries, and then refer the reader to the voluminous literature for detailed accounts of the rocks.

NAMING OF SEQUENCES

Although Midcontinent Pennsylvanian stratigraphy already has multitudes of named lithologic units, the need for an independent series of names for depositional sequences (or any genetic stratal unit) is necessary because the criteria used to correlate depositional sequences are different from the criteria used to correlate lithostratigraphic units. Attempts to equate lithostratigraphic units with genetic units (Heckel, 1994, Fig. 2A) can lead to problems as new data are collected which cause interpretations to change and genetic units to be revised. In addition sequence boundaries can cut across lithostratigraphic units.

To avoid these problems this study identifies and describes new depositional sequences, designates names for each depositional sequence that are not based on previously named lithostratigraphic units, and provides a reference section for each depositional sequence (see Appendix 1 and 2), similar to type sections of lithostratigraphic units. Each reference section contains the basal sequence boundary of a named depositional sequence that is intended to be the standard for correlation to other areas.

By convention we name sequence boundaries for the overlying sequence. Thus the Ash Grove sequence boundary is overlain by the Ash Grove Sequence.

SEQUENCE STRATIGRAPHY

Ash Grove sequence

Description: The Ash Grove sequence extends upward from the paleosol or incision in the Vilas Shale (basal sequence boundary) to the sequence boundary in the Rock Lake Shale. The prominent paleosol in the Vilas Shale extends throughout most, but not all, of southeastern Nebraska and southwestern Iowa. Locality I4 (and see stops 7 and 8 of Heckel and Pope, 1992), at the northernmost extent of the outcrop belt, exposes a very thick (225 cm) paleosol in the Vilas Shale; the top is eroded and overlain by Pleistocene sediments. This paleosol is reddish brown and lacks large slickensides. Directly underneath the paleosol are, in descending order stratigraphically, (1) a thin (40 cm), heavily weathered carbonate grainstone bed; (2) a 55-cm-thick zone of large, irregular carbonate nodules; (3) a 6-cm-thick gray limestone consisting of discoidal to lenticular reddish masses of fine-grained carbonate; and (4) reddish gray shale grading downward to gray shale (225 cm). The overlying Plattsburg Limestone contains no recognized evidence of subaerial exposure. To the southwest at locality I1 and immediately adjacent portions of southeastern Nebraska, the Vilas Shale contains a low chroma paleosol, which indicates poor drainage conditions, and an overlying marine shale, which rests on an erosional surface at the top of the paleosol. The paleosol is generally thin and weakly developed. At I1 it consists of 24 cm of light greenish gray, noncalcareous mudstone with a few small carbonate nodules and small slickensides. There is no indication of well-organized vertisol-like sets of large slickensides. Overlying the paleosol is a very

thin (2 cm), calcareous light greenish gray to gray shale. In Nebraska weathering associated with the Vilas paleosol extends down into the underlying marine Plattsburg Limestone. Farther eastward into the Forest City basin the Vilas Shale changes markedly in character and increases several times in thickness. At locality I2 the Vilas Shale consists of the following ascending succession: (1) a basal gray to dark gray, very strongly calcareous shale with marine fossils (40 cm); (2) gray, noncalcareous to weakly calcareous, coarsening upward finely interlaminated shale and siltstone to sandstone (877 cm), and (5) an uppermost light greenish gray, very fine sandstone with thin mud laminae and flaser bedding (134 cm). The overlying Captain Creek Limestone is a complex package of marine carbonate facies and shales that generally fine upward. Significantly, the basal unit of the Captain Creek is a 95-cm-thick carbonate packstone to grainstone (dominantly grainstone) containing abundant marine fossils and no evidence of subaerial exposure.

In eastern Kansas, evidence of subaerial exposure in the Vilas Shale is present only locally. A paleosol in the Vilas Shale in cores from locality K6 is composed of up to 1.4 m of low chroma blocky mudstone and mixed blocky mudstone and weathered fragments of the underlying Plattsburg Limestone. In other eastern Kansas outcrops (such as locality K15) the Vilas Shale consists of laminated to burrowed mudstone and heterolithic facies, sandstone, and minor limestones. Burrowing and fossil abundance is greatest near the top of the unit. To date, evidence for a sequence boundary has not been identified in this area. There are no known paleosols within the Vilas Shale south of locality K6.

In northeastern Kansas the upper Vilas Shale is locally incised and the incisions are filled with a locally crossbedded conglomeratic limestone (Fig. 4) (Cunningham and Franseen, 1992). The conglomeratic limestone consists of pebble-sized limestone clasts, fossils, and shale clasts. The limestone clasts are fossiliferous packstone to mudstone, and are mostly well rounded. Some clasts are bored; others contain possible evidence of exposure prior to being eroded into clasts. Cross bedding in the conglomerate is bimodal parallel to the valley axis. The conglomerate is overlain by thin (under 10 cm) laminated shale to heterolithic facies, and then by fossiliferous wacke- to packstone of the Captain Creek Limestone.

Regionally, overlying the basal Ash Grove Quarry sequence basal paleosol in the Vilas Shale, where present, is a thin laminated shale to heterolithic facies. Throughout the outcrop belt a Kansas type cyclothem consisting of a thin transgressive limestone (Captain Creek Limestone), core shale (Eudora Shale), and thick regressive limestone (Stoner Limestone) overlies the Vilas Shale. See Heckel (1975) for a comprehensive description of these units.

Interpretation and discussion: The widespread occurrence of the paleosol in the Vilas Shale in the northern portion of the study area indicates regional subaerial exposure following marine inundation associated with the underlying Plattsburg Limestone. Formation of microkarst in the underlying marine limestone occurred during vadose zone weathering that could only have occurred after a relative fall of sea level. The dominant motif expressed by the Vilas paleosol in southeastern Nebraska and in westernmost Iowa (locality I1) is that of a low-relief land surface that underwent subaerial exposure long enough for soils to develop, but which was also characterized by significant local variability in drainage conditions (Joeckel, 1995a). The sequence boundary cannot yet be

identified in areas that lack both a paleosol and conglomerate-filled incision. The boundary may be within the heterolithic facies; this facies is common both below sequence boundaries, and as incised valley fills (IVF's).

The conglomeratic facies locally overlying the Vilas Shale is interpreted as an incised valley fill that formed as a result of a relative sea-level fall. Limestone lithoclasts were eroded after lithification of the host rock, however the source rock has not yet been determined. The size of the lithoclasts and the and borings on lithoclasts indicate a marine-influenced, and likely flood-dominated tidal environment. The fossil debris may have been transported into the valley by the flood tides, or may record in situ faunas. The conglomerate is very similar to other Pennsylvanian basal valley fill facies from the Missourian Garnett incised valley (see below) and the Virgilian Hamilton incised valley (Cunningham *et al.*, 1993).

Transgression following incision and paleosol formation resulted in deposition of the widespread Captain Creek Limestone, Eudora Shale, and Stoner Limestone members of the Stanton Formation. These units are continuous from southern Kansas to the northern portion of the study area.

The Garnett sequence

Description: The Garnett sequence extends upward from the sequence boundary in the Rock Lake Shale or at the top of the Stoner Limestone to the upper sequence boundary occurring at the base of the Wolf Creek sequence. A reddish brown paleosol (1 to 2 m thick) with thick horizons of carbonate nodules characterizes the Rock Lake Shale in southeastern Nebraska west of the Nemaha Uplift/Forest City Basin margin (Joeckel, 1989). Weathering features extend down into the underlying marine Stoner Limestone (Joeckel, 1989). The paleosol is overlain by approximately 10 cm of laminated, fossiliferous shale below the South Bend Limestone. East of the Forest City Basin margin the Rock Lake paleosol is generally greenish gray or gray, and usually much thinner (Joeckel, 1989; Heckel and Pope, 1992). At locality I1 the Rock Lake Shale contains a 160-cm-thick, low chroma (light greenish gray and gray) calcareous paleosol lacking slickensides, but having 10 to 20% carbonate nodules. This paleosol is abruptly overlain by a 33-cm-thick, gray to light gray, very strongly calcareous shale with brachiopods. At locality I2 the marine Stoner Limestone contains microkarstic features indicating subaerial exposure. The overlying Rocks Lake Shale is only 14 cm thick, and consists of light greenish gray, carbonate-cemented mudstone and, commonly, fragments of the underlying Stoner Limestone. This mudstone probably represents a truncated paleosol. It is erosionally overlain by the South Bend Limestone. A thin coal (under 5 cm) rests on the paleosol in Franklin Co., Kansas (Ball, undated), and in one site in Iowa (Heckel and Pope, 1992).

In northern and central eastern Kansas, the sequence boundary occurs as an erosional surface or as a paleosol in the Rock Lake Shale. In Franklin Co., Kansas, the top of the Stoner Limestone is erosional with up to 1 m of relief (Ball *et al.*, 1963) and it is overlain by a limestone breccia in the lower Rock Lake Shale, or, where the Rock Lake Shale is absent, by conglomeratic limestone of the lower South Bend Limestone (locality K8). The limestone breccia extends down into karst solution pits (or possibly root voids) in the upper Stoner Limestone. Farther north, a paleosol is consistently present in the

lower Rock Lake Shale. In northeastern Kansas the paleosol consists of approximately 60 to 150 cm of low chroma gray, blocky mudstone. Pedogenic carbonate nodules appear locally in the paleosol. The upper surface of the paleosol is marked by an abrupt transition from blocky mudstone to laminated, heterolithic bedding.

At locality K6 the Garnett sequence boundary is manifested as an incised valley (Reisz *et al.*, 1982; Feldman *et al.*, 1993). The valley is approximately 11 m (36 ft) deep and 80 m (262 ft) wide. In the interfluvial area, the South Bend Limestone rests unconformably on the Stanton Limestone (Woodruff, 1984). The incision extends through the underlying Stanton Limestone and Vilas Shale into the Spring Hill Limestone (Fig. 5). Polished handsamples from valley walls reveal a weathered zone between valley-fill facies and unaltered marine limestone. The uppermost marine limestone contains cracks, autoclastic? breccias, and faint crust-like laminations. Oxidation is apparent in these rocks as indicated by yellowish brown staining that contrasts with the color of deeper unaltered rocks.

The IVF consists of a lower conglomerate and upper mudstone to siltstone. The conglomerate consists of well-rounded limestone, shale and siltstone lithoclasts identical to facies exposed in valley walls. Grain truncations and cracking of clasts indicate that the clasts were lithified prior to deposition of the conglomerate. Rarely, clasts are deformed without cracking. There are abundant fossils in the conglomerate matrix, which were likely eroded from valley walls. On outcrop the conglomerate is horizontally bedded, and onlaps valley walls. The upper portion of the conglomerate contains interbeds of laminated dark mudstone and bioturbated siltstone, and grades upward into siltstone and mudstone through a decrease in the thickness of limestone beds. The origin of the conglomerate is not well understood. Examination of polished samples from outcrop and cores did not reveal any fossil-encrusted clasts as might be expected in a fully marine environment. Interbedded bioturbated siltstone may indicate a marine-influenced environment.

Overlying the conglomerate and valley walls are (upward from the bottom) bioturbated to thin bedded siltstones, laminated dark gray shale to mudstone, and laminated yellowish brown siltstones. Thin beds of laminated carbonate mudstone are interbedded with the laminated siliciclastic facies. Bioturbation is greatest in the lower siltstone and decreases upward to undisturbed, laminated facies. The dark, laminated mudstone contains abundant, partially-articulated large pelycosaurs and other reptiles (Reisz *et al.*, 1982). The overlying laminated siltstone has clay drapes and rare thick-thin couplets. Surface features include rain drop imprints, runzel marks, planed surfaces, and tetrapod footprints. Thin (under 5 cm) conglomeratic to grainstone beds with erosional bases occur throughout the fine-grained facies. A diverse marine suite of fossils occurs in these strata. Isolated, articulated brachiopods also occur in the upper siltstone facies. Plant fossils, particularly conifers and fusian are common throughout the fine-grained facies. All of these fine-grained facies onlap valley walls. In adjacent interfluvial areas, the South Bend Limestone rests unconformably on the Stoner Limestone (Woodruff *et al.*, 1984).

The Garnett sequence boundary was not investigated south of the reference section (locality K6), however Heckel (1975, personal communication) reports blocky mudstone interpreted as a paleosol at the equivalent stratigraphic position in Montgomery Co., Kansas, near Oklahoma. Deep (21 m) sandstone-filled channels at the equivalent

stratigraphic position in Woodson and Wilson counties, Kansas, (Heckel, 1975) may represent incised valleys associated with the Garnett sequence boundary.

