Cataclysmic burial of Pennsylvanian Period coal swamps in the Illinois Basin: Hypertidal sedimentation during Gondwanan glacial melt-water pulses

ALLEN W. ARCHER*†, SCOTT ELRICK‡, W. JOHN NELSON‡ and WILLIAM A. DIMICHELE§

† *Department of Geology, Kansas State University, Manhattan, Kansas, 66506, USA*
‡ *Illinois State Geological Survey, Champaign, Illinois, 61820, USA*
§ *Department of Paleobiology, NMNH, Smithsonian Institution, Washington, D.C., 20560, USA*
* *E-mail: aarcher@k-state.edu*

ABSTRACT

Roof facies of widespread, Pennsylvanian Period, economically important coals in the Eastern Interior Coal Basin (Illinois Basin) commonly exhibit evidence of extensive and cataclysmic tidal sedimentation during rapid marine-flooding events. Upright Trees and smaller plants were covered and entombed by swiftly deposited, thin-bedded and laminated mud and sand. This facies has historically been interpreted as fluvial-style cross bedding. Detailed examination clearly shows that these facies consist of inclined heterolith stratifications (IHS). Entire forests of upright trunks have been documented in the roof strata of surface and underground coal mines. Detailed sedimentological analyses of mine-roof facies indicate a pervasive and significant tidal influence. In some cases, daily and semi-monthly tidal periods have been preserved within laminated facies ('tidal rhythmites'). Based upon modern analogues, the tidal facies are indicative of hypertidal conditions. The hyper-dynamic tidal regime resulted in rapid sediment accumulation, particularly along pre-existing drainages within the ancient coastal swamp. Stratigraphic successions indicate a recurring pattern of very rapid change from widespread coal-swamp conditions to tidally-influenced deposition. The repetition of these stratigraphic phenomena throughout the Pennsylvanian Period suggests significant external controls on sea-level, probably related to Gondwanan deglaciations and resultant large-scale meltwater pulses. Despite the rapid changes of sea-level rise, the hypertidal depositional dynamics resulted in conditions whereby inundated coastal forests were buried by tidally influenced sedimentation.

Keywords: Pennsylvanian, coal swamps, hypertidal sedimentation, Illinois Basin, Gondwana glaciations, melt-water pulses, Holocene.

INTRODUCTION

Objectives and study area

The objectives of this research include the documentation of the common occurrence of upright plants within shale-rich lithofacies that directly overly coals. From a sedimentological perspective, very rapid generation of accommodation space would apparently be required to preserve rapid plants. Lacking clearly defined modern analogues, the authors suggest that the deglaciations and meltwater surges during the Late Cenozoic Era (Pleistocene and Neogene Epochs) might contain meaningful 'modern' analogues.

Pennsylvanian Period coal forests, in terms of taxonomic composition, diversity and long-term dynamics, lack clearly-defined modern counterparts (Falcon-Lang & DiMichele, 2010). These palaeoforests were unique in the history of the Earth's terrestrial vegetation and were amongst the most globally extensive terrestrial ecosystems in Earth history (DiMichele *et al.*, 2001).

Contributions to Modern and Ancient Tidal Sedimentology: Proceedings of the Tidalites 2012 Conference, First Edition. Edited by Bernadette Tessier and Jean-Yves Reynaud.

Extensive coal-mining activity in the U.S. and Europe has resulted in numerous exposures for study and analysis. Within the Illinois Basin area of the east-central U.S. (Fig. 1) mining of bituminous coal began circa 1820 and became an important industry by 1880. Today, it remains a key component of electrical-power generation worldwide. Due to the economic incentive to core-drill and excavate Pennsylvanian coal-bearing strata, we may know more about these terrestrial ecosystems than any others in Earth history. However, there remain many enigmas, such as upright palaeoforests, that have yet to be completely explained.

'Cyclothem' models

Pennsylvanian coal measures in the U.S. midcontinent contain lithostratigraphic units that in most cases have a very high degree of vertical repetition and lateral continuity. More precisely, many thin Pennsylvanian beds of underclay (palaeosols), coal, black-sheety shale and limestone exhibit great lateral persistence throughout and between major basins, such as the Appalachian Basin to the east and Forest City Basin to the west (Wanless & Weller, 1932; Archer & Greb 2011).

A generalised model of cyclical sedimentation, the 'cyclothem,' was initially developed in Illinois Basin (Weller, 1930, 1931) and subsequently applied to other areas, particularly in Kansas (Moore, 1935, 1964). Despite the seeming elegance of the cyclothem model, the concept has never been statistically or numerically verifiable (Zeller, 1964; Wilkinson, *et al.*, 2003). The model was used to define formations in Illinois during the 1940s and 1950s. Today, neither the Illinois nor the Kansas geological surveys retain the cyclothem concept as a part of formal lithostratigraphic nomenclature.

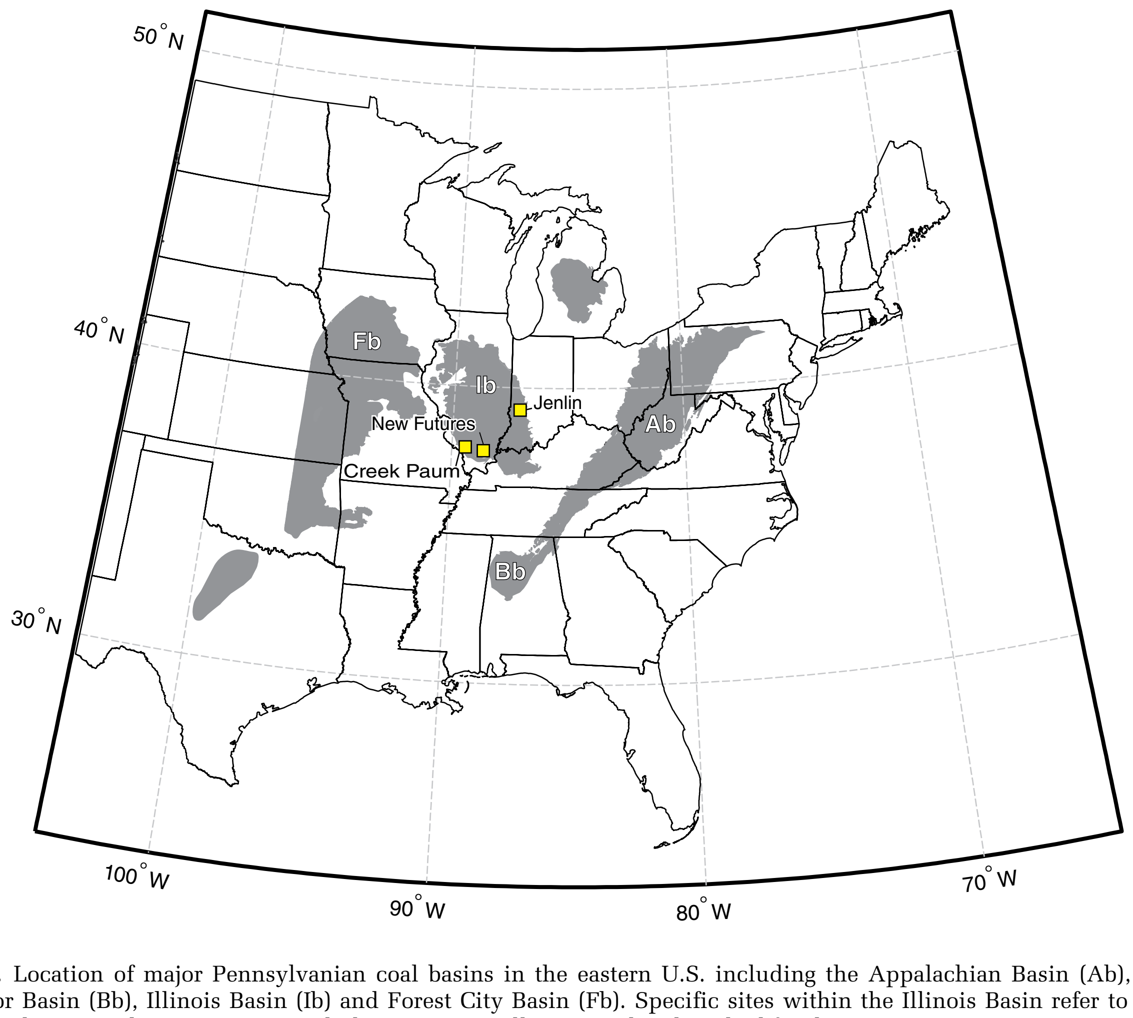

Fig. 1. Location of major Pennsylvanian coal basins in the eastern U.S. including the Appalachian Basin (Ab), Black Warrior Basin (Bb), Illinois Basin (Ib) and Forest City Basin (Fb). Specific sites within the Illinois Basin refer to active mines where upright trees are particularly common, well preserved and studied for this report.

As there are difficulties in defining and mapping 'cyclothems,' the concept should only be used informally (Kosanke *et al.*, 1960; Archer, 2008).

Coals

The stratigraphic succession encompassing the major economic coals of the Illinois Basin is the Desmoinesian Series of the Pennsylvanian System (Fig. 2). The Desmoinesian corresponds to the upper Moscovian and lower Kasimovian stages in the international time scale (Granstein *et al.*, 2012). Although coal beds ranging from Chesterian through Virgilian age have been mined in the Illinois basin, over 95% of resources and historic mining lie within the Desmoinesian Series. Within the Illinois Basin the major coals are of moderate thickness (typically 1 to 3 metres) but are regionally extremely extensive. Many coal beds can be traced with certainty from the Illinois basin into the Forest City basin (easternmost Kansas and environs) and probably into the northern Appalachian basin. In particular, the Herrin and Springfield coals are particularly widespread (Greb *et al.*, 2003).

