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CLIMATICALLY CONTROLLED VARIATION IN SEQUENCE BOUNDARIES AND LOWSTAND VALLEY FILLS: UPPER CARBONIFEROUS (STEPHANIAN) OF THE U.S. MID-CONTINENT

by

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ABSTRACT

Analysis of nine sequence boundaries in the Upper Pennsylvanian of eastern Kansas and adjacent portions of Iowa and Nebraska revealed that there are two end members to sequence boundary expression. One group of sequence boundaries is characterized by high chroma paleosols with slickensides and common pedogenic carbonate. The incised valleys associated with these sequence boundaries are small (under 2 km wide and less than 20 m deep), and are filled mostly with locally derived limestone conglomerate and shale deposited in fluvial to estuarine environments. The plant assemblages are dominated by gymnosperms, mostly xerophytic walchian conifers. These sequence boundaries are interpreted to have formed in relatively dry climates with well-drained interfluves and small valley networks.

The other group of sequence boundaries is characterized by low chroma paleosols. Incised valleys are large (several km wide and at least 20 m deep) and extensive, and are filled with mature sandstone and mudstone deposited in fluvial to estuarine environments. Coal occurs both on interfluvial paleosols and within valley fills. The plant assemblage from the incised valley fills is dominated by fern foliage, seed ferns, and sphenopsids. These sequence boundaries reflect high water tables and large, extensive river systems indicating wetter climates.

All of the sequence boundaries formed during large regressions that exposed vast areas of the midcontinent. There is no apparent relationship between the magnitude of sea level fall and expression of sequence boundaries. The range of sequence boundary expression is best explained by variations in climate. Climate had a dramatic impact on the formation of sequence boundaries and the types of facies preserved in incised valleys including thickness and distribution of reservoir facies.

INTRODUCTION

Late Paleozoic depositional sequences were formed under rather unique global conditions of geography and climate. Aggregation of Pangea resulted in a pole-to-pole spanning supercontinent and a large area of landmass at high latitudes allowed large-scale continental glaciations. Glacioeustacy produced extremely high-magnitude, short-duration relative sea-level oscillations, which are interpreted to have caused the alternation of widespread marine units and paleosols in the U.S. midcontinent (e.g. Heckel, 1977, 1986, 1994). Vast areas of the North American craton were exposed during relative lowstands of sea level and then submerged during subsequent transgressions (Fig. 1). Sequence boundaries are the surfaces that formed during the relative lowstands of sea level, and are characterized by widespread paleosols and incised river valleys (we are following Van Wagoner's [1996] definitions of sequence stratigraphic terms).

Previous studies have documented long term climate change over much of the Pennsylvanian (Cecil, 1990; West et al., 1997) and very short term climate changes during the development of individual sequences (Miller et al., 1996; Rankey, 1997). Our study has revealed that within a few successive sequences there is a wide range of expression of sequence boundaries and types of associated incised valley fills (IVFs), the two end members of which we term small scale (under 2 km wide and under 20 m deep) and large scale incised valleys. There does not seem to be a relationship between the expressions of sequence boundaries and positions of the lowstand or highstand shorelines. For most of these cycles, northeastern Kansas was far from both shorelines (Fig. 1). Other than widespread and gradual basinal subsidence, tectonic influences were minimal in the study area (Watney, et al., 1995). Therefore, the variations in valley-fill successions discussed here appear to be independent of local tectonics, and thus were controlled by sea level and climatic variability. As we attempt to show in this paper, the most likely explanation of the expression of sequence boundaries is that climate varied from cycle to cycle and caused differences in the types of interfluvial paleosols and incised valley that formed.

Humid climates acting on the large-scale continental landmass resulted in the development of large-scale river systems including Amazon-scale fluvial systems that have been documented in the eastern part of North America (Archer and Greb, 1995). During these wetter climate intervals, similar large-scale incised fluvial systems occurred in the midcontinent and these incised valleys were filled with distantly sourced, mature sandstone during sea-level rise. Drier periods resulted in the formation of smaller-scale drainage networks and smaller-scale valleys that were filled with locally derived sediment. This work reveals that detailed climatic information is preserved in the lowstand record and that climate had a dramatic impact on the development of Pennsylvanian cyclothems. Valley fill sandstones are common petroleum reservoirs and recognizing the influence of climate on the formation and filling of incised valleys may lead to better predictive models of reservoir distribution and quality.

GENERAL STRATIGRAPHIC RELATIONSHIPS

The Pennsylvanian succession in Kansas consists of repetitions of siliciclastic- and carbonate-rich units. This repetition led to the "cyclothem" concept (Wanless and Weller, 1932), which was originally applied in the Illinois Basin. Derivatives of this model have been applied extensively to the Kansas section (Moore, 1936; Heckel, 1994). This oscillatory interbedding of siliciclastic and carbonate strata is related to juxtaposition of detrital lowstand systems tracts with comparatively carbonate-rich transgressive to highstand systems tracts. Traditional cyclothem-based models focus on the transgressive- and highstand-systems tracts, which are geographically widespread and tend to display very low lateral heterogeneity. These models tend to ignore the lowstand-system facies and the high degree of lateral variability that occurred within that part of the deposition system. Modern sequence-stratigraphic models can more readily explain the common occurrence of IVFs and widely correlatable paleosols.

There is some confusion in the literature between the terms "channel" and "incised valley." In this paper, we use channel to refer to an abandoned river course, whereas incised valleys are defined as erosional features that formed by entrenched fluvial systems that removed pre-existing, commonly marine, strata during relative sea level lowstands (Van Wagoner, 1996).

An incised valley may contain many smaller fluvial channels that were filled as sediment aggraded within the valley. During relative lowstands of sea level, incised valleys were eroded by rivers while paleosols commonly formed on interfluvial areas. The erosional surfaces (the sequence boundaries) associated with IVFs are laterally significant unconformities, and facies that are preserved below the sequence boundary are not genetically related to facies that occur above it. In contrast, erosion associated with channel bases is only local, and channel fill facies are related to facies into which the channel erodes.

Most of each IVF in this study is within the lowstand systems tract (Archer et al., 1994) because it lies between the sequence boundary and the first major flooding surface (see Van Wagoner, 1996 regarding identification of systems tract boundaries). The transgressive systems tract includes fully marine facies that extend beyond the incised valley and covers interfluvial areas.

In this paper we present data on sequence boundaries from the Upper Pennsylvanian of eastern Kansas and adjacent areas (Fig. 2). All but one of the examples of sequence boundaries and associated incised valleys are from 8 contiguous sequences (Fig. 3). The Hamilton quarry example is of a younger incised valley. We refer to each sequence boundary by the same name as the overlying sequence, so that sequence boundary 3 is overlain by sequence 3.

SEQUENCE BOUNDARIES WITH SMALL-SCALE INCISED VALLEYS

Vilas Shale Sequence Boundary and Incised Valley Fill

Description.-There is a prominent paleosol in the upper Vilas Shale in southeastern Iowa and southwestern Nebraska. The poorly- to well-developed paleosol consists of reddish blocky mudstone with common pedogenic carbonate nodules. To the south in eastern Kansas the paleosol is either not preserved (in northeastern Kansas) or occurs as a low-chroma block mudstone (see Fig. 4). In northeastern Kansas there is a small valley incised into the Vilas Shale (location A on Fig. 2, sequence 1 in Fig. 3, Fig 5). The surface of incision probably correlates with the Vilas paleosol, which is absent in the area of incision. This incised valley is 8 m deep and 1.5 km wide, and filled with a locally crossbedded limestone conglomerate (Cunningham and Franseen, 1992). The conglomeratic limestone consists of pebble-sized limestone clasts, fossils, and shale clasts. The limestone clasts consist of fossiliferous packstone to mudstone, are mostly well rounded and are similar to facies exposed in valley walls. Some clasts are bored; others contain likely evidence of subaerial exposure, such as concentric cracking (resembling soil glaebules) with open pores lined with laminated crusts and possible rhizotubules. Cross bedding in the conglomerate is bimodal parallel to the valley axis, indicating tidal reworking. The conglomerate is overlain by thin (under 10 cm) laminated shale to heterolithic facies, and then by fossiliferous wacke- to packstone of the widespread marine Captain Creek Limestone.

Interpretation.-Both the Vilas paleosol and the surface at the base of the Vilas IVF are sequence boundaries because they formed during subaerial weathering of underlying marine rocks. They are likely the same sequence boundary because they occur at nearly the same stratigraphic level, and because there is no evidence of multiple sequence boundary formation at this level, however we cannot equivocally prove the two surfaces correlate.

The transition from a well-developed high-chroma paleosol in the northern part of the study to more poorly developed, low-chroma paleosol to the south indicates more poorly drained conditions to the south. This is also consistent with a longer period of subaerial exposure landward.

Subaerial exposure indicators in some limestone clasts from the valley fill indicate erosion of valley walls that were exposed to subaerial weathering. The valley was filled by locally-derived material in a high-energy tidal environment prior to widespread marine flooding of the shelf.