The South Bend Limestone marks the base of the transgressive systems tract in the Garnett sequence. The basal of the South Bend is typically sharp and erosional throughout the study area (Heckel, 1975). Where it overlies the IVF, the basal South Bend Limestone consists of sandy (quartz and chert fragments), conglomeratic, oolitic grainstone. The sandy, oolitic limestone fills unlined burrows extending 8 cm down from the contact. In other areas the South Bend Limestone grades downward into bioturbated sandstone that is abruptly underlain by heterolithic facies (e.g. locality K14). In southernmost Kansas sandstone and wackestone of the South Bend Limestone fills a 1.5-m-deep incision into the Rock Lake Shale (Heckel, 1978).

The upper South Bend Limestone is typically a fossiliferous wackestone to packstone, and develops into phylloid algal mounds in southern Kansas (Heckel, 1975). In northeastern Kansas the South Bend Limestone is overlain by dark grey shale. The contact ranges from abrupt and apparently erosional to gradational over a distance of about 5 cm . Locally, there are *Zoophycus* burrows infilled with dark gray shale in the uppermost 15 cm of South Bend Limestone. Northward, in Nebraska, a black platy shale and thick regressive type limestone overlie the South Bend (Heckel, personal communication). Siliciclastic facies between these limestone and the base of the Basehor sequence have not been widely studied.

In southeastern Nebraska, the South Bend Limestone develops into a Kansas type cyclothem (Pabian and Strimple, 1993). The lowest bed, the Little Kaw Limestone Bed, correlates to the entire South Bend Limestone of Kansas. Overlying the Little Kaw is a thin conodont-rich grey to black shale, which, in turn, is overlain by the Kitaki Limestone Bed, a typical regressive limestone. Locally, the Kitaki Limestone is overlain by a paleosol (Heckel, 1997, personal communication).

Interpretation and discussion: The basal Garnett sequence boundary is expressed as a thick paleosol or by a valley incision. The sequence boundary is interpreted to have been formed during a relative fall of sea level because: (1) incision extends into underlying open- marine facies; (2) paleosol features are developed on marine limestones of valley walls and interfluvial areas; (3) a widespread paleosol extends from southeastern Kansas to southeastern Nebraska.

The Garnett IVF was deposited during a relative rise of sea level after valley incision. The origin of the conglomerate, however, remains problematic. Most of the lithoclasts appear to have been locally derived from rocks exposed in valley walls, although some may have been transported landward from open marine facies. Cross bedding is absent, and the unit is only poorly stratified. Interbeds of bioturbated siltstone near the top of the conglomerate indicate a marine influence, at least during latest conglomerate deposition. Clay drapes and thick-thin couplets from the fine-grained facies, which are interbedded with, and overlie, the Garnett conglomerate are characteristic of tidal environments (Nio and Yang, 1991). The preservation of articulated tetrapods and fish within the mudstone facies indicates extremely rapid deposition, which is also consistent with a tidal interpretation. Tetrapod footprints and raindrop imprints from the valley fill indicate intermittent subaerial exposure and the abundance of terrestrial plant and animal fossils indicate close proximity to land. The

fine-grained valley fill facies were deposited in a shallow water, tidally influenced estuary prior to the marine flooding of the interfluves.

There are two prominent erosional surfaces within the Garnett sequence above the sequence boundary. The lowest is at or near the base of the South Bend Limestone. This surface extends at least from southeastern Kansas to northwestern Missouri. The surface typically occurs between estuarine to shallow marine facies below and more open marine facies above. A conglomeratic lag at the surface, commonly with shale rip up clasts, and the sharp contact indicate erosion of underlying facies. Where the Rock Lake Shale is absent, this surface merges with the basal Garnett sequence boundary. Most of the clasts in the basal South Bend are locally derived, however a few chert clasts are present, and chert is not known from the immediately underlying lithologies. This surface is tentatively interpreted as a transgressive surface of erosion. An alternative interpretation is that the surface is another sequence boundary formed during a relative fall in sea level. Evidence for the second interpretation includes the chert clasts that likely have a distant source area, and the lateral extent of the surface. However, to date, no evidence of subaerial exposure has been found at this surface where it is not amalgamated with the Garnett sequence boundary. Resolution of these alternative interpretations must await further data.

A second significant surface occurs at the boundary between the South Bend Limestone and overlying dark grey shale. This is a flooding surface that separates grainstone and wackestone in the South Bend Limestone (or Little Kaw Limestone in Nebraska) from deeper water conodont-rich shales above.

The Meadow sequence

Description: This is the least well-understood sequence that we have studied. In southeastern Nebraska the sequence extends from the paleosol immediately above the Kitaki Member of the South Bend Limestone to the paleosol above the Nehawka Member of the Plattford Limestone (which is probably equivalent to the Iatan Limestone in northeastern Kansas). In southeastern Nebraska the South Bend Limestone comprises a Kansas type cyclothem (sensu Heckel, 1977) including a lower transgressive limestone (Little Kaw Limestone), a core shale (Gretna Shale), and an upper regressive limestone (Kitaki Limestone) (Pabian and Strimple, 1993). In the area of Meadow, Nebraska, a well-developed paleosol occurs immediately above the Kitaki Limestone (Heckel, 1967; Joeckel, 1995). To our knowledge, there is only one good remaining outcrop of this paleosol, and this is at locality N7. At this locality, the interval consists of the following in ascending order: (1) a basal dark gray and dark greenish gray mottled shale, which lacks fossils; (2) the "Nehawka Limestone Member" (of Nebraska Geological Survey Literature), which consists of a basal 15 cm of thinly bedded carbonate mudstone, and an upper 100 cm of weakly microkarstified, thickly laminated, white to pale yellow with reddish and greenish gray stains, carbonate mudstone with a few, low-amplitude teepee structures; (3) a 232-cm-thick blocky mudstone paleosol; and (4) 10 cm of gray, very strongly calcareous, fossiliferous shale. The paleosol is greenish gray in its uppermost 90 cm, grading down to reddish brown blocky mudstone. The paleosol does not appear to have a discrete zone of carbonate nodules or any expression of well-organized

slickensides (although it is only exposed at a single small outcrop). Greenish gray and reddish brown, massive mudstone is present in the interval between the South Bend Limestone and basal Cass Limestone in the locality N2 core, however, the core has been disrupted and a reliable description is impossible. Nonetheless, the same paleosol is probably present at both localities.

Although the South Bend Limestone and overlying shale is well known from many outcrops and cores in northeastern Kansas, there is no indication of exposure or of any erosional surface within this interval. Thus, it is not clear precisely where the sequence boundary correlates southward.

The Iatan Limestone consists of a thin transgressive limestone and conodont-rich core shale, and thicker regressive limestone composed of fossiliferous pack- to wackestone (Goebel *et al.*, 1989). Along the outcrop belt in Missouri, Iowa and Nebraska the upper Iatan is overlain by a paleosol (Goebel *et al.*, 1989), the basal sequence boundary of the next overlying sequence.

Interpretation: The paleosol above the South Bend Limestone in southeastern Nebraska is interpreted as a sequence boundary based on the microkarsting of the underlying marine limestone indicating a relative fall in sea level. The lack of any evidence of subaerial exposure basinward, and the dominance of deeper water facies may indicate that the outcrop described above is near the lowstand shoreline for this sequence.

As a result of the lack of subaerial exposure southwards, this sequence boundary cannot yet be correlated south of the southeastern Nebraska, however, the basinward thinning of the Weston Shale can be used to infer the position of the sequence boundary farther south. The Weston Shale thins basinward as the Iatan Limestone merges with the South Bend Limestone (Fig. 6). Assuming that the Meadow sequence boundary does not cross either limestone, then it must occur within the thin interval of Weston Shale in central Leavenworth Co., Kansas, or in the lowermost Crammer Creek Shale (see Appendix 3) in areas basinward of the limit of the Iatan Limestone.

Basehor sequence

Description: In northeastern Kansas the basal Basehor sequence boundary is represented by a valley incised 41 m into underlying marine facies of older sequences (Feldman *et al.*, 1995). The Basehor sequence extends upward from the sequence boundary associated with this incision to the sequence boundary associated with a large incision at the base of the overlying Ireland Sandstone (see next sequence). The large incised valley at the Basehor sequence boundary is name after the Tonganoxie Sandstone which fills it. The Tonganoxie incised valley is approximately 11 km wide and 240 km long. At the base of the IVF are fluvial sandstone and conglomeratic facies that rest unconformably on older marine facies. The fluvial facies are overlain by a succession of estuarine through marine facies (Feldman *et al.*, 1995). See Feldman *et al.* (1995) for a detailed account of the deposits in this IVF.

At most locations where the sequence boundary is deeply incised, there is no unequivocal evidence of subaerial exposure. However, at a few localities (K9, K11, K14, K16, K17) there is up to 20 cm of blocky mudstone at the sequence boundary which is interpreted as a paleosol. This mudstone, however, may have been an early phase of

valley fill. At locality K8, near the valley edge, there is a rooted coal resting on a mudstone-clast conglomerate and a second weakly developed paleosol on the underlying Crammer Creek Shale. The conglomeratic facies is crudely bedded, lacks marine fossils, borings, or encrustations and, therefore, is interpreted as an alluvial deposit.

The only exposures of the sequence boundary in interfluvial areas are in northwestern Missouri (locality m1) where a gley mudstone rests on the Iatan Limestone (See Feldman *et al.*, 1995, Fig. 6). However, near the northern edge of the incised valley subsurface correlations indicate that a coal (under 0.5 m thick) locally rests on the sequence boundary (see Feldman *et al.*, 1996).

The Basehor sequence boundary cannot yet be correlated south of the Tonganoxie valley and the basinward limit of subaerial exposure is unknown. The valley dies out basinward, as the single thick sandstone in the trunk valley fans out into discontinuous lobes of sandstone (Feldman *et al.*, 1995; Sanders, 1959) (Fig. 7). South of the Tonganoxie incised valley, there are many narrow (approximately 1 km wide) incised valleys that may correlate with the Stalnaker Sandstone, a large sandstone blanket that merges basinward with a thick immature siliciclastic facies in the Anadarko Basin . The bases of these narrow incised valleys may correlate with the Basehor sequence boundary at the reference section.

In Missouri and Nebraska the Basehor sequence boundary appears at a prominent paleosol that overlies the Iatan Limestone and its stratigraphic equivalents. The paleosol consists of up to 2.4 m of non-calcareous blocky mudstone and the microkarsted uppermost Iatan Limestone (Goebel *et al.*, 1989). In Iowa and Missouri the paleosol is overlain by fossiliferous marine shale or unfossiliferous shale or sandstone (Goebel *et al.*, 1989).

Interpretation: The Tonganoxie incised valley was formed and filled during a relative lowstand of sea level because: (1) within the incision fluvial facies rest unconformably on older marine facies; (2) paleosols are extensively developed on interfluvial areas north of the incised valley, and locally within the valley; and (3) underlying marine Iatan limestone contains evidence of subaerial exposure.

The Tonganoxie incised valley is larger than other midcontinent Pennsylvanian incised valleys, which are typically about 1 km wide. The source area for the sandstone fill was probably from the Canadian Shield in the Lake Superior area (Minor, 1969). Thus, the Tonganoxie valley likely drained a large watershed during a major relative fall of sea level. In southeastern Kansas, the valley fill is represented as a series of smaller and thinner sandstone lobes. In the adjacent outcrop belt (in an interfluvial position) there are no known paleosols at this stratigraphic level, although exposures are poor, and stratigraphic control is limited. The position of the lowstand shoreline is not known and the nature of the downdip termination of the trunk incised valley and its relationship to the deltaic Stalnaker sandstone is not yet worked out.

The Tonganoxie valley was filled during rising sea level with a succession of fluvial, estuarine, and marine facies (Feldman *et al.*, 1995). There is an upward increase in the diversity and abundance of burrows. However, there may not be any fully marine facies within this sequence in northeastern Kansas. The upper sequence boundary of the Basehor sequence in northeastern Kansas was originally interpreted to be at the base of

the Ireland sandstone (Feldman *et al.*, 1995), another IVF, but further work reported herein revealed another sequence boundary in the Vinland Shale (see next section).

Woodson sequence

Description: At the reference section for this sequence (locality K2) the Vinland Shale at the base of the sequence consists of green-grey blocky mudstone with small slickensides and is interpreted as a paleosol that forms the basal Woodson sequence boundary. The underlying Westphalia Limestone appears to have evidence of microkarst. Directly overlying the paleosol is a-one-cm-thick laminated shale that contains abundant plant debris. This shale is overlain by another laminated shale that grades upward to bioturbated, fossiliferous shale, which in turn grades up into limestone of the Haskell Limestone.