Siliciclastic units

There two basic types of shale that directly overlie coal beds. This includes very black shale or shale that exhibits lighter-coloured shades of grey. The black, highly fissile phosphatic shale is commonly associated with thin limestone beds and both of these lithofacies can be very laterally continuous. This type of shale has been informally described as 'slate-like' or 'sheety' because it readily breaks into thin lamina and beds. Overall thicknesses of these units are rarely greater than 2 m and vertebrate and invertebrate faunas indicate widespread marine influences (Zangerl & Richardson, 1963). Some common fossils include the scallop *Dunbarella*, the inarticulate brachiopods *Lingula* and *Orbiculoidea*, occasional nautiloids and also fish remains, particularly sharks. Abundant conodonts provide a useful biostratigraphic framework. Within the subsurface, elevated amounts of radioactive elements yield a strong gamma-log response in the geophysical logs of black shale. Thus, the black shales are important for regional biostratigraphic and lithostratigraphic correlations. Many black shale units are so confidently correlated (e.g. Anna, Excello) that they carry the same name throughout the Illinois and Forest City basins.

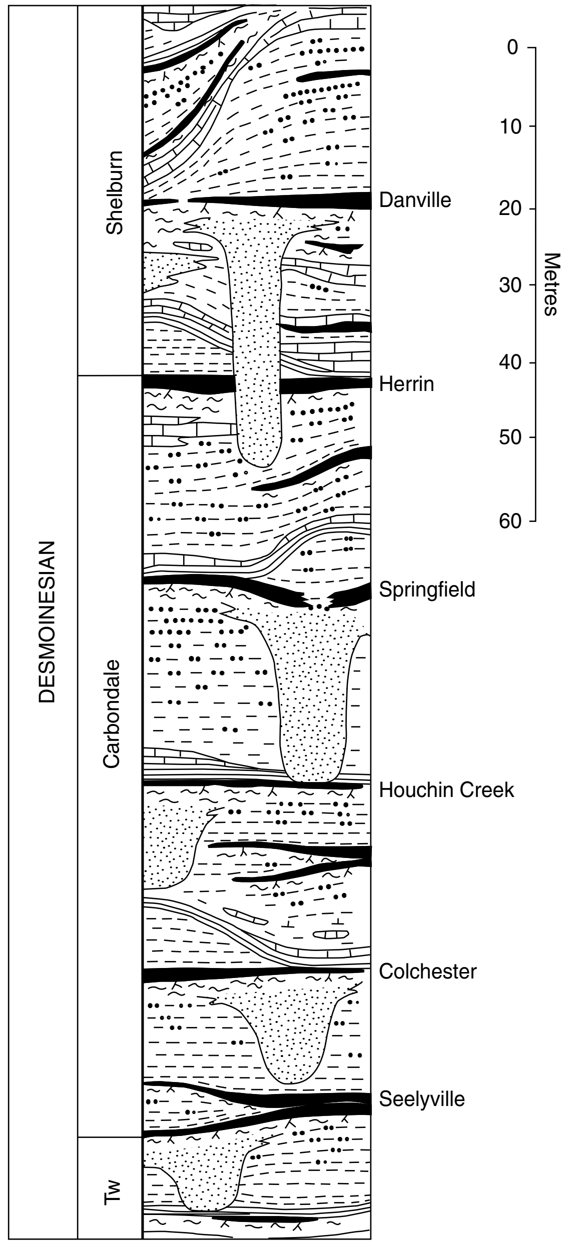

Fig. 2. Stratigraphic diagram showing positions of major coals and associated grey-shale wedges (tongue-like channels). Scale in metres.

At the other end of the shale spectrum, gray-shale units also include siltstone and sandstone. This lithofacies has been termed a 'gray shale wedge' (GSW) and, as compared to black shale, exhibits a much higher degree of lateral and vertical variability (Wanless, 1964). GSW facies are thickest adjacent to major river drainages that were contemporaneous with the widespread peat swamps (Hopkins, 1968; Gluskoter & Hopkins, 1970; Allgaier & Hopkins, 1975). GSWs are the most important factor in coal quality and thickness. Thicker coal seams, overlain by more than 6 m-thick GSW, are lower in sulphur (1 to 2%) when compared to the usual levels of sulphur (3 to 5%) that occur in coal beds overlain directly by black shale. This pattern has been documented within several coal seams but most thoroughly for the Colchester, Springfield and Herbrin Coals (Hopkins 1968; Gluskoter & Simon, 1968, Gluskoter & Hopkins, 1970; Allgaier & Hopkins, 1975; Kvale & Archer, 1990).

Sequence stratigraphy

A prominent regional unconformity separates the older Mississippian System from the overlying Pennsylvanian strata in the Illinois Basin. A sub-Pennsylvanian unconformity is present in most places across the North American craton (Bristol & Howard, 1971, 1974).

GSW and the associated lateral lithostratigraphic variability were initially interpreted as the product of a terrestrial environment of deposition. This was related to the lack of obvious marine fossils and the common occurrence of well-preserved plant fossils. The progressive development of incised, valley-fill (IVF) models as well as tidal-estuarine models in the 1980s provided an alternative depositional model (Dalrymple *et al.*, 1991, 1994, 2012; Archer & Kvale, 1993; Archer *et al.*, 1994; Archer & Feldman, 1995; Nelson *et al.*, 2002).

IVF models helped to explain the localised deposition within sub-Pennsylvanian valleys first noted by Bristol & Howard (1974) and also served to explain the GSWs initially described by Wanless (1964). Owing to concurrent palaeoglacial-eustatic flux, IVFs appear to be particularly common in the late Palaeozoic (Falcon-Lang, 2004; Falcon-Lang & DiMichele, 2010). Sites of abundant, well-preserved and diverse fossils, in many cases, can be related to IVF erosion and subsequent deposition (Feldman *et al.*, 1993). Similar features termed 'incised channel fills' have also been described (Falcon-Lang *et al.*, 2009).

OBSERVATIONAL DATA SUPPORTING CATACLYSMIC BURIAL

Recognition of tidal sedimentation within GSWs

In the late 1980s and early 1900s, cyclic ('tidal') rhythmites were described from GSWs exposed within coal mines in south-central Indiana (Kvale *et al.*, 1989; Kvale & Archer, 1990; Archer & Kvale, 1993; Batemann, 1992) and north-eastern Illinois (Kuecher *et al.*, 1990). These include essentially planar to low-angle, heterolithic rhythmites (Fig. 3A) that consist of low-angle, thinly interlaminated fine-grained sandstone and gray shale (Fig. 3B). Since their initial discovery, tidally influenced sedimentation has been recorded in many coal-bearing sections, including coals much older than those described herein; and from other coal basins in the eastern U.S. (Greb & Archer, 1995; Gastaldo *et al.*, 2004a).

Where sediment accumulation was extremely rapid, the laminae within the rhythmites can exhibit a variety of small-scale cyclicity. The most common are neap-spring tidal bundles There are a number of analogues for such rhythmites and they have been documented within modern, hypertidal settings (Tessier *et al.*, 1989; Dalrymple & Makino, 1989; Dalrymple *et al.*, 1991, 2012; Tessier, 1993; Tessier *et al.*, 1995; Archer, 2004, 2013). Ancient counterparts of tidal rhythmites exhibiting neap-spring cycles are also common throughout the geologic column (Archer, 1996a). Within inclined heterolith stratifications (IHS), sand-rich foresets are capped by thin mud drapes (Fig 3B).

Despite the strong imprint of tidal periodicities, geochemical evidence suggests that some deposition occurred within freshwater settings (Kvale & Mastalerz, 1998). The sparse fauna of GSW deposits, including pectinoid bivalves, linguloid brachiopods and the branchiopod *Leaia tricarinata*, are suggestion of fresh to brackish-water settings.

Due to the great extent of the supercontinent of Pangaea, palaeofluvial systems could easily have been of a similar magnitude, or larger, scale than the modern Amazonian system (Archer & Greb, 1995). Similar low salinity to freshwater conditions have been documented in modern hypertidal analogues of rhythmites (Archer, 2004, 2013). Today, the largest area of freshwater tidal flats is within the lower reaches of the Amazon River. Here, tidal effects extend for more than 1000 km inland and also extend out onto the continental shelf (Archer, 2005). In addition to the globe-spanning continent of Pangaea, the globe-spanning ocean of Panthalassa could have resonated strongly with the tide-raising forces of the moon and sun (Archer, 1996b). This could have resulted in the development of hypertidal conditions along the coastal areas of Pangaea.

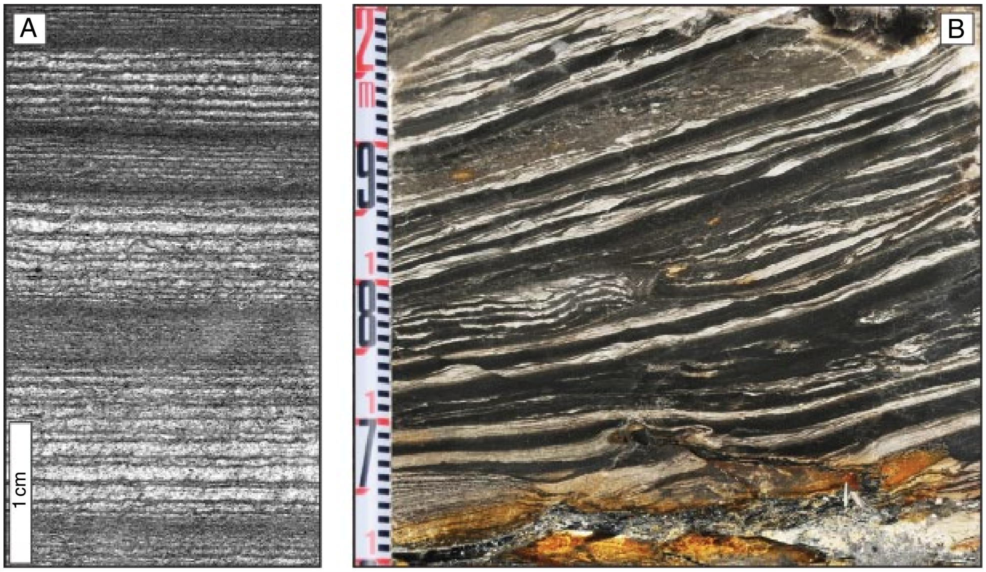

Fig. 3. (A) Cyclical, tidal rhythmite from Creek Paum Mine in southern Illinois. Neap-spring cycles and perigean-spring cycles are evident (Archer & Greb, 2011). (B) Close-up of mine wall showing inclined heterolithic stratification. Scale in cm and decimetres.

