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New Insights into Carboniferous Cyclothems. The Fourth Biennial Field Conference of the American Association of Petroleum Geologists (AAPG) Midcontinent Section Fourth Biennial Field Conference Abstracts and Guidebook

Robert Matthew Joeckel
University of Nebraska - Lincoln, rjoeckel3@unl.edu

Christopher R. Fielding
University of Nebraska-Lincoln, cfielding2@unl.edu

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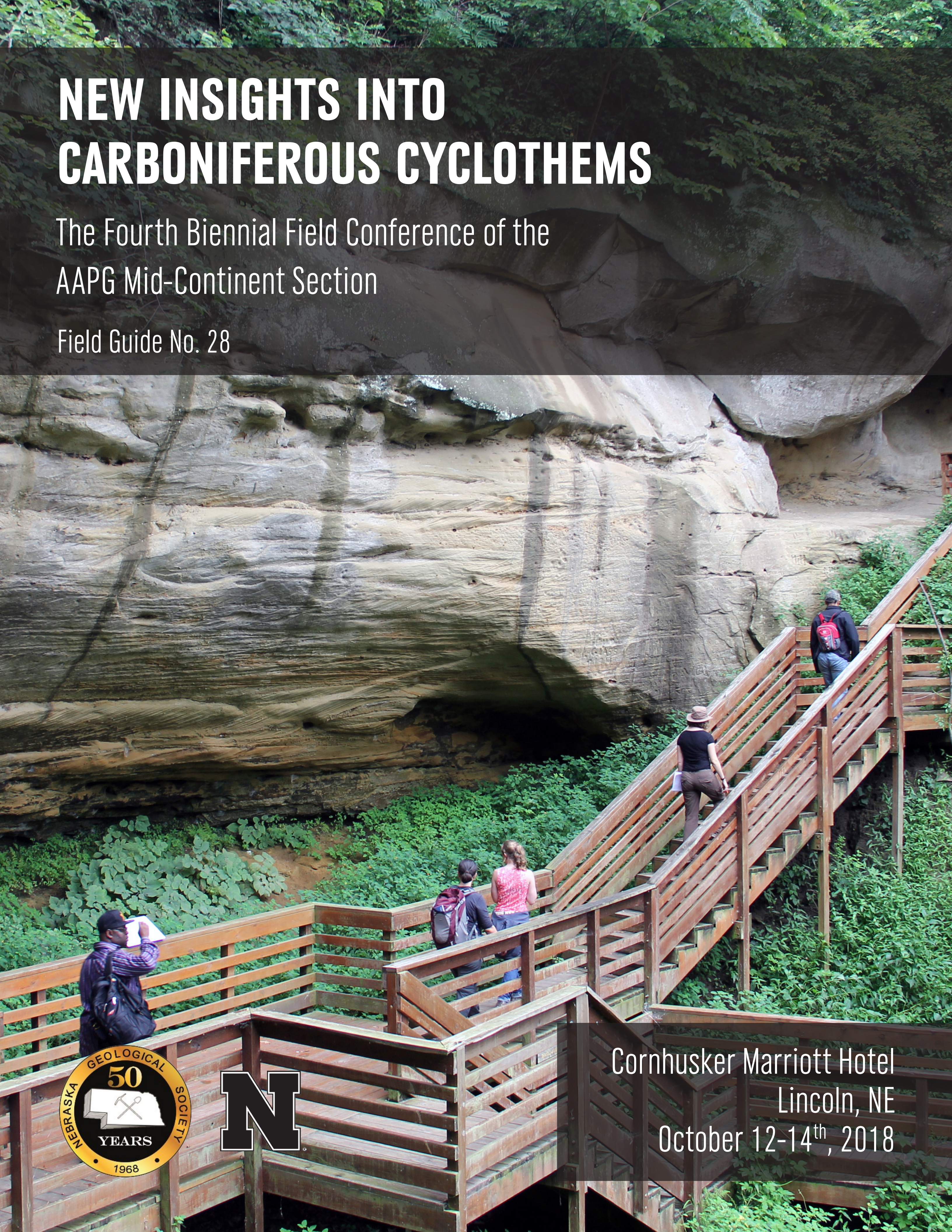

NEW INSIGHTS INTO CARBONIFEROUS CYCLOTHEMS

The Fourth Biennial Field Conference of the
AAPG Mid-Continent Section

Field Guide No. 28

Cornhusker Marriott Hotel
Lincoln, NE
October 12-14th, 2018

University of Nebraska–Lincoln

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American Association of Petroleum Geologists
Midcontinent Section Fourth Biennial Field Conference

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"New Insights into Carboniferous Cyclothems"

Field Guide No. 28

Hosted by the

Nebraska Geological Society
University of Nebraska-Lincoln Department of Earth & Atmospheric Sciences
University of Nebraska-Lincoln School of Natural Resources Conservation and Survey Division

Conference Guidebook

Compiled and edited by
Christopher R. Fielding and R.M. Joeckel

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General session, Friday (presenter in bold lettering)

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SUNDAY, October 14th, 2018

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Sunday, Introduction

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Hallum, D.R. (University of Nebraska-Lincoln) Geology of a deep test hole in southwest Nebraska.

Core workshop

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Clark, R.J., Witzke, B.J. & Pope, J.P. (Iowa Geological Survey) The Riverton core – Iowa's most complete Pennsylvanian section.

Ahern, J.P., Fielding, C.R., & Bottjer, R.J. (UNL/Coal Creek Resources) The Rock Happy core from the Big Snowy Trough, Montana: late Mississippian cyclothems and an unconventional petroleum play.

Joeckel, R.M. & Fielding, C.R. (UNL) CSD Indian Cave State Park-1, a new core through the Indian Cave Sandstone interval of the uppermost Pennsylvanian (Virgilian).

Webb, N.D., Best, J.L. & Fielding, C.R. (Illinois State Geological Survey) Fluvio-tidal incised valley deposits of the Pennsylvanian Caseyville Formation, Illinois – examples from core.

Doveton, J.H. (Kansas Geological Survey) "Paper cores": electrical borehole image logs of the Oread Limestone from southern Kansas.

1:20 – 1:40 pm

CYCLOTHEMS: AN INTRODUCTION

Christopher R. Fielding[1*] and R. M. Joeckel[2]

[1]*Department of Earth & Atmospheric Sciences, 126 Bessey Hall, University of Nebraska-Lincoln, NE 68588-0340.*

[2] *Conservation and Survey Division, School of Natural Resources, Department of Earth & Atmospheric Sciences & University of Nebraska State Museum, University of Nebraska-Lincoln, 615 Hardin Hall, Lincoln, NE 68583-0996.*

**e-mail: cfielding2@unl.edu*

The term "cyclothem" was coined by Wanless & Weller (1932) to describe repetitive stratigraphic successions of Carboniferous age in Illinois. Nonetheless, comparable rhythmicity had been identified in Carboniferous rocks both in the central and eastern USA, and in Europe during the preceding century. Cyclothems were found to comprise repetitive vertical successions of sandstones, heterolithic (thinly interbedded) sandstones and mudrocks, mudrocks, limestones, and coals, in many cases with pedogenic overprinting of these lithologies. As usage of the term "cyclothem" increased, so did the diversity of successions to which the term was applied, to the point where many geologists advocated abandonment of the expression. An example of this misuse was the modified term "continental cyclothem", used to describe alternations of coarse- and fine-grained alluvial and other strata. Using the term "cyclothem" to describe essentially non-cyclic, binary arrays of lithologies is here considered a retrograde step, as it introduces confusion as to what a cyclothem is and represents geologically. The original definition of "cyclothem" as an alternation of marine and nonmarine lithologies, however, is a robust and useful concept, and by this definition cyclothems are largely confined to Carboniferous and Permian systems in the paleotropics of North America and Europe. Their stratigraphic range broadly coincides with the timing of the late Paleozoic Ice Age, and many researchers have postulated that they are a record of eustatically-controlled rises and falls in sea-level associated with waxing and waning of Gondwanan ice centers. We propose a restricted definition of "cyclothems" that is limited to successions that were deposited (1) on low-gradient pericontinental shelves in paleotropical regions, (2) as far-field products of Gondwanan glacial growth and decay at various timescales, and (3) under conditions of low sediment supply in most cases (Fig. 1). As such, they are important archives of late Paleozoic paleoenvironmental change, and the concept can be used in a number of ways. For example, the onset of a cyclothemic motif in stratigraphic successions of late Visean age across Euramerica has been used to infer the onset of the main phase of glaciation in Gondwana. Cyclothems are also important as hosts for economic mineral resources, including oil and gas, coal, lime, water, and base and precious metals.

This symposium introduces Field Conference participants to the nature and variety of cyclothems, and their geology. Papers concern aspects of cyclothems in numerous states of the USA from Illinois in the east to Utah in the west, and from Montana in the north to Texas in the south. Papers describe the stratigraphy, sedimentology, and resource geology of Carboniferous cyclothemic successions, including numerous petroleum-prospective regions and plays. The Field Excursion will allow participants to view well-exposed examples of classical Midcontinent cyclothems in SE Nebraska (the Virgilian--or uppermost Pennsylvanian--Indian Cave Sandstone). The Core Workshop will feature examples of cyclothemic Carboniferous successions from Illinois, Iowa, Nebraska, Kansas, and Montana, some of which are in active petroleum-producing areas.

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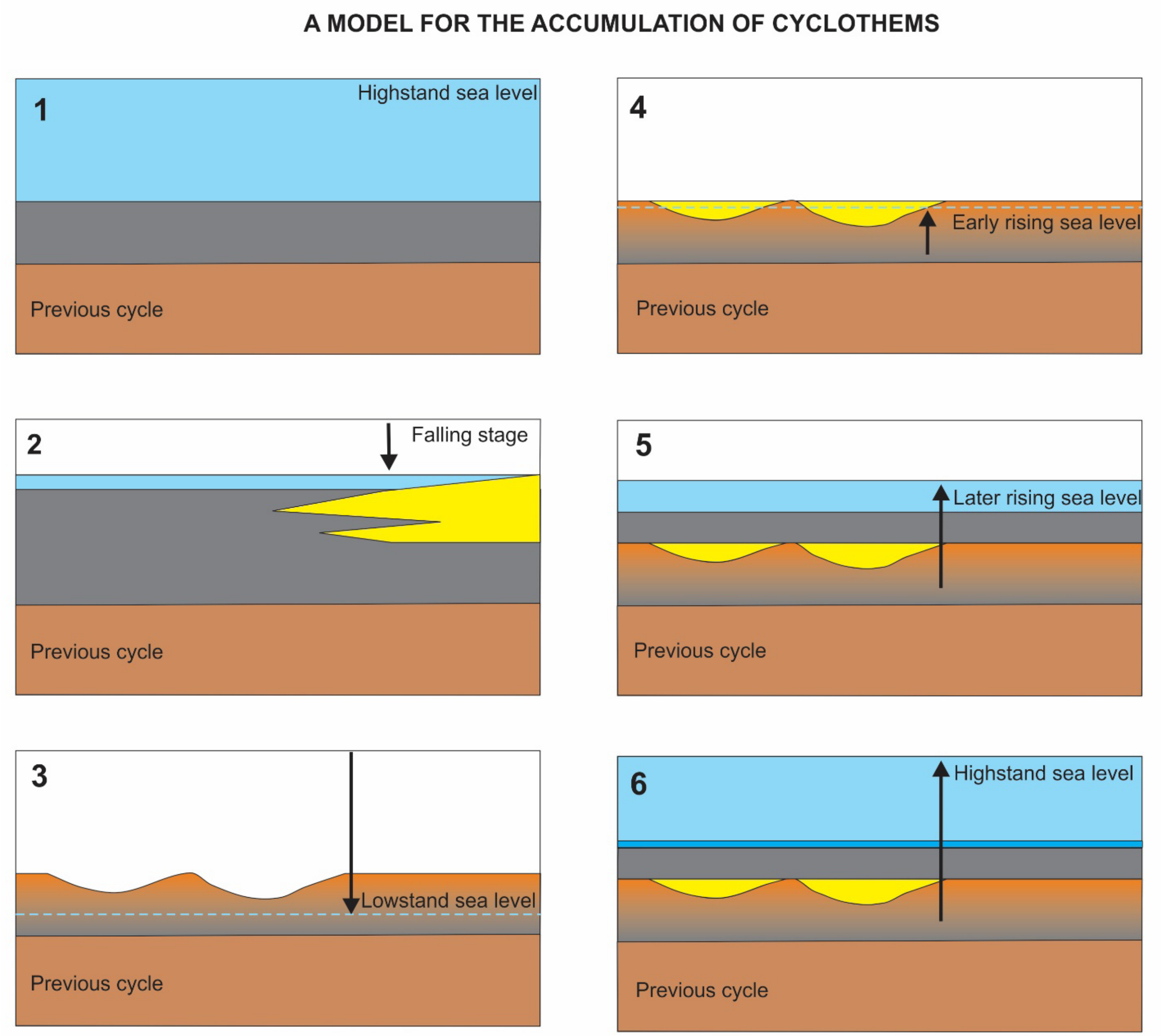

Figure 1. A model for the accumulation of Carboniferous cyclothems in the paleotropical realm. In Stage 1, sea-level is at a eustatic high, coinciding with a minimum in the volume of glacial ice in the (paleo)polar regions. Mud accumulates in nearshore regions, and bioclastic and biochemical carbonate accumulates in warm, shallow seas beyond the reach of clastic sediment. In Stage 2, sea-level falls due to sequestration of water to form ice centers in paleopolar regions. In some regions, coarse clastic depositional systems form forced regressive deltaic and other systems that in many cases are later excised by erosion during continued sea-level fall. In Stage 3, sea level is at a lowstand, coincident with a maximum in Gondwanan glacial extent. Much of the low-gradient shelf is subaerially exposed, leading to erosional degradation and pedogenic modification of surface and near-surface substrate. Valleys are incised by fluvial erosion during Stages 2 and 3. In Stage 4, the sea level begins to rise in response to deglaciation in Gondwana. Sediment accumulation increases, initially in topographic lows (incised valleys) and later more broadly across the transgressed landscape. In Stage 5, the rising sea has drowned the lowstand landscape, leading to the accumulation of mainly fine-grained clastic sediments in shallow marine environments. In Stage 6, sea level reaches a highstand associated with a glacial minimum in Gondwana, leading once again to carbonate accumulation in warm, offshore marine waters with minimal clastic sediment supply. Since such landscapes are inferred to have experienced seasonal tropical or subtropical paleoclimates, sediment supply was low except in regions close to orogenesis (such as the Appalachians). This was a major contributing factor to the modest thickness of the resulting cyclothems, in which intervals as thin as 2 m or less probably record sea-level excursions of tens of metres amplitude.

1:40 – 2:00 pm

OUTCROP TO SUBSURFACE RESERVOIR CHARACTERIZATION OF THE MISSISSIPPIAN PLAY IN THE SCOOP AREA

Benmadi Milad[1*], and Roger Slatt[1]

[1]*ConocoPhillips School of Geology and Geophysics, University of Oklahoma, Sarkeys Energy Center*

100 East Boyd Street, Norman, Oklahoma 73019.

**e-mail: benmadi.milad@ou.edu*

Recently, the Mississippian Formation in the informally-named SCOOP (South Central Oklahoma Oil Province) area has become an important unconventional play in the oil industry. Road cuts made for the interstate Highway 35 in the Arbuckle Mountains exposed a magnificent cross section of the Mississippian strata which can be used for the subsurface reservoir characterizations. The exposed section comprises of 261 ft. of stratigraphic thickness, and its underlying and overlying units of the Woodford Shale and Caney Shale respectively. The lower contact is characterized by the presence of cherts of the upper Woodford Shale. The upper contact of the Caney Shale is sharp and unconformable. The outcrop section provided this study with the opportunity to integrate lithologic, Scanning Electron Microscopy (SEM), geochemical, and fracture analyses in an investigation into the reservoir quality of the formation to be used for subsurface exploration and development.

Externally, at the outcrop scale, four sections can be recognized in the I-35 Sycamore outcrop: the lower "transition" section is composed of bioturbated siliceous mudstone, the second section is composed of dolomitic siltstone, the third is siliceous mudstone, and the upper section consists of massive calcareous siltstone. Internally, at the bed scale of the Sycamore strata, five lithofacies were recognized, considering textural and compositional attributes based on outcrop observations, petrographic, X-ray Diffraction (XRD), X-ray Fluorescence (XRF), Scanning Electron Microscopy (SEM) analyses from ten samples. The lithofacies are: siliceous mudstone, bioturbated siliceous mudstone, dolomitic mudstone, siliceous dolomitic calcite-cemented peloidal siltstone, and massive calcite-cemented peloidal siltstone.

Fracture orientations and intensities were obtained from the outcrop. Two fracture sets were observed and restored to the horizontal bed in order to predict the fracture orientations in the subsurface. Set-1 strikes N18E and dips 85SE, whereas set-2 strikes N63W and dips 80NE. Fracture intensity was calculated at each bed when possible. Most fractures are filled with calcite, but some contained bitumen.

The Rock Eval Pyrolysis analyses of seven samples reveal that the I-35s Sycamore intervals are dominated by apparent type II and type III kerogen (oil prone and oil/gas prone) with an average Tmax of 440ºC. The production data from a nearby well shows oil and gas production from the Sycamore interval. Total organic matter ranges from 0.1 to 1.5 wt %.

Vertical stacking of lithofacies tied with the hand-held Gamma Ray profile and correlated well with one of the nearby subsurface GR logs. Therefore, outcrop studies can be used directly for the subsurface exploration and development programs.

The geological assessment of reservoir quality was assessed using the lithofacies, fracture analyses, and geochemical analyses. The bioturbated siliceous mudstone can be a potential target zone due to the presence of pore spaces, relatively high TOC (up to 1.5 wt. %) compared to other lithofacies, and a higher amount of quartz (more than 45%). Statistically, the bioturbated siliceous mudstone represents 35% of the lithofacies' presence.

Acknowledgements

This work was supported by the Woodford Consortium Project at the Institute of Reservoir Characterization. We thank our consortium sponsors for their support of this research.

2:00 – 2:20 pm

LATE CARBONIFEROUS CYCLOTHEMS IN THE CLARE BASIN, WESTERN IRELAND; THEIR STRATIGRAPHIC ARCHITECTURE AND IMPLICATION FOR RESOLUTION OF GLACIO-EUSTASY

Andy Pulham

Earth Science Associates C&T Inc., Boulder, Colorado, USA

pulham.andy@gmail.com

The coast of West County Clare, Ireland comprises near continuous exposures of Carboniferous age stratigraphy. Mississippian shelfal carbonates are overlain by a siliciclastic succession that culminates in Lower Pennsylvanian fluvio-deltaics; the Central Clare Group (Figure 1). There has been a long history of research investigations concerning the sedimentology and stratigraphy of the Central Clare Group, initiated by Rider (1969).

The Central Clare Group exhibits a distinctive cyclic sedimentation and is subdivided into five cyclothems, the lower three of which are named (Figure 1). Classic Carboniferous cyclothems of Western Europe are bounded by thin, dark and often organic-rich mudstones that contain marine fauna, including ammonoid zonal species; termed Marine Bands. The sedimentology of Carboniferous cyclothems has until recent decades been interpreted as representing an initial deepening, culminating in a Marine Band, followed by overall shallowing of settings from fully marine to marginal marine and/or continental.

The fundamental influence of glacio-eustatic forcing on the cyclothem stratigraphy of the Carboniferous has also been long recognised and in recent years has been the subject of investigations into the signals of relative sea-level change that are recorded in cyclothem architectures; e.g. Waters and Condon (2012). Central Clare Group cyclothems are early Morrowan and are in one of the higher resolution periods of ammonoid zones in NW Europe; ~520Ka, and for Marine Bands ~150Ka; e.g. Korn and Klug (2015). These average cyclicities indicate a possibly strong climatic component driven by the eccentricity of the Earth. In the early Morrowan temporal spacing of Marine Bands is considered shorter than the average; ~100Ka.

The basin position and paleogeographic context of the Central Clare Group cyclothems provide a somewhat unique stratigraphic record of early Morrowan deposition. (1) Accommodation was very high and driven by rapid compaction and rapid post-rift tectonic subsidence. The first two cyclothems have a combined thickness of up to 400m (1,300ft), much thicker than equivalent Carboniferous stratigraphy of Western Europe. (2) Fluvial discharge was copious with an estimate of drainage basin size of ≥500,000 km^3; similar in scale to the modern Ohio or Columbia river valleys. (3) The coastal sections reveal a regional strike section through the cyclothems with Variscan (Alleghenian) folding resulting in repeated profiles. This perspective allows a best opportunity to distinguish between local autocyclic patterns in sedimentation versus those that are controlled by external controls, such as glacio-eustasy.

Analyses of marine flooding surfaces in the Central Clare cyclothems reveals a hierarchy. The most important flooding surfaces, the Marine Bands, are interpreted as maximum flooding surfaces (MFS) and contain the zonal ammonoids. In at least two cases, there are two Marine Bands in a single cyclothem. Secondary MFS are recognised within cyclothems and comprise fossil bands that generally lack the ammonoids, but have brachiopod macrofauna. Below the MFS in importance are brachiopod fossil bands with rare ammonoids which mark the onset of regional transgressive episodes. The lowest order flooding surfaces yield little or no macrofauna and mark switches in depositional focus and are diachronous along strike. Sequence boundaries are also recognised and are either erosive bases of fluvial-dominated incised valleys or are interfluves.

Stratigraphic hierarchy of the Central Clare Group reveals that single cyclothems comprise at least two and up to three cycles of sea-level change (Figure 2). This cyclicity strongly suggests obliquity and precession controls on early Morrowan glaciations; ~41Ka and ~23Ka cycles, and the potential exists to document the interference pattern of climatic variations and waxing and waning Gondwanan ice for this time period. Recent coring in the deep-water stratigraphy immediately below the Central Clare Group is also revealing a hierarchy of flooding surfaces previously unrecognised at outcrop. The western Ireland record could provide a high resolution template for marine early Morrowan stratigraphy.

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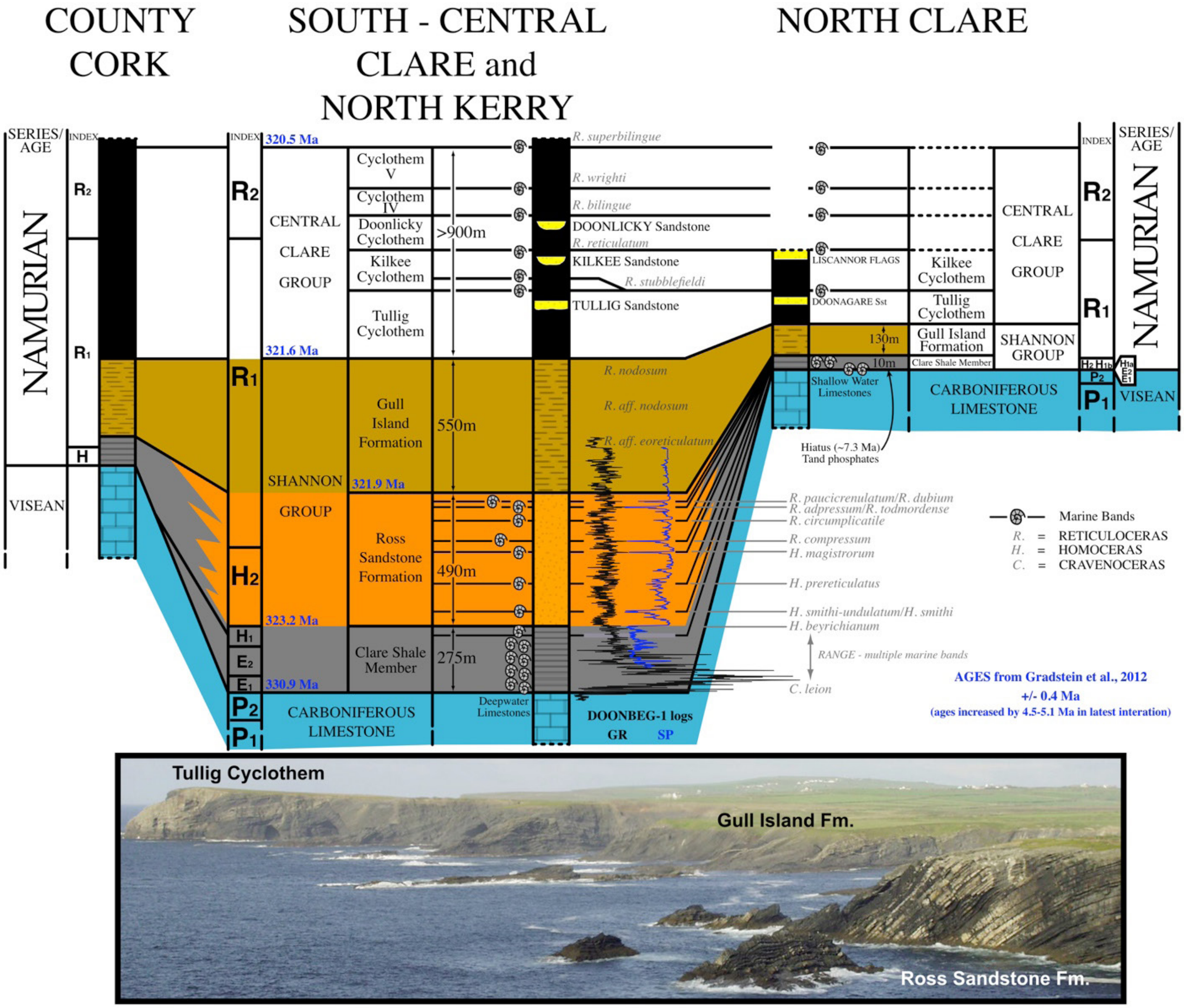

Figure 1. The Central Clare Group exhibits a distinctive cyclic sedimentation and is subdivided into five cyclothems, the lower three of which are named.