Bowsher and Jewett (1943) first noted that local "channel" sandstones of the Vinland Shale cut through the Westphalia Limestone in southeastern Coffey Co., Kansas. Cores and well logs reveal that such incisions are locally common in the area, and a series of cores provides a transect through one such feature (Fig. 8). The Vinland Shale thickens from as little as 1 m in an interfluvial location to 22 m in the middle of the incision. Description of the valley fill is based on core descriptions and photographs in Kansas City Power and Light Company (1975). At the base of the IVF is a fossiliferous conglomeratic limestone up to 3.6 m (12 ft) thick. This is overlain by up to 19 m of clean sandstone, heterolithic facies, shale, and coal. There is no consistent succession of facies, but most of the sandstone is within the lower 15 m (49 ft) of the fill, and the coals are all in the upper 4.5 m (15 ft).

The basal Woodson sequence boundary may correlate to the Upper Sibley coal and underlying paleosol in northeastern Kansas. The Upper Sibley Coal occurs throughout most of northeastern Kansas (Bowsher and Jewett, 1943) and onlaps the basal Basehor sequence boundary near the edge of the Tonganoxie incised valley (Feldman *et al.*, 1995). The coal ranges up to 51 cm (20 inches) thick and is underlain by a 2-m-thick paleosol at locality K14. This paleosol consists of greenish grey, slickensided, blocky mudstone, and the lower portion contains abundant irregularly shaped limestone concretions that lack fossils. The paleosol grades downward into laminated to rippled argillaceous siltstone and shale. Locally, the coal is overlain by an ostraocod-rich, coaly lime mudstone, which has been previously correlated with the Westphalia Limestone of central Kansas (Ball, 1971), however, this correlation is probably not correct. We suggest that the Woodson sequence boundary at the paleosol at locality K2 most likely correlates to the base of the Upper Sibley Coal, and that the limestone overlying the coal is younger than the Westphalia Limestone at the type section. Even within northeastern Kansas, the Upper Sibley Coal is not present everywhere, and at locality K10 there is no obvious surface (sequence boundary) that can be confidently correlated with the Woodson sequence boundary. At K10, both the Upper Sibley Coal and Westphalia Limestone are absent, and upper Tonganoxie facies are indistinguishable from the lower Vinland Shale.

The Vinland Shale was not studied south of Woodson County. Therefore, the basinward extent of subaerial exposure is not known at this time. In Missouri, Nebraska,

and Iowa the basal Woodson sequence boundary merges with the paleosol overlying the Iatan Limestone.

Overlying the sequence boundary in interfluvial areas are a range of facies including laminated mudstone with well-developed neap-spring cycles to bioturbated marine mudstone. The upper Vinland Shale in northeastern Kansas consists of sandstone with marine burrows. This grades upwards to the widespread marine Haskell Limestone. Overlying the Haskell is a thick marine shale. The lower 30 cm of this shale contains phosphate concretions and phosphatic fossils such as fish scales, fish neurocrania casts, and phosphatic brachiopods (Miller and Swineford, 1957). Also present are nektonic fossils, such as ammonites and nautiloids (Miller and Swineford, 1957). Northward in Missouri, Nebraska, and Iowa the phosphatic zone correlates with a thin, platy black shale that is overlain by a thick shoaling upward limestone (Ball, 1964, 1985).

Interpretation: The basal Woodson sequence boundary was not originally recognized by Feldman *et al.* (1995) or Archer *et al.* (1994b) who incorrectly included all of the Woodson sequence with the underlying Basehor sequence. The basal Woodson sequence boundary is interpreted to be a result of a lowering of relative sea level due to the valley incision and development of interfluvial paleosols that, at the reference section, extend down to the underlying marine Westphalia Limestone and apparently fill microkarstic fractures in the upper portion of the limestone indicating weathering of the limestone in the vadose zone during subaerial exposure. The basal Woodson sequence boundary onlaps the Basehor sequence boundary at the edge of the Tonganoxie valley. Thus, the underlying Basehor sequence does not include marine facies in northeastern Kansas.

The Vinland Shale above the basal Woodson sequence paleosol consists of a complex mosaic of marine and estuarine shale and sandstone facies. The stratigraphic relationships among these facies remain undetermined, but they all record deposition in relatively shallow, nearshore environments. At locality K2, marine shale directly overlies the paleosol, but in most of northeastern Kansas, heterolithic facies are common at this stratigraphic position. The heterolithic facies with sparse burrows, no body fossils, and common tidal cyclicity probably represent estuarine deposition. The upward transition to the marine Haskell Limestone represents open marine conditions.

The overlying phosphatic gray to black shale is a condensed section that includes the maximum flooding surface. In Nebraska the Woodson sequence consists of a Kansas type cyclothem consisting of a transgressive limestone, core shale, and regressive limestone (Haskell Ls. Mbr., Little Pawnee Sh. Mbr, and unnamed member of the Cass Limestone) bounded above and below by paleosols that represent the lower and upper sequence boundaries.

Hole-in-the-Rock sequence

Discussion: We have not investigated this sequence in detail, however there are well-documented examples in which fluvial facies of the Ireland Sandstone are incised into underlying marine shale, and even through the marine Haskell Limestone (Ball *et al.*, 1963; O'Connor, 1960; Bowsher and Jewett, 1943; Lins, 1950). The lower Ireland Sandstone consists of trough cross bedded sandstone without clay drapes or fossils, and is interpreted to be fluvial. At the base of the sandstone is a thin (under 1 m) conglomerate

composed of limestone, goethite, shale, and coal clasts, as well as rare reworked phosphatic concretions (Ball *et al.*, 1963; Bowsher and Jewett, 1943; Rich, 1933)

Most reported outcrops of the basal Ireland Sandstone (Rutan, 1980, Bowsher and Jewett, 1943) are no longer exposed.

The more-or-less continuous Amazonia Limestone occurs near the top of the sequence and extends from southern Kansas to northwestern Missouri (Bowsher and Jewett, 1943; Ball, 1964). The Amazonia represents marine flooding near the top of the Hole-in-the-Rock sequence. In northeastern Kansas the Amazonia Limestone is extensively altered from subaerial exposure associate with the overlying paleosol at the top of the sequence.

Government Hill Sequence

Description: The Government Hill sequence extends upward from an extensive paleosol in the upper Lawrence Shale to an extensive paleosol in the Snyderville Shale. There are actually up to three paleosols in the upper Lawrence Formation (Joeckel, 1995). The most laterally extensive and the thickest is the uppermost paleosol which occurs just above the widespread marine Amazonia Limestone. We place the Government Hill basal sequence boundary at the top of this paleosol. For detailed descriptions and interpretations of these paleosols see Joeckel (1994, 1995). The paleosols extend northward from central eastern Kansas through northwestern Missouri and into southeastern Nebraska and southeastern Iowa. The paleosols are also analogous to modern vertisols and consist of blocky mudstone in which little or no bedding is preserved except in the lowest portions, and they contain nested synformal-antiformal slickensides. The paleosols are interpreted to have formed in generally well-drained areas in which the water table was well below the land surface. The slickensides indicate alternate (seasonal?) wetting and drying of the soils.

The Government Hill basal sequence boundary paleosol is typically about 1.5 to 2.5 m thick in northeastern Kansas and adjacent portions of Missouri. It is characterized by a lower high-chroma reddish zone and an upper grayish zone. It extends south to the Oklahoma border where it still has a characteristic red lower zone (Bowsher and Jewett, 1943). In the northern areas the paleosol is typically a mottled high-chroma red and grey grading up to grey in the upper half. Original preserved pedogenic fabric include brecciation, cracks filled with overlying sediment, pedogenic carbonate nodules, and well-developed ped structures. In central and southeastern Kansas the Upper Williamsburg Coal rests on the paleosol.

Resting abruptly upon the Lawrence Formation paleosol (or upon the coal) is typically 10 cm to 5 meters of a range of siliciclastic facies including laminated shale containing marine fossils to heterolithic facies that was probably deposited in an estuarine environment. Overlying these facies is the marine Toronto Limestone. This limestone extends throughout the study area with little change in thickness or facies. No black shales are associated with the Toronto Limestone in the study area.

Overlying the Toronto Limestone is the Snyderville Shale which, throughout most of the study area, consists predominantly of a thick paleosol that forms the upper sequence boundary of the Government Hill sequence.

To date, we have only identified one small incised valley at the basal Government Hill sequence boundary. At locality K19, a single small exposure reveals a limestone conglomerate (about 30 cm thick) that is overlain by laminated limestone containing exquisitely well preserved plant fossils including large *Walchia* fronds (early conifers) and a variety of other foliage such as ferns, seed ferns, and chordites. Large chunks of fusane (up to 5 cm in diameter) are common on some bedding plains. Spiral coprolites are common but no articulated animals are known from the site. The laminated limestone is overlain by 20 cm of laminated shale and then the Toronto Limestone. The interval from the base of the Toronto to the base of the Heebner Shale is condensed to approximately 40 cm thick. This is quite unusual so that there remains some degree of uncertainty that this incised valley fill belongs within the Government Hill sequence. The paleosol in the Snyderville Shale also forms the sequence boundary of the Mahoney Park sequence (see next sequence).

Interpretation: The lower Government Hill sequence boundary paleosol is interpreted to have formed during a relative lowering of sea level because the Amazonia Limestone below the paleosol, a widespread marine limestone (extending from central eastern Kansas to northwestern Missouri; Hinds and Greene, 1915; Moore, 1949) that represents maximum flooding in the preceding sequence, was extensively altered by subaerial exposure processes in northeastern Kansas during formation of the paleosol. The paleosol is characterized by vertisol features indicating formation primarily in the vadose zone.

Subsequent to development of vertisol features, there was a change in conditions leading to local deposition of peat in eastern Kansas. The change in the water table may have been due to a change in precipitation, or to rising water tables during transgression (Feldman and Archer, 1995).

The single incised paleovalley that is probably associated with the basal Government Hill sequence boundary is relatively small, but otherwise very similar to other incised paleovalleys that we have observed. Both the Garnett incised paleovalley (see Garnett sequence) and the Virgilian Hamilton incised paleovalley of eastern central Kansas (see Cunningham *et al.*, 1994) have similar paleovalley fills with lower limestone conglomerates and upper laminated limestones that contain well-preserved fossils.

Mahoney Park sequence

Description: The basal Mahoney Park sequence boundary is at a laterally extensive vertisol type paleosol in the Snyderville Shale. For a complete description of this paleosol see Joeckel (1994). The paleosol extends throughout the study area and is typically 2.5 to 3.7 m thick in the 2.5- to 4-m-thick Snyderville Shale. The paleosol consists of low chroma, faintly mottled, blocky shale with common large, intersecting slickensides. Some slickensides also form voids that were filled with overlying material. A few pedogenic carbonate nodules also occur dispersed throughout the paleosol at most localities. In most exposures the upper Toronto Limestone exhibits microkarst consisting of subvertical to horizontal mud-filled voids that occur to depths of 30 to 120 cm below the top of the limestone. In southern Kansas the Snyderville has a relatively thin (110 cm thick) weakly developed paleosol. There is one known small incised valley reported by Ball (1964, p. 361-362) which is associated with this sequence, however we were not

able to verify his observations. Ball (1964) reported that the incisions were filled with limestone conglomerate. We have not studied the rest of this sequence.

Interpretation: The Snyderville Shale paleosol is interpreted as a sequence boundary because pedogenic features extend down into the underlying marine Toronto Limestone. The lateral extent of the paleosol indicates that the lowstand shoreline was basinward of the study area. Despite the lateral extent of the paleosol and the large number of outcrops that have been examined by us and others (see Joeckel, 1994, Ball, 1964) the only known incisions are small and filled with locally derived limestone conglomerate. The preservation of surface features of the paleosol and complete soil profiles indicates that there is very little erosion associated with the sequence boundary.

The paleosol formed in a broad low-relief coastal plain similar to conditions during formation of the upper Lawrence Formation paleosol of the previous sequence. The well-developed slickensides suggest soil development above the water table in an environment of alternate wetting and drying of the clays. This is commonly associated with soils that form in areas of seasonal rainfall The Snyderville paleosol likely formed in a somewhat wetter environment compared to the Lawrence because it has generally lower chroma colors and less pedogenic carbonate. However the landscape was generally well drained, and there are no coals associated with the paleosol.

DISCUSSION

Sequence boundaries are the primary genetic surfaces in the cyclothems we have studied. Sequence boundaries represent widespread unconformities that persist updip of the lowstand shore even in areas otherwise dominated by marine strata. Despite the diversity of expression of these surfaces they all represent periods of relative lowering of sea level and emergence of vast areas of the continent. Incision and widespread paleosol development indicate that for many of the cycles the lowstand shorelines were basinward of the study area or near south central Kansas (Fig. 9). The principle exception is the Meadow sequence for which evidence of subaerial exposure is known only for the most up dip localities. Because of the very limited extent of the Meadow Sequence paleosol in our study area it will not be discussed further.