Upright plants, trees and forests

Upright forests of *in situ* trees have attracted a great deal of attention since the beginning of the formal study of Pennsylvanian geology and the number of mentions in the literature is very large (DiMichele & Falcon-Lang, 2011, 2012). Trees are so common in some mining regions that miners have given them nicknames such as 'kettlebottoms' and treat them as a serious hazard; the plug of rock within an upright fossil stump is prone to fall out of the mine roof (Chase & Sames, 1983). In the Illinois Basin such upright trees are commonly found almost exclusively within GSW facies. Large trees, ranging up to nearly 2 m in diameter, are often observed in the high walls of strip (opencast) mines. These trees seem to be concentrated along channel margins and the preserved stumps commonly attain vertical heights of 2 to 3 m. Upright, *in situ* trees and smaller plants (Fig. 4A) are common in GSW roof facies. Such in-place fossil plants are totally absent in mines with black shale or limestone roof facies. *In situ* fossil forests have been reported from a number of sites directly overlying coals (DiMichele & Nelson, 1989; DiMichele *et al.*, 2009). Within the Illinois Basin the more extensive entombed forest includes hundreds of upright trees that can be observed within single, underground mines (DiMichele & DeMaris, 1987; DiMichele *et al.*, 2009). Upright plants are also common above laterally equivalent coals in the Appalachians (Chase & Sames, 1983; Gastaldo, *et al.*, 1995; DiMichele *et al.*, 1996; Gastaldo *et al.*, 2004b).

The most commonly encountered standing trees (Fig. 4A) are arborescent lycopsids or 'club-mosses', an extinct group of giant trees related to the modern, diminutive *Isoetes* (Bateman, 1992; Phillips & DiMichele, 1992; DiMichele & DeMaris, 1985; DiMichele & Phillips, 1994). Giant lycopsids were particularly prone to upright, *in situ* preservation because of their unique construction. The stems were supported by a thick rind of decay-resistant bark (Boyce *et al.*, 2010); such that water transport and support functions were entirely separated. This is quite different from modern seed-plant trees, where these functions are combined in the wood. As a consequence, the internal tissues of the ancient tree trunks decayed rapidly during or after tree maturation, producing a natural, cylindrical mould into which sediment could accumulate. The infilling sediments supported and preserved the hollow stump as cast and mould. The bark is commonly coalified. Lycopsid trees had an extensive, shallowly penetrating but tenacious rooting system, known as 'stigmaria'. These stout roots radiated horizontally up to at least 15 m from base of the trunk. Outrigger-like roots provided secure support for these tall (30 to 40 m) trees that often grew in soft

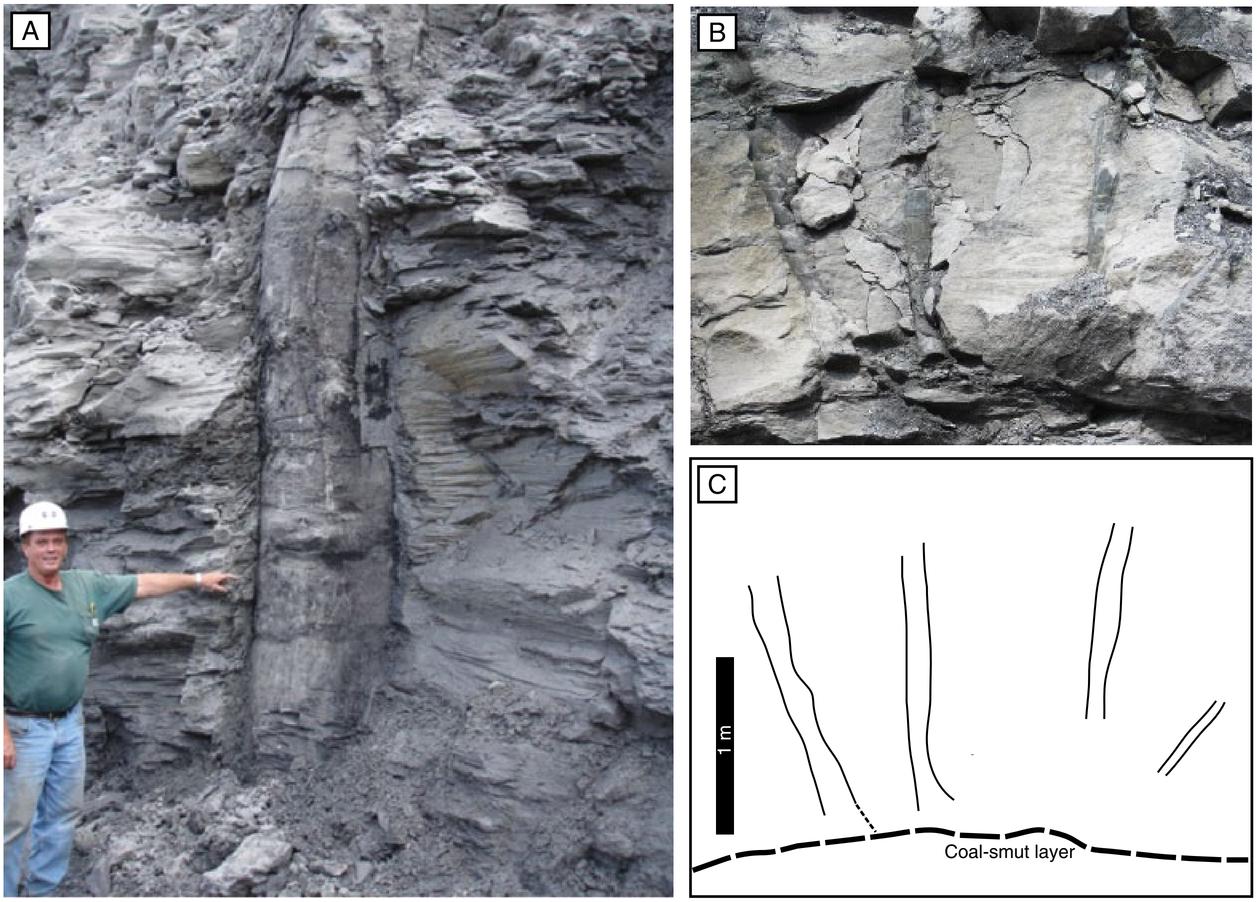

Fig. 4. (A) 3.3 m-tall trunk of an upright lycopod within the highwall of Creek Paum mine. Upright trunk is estimated to be 5.5 m in height. Photograph provided by Barry Sargent of Knight Hawk Coal. (B) Upright *Calamites* in shale overlying Murphysboro Coal in Jackson County, Illinois. (C) Tracing of B showing location of *Calamites* above a clastic-rich, coaly-shale layer ('coal smut').

substrates, such as uncompacted peat. Thus, lycopsids did not uproot and fall over like modern seed-plant trees. Despite several decades of mine-based research, none of the authors has ever seen an uprooted lycopsid trunk, nor have any of their field-experienced colleagues. Such trees would have stood upright for only a short period of time before decay eliminated the organic rind. Thus, all reported occurrences provide convincing evidence of rapid burial.

In addition to the lycopsids, smaller calamitean stems (Fig. 4B and C) are common and formed dense, monospecific stands (DiMichele *et al.*, 2009). This group is related to modern *Equisetum* and includes extant horsetails and scouring rushes. Calamiteans had, even during life, a hollow central stem. After death, the decay of tissue partitions within the stem permitted the entry of sediment. The result was upright preservation with a remaining thin coaly rind. Despite small stem diameters, calamiteans have been preserved to heights of several metres (DiMichele *et al.*, 2009) (Fig. 4B). Thus, a much smaller and architecturally very different plant also provides evidence of rapid burial within GSW facies.

Finally, much smaller scale but effectively *in situ* plants have also been recognised in association with upright lycopsid stumps (Gastaldo *et al.*, 2004a; DiMichele *et al.*, 2007). These smaller plants are generally represented by clumps of ground cover and by the stems and large foliar fragments of seed ferns and marattialean (true spore-bearing) ferns. Stems and large leaves of these plants do not form natural hollows during natural decay and would have been subject to rapid decay and degradation if exposed to oxidation. Thus, once the stems fell, rapid burial was necessary to isolate the plant remains from potential aerobic decay and destruction (Gastaldo, 2010). The famous Mazon Creek fauna of soft-bodied organisms from northern Illinois occurs in siderite concretions within a GSW overlying the Colchester Coal (Shabica & Hays, 1997). The preservation of such fossils demands rapid burial.

Thus, to conclude, a great variety of sizes of fossil plants have been preserved in place and encased within rhythmites. The plants are diverse and ranged from 30 m-tall lycopsids, several m-tall sphenopsids and smaller-scale ground foliage including ferns. Very high sedimentation rates, related to the local and regional development of hypertidal conditions, allowed the rapid creation of accommodation space and the entombing of plants. Finally, the grown and decay of Gondwanaland glaciations, particularly during periods of deglaciations also created abundant accommodation space for extended periods of deposition.

PROCESSES THAT CAN RAPIDLY INCREASE ACCOMMODATION SPACE

Peat compaction

A number of workers have tried to portray a palaeoenvironmental setting in which upright plants could be commonly preserved immediately above coal seams. It is widely accepted that the conversion of peat to coal involves some degree of compaction and dewatering. However, the timing of compaction is not well understood. Making a simplistic assumption that there was minimal internal compaction during peat accumulation, a 1 m-thick coal could have originally been a 10 to 20 m-thick peat. Assuming that approximately half of compaction occurred in the lower, buried portion of the peat pile, then the remaining compaction of the entire peat column could generate from 5 to 10 m of sediment accommodation space. This value falls within the measured heights of upright lycopsids discussed above. Compaction rates for various types of peats have been estimated to range as low as 1.4 : 1 up to rates of 30 : 1 (Ryer & Langer, 1980). Conversely, post-burial compaction, on the order of 3 : 1 at the most, was proposed by Wanless (1964) and Nadon (1998). Peat compaction could certainly generate some degree of accommodation space (Kvale & Archer, 1990), but whether or not the peat could compact in a short-enough timeframe is open for debate. Margins of coal beds commonly exhibit what appears to be significant erosion (Fig. 5). This style of erosion suggests that significant peat compaction had already occurred prior to GSW deposition.