Rock Lake Shale Sequence Boundary and Incised Valley Fill

Description.-Sequence boundary 2 (Fig. 3) is expressed as a prominent widespread paleosol in the Rock Lake Shale throughout the study area (Joeckel, 1989) with an associated incised valley at Garnett, Kansas (locality C in Fig. 2, Figs 4, 6). In southeastern Nebraska the paleosol is 1 to 1.6-m-thick (Fig. 7) and consists of greenish gray to reddish brown and dark reddish brown claystone to siltstone (Joeckel, 1989). Pedogenic features include a prominent calcrete, glaebules, peds, slickensides, and filled cracks. Pedogenic features also occur in the uppermost Stone Limestone just below the Rock Lake shale, including microkarst and small root traces. The upper surface of the paleosol is marked by an abrupt transition from blocky mudstone to laminated, heterolithic mudstone. In northeastern Kansas the Rock Lake paleosol consists of approximately one meter of low chroma grey, blocky mudstone. Locally, where the paleosol is absent, there is a brecciated zone at the top of the Stoner Limestone.

The only known incised valley associated with this sequence boundary is at Garnett, Kansas (Figs. 4, 6). This small-scale IVF within the Rock Lake Shale Member of the Stanton Limestone is well known for its diverse fossil assemblage of terrestrial plants, arthropods, fishes, amphibians, and reptiles (Reisz et al., 1982). The valley is approximately 11 m. deep and 80 m wide. The IVF can be subdivided into a lower carbonate conglomerate and an overlying succession of fine-grained facies. In the interfluvial area, the widespread marine South Bend Limestone rests unconformably on the Stoner Limestone Member (Woodruff, 1984) (Fig. 4). The incision extends through the underlying members of the Stanton Limestone and Vilas Shale into the Spring Hill Limestone. Polished hand samples from valley walls reveal a weathered zone between unaltered marine limestone and valley-fill facies (Fig 6B). The marine limestone from the valley wall 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 gray color of deeper unaltered rocks.

The conglomerate facies within the lower portion of the Garnett IVF consists of well-rounded limestone, shale, and siltstone lithoclasts identical to facies exposed in the valley walls. Grain truncations and cracking of clasts indicate that the clasts were lithified prior to deposition of the conglomerate. Only rarely were clasts deformed without cracking. Abundant fossils in the conglomerate matrix are the same as those from strata exposed in valley walls. On outcrop the conglomerate is horizontally bedded, and onlaps the valley walls. The upper portion of the conglomerate contains thin interbeds of laminated dark siliciclastic mudstone and bioturbated siltstone, and grades upward into dominantly siltstone and mudstone strata through a decrease in the thickness of limestone beds.

Overlying the conglomerate and valley walls are (upward from the bottom) bioturbated to thin bedded siltstones, and laminated dark gray shales to 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 common clay drapes, and thick-thin couplets and thickness periodicities similar to tidal cycles (Feldman et al., 1993; Archer et al., 1995). Surface features include raindrop imprints, runzel marks, planed surfaces, and tetrapod footprints. Thin (under 5 cm) fossiliferous, conglomeratic to grainstone beds with erosional bases occur throughout the fine-grained facies.

Terrestrial fossils are abundant in the fine-grained facies of the valley fill and many of these fossils are particularly well preserved. Plant fossils, such as conifer needles and fusain, are common throughout the fine-grained facies (Fig. 6E). Other plant fossils include cordaites, seed ferns and rare calamites and ferns (Rothwell and Mapes, 1988).

Interpretation.-The paleosol and incised valley at the base of the Rock Lake Shale is identified as a sequence boundary because the marine limestones from the incised valley walls were subaerially exposed, and because of the Rock Lake paleosol is widespread with marine facies above and below it. This indicates that the entire shelf in the study areas was subaerially exposed, but valley incision was not widespread.

The Rock Lake paleosol is more poorly developed basinward where the area would have been subaerially exposed for a shorter period of time. In Nebraska the paleosol formed under mostly dry conditions as indicated by the reddish colors and the calcrete (Joeckel, 1989).

The Garnett valley was incised into lithified marine limestone as indicated by the subaerial alteration of valley walls, including cracking and crust formation, and by the cracked and abraded limestone clasts that filled the lower part of the valley. The origin of the lowest valley fill facies, the limestone conglomerate, is not well understood because of a lack of diagnostic environmental indicators; examination of polished samples from outcrop and cores did not reveal any fossil-encrusted or bored clasts that might be expected in a fully marine environment, and no cross bedding was observed. Because of lithologic similarities, all the clasts and fossils were likely derived from units exposed in valley walls.

The overlying fine-grained facies were deposited in shallow terrestrial to estuarine environments. The prominence of subaerial exposure indicators in the siltstone and probable tidal cycles indicate an intertidal setting. The abundant well-preserved terrestrial fossils indicate proximity to terrestrial environments on the interfluves, and rapid burial of the fossils. Conifer forests probably existed on interfluves based on the abundance of their remains in the valley fill. Abundant fusain may indicate common forest fires. Marine flooding of the shelf is indicated by the widespread South Bend Limestone Member of the Stanton Limestone.

Upper Lawrence Shale Sequence Boundary and Incised Valley Fill

Description.-The upper Lawrence Shale contains a well-developed paleosol (sequence 7 on Fig. 3) that extends from southeastern Kansas to southeastern Nebraska and southwestern Iowa (Joeckel 1994, 1995). This paleosol is analogous to a modern vertisol and consists of reddish blocky mudstone in which little or no bedding is preserved except in the lowest portions. It contains nested synformal-antiformal slickensides, rare filled soil cracks, and rare pedogenic carbonate. The paleosol is thickest and best developed shelfward where it ranges from 156 to 264 cm thick. Basinward to the south in Kansas it decreases to 100 cm thick and has less well developed soil structures. Also a discontinuous coal is developed on the paleosol in Kansas.

A valley fill associated with this sequence boundary is known from a single exposure near Pomona, Kansas (location B on Fig. 2). This exposure reveals a limestone conglomerate (about 30 cm thick) that is overlain by laminated limestone about 30 cm thick. The laminated facies has abundant plant remains dominated by conifers with less common cordaites, seed ferns, fern foliage, and calamites. Many large well-preserved fronds of *Walchia* are present indicating that the conifers grew on nearby interfluves. Large chunks of fusain (up to 5 cm in diameter) are common on some bedding planes. 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 widespread marine Toronto Limestone.

Interpretation.-The Lawrence Shale paleosol is interpreted as a sequence boundary because it is widespread and records extensive subaerial weathering of marine facies. The decrease in thickness and development of the paleosol southward is likely due to a shorter duration of subaerial exposure closer to the lowstand shoreline (Joeckel, 1994). The slickensides and filled cracks indicate alternate wetting and drying of the soil in a well-drained setting. The coal indicates rising water tables, probably associated with transgression.

The single known exposure of a small incised valley in this intensively studied unit indicates limited local valley incision. The succession of facies and depositional environments of the Lawrence Shale IVF are very similar to those of the Garnett IVF, although the Lawrence Shale IVF is much smaller.

Snyderville Shale Sequence Boundary

Description.-A prominent paleosol in the Snyderville Shale extends from central eastern Kansas to southeastern Nebraska and southwestern Iowa (Joeckel 1994, 1995) (sequence boundary 8 in Fig. 3). This 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, and a few pedogenic carbonate nodules also occur dispersed throughout the paleosol at most localities. In Nebraska there are two partially welded paleosols at some localities. Pedogenic features extend through the Snyderville Shale into the underlying Toronto Limestone, which commonly shows microkarst.

Ball (1964, p. 361-362) reported an exposure of a limestone conglomerate within the Snyderville which we interpret as a small IVF similar to the Vilas IVF. The depth and extent of this IVF are not known.

Interpretation.-The Snyderville Shale paleosol is interpreted as a sequence boundary because of the intense subaerial weathering of underlying widespread marine facies. The paleosol is interpreted as a vertisol that formed in slightly wetter conditions than the Upper Lawrence paleosol, however the intersecting sets of slickensides indicate wetting-drying (or swelling and shrinking) cycles characteristic of seasonal climates and a well-drained setting (Joeckel, 1995). Fluvial incision in the study must have been rare because only a single known exposure of an incised valley has been reported despite extensive investigation of this unit.

Hamilton Incised Valley Fill

Description.-Although this incised valley is not part of the stratigraphic interval in Fig. 3, we include it here because the IVF is remarkably similar to the Garnett IVF and adds to our evidence of climatic impact on sequence boundary formation. This sequence boundary is known only from the valley incision at Hamilton, Kansas (location E on Fig. 2) and has not yet been correlated into interfluvial areas. The sequence boundary is incised into widespread marine units of the lower part of the Topeka Limestone, Calhoun Shale, and Deer Creek Limestone (Fig. 8) (see Cunningham, et al., 1993, for a detailed account of the incised valley and its facies). The north-south-trending incised valley is approximately, 270 m wide, up to 20 m deep and at least 10 km long

The valley fill facies include a lower lithic conglomerate and an upper assemblage of fine-grained facies. The conglomerate consists of limestone, shale, and sandstone clasts similar to facies exposed in valley walls. Other rare clast types are laminated caliche crusts, and fusain. Abraded marine fossils are also common as well as few unabraded, presumably in-place marine fossils (West, 1988). The conglomerate is crossbedded and has abundant cut and fill structures (French et al., 1988). Cross beds are oriented to the southwest and southeast, generally at a low angle to the valley axis.