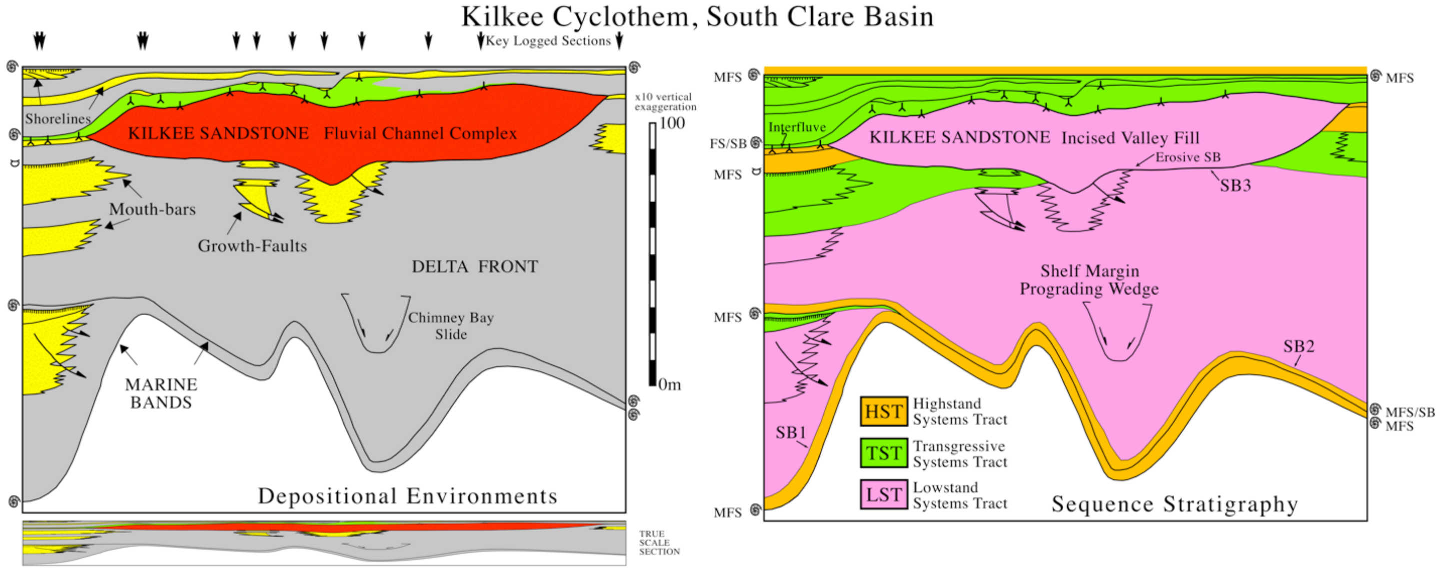

Figure 2. Stratigraphic hierarchy of the Central Clare Group reveals that single cyclothems comprise at least two and up to three cycles of sea-level change.

2:20 – 2:40 pm

BOGGY FORMATION SEQUENCE STRATIGRAPHY ACROSS THE CHEROKEE PLATFORM AND ARKOMA BASIN OF OKLAHOMA

Dennis R. Kerr[1] *

The University of Tulsa

[1]Department of Geosciences, 800 South Tucker Drive, Tulsa, Oklahoma 74104, USA.

**dennis-kerr@utulsa.edu*

Boggy Formation (Desmoinesian Stage), including its lithostratigraphic subdivions[1,2], is composed of at least three stratigraphic sequences[3,4,5,6,7] (Fig 1). Sequence boundaries (SB) are recognized at the base of the Bluejacket Sandstone, and at base of unnamed sandstone in middle Boggy. The stratigraphic sequences are referred to as lower Boggy, middle Boggy and upper Boggy, respectively. The lower Boggy sequence is distributed across the Cherokee Platform and into the Arkoma Basin. The middle Boggy is best developed in the Arkoma Basin where it is truncated above by the sub-Cabaniss regional unconformity[1] in western Arkoma Basin and upper Boggy SB in eastern Arkoma Basin[7]. The upper Boggy is not as well studied but it is recognized in eastern Arkoma Basin[7] and is developed across parts of Cherokee Platform[4] where it is truncated by the sub-Chelsea Sandstone SB[4,8].

Lower Boggy systems tracts include a variety of facies (Fig 2). The lowstand systems tract (LST) is exemplified by outcrops at the north abutment of Eufaula Lake Dam[3,9] (Fig 3) where: 1) braided fluvial facies rest above Savanna Formation middle shelf facies; 2) erosional stratal terminations below and onlap terminations above SB; 3) as much as 23 m of local erosional relief[3]. In eastern Arkoma Basin OK-82 exposures in San Bois Mountains, LST is represented by shoreface progradational parasequences (PS)[7]. The transgressive systems tract (TST) is made up of diverse set of facies. In eastern San Bois Mountains the TST facies include central and marginal estuarine, coal mires, lagoonal and foreshore-shoreface, and on upward to inner shelf dark gray mudstones and HCS sandstones arranged in retrogradational and aggrational PS sets[7]. To the west at Robbers Cave State Park, TST is expressed as retrogradational PS sets of bayhead delta facies[3] (Fig 2). Continuing northward on across the Cherokee Platform, the TST is dominated by meandering fluvial facies that include ever increasing tidal influences in exposures in the south and stratigrapically higher to the north[3]. The OK-20 road cuts west of Pryor, OK, also provide views of TST meandering fluvial facies[10,11]. Lower Boggy LST and TST described thus far are confined to the erosional limits of an incised paleo-valley[3]. The superjacent TST is interstratified carbonaceous mudrocks and open shelf limestones[3,12]. The Inola is regarded as a compressed section deposited across the entire Cherokee Platform once relative sea level surmounted the incised valley interfluvs. Highstand systems tract (HST) is not well represented in outcrop and is mainly inferred from well logs[4,8]. Limited preservation of HST is in part due to subsequent erosion at the base of the middle Boggy sequence.

Middle Boggy sequence systems tracts are exposed near Eufaula, OK and OK-82 road cuts eastern San Bois Mountains[5,7,13]. LST is represented by braided fluvial facies resting above more distal shelf facies. In most places, the erosional relief along the basal disconformity is less compared to the lower Boggy SB. An exception is in the vicinity of the Warner Uplift where the sub-middle Boggy disconformity creates an erosional vacuity that cuts downward through the Inola, Secor Rider, Secor and nearly to the base of Bluejacket[6] (Figure 2). Similar erosional relief is noted for the south limb of the San Bois syncline in exposures along OK-82[7]. TST consists of meandering fluvial deposits and coals in Eufaula area[5,6], and by much thicker central basin estuarine facies in eastern San Bois Mountains[7]. In the Eufaula area, the mfs occurs at the top of a myalinid rudstone that is overlain by carbonaceous mudstone. Also here, the HST is made up meandering fluvial facies..

Upper Boggy is better represented in subsurface[4] of Cherokee Platfrom where the transgressive surface and SB are coincidental. The Tiawah Limestone is associated with compressed section. In the eastern San Bois Mountains, the LST is represented by braided fluvials, the TST by central basin estuarine facies[7]; the entire sequence is not preserved due to modern erosion.

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Acknowledgements

Numerous graduate students (see citations above) greatly contributed to this research. Special thanks go to Scott Ye who initiated the entire sequence stratigraphy thought – a break from the cyclothem paradigm.

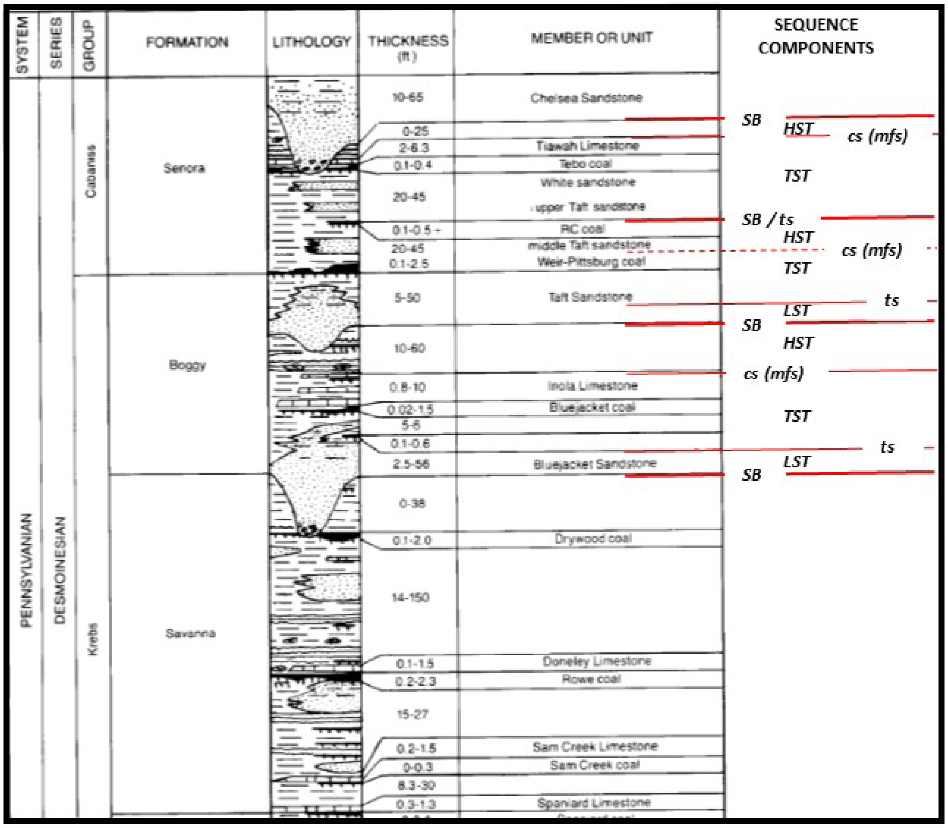

Figure 1. Boggy sequence components tied to lithostratigraphic terms in common use[2]. Abbreviations are: SB = sequence boundary; ts = transgressive surface; cs (mfa) = compressed section, maximum flooding surface; systems tracts are same in caption for Figure 2.

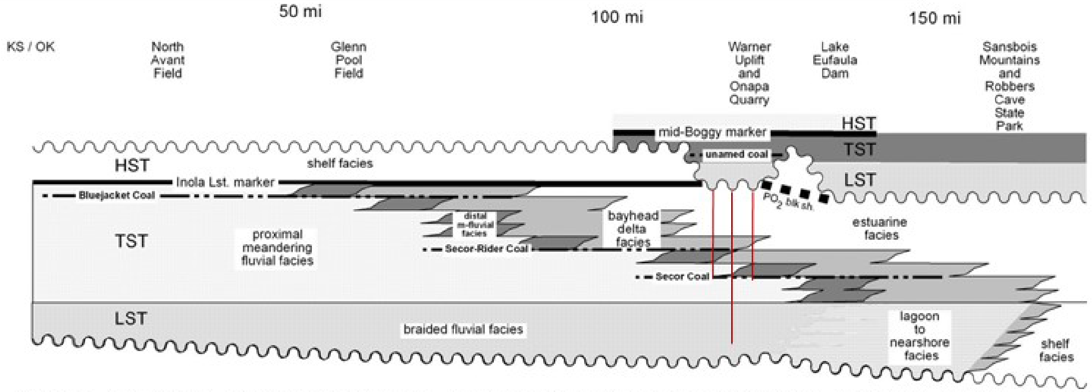

Figure 2. Lower and middle Boggy sequence stratigraphy schematic diagram. Cross section extends from KS/OK state line southward across Cherokee Platform and on into Arkoma Basin (approximate distance from stateline shown at top). Vertical dimension is not drawn to scale in order to illustrate facies components of each systems tract (LST = lowstand; TST = transgressive; HST = highstand). Sub-middle Boggy sequence boundary locally erodes deeply into lower Boggy sequence (red vertical lines indicates magnitude of erosional vacuity) in the vicinity of Warner Uplift.

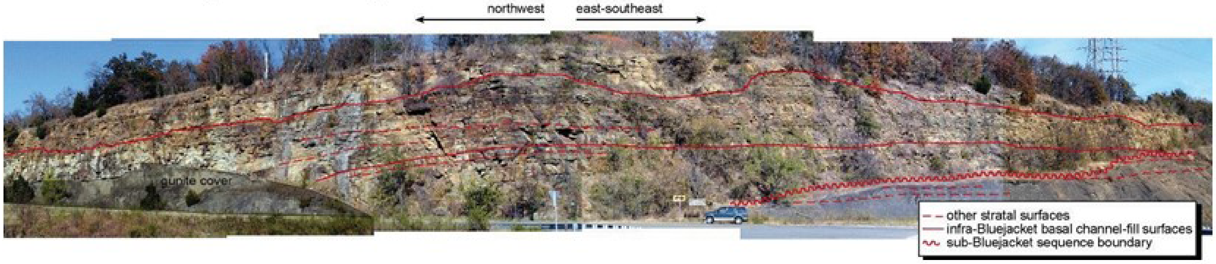

Figure 3. Photopan of Bluejacket Sandstone exposure at north abutment of Eufaula Lake Dam. Note local erosional relief at sequence boundary with underlying Savanna Formation middle shelf gray mudstones (in lower right), and stratal terminations along sequence boundary (erosional below; onlap above).

2:40 – 3:00 pm

TRANSGRESSIVE SHOREFACE EROSION, TRANSLATION, AND WAVE RAVINEMENT ON AN EPEIRIC SHELF AS RECORDED BY A SOIL NODULE CONGLOMERATE-ARENITE IN THE UPPER PENNSYLVANIAN OREAD CYCLOTHEM, SE KANSAS AND NE OKLAHOMA

W. Yang[1*]

[1]*Department of Geology, Wichita State University, Wichita, KS 67260*

**e-mail: wan.yang@wichita.edu*

Transgressive deposits of the Leavenworth-Heebner-Plattsmouth-Heumader minor cyclothem of the Oread Cyclothem overlie multi-story Calcisols and Vertisols and consist upward of thin Gleysol, conglomerate-arenite (5-25 cm), and fossiliferous shale and Leavenworth Limestone (1-2 m). The conglomerate-arenite is present in 15 outcrop sections covering 100 km, and 76 wells and cores in SE Kansas and NE Oklahoma. It is a single bed with conformable lower and upper contacts, composed of blackened clasts (80-95%), bedding-plane-parallel fossil fragments (5-20%), and rare coal fragments. Clasts are rounded, equant-to-elongate, coarse-sand-to-pebble size, and moderately sorted, including micritic and radial-fibrous calcite grains, and pisoids. Micritic grains contain quartz silt, radiating and concentric spar-filled cracks, and rounded central molds with micrite or spars. Pisoids have micritic-clast cores and superficial micritic or ferruginous clay cortexes. They have the same texture and composition as pebble-sized calcitic nodules, rhizoliths, and clasts of a channel-fill conglomerate in underlying paleosols and were probably derived from soil nodules.

Landward and upward shoreface translation during early transgression on a fluvial peneplain eroded underlying paleosols and coeval early-transgressive deposits landward of the shoreline. Excavated soil nodules were reworked and transported to inner shelf by storm return flows and concentrated as a transgressive lag, forming soil nodule conglomerate-arenite. The base of the conglomerate-arenite is a wave ravinement surface, under which Gleysols formed by leaching and reworking of underlying paleosols by seawater. The persistent conglomerate-arenite suggests extensive transgressive ravinement on the gentle Kansas Shelf. The transgressive record is a T-C1 succession with a simple transgressive lag, composed of mixed carbonate and siliciclastic rocks.

3:00 – 3:20 pm

A PALEOTROPICAL RECORD OF CARBONIFEROUS SEA-LEVEL AND PALEOCLIMATE OSCILLATIONS IN WESTERN LAURENTIA: DOCUMENTING THE INTERACTIONS OF ICE DYNAMICS, PLATE MIGRATION AND CLIMATE PATTERNS

Justin Ahern[1] & Christopher R. Fielding[1]

[1]*University of Nebraska- Lincoln, 1400 R St, Lincoln, NE 68588, USA*

** justin.ahern@huskers.unl.edu; cfielding2@unl.edu*

The late Paleozoic stratigraphy of the Big Snowy Mountains in central Montana and Unita Mountains in northeast Utah preserve some of the most complete Carboniferous stratigraphic records from paleotropical latitudes of western Laurentia (Fig. 1). The sedimentary records observed in this study both commence at the Madison Group karst surface (Visean) and terminate in the Alaska Bench Formation (Bashkirian) in central Montana and the Weber Formation (Moscovian to Permian)

in northeast Utah (Fig. 2). The late Mississippian (Serpukhovian) interval of these successions preserve cyclothemic strata in central Montana (Heath Fm.) and Utah (Manning Canyon Fm.) that broadly coincide with current estimates of the onset of Late Paleozoic Ice Age (LPIA). The LPIA was ~76 myr icehouse period when ice centers waxed and waned during asynchronous (Cagliari et al., 2016) glaciations across Gondwana, resulting in complex glacio-eustatic sea-level oscillations (Veevers & Powell, 1987; Isbell et al., 2003; Fielding et al., 2008; Montañez & Poulsen, 2013) from the late Mississippian to the late Permian. As the only record of the transition of a vegetated Earth both into and out of a long-lived icehouse regime, and a proposed analog for the Quaternary icehouse (Raymond & Metz, 2004), the LPIA has furnished decades of research; however, this event still remains incompletely documented. Sedimentologic and stratigraphic analysis of the Heath and Manning Canyon Formations in addition to enclosing strata permits an appraisal of late Paleozoic climate change and sea-level oscillations in western Laurentia.

Formations from both study areas will henceforth be summarized from oldest (Visean) to youngest (Gzhelian). The upper Madison Gp. contains silicified and brecciated limestone overprinted by karst that is overlain by the Humbug Formation in northeast Utah and by the Kibbey and Otter Formations in central Montana. The Humbug predominately consists of variably bioturbated cross-bedded and rippled quartz arenite with stochastic intervals of silicified and brecciated microbialite and peloidal micrite. The Kibbey contains red channel-form clastics and brecciated limestone that grade into randomly dispersed intervals of micrite, oolite, wackestone, brecciated microbialite, and silicified, carbonate-bearing paleosol of the Otter Formation.

The Heath and Manning Canyon Formations contain cyclothemic packages of shale, sandstone, and clastic, argillaceous limestone herein interpreted within the context of a protected, muddy, homoclinal carbonate ramp. Paleosol and coal are coastal plain and mire facies preserved in the upper Manning Canyon and lower Heath, whereas microbialite and anhydrite are peritidal facies exclusive to the upper Heath. Regional-scale sandstone beds of the Tyler Formation incise into the Heath and contain intervening coaly shale, log casts, siderite-bearing paleosols, and minor ironstone that grade into repetitive sequences of limestone, red siltstone, and silicified microbialites of the Alaska Bench Formation. In Utah the Manning Canyon is overlain by cyclic alterations of marine limestone, silicified microbialite and mudstone of the Round Valley Formation. A mature, regional-scale paleosol marks the transition in to the cyclic alterations of marine limestone, carbonate-bearing paleosol, red siltstone with desiccation and rain drop impressions, and mixed coastal and eolian sandstone of the Morgan Formation, which grade into the predominately cross-bedded eolian sandstone of the Weber Formation.

Discussion:

The Carboniferous stratigraphic records of the Big Snowy and Uinta Mountains are herein interpreted to record a broad long-term progression from humid and seasonally humid climates to arid climates throughout the extent of the Carboniferous (Fig. 1&2). This first order humid to arid trend is best explained by northern plate migration of western Laurentia though progressively more arid climate belts during the Carboniferous. Discrete ≤5 myr intervals of alternating arid to humid conditions (Fig. 2&3) that stray from the first order pattern of progressive aridity previously described are here interpreted to reflect the influence of discrete periods of ice center expansion and contraction (C1-C4 of Fielding & Frank, 2008) on low-latitude paleoclimate patterns. According to Miller and Eriksson (1999) periods of glacial ice accumulation would concentrate moist low pressure cells at paleo-low latitudes, broadly resulting in more humid paleoclimates. Conversely, during periods of glacial ice contraction, the dilation of moist low-pressure cells would promote climates of increased seasonality and aridity in the paleotropics (Eriksson, 1999). Considering the climate models of Peyser and Poulsen (2008), variations in cross-hemispheric temperature gradients are more pronounced during glacial episodes as compared to non-glacial episodes. In turn, this phenomenon would have driven intensified Hadley convection, resulting in higher precipitation rates at low latitudes during glacial periods as compared to non-glacial episodes. Current stratigraphic and sedimentologic evidence from this study is in agreeance with the findings put forth by Miller & Eriksson (1999) as well as Peyser & Poulsen (2008).

A sustained arid climate shift is observed in the Alaska Bench Formation (Bashkirian) of central Montana, whereas a comparable shift is not observed in northeastern Utah until the Moscovian (Fig. 2&3). An inferred ~10° difference in paleolatitude between the study areas, coupled with persistent northward plate migration into increasingly arid climate belts is likely a primary factor in the temporal offset of these sustained arid climate shifts. Additionally, the inferred ~10° variance in paleolatitude of central Montana and northern Utah during the Carboniferous shows that northeastern Utah (Fig. 1) was consistently more centrally located within paleotropical humid climate belts than was central Montana during the late Mississippian and early Pennsylvanian. Considering this attribute, northeastern Utah was less susceptible to oscillations in the width of moist low-pressure cells (Miller & Eriksson, 1999) during glacial and non-glacial episodes than was central Montana, which is inferred to have occupied the boundary between tropical and arid climate belts (Fig. 1)

Furthermore, current estimates of LIPA onset are broadly coeval with distinct arid to humid shifts preserved in the late Mississippian stratigraphy of central Montana and northeastern Utah, in addition to numerous other basins at this time (Fig. 3). This arid to humid paleoclimatic signal near the main onset of the LPIA provides further evidence that ice center expansion during the Carboniferous enforced climates of increased humidity in the paleotropics, which served as a prelude to the influence that Gondwanan ice dynamics would have on late Paleozoic climate patterns that followed.

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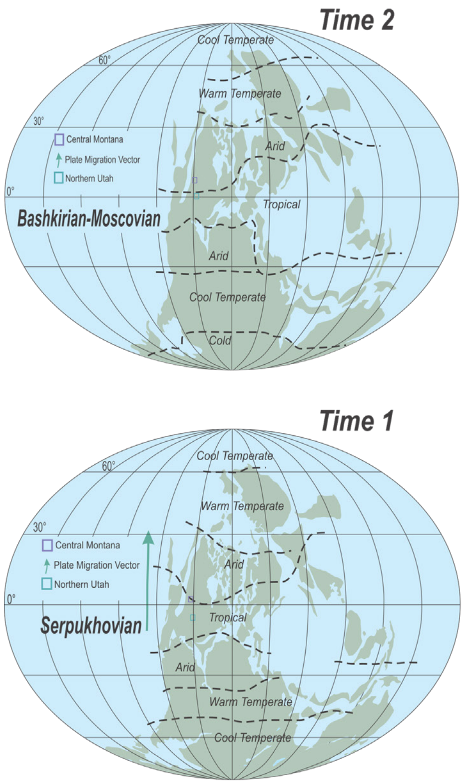

Fig. 1) Paleogeographic maps that outline broad, global climate belts during deposition of the Heath & Manning Canyon Formations- ***modified after*** Boucot et al. (2013). Progressive northward plate migration continued throughout the Carboniferous (Boucot et al., 2013), which forced central Montana and later, NE Utah, from tropical to arid climate belts, a plausible mechanism responsible for the humid-arid shift preserved in the stratigraphic records of central Montana and northern Utah.

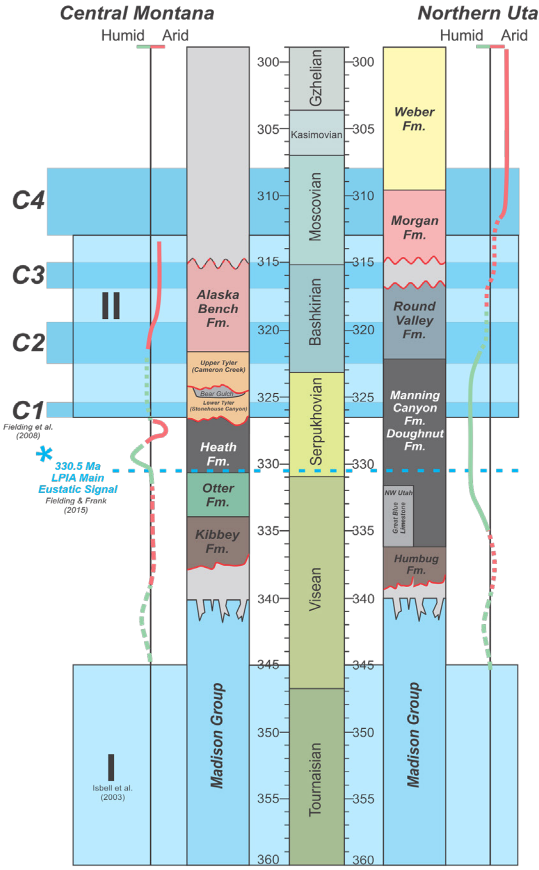

Fig. 2) Idealized depiction of observed Carboniferous stratigraphy in central Montana and northern Utah coupled with inferred paleoclimate trends determined from sedimentologic indicators recorded during this study. Carboniferous glacial intervals of Isbell et al. (2003) (I-II), Fielding et al,. (2008) (C1-C4), and the inferred main eustatic signal of the LPIA (Fielding & Frank , 2015) are provided so that a direct comparison of Gondwanan ice dynamics and paleoclimate trends can be observed.

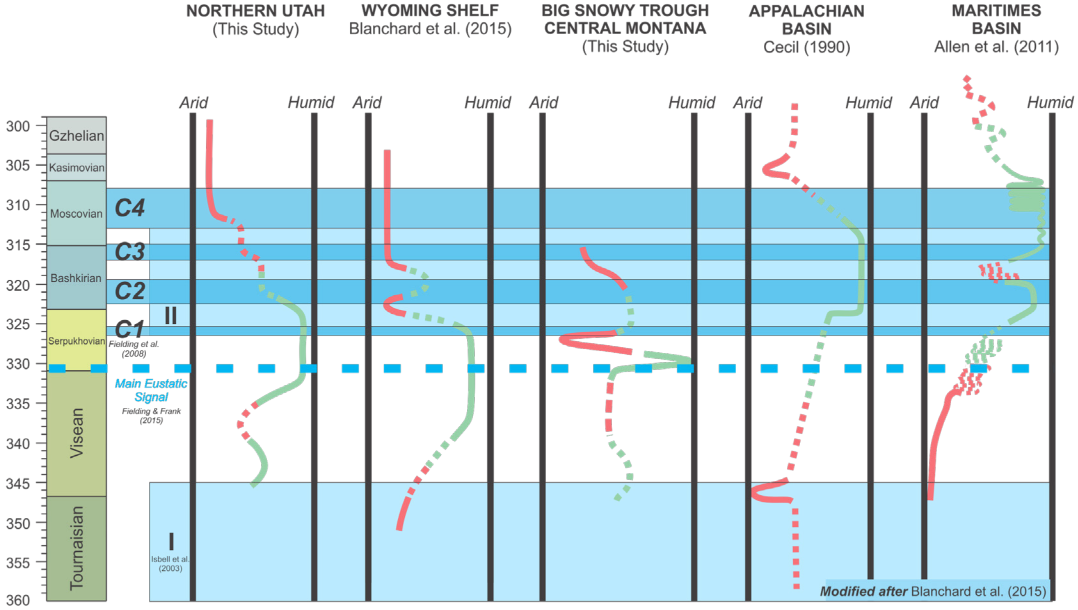

Fig. 3) Idealized depiction of Carboniferous paleoclimate trends from sedimentary basins throughout Laurentia ***modified after*** Blanchard et al. (2015). Inferred Carboniferous glacial intervals of Isbell et al. (2003) and Fielding et al. (2008) are provided in addition to estimated onset of the main eustatic signal of the LPIA (Fielding & Frank, 2015). Note the broad shift to more arid conditions throughout the Carboniferous that is interpreted to reflect the influence of northward plate migration through progressively more arid climate belts (Blanchard et al., 2015). Additionally, a distinct humid shift is preserved in numerous basins at the inferred timing of the main eustatic signal of the LPIA. Furthermore, note the broad pattern of coeval humid paleoclimates with the discrete glacial intervals of Fielding et al., (2008).