Occurrences of large, upright trees indicate that the peat would need to have compacted by several metres prior to the influx of the GSW. In addition, the IHS indicates that 2 to 4 m of water had to have been present so that the bar forms could migrate. Thus, a simple model invoking autocompaction alone does not seem to offer a viable explanation.

GSW rhythmites that directly overlie coal have a high degree of variability. In some parts of a mine, low-angle rhythmites are common (Fig. 6) and such rhythmites tend to contain relatively small upright plants. Close to the palaeochannels, GSW rhythmites are noticeably more thickly laminated, particularly in the lower parts of the section (Fig. 7). Inferred rates of vertical or lateral accretion would be decimetres or metres per month. Such rates commonly occur in modern hypertidal estuaries (Archer, 2013).

Despite the lingering uncertainties regarding the magnitude of Pennsylvanian peat compaction, this process, over regional scales, could provide a significant generation of accommodation space for the preservation of rapidly deposited, hypertidal lithofacies. Much more work on this topic will be necessary in order to understand the magnitudes and rates of both the coals as well as the enclosing sediments.

Faulting

Abrupt submergence caused by fault movements has been invoked as a mechanism to explain preservation of upright trees in the fossil record (Gastaldo *et al.*, 2004a). While examples can be cited from the modern record, investigations in the Illinois Basin disclose that tectonic movements played only a peripheral role in the burial and preservation of standing vegetation.

Similar to most of the Midcontinent and western United States, the Illinois Basin was tectonically active during the Pennsylvanian. This activity was part of the Ancestral Rocky Mountains (ARM) orogeny. Recurrent displacements along deep-seated strike-slip and high-angle reverse faults, with attendant folding of sedimentary cover, characterize this event. Most ARM structures in the Illinois Basin trend north to northwest and take the form of monoclines and belts of domes or anticlines at Pennsylvanian level. Chief among these are the Du Quoin Monocline, the La

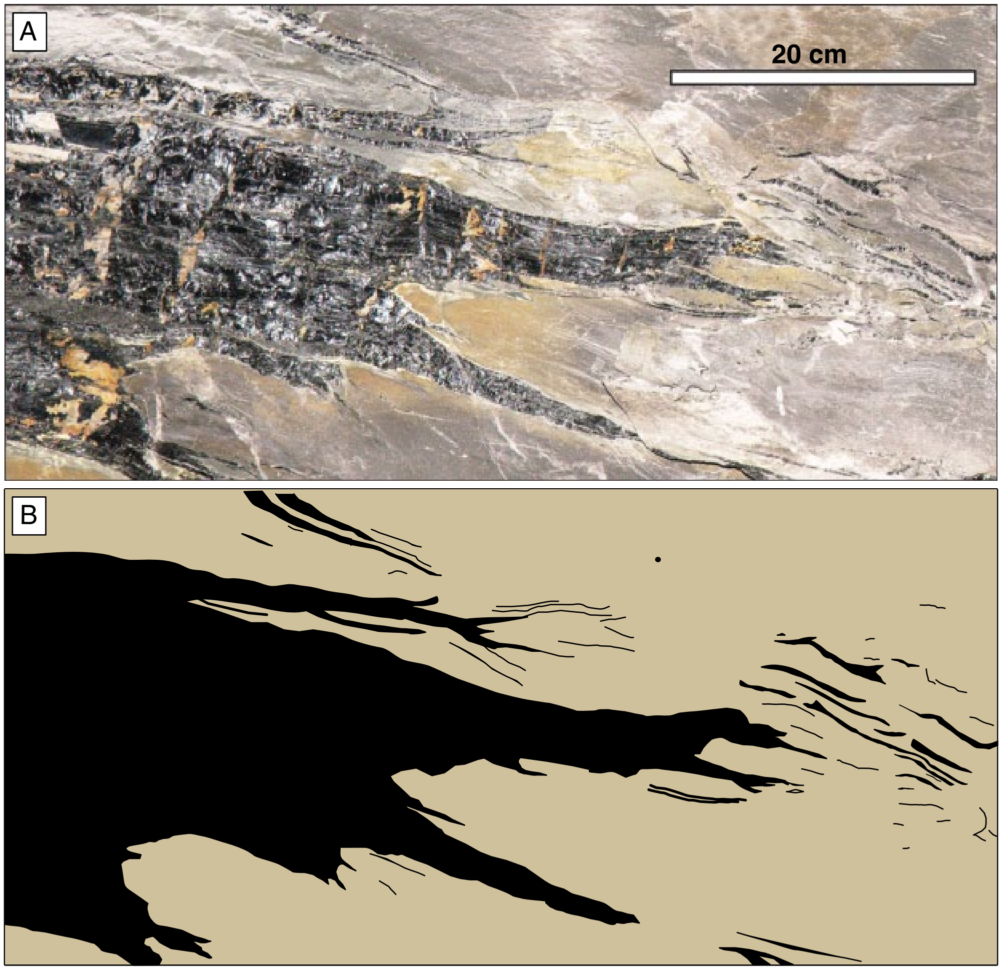

Fig. 5. (A) Frayed and abraded area of coal in an underground mine wall and (B) interpretation. Matrix sediment consists of basal grey-shale wedge lithofacies. The original peat must have been significantly compacted before the erosional event. This event was apparently penecontemporaneous with the deposition of the gray shale. Very thin coaly stringers are probably individual, coalified leaves and branches. Owing to the apparently resistant (felted) nature of the peat, the degree of erosion is remarkable and perhaps is related to event of significant energy, such as the passage of tidal bores.

Salle Anticlinorium and the Salem and Louden Anticlines (McBride & Nelson, 1999).

The structure of the Illinois Basin has been mapped in great detail, using the records of tens of thousands of exploration holes for oil, gas and coal along with seismic reflection and other geophysical surveys (Nelson, 1991; 1995; Nelson & Bauer, 1987; Kolata & Nelson, 1991). As a result, the structural framework of this basin is very thoroughly understood. Moreover, extensive and detailed mapping of faults and other structural disturbances has been carried out in underground coal mines (Krausse *et al.*, 1979; Nelson, 1981, 1983). Some of this underground mapping encompasses fields of fossil tree stumps; and the relationship of these fossils to regional features has been considered carefully.

On the grand scale, palaeochannels associated with GSW deposits and fossil trees tracked along trends of maximum basin subsidence. Locally, contemporaneous fault movements influenced channel trends. For example, the southern segment of the Walshville channel in the Herrin Coal parallels the eastern, downthrown side of the Du Quoin Monocline. *In situ* fossil stumps have been observed overlying the Murphysboro Coal in an area of south-western Illinois where thick coal and attendant GSW lie on the downthrown side of a monocline (Nelson *et al.*, 2011). A fossil forest above the Herrin Coal of east-central Illinois occurs on the downthrown side of an inferred north-east-striking basement fault (DiMichele *et al.*, 2007). However, the two best-known palaeochannels, the Walshville and the Galatia, each

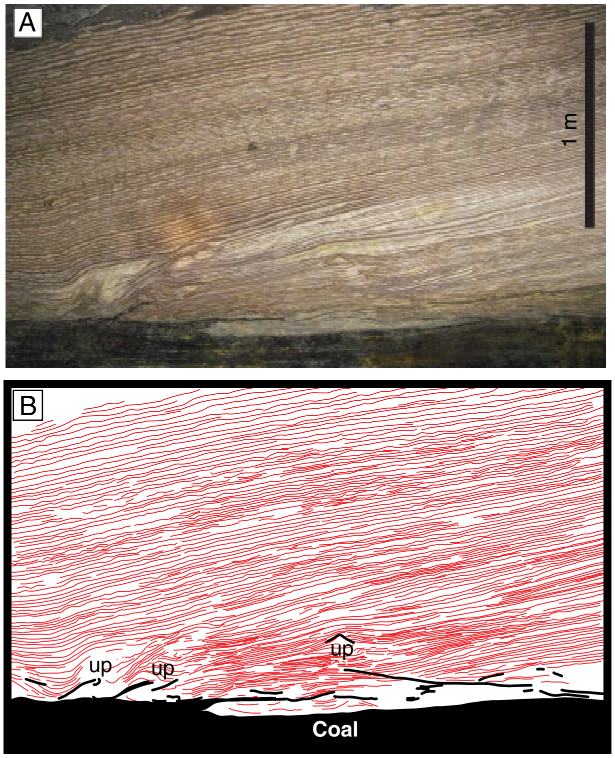

Fig. 6. (A) Mine-wall photograph and (B) interpretation (red lines) of cm-scale rhythmic bedding. Top of the Herrin Coal is exposed in the lower part of the image. Small upright plants ('up') are common along the top of the coal seam. In the lower left is an in-place, small tree trunk (rooted in underlying coal). Soft-sediment deformation around this trunk suggests the contemporaneous nature of plant growth and rhythmite deposition. This surface has been long-wall mined and thus has a slightly undulose surface produced by the cutter blades.

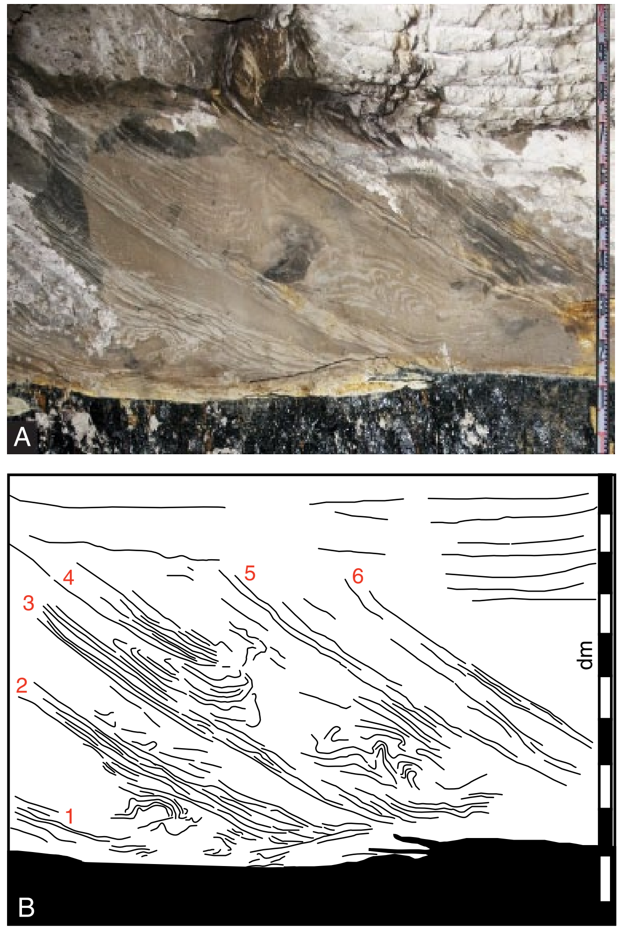

Fig. 7. (A) Mine-wall photograph and (B) interpretation of cross bedding and soft-sediment deformation. Planar sand beds (30 cm-thick) occur across the top the photograph. In places, these planar beds and other areas are obscured by white, limestone dust. This was sprayed on mine walls to reduce fire danger. Six individual sets of crossbeds are evident and these are separated by zones of slumping and extreme soft-sediment deformation.

meandered for hundreds of kilometres across the basin are largely independent of mapped faults. In most of the mines where we have observed standing fossil trees, no tectonic disturbance of the coal and enclosing strata can be detected.