Overlying the conglomerate are several fine-grained facies, including ostracod wackestone, laminated wackestone, and laminated siliciclastic mudstones. These facies contain abundant and well-preserved terrestrial and aquatic fossils (Mapes and Mapes, 1988; Cunningham, et al., 1993; Schultze, 1996). The fossil assemblage includes plants, terrestrial and aquatic arthropods, fishes, amphibians, reptiles, and rare marine invertebrates. The most common terrestrial animal fossils include cockroaches, other insects, and reptiles. The plant fossil assemblage includes conifers, cordaites, seed ferns, sphenopsids and rare lycopsids (Rothwell and Mapes, 1988). The most common plant fossils are needles of the conifer *Walchia*. In one of the fossil-bearing beds, the laminations form distinctive patterns of thickening and thinning that are interpreted as tidal rhythmites (Cunningham *et al.*, 1993; Feldman *et al.*, 1993; Archer and Feldman, 1994).

Interpretation.-The base of the incision at Hamilton is interpreted as a sequence boundary because of the extent of incision into widespread marine facies, juxtaposition of open marine facies below the boundary with restricted estuarine facies above it, and presence of caliche crust clasts in valley fill that were likely derived from interfluve paleosols. The valley filling history of the Hamilton incised valley is similar to the Garnett incised valley. The lower conglomerate valley fill facies was derived from valley walls and probably deposited in high-energy migrating tidal channels (Cunningham *et al.*, 1993; Feldman *et al.*, 1993). The fine-grained facies was deposited in a low energy tidal, estuarine environment. The high quality of fossil preservation indicates rapid deposition of the fine-grained facies and is characteristic of tidal deposits (Feldman et al., 1993). The plant assemblage indicates that a confer forest grew in the interfluvial areas that were generally well-drained (Rothwell and Mapes, 1988).

SEQUENCE BOUNDARIES WITH LARGE-SCALE INCISED VALLEYS

Tonganoxie Incised Valley Fill

Description.-Within the lower Douglas Group is the large-scale Tonganoxie IVF (Feldman et al., 1995), which is approximately 41 m deep, 11 km wide, and 240 km long, and was fed by 1-km-wide tributary valleys oriented roughly normal to the trunk valley (Fig. 2, sequence 4 on Fig. 3, Figs. 9A,B and 10). Paleosols are not well preserved in interfluvial areas adjacent to the Tonganoxie IVF in southeastern Kansas. Locally in northeastern Kansas a coal rests on the sequence boundary, and from Missouri to Nebraska the sequence boundary occurs at a prominent paleosol that overlies the Iatan Limestone and its stratigraphic equivalents. This paleosol consists of up to 2.5 m of non-calcareous, low chroma, blocky mudstone at resting on the Iatan Limestone in southeastern Iowa (Goebel et al., 1989).

The Tonganoxie IVF was described in detail by Feldman et al. (1995). At the base of the IVF are cross-bedded sandstone and minor conglomeratic facies, which rest unconformably on older marine rocks. Cross bedding in the lower sandstone facies is generally parallel to the valley axis and oriented downdip to the southwest. This facies is overlain by current rippled to burrowed sandstone and mudstone. Upward through the valley-fill facies there is an increase in mud content, burrowing and marine fossils, and a decrease in bedform size. In the upper part of the valley fill current ripples are commonly oriented up-valley. Clasts that are derived from units exposed in valley walls occur only in the lower one to two meters of the valley fill. Most of the coarse-grained facies are composed of quartz sandstone.

Abundant plant fossils are known from an exposure of laminated siltstone that occurs in the upper portion of the IVF near the edge of the valley. The laminated siltstone includes abundant evidence of alternating submergence (current ripples) and subaerial exposure (raindrop imprints) and overlies a rooted coal (Fig. 9A; see Lanier et al., 1993). Abundant plant remains are dominated by fern and seed fern foliage and calamite trunks.

Interpretation.-The widespread paleosol to the north and deep incision of the Tonganoxie incised valley indicate relative lowering of sea level and exposure of the shelf as far south as at least the downdip limit of incision in southeastern Kansas (Fig. 1). Little climatic data can be collected from the paleosol developed on the Iatan Limestone other than extensive vadose weathering of the marine limestone.

The lowest valley fill facies of cross-bedded sandstone to conglomerate is interpreted as a braided stream fluvial deposit (Feldman et al., 1995). Minor's (1969) analysis of the heavy minerals from this facies revealed that the source area for the sandstone fill was probably from the Canadian Shield in the Lake Superior area. Thus, the Tonganoxie valley likely drained a large watershed during a major relative fall of sea level. Large-scale rivers transported the sand long distances down the incised valley. The upward increase in mud drapes, burrow diversity, and the reversal of paleocurrents all indicate tidal estuarine conditions with increasing marine influence upwards.

The laminated siltstone facies in the upper part of the IVF is interpreted as a tidal flat based on the subaerial exposure indicators and well preserved tidal perodicities in bed thicknesses (Lanier et al., 1993; Tessier, et al., 1995). This facies preserves a diverse plant assemblage, but, importantly, the most common plants of the small incised valleys are rare or lacking. The Tonganoxie valley fill includes several coals and plant assemblages dominated by swamp dwellers. This indicates high water tables during filling of the valley.

Vinland Shale Sequence Boundary and Incised Valley Fill

Description.-The Vinland Shale sequence boundary (sequence boundary 5 on Fig. 3) occurs at a paleosol in the Vinland Shale. In Woodson County, the lower meter of Vinland Shale is a paleosol consisting of green-gray blocky mudstone with very small slickensides that are not organized into intersecting sets (Fig. 9D). The top of the underlying Westphalia Limestone is apparently microkarst. Directly above the paleosol is one cm of laminated shale with abundant plant debris, overlain by laminated shale that grades upwards to bioturbated, fossiliferous shale, to limestone of the widespread marine Haskell Limestone. This sequence boundary probably correlates with the Upper Sibley coal and underlying paleosol in northeastern Kansas (Fig. 9C). The Upper Sibley Coal occurs throughout most of northeastern Kansas (Bowsher and Jewett, 1943) and onlaps sequence boundary 4 (of Fig. 3) near the edge of the Tonganoxie incised valley (Feldman et al., 1995). The coal ranges up to 51 cm thick and is underlain by a 2 meters of greenish gray, slickensided, blocky mudstone (Fig. 9C).

Cores and well logs reveal that incisions are locally common in the sequence (e.g. Fig. 11). The IVFs are approximately 20 m thick and 1 to 4 km wide. At the base of the only cored Vinland Shale IVF is a fossiliferous conglomeratic limestone up to 3.6 m thick, which 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 of the fill, and the coals are all in the upper 4.5 m (Kansas City Power and Light Company, 1975).

Interpretation.-The Vinland Shale paleosol and associated incision into underlying open marine facies indicates a relative lowering of sea level. The grey color of the paleosol and common coal indicate poorly drained conditions on the interfluve though the small slickensides may indicate minor episodes of wetting and drying. The facies filling the incised valley are similar to the Tonganoxie valley fill and are similarly interpreted as representing fluvial through estuarine and coal swamp environments. The fill is dominated by sandy facies and not just clasts derived from valley walls. However, limited subsurface data did not allow us to determine if the common valleys link up into a drainage network. This valley is included in the large-scale incised valleys because it is deeper than any of the valleys dominated by limestone conglomerate fills.

Ireland Incised Valley Fill

Description.-The Ireland Sandstone incised valley (sequence 6 of Fig. 3) is poorly understood because of limited exposure and subsurface control. No interfluve paleosol has been identified, but the valley can be mapped based on a deep, sandstone-filled incision in northeastern Kansas. In this area the valley is at least 30 m deep and several km wide (O'Connor, 1960). A few meters of conglomerate is commonly at the base of the valley fill. Most of the valley is filled with cross bedded sandstone. There is an upward increase in mud content.

Above the Ireland incised valley fill in northeastern Kansas is a mosaic of muddy to sandy facies. Small channels approximately one meter thick and a few meters wide are common and contain bimodal current indicators. Tidal rhythmites are well developed in heterolithic facies (Archer, 1994). Coal and plant fossils are common in the shaly estuarine facies and include abundant fern and seed fern foliage, calamite stems, and lycopod trunks. The lycopods are of particular interest because of the general decline that this previously important group had undergone by this time (Phillips, et al., 1985).

Interpretation.-The incision at the base of the Ireland Sandstone is due to a relative lowering of sea level because fluvial facies of the lowest Ireland Sandstone unconformably rest on open marine facies of the Robbins Shale. The IFV facies are interpreted as representing fluvial, estuarine and coal swamp environments. Marine influence increases upwards throughout the valley fill and overlying facies. The upper muddy facies were deposited in a mosaic of nearshore to estuarine facies. The small channels are interpreted as tidal channels developed on muddy tidal flats. The plant assemblage, dominated by swamp dwellers, and the coals, indicate generally high water tables.