Sequence Stratigraphic Controls on Lower to Middle Carboniferous Siliciclastic Deposition in the “STACK” Play, North-Central Oklahoma, USA

J. Bynum[1],*

Oklahoma State University

[1]PhD Candidate, Oklahoma State University, 105 Noble Research Center, Stillwater, Oklahoma, USA.

**Jamar.Bynum@okstate.edu*

The STACK play in North-Central, Oklahoma is one of the most prolific hydrocarbon producing plays in North America. Recent production is concentrated within the Lower to Middle Carboniferous strata, which is a mixed siliciclastic and carbonate depositional system. The global transition from the Visean carbonate dominated world to the Serpukhovian siliciclastic dominated world can be identified within multiple cored wells in the STACK play. A sequence stratigraphic model based on these cored wells exemplifies harmonic progression of 2nd, 3rd, and 4th order sea level cycles along with their impact on carbonate vs siliciclastic deposition. The Kaskaskia 2nd order transgressive systems tract progresses through the Devonian into the Lower Carboniferous, Tournaisian, which resulted in the widespread deposition of organic-rich fine-grained siliciclastics during this maximum flooding interval. This was followed by a transition to a stable high stand systems tract in the Lower Carboniferous, Upper Tournaisian through Upper Visean, which allowed for re-establishment of a carbonate depositional system. Later, this carbonate system was choked out by the influx of siliciclastics during the low stand systems tract in the Middle Carboniferous, Serpukhovian. From here reservoir compartmentalization occurs within STACK due to superimposition of higher frequency 3rd and 4th order cycles on the Kaskaskia 2nd order cycle. Harmonic coupling occurs in the late Visean where a 3rd order low stand coincides with the 2nd order highstand. This was the last progradational push of the carbonate system and marks the onset of the siliciclastic influx. Serpukhovian deposition is dominated by the 2nd order lowstand systems tract, and exhibits higher frequency 3rd and 4th order cycles that are dominated by siliciclastic deposition instead of carbonate deposition. This has significant implications because the reservoir quality within the STACK play will be driven by different variables and parameters depending on where the targeted interval is located within this sequence stratigraphic framework.

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Acknowledgements

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3:40 – 4:00 pm

FLUVIO-TIDAL INCISED VALLEY DEPOSITS OF THE PENNSYLVANIAN CASEYVILLE FORMATION, ILLINOIS

N. D. Webb[1,*], C. R. Fielding[2], J. L. Best[3]

[1]Associate Research Scientist, Petroleum Geologist, Illinois State Geological Survey, Prairie Research Institute,

University of Illinois at Urbana-Champaign, 615 E. Peabody Dr., Champaign, IL, USA

[2] Professor, Coffman Chair, Department of Earth & Atmospheric Sciences,

University of Nebraska-Lincoln, 214 Bessey Hall, Lincoln, NE 68588, USA.

[3] Jack and Richard Threet Professor of Sedimentary Geology, Department of Geology,

Natural History Building, University of Illinois at Urbana-Champaign, 1301 West Green Street, Urbana, IL 61801, USA.

**e-mail: ndwebb2@illinois.edu*

Caseyville Formation strata preserve a succession, deposited along the systemic (Mississippian-Pennsylvanian) sub-Absaroka unconformity surface, which reflects: intraplate tectonics and differential subsidence related to the Alleghenian Orogeny; and the far-field record of climate change and eustatic sea-level fluctuations related to Gondwanan glaciation. The interplay between tectonic, base-level, and climate driven controls on sedimentation were addressed by performing a subsurface study using a process stratigraphic approach to develop a geological conceptual model for the study area. Creating the geological conceptual model required the development of a stratigraphic framework with a detailed understanding of dimensions and architecture of the sedimentary bodies, the sedimentology, and associated reservoir properties. The construction and analysis of a robust subsurface dataset of over 6,500 geophysical well logs and 100 cores over a ~700 km^2 area were used to determine the nature of the facies that comprise the succession and allow examination of the relative controls on sedimentation. Cores were described and lithofacies were calibrated against the wireline logs, and both cores and wireline log facies were used to subdivide and correlate the paleovalley fill succession.

In southeastern Illinois, the Caseyville Formation consists of a 60 to120 m thick succession of fluvio-tidal valley-fill and coastal plain deposits. The Caseyville Formation was deposited in channels and on interfluves of a bedrock confined coastal plain incised valley system found along the sub-Absaroka unconformity. The unconformity surface was reconstructed through the correlation and mapping of geophysical logs across the study area. Though a complex system of southwestwardly oriented paleovalleys have been previously mapped for the basin, new mapping in the study area provided higher resolution, highlighting additional smaller-scale valley segments, the diversion of valleys around anticlines and aligned with faults, and significantly, the magnitude of topography on the unconformity surface (Figure 1). The geometry of the multi-threaded paleovalley system was influenced by local tectonic movements; some of the valleys cut obliquely across areas of contemporaneous uplift as antecedent rivers while others were routed through saddles between tectonically-controlled structures. The aspect ratio of the paleovalleys reflect this relationship. Where cutting across anticlines, the valley widths narrow from 4-5 km wide to less than 1 km and their depth increases. Incision into the underlying bedrock of 30 m or more is common.

Paleovalley fills generally consist of ribbon-shaped sandstone bodies encased in mudstone (Figure 2) that occur in three main facies associations: 1) Fluvial sandstone occurs along the axis, or sides, at the base of the paleovalleys and are generally medium- to coarse-grained, planar cross-bedded and ripple bedded sandstones that lack shaley interbeds and exhibit basal lag gravels. In some places, a second fluvial sandstone element can occur higher within the paleovalley fill. These sandstones possess a high porosity and permeability, making them a high quality reservoir rock. These fluvial sandstone bodies are generally up to 10 m thick, 1 km wide, and 3-5km long where they wedge out up and down valley and underfill the paleovalley in which they occur. The sandstones are generally completely isolated and are not connected to other sandstone bodies, leading to a high degree of reservoir compartmentalization and an opportunity for hydrocarbon trapping. 2) Heterolithic tidally-influenced fluvial facies comprise interbedded silty sandstones and shales that exhibit rhythmic laminations, synaeresis cracks, and contain an assemblage of diminutive and low diversity trace fossils indicating increasing tidal modulation. These facies overlie the fluvial sandstones. 3) Estuarine central basin facies consist of a succession of dark grey siltstone/mudstone strata with interbeds of highly disturbed to well preserved pinstripe laminated sandstone and shale. Embedded sandstone lenses usually have lenticular bedding, may contain clay/siderite chips, and have common syneresis cracks. The estuarine central basin facies dominates the valley fill succession, in some places constituting up to 70% of the fill, reaching thicknesses of 40 m or more, and often extends beyond the paleovalley boundaries over a larger spatial extent. In interfluve areas, the estuarine central basin facies overlie sheet-like Caseyville sandstone bodies that rest directly on the unconformity surface and exhibit coarse grains and quartz granules.

Observations from core and log correlations are the basis for a new model for deposition within the basal Pennsylvanian paleovalleys. Fluvial down cutting was responsible for the development of significant paleotopography of the unconformity surface. This incision was caused by a global sea-level lowstand, but localized alignment of the drainage system was impacted by contemporaneous differential subsidence and displacement along faults. The underfilling of the paleovalleys with coarse-grained sediment indicates a limitation of fluvial sediment supply. The dominance of estuarine strata and the backfilling of paleovalleys with relatively short fluvial sandstones that thicken downstream indicates the overall setting to be transgressive, reflecting a base level control on sedimentation. Tidal influence is pervasive in the facies transition from fluvial to estuarine and throughout the central basin facies, but the presence of a central basin indicates a degree of wave influence with a hypothetical offshore barrier providing a protected setting in which the fine grained sediments could accumulate.

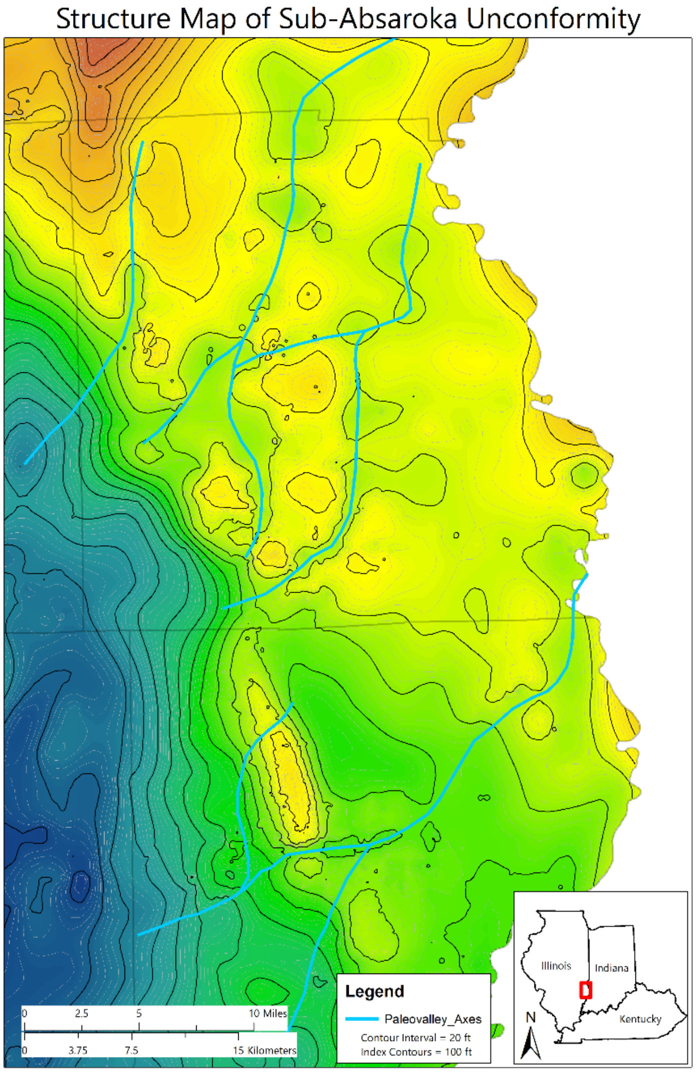

Figure 1. Map of Sub-Absaroka unconformity structure. Paleovalley network is highlighted with blue lines delineating the axes of the valleys. Paleovalleys can be observed being routed between or cutting through positive structures.

References

None

Acknowledgements

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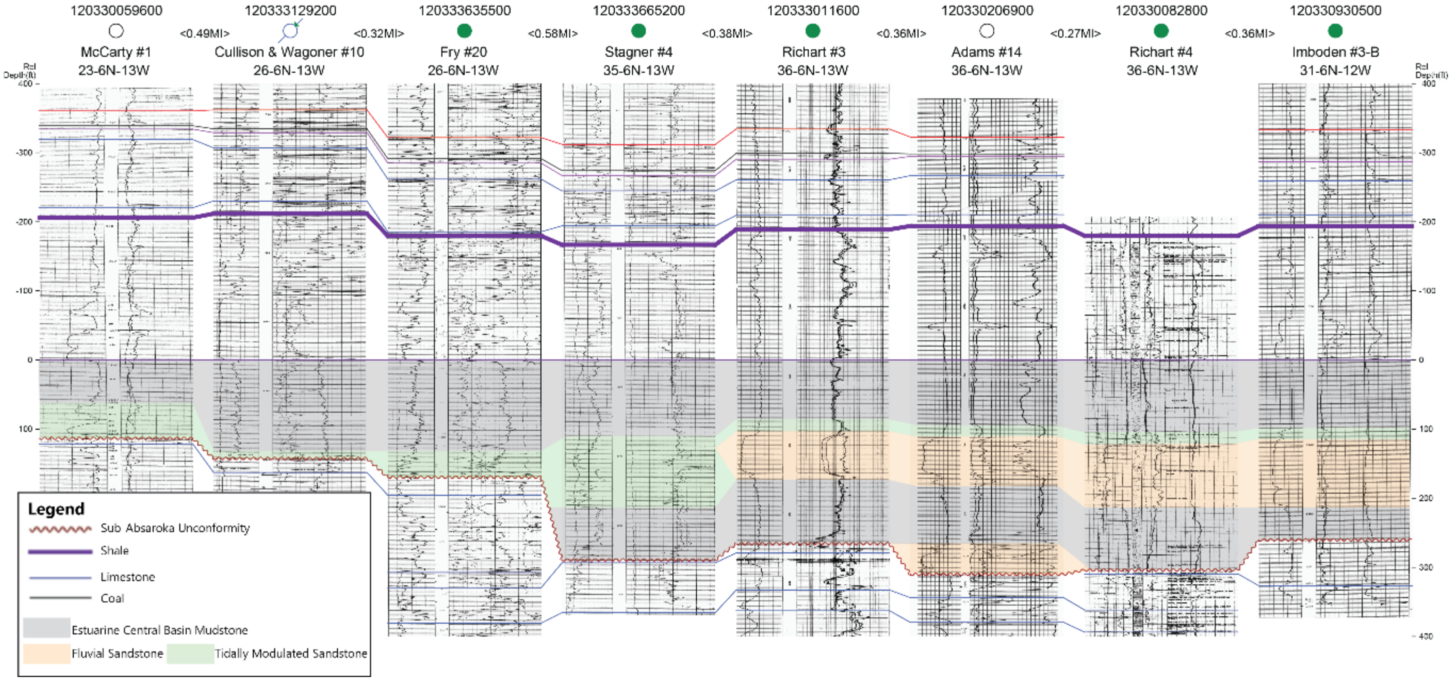

Figure 2. Well log cross section across an example paleovalley showing the distribution of facies that comprise the fill.

4:00 – 4:20 pm

Time for Shales to Come in from the Cold? A Midcontinent Example

Paul Enos[1]*, Diana Ortega-Ariza[1,2], Justin M. Fairchild[1,2]

[1] *Department of Geology, University of Kansas, 1475 Jayhawk Drive, Lawrence, Kansas USA 66045*

[2] *Department of Earth and Space Sciences, Columbus State University,*

4224 University Ave., Columbus, Georgia USA 31907

**enos@ku.edu*

Shales and mudrocks have long been the neglected stepchild of sedimentary rocks, despite comprising ~3/4 of the total mass. Neglect began to turn to veneration with the advent of massive hydrocarbon production from fine-grained sedimentary rocks. Shales (*sensu lato*) in the Late Pennsylvanian and Early Permian cyclothems of Midcontinent USA come in several flavors. By far the most important volumetrically are the heterolithic "outside shales" that sandwich each limestone-dominated cyclothem. The Calhoun Shale (Shawnee Group, Virgilian, Upper Pennsylvanian (Gzhelian)) of northeast Kansas exemplifies outside shales. Typically 10 to 15 m thick, it conformably overlies a shallow-water regressive limestone, without apparent shoaling or exposure. The bulk of the Calhoun consists of heterolithic mudrock: claystone, clay shale, silty mudrock, and thin intercalations of siltstone with ripple marks, trace fossils, and, locally, depauperate marine biota. Additional litologies include lenticular sandstone, thin coals, underclays, and, locally, limestone. Things get even more interesting toward the top of the unit, as a drop in relative sea level led to multiple deeply incised, sandstone-filled channels. Most channel fills are fluvial, although tidal influence is evident in one exposure. A very thin coal seam drapes adjacent interfluves. The Calhoun is capped by silty claystone with abundant terrestrial plant fragments and low-diversity marine biota that grades up into the basal transgressive limestone of the overlying cyclothem.

Outside shales are generally interpreted as distal deltaic deposits on the expansive, shallow Midcontinent shelf. The repetitive pattern of the Midcontinent cyclothems enables predictive generalizations about comparable units throughout the upper Pennsylvanian and lower Permian strata from observations of a single unit, such as the Calhoun. For example, incision by channels is found within at least 2/3 of the Pennsylvanian outside shales. The channels provide a maximum-regression marker for sequence stratigraphy. Some of the largest channels form potential small reservoirs. Outside shales, however, are not potential source rocks nor unconventional reservoirs.

4:20 – 4:40 pm

INTRODUCTION TO THE FIELD EXCURSION

Christopher R. Fielding[1*] and R. Matthew Joeckel[2]

[1]*Department of Earth & Atmospheric Sciences, 126 Bessey Hall, University of Nebraska-Lincoln, NE 68588-0340.*

[2] *Conservation and Survey Division, School of Natural Resources, Department of Earth & Atmospheric Sciences & University of Nebraska State Museum, University of Nebraska-Lincoln, 615 Hardin Hall, Lincoln, NE 68583-0996.*

**e-mail: cfielding2@unl.edu*

A FIELD GUIDE TO THE UPPERMOST PENNSYLVANIAN (VIRGILIAN) INDIAN CAVE SANDSTONE, SOUTHEAST NEBRASKA

Christopher R. Fielding[1], R. M. Joeckel[1],[2], and Steven A. Fischbein[3]

[1] – Department of Earth & Atmospheric Sciences, 126 Bessey Hall,
University of Nebraska-Lincoln, Lincoln, NE 68588-0340

[2] – Conservation and Survey Division, School of Natural Resources, and University of Nebraska State Museum,
615 Hardin Hall, University of Nebraska-Lincoln, Lincoln, NE 68583-0996

[3] – Division of Arts and Sciences, Rm A12, Southeast Community College, 8800 O Street, Lincoln, NE 68520

SAFETY CONSIDERATIONS

The field excursion will visit steep slopes and rock types that may pose hazards under particular circumstances, such as ongoing or recent heavy rains, so please exercise caution and do not attempt to negotiate unstable or slippery slopes. Furthermore, be aware of the overhead environment and of undergrowth, debris, and other obstacles at ground level. Please stay on trails that are designated for foot traffic and do not attempt to negotiate those that are not.

Ticks, chiggers, and spiders abound in warmer weather. Poisonous timber rattlesnakes (*Crotalus horridus*) and copperheads (*Agkistrodon contortrix*) are native to the area. The honey locust (*Gleditsia triacanthos*), a common native tree, has many large, sharp spines on its trunks and branches, frequently at eye level.

Please follow instructions given by the excursion leaders at all times in order to facilitate a safe and enjoyable experience.

ABSTRACT

The uppermost Pennsylvanian (Virgilian, Gzhelian) Indian Cave Sandstone (ICS) is well-exposed in bluffs along the eastern edge of the Missouri River valley at Brownville, Peru, and Indian Cave State Park in southeastern Nebraska. The ICS comprises erosionally-based bodies of fine- to medium-grained, lithic and micaceous sandstone (arenite) that typically fine upwards into heterolithic, interbedded sandstone and siltstone strata, as well as local, discontinuous coal beds. The ICS is overlain by estuarine to marine mudrocks and marine limestones. Mapping has shown that the ICS is overlain by the Falls City Limestone of the Admire Group. While some previous studies (e.g., Ossian, 1974) argued that the ICS is a deltaic deposit, more recent analysis (Fischbein, 2006, Fischbein et al., 2009) demonstrate that it fills incised valleys and channels, eroded into underlying, cyclothemic, mudrock and limestone-dominated strata. The lower, sandstone-dominated portion of the ICS is interpreted as tidally-influenced fluvial deposits in the lower reaches of a large continental drainage system dispersing southward. In contrast, the heterolithic upper part of the ICS is viewed as the product of down-valley, estuarine settings, closer to the contemporary valley mouth and the contiguous marine coastline. The base of the ICS records a sequence boundary, and the fill itself records lowstand and early transgressive systems tracts. Mudrocks overlying the ICS represent the late transgressive systems tract, and the overlying Falls City Limestone as the maximum flooding event in the cycle. The magnitude of erosional relief on the basal surface indicates sea-level drawdown of at least 30 m at the base of the sequence, and is probably a far-field glacio-eustatic response to Gondwanan glacial ice growth.

INTRODUCTION

This excursion is designed to introduce participants to the geology of the uppermost Pennsylvanian (Virgilian, Gzhelian) Indian Cave Sandstone (ICS) in southeast Nebraska (Fig. 1). The excursion will visit three key exposures of this unit at Peru, Brownville, and Indian Cave State Park (Fig. 2A), allowing close inspection of the sedimentology, stratigraphy, and reservoir characteristics of the ICS. Although it is not a producing petroleum reservoir in Nebraska, the ICS is a productive reservoir in Kansas.

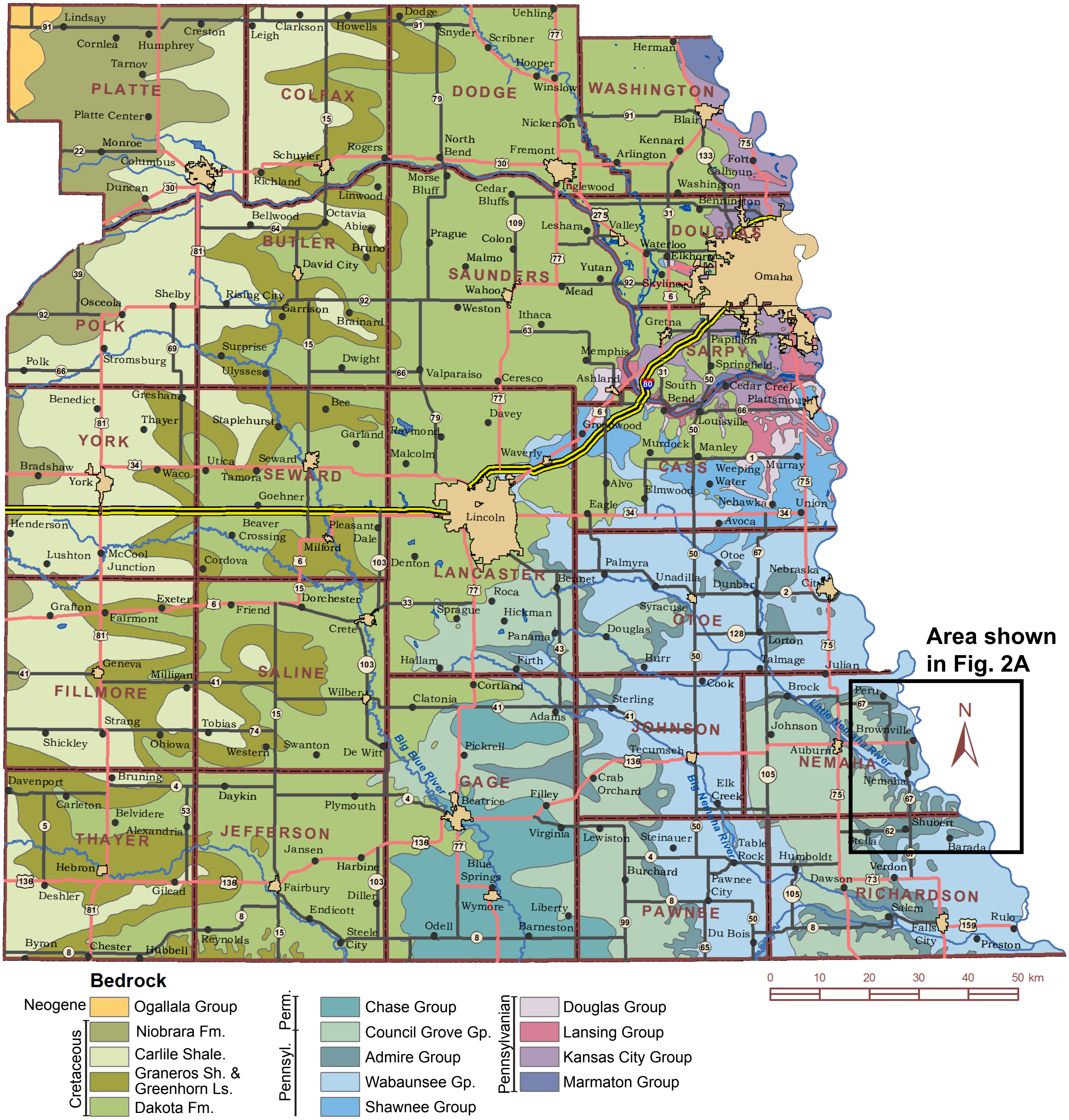

Figure 1. Bedrock geology of southeastern Nebraska (Conservation & Survey Division).

The Pennsylvanian northern Midcontinent was a slowly- and passively-subsiding, low-relief, extremely low gradient (10^{-1} to 10^{0} m/km) epicontinental platform with imposed structural dips ranging no more than 0.15° - 0.25° (Heckel, 1977, 1980; Olszewski and Patzkowsky, 2003). This platform was more than 500 km in width, and it was bordered distantly to the south by the Marathon-Ouachita foreland system (Fig. 2B). Repeated, short-interval stratigraphic cycles (cyclothems), dominated by mudrocks and carbonates, were deposited across the region under conditions of fluctuating relative sea level, limited input of clastic sediment, a seasonal tropical paleoclimate, and low rates of regional subsidence. Major, southwestward-flowing, continental drainage networks incised the exposed formerly inundated marine shelf and deposited sands in narrow tracts following major sea-level drawdowns (e.g., Archer et al., 1994; Feldman et al., 2005). The areal distribution of these rare sandstone bodies is very limited in comparison to many marine units (usually thinner than 0.5 m) in the same succession that extend for hundreds of kilometers (e.g., Heckel, 1986; 1994; Olszewski & Patzkowsky, 2003).

P. H. Heckel (e.g., Heckel, 1977, 1980, 1986, 1994, 2002) developed the most widely-known model for Midcontinent Upper Pennsylvanian cyclothems. This model invokes glacioeustatic sea-level changes in the Milankovitch band as the chief driving force and the main explanation for the lateral continuity of stratigraphic units. In the Heckel model, black, phosphatic "core" shales in the middle of individual cyclothems represent maximum water depths; transgressive deposits in such a cyclothem lie below its "core" shale and regressive deposits lie above it. We propose that the thick, incised sandstone bodies, which are the main focus of interest in this field trip, are insufficiently addressed by the Heckel model. Moreover, a newer generation of sequence stratigraphic models includes incised valley fills in their stratigraphic frameworks (e.g., Olszewski and Patzkowsky, 2003; Feldman et al., 2005, and see Fielding & Joeckel, this volume). In these models, incision of valleys took place during drawdown and lowstand of sea level, fluvial sands and gravels accumulated during this time and during the early stages of rising sea-level, and the valleys were then progressively drowned to become estuaries during the main transgressive phase of the ensuing sea-level rise. Once sea level had flooded the entire landscape, muds and later bioclastic carbonates were deposited in shallow highstand seas. Given the low relief, low sediment supply, and inferred seasonal tropical paleoclimate, the stratigraphic record of large-magnitude (tens of meters) cycles of sea-level change can be as little as 1-2 m of vertical section.