The sequences share a basic architecture that has long been the recognized basis of the Kansas type cyclothem (see Heckel, 1994). The expression of the sequence boundaries and the lithologic components of the systems tracts varies both from sequence to sequence and along depositional dip within each sequence (Figs. 10, 11). In the upper shelf position the sequences are dominated by limestones of the transgressive and highstand systems tracts. The transgressive systems tract extends from the sequence boundary to the maximum flooding surface typically in the lower portion of the core shale. The highstand systems tract is composed of the rest of the core shale, the upper limestone, and the overlying shale up to the next sequence boundary. The marine facies of the core shales and marine limestones are well developed indicating that the most proximal portion of our study area is far from the highstand shoreline. The types of paleosols and lack of coals indicate that during lowstands the upper shelf was well drained. The lack of incised valleys may relate the position of these outcrops relative to the major drainage fairways. The Tonganoxie incised valley, at least, trended northeast

based on projecting the trend of the valley updip, and based on provenance of the sediment (Minor, 1969). Thus, the outcrop is oblique to true depositional dip.

In the middle shelf position in northeastern Kansas the limestones are thinner, and particularly the upper limestone within a cyclothem is typically less well developed. Also the core shales are less well developed. Most of the basinward increase in thickness of the section is due to increased thickness of the highstand systems tract shales. These shales have been poorly studied, but are generally thoroughly bioturbated and contain sparse marine fossils. The sequence boundaries in the middle shelf position include common incised valleys. Coals are more common both within the larger incised valleys and on the interfluve paleosols suggesting more poorly drained conditions.

Farther basinward the limestone and core shales are even less well developed, there is dramatic thickening of the highstand systems tract shales, and some of the sequence boundaries pass into the marine conformities (Fig. 10).

There is also a range of expression of sequence boundaries among the sequences. The lowstand valley fills fall roughly into two groups. One group includes IVF's of the Ash Grove, Garnett, Government Hill, and Mahoney Park sequences. All of these sequence boundaries are characterized by low to high-chroma, blocky mudstone paleosols with little or no coal and all have associated small incised valleys filled mostly with limestone conglomerate. All of the paleosols were interpreted to have formed in generally well-drained vadose conditions. The paucity of coal indicates that coal swamps, which require high water tables, were not widely developed at these times. High chroma values generally result from oxidation of iron in the vadose zone and also indicate that water tables were low.

The valleys tend to be small, generally less than 1 km wide and cannot be traced very far. The valley fills are dominated by a lower limestone conglomerate facies. This facies fills most or all of each of the valleys. In most cases the source of the limestone clasts can definitely be identified as the host rock exposed in valley walls. The origin of the conglomeratic facies probably ranges from fluvial to tidal, however unambiguous fluvial facies have not been identified. Mostly the conglomerates seem to have been reworked in tidal environments during flooding of the valleys. However, paleosols from the interfluves, and in one case from valley walls, as well as the incision into lithified limestone leaves no doubt that these valleys were incised during subaerial exposure.

Overlying the conglomerate facies in the Garnett and Government Hill IVF's is a fine-grained laminated facies with well preserved fossils. Mud drapes and rare couplets suggest a tidal influence, and the tetrapod footprints and other exposure indicators in the Garnett IVF indicate intermittent exposure, possibly in an intertidal environment. In each case the most common plant remains are conifer needles. Ferns, sphenopsids and other plants are also present, but are much less common. Also common are abundant layers of fusane. Another well-studied example of this type of valley is the Hamilton IVF (see Cunningham *et al.*1994). This Virgilian valley fill is also characterized by a small valley filled with a lower, locally derived conglomerate and an upper fine-grained laminated facies with well-preserved fossils. The fossils include fish, insects, reptiles, and abundant plants, mostly conifer needles.

The smaller IVF's contrast sharply with IVF's from the Basehor, Woodson, and Hole-in-the-Rock sequences. These valleys are several km wide and can be traced for up to two hundred km. Locally derived limestone conglomerate occurs only in the basal

meter of these valley fills. Most of the lower portions of each of the valleys are filled with mature sandstone deposited in fluvial through estuarine facies. The source area for the Basehor sequence IVF is the Lake Superior region indicating that the valley was draining a large watershed. The upper portions of these valleys are filled with muddy estuarine facies. Rooted coals suggest coal swamps developed during filling of the valleys. Plant fossils from these valley fills are dominated by fern-type foliage, seed ferns, and sphenopsids.

Interfluve paleosols, where known for these sequences, consist of very low chroma paleosols with little or no carbonate. Slickensides, if present, are not organized into pseudoanticlines characteristic of vertisols. The Woodson sequence boundary also has a widespread coal resting on the paleosol.

Climatic differences can best explain the two types of lowstand valleys associated with sequence boundaries. The sequence boundaries with small valleys were formed in relatively drier climates. The small size of the valleys, and the fill dominated by locally derived material suggests relatively small drainage systems compared to the distantly sourced mature sediment fill of the larger IVF's. The conifer flora reflects well-drained conditions in the interfluvial areas and contrasts sharply with the coals and fern foliage of the larger valley fills. Also the smaller valleys are associated with low to high chroma paleosols with pedogenic carbonate and little or no coal. The smaller, conglomerate filled valleys are not similar to tributaries of the larger valley systems. Subsurface and outcrop study of the Basehor valley system revealed many tributary valleys, each of which was filled with sandstone, not conglomerate, and some of which contained local coals (Feldman *et al.*, 1995).

SUMMARY

A study of midcontinent Pennsylvanian cyclothems sequences reveals that they are punctuated by areally extensive unconformities or sequence boundaries that were formed during relative lowstands of sea level at which time large areas of the continent were exposed. The sequence boundaries are manifest as widespread paleosols with associated incised valleys, however paleosols are not preserved for every cycle even where valley incision is prominent. Subsequent erosion of only a few meters may remove paleosols from interfluves and leave behind only incised valleys.

The two end-member expressions of sequence boundaries likely results from differences in climate during periods of sea-level lowstand. Sequence boundaries that formed during relatively drier times are characterized by generally higher chroma paleosols with pedogenic carbonate. Slickensides are common and organized into intersecting sets which are characteristic of vertisols indicating alternate wetting and drying of the clays. These paleosols formed on low-relief, well-drained coastal plains with low water tables. Coals are rare and thin. Associated incised valleys are small and filled with locally derived material, mostly limestone conglomerates. Plant assemblages are dominated by relatively xerophytic conifers.

Sequence boundaries that formed during relatively wetter times have large incised valleys that drained large portions of the Midcontinent. The sediment that fills the valleys is mostly mature sandstone. In one well-documented case the sand was derived from the Lake Superior region. Coals are common both within the valley fills and, to a

lesser extent, on interfluve paleosols. Plant assemblages from the valley fills lack conifer remains, and are instead dominated by fern foliage and seed ferns. The paleosols, where known, are very low chroma, lack slickensides organized into intersecting sets, and have little pedogenic carbonate. In one case the paleosol has a widespread coal.

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APPENDIX 1: Reference localities.

Ash Grove Quarry sequence
Reference section for basal sequence boundary: Locality N5 (Ash Grove Quarry), paleosol in Vilas Shale.
Other sections: Paleosols in Vilas Shale at N1 (Butler Co. core), N2 (Mid-Am 62-1 core), K6 (Garnett cores) and I4. Conglomerate-filled incision in upper Vilas Shale at K13.

Garnett sequence
Reference section for basal sequence boundary: Several exposures and cores of Rock Lake Shale thickening into an IVF at locality K6. Sequence boundary is at erosional top of Stoner Limestone and base of Rock Lake Shale.
Other sections: Paleosol in Rock Lake Shale at K11, K14, K16, N1, N4, N5 and N8.

Meadow sequence
Reference section for basal sequence boundary: Quarry exposure at N7. The sequence boundary is at the top of the paleosol of the shale overlying the South Bend Member and below the Nehawka Member.
Other sections: Burchett and Reed (1967) describe a 12.8 ft of blocky dark reddish-brown shale directly above the South Bend Member at locality N8. This is probably a paleosol. There is also a poorly exposed red mudstone above the South Bend Limestone at locality N5. In addition there is probably a paleosol in the Plattford shale overlying the South Bend Limestone in locatity N2 (a core), however this interval of the core has been disrupted. No other evidence of subaerial exposure is known.

Basehor Sequence
Reference section for basal sequence boundary: K17 and K17a. These exposures are road cuts in which the basal Tonganoxie rests unconformably on the South Bend Limestone through the Stanton Limestone.
Other sections: Base of Tonganoxie Sandstone at K8, K9, K10, K11, K14, K16, M1, and paleosol above Iatan limestone in Missouri, Iowa, and Nebraska as described by Geobel *et al.* (1989); paleosol above Nehawka Ls. (probably equivalent to Iatan Ls.) at N7.

Woodson sequence
Reference Section: Locality K2, the sequence boundary is at the top of the paleosol in Vinland Shale.
Other sections: Localities 4, incised valley in cores described in Kansas City Power and Light (1975); locality K14, Oeschlaeger core, sequence boundary at Upper Sibley Coal.

Hole-in-the-rock sequence
Reference Section: Locality K20 The sequence boundary is...TO BE PROVIDED BY ARCHER.

Other sections: No other exposures of the sequence boundary are known although exposures of the associated incised valley fill are abundant and well documented (see Bowsher and Jewett, 1944).

Government Hill sequence
Reference Section: Locality K18, the sequence boundary is at the top of the paleosol in Lawrence Shale.
Other sections: Localities K9, K10, K12, K 19, M2, N3.

Mahoney Park sequence.
Reference Section: Locality N9. The sequence boundary is at the lower paleosol in the Snyderville Shale.
Other sections: Localities N2, I1, I2, K12,K18. For additional localities see Joeckel (1994).

APPENDIX 2: Locality list

Kansas

K1. SE SW SE sec. 33, T33S, R11E, Chautauqua Co. Road cut along Kansas Highway 99. Exposes upper Lawrence Sh. through Plattsmouth Ls. Locality LS-22 of Joeckel (1994).

K2. E/2 SE NE sec. 14, T26S, R 14E, Woodson Co. Westphalia Limestone through Haskell Limestone. Well-developed paleosol in lower Vinland Shale.

K3 SW SE SW sec 26, T25S, R13E, quarry and adjacent road cut on Highway 54. Exposes upper Lawrence through Snyderville.

K4. SW SE sec. 8, T21S, R16E, Coffee Co. Core B11 of Kansas City Power and Light Company (1975) from Toronto Limestone to South Bend Limestone.

K5. SW 1/4, SW 1/4, SW 1/4, SE 1/4, sec. 27, T20S, R17E. Coffee Co. Erosional contact between fusulinid Westpahlia Ls. and Tonganoxie Sandstone.

K6. NE NW sec. 5, T. 20 S, R. 19E, Anderson County. Several exposures along excavations and creek banks, approximately 46 m (150 ft) south of road, and a series of 8 cores taken between the road and creek. Outcrops expose Stoner Limestone through South Bend Limestone. Cores extend from upper Lane Shale through South Bend Limestone. Cores at the Kansas Geological Survey.

K7. NW sec. 24, T18S, R19E, Franklin Co. Active quarry. Exposure of Eudora Shale through South Bend Ls. Also see photograph of adjacent abandoned quarry in Plate 7A of Ball *et al.* (1963).

K8. NW NW SEC. 23, T17S, R19E, Franklin Co., Large quarry exposure of Crammer Creek Shale, Ottawa Coal, and lower Tonganoxie Sandstone, and core (KGS Buildex 10) that extends down to upper Vilas Shale.

K9. S/2 SW sec. 11, T14S R18E, Douglas Co. KGS Mechaski core. Extends from Heebner Shale to upper Vilas Shale.

K10. NW sec. 35, T 13S, R18E. KGS Wireline test core.

K11 SW SW SE sec. 12, T13S, R19E, Douglas Co., KGS 31st Street core, extends from middle Tonganoxie Sandstone to upper Vilas Shale.

K12. NW NW NE sec. 7, T13S, R19E, Douglas Co., KGS Clinton Core #1, extends from Haskell Limestone up to Heebner Shale.

K13. NW NW sec. 4, T13S R22E, Johnson Co., East side of Sunflower Quarry enterence. Limestone conglomerate incised into upper Vilas Shale.

K14., SW NW NW sec. 5, T12S R22E, Leavenworth Co. KGS Oeschlaeger core. Upper Vilas Shale through Haskell Limestone. Paleosol in lower Rock Lake Shale, Tonganoxie rests unconformably on a thin shale above the South Bend Limestone.

K15. SW NE sec. 7, T12S, R24E, Road cut at Johnson Drive exit of Rt. 435. Vilas Shale with no apparent exposure surface..

K16. NE NE SW sec. 18, T11S, R23E, Wyandotte Co., Road cut on north and south sides of Interstate 70, Captian Creek Limestone through Tonganoxie Sandstone. Tonganoxie is resting unconformably on South Bend Limestone. There is a palesol in the lower Rock Lake Shale.