DISCUSSION

Climate had a dramatic impact on the expression of sequence boundaries including the types of paleosols, the sizes of incised valleys, and the nature of the valley fill facies in Upper Pennsylvanian sequences in eastern Kansas. The key to being able to interpret climate is based on analysis of the paleosols from interfluves and on plant assemblages from the IVFs. Drier conditions are interpreted for IVFs associated with vertisol-like paleosols. These paleosols have organized sets of slickensides, contain pedogenic carbonate, and usually exhibit high chroma values. 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. High chroma values of most of the paleosols generally resulted from oxidation of iron in the vadose zone, also indicating that water tables were low. These paleosols are interpreted to have formed in generally well-drained vadose conditions with no areas of ponded fresh water where coals could have developed except during transgression.

The incised valleys that are laterally associated with these vertisol-like paleosols tend to be generally under 1 km wide and under 20 m deep and cannot be traced very far suggesting small, local drainage networks. The small size of these IVFs probably also reflects incision into lithified limestone for some of the valleys. The valley fills are overwhelmingly dominated by locally-derived limestone conglomerate facies. In most cases the source of the limestone clasts can unambiguously be identified as the host rock exposed in valley walls. However, the depositional environments of the conglomeratic facies are not certain; high-energy settings could be associated with either tidal or fluvial systems. Some of the conglomerates appear to have been reworked in tidal environments during flooding of the valleys as indicated by bimodal paleocurrents parallel to valley axes.

The small incised valleys commonly include an upper fine-grained facies deposited in low-energy estuarine environments. Overlying the conglomerate facies at Hamilton, Garnett (sequence 2), and Pomona (sequence 7) is a fine-grained laminated facies with well-preserved fossils. Mud drapes and rare couplets indicate tidal influence. Tetrapod footprints and other subaerial exposure indicators in the Garnett IVF indicate intermittent subaerial exposure, possibly in an intertidal environment.

Plant assemblages from these IVFs are dominated by conifer remains, interpreted to have inhabited well-drained settings. Rothwell and Mapes (1988) determined the plant communities that inhabited interfluves of the valleys at Garnett, Pomona (sequences 2 and 7 of Fig. 3) and Hamilton to be dominated by seed bearing plants, mostly walchian conifers and less commonly cordaites and seed ferns. These plants are not common in coal swamps, and the walchian conifers, in particular, are interpreted as xerophytic (Rothwell and Mapes, 1988).

Conversely, wetter conditions are interpreted for the larger incised valleys (sequences 4, 5, and 6 on Fig. 3) mostly because of the types of interfluve paleosols, the larger drainage networks, and the type of fossil plant assemblage. 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 intersecting sets characteristic of vertisols. The Vinland Shale sequence boundary (sequence 5 of Fig. 3) has a widespread coal resting on the paleosol toward the north (Fig. 9C). Low chroma paleosols and coals are indicative of a poorly drained landscape with high water tables. And the plant fossil assemblages from throughout these valley fills are dominated by fern-type foliage, seed ferns, and sphenopsids with rare lycopods, which are interpreted as swamp dwellers (Gastaldo, 1987; DiMichele and Philips, 1994).

The valleys interpreted as forming in wetter environments are large, generally several km wide and at least 20 m deep. The valleys are filled mostly with sediment derived from distant source areas reflecting large watersheds. Locally derived limestone conglomerate occurs only in the basal few meters of these IVFs and is overlain by thick successions of mature sandstone. Lower fluvial sandstone and conglomerate is overlain by sandy to muddy estuarine facies with common tidal indicators. Rooted coals show that coal swamps developed during filling of the valleys.

Factors other than climate had only a limited impact on the expression of these sequence boundaries. Unlike many Carboniferous basins, the effects of local tectonics were minimal and can be excluded as a significant variability-producing factor. Relative changes of sea-level were a major control on the sequence stratigraphy; however, the general magnitude and duration of the glacio-eustatically driven sea-level changes does not appear to have been the major factor in depth of valley incision; for all the sequences the lowstand shore line was probably basinward of the study area, although the lowstand shorelines are difficult to fully document. The transgression following the IVFs tends to be larger for the smaller valleys than the larger valleys (Heckel, 1986) suggesting that the smaller IVFs were associated with larger magnitude sea-level fluctuations. One locally important factor affecting valley size may be the substrate that was incised. Most of the smaller valleys are incised into limestone, which is much more resistant to erosion than the marine shales into which the larger valleys are incised. The smaller-scale valleys also formed only a few small drainage networks as indicated by the few known outcrops of these valleys despite intensive study of the section by many geologists. Climate is still the best explanation for the range of observations we have documented for these sequence boundaries.

We have documented a dramatic range of expression of sequence boundaries including the size and extent of valley incision. Clearly valley depth and the types of facies in the valley fill are not directly related only to sea level history. These observations raise many interesting questions of variability in the rates of large-scale geomorphic denudation, which we have only just begun to explore.

CONCLUSIONS

Nine Pennsylvanian sequence boundaries and associated incised valley fills were studied along the outcrop belt in eastern Kansas to northwestern Missouri and adjacent portions of Iowa and Nebraska. All of the sequence boundaries formed during large regressions that exposed vast areas of the midcontinent. The range of expression of the sequence boundaries can best be explained by differences in lowstand climates. Sequence boundaries that are interpreted to have formed during drier climates have high-chroma paleosols with well-developed slickensides and common pedogenic carbonate. These features indicate a well-drained landscape with low to seasonally fluctuating water tables. Plant assemblages preserved in incised valley fills are dominated by gymnosperms, mostly xerophytic walchian conifers. The incised valleys are small (under 20 m deep) and filled with locally-derived detritus eroded from adjacent valley walls.

Sequence boundaries that are interpreted to have formed in wetter environments have low-chroma paleosols. Coals occur on some interfluve paleosols and in valley fills reflecting high water tables. Plant assemblages from incised valley fills are dominated by fern-type foliage, seed ferns, and sphenopsids, which are commonly associated with more poorly drained conditions. The incised valleys associated with these sequence boundaries are large (over 20 m deep) and filled mostly with distantly sourced mature sandstone reflecting large watersheds.

Although relative lowering of sea level caused valley incision, sea level history alone cannot explain the range of incised valley fills and expression of sequence boundaries in interfluvial areas. Some of the smaller incised valleys are associated with the largest amplitude sea level fluctuations. Also tectonics was not a major influence because the area was, in general, tectonically stable. Some of the size differences in the incised valleys may be due to the types of rock being incised, however, the range of observations all indicate major climatic differences between the larger and smaller-scale incised valleys.

This study documents that sequence boundaries and incised valley fills preserve information on climates, even in successions dominated by marine facies, and that climate varied from sequence to sequence in the study area. We have also shown that there were important differences between the types of facies preserved in incised valley fills that formed in wetter vs.

drier climates. This has direct implications for understanding reservoir distribution in incised valleys.

ACKNOWLEDGMENTS

Research related to this study was performed in conjunction with several projects. The general understanding of estuarine facies and delineation of incised valleys related to fossil-rich sites, such as the Garnett and Hamilton incised valleys, was funded by the National Science Foundation (Grant EAR-9018079). Coring of the Douglas Group was supported by the National Science Foundation (Grant EAR-9405123). Earlier work on the Lawrence Shale (Douglas Group) was supported by the Kansas Department of Transportation (Grant K-TRAN: KSU-91-6). Various aspects of the field work were supported by Kansas State University and the Kansas Geological Survey. Ongoing collaborative work has greatly assisted our current understanding of the depositional systems. In particular, we have greatly benefited from interactions with Martin Gibling on Douglas Group sedimentology, and Lynn Watney on stratigraphic relationships. We are grateful to P. Heckel and R. Flores for their reviews, which significantly improved this paper. This paper is dedicated to the memory of William P. Lanier.

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FIGURE CAPTIONS

Figure. 1. Generalized paleogeography during Late Pennsylvanian time showing approximate maximum highstand and lowstand shorelines for the Douglas Group (modified from Archer and Feldman, 1995 and Moore et al., 1951).

Figure. 2. Map showing extent of Tonganoxie incised valley (exposed only where it intersects the Douglas Group outcrop belt in northeastern Kansas) and localities referred to in text. **A)** Small-scale incised valley in the Vilas Shale described by Cunningham and Franseen (1992); **B)** Small-scale incised valley in the upper Lawrence Shale near Pomona, Kansas; **C)** Small-scale incised valley near Garnett, Kansas; **D)** Large scale incised valley in the Vinland Shale (known only from subsurface cores and well logs); **E)** Small-scale Hamilton incised valley in Calhoun Shale.

Figure. 3. Generalized stratigraphy in northeastern Kansas of strata referred to in text. Numbers refer to sequences mentioned in text, and sequence boundaries are named for the overlying sequence. Sequence boundary 3 is basinward of the lowstand shoreline for this area. Sequences 1, 2, 7 and 8 contain small incised valleys, whereas sequences 4, 5, and 6 contains large, sand-filled incised valleys.