To summarise, rapid or sudden earth movements may have contributed to the burial of standing trees in isolated instances. However, the large majority of fossil forests in the Illinois Basin cannot be related to contemporaneous fault movements.

DYNAMICS OF DEGLACIATION

Applying Neogene models to Pennsylvanian Period settings

Dynamics of the deglaciation at the close of the Pleistocene are exceedingly complex and the study of global-climate changes is a very active area of on-going research. A number of calibrated data sets have been generated using proxy, palaeoclimatic information derived from a disparate variety of sources. These datasets, which include long ice cores, tree-ring measurements, submerged reef corals and speleothems, to name a few, provide very important constraints on the evaluation of climate-change and sea-level models (Milne *et al.*, 2005). Detailed understanding of Pleistocene processes can provide hypothetical models that can be compared to Pennsylvanian palaeoenvironments.

There are relatively direct linkages between global warming, deglaciation and sea-level changes. However, rapid changes in sea-level are not necessarily a direct response to climatically induced melting. Instead, periods of particularly rapid sea-level rise might relate much more directly to glacial hydrology (Shaw, 1989; Douglas, 1992; Alvarez *et al.*, 2011) than to simple, linear climate change.

Ice-rafted debris and Heinrich events

Within the late Pleistocene and Holocene, a number of Ice-Rafted-Debris (IRD) events have been recognised. IRD zones are found within cores taken from continental shelves and deep- ocean areas. These zones contain sand-sized sediment. As the background sedimentation was very fine grained, the occurrence of the thin, coarser zones is problematic. The coarser zones have been interpreted to be the result of armadas of icebergs that melted and dumped their load of coarser sediment.

Heinrich events are particularly well-developed IRD events and have an average duration of about 750 years (Maslin *et al.*, (2001). Roche *et al.* (2004) suggested that Heinrich event 4, which lasted for about 250 years, resulted in a 2 m sea-level rise. These events are related to global climatic fluctuations that coincide with the destruction of northern hemisphere glaciers. Heinrich events were produced by the release of a large volume of icebergs from tide-water glaciers. These events had an apparently abrupt onset that may have occurred within a few years (Maslin *et al.*, 2001). The Younger Dryas can be correlated with the youngest Heinrich Event (H0, see Fig. 8), which occurred at c. 12 ka. H1, the second Heinrich event occurred from 17 ka (Hemming, 2004) to 14 ka (Vidal, 1999). Vidal *et al.* (1999) discuss a linkage between such events in both the North and South Atlantic oceans.

Palaeomegafloods

The Last Glacial Maximum (LGM) was approximately 23 to 19 ka ago. The subsequent deglaciation included a great number of megafloods. The megafloods included the releases of meltwater from subglacial lakes as well as cataclysmic failure of large ice-based or morainal dams. To adequately describe the scale of these titanic discharges an oceanography term, the 'Sverdrup' unit, has been commonly applied. One Sverdrup (Sv) is equivalent to 10^6 $m^3 s^{-1}$. The entire average input of freshwater from the world's rivers into the ocean is approximately equal to 1 Sv. By comparison to modern large rivers, the freshwater outflow of the Amazon River is approximately 0.3 Sv. The Meghna/Padma/Brahmaputra system and Chanjiang (Yangtze) have discharges of 0.05 Sv and 0.04 Sv, respectively. For comparison, the North American Mississippi River system has discharge of 0.02 Sv; thus it would require the simultaneous discharge of about 50 Mississippi-size rivers to equal 1 Sv.

In the following discussion of megafloods, we will first discuss the oldest and then proceed to the youngest events (Fig. 8). Following the LGM, some of the oldest megafloods were located in the region of Eurasia. Around 18 ka, large flows from Eurasian meltwater outbursts were spilling into the Aegean Sea (Baker, 2008).

Perhaps the best-studied series of megafloods occurred in the state of Washington in the northwestern U.S. The palaeofloods are commonly referred to as the 'Lake Missoula' floods or as the 'Spokane Flood.' Tremendous palaeofloods created an erosional landscape termed the 'Channelled Scablands' (Bretz, 1923; 1969). The Missoula floods were postulated to have been a single megaflood event (Bretz, 1969; Shaw *et al.*, 1999). Other workers have suggested multiple floods (Waitt, 1980). Benito & O'Conner (2003) suggested that some Lake Missoula discharges exceeded 3 Sv and that the largest single flood had a discharge near 10 Sv. This range of floods would have been equivalent to 10 to 33 times the discharges of the modern Amazon River system. Theoretical discharge models suggest that the lake could have been totally emptied into the ocean in about '100 days' (Shaw *et al.*, 1999, p. 608).

Within Arctic Canada, the Laurentide Ice Sheet formed a 3 km-thick dome over the Hudson Bay area approximately at 8.5 ka (Clark & Mix, 2002). During the on-going deglaciation, the moraine-dammed and ice-dammed megalakes included Lake Agassiz. As the thick ice sheet melted, approximately at 8.45 ka, megafloods emanating from this glacial megalake system included the most abrupt and widespread global-cooling event that has occurred over the last 100 ka (Clarke *et al.*, 2003, p. 923). Maximum discharges ranged from 5 to 10 Sv and the duration of the flow may have lasted 'less than one year' (Clarke *et al.*, 2003). The 8.2 ka cooling event is probably the combined result of these meltwater pulses. In Asia, megaflood discharges have been estimated to have been 11 Sv (Herget & Agatz, 2003). Very little is known about these systems at this time.

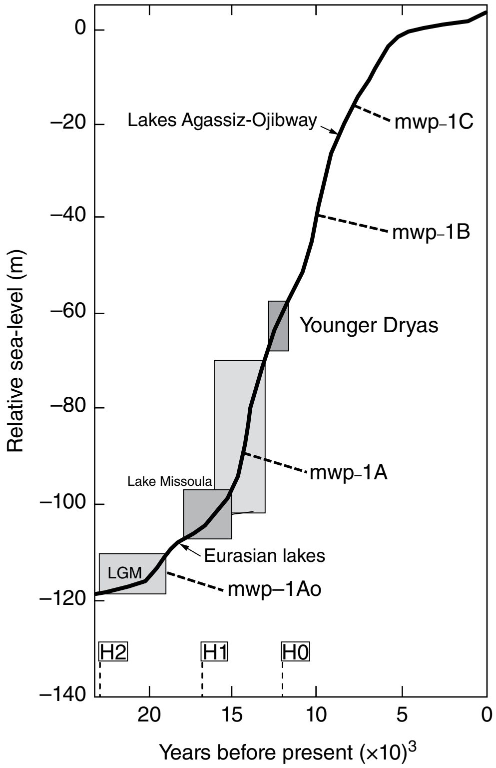

Fig. 8. Selected deglaciational events related to global changes in sea-level from 23 ka to the present (modified from Gornitz, 2009). Time range of the last glacial maximum (LGM) is based upon Clark & Mix (2002). Timings of meltwater-water pulses (mwp) are from Gornitz (2009). Megafloods related to large freshwater fluvio-glacial meltwater outbursts include: Eurasian lakes, outflows from Lake Missoula and discharges from the Lake Agassiz/Ojibway complex. Heinrich Events (H1 and H2) related to ice-rafted debris; H0 can be roughly equated to the Younger Dryas.

Melt-water Pulses (mwp)

Modern rates of sea-level rise have been estimated to average about 1.7 to 1.8 mm yr^{-1} (Douglas, 1992; Church *et al.*, 2004; Holgate & Woodworth, 2000). During the last deglaciation, short intervals exhibited rapid, sea-level rise and are referred to as 'melt-water pulses' ('mwp'). Even without a concurrent period of warming, rapid rises in sea-level could trigger: (1) destabilization of ice shelves, (2) collapse of continental-scale ice sheets and (3) initiate the release of tremendous volumes of glacial-megalake and subglacial meltwater (Weaver *et al.*, 2003). The mwp events were apparently very short and ranged from '10 to 10^3 years' (Gornitz, 2009, p. 887) and involved rapid changes in temperature and salinity of the oceans. Smaller scale modern events are termed jökulhlaups' and are caused by subglacial melting or release of ice-dammed meltwater. Contemporary examples have been described as 'self-dumping glacial-dammed lakes' (Clague & Mathews, 1973, p. 501).

The most widely accepted meltwater pulses are designated as 'wmp-1A' and 'wmp-1B' (Fig. 8). These pulses have been discussed by many authors (see summary in Gornitz, 2009, table S1, p. 890). Event mwp-1A occurred from about 14.5 to 14.2 ka (Weaver *et al.*, 2003). Sea-level rose at rates exceeding 2 cm yr^{-1} or 20 m over a period of 1.0 ka (Fairbanks, 1989) whereas Weaver *et al.* (2003) estimated an average rate of rise of about 4 cm yr^{-1}. Based upon contemporary rates of sea-level rise of about 2 mm yr^{-1}, the estimated rates of flow for wmp-1A were 200 to 400 times quicker (Douglas, 1992; Holgate & Woodworth, 2008).