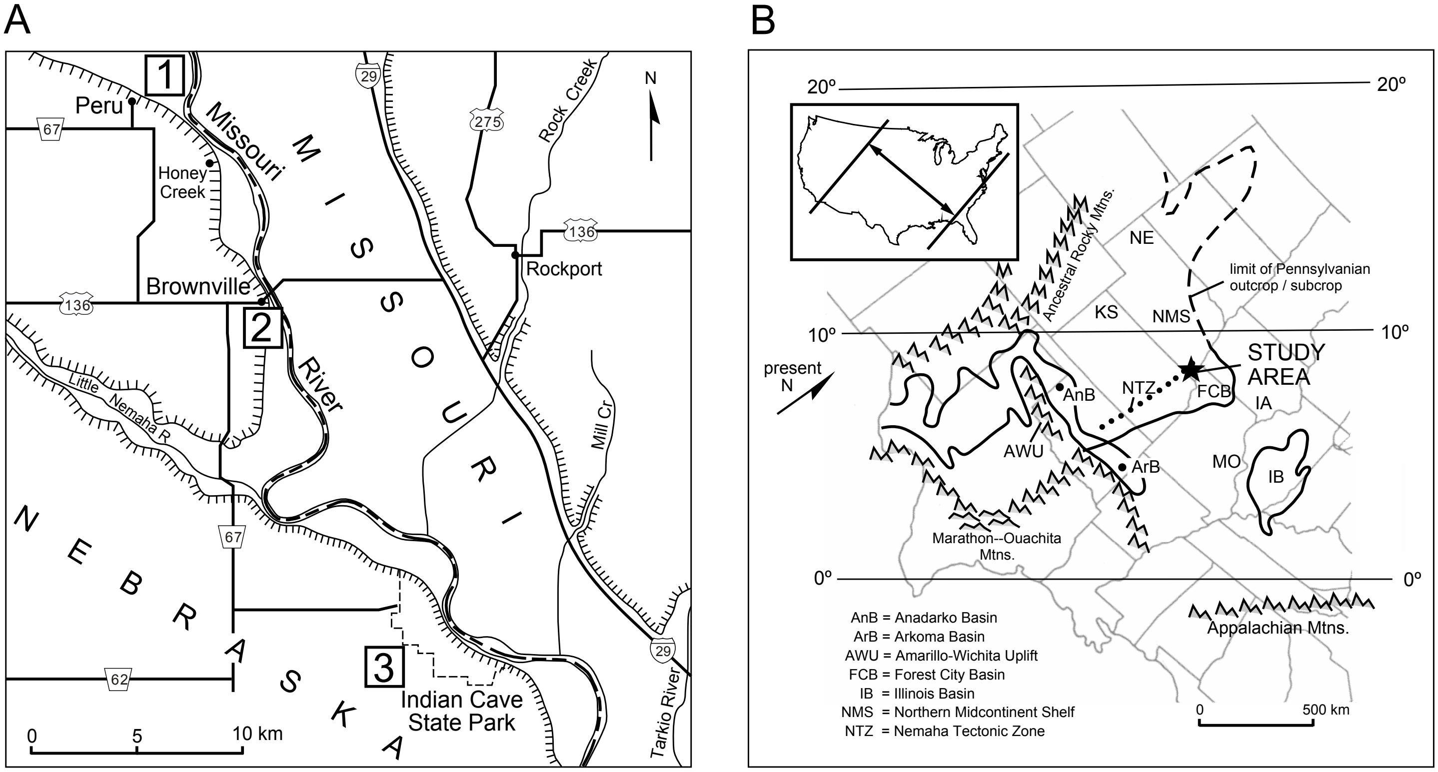

Figure 2. A) Map showing the location of the three field sites to be visited, 1 – Peru, 2 – Brownville, and 3 – Indian Cave State Park. See Figure 1 for location of the boxed area. B) Paleogeography of the Midcontinent USA during the Pennsylvanian (from Fischbein et al., 2009).

Thick sandstone bodies in these cyclothem successions, being exceptional records of fluvial-system response, are unique but underutilized sources of data about sea-level change and the response of terrigenous clastic systems. Historically, these sandstone bodies were given specific names and depicted as discrete stratigraphic units in published stratigraphic columns (Mudge, 1956; Mudge and Yochelson, 1962; Heckel, 1994, Heckel et al., 1998; Feldman et al., 1995). Many such sandstone bodies, including the ICS were interpreted as the product of deltas that prograded into shallow paleotropical seas (e.g., Ossian, 1974). Careful mapping of many bodies, however, has revealed them to be elongate "shoestring" sandbodies with profoundly erosional bases and fining-upward tendencies (rather than coarsening-upward vertical profiles that are typical of deltas), that display abrupt thinning at their lateral margins, passing outward into pedogenically modified finer-grained lithologies (e.g., Archer et al., 1994; Gibling & Bird, 1994; Bowen & Weimer, 2003; Feldman et al., 1995, 2005). Fischbein (2006) and Fischbein et al. (2009) established that the ICS is also a narrow, elongate body with a strongly erosional base, and proposed an incised valley fill origin for the unit.

LITHOSTRATIGRAPHY

No official type section of the ICS has ever been designated, but its presumed type area is the current Indian Cave State Park (ICSP) in southeastern Nebraska, which includes the eponymous physiographic feature (Fig. 2A), that being a shallow rock overhang cave. Several other Pennsylvanian sandstones in in southeastern Nebraska, northwesternmost Missouri, eastern Kansas, and as far afield as north-central Oklahoma have all been called "Indian Cave Sandstone" in published literature (Moore and Moss, 1934; Moore, 1936; Mudge, 1956; Mudge and Yochelson, 1962; Ossian, 1974; Campbell et al., 1988; Mazzullo et al., 2005). Nonetheless, rigorous systematic correlations were never performed for the ICS, even between putative ICS sandstones cropping out along the Missouri River bluffs in the relatively small type area (Fig. 2A). Unfortunately, the indiscriminate application of the name "Indian Cave Sandstone" across the Midcontinent, as well as the concept of genetic stratigraphy its usage implies, is at best slightly misleading and at worst entirely erroneous.

The ICS has always been considered a part of the Towle Shale in its type area (Moore, 1936; Mudge, 1956; Mudge and Yochelson, 1962; Ossian, 1974; Archer and Feldman, 1995) and it was traditionally thought to be underlain by the Brownville Limestone and overlain by the Aspinwall Limestone (Fig. 3). Much to the contrary, the study of Fischbein et al. (2009) demonstrates that: (1) the ICS in the type area occupies a higher stratigraphic position and is found between the Falls City and Brownville limestones (Fig. 3D), and (2) certain marine units bounding the study interval are continuous, but also that (3) sandstone bodies long considered to be part of one essentially continuous Indian Cave Sandstone are, in fact, separate entities having different stratigraphic positions and depositional histories (Fig. 3A-D, 4). At Peru, Nebraska the ICS lies between the Falls City and Nebraska City limestones (Fig. 3A). In some outcrops along Honey Creek, Nebraska the ICS lies between the Aspinwall and Brownville limestones, but in other outcrops near Honey Creek and in recorrelated borehole logs from Burchett (1977) the ICS penetrates the Brownville Limestone and extends downward to the Nebraska City Limestone (Fig. 3B). At Brownville, Nebraska the ICS is neither underlain by the Brownville Limestone nor overlain by the Aspinwall Limestone (Fig. 3C). It is plausible if not likely that the exposures at Peru, Brownville, and ICSP are part of the same trunk valley system, whereas the smaller body at Honey Creek is a separate, incised, (single story) channel body at a different stratigraphic level (Figs. 3, 4).

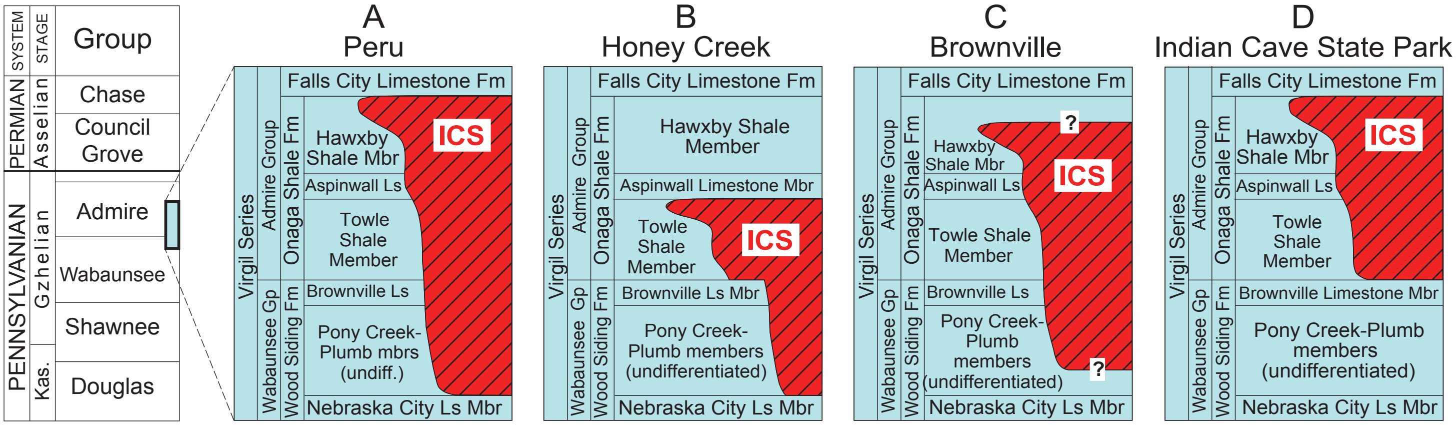

Figure 3. Generalized stratigraphic columns showing positions of Indian Cave Sandstone bodies at: A) Peru, B) Honey Creek, C) Brownville, and D) Indian Cave State Park (ICSP), Nebraska (modified from Fischbein et al., 2009).

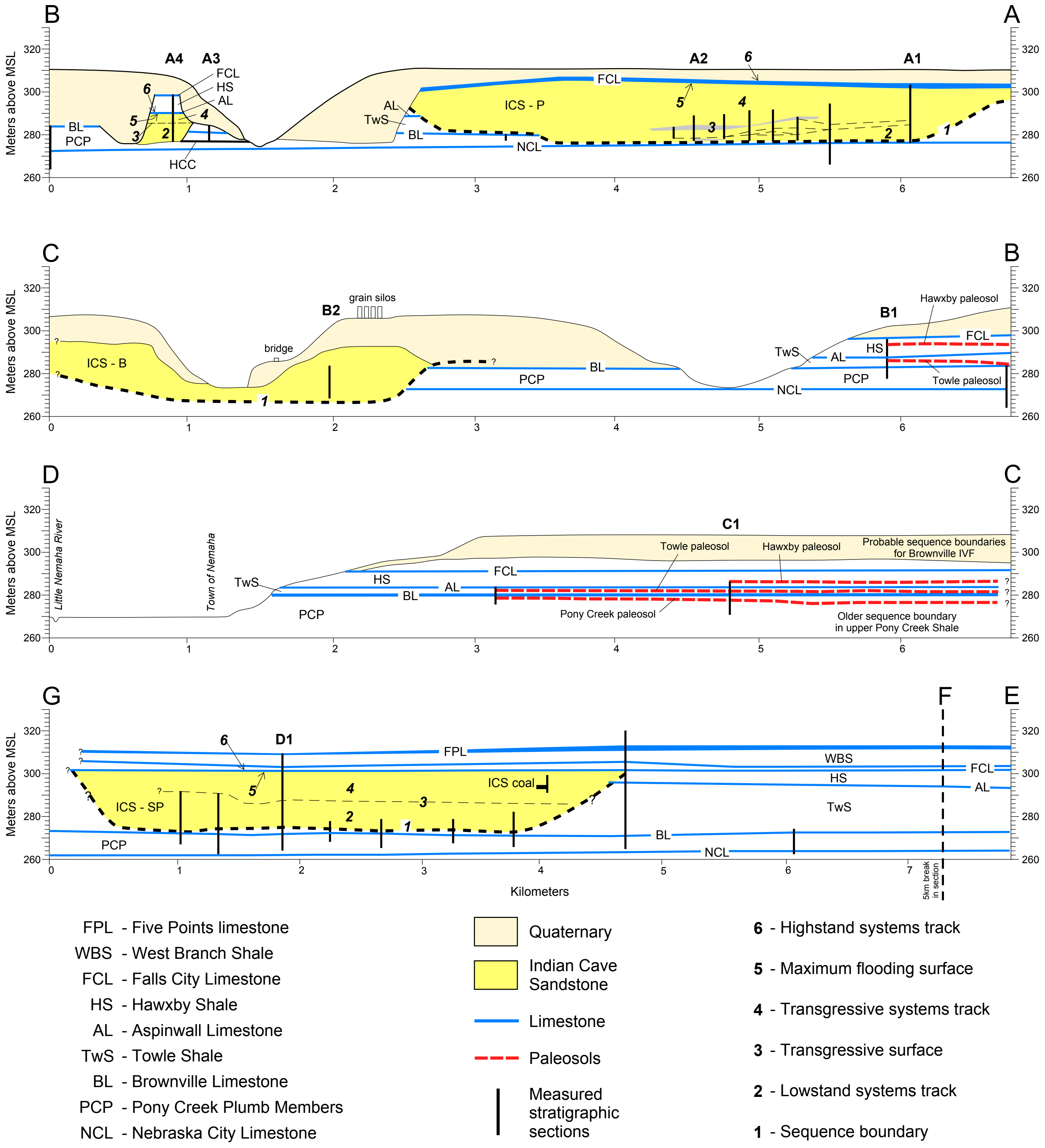

Figure 4. Geologic cross-sections from Peru to ICSP, illustrating the cross-sectional geometry of Indian Cave Sandstone bodies. A-B: Peru to Honey Creek, B-C: Honey Creek to Brownville, C-D: Brownville to Little Nemaha River, E-F-G: Little Nemaha River to ICSP (from Fischbein et al., 2009).

FACIES ANALYSIS

The facies analysis reported by Fischbein et al. (2009) is adopted herein (Table 1).

We interpret the ICS as a fluvial to estuarine deposit filling incised paleochannels or paleovalleys on the basis of: (1) prominent basal incision surfaces, (2) overall geometry, (3) unidirectional flow evinced by lithofacies St$_1$ and St$_2$, (4) the predominance of fining-upward trends, and (5) the overall abundance of heterolithic facies with depauperate brackish to marine trace fossils. In this context, Ci$_b$ is a lag formed on valley floors or channel bases above a basal incision surface (Table 1). Some C$_{ih}$ units may also have formed in a similar setting, but others clearly formed by the disaggregation of large masses of fine-grained sediment produced by bank collapse (Table 1). Lithofacies St$_1$ and St$_2$ are interpreted to have formed through the migration of large and small dunes on the floors and bars of large, deep channels (Table 1). The unidirectional paleocurrent distributions derived from these facies (broadly southward) indicate that sediments were deposited from unidirectional aqueous flows, and the low dispersion of paleocurrent data within individual bodies suggests that channels were of low sinuosity, consistent with confinement within incised margins. Furthermore, low-angle cross-bedded sandstones (S$_L$) probably record the migration of bed waves under transitional (lower to upper) flow regime conditions. The geometry of the cross-strata and their lateral transition into flat lamination locally are similar to structures described from modern alluvium and from a variety of ancient fluvial successions.

Lithofacies H$_1$ and H$_2$ record low-energy current flow alternating with deposition from suspension. The unidirectional nature of ripple cross-lamination in these facies suggests a current-dominated environment, but the delicate interlamination of sandstone and mudstone also records frequent, short-term fluctuations in current activity. Although heterolithic facies are very common in coastal tidal environments (e.g., Reineck and Singh, 1986; Nio and Yang, 1991), they are not unique to

Table 1. List of facies and their characteristics (from Fischbein et al., 2009).

Facies code	Facies Name	Lithology	Sedimentary Structures	Interpretation
H$_2$	Mudstone-Dominated Heterolith	Interlaminated and thinly interbedded mudstone and very fine- to fine-grained sandstone: 60-80% mudstone in laminae and beds 1-300 mm thick, 20-40% sandstone in laminae and beds 1-500 mm thick.	Pinstripe (linsen), lenticular and wavy bedding, microfaults, coaly plant debris, rare, simple faunal traces (*Planolites*, *Palaeophycus*)	Deposition of mud and sand from lower flow regime, unidirectional currents and from suspension.
H$_1$	Sandstone-Dominated Heterolith	Interlaminated and thinly interbedded sandstone and mudstone: 40-80% sandstone in laminae and beds 5-500 mm thick, 20-60% mudstone in laminae and beds 1-500 mm thick.	Pinstripe (linsen), lenticular, wavy and flaser bedding, ripple cross-lamination, flat lamination, coaly plant debris, rare eurypterid body fossils, rare, simple faunal traces (*Planolites*, *Conichnus*)	Deposition of sand and mud from lower flow regime, unidirectional currents and from suspension.
S$_L$	Low-Angle Cross-Bedded Sandstone	Fine- to medium-grained sandstone, Intervals typically <0.75 m thick.	Dominated by sets of low-angle (<1 - 10°) cross-bedding <0.75 m thick passing laterally into flat lamination, minor ripple cross-lamination, mudstone drapes and mudstone clasts on some bedding planes.	Migration of sediment waves in transitional upper flow regime conditions.
St$_2$	Small-Scale Trough Cross-Bedded Sandstone	Fine- to medium-grained sandstone, erosionally-based intervals <5 m thick.	Trough cross-bedding in sets <0.25 m thick, mudstone clasts on basal scour surfaces.	Migration of small, sinuous-crested, sandy dunes on channel floors and bars.
St$_1$	Large-Scale Trough Cross-Bedded Sandstone	Fine- to medium-grained sandstone, erosionally-based intervals <5 m thick.	Trough cross-bedding in sets 0.25-1.0 m thick, mudstone clasts on basal scour surfaces, minor ripple cross-lamination and mudstone drapes.	Migration of large, sinuous-crested, sandy dunes on channel floors and bars.
Ci$_h$	Intraformational, Monomictic, Heterolithic Clast Conglomerate	Matrix-to clast-supported, very poorly to moderately sorted, angular to subrounded granule to cobble clast conglomerate and breccia, clasts exclusively of mudrocks and heterolithic facies with fine-grained sandstone matrix, erosionally-based intervals <1 m (rarely, more) thick.	Long axes of clasts define crude parallel stratification, local clast imbrication.	Coarse-grained lag on valley and channel floors, disaggregation of bank collapse masses.
Ci$_b$	Basal, Polymictic Conglomerate	Matrix- to clast-supported, very poorly to moderately sorted, very angular to subrounded, granule to boulder clast conglomerate and breccia, clasts mostly of mudrock and limestone with fine-to medium-grained sandstone matrix, erosionally-based intervals <2 m thick.	Chaotic to crudely flat-stratified, coalified wood debris, rare eurypterid and vertebrate fossil fragments.	Coarse-grained lag overlying basal incision surface on valley and channel floors.

such settings. Nevertheless, a distinct tidal influence is suggested in the ICS by rhythmically interlaminated/interbedded sandstone/mudstone with ripple form sets on the upper surfaces of sandstone beds (cf. Reineck and Singh, 1986; Nio and Yang, 1991). Some level of marine or brackish influence on paleoenvironments is clearly indicated by the presence of fossil eurypterids (within the H_1 Facies) and by the low-diversity *Cruziana* Ichnofacies trace assemblage (within the H_2 Facies; cf. Bann et al., 2004). The extremely low diversity and abundances in these fossil/trace fossil assemblages suggest some tidal influence (cf. Pemberton and Wightman, 1992; Gingras et al., 1999).

Two distinct facies associations can be distinguished in ICS lithosomes (Figs. 5, 6), particularly when key bounding surfaces are taken into account. Such surfaces are identified here in a hierarchical classification in which "first order" denotes fundamental surfaces of greatest lateral extent; "second order" denotes subordinate ones truncated against first order surfaces, and so on. Our basal, Fluvially-dominated, Tidally-Influenced Zone Facies Association overlies the basal incision surface (First Order Bounding Surface) and comprises multiple stories, each separated from the next by a Third Order Bounding Surface. This Association is separated from the overlying Tidally-Dominated, Fluvially-Influenced Facies

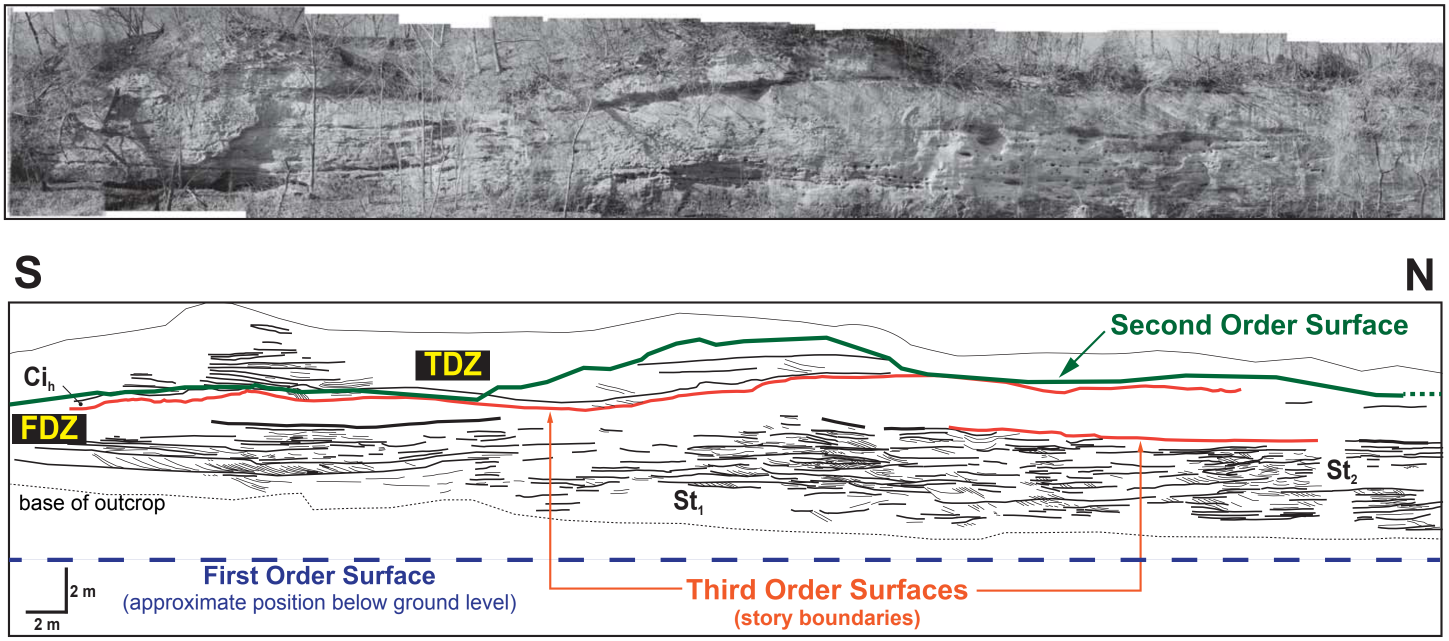

Figure 5. Photomosaic and annotated line drawing illustrating the cross-sectional architecture of the Indian Cave Sandstone at Peru. The first-order bounding surface at the base of the body is below ground level. The main cliff is composed of cross-bedded sandstones of the FDZ facies association, punctuated locally by third order bounding surfaces. A second order surface in the upper cliff separates the FDZ facies association from the overlying TDZ facies association. See Table 1 for facies codes. Modified from Fischbein et al. (2009).

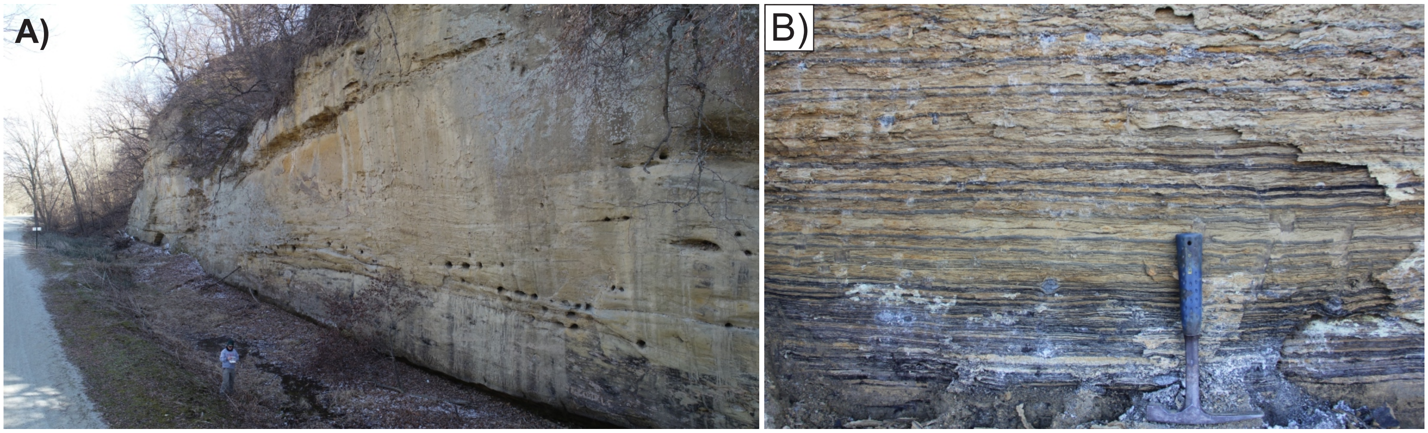

Figure 6. Illustrations of the dominant lithologies of A) the FDZ facies association and B) the TDZ facies association.

Association by a Second Order Bounding Surface. Figure 7 is a framework diagram summarizing the key process characteristics of these geomorphic zones within the fluvial to marine transition zone of modern coastal rivers (Gugliotta et al., 2016).

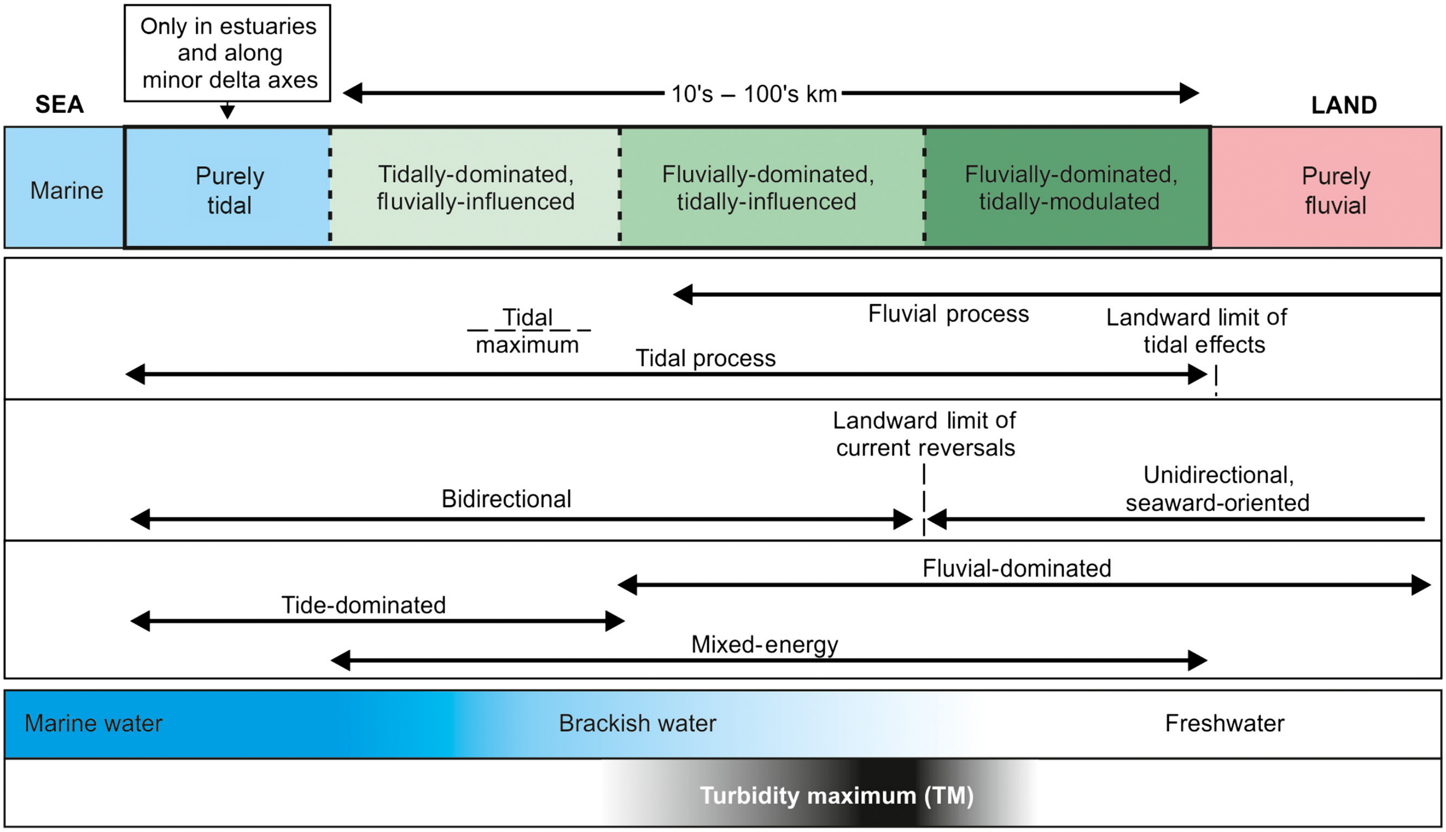

Figure 7. Framework diagram showing the principal divisions and changes in physical process across the fluvial to marine transition zone (from Gugliotta et al., 2016).