Figure. 4. Cross section of small-scale incised valley fill (shaded area) at Garnett (sequence 2 in Fig. 3) based on cores.

Figure 5. Cross section of the small, conglomerate-filled incised valley in the Vilas Shale (locality A in Fig. 2). The position of the interfluve sequence boundary is not clear. Data from Cunningham and Franseen (1992).

Figure. 6. Photographs of features associated with the small-scale Garnett incised valley. **A)** Outcrop of Garnett incised valley near Garnett. The staff rests against overlying South Bend Limestone. The sloping surface at left is valley wall cut into underlying Stoner Limestone. Mudstones of upper valley fill were excavated for articulated pelycosaurs. Divisions on staff are 15 cm. **B)** Polished hand sample cut out from valley wall showing yellowish brown areas (dark in the photograph). The host rock is brecciated (see arrow) and there is a laminated crust in the upper part. Scale bar is one cm. **C)** Core (with top on upper left) showing basal conglomerate of valley fill and sequence boundary (arrow) upon phylloid algal facies of upper Plattsburg Limestone. Scale bar is 5 cm. **D)** Contact of valley fill with overlying South Bend Limestone. Note that sandy oolitic limestone is piped down into a burrow in valley-fill mudstone. Scale bar is two cm. E. Frond of the conifer *Walchia* from laminated mudstones of upper part of valley fill. Scale bar is two cm.

Figure 7. Paleosol in the Rock Lake shale in southeastern Nebraska. The top of the paleosol is near the base of the Stoner Limestone, which forms the ledge over the scale rod. The scale rod rests on a calcrete horizon within the paleosol. The arrow denotes the top of the South Bend Limestone. Scale rod is 1 m. Modified from Joeckel (1989).

Figure. 8. Cross section of the Hamilton incised valley fill based on cores and outcrops in the area of the fossil excavations. Modified from Cunningham et al. (1993).

Figure. 9. Photographs of features associated with large scale incised valley fills. **A)** Outcrop of edge of the Tonganoxie trunk valley. Coal rests on sequence boundary (arrow), above which is laminated siltstone deposited in a tidal flat. The siltstone encases upright trees and abundant fern fossils. **B)** Outcrop near middle of Tonganoxie incised valley showing basal facies of cross bedded sandstone and conglomerate. The sequence boundary is at base of outcrop. Divisions on staff are 15 cm. **C)** Photograph of Upper Sibley coal (black, lower center) from core in northeastern Kansas. Paleosol beneath the coal consists of blocky mudstone with slickensides extending down to just above 58-ft mark. This coal presumably rests on the same sequence boundary at base of the IVF in Fig. 9. Scale bar is 5 cm. **D)** Outcrop of interfluvial paleosol in lower part of Vinland Shale (sequence 5 of Fig. 3) in Woodson Co. Paleosol consists of greenish grey blocky mudstone; top of paleosol is in middle of photograph.

Figure. 10. Well-log cross section of Tonganoxie incised valley. For location of cross section see Feldman et al. (1995), from which this figure is modified.

Figure. 11. **A)** Cross section through incised valley fill (shaded area) in Vinland Shale in subsurface of Coffee Co., Kansas, based on core descriptions and photographs in Kansas City Power and Light (1975). Other sequence boundaries in this cross section are not shown. **B)** Map showing location of section shown in A and isopach map (in meters) of Vinland Shale (interval between sequence boundary and Haskell Limestone). Note other possible tributary valley to southwest. Most of this thickness consists of lowstand incised valley-fill deposits, but it probably also includes some transgressive deposits above valley fill because the Haskell limestone does not everywhere rest directly on top of lowstand systems tract. Dots indicate data points from cores (from Kansas City Power and Light, 1975) and wireline well logs.

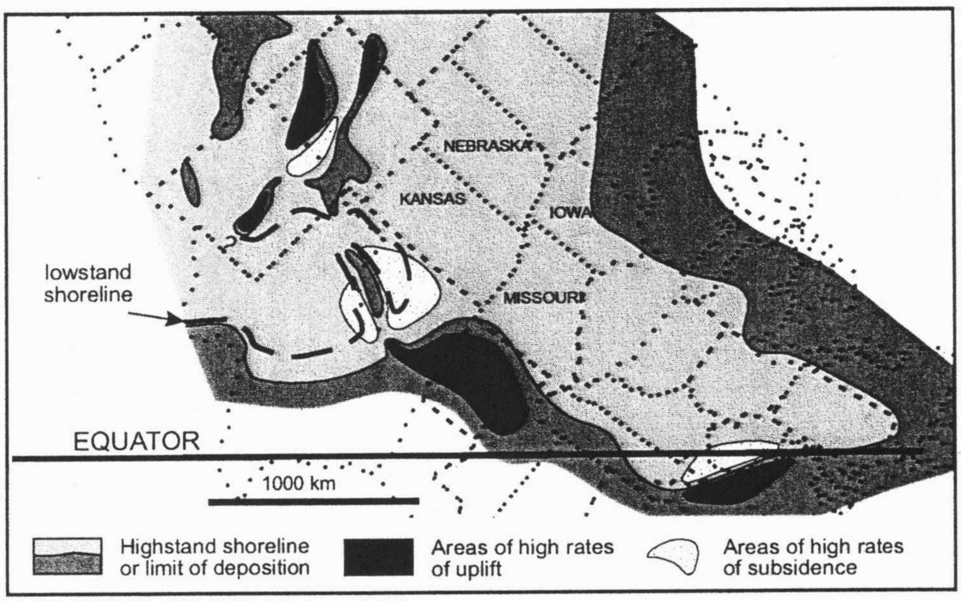

NEBRASKA
KANSAS
IOWA
MISSOURI
lowstand shoreline
EQUATOR
1000 km
Highstand shoreline or limit of deposition
Areas of high rates of uplift
Areas of high rates of subsidence

Fig. 1

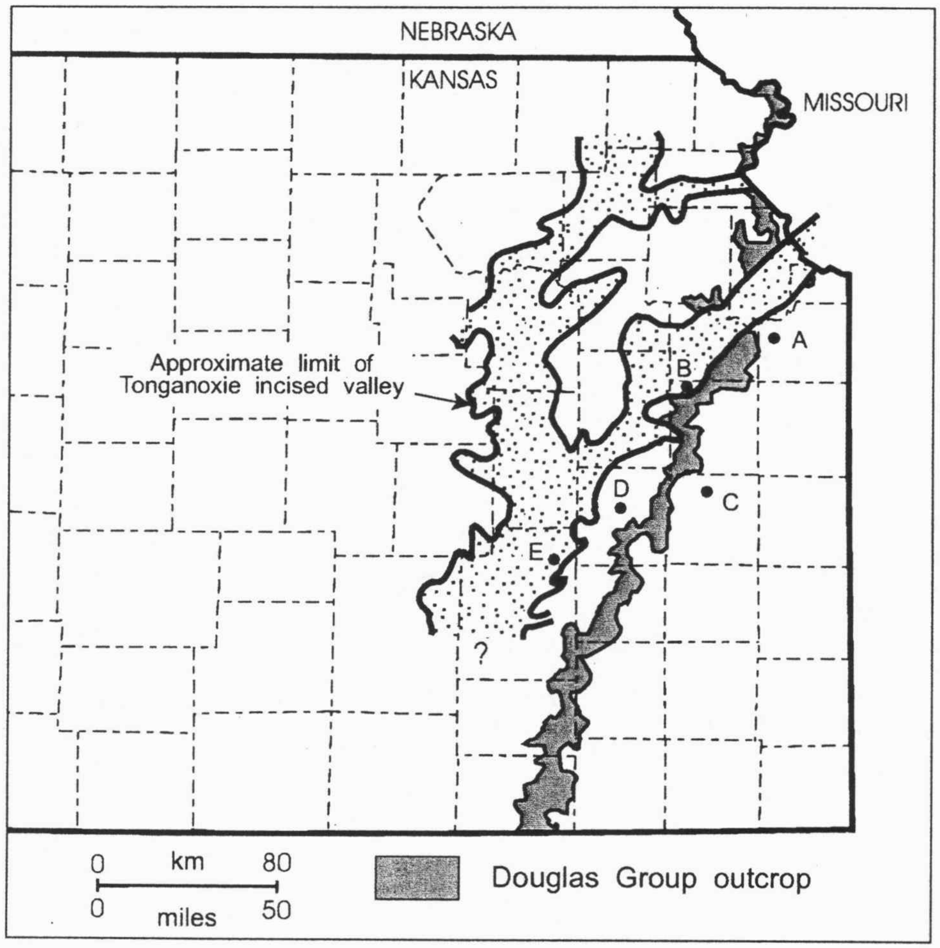

NEBRASKA
KANSAS
MISSOURI
Approximate limit of Tonganoxie incised valley
A
B
C
D
E
?
0 km 80
0 miles 50
Douglas Group outcrop