Other pulses, such as mwp-1Ao and mwp-1C (see Fig. 8) are far less widely noted. Event mwp-1Ao would be the oldest meltwater pulse and it ranged from about 19.2 ka to 19.0 ka (Yokoyama *et al.*, 2000; Clarke *et al.*, 2003). This pulse occurred within the youngest portion of the LGM. On the other hand, mwp-1C is the youngest major pulse and occurred at about 7.6 ka. This pulse caused a rise in sea-level of 4 cm yr^{-1} (Cronin *et al.*, 2007; Blanchon & Shaw, 1995). Older estimates for the timing of this pulse range from 8.2 ka (Törnqvist *et al.*, 2004) down to 7.6 ka (Blanchon & Shaw, 1995).

Comparison of Late Pennsylvanian and Late Cenozoic analogues

There are many similarities between Late Palaeozoic, coal-bearing rocks discussed herein and Late Cenozoic deglaciational events that have been compared and discussed herein. Both stratigraphic intervals occurred during extended periods of continental-scale cycles of glaciation and deglaciation. Based upon the observations discussed above, a typical Pennsylvanian grey-shale wedge (GSW) could have been initiated by a mwp event mechanically similar to Neogene events. A rapid rise in Pennsylvanian sea-level would have resulted in large, horizontal inland shifts of the coastline. The resultant transgression of an epicontinental basin, such as the low-slope Illinois Basin, would have quickly flooded coastal parts of widespread cratonic peats and rapidly progressed inland along riverine corridors. Initial generation of accommodation space could be related to peat compaction. Deposition of mud-rich laminae and mud-draped IHS, following the rapid compaction of the upper peat, resulted in slower and longer-term dewatering of the entire, laterally extensive peat bodies. Following this initial and internal peat compaction, sea-level rise related to a mwp could have allowed continued rapid deposition of tidal facies overlying the peat mires.

This scenario explains the initial and cataclysmic sedimentation that encased the upright plants. As the accommodation space was filled, there would be a shift to gradually decreasing sedimentation. Such observations are consistently seen within single mines and also in the repeatedly stacked 'cyclothems' that characterize the Illinois Basin coal measures. This depositional scenario also explains the common co-occurrence of thick coals and an overlying GSW. The thickest peats had a greater potential for internal dewatering and a higher potential for significant compaction.

The magnitude of the control of GSW deposition by mwp and Heinrich dynamics on the extremely flat landscape could have been very large. The botanical and sedimentological evidence demand rapid sedimentation within the lower GSW. The commonality of the upright trees, suggests that a synergistic combination of: (1) peat compaction, (2) mwp and Hienrich events and megafloods; and (3) rapid tidal sedimentation could have been a tipping point regarding the termination of peat accumulation. Over much longer periods of time and of a much smaller rate, a protracted regional to global transgression could have been driven by the processes related to Pangaean deglaciation.

CONCLUSIONS

The Late Palaeozoic encompasses the longest lasting glacial episodes that occurred during the Phanerozoic Eon. Within Pennsylvanian-age coals of the Illinois Basin a number of features can be interpreted to have been the result of coastal flooding and cataclysmic burial of mires by tidal-estuarine sedimentation. The dramatic flooding occurred during periods of active peat accumulation and fossil forests comprised of upright trees have been widely and spectacularly preserved.

The rapidity of the tidal-estuarine sedimentation was aided by a concurrent generation of sufficient accommodation. Several different processes have been put forth to explain the forests of upright trees. These include: (1) peat dewatering and compaction, (2) local to regional fault-related subsidence, or (3) dramatic, short-term rises in ancient sea-level changes related to glacio-eustacy. The notably and repetitious occurrences of GSW facies includes their deposition directly overlying major, economic coals. There is a very consistent stratigraphic occurrence of GSW facies that encased upright forests. These forests were growing in swamps that were subsequently converted to bituminous coal. The stratigraphic repetition indicates that unusual local or even regional factors were not the primary, underlying drivers. Invoking a global-scale, allogenic event of short duration appears to offer a more reasonable hypothesis.

Cenozoic glacial processes, which have occurred since the last LGM and throughout the ensuing deglaciation, indicate that sea-levels did not rise in a slow and uniform manner. During specific short-term intervals, melt-water pulses (mwp) resulted in very rapid and short-term rises of global sea-level. Some mwp events can be correlated to specific events of cataclysmic flooding caused by fluvio-glacial megafloods, such as those related to the megafloods released from Lake Missoula. It is suspected that similar large-scale mwp could have been common during Gondwana deglaciations. This simple mwp-based model could explain the common preservation of upright fossil forests within GSW that were originally rooted within the underlying coal beds.

ACKNOWLEDGEMENTS

Many persons and entities allowed access to and information regarding the underground and surface mines discussed in this manuscript. Without access to active mines, this research would not have been possible. Gregory M. Molinda (CDC/NIOSH/PRL) provided some very useful photographic information from underground mines. WD acknowledges funding from the NMNU Small Grants Program to support fieldwork.

REFERENCES

Allgaier, **G.J.** and **Hopkins**, **M.E.** (1975) Reserves of the Herrin (No. 6) Coal in the Fairfield Basin in southeastern Illinois. *Illinois State Geol. Surv. Circular*, **489**, 31 pp.

Alvarez, **S.J.**, **Montoya**, **M.**, **Ritz**, **C.**, **Ramstein**, **G.**, **Charbit**, **S.**, **Dumas**, **C.**, **Nisancioglu**, **K.H.**, **Dokken**, **T.** and **Ganopolski**, **K.A.** (2011) Heinrich event 1: an example of dynamical ice-sheet reaction to oceanic changes. *Climate of the Past*, **7**, 1297–1306.

Archer, **A.W.** (2008) Cyclic sedimentation (cyclothem). In: *Encyclopedia of Paleoclimatology and Ancient Environments* (Ed. **V. Gornitz**), pp. 226–228, Springer, Dordrecht, The Netherlands.

Archer, **A.W.** (1996a) Panthalassa: paleotidal resonance and a global paleo-ocean seiche: *Paleoceanography*, **11**, 625–632.

Archer, **A.W.** (2004) Recurring assemblages of biogenic and physical sedimentary structures in modern and ancient extreme macrotidal estuaries. *J. Coastal Res.*, **43**, 4–22.

Archer, **A.W.** (1996b) Reliability of lunar orbital periods extracted from ancient cyclic tidal rhythmites. *Earth Planet. Sci. Lett.*, **141**, 1–10.

Archer, **A.W.** (2005) Review of Amazonian depositional systems. *Int. Assoc. Sedimentol. Spec. Publ.*, **35**, 17–39.

Archer, **A.W.** (2013) World's highest tides: Hypertidal coastal systems in North America, South America and Europe. *Sed. Geol.*, **284–285**, 1–25.

Archer, **A.W.** and **Feldman**, **H.R.** (1995) Incised valleys and estuarine facies of the Douglas Group (Virgilian): implications for similar Pennsylvanian sequences in the U.S. Mid-Continent. In: *Sequence stratigraphy of the mid-Continent* (Ed **N. Hyne**) Tulsa Geological Society, Tulsa, Oklahoma, pp. 119–140.

Archer, **A.W.**, **Feldman**, **H.R.**, **Kvale**, **E.P.** and **Lanier**, **W.P.** (1994) Pennsylvanian (Upper Carboniferous) fluvio- to tidal-estuarine coal-bearing systems: delineation of facies transitions based upon physical and biogenic sedimentary structures. *Palaeogeogr. Palaeoclimatol., Palaeoecol.*, **106**, 171–185.

Archer, **A.W.** and **Greb**, **S.F.** (1995) An Amazon-scale drainage in the early Pennsylvanian of Central North America: *J. Geol.*, **103**, 611–628.

Archer, **A.W.** and **Greb**, **S.F.** (2011) Hypertidal facies from the Pennsylvanian Period: Eastern and Western Interior Coal Basins, USA. In: *Principles of tidal sedimentology* (Eds **R.A. Davis**, Jr. and **R.W. Dalrymple**) pp. 421–436. Springer. The Netherlands.

Archer, **A.W.** and **Kvale**, **E.P.** (1993) Origin of gray-shale lithofacies ('clastic wedges') in U.S. midcontinental coal measures (Pennsylvanian): an alternative explanation. In: *Modern and Ancient Coal-Forming Environments* (Eds J.C. Cobb and B. Cecil), *Geol. Soc. Am. Spec. Pap.*, **286**, 181–192.

Baker, **V.** (2008) Late Quaternary megafloods. In: *Encyclopedia of paleoclimatology and ancient environments* (Ed **V. Gornitz**) pp. 506–507. Springer, The Netherlands.

Bateman, **R.M.** (1992) Evolutionary-developmental change in the growth architecture of fossil rhizomorphic lycopsids: scenarios constructed on cladistics foundations. *Biol. Rev.*, **69**, 527–597.

Benito, **G.** and **O'Connor**, **J.E.** (2003) Number and size of last-glacial Missoula floods in the Columbia River valley between the Pasco Basin, Washington and Portland, Oregon. *Geol. Soc. Am. Bull.*, **115**, 624–638.

Blanchon, **P.** and **Shaw**, **J.** (1995) Reef drowning during the last deglaciation: evidence for catastrophic seal-level rise and ice-sheet collapse. *Geology*, **39**, 4–8.

Boyce, **C.K.**, **Abrecht**, **M.**, **Zhou**, **D.** and **Gilbert**, **P.U.P.A.** (2010) X-ray photoelectron emission spectromicroscopic analysis of arborescent lycopsid cell wall composition and Carboniferous coal ball preservation. *Int. J. Coal Geol.*, **83**, 146–153.

Bretz, **J.H.** (1923) The Channeled Scablands of the Columbia Plateau. *J. Geol.*, **31**, 617–649.

Bretz, **J.H.** (1969) The Lake Missoula floods and the Channeled Scabland. *J. Geol.*, **77**, 505–543.

Bristol, **H.M.** and **Howard**, **R.H.** (1971) Paleogeographic map of the sub-Pennsylvanian Chesterian (upper Mississippian) surface in the Illinois Basin. *Illinois State Geological Survey Circular*, **458**, 16 p.