Fluvially-Dominated, Tidally-Influenced Zone Association (FDZ)

The FDZ facies association comprises lithofacies Ci_b, Ci_h, St_1, St_2, S_L, and minor H_1. In the larger three lithosomes (Peru, Brownville and ICSP), a composite, multi-storey internal architecture is apparent, and storey boundaries are defined by erosional surfaces with several meters of relief. In some cases, these third order bounding surfaces are overlain by Ci_h. Typically, the lower portion of each story, above the basal conglomerate lags, is dominated by St_1, but St_2 increases in abundance upward. In the few places where the inclination of major, internal (third order) bounding surfaces can be ascertained, the measured paleocurrent direction of these surfaces are coincident with those of other measured sedimentary structures in the same units and suggests that sediments accumulated primarily by downstream accretion on composite, mid-channel barforms. The multi-storey nature of the ICS bodies resulted either from repeated autocycles of channel incision and filling, or from an external forcing control (e.g., sea-level change).

The rarity of heterolithic facies (H_1 and H_2), and the local occurrences of backflow ripple cross-lamination, flaser bedding, rhythmic mud laminae, and paired mud drapes on cross-bed foresets in various facies within this association indicates a subordinate tidal influence on the depositional environment. These features record counter-current flows and slack-water conditions, which we interpret as due to weak tidal inundation. (cf. Reineck and Singh, 1986; Nio and Yang, 1991; Van den Berg et al, 2007; Gugliotta et al., 2016). Abundant, finely-divided organic debris ("coffee grounds") is preserved in these laminae. Discontinuous lenses of heterolithic facies in the uppermost parts of trough fills and in other settings may indicate that tidal influence was more persistent, at least at times, but that its products were infrequently preserved.

The preceding observations implicate deposition in the uppermost reaches of a fluvial-estuarine system (Fig. 7) near the upstream terminus of the fluvial-tidal transition zone. Flows in this zone in were overwhelmingly fluvial during peak discharge and neap tides, but a subordinate tidal inflow may have been produced during spring tides (cf. Dalrymple et al., 1992; Dalrymple and Choi, 2007; Van den Berg et al, 2007; Gugliotta et al., 2016). This interpretation is entirely consistent with recent analyses of other Pennsylvanian incised valley fills (e.g., Feldman et al., 1995; Archer and Feldman, 1995; Bowen and Weimer, 2003; Feldman et al., 2005) and with many other studies of both modern and ancient systems.

Tidally-Dominated, Fluvially-Influenced Zone Association (TDZ)

The TDZ association is dominated by facies S_L, H_1 and H_2. It typically overlies all of the cross-bedded sandstone-dominated stories of the FDZ and forms the uppermost portions of the ICS bodies. Internal facies architecture is less clear-cut in the TDZ, however, because outcrops of it are poor. TDZ typically has S_L as basal units and passes upward into H_2 facies with S_L being restricted to lenses within it. The overall finer texture, dominance of the H_2 lithofacies, and restricted trace fossil assemblage in this association suggests a diminished fluvial influence and a more tidal dominated environment. Therefore, TDZ is considered to represent a mud-dominated, tide-influenced, uppermost estuarine environment (Fig. 7). This interpretation is consistent with studies of both modern and ancient environments (e.g., Dalrymple et al., 1992; Dalrymple and Makino, 1989; Tessier, 1993; Zaitlin et al., 1994; Dalrymple et al., 1994; Tessier et al., 1995; Feldman et al., 1995; Archer and Feldman, 1995; Lanier and Tessier, 1998; Bowen and Weimer, 2003; Feldman et al., 2005).

Overall Stratigraphic Trend

An overall transgressive trend is evident from the complete vertical succession of facies within each ICS body. The order of events revealed therein is: (1) incision of a linear topographic low, (2) deposition of sand in predominantly fluvial environments, and (3) progressive transition to more muddy and tide-influenced settings over time (Figs. 7, 8). The ICS bodies are overlain by mudrocks or limestones that could be said to record the maximum extent of transgression in a cycle of relative sea-level fall and rise (Fig. 8).

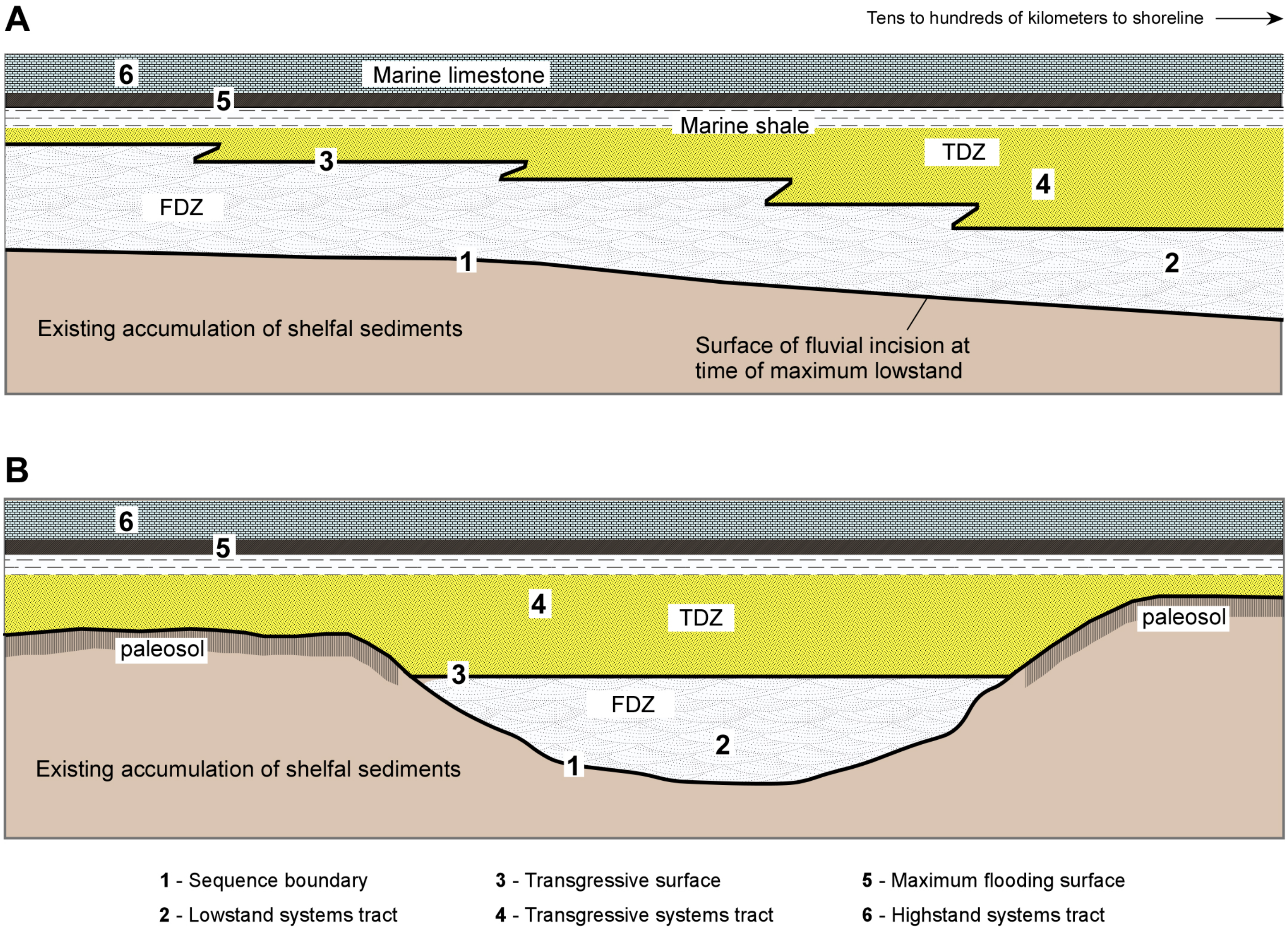

Figure 8. A sequence stratigraphic model for the Indian Cave Sandstone incised valley fills on a tropical, shallow, slowly subsiding and low-gradient shelf. A) longitudinal (slope-parallel) section, B) transverse section (modified from Fischbein et al., 2009).

FIELD EXCURSION SITES

The excursion will visit three sites in southeastern Nebraska: (1.) the Steamboat Trace Trail near Peru, (2.) The Steamboat Trace Trail at Brownville, and (3.) bluffs along the Missouri River at Indian Cave State Park (Figs. 2A, 9). The salient features of each locality are presented below.

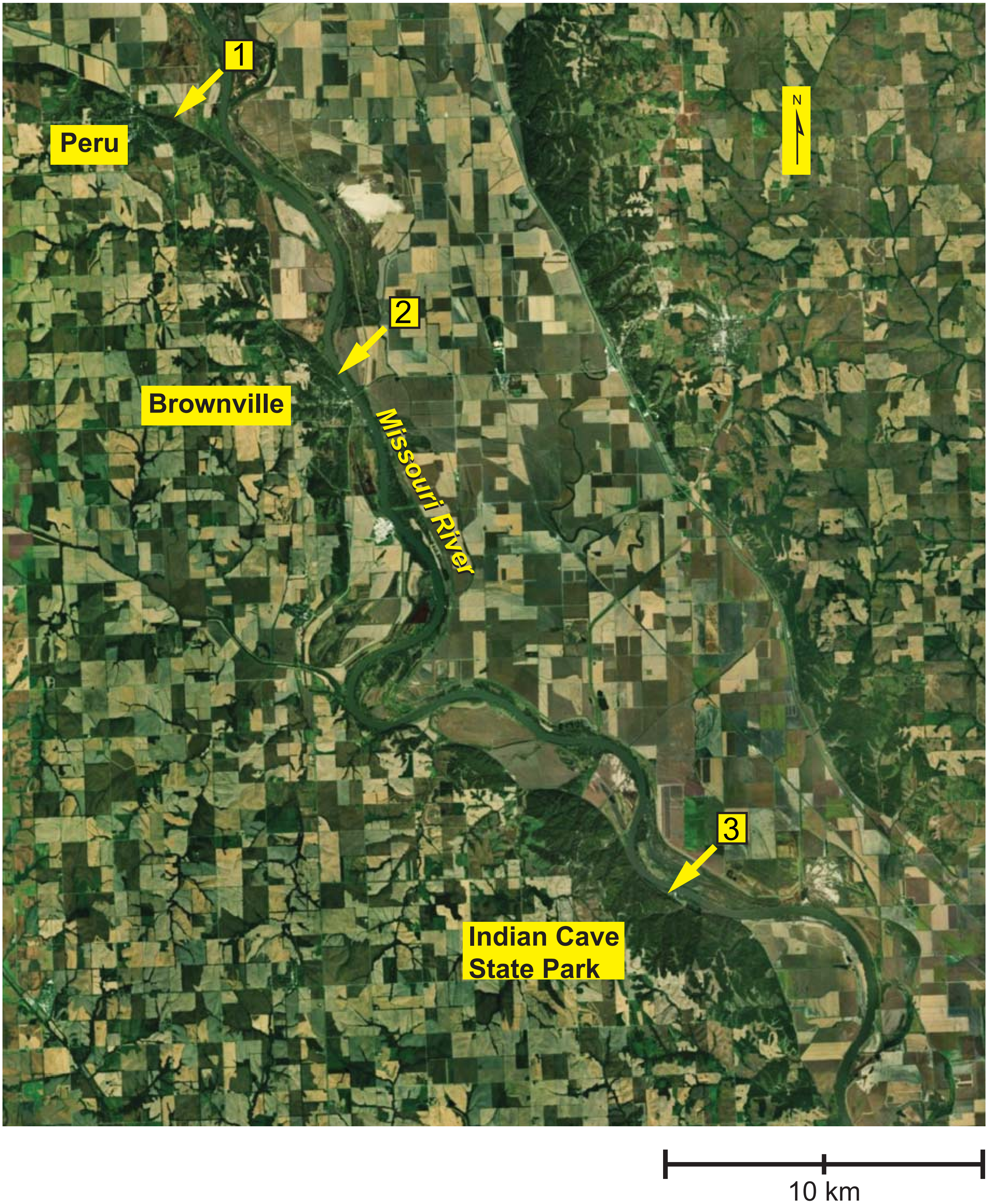

Figure 9. Aerial image showing the locations of the three field sites to be visited.

1. Steamboat Trace Trail at Peru, NE

Directions: Travel east from Lincoln on State Highway 2 to the main Nebraska City junction (at a new overpass, junction with US75) and turn south towards Auburn. Proceed south along US Highway 75 until the junction of State Highway 67, turn left (east) and then in 5.4 miles left (north) into the town of Peru, NE. Continue through town, past the Peru State College, down a steep hill and onward to the north end of town, then park at the old railroad station (restrooms are available for visitors here). We will walk southeastward along the Steamboat Trace trail from this point, following the abandoned railroad line.

Description: There is an approximately 15 minute walk from the railroad station to the first outcrop of the ICS. The lateral margin of the ICS is not fully exposed (Fig. 4), but more abundant and thicker-bedded sandstone becomes visible southeastward at successively lower elevations, until cliff-forming sandstone becomes visible near a park bench donated by the local Girl Scout troops "Girl Scout Bench"). The erosional base of the ICS (about 1 m below ground level) was established by drilling in 2005, and is incorporated into Figure 10, which is a log of a vertical section measured near the Girl Scout Bench. The lower FDZ Facies Association (see above) is well-exposed in cliffs which become taller as we progress southeastward (< 20 m high).

Another feature of the cliffs is the rock sculptures of deceased local artist Roland Sherman, who carved several shallow reliefs into the soft sandstone, including a bobcat (Peru State College emblem), a skeleton, an American Eagle, a genie, and a "diving diva." Look out for these sculptures in the cliffs, some of which are deteriorating due to weathering. A link to a newspaper article on Sherman's art is given below.

https://journalstar.com/.../article_10f049f5-6602-585e-9ceb-5097cc81da86.html

The principal facies visible are cross-bedded sandstones (St_1 and St_2 of Table 1) with minor occurrences of other facies, including sandstone-dominated heterolith (H_1) and intraformational conglomerate (C_{ih}: Table 1). Trough cross-bedding, in sets up to one meter in thickness, is exposed in three dimensions. Paleoflow readings indicate westsouthwestward sediment dispersal (Fig. 11). Some cross-beds preserve mud drapes and locally paired mud drapes on foresets, with rare backflow ripple cross-lamination directed up the foreset of a cross-bed (Fig. 12). Intervals of cross-bedded sandstone are locally truncated by erosional bounding surfaces (Fig. 5), along which are concentrated petrified wood and coaly compressions of plant axes. Beneath some of these surfaces are locally

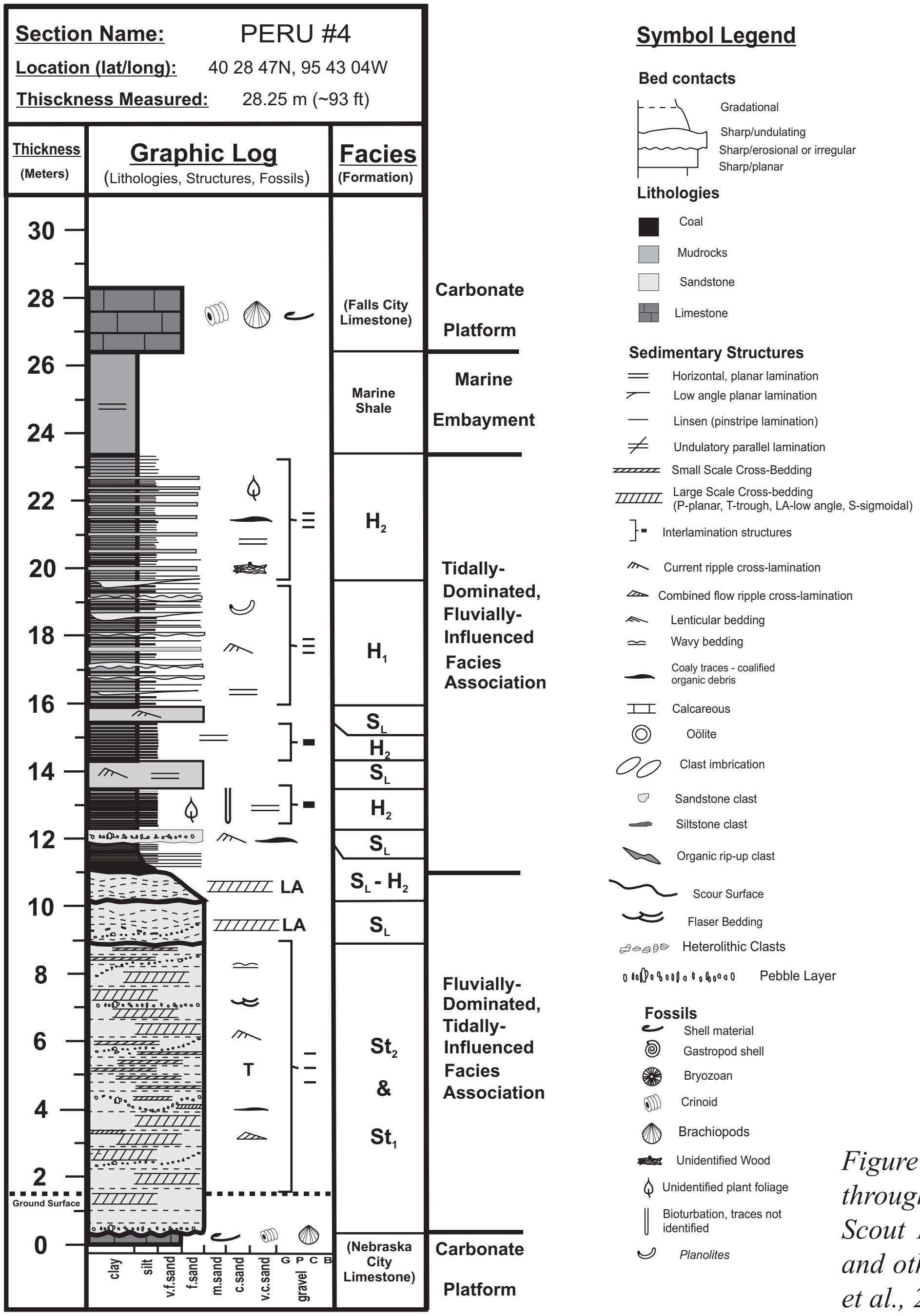

Figure 10. Graphic log of a measured section through the Indian Cave Sandstone at the "Girl Scout Bench", and key to symbols used in this and other graphic logs (modified from Fischbein et al., 2009).

preserved lenses of sandy heterolith (Facies H_1: Table 1) with various kinds of rhythmic interlamination structures (Fig. 12). Lenses of intraformational conglomerate fill trough-shaped erosional scours. Historically, these conglomerate lenses have yielded eurypterid fossils (Barbour, 1914; Fig. 12), and also vertebrate bones (Ossian, 1974).

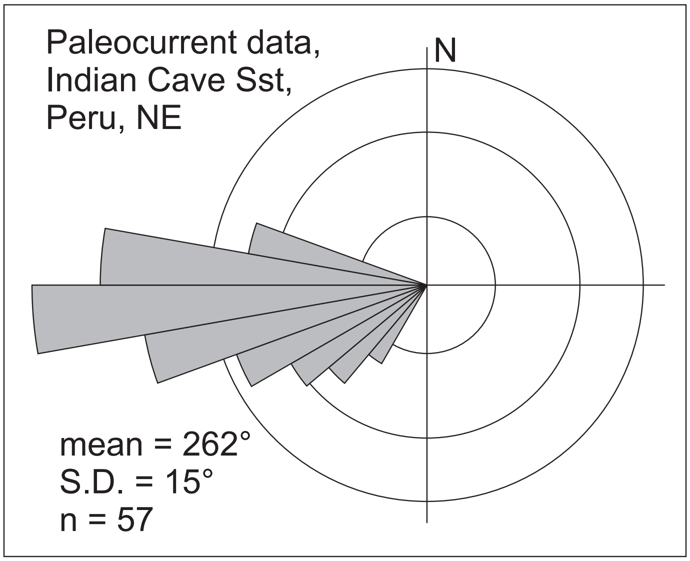

Figure 11. Paleocurrent data from the Peru exposures, showing a westsouthwesterly modal direction. Mean direction, standard deviation (S.D.), and number of data (n) are given.

Moving southeastward along the bluffs brings us to more continuous cliff exposures of the FDZ Facies Association, and the contact with the overlying, thinly-bedded TDZ Facies Association (Fig. 5) becomes visible in places. At a footbridge over a tributary gully, a short diversion leads to the so-called “Genie Hollow” where one of Sherman’s sculptures can be seen. Southeast of this are the bobcat and “diving diva” sculptures.

Beyond a pump house for the Missouri River overflow channel is an interesting exposure of a monomictic, siltstone clast breccia with a sand matrix, passing up into the more typical sandstone facies. Over tens of meters southeast of this exposure, the sandstone is no longer exposed, and further on there are smaller exposures of limestones, mudrocks and paleosols. At this point, return on the trail back to the parking lot at the old railroad station in Peru.

The FDZ facies association in the main bluffs is interpreted as tidally-influenced fluvial deposits of a coastal river that was confined to a broader, incised valley form (Fig. 8). In this locality, the main flow direction was westsouthwestward, implying that was also the trend of the incised valley. Evidence of tidal modulation is in the form of paired mud drapes, rhythmically interlaminated heterolith, and rare backflow structures, together with the discovery of eurypterid fossils (taxa that are only known from marine and coastal paleoenvironments). On the other hand, the unidirectional paleoflow distribution and the abundance of plant debris ranging from large axes to finely disseminated “coffee grounds” attests to a location some distance upstream from the river mouth, within the fluvial-to-marine transition zone (Fig. 7). The siltstone clast breccia at the southeastern end of the bluffs is interpreted to record bank collapse near the margin of the channel and paleovalley, with siltstone clasts representing dismembered masses of bank material that were remobilized into flows. The overlying, more thinly-bedded and interbedded TDZ facies association is interpreted to record a location further downstream in the ancient paleovalley, in which tidal backflow was more frequent and a greater influence on sediment accumulation. This Facies Association will be examined in closer detail at the next site, Brownville.

2. Steamboat Trace at Brownville

Directions: From the parking lot at the northern limit of Peru, return through the town and turn left (east, then south) onto State Highway 67 at the T-junction. Travel 5.8 miles to the junction with Highways 67 and 136, turn left (east), and proceed into the town of Brownville, NE. At the base of the hill, before the road bridge over the Missouri River, turn right onto a side road at the old railroad station, and park at the Steamboat Trace trailhead by some old silos. Walk a short distance up-river (northwest) along the trail, under the road bridge and beyond, to view exposures of thinly-interbedded TDZ Facies Association in banks above the trail level.