Fig. 2

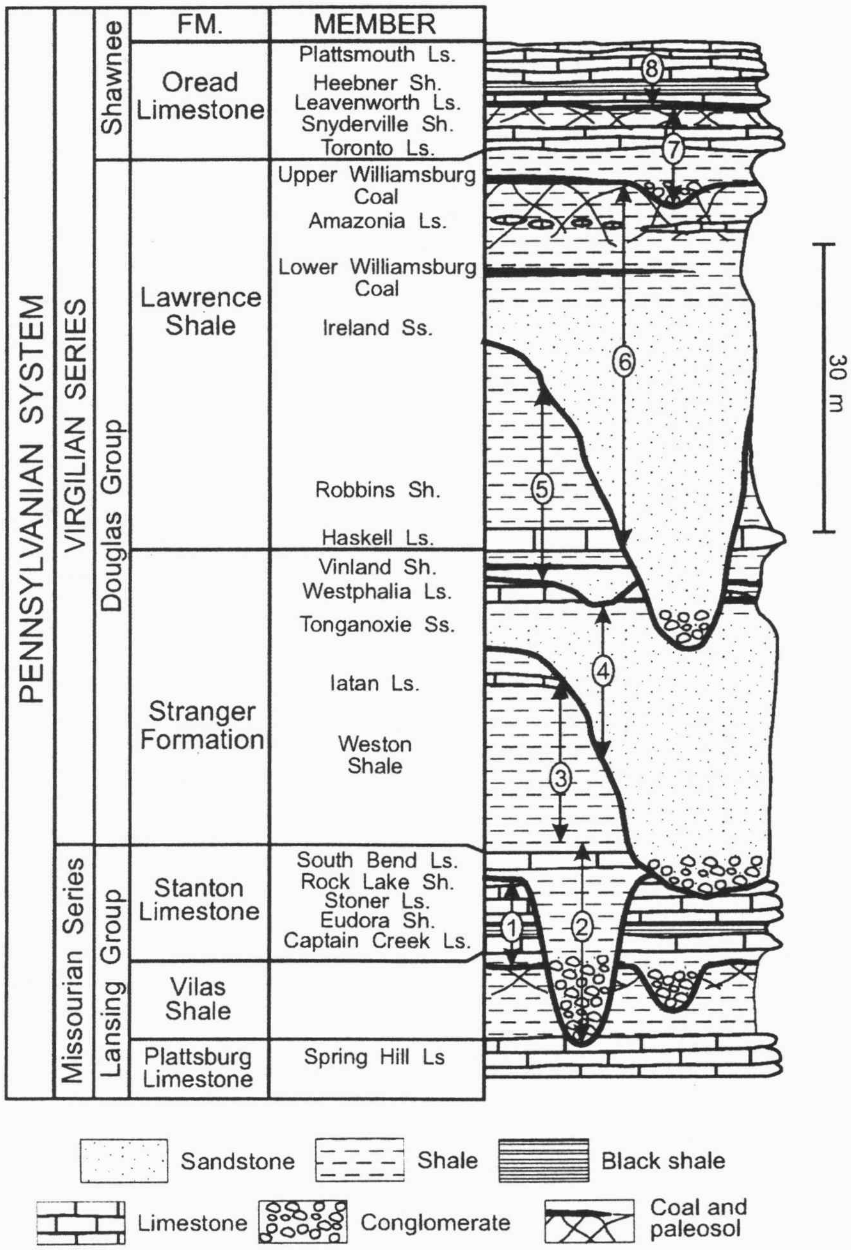
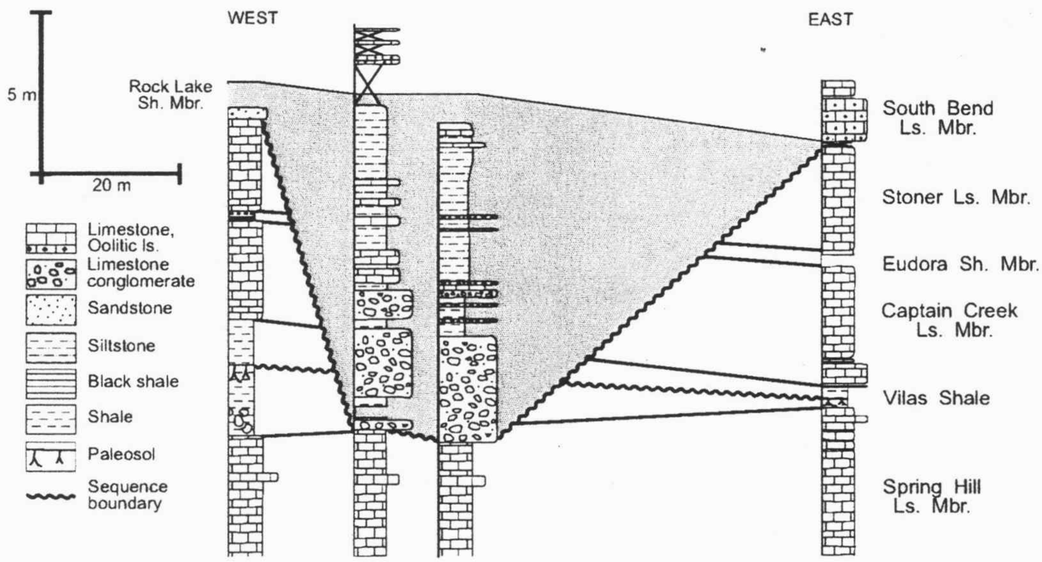

PENNSYLVANIAN SYSTEM
VIRGILIAN SERIES
Missourian Series
Shawnee
Douglas Group
Lansing Group
FM.
MEMBER
Oread Limestone
Plattsmouth Ls.
Heebner Sh.
Leavenworth Ls.
Snyderville Sh.
Toronto Ls.
Lawrence Shale
Upper Williamsburg Coal
Amazonia Ls.
Lower Williamsburg Coal
Ireland Ss.
Robbins Sh.
Haskell Ls.
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
1
2
3
4
5
6
7
8
30 m
Sandstone
Shale
Black shale
Limestone
Conglomerate
Coal and paleosol