K17. SW NW sec. 8, T11S R23E, Wyandotte Co. Road cut on east and west sides of Kansas Route 7. Stoner Limestone through Tonganoxie Sandstone. Tonganoxie Sandstone rests unconformably on Crammer Creek Shale?

K17A. SE SW SE sec. 6, T11S R23E, Wyandotte Co. Road cut on north side of Kansas Rout 40. Conglomeratic lower Tonganoxie Sandstone rests unconformably on Stoner Ls.

K18. SW sec. 22, T8S, R22E, Leavenworth Co. Road cut on Kansas Highway 7. Exposes upper Lawrence paleosol through Heebner Shale. Section LS-12 of Joeckel (1994).

K19. NE sec. 31, T15S, R18E, Franklin Co. Exposures near barn of Lloyd Robbins Jr. Exposes incised valley fill in upper Lawrence Formation through Heebner Shale.

K20 ARCHER this is for the Ireland outcrop.

Missouri

M1. NW NW sec. 33, T54N, R36W. Platte Co. Abandoned quarry on E side of highway. Section from Iatan to shale above Haskell Ls.,

M2. N/2 NE sec. 33, T59N R35W, Andrew Co., Breit Quarry. Upper Lawrence paleosol through Plattsmouth Limestone.

Nebraska

N1. sec. 35, T16N R4E, Butler Co. Core. Includes Leavenworth Limestone through Plattsburg Limestone.

N2. sec. 1, T11N, R8E, Lancaster Co. Mid-America Pipeline core 62-1. Haskell Limestone through Plattsburg Limestone. Section LS-1 of Joeckel (1994).

N3. W/2 NW SW sec. 15, T12N, R10E, Cass Co. Hopper Bothers quarry. Exposes upper Lawrence paleosols through Leavenworth Ls.

N4. SW SE sec. 12, T12N R10 E Sarpy Co., Schramm Park. Rock Lake paleosol.

N5. Sec. 13, T12N R11E. Ash Grove quarry. Captian Creek Limestone through Nehawka Limestone (Iatan equivalent?).

N6. N/2 SW sec. 18, T12N R11E, Sarpy Co. Road cut on Highway 31, exposing Plattsburg Limestone through Eudora Shale, with a well-developed Vilas Shale paleosol.

N7. N/2 NE SE NE sec. 16, T 12 N, R 11 E., Sarpy Co., Nebraska. Stone Products Quarry, approximately 2 km (1.25 miles) west of Meadow, Nebraska. Sequence boundary is at the top of the paleosol in the shale overlying the South Bend Limestone and under the Nehawka limestone.

N8. C S/2 SW sec. 9, T12 N, R 11 E., Sarpy Co., Nebraska. Meadow Rock Quarry. Base on old descriptions of Burchett and Reed (1967) there is are dark red blocky mudstones (probably paleosols) within the Rock Lake Shale (Garnett sequence boundary) and directly above the South Bend Member (probably Meadow sequence boundary).

Iowa

I1 SW SW sec 5, T71N R41W, Mills Co. Malvern core (W-28868), Iowa Department of Natural Resources. Cass Limestone through Leavenworth Limestone. Section LS-4 of Joeckel (1994).

I2. SE sec. 4, T67N R34W, Taylor Co. Bedford Core (W-30816), Iowa Department of Natural

APPENDIX 3: The Crammer Creek Shale.

A new stratigraphic name is required for the predominantly shale unit between the top of the Iatan Limestone and the base of the Tonganoxie Sandstone. These rocks have previously been incorrectly referred to the Weston Shale, however the Weston Shale includes only strata below the Iatan Limestone and above the South Bend Limestone (Keyes, 1899; Moore, 1935; Zeller, 1968). In outcrops in northeastern Kansas and immediately adjacent areas the top of the Iatan Limestone is at or very near the base of the Tonganoxie Sandstone. In outcrops in northwestern Missouri, southwestern Iowa and southeastern Nebraska the top of the Iatan is at the base of a paleosol that correlates with the base of the Tonganoxie Sandstone. South of Leavenworth Co., Kansas, the Iatan Limestone is not exposed, and the shale between the Tonganoxie Sandstone and Stanton Limestone was correlated with the Weston Shale based on the assumption that the Iatan Limestone is truncated by the erosional unconformity at the base of the Tonganoxie. Previous work on lower Douglas Group rocks in areas where the Iatan is absent have referred to shale below the Tonganoxie and above the South Bend Limestone as the Weston Shale Member of the Stranger Formation (Moore, 1935; Bowsher and Jewett, 1942; Lanier *et al.*, 1993). This is not correct. Howe (1986) noted that the Weston Shale ranges from a few cm thick to as much as 30 m thick in Platte Co, Mo. Well logs reveal that the Weston Shale thins basinward to a feather edge in Leavenworth Co., Kansas, as the Iatan Limestone thins and merges with the South Bend Limestone (Figs. 6.A, B). Strata between the top of the Iatan Limestone and base of the Tonganoxie Sandstone are hereby termed the Crammer Creek Shale Member of the Stanton Formation. The type section of the Crammer Creek Shale Member is designated as the Holland No 1 well in SW SW NE sec. 13, T. 8 S, R 21 E, in Leavenworth Co., Kansas. The base of the Crammer Creek Shale is at a depth of 239 ft and the top is at 196 ft.

There are no outcrops known to us that can be unambiguously attributed to the Crammer Creek Shale. However the absence of the Iatan Limestone west and south of Leavenworth Co., Kansas, suggests that most of the section between the base of the Tonganoxie Sandstone and top of the Lansing Group in central and northeastern Kansas (where the Iatan is absent) correlates with the Crammer Creek Shale. This includes a well-exposed quarry section at NW sec. 23, T. 16 S, R. 19 E. At the quarry approximately 18 to 20 m of shale and mudstone are exposed below the Tonganoxie Sandstone. The Kansas Geological Survey Buildex #10 core taken from behind the quarry highwall includes 29.5 m of strata between the top of the Lansing Group and base of the Tonganoxie Sandstone (see Feldman *et al.*, 1995, Fig. 5). This interval, which consists of laminated to bioturbated shale to mudstone, is the Crammer Creek Shale.

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Zaitlin, B. A., R. W. Dalrymple, and R. Boyd, 1994, The stratigraphic organization of incised-valley systems associated with relative sea-level changes, *in* R. W. Dalrymple, R. Boyd, and B. Zaitlin, B., eds., Incised-valley systems: orgin and sedimentary sequences: SEPM Special Publication 51, p. 45-60.

FIGURE CAPTIONS

Figure1. Generalized paleogeography during late Missourian time showing approximate maximum highstand and lowstand shorelines for the Douglas Group (modified from Archer and Feldman, 1995)

Figure 2. Generalized stratigraphy of latest Missourian through early Vigilian strata in northeastern Kansas. The numbered sequences described in the text are 1, Ash Grove Quarry sequence; 2, Garnett sequence; 3, Meadow sequence; 4, Basehor sequence; 5, Woodson sequence; 6, Hole-in-the-Rock sequence; 7, Government Hill sequence; 7, Mahoney Park sequence.

Figure 3. Map of locations referred to in text. See Appendix 2 for detailed locality information.

Figure 4. Cross section through a congomerate-filled incised valley in the Ash Grove sequence in northeastern Kansas. The sequence boundary is not recognizable in interfluvial areas. Data from Cunningham and Franseen (1992)

Figure 5. Cross section of the Garnett sequence incised valley at locality K6 based on cores.

Figure. 6. A, East-west cross section from northeastern Kansas, showing thinning of Weston Shale. Type log for Crammer Creek Shale is Holland no 1 well (see Appendix 3). Location of cross section shown in B. B, Isopach map in meters of the Crammer Creek Shale.

Figure 7. Map of the Tonganoxie incised valley of the Basehor sequence. Modified from Feldman *et al* (1995). The Stalnaker sandstone is approximately in the same stratigraphic position as the Tonganoxie, however, the precise relationship between the two is not clear.

Figure 8., A, Cross section of an incised valley within the Woodson sequence (Vinland Shale) based on cores. Location of the cross section is shown in B. B, Isopach of the Vinland Shale. Most of this interval consists of incised valley fill deposits.

Figure 9. Exent along dip of the major components of transgressive and highstand systems tracts of the sequence discussed in the text. Note that the marine limestone and black shales are best developed in the updip areas. Sequences are numbered that same as shown in Fig.C.

Figure 10. Cross section of the study interval along the outcrop belt. Sequence boundaries shown only in areas where they can be confidently identified. All thicknesses are shown to scale except that coals have been exaggerated for clarity.

Figure 11. Schematic comparison of a sequence in up dip and down dip portions of the study area.

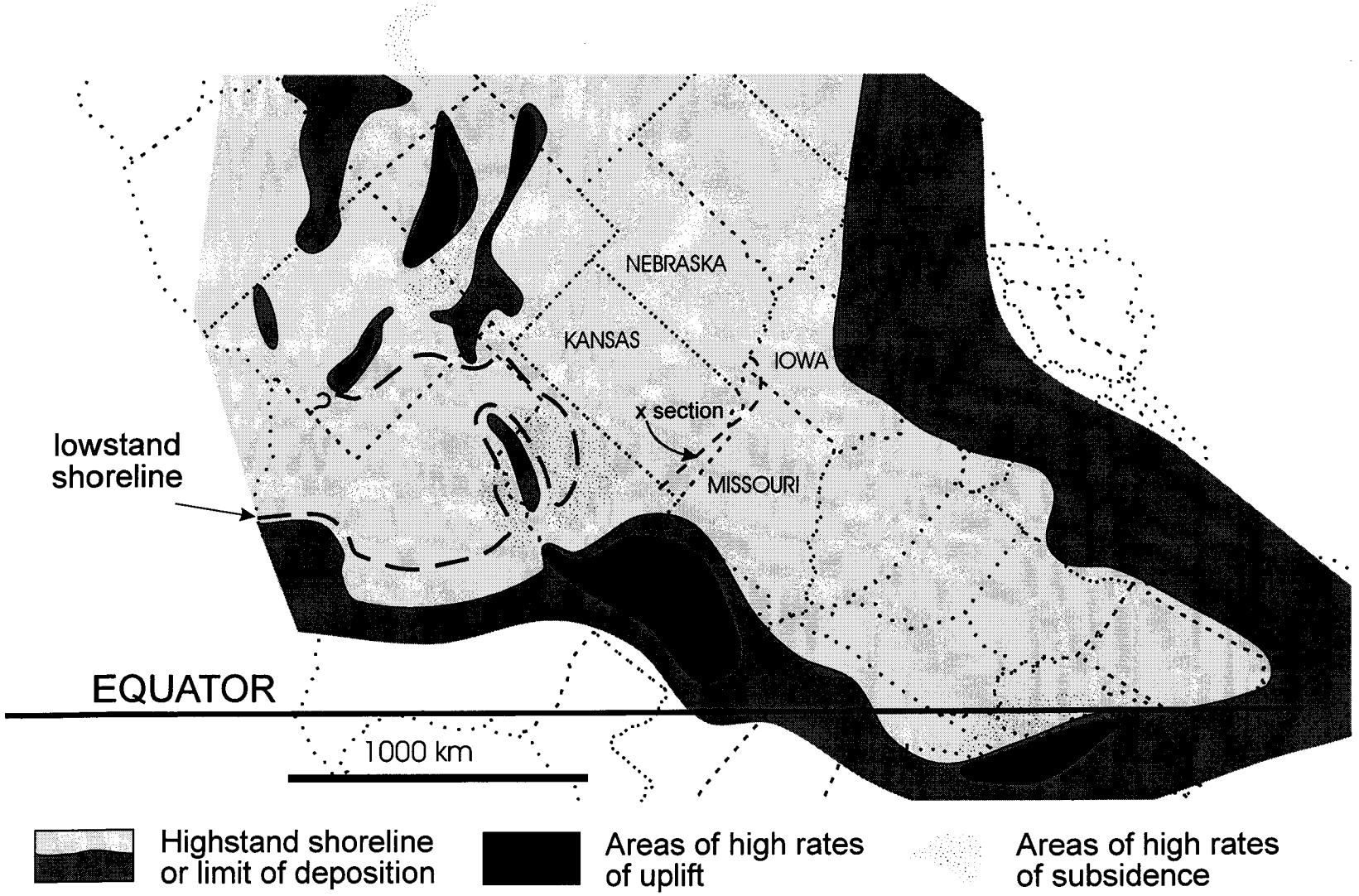
NEBRASKA
KANSAS
IOWA
x section
MISSOURI
lowstand
shoreline
EQUATOR
1000 km
Highstand shoreline
or limit of deposition
Areas of high rates
of uplift
Areas of high rates
of subsidence