Description: The lower part of the ICS is exposed below the trail level down to river level, and it is composed of the FDZ Facies Association. At and above the trail level are good exposures of the overlying TDZ Facies Association that can be accessed directly. A crudely thickening- and coarsening-upward unit some 3 m thick is overlain by more thickly-bedded tabular sandstones in the low cliffs beside the trail. Facies pass upward from H_2 to H_1, and also laterally from north to south become more sandstone-dominated. Heteroliths in this area preserve a variety of interlamination structures (linsen, lenticular, wavy, and flaser bedding: Fig. 13) with rhythmic alternation of coarse and fine laminae on a variety of scales. Current ripple cross-lamination is the most common sedimentary structure, with a dominant southsoutheasterly mode and a subordinate northnorthwesterly mode (Fig. 13). Coalified plant debris

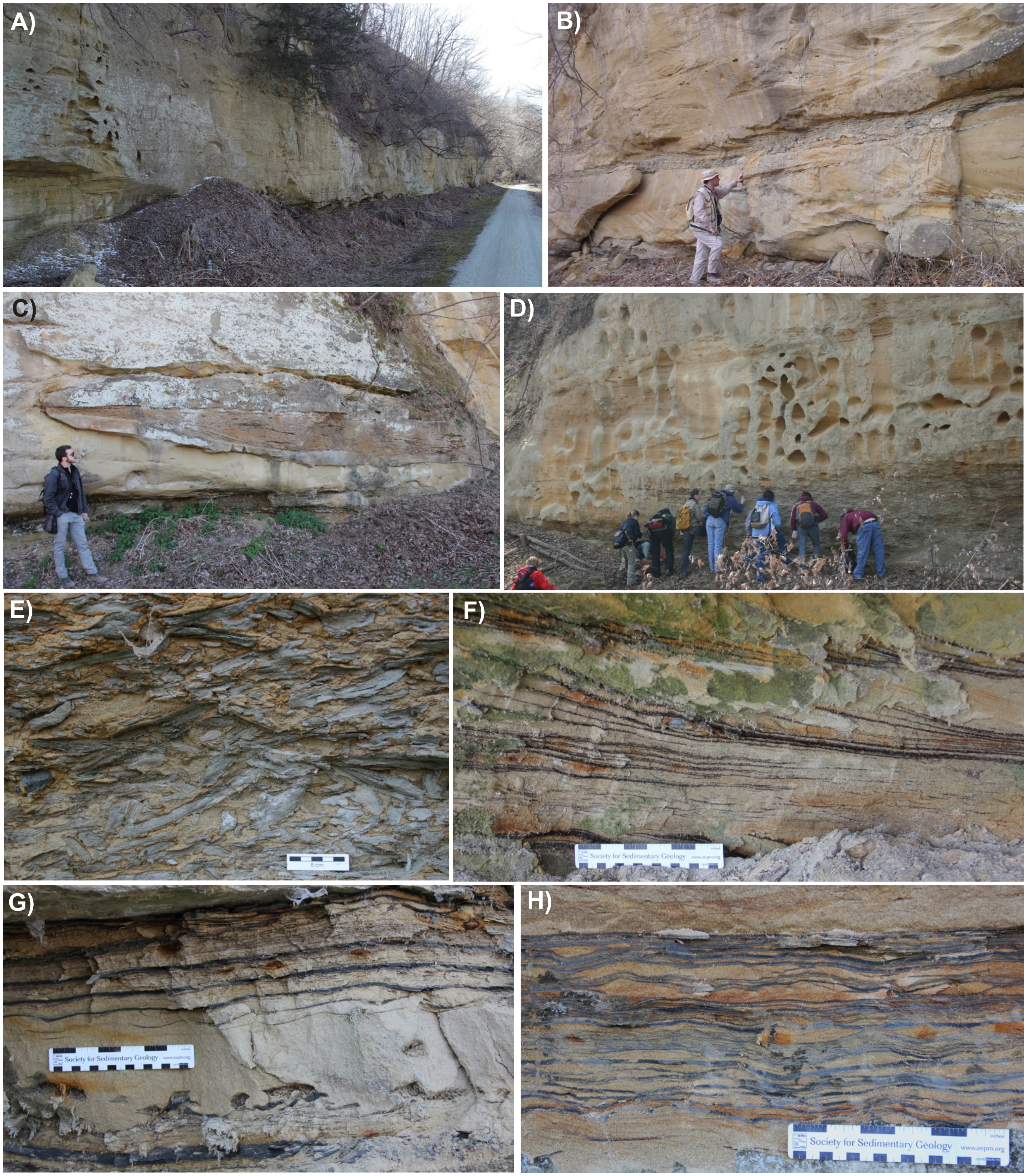

Figure 12. Field photographs of the Indian Cave Sandstone at Peru. A) General view of cross-bedded sandstones (FDZ facies Association) along the Steamboat Trace trail. Cliff is ~15 m high. B) Close-up view of cross-bedded sandstones and heterolith-lined bounding surfaces, Person for scale. C) Close-up view of cross-stratified conglomerate lens within the sandstone, from which eurypterid and vertebrate fossils have been collected in the past. Person for scale. D) Interfingering of intraformational clast breccia (gray) and sandstone (light brown) at the southeast end of the incised sandstone body. Students for scale. E) Close-up view of the intraformational clast breccia seen in D). Scale card 5 cm. F) Close-up view of fine-grained drapes and paired drapes down the foresets of a cross-bed, which overlies ripple cross-laminated sandstone showing flaser bedding (above scale card, 15 cm). G) Close-up view of sandstone overlain by sandstone-dominated heterolith, showing rhythmicity in stratification both at the wavy bedding (cm) and pinstripe bedding (mm) scales. Scale card 15 cm. H) Close-up view of mudstone-dominated heterolith showing a variety of interlamination structures (pinstripe, lenticular, wavy, and flaser bedding). Scale card 15 cm.

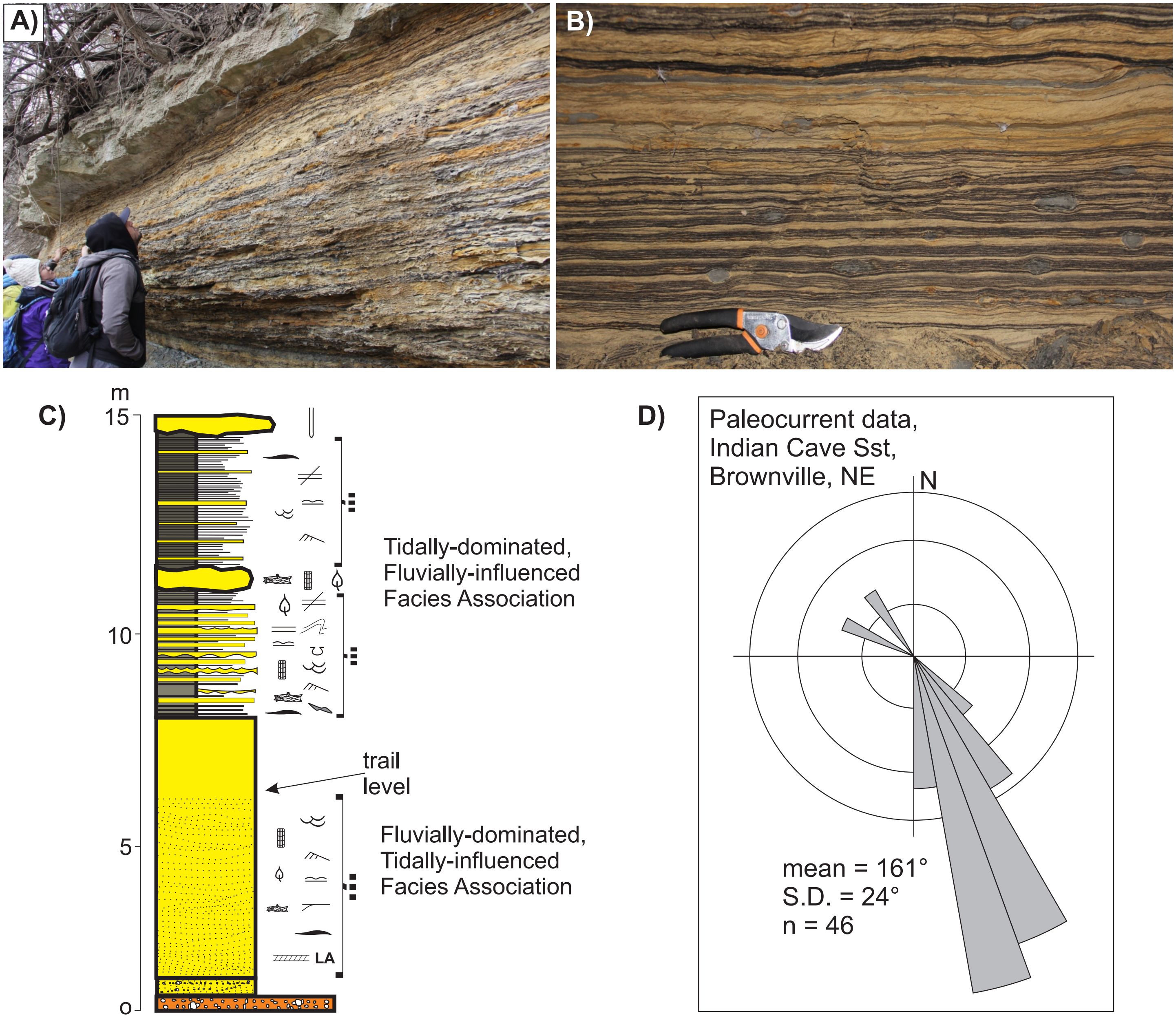

Figure 13. Indian Cave Sandstone exposures at Brownville, NE. A) General view of heterolithic interbedded sandstone-siltstone (Facies H_1 and H_2), overlain by tabular sandstone bed. B) Close-up view of mudstone-dominated heterolith (Facies H_2), showing rhythmicity at different scales. Clippers 18 cm long. C) Graphic log of section measured by the old loading facility. See Figure 10 for key to symbols used. D) Paleocurrent data from the Brownville exposures, showing a dominant southsoutheasterly mode and a minor northnorthwesterly mode.

is abundant throughout, and pyrite nodules are common. Locally, the heterolith is bioturbated by a virtually monospecific trace assemblage (*Planolites*), while other zones are disrupted by soft-sediment deformation.

The TDZ Facies Association exposed at Brownville is interpreted as the record of sediment accumulation under the combined influence of fluvial outflow and tidal flows (ebb and flood) in an open, estuarine setting. Tidal influence is indicated by the bipolar paleoflow distribution (Fig. 13), rhythmic interlamination of coarse and fine laminae, and the stressed trace fossil assemblage. This motif is typical of the upper part of the ICS throughout the outcrop belt.

3. Indian Cave State Park

<u>Directions</u>: Return to the parking lot, drive back westward out of Brownville on US Highway 136 and turn left (south) onto State Highway 67 towards and through Nemaha. After 9.0 miles, turn left (east) onto State Highway 64E Spur and drive east to the entrance of Indian Cave State Park (5.0 miles). Once we enter the park, continue on the main road through the park, which descends the bluffs to river level and ends in a turning circle at the eponymous cave (a further 5.5 miles). Restrooms are available at this stop.

Description: The boardwalk leading to the cave affords excellent views of the lower, FDZ Facies Association of the ICS, and its basal incision surface. The complete stratigraphy of the ICS was mapped here by Fischbein (2006), including a bed of coal less than one meter in thickness, in the upper part of the incised valley fill (Figs. 4, 14). The basal erosion surface can be traced along the cliffs either side of the cave site, where it is in many places lined with intraformational and minor extraformational clast conglomerate (Facies C_{ih} and C_{ib}, respectively: Table 1), and with large, coalified plant axes. At one site, an adit was excavated into the cliff at a presumed coal raft under the misapprehension that the coal was a continuous bed. The siltstones underlying the basal erosion surface contain marine body and trace fossils and pass downward into a bioclastic limestone correlated to the Brownville Limestone (Fig. 4). Lower on the slope, strongly colored mudrocks interpreted as a paleosol are exposed.

The Cave Trail leads up the bluffs from the turning circle passing through the FDZ and TDZ Facies Associations, to an excellent view point overlooking the bluffs and the Missouri River.

These exposures demonstrate the erosional base of the ICS, and reinforce the interpretation of a fluvial origin for the lower, FDZ Facies Association. As at Peru, however, mud drapes on some cross-set foresets suggest a degree of tidal modulation of fluvial outflow currents. Paleocurrent data indicate a unimodal, southeast to southward paleoflow direction (Fig. 14).

A new, fully cored hole was drilled by the Nebraska Conservation and Survey Division in 2018 on the western edge of the Indian Cave State Park, some 3.7 km due west of the cave itself. The stratigraphy equivalent to the ICS was penetrated, including the Falls City Limestone above and Brownville Limestone below. However, the core did not encounter an incised sandstone body and the equivalent interval is represented by mudstone-dominated heterolith (Facies H_2: Table 2) that exhibits an upward increase in pedogenic alteration (Fig. 15). This discovery was unexpected, and yet it amplifies out prior conclusions about the ICS. We interpret this new core as a record of "background" cyclothems beyond the margins of the ICS incised valley, and specifically on an interfluve (an elevated flat plain outside of the incised topography; see cross-section in Figure 16). Thus, we present a tentative paleogeographic map, in accordance with paleoflow data and the new cored hole, in Figure 16. We envisage the ICS as a linear tract a few kilometers in width and elongate towards the south or south-southwest (Fig. 16). This trend and width are comparable to other interpreted incised valley fills described from the Pennsylvanian of Kansas (e.g., Feldman et al., 1995, 2005), and the paleovalley tracks parallel to the modern Missouri River. This is a rare case for the Midcontinent region where the sedimentary record of both a latest Pennsylvanian incised valley and its immediately adjacent interfluve can be examined together. We hope that this dataset will stimulate further research into the role of incised valley fills in Pennsylvanian stratigraphy of the Midcontinent and beyond.

From Indian Cave, we return to Lincoln by the outward route.

CONCLUSIONS

The incised basal surface, linear planform, fluvial to estuarine facies associations, and fining-upward character of the Indian Cave Sandstone (ICS) indicate that it was formed by incision of one or more incised valleys and channels during drawdown of sea-level on the Midcontinent platform in the latest Pennsylvanian. Erosional relief of up to 30 m on the basal surface provides a minimum estimate of the sea-level drawdown, which was probably a far-field response to Gondwanan glacial ice growth. Fluvial discharge was dispersed southward towards the Ouachita-Marathon foreland basin during falling stage and lowstand, after which the incised valleys and channels began to backfill during early stages of transgression. Estuarine facies dominated and then were ultimately drowned by shallow marine muds and bioclastic carbonate deposits during the later transgressive phase and sea-level highstand. The ICS is anomalous in the context of the typical "Kansas-City type" cyclothems, but is a facies that is well-represented in the region in certain locations and at a variety of stratigraphic levels (Archer et al., 1994). We submit that the incorporation of incised valley fills and their lateral equivalent interfluve facies to stratigraphic models for Pennsylvanian cyclothems of the Midcontinent contributes to an improved understanding of these rocks. The future recognition of other out-of-context sandstone bodies will likely lead to further discoveries of energy resources as well.

ACKNOWLEDGEMENTS

We thank Matt Marxsen, John Seamann, and Michele Waszgis of the Conservation and Survey Division (CSD) for drilling the core hole described herein. Dee Ebbeka

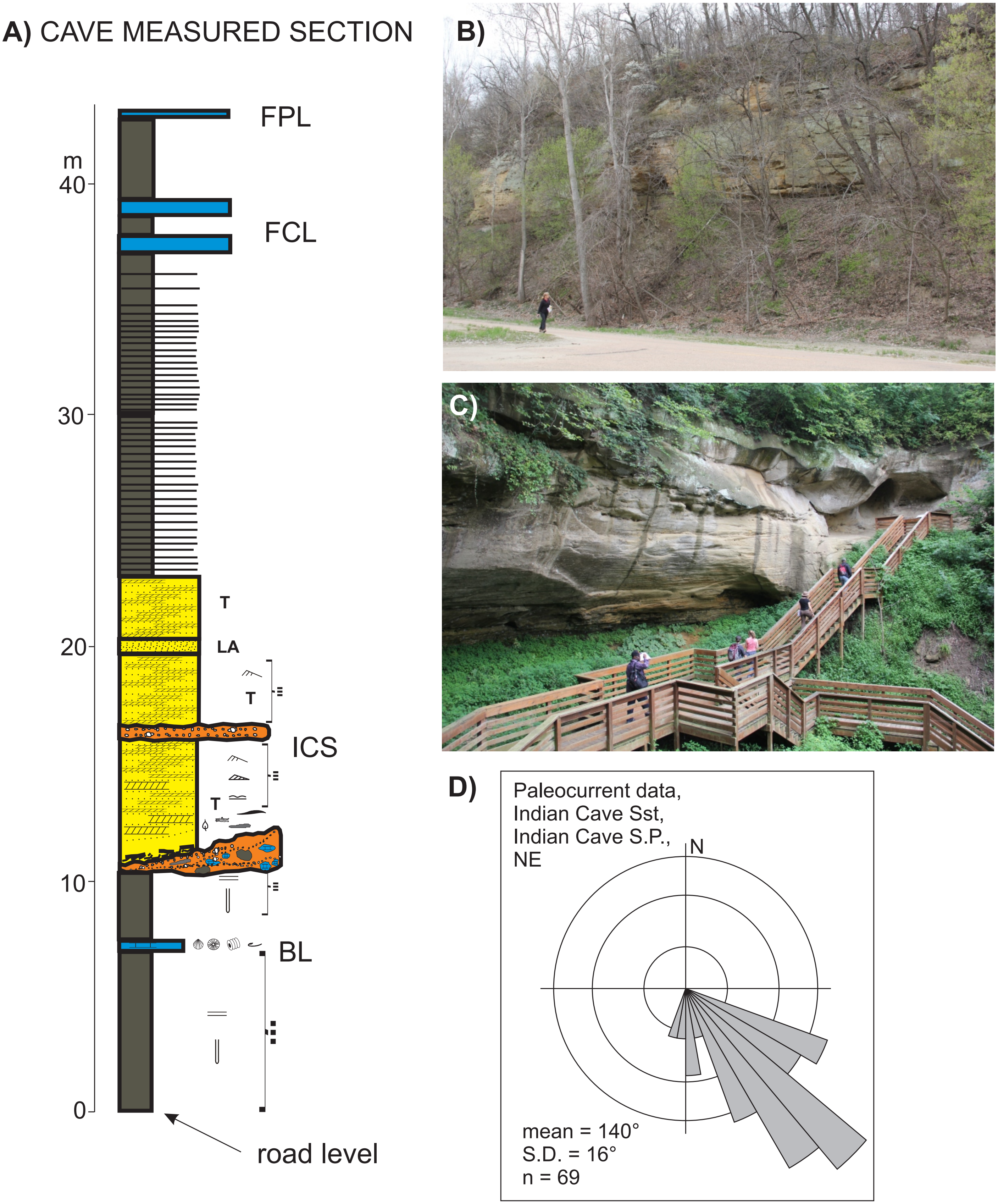

Figure 14. Indian Cave Sandstone at Indian Cave State Park (ICSP). A) Graphic log of a section measured near the cave site. BL – Brownville Limestone, ICS – Indian Cave Sandstone, FCL – Forest City Limestone, FPL – Five Point Limestone. See Figure 10 for key to symbols used. B) View of the main cliff, showing the erosionally-based, FDZ facies association of the ICS. C) View of the sandstone exposure at the eponymous cave. D) Paleocurrent data from the ICSP exposures, showing a southeasterly mode.

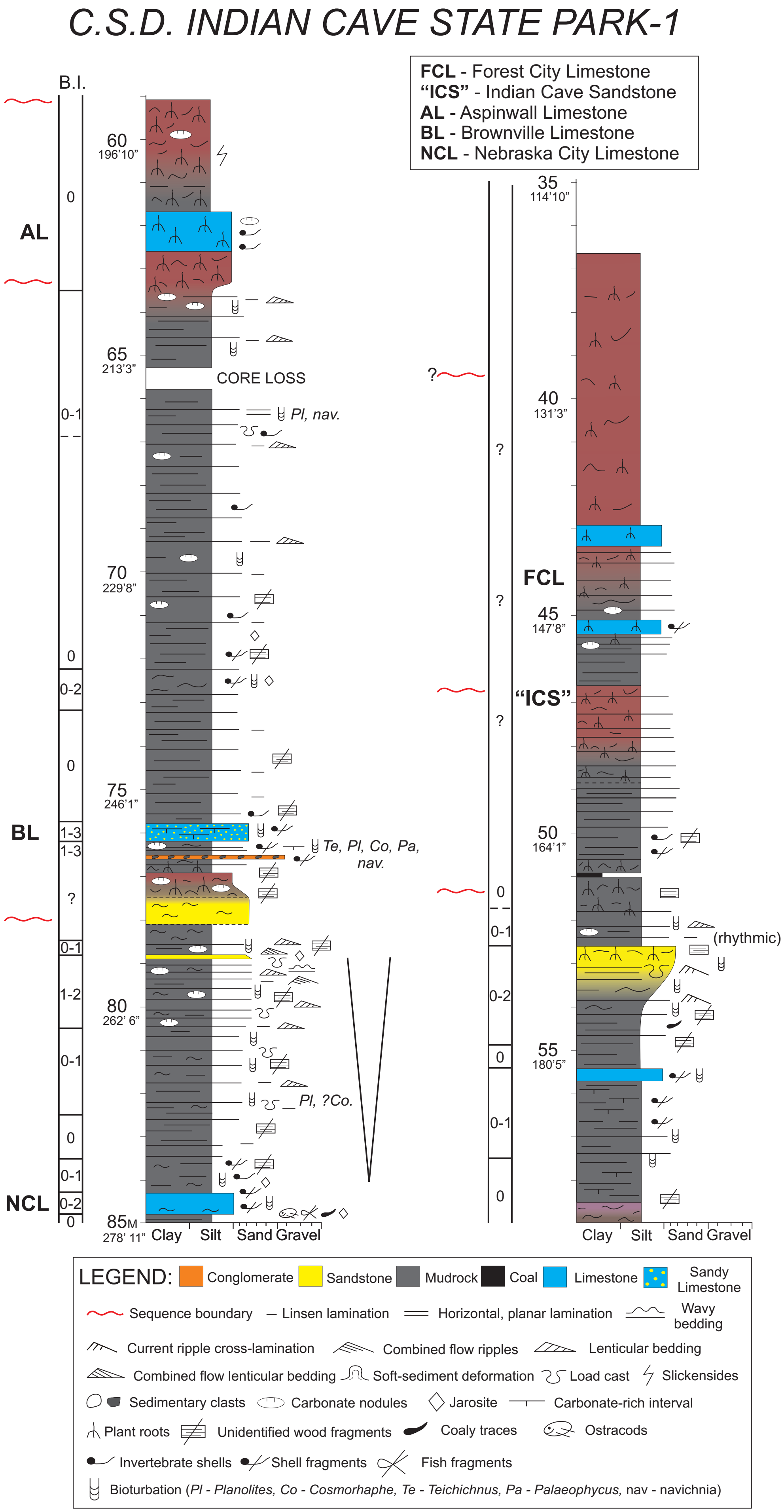

Figure 15. Graphic log of the ICSP-1 core, with key to symbols and abbreviations used. The hole terminated immediately below the interpreted Nebraska City Limestone, and includes the interval of the ICS. At this locality, however, the ICS is represented by a pedogenically-modified siltstone 47-48 m below the surface. See Figure 16 for location of ICSP-1.

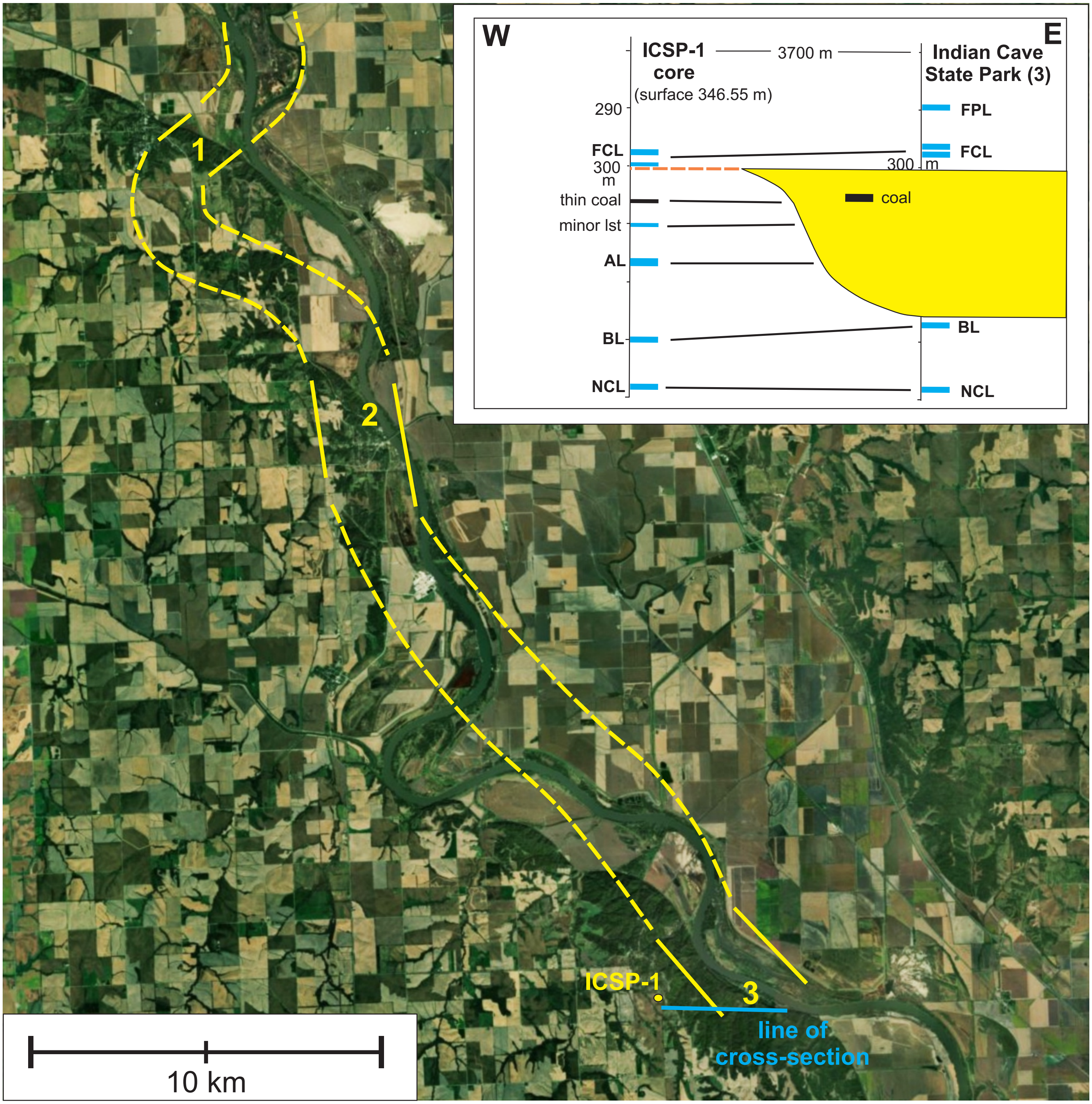

Figure 16. Aerial image showing the interpreted trace of the ICS paleovalley, based on the three exposures visited, and paleocurrent data from those exposures: 1 – Peru, 2 – Brownville, 3 – Indian Cave State Park. Note the parallelism with the modern Missouri River. Inset: stratigraphic cross-section illustrating interpreted lateral relationships between the ICSP-1 core and the cave exposures. Numbers indicate true elevations in each case. Line of cross-section is shown in blue.

and Les Howard, also of CSD, drafted some of the figures included in this field guide. Justin Ahern (UNL EAS) drafted Figure 15. Paleocurrent diagrams were compiled using EZ-ROSE by Baas (2000).

The Nebraska Game and Parks Commission, through the efforts of Charla Rasmussen and Adam Jones, generously provided permission for drilling and access to Indian Cave State Park for field research. Likewise, the Nemaha Natural Resources District has long allowed, and even facilitated, geological research along the Steamboat Trace Tail from Brownville to Peru, Nebraska.

This field trip and the associated conference were greatly facilitated by the efforts of the organizing committee, comprising Doug Hallum (CSD), Jacki Loomis (School of Natural Resources, UN-L), Dan Blankenau (Coranco Great Plains), Bob Gjere, and Ted Huscher (USDA).