Fig 3



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

Fig. 4

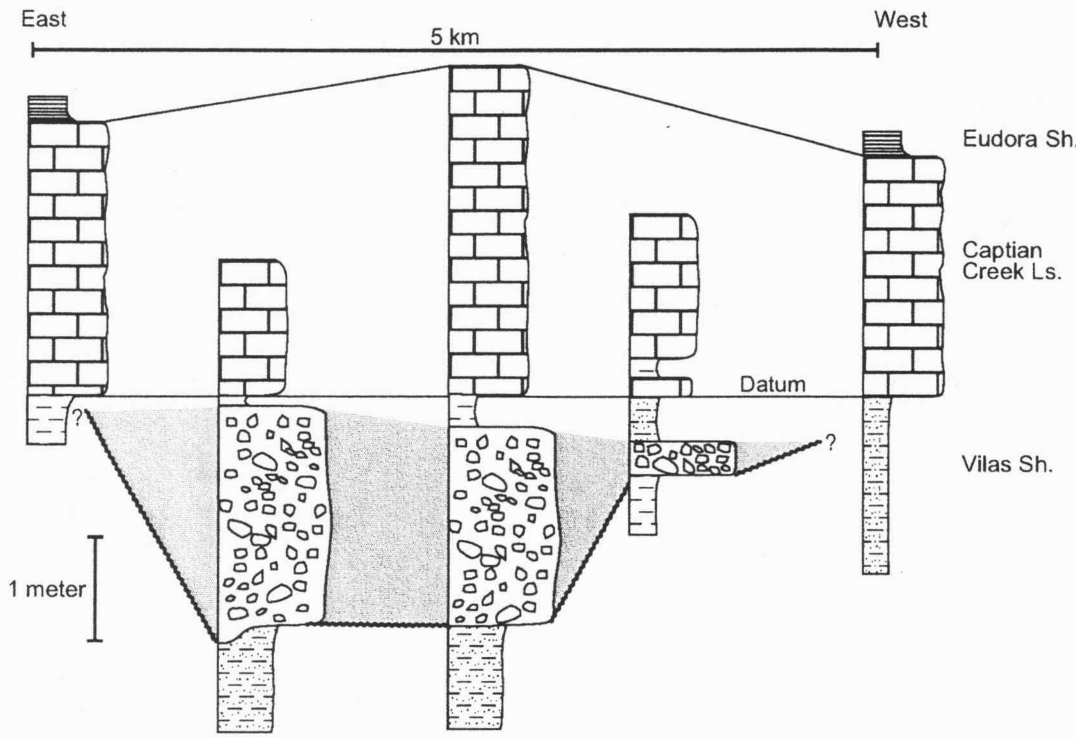

East
5 km
West
Eudora Sh.
Captian
Creek Ls.
Datum
?
?
Vilas Sh.
1 meter

Fig. 5

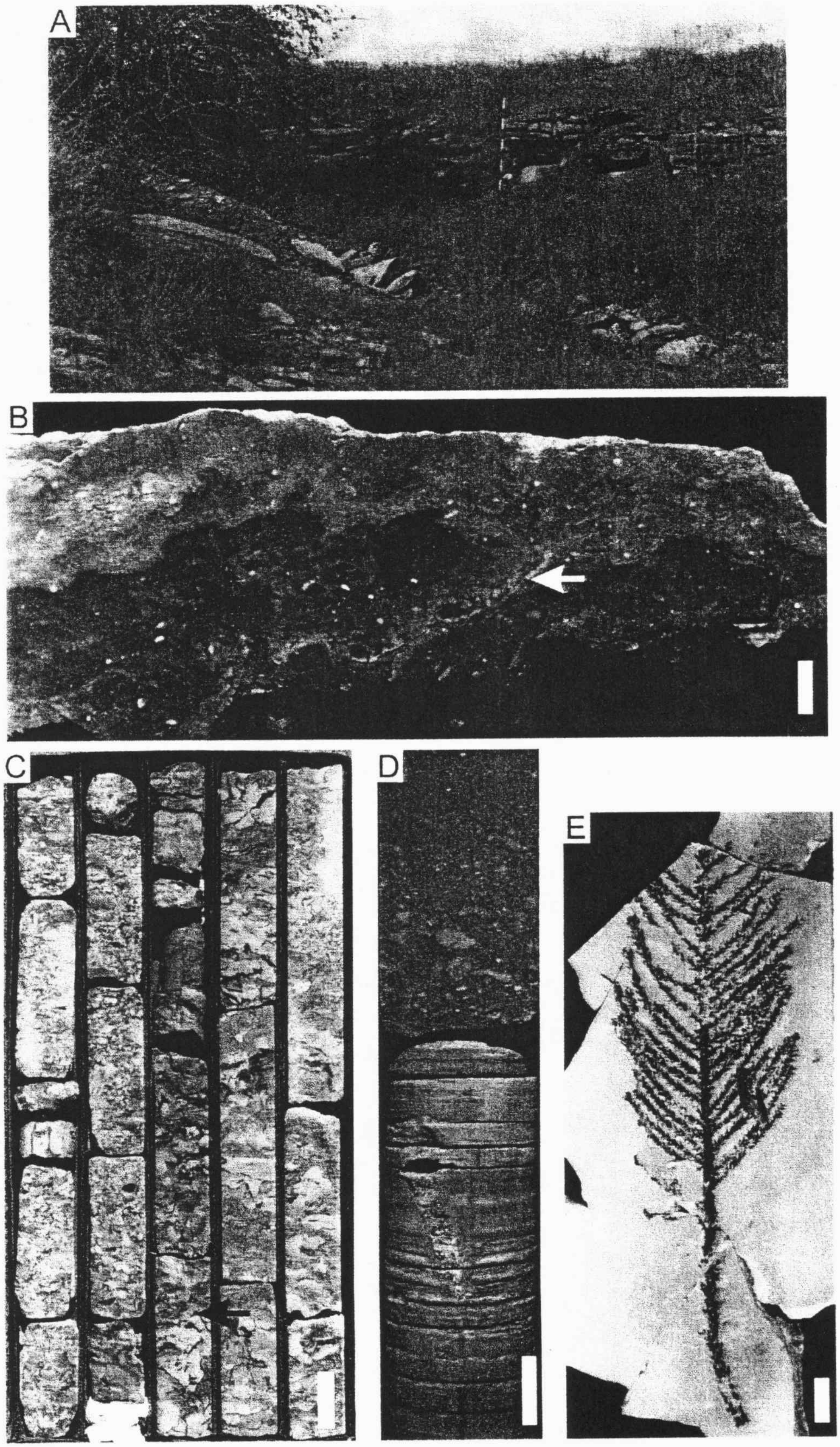


Fig. 6

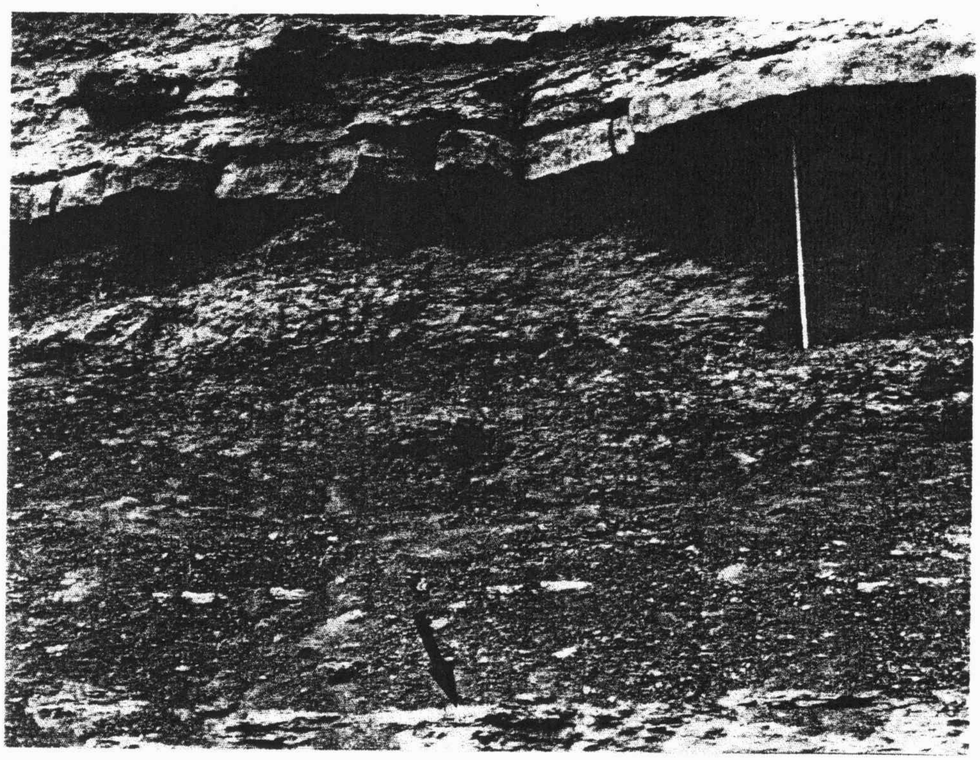


Fig. 8 7

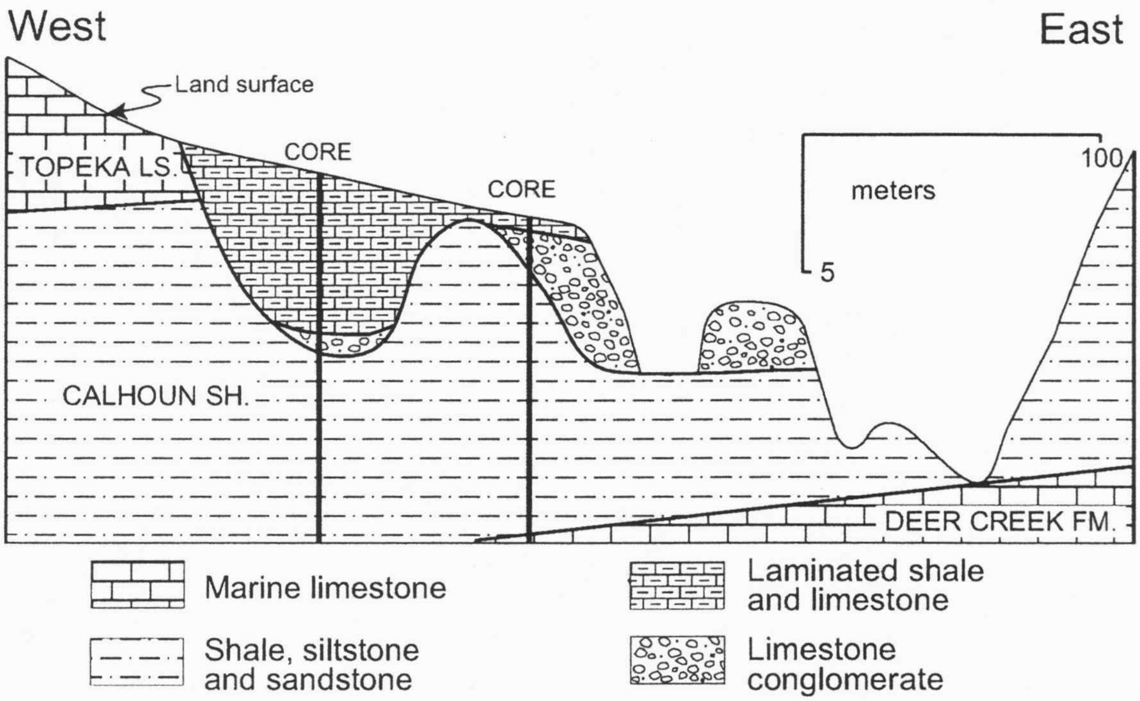

West
East
Land surface
CORE
CORE
TOPEKA LS.
meters
100
5
CALHOUN SH.
DEER CREEK FM.
Marine limestone
Laminated shale and limestone
Shale, siltstone and sandstone
Limestone conglomerate