Figure 1

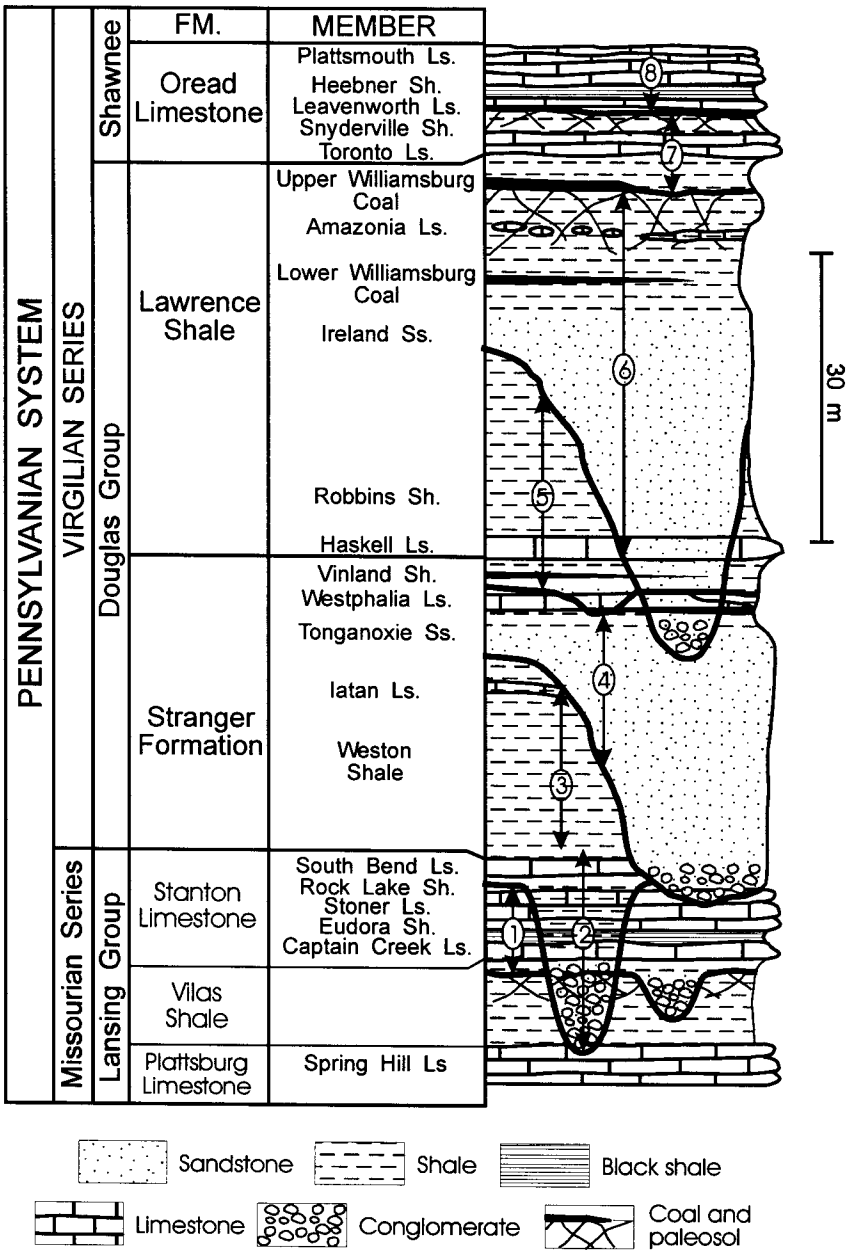
PENNSYLVANIAN SYSTEM
VIRGILIAN SERIES
Missourian Series
Shawnee
Douglas Group
Lansing Group
FM.
MEMBER
Oread Limestone
Plattsmouth Ls.
Heebner Sh.
Leavenworth Ls.
Snyderville Sh.
Toronto Ls.
Lawrence Shale
Upper Williamsburg Coal
Amazonia Ls.
Lower Williamsburg Coal
Ireland Ss.
Robbins Sh.
Haskell Ls.
Stranger Formation
Vinland Sh.
Westphalia Ls.
Tonganoxie Ss.
Iatan Ls.
Weston Shale
Stanton Limestone
South Bend Ls.
Rock Lake Sh.
Stoner Ls.
Eudora Sh.
Captain Creek Ls.
Vilas Shale
Plattsburg Limestone
Spring Hill Ls
30 m
Sandstone
Shale
Black shale
Limestone
Conglomerate
Coal and paleosol

Figure 2

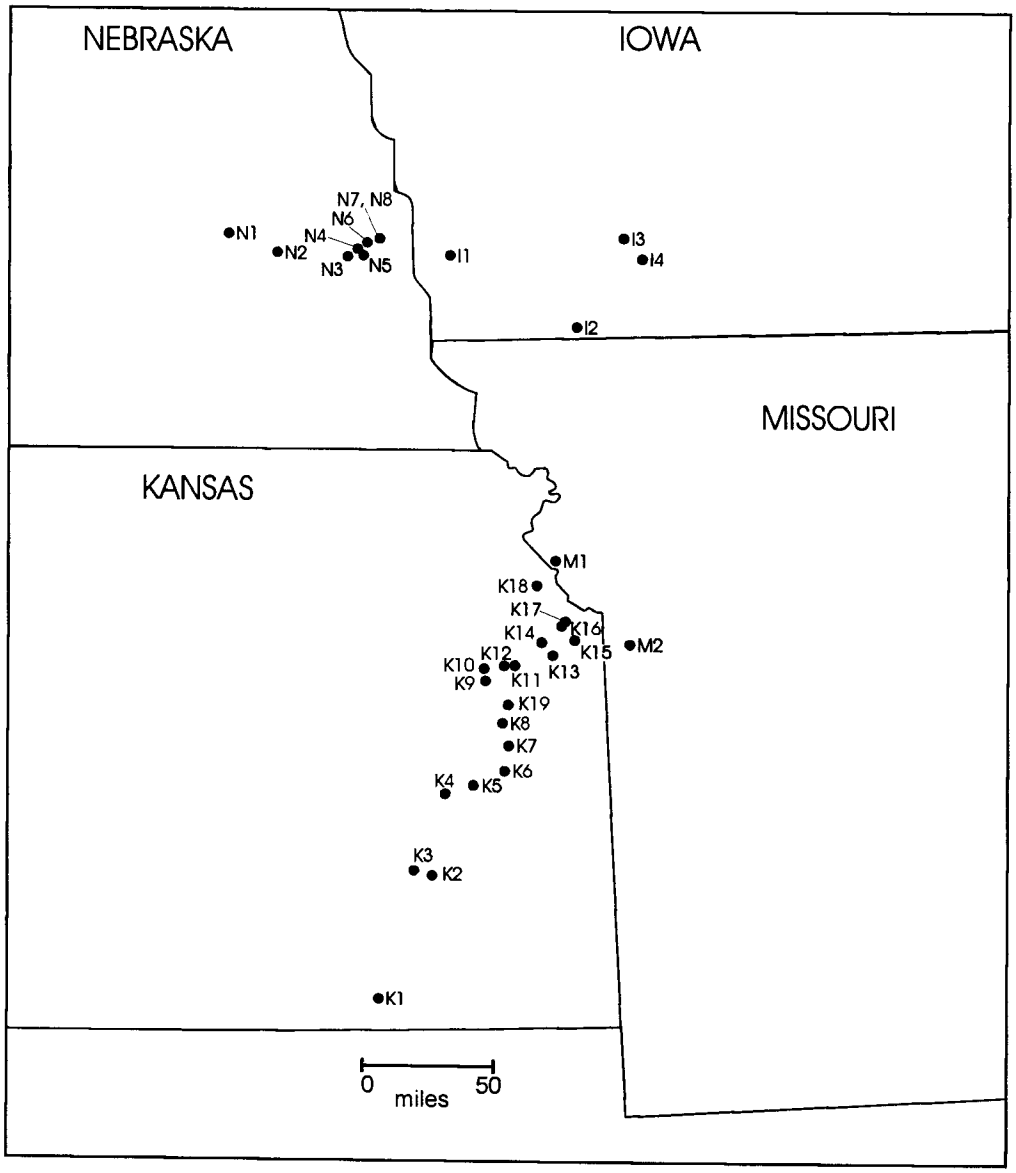
NEBRASKA
IOWA
MISSOURI
KANSAS
N1
N2
N3
N4
N5
N6
N7, N8
I1
I2
I3
I4
M1
M2
K1
K2
K3
K4
K5
K6
K7
K8
K9
K10
K11
K12
K13
K14
K15
K16
K17
K18
K19
0
50
miles