Bristol, **H.M.** and **Howard**, **R.H.** (1974) Sub-Pennsylvanian valleys in the Chesterian surface of the Illinois Basin and related Chesterian slump blocks. *Geol. Soc. Am. Spec. Pap.*, **148**, 315–335.

Chase, **F.E.** and **Sames**, **G.P.** (1983) Kettlebottoms: their relation to mine roof and support: *U.S. Bureau of Mines*, *Report of Investigations*, 8785, 12 p.

Church, **J.A.**, **White**, **N.J.**, **Coleman**, **R.**, **Lambeck**, **K.** and **Mitrovica**, **J.** (2004) Estimates of the Regional Distribution of Sea-level Rise over the 1950–2000 Period. *J. Climate*, **17**, 2609–2625.

Clague, **J.J.** and **Mathews**, **W.H.** (1973) The magnitude of jökulhlaups. *J. Glaciology*, **12**, 501–504.

Clark, **P.U.** and **Mix**, **A.C.** (2002) Ice Sheets and sea-level of the Past Glacial Maximum. *Quatern. Sci. Rev.*, **21**, 1–7.

Clarke, **G.**, **Leverington**, **D.**, **Teller**, **J.** and **Dyke**, **A.** (2003) Superlakes, megafloods and abrupt climate change. *Science*, **301**, 922–923.

Cronin, **T.M.**, **Vogt**, **P.R.**, **Willard**, **D.A.**, **Thunell**, **R.**, **Halka**, **J.**, **Berke** and **M.**, **Pohlman**, **J.** (2007) Rapid sea-level rise and ice sheet response to 8, 200-year climate event. *Geophy. Lett.*, **34**, L20603.

Dalrymple, **R.W.**, **Boyd**, **R.** and **Zaitlin**, **B.A.** (1994) Incised-valley systems: origin and sedimentary sequences: *SEPM Spec. Publ.*, **51**, 391 p.

Dalrymple, **R.W.**, **Mackay**, **D.A.**, **Ichaso**, **A.A.** and **Choi**, **K.S.** (2012) Processes, morphodynamics and facies of tide-dominated estuaries. In: *Principles of Tidal Sedimentology* (**R.A. Davis** Jr. and **R.W. Dalrymple**). Springer, pp. 79–107.

Dalrymple, **R.W.** and **Makino**, **Y.** (1989) Description and genesis of tidal bedding in the Cobequid Bay-Salmon River estuary, Bay of Fundy, Canada In: *Sedimentary Facies of the Active Plate Margin* (Eds **A. Taira** and **F. Masuda**) pp. 151–177. Terra Publishing, Tokyo.

Dalrymple, **R.W.**, **Zaitlin**, **B.A.** and **Boyd**, **R.** (1991) Estuarine facies models: conceptual basis and stratigraphic implications. *J. Sed. Petrol.*, **62**, 1130–1146.

DiMichele, **W.A.** and **DeMaris**, **P.J.** (1985) Arborsecent lycopod reproduction and paleoecology in a coal-swamp environment of late Middle Pennsylvanian age (Herrin Coal, Illinois, U.S.A.). *Rev. Palaeob. Palynol.*, **44**, 1–26.

DiMichele, **W.A.** and **DeMaris**, **P.J.** (1987) Structure and dynamics of a Pennsylvanian-age *Lepidodendron* forest: colonizers of a disturbed swamp habitat in the Herrin (No. 6) Coal of Illinois. *Palaios*, **2**, 146–157.

DiMichele, **W.A.**, **Eble**, **C.F.** and **Chaney**, **D.S.** (1996) A drowned lycopsid forest above the Mahoning coal (Conemaugh Group, Upper Pennsylvanian) in eastern Ohio, U.S.A. *Int. J. Coal Geol.*, **31**, 249–276.

DiMichele, **W.A.** and **Falcon-Lang**, **H.J.** (2011) Pennsylvanian 'fossil forests' in growth (To assemblages): origin, taphonomic bias and palaeoecological insights. *J. Geol Soc. London*, **169**, 585–605.

DiMichele, **W.A.** and **Falcon-Lang**, **H.J.** (2012) Calamitalean 'pith casts' reconsidered. *Rev. Palaeob. Palynol.*, **173**, 1–14.

DiMichele, **W.A.**, **Falcon-Lang**, **H.J.**, **Nelson**, **W.J.**, **Elrick**, **S.** and **Ames**, **P.** (2007) Ecological gradients within a Pennsylvanian forest: *Geology*, **35**, 415–418.

DiMichele, **W.A.** and **Nelson**, **W.J.** (1989) Small-scale spatial heterogeneity in Pennsylvanian-age vegetation from the roof shale of the Springfield Coal (Illinois Basin). *Palaios*, **4**, 276–280.

DiMichele, **W.A.**, **Nelson**, **W.J.**, **Elrick**, **S.** and **Ames**, **P.R.** (2009) Catastrophically buried Middle Pennsylvanian *Sigillaria* and calamitean sphenopsides from Indiana, USA: What kind of vegetation was this? *Palaios*, **24**, 159–166.

DiMichele, **W.A.**, **Pfefferkorn**, **H.W.** and **Gastaldo**, **R.A.** (2001) Response of Late Carboniferous and Early Permian plant communities to climate changes. *Annu. Rev. Earth and Planet. Sci.*, **29**, 461–487.

DiMichele, **W.A.** and **Phillips**, **T.L.** (1994) Paleobotanical and paleoecological constraints on models of peat formation in the Late Carboniferous of Euramerica. *Palaeogeogr., Palaeoclimatol*, *Palaeoecol.*, **106**, 39–90.

Douglas, **B.C.** (1992) Global sea-level rise, *J. Geophys. Res.*, **96**, 6981–6992.

Fairbanks, **R.G.** (1989) A 17,000-year glacio-eustatic sea-level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature*, **342**, 637–642.

Falcon-Lang, **H.J.** (2004) Pennsylvanian tropical rainforests responded to glacial-interglacial rhythms. *Geology*, **32**, 689–692.

Falcon-Lang, **H.J.** and **DiMichele**, **W.A.** (2010) What happened to the coal forests during Pennsylvanian glacial phases? *Palaios*, **25**, 611–617.

Falcon-Lang, **H.J.**, **Nelson**, **W.J.**, **Elrick**, **S.**, **Looy**, **C.V.**, **Ames**, **P.R.** and **DiMichele**, **W.A.** (2009) Incised channel fills containing conifers indicate that seasonally dry vegetation dominated Pennsylvanian tropical lowlands. *Geology*, **37**, 923–926.

Feldman, **H.R.**, **Archer**, **A.W.**, **Kvale**, **E.P.**, **Cunningham**, **C.R.**, **Maples**, **C.G.** and **West**, **R.R.** (1993) A tidal model of Carboniferous Konservat Laggerstätten formation: *Palaios*, **8**, 485–498.

Gastaldo, **R.A.** (2010) Peat or no peat: why do the Rajang and Mahakam deltas differ? *Inter. J. Coal Geol.*, **83**, 162–172.

Gastaldo, **R.A.**, **H.W. Pfefferkorn** and **W.A. DiMichele** (1995) Characteristics and classification of Carboniferous roof shale floras. In: *Historical perspectives of early Twentieth Century Carboniferous paleobotany in North America* (Eds P.C. Lyons, E.D. Morey and R.H. Wagner) *Geol. Soc. Am. Mem.*, **185**, 341–352.

Gastaldo, **R.A.**, **Stevanovic-Walls**, **I.M.** and **Ware**, **W.N.** (2004a) Erect forests are evidence for coseismic base-level changes in Pennsylvanian cyclothems of the Black Warrior Basin, U.S.A. In: *Sequence stratigraphy, paleoclimate and tectonics of coal-bearing stratigraphy* (Eds J.C. Pashin and R.A. Gastaldo), *AAPG Studies in Geology*, **51**: 219–238.

Gastaldo, **R.A.**, **Stevanovic-Walls**, **I.M.**, **Ware**, **W.N.** and **Greb**, **S.F.** (2004b) Community heterogeneity of early Pennsylvania peat mires. *Geology*, **32**, 693–696.

Gluskoter, **H.J.** and **Hopkins**, **M.E.** (1970) Distribution of sulfur in Illinois coals. In: *Depositional environments in parts of the Carbondale Formation - Western and northern Illinois* (W.H. Smith, R.B. Nance and R.G. Johnson). *Illinois State Geol. Surv. Guidebook Series*, **8**, 89–95.

Gluskoter, **H.J.** and **Simon**, **J.A.** (1968) Sulfur in Illinois coals. *Illinois State Geol. Surv. Circ.*, **432**, 28 p.

Gornitz, **V.** (2009) Sea-level change, post-glacial. In: *Encyclopedia of paleoclimatology and ancient environments* (Ed. **V. Gornitz**) pp. 887–893. Springer, Dordrecht, The Netherlands.

Gradstein, **F.M.**, **Ogg**, **J.G.**, **Schmitz**, **M.D.** and **Ogg**, **G.M.** (2012) The geologic time scale. Elsevier, New York, 1176 p.

Greb, **S.F. Andrews**, **W.M.**, **Eble**, **C.F.**, **DiMichele**, **W.**, **Cecil**, **C.B.** and **Hower**, **J.C.** (2003) Desmoinesian coal beds of the Eastern Interior and surrounding basins: The largest tropical peat mires in earth history. In: *Extreme depositional environments: Mega-end members in geologic time* (Eds M.A. Chan and A.W. Archer), *Geol. Soc. Am. Spec. Pub.*, **370**, 127–150.

Greb, **S.F.** and **Archer**, **A.W.** (1995) Rhythmic sedimentation in a mixed tide and wave deposit, eastern Kentucky, U.S.A. *J. Sed. Res.*, **B65**, 96–106.

Hemming, **S.R.** (2004) Heinrich events: massive Late Pleistocene detritus layers of the North Atlantic and their global climate imprint. *Rev. Geophys*, **370**, 127–150.

Herget, **J.** and **Agatz**, **H.** (2003) Modelling ice-dammed lake outburst floods in the Altai Mountains (Siberia) with HEC-RAS. In: *Palaeofloods, historical data and climatic variability: applications in flood risk assessment* (Eds **V.R. Thorndycraft**, **G. Benito**, **N.M. Barriendos** and **M.S. Llast**) Madrid, Proceedings of the PHEFRA Workshop, Centro de Ciencias Medioamientales pp. 177–181.