Fig. 8

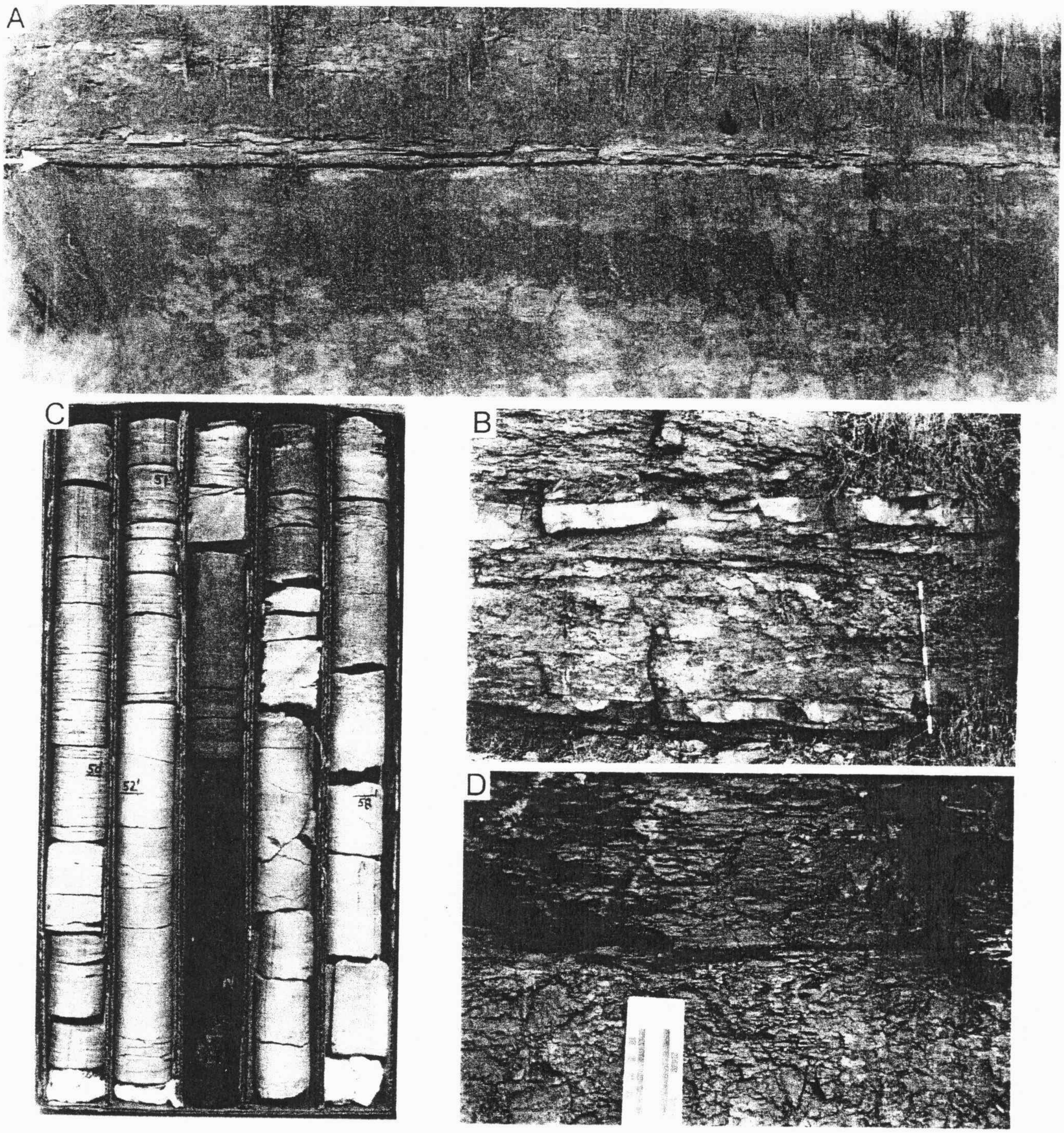


Fig. 9

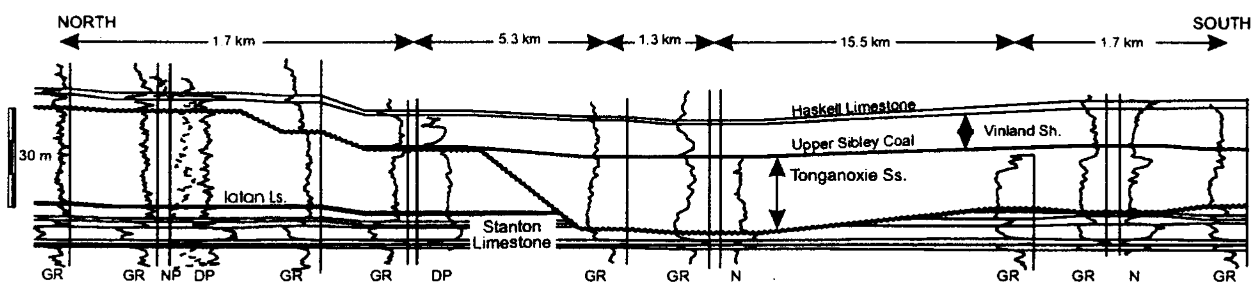
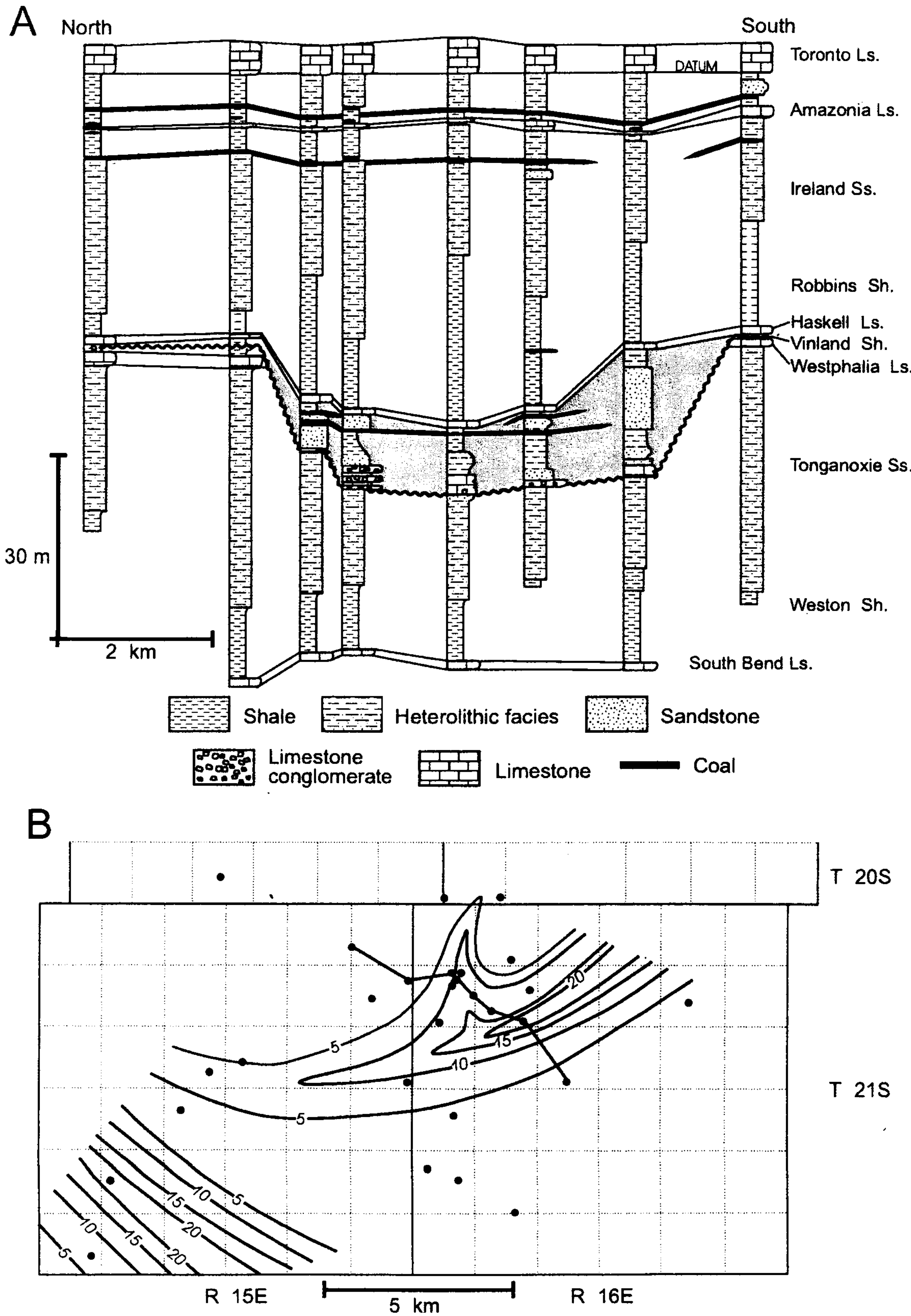

NORTH
SOUTH
1.7 km
5.3 km
1.3 km
15.5 km
1.7 km
30 m
Haskell Limestone
Vinland Sh.
Upper Sibley Coal
Tonganoxie Ss.
Iatan Ls.
Stanton
Limestone
GR
GR
N
DP
GR
GR
DP
GR
GR
N
GR
GR
N
GR

Fig 10



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

Fig. 11