Figure 3

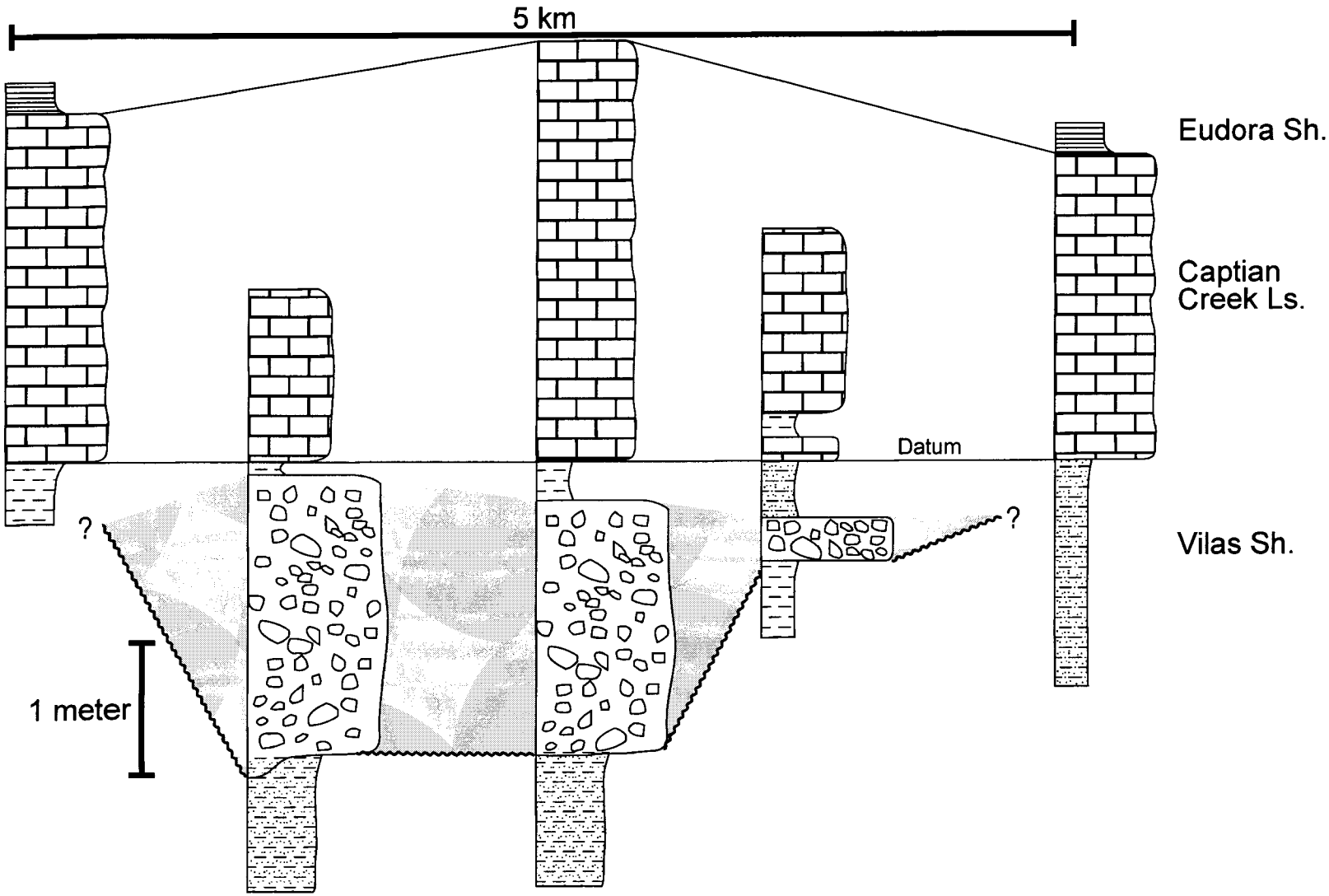

Figure 4

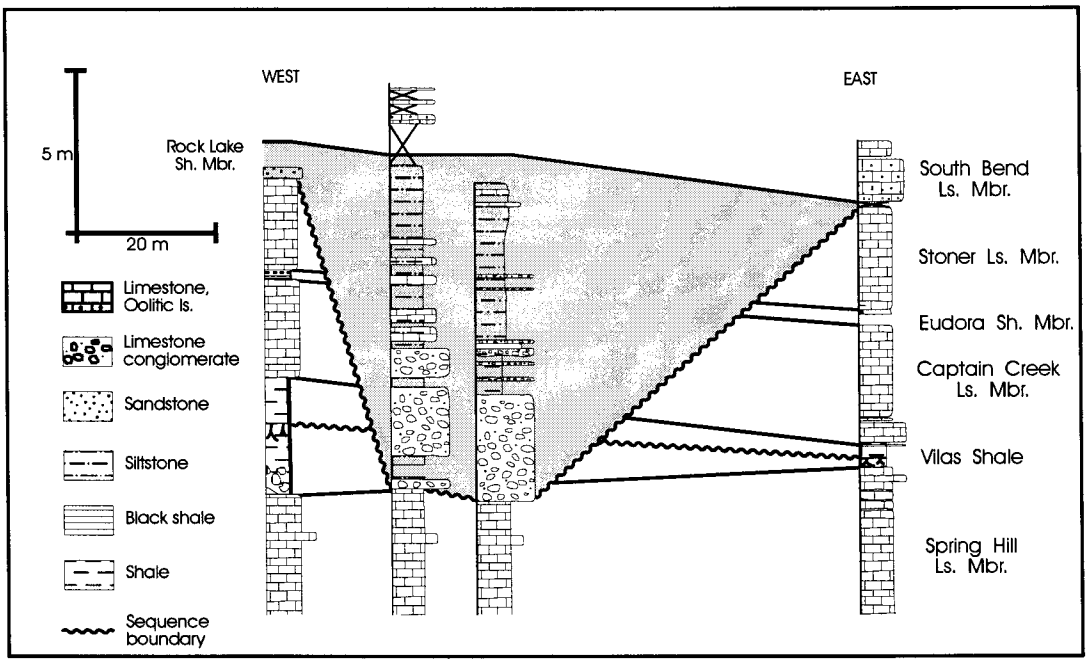
WEST
EAST
5 m
20 m
Rock Lake
Sh. Mbr.
Limestone,
Oolitic ls.
Limestone
conglomerate
Sandstone
Siltstone
Black shale
Shale
Sequence
boundary
South Bend
Ls. Mbr.
Stoner Ls. Mbr.
Eudora Sh. Mbr.
Captain Creek
Ls. Mbr.
Vilas Shale
Spring Hill
Ls. Mbr.

Figure 5

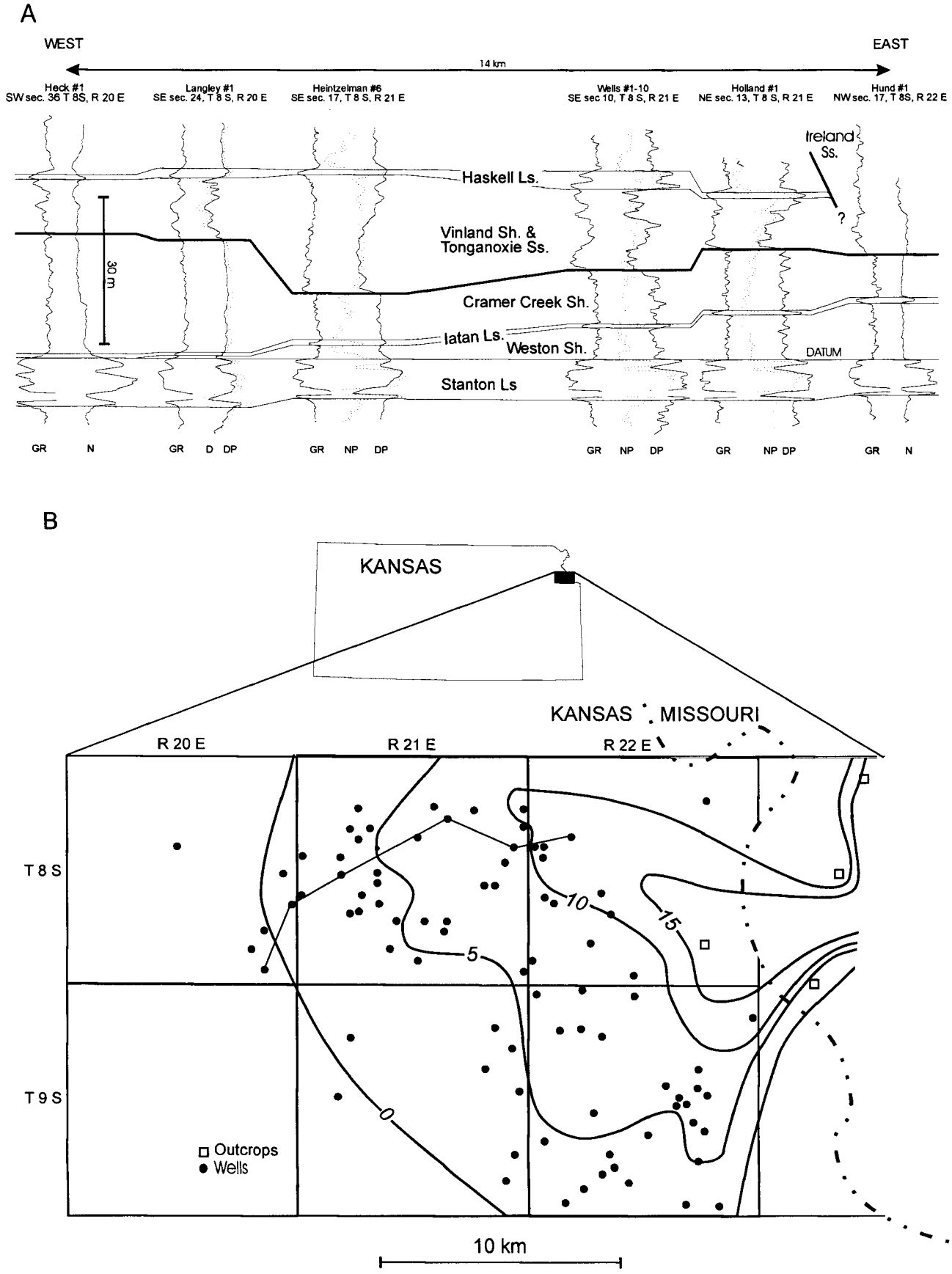
A
WEST
EAST
14 km
Heck #1
SW sec. 36 T 8S, R 20 E
Langley #1
SE sec. 24, T 8 S, R 20 E
Heintzelman #6
SE sec. 17, T 8 S, R 21 E
Wells #1-10
SE sec 10, T 8 S, R 21 E
Holland #1
NE sec. 13, T 8 S, R 21 E
Hund #1
NW sec. 17, T 8S, R 22 E
Haskell Ls.
Ireland Ss.
?
Vinland Sh. &
Tonganoxie Ss.
30 m
Cramer Creek Sh.
Iatan Ls.
Weston Sh.
DATUM
Stanton Ls
GR N
GR D DP
GR NP DP
GR NP DP
GR NP DP
GR N
B
KANSAS
KANSAS MISSOURI
R 20 E
R 21 E
R 22 E
T 8 S
T 9 S
10
15
5
0
Outcrops
Wells
10 km

Figure 6

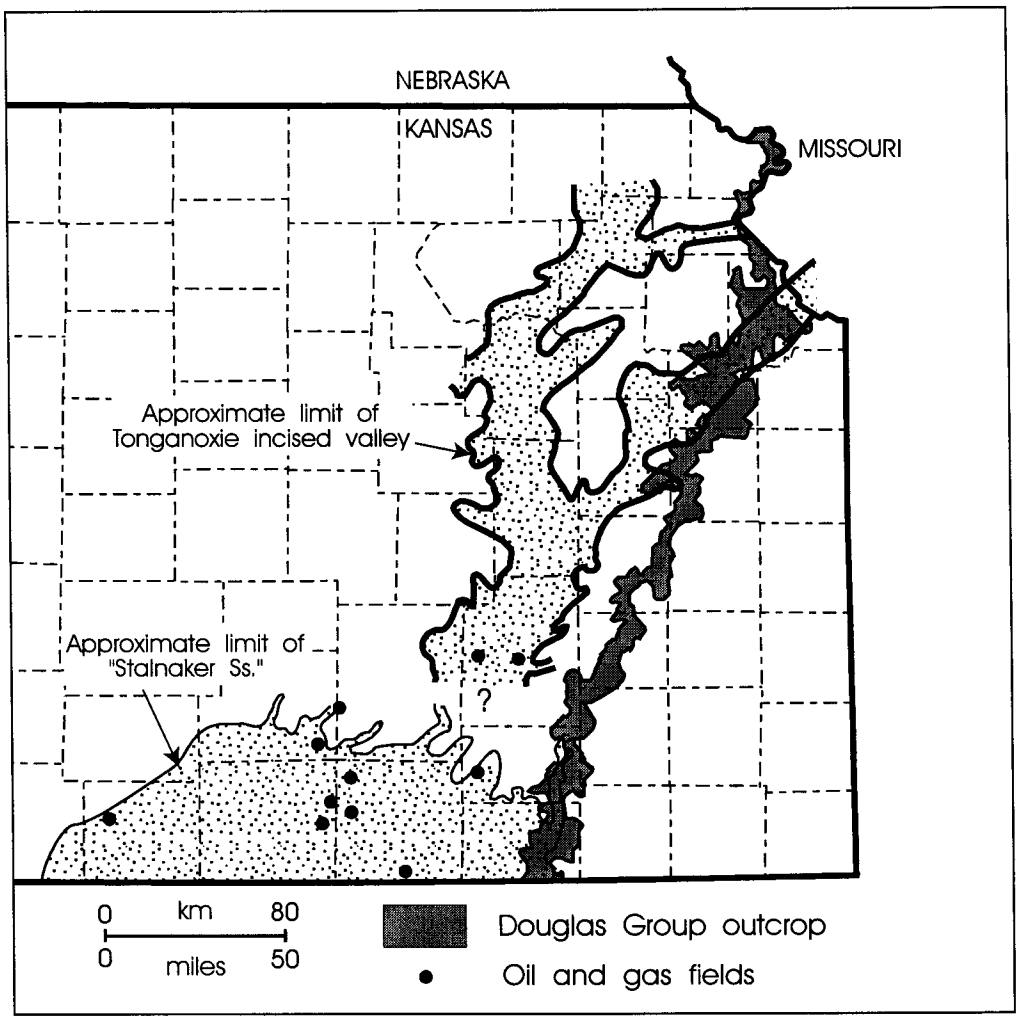
NEBRASKA
KANSAS
MISSOURI
Approximate limit of
Tonganoxie incised valley
Approximate limit of
"Stalnaker Ss."
?
0 km 80
0 miles 50
Douglas Group outcrop
Oil and gas fields

Figure 7

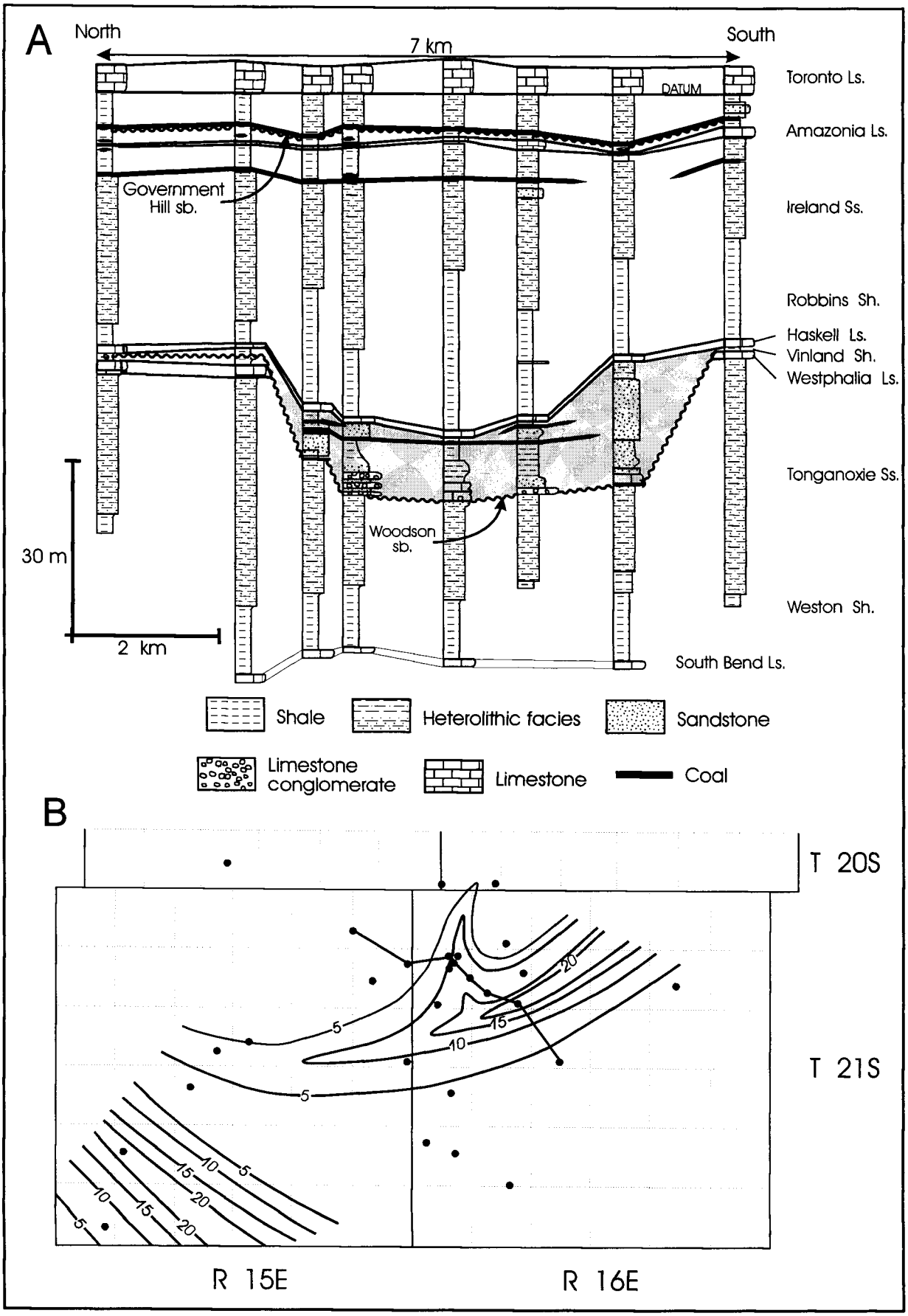
A
North
7 km
South
DATUM
Toronto Ls.
Amazonia Ls.
Government Hill sb.
Ireland Ss.
Robbins Sh.
Haskell Ls.
Vinland Sh.
Westphalia Ls.
Tonganoxie Ss.
Woodson sb.
30 m
2 km
Weston Sh.
South Bend Ls.
Shale
Heterolithic facies
Sandstone
Limestone conglomerate
Limestone
Coal
B
T 20S
T 21S
R 15E
R 16E
5
10
15
20