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View of the lower, fluvially-dominated facies association (mainly cross-bedded sandstone) of the Indian Cave Sandstone on the Steamboat Trace Trail southeast of Peru

SUNDAY, October 14th, 2018

8:00 – 8:20 am

LOWER-MIDDLE PENNSYLVANIAN STRATA IN THE NORTH AMERICAN MIDCONTINENT RECORD THE INTERPLAY BETWEEN EROSIONAL UNROOFING OF THE APPALACHIANS AND EUSTATIC SEA LEVEL RISE

Finzel, E.S.[1*], Kissock, J.K.[1], Malone, D.H.[2], Craddock, J.P.[3]

[1]Earth & Environmental Sciences, University of Iowa, 115 Trowbridge Hall, Iowa City, IA 52242

[2]Department of Geography-Geology, Illinois State University, Normal, IL 61790-4400

[3]Geology Department, Macalester College, St. Paul, MN 55105

**email: emily-finzel@uiowa.edu*

Morrowan, Atokan, and Desmoinesian (Lower-Middle Pennsylvanian) clastic strata in the Forest City (Iowa, northwest Missouri, eastern Nebraska and Kansas) and Illinois basins on the North American midcontinent record the interaction between fluctuations in eustatic sea level and major tectonic events. One of three major Paleozoic eustatic sea level lows occurred near the Mississippian/Pennsylvanian boundary and was followed by a eustatic rise that continued into Late Pennsylvanian time. Alleghenian mountain building that is linked to the creation of the Pangean supercontinent also began during latest Mississippian time and continued until latest Pennsylvanian or earliest Permian time. Detrital zircon geochronology and stratigraphic descriptions allow reconstruction of sediment dispersal patterns associated with these events. Our detrital zircon signatures from Morrowan-lower Desmoinesian strata in the Illinois basin are interpreted to reflect a change from regional drainages that reworked underlying Mississippian strata to extensive extra-basinal fluvial systems that supplied detritus shed from southeastern New England. By middle Desmoinesian time, detrital zircon signatures in the Illinois basin are more similar to those from coeval units in the central Appalachian Basin, indicating a southward shift in the provenance of the fluvial systems. In the Forest City basin, Morrowan strata are absent and our detrital zircon data indicate that Atokan-early Desmoinesian sedimentation was dominated by regional fluvial systems that recycled underlying strata. The introduction of extra-basinal fluvial systems with New England headwaters in the middle Desmoinesian coincided with the overtopping of the Mississippi River Arch and depositional linking of the Forest City and Illinois basins. The Forest City and Illinois basins collectively contain an Early-Middle Pennsylvanian sedimentary record in the backbulge depozone of the Alleghenian foreland basin system that records overtopping of the forebulge located along the Cincinnati Arch and the effects of eustatic sea level rise. These results lend credence to the previously proposed transcontinental fluvial systems during Late Paleozoic time and help to better constrain their courses.

8:20 – 8:40 am

AN INTRODUCTION TO THE CORE WORKSHOP

Christopher R. Fielding[1*] and R. Matthew Joeckel[2]

[1]*Department of Earth & Atmospheric Sciences, 126 Bessey Hall, University of Nebraska-Lincoln, NE 68588-0340.*

[2] *Conservation and Survey Division, School of Natural Resources, Department of Earth & Atmospheric Sciences & University of Nebraska State Museum, University of Nebraska-Lincoln, 615 Hardin Hall, Lincoln, NE 68583-0996.*

**e-mail: cfielding2@unl.edu*

SCIENTIFIC POSTER ABSTRACT

GEOLOGY OF A DEEP TEST HOLE IN SOUTHWEST NEBRASKA

Douglas R. Hallum

Conservation and Survey Division

School of Natural Resources, University of Nebraska-Lincoln West Central Research and Extension Center,

402 West State Farm Road, North Platte, Nebraska, USA.

dhallum2@unl.edu

In July and August 2018, Kugler Oil Company, Inc. drilled a 2491 ft (759 m) test hole and cemented casing in order to evaluate the Permian Cedar Hills Formation as a possible reservoir for the disposal of wastewater from its Culbertson, Nebraska facility. Descriptions of borehole cuttings (made by the author) compiled with geophysical and caliper data collected by Pioneer Energy Services enable Kugler and their engineering team to: (1) select intervals for drill stem tests (DSTs), and (2) design of a Class I injection well.

In the test hole, Republican River alluvium (0-60 ft), consists of fine gravel and sand that had a strong tendency to slough into the bore, causing a brief drilling delay while the bore was stabilized. Bedrock strata were encountered from 60 ft downward.

The Upper Cretaceous Pierre Shale (60-720 ft) includes dark green-gray claystone and shale, calcareous shale, silty shale, and shale with bentonite strata. Intervals of shale within this unit are moderately well indurated, and calcite-filled fractures are present in some intervals. The top of the Sharon Springs Member of the Pierre Shale lies at a depth of 613 ft. The Niobrara Formation (720-1108 ft) Smoky Hill Chalk Member (720-1020 ft) consists mostly of light gray limestone and dark gray chalky shale, as well as minor bentonite strata. The Fort Hays Limestone Member (1020-1108 ft) is a very clean, light colored limestone with interbeds of shale in its lower part. The Carlile Shale (1108-1280 ft) is mostly indurated shale, and it is calcareous in a few intervals. A silica-cemented sand at 1204 ft is correlated as the Codell Sandstone Member. The Greenhorn Limestone (1280-1334 ft) contains abundant limestone with a pronounced granular appearance, with several interbedded shale sections. The Graneros ("Belle Fourche") Shale ((1334-1396 ft) exhibits a distinct fracture character in the cuttings, being more fissile, angular and splintery than cuttings from overlying formations. A positive gamma excursion at 1391 ft is correlated as the "X"-bentonite marker bed. The Dakota Group[1] is a long section of siltstone, sandstone, and sand from 1396 to 2078 ft. Cementation in this unit is variable, it contains some pyrite, and it is stained by iron oxyhydroxides in places. A bluish-white claystone (possible tephra or bentonite) is identified near the base of the Dakota Formation.

The Morrison Formation (2078-2140 ft) consists of multicolored siltstone with a trace of ash or bentonite and soft calcareous mudstone. Directly underneath a regional disconformity at the base of the Jurassic System is the

Permian System, including the Dog Creek Formation (2140-2188 ft), Blaine Formation (2188-2208 ft), Flower Pot and (2208-2245ft) Cedar Hills Members of the Salt Fork Formation (2245-2275 ft), and Salt Plain Formation (2275-2488 ft) of the Nippewalla Group and the Stone Corral Formation (2488-? ft) of the Sumner Group. Permian strata above the Cedar Hills (Dog Creek, Blane, Flower Pot) consist chiefly of mudstones (usually red, but also light gray-greenish gray), with much of the red mudstone being incorporated into the drilling fluid, which turned red. The Cedar Hills Member of the Salt Fork Formation contained clean, hard, well indurated very fine grained sandstone. The Salt Plain Formation was composed of red mudstone that would readily suspend and wash away when processed with clean water. The Stone Corral Formation was not identified in cuttings, but inferred from the rig behavior and change in penetration rate at 2488 ft.

This project demonstrated that detailed descriptions of cuttings, combined with geophysical, caliper and penetration rate data, can support improved permitting decisions by the Nebraska Department of Environmental Quality. The interpretive stratigraphic log resulting from this work improves confidence in the placement of contacts and facies transitions because of the ability to directly observe changes in the cuttings representing discrete intervals. In nearby test holes that penetrate the Permain System, some of the geophysical data are available, and cuttings have been preserved. There are uncertainties regarding the sampling process that may have been used for these cuttings, rendering difficult the valuation of those physical samples relative to any archived geophysical measurements. Thus, the analysis of the Kugler test hole provides a means for improving concepts of local to regional stratigraphy.

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CORE WORKSHOP ABSTRACTS

THE KGS GAYDUSEK #1 CORE IN WASHINGTON COUNTY, KANSAS: A RECORD OF THE MID-CRETACEOUS OAE1d AND OAE2 IN ALBIAN-TURONIAN STRATA

G.A. Ludvigson[1*], R.M. Joeckel[2], J. Doveton[1], R.D. Mandel[1]

[1]*Kansas Geological Survey, University of Kansas, Lawrence, Kansas, USA*

[2]*School of Natural Resources, University of Nebraska-Lincoln, Lincoln, Nebraska, USA*

**e-mail: gludvigson@kgs.ku.edu*

The KGS Gaysdusek #1 core (KID: 1028187622) was drilled by the Kansas Geological Survey, with completion in November 1989. The 534' length core is a complete penetration of all Cretaceous units present at the dip slope rim of the Rose Creek Escarpment along the Kansas-Nebraska border, and serves as an important reference section that captures multiple mid-Cretaceous global change events. Our core display will include the upper 200' of core, including the Greenhorn Limestone, Graneros Shale, and upper part of the Dakota Formation. Lithologic core logging, high-resolution organic carbon $\delta^{13}C$ profiling, and borehole spectral gamma-ray logging reveal several salient features of the succession.

Strata of the Dakota Formation have baseline $\delta^{13}C_{org}$ values of about -25‰ VPDB. The negative and positive carbon isotope excursions associated with OAE1d at the Albian-Cenomanian stage boundary (100.5 Ma)[1,2] are captured in the core at the 165' to 155' depth level, and are associated with a short-lived spike in TOC% values starting from baseline values near 0% going up to 5%.

An abrupt positive carbon isotope excursion (possibly the mid-Cenomanian Event at 97 Ma?) in the lower part of the Graneros Shale peaks at a $\delta^{13}C$ value greater than -22‰ at the 95' depth level, and also coincides with an abrupt shift in baseline organic $\delta^{13}C$ values from -25‰ VPDB below to -27‰ VPDB above, possibly associated with an abrupt shift from terrestrially-sourced to marine microplanktic organic matter attending a eustatic landward step in the eastern shoreline of the Western Interior Seaway.

The so-called X-bentonite is encountered in core at the 82' depth level in the Graneros Shale, and is associated with an abrupt peak in Thorium concentrations to > 18 ppm. A short distance away, a State Highway 15 roadcut exposure of the X-bentonite just below the rim of the Rose Creek Escarpment has recently produced a large population of volcanogenic zircon phenocrysts that have been analyzed by LA-ICP-MS to yield an age of 95.53±0.36 Ma[3].

Marls of the lower part of the Greenhorn Limestone occur at a depth range of 42' to 72', and are associated with peak TOC values ranging from 15 to 30%. This same interval coincides with peak Uranium concentrations in the core ranging between 10 to 19 ppm. Moreover, this same stratigraphic interval has been reported as conspicuously lacking in benthic foraminifera from studies in the Big Sioux River Valley of NW Iowa—a so-called "dead zone" related to fluvial runoff and fertilization from the landmass to the east of the Western Interior Seaway[4].

The interval of OAE2 in the upper part of the Greenhorn Limestone occurs over the depth range from 32' to 46', with organic $\delta^{13}C$ values of the rising limb (~ 94.5 Ma) starting from a baseline of -28‰ going up to peak $\delta^{13}C$ values of -23‰ VPDB. Organic matter values through this interval fall from TOC values of 25% at the base to near 0% at the top, possibly related to the influence of oxidation from Cenozoic weathering processes at the bedrock surface.

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THE RIVERTON CORE – IOWA'S MOST COMPLETE PENNSYLVANIAN SECTION

Clark, Ryan J.[1*], Witzke, Brian J.[2], Pope, John P.[3]

[1]*Iowa Geological Survey, University of Iowa, Iowa City, IA 52242*

[2]*Department of Earth and Environmental Sciences, University of Iowa, Iowa City, IA 52242*

[3]*Department of Natural Sciences, Northwest Missouri State University, Maryville, MO 64468*

**e-mail: ryan-j-clark@uiowa.edu*

Iowa lies mostly west of the northern confluence of two major depositional basins hosting thick sequences of Pennsylvanian strata, the Forest City Basin to the southwest and the Illinois Basin to the southeast. In 1985, the Iowa Geological Survey (IGS) drilled a core near the town of Riverton in southwestern Iowa (Fig. 1) in the hopes of encountering the thickest Pennsylvanian succession in Iowa. The Riverton core (W-27556) was indeed a success, reaching a total depth of 1,116 feet, starting in the Stotler Formation of the upper Virgilian Wabaunsee Group and ending in the Nowata Shale Formation of the upper Desmoinesian Marmaton Group. The upper part of the Riverton core, from 174.0 – 788.5 feet, serves as a reference section for the Virgilian Stage in Iowa (Pope, 2012). This core allowed workers to improve correlations among Pennsylvanian units in Iowa and surrounding states. A portion of the core from the Virgilian Stage will be on display, including the Deer Creek Formation cyclothem from the Shawnee Group (Fig. 2).

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To access records of public, private, and municipal water wells, exploration wells, and core holes through the Iowa Geological Survey's online database, *GeoSam,* go to https://www.iihr.uiowa.edu/igs/geosam/home and use the unique well identification number (W-#####).

To access photos of rock core samples through the Iowa Geological Survey's online database, *GeoCore*, go to https://www.iihr.uiowa.edu/igs/geocore/home and use the unique well identification number (W-#####).

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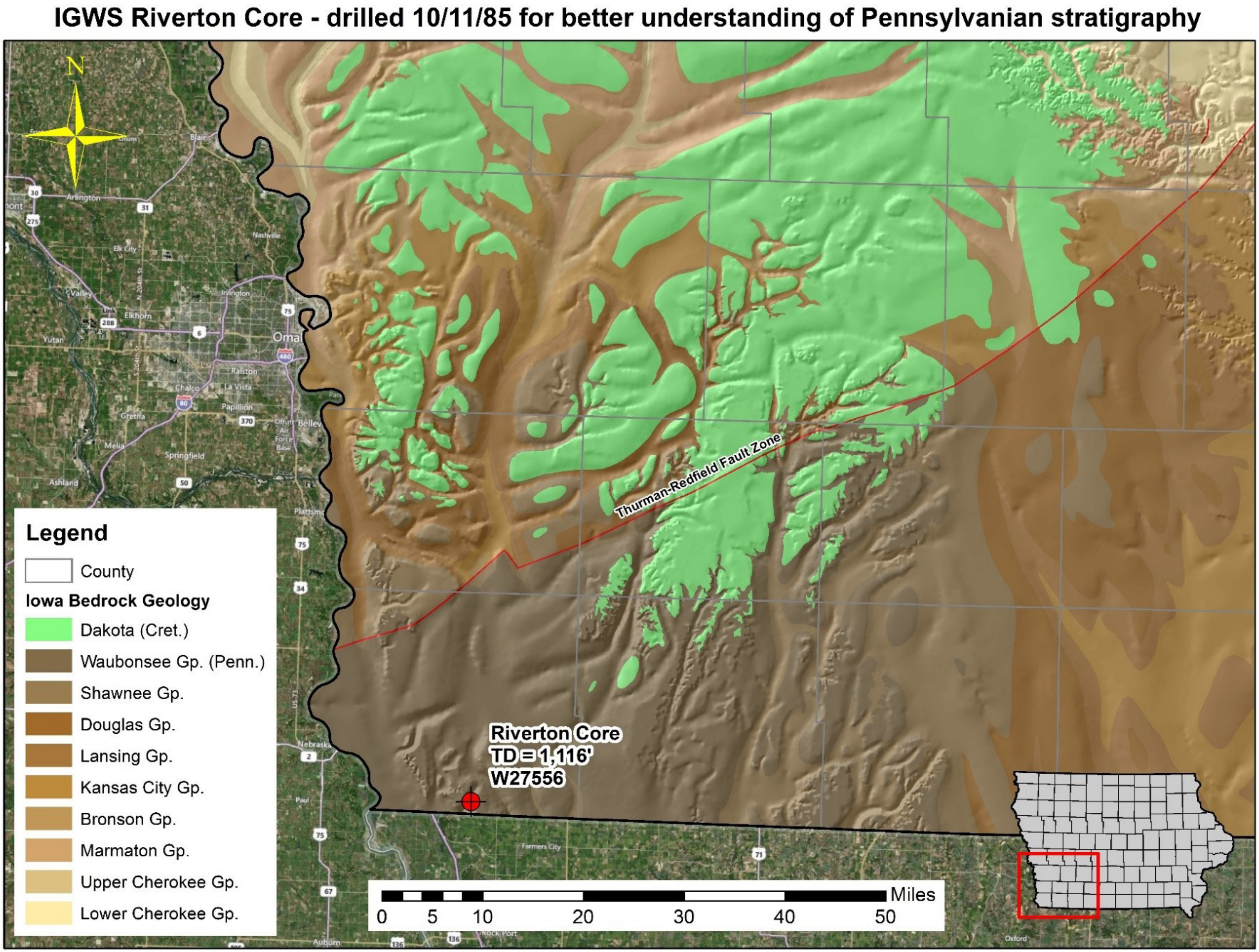

Figure 1: Portion of the Bedrock Geologic Map of Iowa (Witzke et al., 2010) showing southwestern Iowa and the location of the Riverton core.

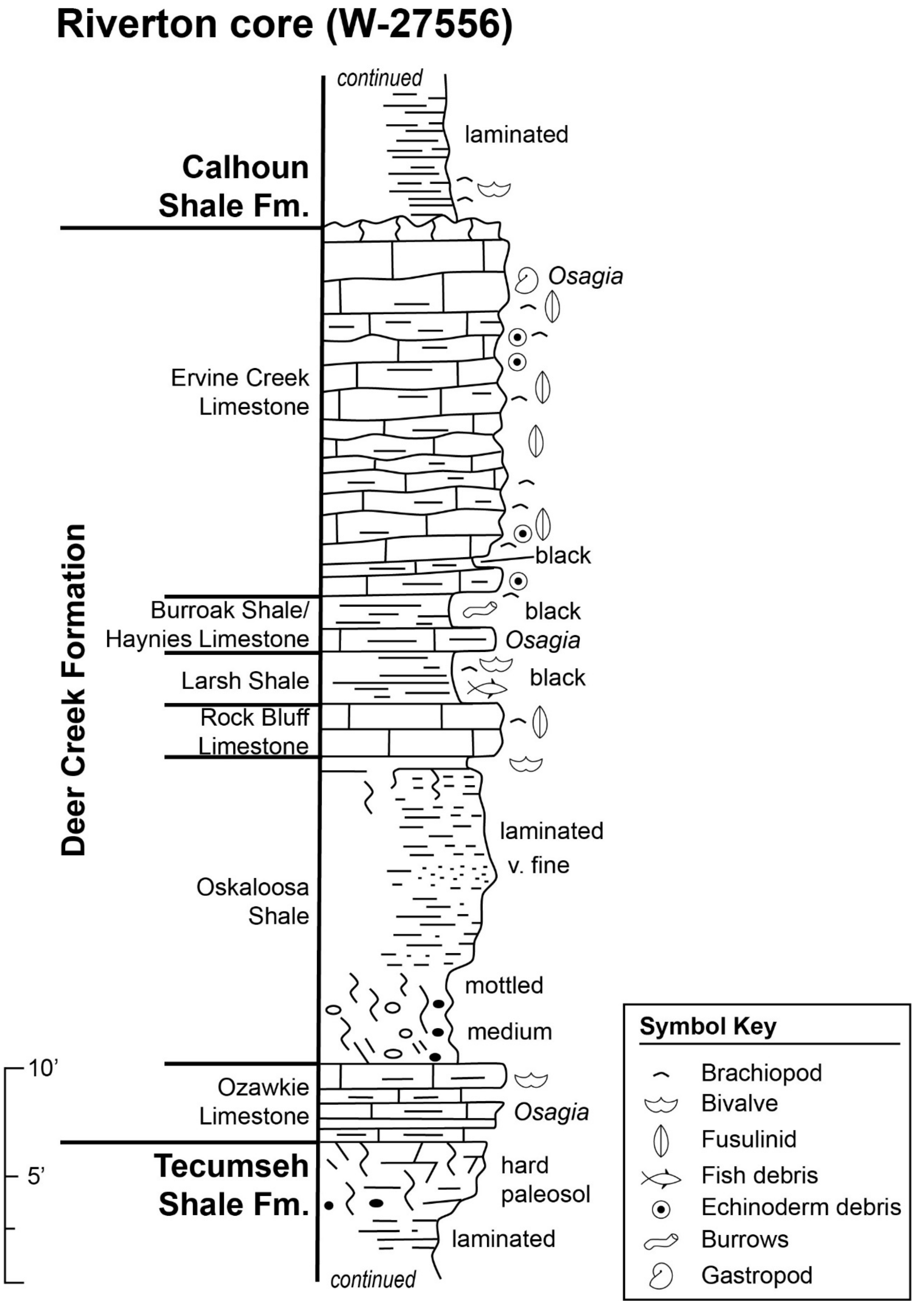

Figure 2: Graphic log of a portion of the Riverton Core (W-27556) illustrating the Deer Creek cyclothem section of the Virgilian Shawnee Group. (Above illustration was modified from the original drawn by Brian Witzke)

DEPOSITIONAL ENVIRONMENTS AND CYCLES OF THE SERPUKHOVIAN HEATH FORMATION: A CASE STUDY FROM THE 33-3H ROCK HAPPY CORED INTERVAL, ROSEBUD COUNTY, CENTRAL MONTANA

Justin Ahern[1], Christopher R. Fielding[1], Richard Bottjer[2]

[1]*University of Nebraska- Lincoln, 1400 R St, Lincoln, NE 68588, USA*

[2]*Coal Creek Resources, Denver, CO, USA*
**justin.ahern@huskers.unl.edu; cfielding2@unl.edu; rjbottjer@coalcreekresources.com*

Introduction:

The late Mississippian (Serpukhovian) Heath Formation present in Central Montana preserves numerous organic rich mudstone and limestone-dominated cyclothems that broadly coincide with the onset of the Late Paleozoic Ice Age (LPIA) and are prospective unconventional hydrocarbon plays. The Heath Formation has long been considered the primary source rock for the Heath-Tyler petroleum system, from which over 137 million bbl of oil have been produced through conventional development since 1919 (Knapp, 1956). Recent work on the internal stratigraphy of the Heath suggests that it comprises a stand-alone petroleum system, with the potential to produce over 13 billion bbl of oil through unconventional development (Bottjer, 2014; McClave, 2012). In 2013, direct oil production from the Heath provided support for its consideration as a viable resource play, though it is still in the early stages of development.

Aside from its resource potential, the Heath Formation preserves a paleotropical stratigraphic record that is broadly coincident with the onset of the late Paleozoic Ice Age (LPIA). The LPIA was a ~76 myr icehouse period when ice centers waxed and waned during asynchronous (Cagliari et al., 2016) glaciations across Gondwana, resulting in complex glacio-eustatic sea-level oscillations (Veevers & Powell, 1987; Isbell et al., 2003; Fielding et al., 2008; Montañez & Poulsen, 2013) from the late Mississippian to the late Permian. This event has garnered decades of research because it records the only transition of a vegetated Earth both into and out of a long-lived icehouse regime and is considered an analog for the Quaternary icehouse (Raymond & Metz, 2004); however, the LPIA still remains incompletely documented. This study informs a greater understanding of sea-level and paleoclimate oscillations related to LPIA onset, in addition to new depositional and sequence stratigraphic models for the Heath Formation.

Geologic Setting:

Field observations of this study encompass the Big Snowy, Little Snowy and Judith Mountains of central Montana. Observed cores of the Heath Formation were sourced east of the Big Snowy Mountains in Rosebud, Musselshell, Garfield and Petroleum counties (Fig. 1). The 33-3H Rock Happy cored interval, previously drilled by Cirque Resources, will serve as the model for this presentation (Fig. 5).

In the late Paleozoic, central Montana was situated within the Big Snowy Trough (Fig. 2), an E-W trending structural sag that initiated in the latest Devonian (Nelson & Lucas, 2011) as tectonic flexure related to the Antler Orogeny down-warped central Montana and differentially uplifted the surrounding Alberta and Wyoming Shelves (Maughan, 1984). Continuous development of the Big Snowy Trough was facilitated by subsidence along high-angle Proterozoic bounding faults of the underlying Montana Aulacogen (Maughan, 1984; Nelson, 1995), which were conduits for later structural inversion that culminated in the present-day Big Snowy Mountains (Marshak, 2000; Nelson, 1995). Following the early Mississippian, tectonic quiescence and passive subsidence ensued in central Montana up to the early Pennsylvanian (Nelson, 1995), as distant topographic highs including the Siouxia Arch, the Transcontinental Arch, and the Milk River Uplift (Maughan, 1984) provided sediments that filled the trough.

The Big Snowy Group (375m thick; Scott, 1935) is composed from bottom to top of three conformable units: the Kibbey, Otter, and Heath Formations (Maughan & Roberts, 1967- Fig. 3). The Kibbey Formation preserves brecciated calcareous red siltstone with dolomicrite nodules and intraclasts, microbialite, and channel-form sandstone with intervals of silicified breccia. The Otter Formation is composed of stochastic alternations of calcareous green mudstone, wackestone-packstone, oolite, quartz arenite, algal boundstone, silicified breccia, and pedogenically modified siltstone. The Heath Formation preserves a lower coal and paleosol-bearing assemblage and an upper microbialite and evaporite-bearing assemblage, each of which contains interval of organic-rich fossiliferous mudstone and gray clastic limestone with open marine to restricted fauna.

The Big Snowy Group is disconformably overlain by the mixed carbonate and clastic deposits of the Tyler Formation (Maughan, 1984) that consists from base to top of the Stonehouse Canyon Member, the Bear Gulch

Limestone, and the Cameron Creek Member (Fig. 1). Regional-scale erosional and hiatal surfaces separate the Stonehouse Canyon from the Heath Formation (Foster, 1959; Bottjer, 2017), and the Bear Gulch Limestone from the Cameron Creek Member (Bottjer, 2017; this study), which grades upward into the cyclic, carbonate-dominated stratigraphy of the Alaska Bench Formation (Gilmour, 1969) (Fig. 3).

Depositional Model:

Previous work suggests the Heath Formation was deposited in a broad array of oxic to anoxic, nearshore marine, coastal, and sabkha environments (Maughan, 1984; McClave, 2012; Bottjer, 2014); however, an incomplete assessment of microfacies, and lack of comparable modern analogues, has not fully accounted for the range of environments preserved in the Heath.

In this study, a thorough microfacies analysis of the Heath Formation argues for deposition in 5 recurring Facies Associations: Offshore Outer Ramp (OR), Outer to Mid Ramp (MOT), Inner Ramp (IR), Coastal Plain (CAP), and Sabkha (SAB) environments, herein interpreted within the context of a protected, muddy, homoclinal carbonate ramp (cf. Burchette & Wright, 1992; Read, 1998) (Fig. 6). Individual facies were determined based on their relative proportion of siliciclastic and carbonate components, grain size, grain abrasion, relative proportions of constituent fossils, sedimentary structures, and ichnofossil abundance (MacEachern et al. 2007). Descriptions of individual facies that together, constitute each Facies Association are provided in Figure 4.

The 4 facies associations identified in this study are distinct from one another; however, acute differences between Inner Ramp (IR) facies associations and the relative proportion of paleosol-coal and microbialite-evaporite facies exist between the lower and upper portions of the Heath Formation. This variation is preserved by the presence of normal marine to brackish littoral platform (IR) and paleosol-coal (CAP) facies in the lower Heath, and metahaline to hypersaline littoral platform (IR), lagoon (IR), and anhydrite-bearing sabkha (SAB) facies that are exclusive to the upper Heath (Fig. 4).

The eastern Nicaragua Shelf and the Sunda Shelf of Indonesia (Friedman, 1988; Roberts, 1987) provide plausible modern analogues for the lower Heath from which estimates of water depth necessary to produce mixed mudstone and clastic limestone intervals in humid tropical latitudes can be inferred (Fig. 6). The Persian Gulf (Kendall et al., 1969; Wagner & Van der Togt, 1973) provides a suitable modern analogue for depositional environments preserved in the upper Heath Formation, from which depth constraints of mixed mudstone and clastic limestone facies in arid settings can be inferred (Fig. 6). Muddy clastic carbonate sediments extend from ≥24 m water depth on the eastern Shelf of Nicaragua, whereas muddy clastic carbonates and siliciclastic mud inter-finger at ≥30 m water depth in the Sunda Shelf. In comparison to its humid counterparts, muddy clastic carbonates and fossiliferous muds interfinger at depths ≥18-37 m in the Persian Gulf.