Holgate, **S.J.** and **Woodworth**, **P.L.** (2000) Evidence for enhanced coastal sea-level rise during the 1990s. *Geophys. Res. Lett.*, **31**, L07305.1-L07305.4.

Hopkins, **M.E.** (1968) Harrisburg (No. 5) Coal reserves of southeastern Illinois. *Illinois State Geol. Surv. Circ.* **431**, 25 p.

Kolata, **D.R.** and **Nelson**, **W.J.** (1991) Tectonic history of the Illinois Basin. *AAPG Mem.*, **51**, 25 p.

Kosanke, **R.M.**, **Simon**, **J.A.**, **Wanless**, **H.R.** and **Willman**, **H.B.** (1960) Classification of the Pennsylvanian strata of Illinois. *Illinois State Geol. Surv. Report of Investigations*, **214**, 84 p.

Krausse, **H.-F.**, **Damberger**, **H.H.**, **Nelson**, **W.J.**, **Hunt**, **S.R.**, **Ledvina**, **C.T.**, **Treworgy**, **C.G.** and **White**, **W.A.** (1979) Roof strata of the Herrin (No. 6) Coal Member in mines of Illinois: their geology and stability: *Illinois State Geological Survey, Illinois Minerals Note*, **72**, 53 p.

Kuecher, **G.M.**, **Woodland**, **B.G.** and **Broadhurst**, **F.M.** (1990) Evidence of deposition from individual tides and of tidal cycles from the Francis Creek Shale (host rock to the Mazon Creek Biota, Westphalian D (Pennsylvanian), northeastern Illinois. *Sed. Geol.*, **68**, 211–221.

Kvale, **E.P.** and **Archer**, **A.W.** (1990) Tidal deposits associated with low-sulfur coals, Brazil Fm. (Lower Pennsylvanian), Indiana. *J. Sed. Petrol.*, **60**, 563–574.

Kvale, **E.P.**, **Archer**, **A.W.** and **Johnson**, **H.J.** (1989) Daily, monthly and yearly tidal cycles within laminated siltstones of the Mansfield Formation (Pennsylvanian) of Indiana. *Geology*, **17**, 365–368.

Kvale, **E.P.** and **Mastalerz**, **M.** (1998) Evidence of ancient freshwater tidal deposits. In: *Tidalites: Processes and Products* (Eds C.R. Alexander, R.A. Davis and V.J. Henry), *SEPM Spec. Pub.*, **61**, p. 95–107.

Maslin, **J.**, **Seidov**, **D.** and **Lowe**, **J.** (2001) Synthesis of the nature and causes of rapid climate transition during the Quaternary. *Geophys. Monogr.*, **126**, 9–52.

McBride, **J.H.** and **Nelson**, **W.J.** (1999) Style and origin of mid-Carboniferous deformation in the Illinois Basin, USA. Ancestral Rocky Mountains deformation. *Tectonophysics*, **305**, 249–273.

Milne, **G.A.**, **Long**, **A.J.** and **Bassett**, **S.E.** (2005) Modeling Holocene relative sea-level observations from the Caribbean and South America. *Quatern. Sci. Rev.*, **24**, 1183–1202.

Moore, **R.C.** (1964) Paleoecological aspects of Kansas Pennsylvanian and Permian cyclothems. In: *Symposium on Cyclic Sedimentation* (Ed D.F. Merriam) *Kansas Geol. Surv. Bull.*, **169**, 287–380.

Moore, **R.C.** (1935) Stratigraphic classification of the Pennsylvanian rocks of Kansas. *Kansas Geol. Surv. Bull.*, **22**, 256 p.

Nadon, **G.C.** (1998) Magnitude and timing of peat-to-coal compaction. *Geology*, **26**, 727–730.

Nelson, **W.J.** (1981) Faults and their effect on coal mining in Illinois. *Illinois State Geol. Surv. Circ.*, **523**, 45 p.

Nelson, **W.J.** (1983) Geologic disturbances in Illinois coal seams. *Illinois State Geol. Surv. Circ.* **530**, 52 p.

Nelson, **W.J.** (1995) Structural features in Illinois: *Illinois State Geological Survey, Bulletin* **100**, 144 p.

Nelson, **W.J.** (1991) Structural styles in the Illinois Basin. *AAPG Mem.*, **51**, 209–246.

Nelson, **W.J.** and **Bauer**, **R.A.** (1987) Thrust faults in southern Illinois Basin – result of contemporary stress? *Geol. Soc. Am. Bull.*, **98**, 302–307.

Nelson, **W.J.**, **Devera**, **J.A.**, **Williams**, **L.M.** and **Staub**, **J.R.** (2011) Bedrock geology of Oraville quadrangle, Jackson County, Illinois. *Illinois State Geological Survey, Illinois Geologic Quadrangle Map IGQ Oraville-BG*, 2 sheets, scale 1:24,000.

Nelson, **W.J.**, **Smith**, **L.B.** and **Treworgy**, **J.D.** (2002) Sequence stratigraphy of the Lower Chesterian (Mississippian) strata of the Illinois Basin. *Illinois State Geological Survey Bulletin* **107**, 70 p.

Phillips, **T.L.** and **DiMichele**, **W.A.** (1992) Comparative ecology and life-history biology of arborescent lycopods in Late Carboniferous swamps of Euramerica. *Annals of the Missouri Botanical Garden*, **79**, 560–588.

Roche, **D.**, **Paillard**, **D.** and **Corgijo**, **E.** (2004) Constraints on the duration and freshwater release of Heinrich event 4 through isotope modeling. *Nature*, **432**, 379–382.

Ryer, **T.A.** and **Langer**, **A.W.** (1980) Thickness change involved in the peat-to-coal transformation for a bituminous coal of Cretaceous age in central Utah. *J. Sed. Petrol.*, **50**, 987–992.

Shabica, **C.W.** and **Hays**, **A.A.** (1997) Richardson's guide to the fossil fauna of Mazon Creek. *Northeastern Illinois University, Chicago*, 308 p.

Shaw, **J.** (1989) Drumlins, subglacial meltwater floods and ocean responses. *Geology*, **17**, 853–856.

Shaw, **J.**, **Munro-Stasiuk**, **M.**, **Sawyer**, **B.**, **Beaney**, **C.**, **Lesemann**, **J-E.**, **Musacchio**, **A.**, **Rains**, **B.** and **Yung**, **R.R.** (1999) The Channeled Scabland: back to Bretz? *Geology*, **27**, 605–608.

Tessier, **B.** (1993) Upper intertidal rhythmites in the Mont-Saint-Michel Bay (NW France): perspectives for paleoreconstruction. *Mar. Geol.*, **110**, 355–367.

Tessier, **B.**, **Archer**, **A. W.**, **Lanier**, **W. P.** and **Feldman**, **H. R.** (1995) Comparison of ancient tidal rhythmites (Carboniferous of Kansas, U.S.A.) with modern analogues (the Bay of Fundy and Mont-Saint-Michel, N.W. France). *Int. Assoc. Sedimentol. Spec. Publ.*, **24**, 259–271.

Tessier, **B.**, **Monfort**, **Yt** ., **Gigot**, **P.** and **Larsonneur**, **C.** (1989) Enregistreme des tidaux en accretion verticale, ples en baie du Mont-Saint-Michele et dans la molasses marine Miocene du basin de Digne. *Bull. Soc. Geologie France*, **5**, 1029–1041.

Törnqvist, **T.E.**, **Bick**, **S.J.**, **Gonzalez**, **J.L.**, van der **Borg**, **I.** and de **Jong**, **A.F.M.** (2004) Tracking the sea-level signature of the 8.2 ka cooling event: new constraints from the Mississippi Delta. *Geophys. Res. Lett.*, **31**, L23309.

Vidal, **L.**, **Schneider**, **R.R.**, **Marchal**, **O.**, **Bickert**, **T.**, **Stocker**, **T.F.** and **Wefer**, **G.** (1999) Link between the North and South Atlantic during the Heinrich events of the last glacial period. *Climate Dynam.*, **15**, 909–919.

Waitt, **R.B.**, Jr. (1980) About 40 last-glacial Lake Missoula jökulhlaups through southern Washington. *J. Geol.*, **88**, 653–679.

Wanless, **H.R.** (1964) Local regional factors in Pennsylvanian cyclic sedimentation. In: *Symposium on cyclic sedimentation* (Ed. D.F. Merriam). *Kansas Geol. Surv. Bull.*, **169**, pt. 2, 593–606.

Wanless, **H.R.** and **Weller**, **J.M.** (1932) Correlation and extent of Pennsylvanian cyclothems. *Geol. Soc. Am. Bull.*, **43**, 1177–1206.

Weaver, **A. J.**, **Saenko**, **O.A.**, **Clark**, **P.U.** and **Mitrovica**, **J.X.** (2003) Meltwater Pulse 1A from Antarctica as a trigger of the Bølling-Allerød warm interval. *Science*, **299**, 1709–1713.

Weller, **J.M.** (1930) Cyclical sedimentation of the Pennsylvanian Period and its significance: *J. Geol.*, **38**, 97–135.

Weller, **J.M.** (1931) The conception of cyclical sedimentation during the Pennsylvanian Period. *Illinois State Geol. Surv. Bull*, **60**, 163–177.

Wilkinson, **B.H.**, **Merrill**, **G.K.** and **Kivett**, **S.J.** (2003) Stratal order in Pennsylvanian cyclothems. *Geol. Soc. Am. Bull.*, **115**, 1068–1087.

Yokayama, **Y.**, **Lambeck**, **K.**, **De Deckker P.**, **Johnston**, **P.** and **Fifield**, **L.K.** (2000) Timing of the Last Glacial Maximum from observed sea-level minima. *Nature*, **406**, 713–716.

Zangerl, **R.** and **Richardson**, **E.S.** (1963) The paleoecological history of two Pennsylvanian black shales. *Fieldiana Geol. Mem.*, **4**, 1–352.

Zeller, **E.J.** (1964) Cycles and psychology. In: *Symposium on cyclic sedimentation* (Ed. D.F. Merriam), *Kansas Geol. Surv. Bull.*, **169**, pt. 2, 631–636.