Figure 8

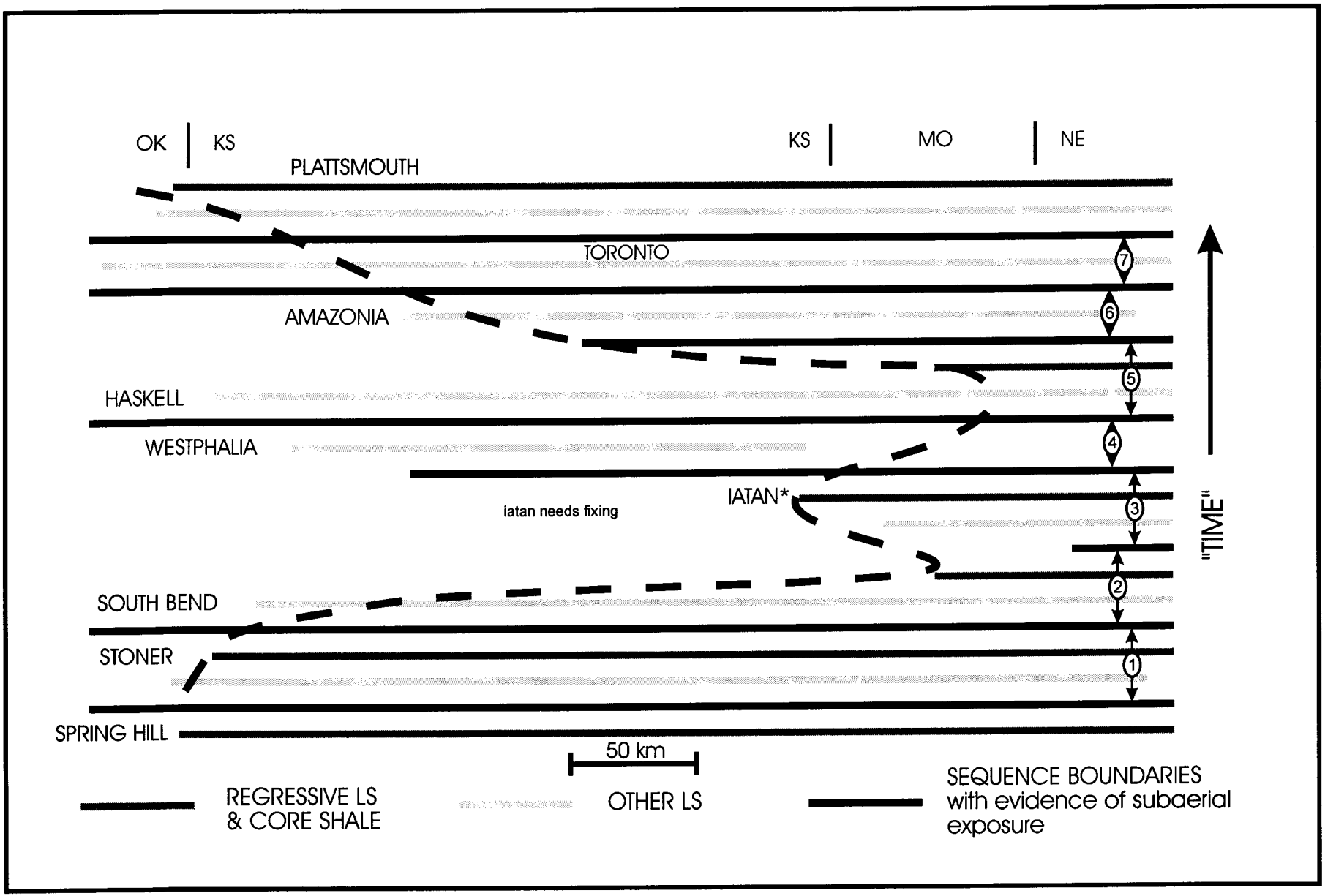
OK
KS
KS
MO
NE
PLATTSMOUTH
TORONTO
AMAZONIA
HASKELL
WESTPHALIA
IATAN*
iatan needs fixing
SOUTH BEND
STONER
SPRING HILL
7
6
5
4
3
2
1
"TIME"
50 km
REGRESSIVE LS
& CORE SHALE
OTHER LS
SEQUENCE BOUNDARIES
with evidence of subaerial
exposure

Figure 9

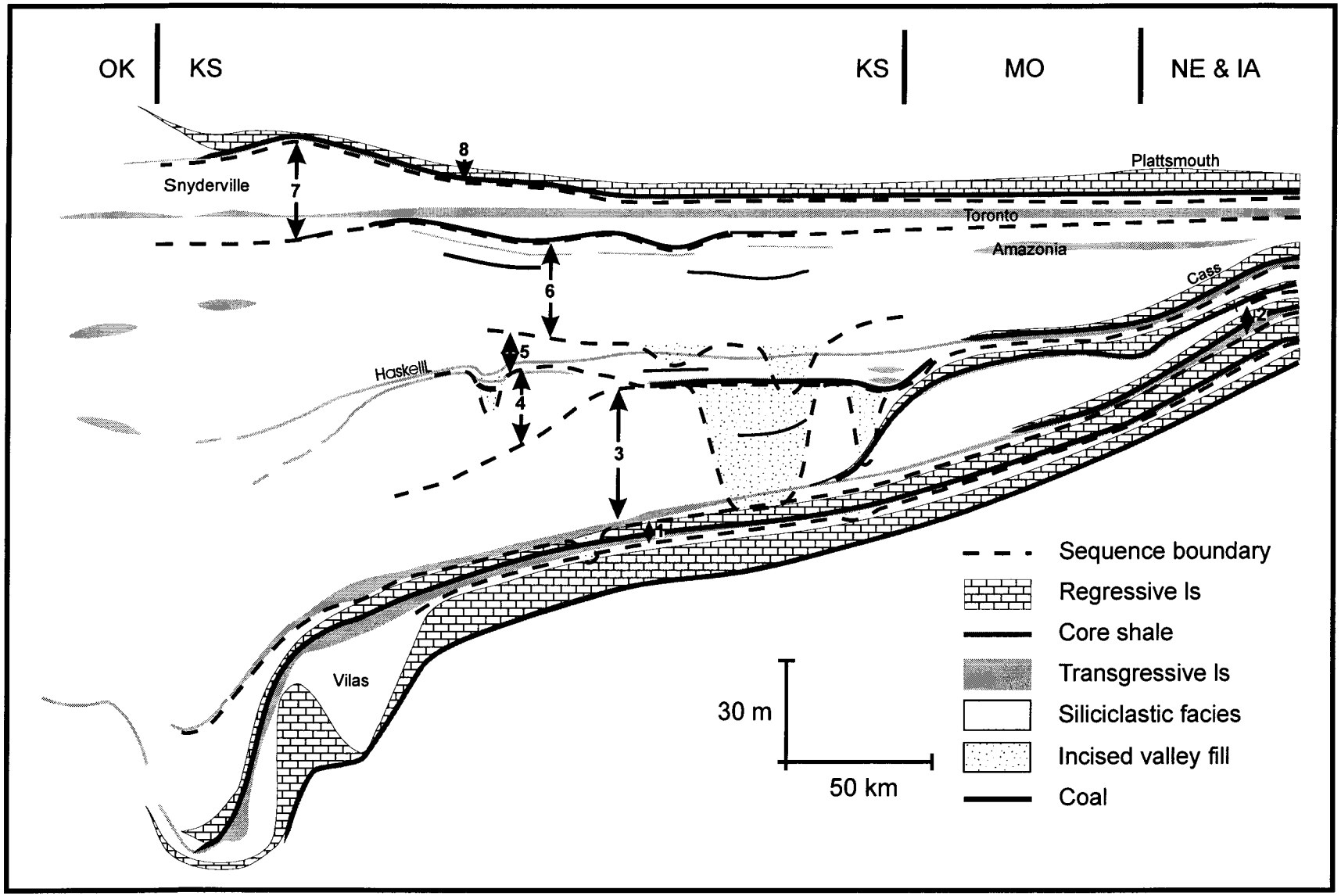
OK
KS
KS
MO
NE & IA
Snyderville
Plattsmouth
Toronto
Amazonia
Cass
Haskell
Vilas
8
7
6
5
4
3
2
1
30 m
50 km
Sequence boundary
Regressive ls
Core shale
Transgressive ls
Siliciclastic facies
Incised valley fill
Coal

Figure 10

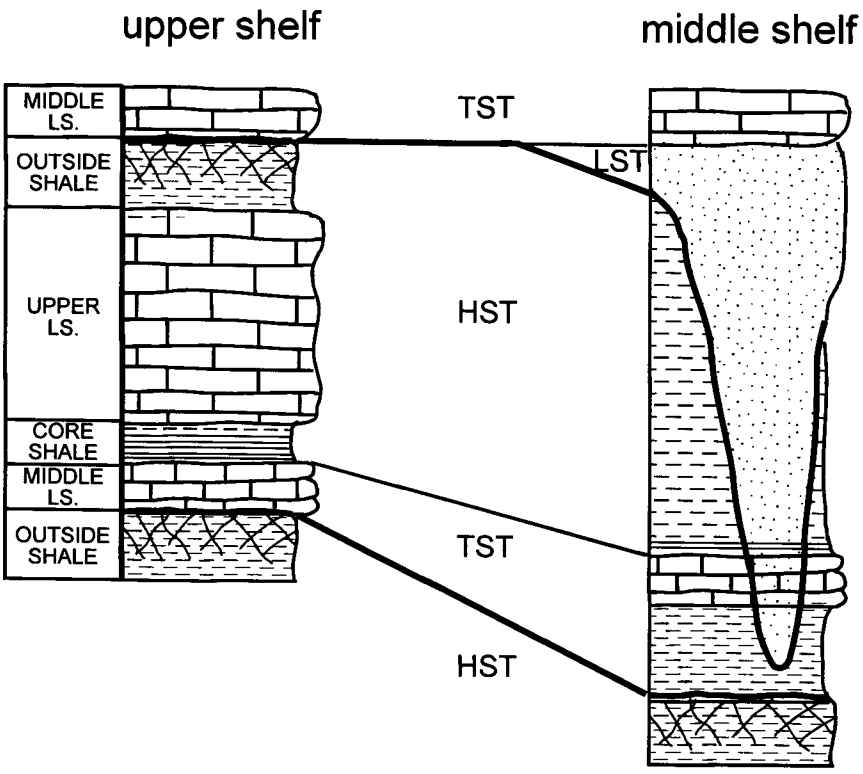
upper shelf
middle shelf
MIDDLE LS.
OUTSIDE SHALE
UPPER LS.
CORE SHALE
MIDDLE LS.
OUTSIDE SHALE
TST
LST
HST
TST
HST

Figure 11