Sequence Stratigraphy:

In the lower half of the Heath Formation, repeated alternations of Coastal Plain Facies Associations (CAP), Inner Ramp Facies Associations (IR), and Offshore Outer Ramp (OR) and Mid to Outer Ramp Facies Associations (MOT) are preserved. An ideal depositional sequence of the lower Heath contains in ascending order: CAP paleosol overlain by CAP coal, OR silty shale with bioclastic siltstone and minor shell horizons, MOT interbedded calcareous mudstones and clastic limestones with open marine fauna, IR nearshore low-diversity fossiliferous micrite to wackestone, continuing once again into CAP paleosol (Fig. 6). Of the 4 depositional cycles preserved in the lower Heath, not all cycles preserve this complete ideal assemblage of facies associations; however, each cycle preserves MOT fossiliferous mudstone enclosed above and below by pedogenically modified mudstones.

In the upper half of the Heath Formation, cyclical alternations of Sabkha Facies Associations (SAB), Inner Ramp Facies Associations (IR), Mid to Outer ramp Facies Associations (MOT), and Outer Ramp (OR) Facies Associations are preserved. An ideal depositional sequence of the lower Heath formation contains in ascending order: SAB microbialite-evaporite facies, OR silty shale with thin shell horizons, MOT mixed calcareous mudstones and clastic limestones with open marine fauna, restricted IR sublittoral fossiliferous micrite to wackestone, continuing once again into IR rhythmically laminated micrite, microbialites and SAB microbialite-evaporite facies (Fig. 6).

In the lower Heath, coastal plain paleosols demarcate subaerial exposure surfaces whereas coals and carbonaceous shales represent initial flooding during transgression (Heckel, 1994) (Fig. 6). Shale, fossiliferous mudstones and thin argillaceous limestones preserve continued transgression to maximum flooding and early highstand respectively (cf. Heckel, 1994; James & Jones, 2015) (Fig. 6). During the transgressive systems tract anoxic environments of organic mudstone deposition (Wignall, 1991) expanded, severely inhibiting marine invertebrate growth. Conversely, during early highstand, the anoxic mudstone environments of deposition contracted and carbonate producers proliferated, filled accommodation, and were transported across the ramp as clastic limestones (Dolan, 1989), though the products of "highstand shedding" are muted on ramps as compared to rimmed platforms (Catuneanu, 2006; James & Jones, 2015; Schlager et al., 1994). Inner ramp fossiliferous calcareous mudstones, wackestones and subsequent paleosol development preserve the progradation of inner ramp facies and abrupt subaerial exposure, accounting for late highstand and lowstand system tracts respectively (James & Jones, 2015) (Fig. 6). In the upper Heath, sabkha microbialite-evaporite associations represent subaerial exposure surfaces, whereas shale, fossiliferous mudstone, with clastic limestone preserve maximum flooding and early high stand deposits respectively that are equivalent to those recognized in the upper Heath (Fig. 6). Inner Ramp calcareous mudstones and wackestone, intertidal rhythmites, and capping microbialite-evaporite associations represent late highstand and lowstand system tracts respectively (Fig. 6).

Contrary to sequence stratigraphic models provided above, an additional interpretation may be also considered for the differentiation of maximum flooding surfaces in the Heath (Moore 1964; see fig. 1 *in* Klein, 1996). Considering these studies organic shale facies would not record maximum flooding intervals, instead argillaceous limestones are interpreted to record the deepest environments of deposition and the influence of increased open marine circulation. Though this interpretation carries validity, it does not most effectively account for facies that record highstand system tracts in the Heath, nor the facies patterns preserved in the Heath that reflect dysoxic to euxinic conditions commonly observed with increasing depth in silled basins (Byers, 1977; Wignall, 1991; Heckel, 1994).

Discussion:

Multiple lines of evidence support the interpretation that depositional cycles preserved in the Heath Formation record high frequency and high magnitude relative sea-level oscillations. First, observed depositional cycles are generally are ≤8m thick, which are inconsistent with progradational processes into standing water (Fielding & Frank, 2015), especially when considering that muddy clastic limestones accumulate at a minimum water depth of 24m in modern humid tropical settings (Friedman, 1988; Roberts, 1987) and a minimum water depth of 18m in modern arid settings (Kendall et al., 1969; Wagner & Van der Togt, 1973). Second, in the lower Heath Formation, direct pedogenic modification of inner ramp facies is observed, in addition to immediate juxtaposition of paleosols over marine mudstone and wackestone, both of which are suggestive of abrupt high-magnitude relative sea-level falls. A comparable array of paleosols directly superimposed on carbonate and clastic facies in the Lower Limestone Group of East Fife, Scotland (Fielding et al., 1988) also preserve an analogous record of abrupt major relative sea-level falls. Additionally, juxtaposition of marine mudstones and wackestones over intertidal and sabkha deposits in the upper Heath Formation provides further evidence of abrupt relative sea-level fluctuations. A regime of tectonic quiescence and passive subsidence during Heath deposition (Nelson, 1995) provides further support that observed depositional cycles were likely not of tectonic origin.

Considering the evidence above, ≥7 fourth-order relative sea level oscillations that are bounded by sequence boundaries and can be resolved into complete Vail-EXXON depositional cycles (Catuneanu et al., 2009) are recognized in Heath Formation (Figs. 5&6). Observed depositional cycles are typically ≤8m thick and encompass a broad array of offshore to coastal environments, suggesting deposition occurred in a sediment-starved and low accommodation setting.

No grainy inner ramp deposits, commonly preserved in ramp settings (Ahr, 1973; Burchette & Wright, 1992; Read, 1998), were observed in the Heath Formation; however a number of factors may account for this disparity. First, high frequency and high magnitude relative sea-level oscillations suppress long-term carbonate growth, which results in relatively thin limestone accumulations and unfilled accommodation (Read, 1998). Since accommodation in inner ramp locales is relatively low compared to deeper ramp environments, it is likely that frequent high-magnitude sea-level oscillations could have severely inhibited thick, grainy carbonate accumulations in the Heath Formation. Second, it is plausible that the Antler Highlands and Lombard Arch (Fig. 5) could have served as physical barriers by which wave energy from the Panthalassan Ocean was baffled in the Big Snowy Trough. As such, these barriers could have limited wave-derived processes and the subsequent accumulation of grainy inner ramp deposits in the Heath. Third, intracratonic basins have a propensity to be fetch-limited in comparison to their open ramp counterparts (Burchette & Wright, 1992), which may have further limited wave energy and subsequent accumulation of inner ramp bioclastic limestone barriers in the Heath Formation. Considering the paleotropical position and elongate E-W trending morphology of the Big Snowy Trough (Figs. 2 & 6)), it is likely that sufficient fetch was available for southwesterly trade winds to have produced periodic storm waves.

It is proposed that Lombard Arch (Guthrie, 1984; Harris, 1973) served as a hydrographic barrier and partial sill for the Big Snowy Trough (Fig. 6), which inhibited circulation and facilitated a stratified water column. Freshwater runoff into inner ramp environments could have enforced a regime of quasi-estuarine circulation (Byers, 1977) during deposition of the lower Heath, whereas high rates of evaporation in inner ramp settings during deposition of the upper Heath could have resulted in a regime of anti-estuarine circulation (James & Jones, 2015-Fig. 6). The presence of coeval coastal mires, brackish inner ramp and organic rich, phosphate-bearing outer ramp deposits in the lower Heath, and coeval evaporite-bearing sabkha, hypersaline lagoon, and organic rich, phosphate-bearing outer ramp deposits preserved in the upper Heath, provide supporting evidence of a stratified water column with quasi-estuarine and anti-estuarine circulation patterns respectively. Ultimately, these factors could have provided the oxygen-depleted conditions necessary to preserve organic rich sediments predominately in offshore Mid to Outer Ramp settings. Additionally, the stratigraphic partitioning of coal and paleosol-bearing units in the lower Heath, and microbialite and evaporite-bearing units exclusive to the upper Heath, is interpreted to preserve a distinct increase in aridity and hydrographic restriction stratigraphically upward in the formation.

Conclusions:

Four facies associations were identified in the Heath Formation: Offshore Mid to Outer Ramp Transition, Inner Ramp, Coastal Plain, and Sabkha. Facies associations preserved in the Heath Formation are here in explained within the context of a protected homoclinal carbonate ramp (Burchette & Wright, 1992; Read, 1998) (Fig. 6). Modern analogues for the lower Heath (Nicaragua Shelf and Java Shelf), and upper Heath (Persian Gulf) provide first order approximations for the magnitude (18-36 m) of relative sea-level oscillations preserved in the Heath Formation (Fig. 6). A shift from stochastic, low-magnitude relative sea-level oscillations preserved in the Otter Formation, to an ordered stratigraphic pattern entailing ≥7 fourth-order, high frequency and high magnitude relative sea-level fluctuations in the Heath Formation is herein interpreted to record the main eustatic signal of the LPIA (Fig. 6).

The observed Carboniferous lithostratigraphy of Central Montana in addition to known biostratigraphic constraints from the literature was plotted against the absolute geologic timescale of Gradstein et al. (2012) (Fig. 3), which estimates the main eustatic signal of the LPIA to have occurred between 331 and 326 Mya (Figure). This interpretation is broadly consistent with estimates from additional far-field records: East Fife, Scotland (Fielding & Frank 2015), the Appalachian Basin, USA (Al-Tawil & Read, 2003), the Illinois Basin, USA (Smith & Read, 2000), Arrow Canyon, USA (Bishop et al., 2009), and SW Great Britain (Wright & Vanstone, 2001) and NW Ireland (Barham et al., 2012), in addition to the timing of the first major expanse of ice centers during the main body of the LPIA (Caputo et al 2008; Bishop et al., 2009). A consensus among most sedimentological and stratigraphic studies, in addition to marine isotope records (Chen et al., 2018; Frank et al., 2008; Mii et al. 1999; Montañez et al., 2007, 2018), suggests major climate perturbation related to LPIA onset likely initiated during the Serpukhovian and progressively grew in intensity toward the mid-Carboniferous boundary.

Additionally, this study illuminates the utility of a detailed microfacies analysis in providing robust depositional and sequence stratigraphic models for mixed mudstone-carbonate successions deposited in low accommodation and sediment starved settings (Fig. 4). Without the use of thinsection microscopy, facies-specific fossil assemblages, micro sedimentary structures, grain abrasion, and micro-scale bedding patterns would have been overlooked, leaving an incomplete understanding of the array of depositional environments and the magnitude of paleo-water depth oscillations preserved in the Heath Formation (Figs. 4-6).

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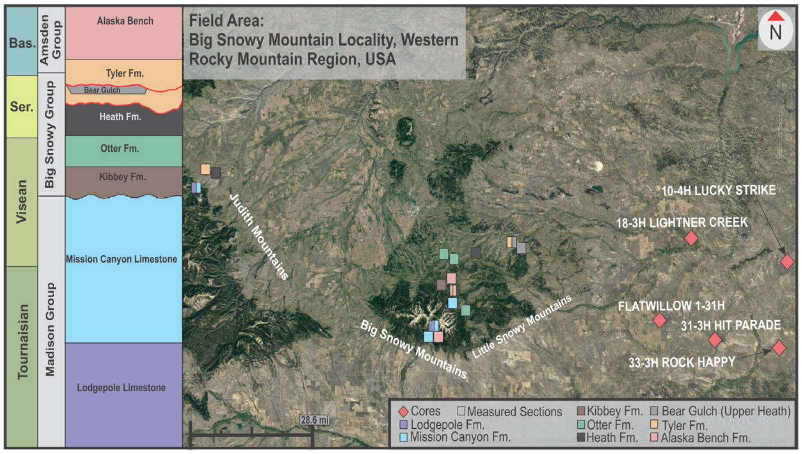


Fig. 1) Annotated field map that displays the following data: 1) idealized depiction of the Carboniferous stratigraphy of central Montana that was observed during this study (left-not to true scale), 2) locations of measured sections colored coded by formation name (boxes), 3) locations of observed cored intervals (red diamonds).

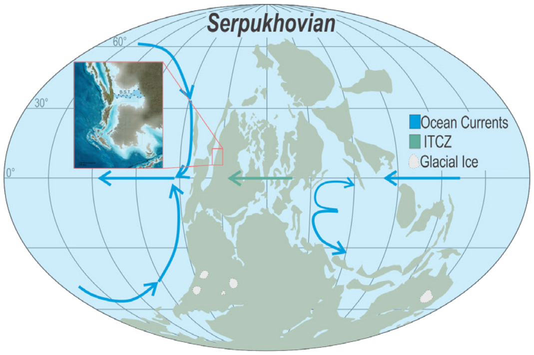


Fig. 2) Global paleogeographic map ***modified after*** Boucot et al. (2003) that displays inferred ocean currents post Rheic Seaway Closure (Saltzman et al., 2003), inferred ice centers (Montanez & Poulsen, 2013; Fielding et al., 2008), and an annotated inset paleogeographic map ***modified after*** Blakey (2013) that displays the location of the Big Snowy Trough (B.S.T.).

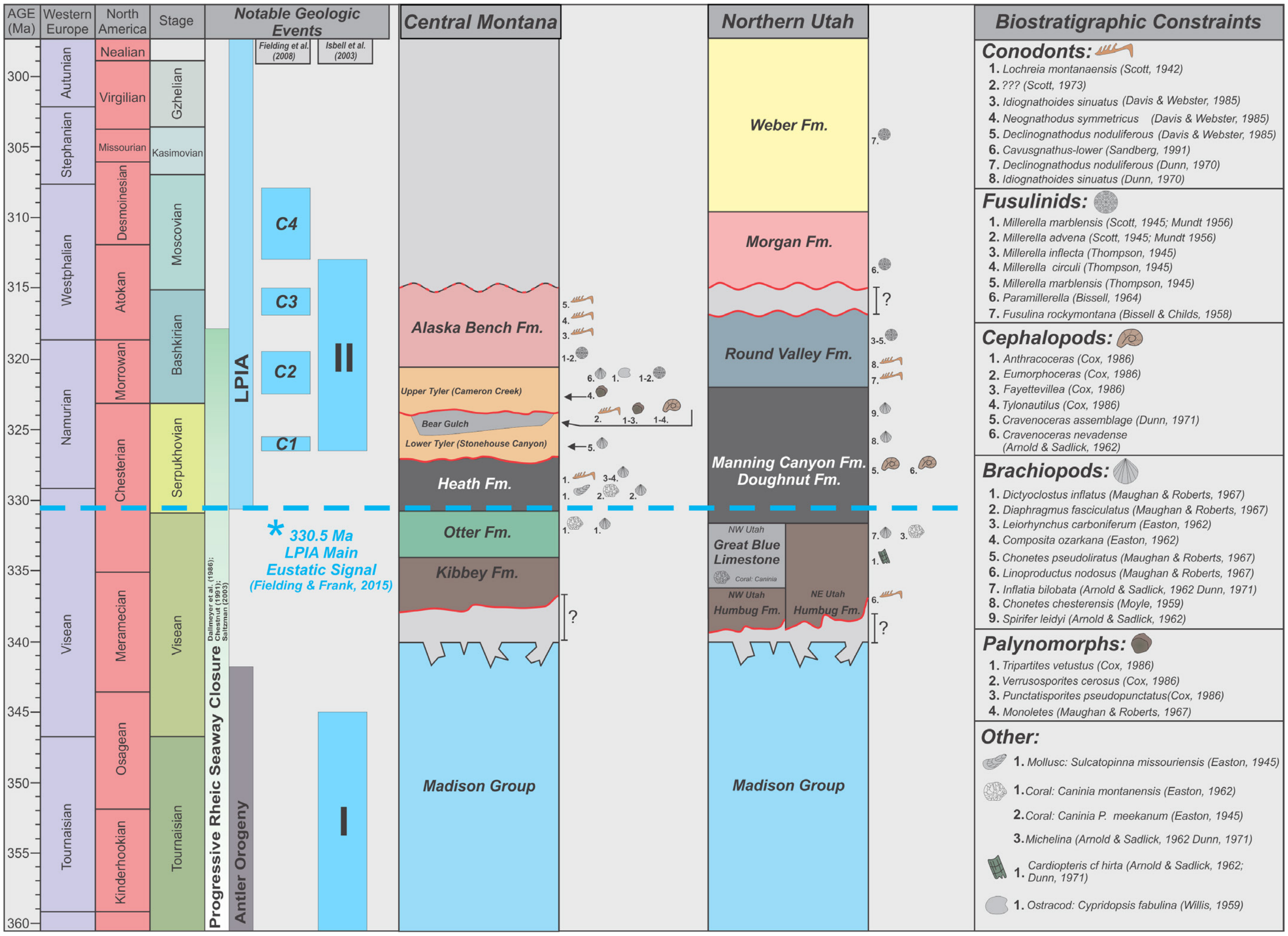


Fig. 3) Carboniferous stratigraphy of central Montana and northern Utah that was observed during this investigation. The stratigraphic positions of depicted units are derived from observations made during this study, where as biostratigraphic constraints are solely from a detailed literature review. Notable geologic events, in addition to the Carboniferous glacial intervals of Isbell et al. (2003) and Fielding et al. (2008) are provided for additional context. The timescale of Gradstein et al. (2012) is used here in and is implemented throughout the remainder of this investigation.

Facies Association/Facies	Lithology	Sedimentary Structures	Biota	Allochem Abrasion Index
Offshore Marine Mud Rocks ***(OR)***	≤4m thick tabular intervals of of shale, silty shale, muddy bioclastic siltstone (calcilutite of Heckel, 1994) and thin (≤7cm thick) intervals of mixed bioclastic and quartz siltstone. Randomly dispersed 1cm pyritized shell intervals.	Delicate parallel laminations, low relief scours, vague low angle laminations, rare ripple cross lamination, normal grading. Wave enhanced gravity flows of Macquacker et al. (2010)?	Brachiopods, bivalves, fish bones and otoliths, rare benthic foraminifera. Fossils are commonly pyritized. *Planolites*, *Chondrites*, *Cosmorhaphe*, and *Cruziana* traces; B.I. 0-1.	Wackestone Intervals = 1-2 Bioclastic Siltstone = 6
Brachiopod-Bryozoan Biostrome ***(MOT)***	≤40cm thick tabular intervals consisting of a basal medium gray fossiliferous silty mudstone that typically grades upward into a brachiopod and bryozoan wackestone.	——	Fenestrate, encrusting, and branching bryozoans in addition to brachiopods and brachiopod spines. Lesser proportions of pelmatozoans and fish bones. Pyrite and silica replacement of shells observed. *Planolites*, *Chondrites*, *Cosmorhaphe*, *Asterosoma* traces; B.I. 0-3.	2-3
Bivalve-Brachiopod Biostrome ***(MOT)***	≤20cm thick intervals consisting of dark gray wackestone-packstone that alternate and grade with laminated dark gray calcareous mudstones of comparable thickness.	——	Dominated by brachiopod and bivalves, conspicuously preserved in concave-up position. Lesser proportions of bryozoans, pelmatozoans, ostracods, benthic *miliolid* and *fusilinid* foraminifera, and fish bones. Pyrite (common) and silica (uncommon) replacement of shells observed. B.I. 0-2.	2-4
Pelmatozoan Biostrome ***(MOT)***	≤10cm thick intervals consisting of dark gray wackestone-packstone.	Erosional basal contacts and sharp to gradational tops.	Primarily pelmatozoan columnals with subordinate proportions of bivalve, brachiopod and bryozoan fragments. Basal, shell-filled palimpest burrows. B.I. 0-2.	2-4
Heterozoan Biostrome ***(MOT)***	≤30cm thick tabular intervals of dark gray to light gray wackestone-packstone.	——	Primarily brachiopod, bivalve, pelmatozoan, and bryozoan fragments with subordinate proportions of solitary rugose corals, sponge spicules, benthic foraminifera, trilobite fragments and fish bones. Basal, shell-filled palimpest burrows. *Planolites*, *Chondrites*, *Cosmorhaphe, Asterosoma* traces; B.I. 0-4.	2-4
Restricted Littoral Platform ***(IR)***	≤1m thick tabular intervals of medium to light gray micrite, silty micrite, and wackestone with blocky and sub-laminated textures.	——	Primarily ostracods with lesser proportions of bivalves and peloids. Rare occurrences of brachiopod and bryozoan fragments. Micritization of fossil fragments is observed with lesser proportions of pyrite and silica replacement. B.I. 0-3.	1-3
Hypersaline Intertidal Lagoon ***(IR)***	≤1.5m thick tabular intervals of inter-laminated calcareous siltstone, silty micrite, and dolomicrite.	Rhythimic laminae, soft sediment deformation, breccia with flat-pebble intraclasts, desiccation cracks, fenestral pores, euhedral pyrite, minor cat's eye and nodular gypsum.	Microbial laminations, peloids, rare diminutive ostracods. Infrequent bioturbation; B.I. 0-3.	1-3
Sabkha ***(SAB)***	≤3.5 m thick intervals of microbially laminated micrite, dolomicrite and anhydrite with nodular-displacive, cat's eye and chicken-wire morphologies in varying proportions.	Soft-sediment deformation, micro faults, teepee structures, brecciated and silicified surfaces with flat pebble intraclasts, fenestral pores, desiccation cracks.	Microbial laminations and rare peloids.	——
Brackish Littoral Platform ***(IR)***	≤2m thick tabular intervals of green-gray silty calcareous mudstone to wackestone with a mixture of sub-laminated, blocky and nodular fabrics.	——	Variable proportions of bivalves, ostracods and gastropods. Micritic envelopes and algal borings are common, in addition to complete micritization of some shell fragments. B.I. 0-3.	1-3
Coastal Plain Paleosol ***(CAP)***	≤3m thick intervals of green-gray silty calcareous mudstone with a mixture blocky and nodular pedogenic fabrics.	Slickensides, organic debris, red-brown color mottling.	Rootlets, undifferentiated bioturbation.	——
Coastal Plain Mire ***(CAP)***	≤15 cm thick tabular beds of dull banded, bright banded and bituminous coal (≤6 cm) and carbonaceous shale (≤10 cm).	Calcite-filled fractures, large pyrite nodules.	——	——

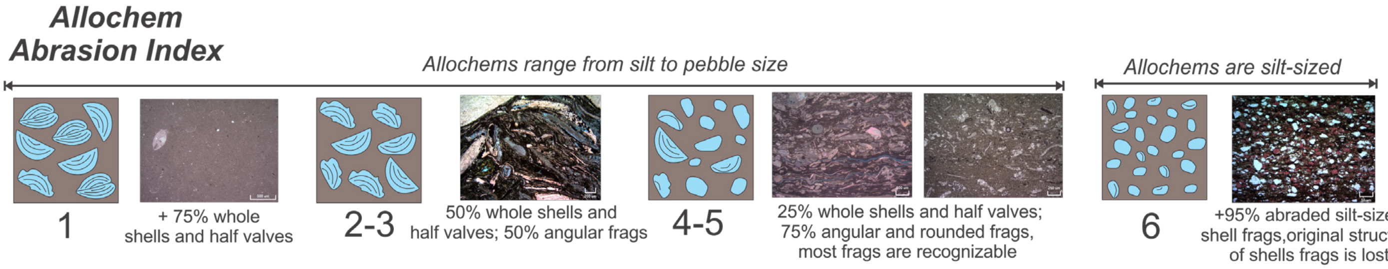
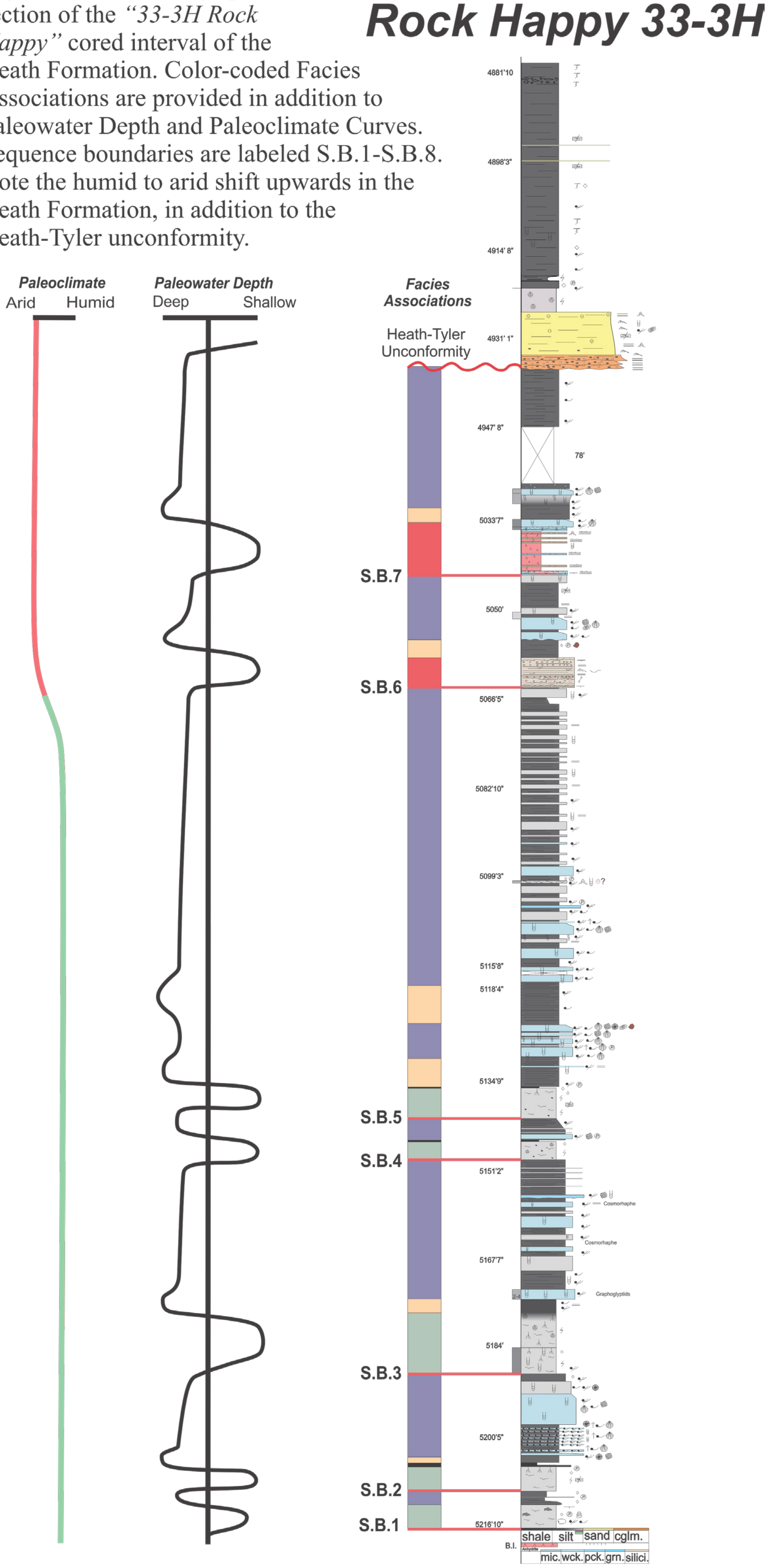


Fig. 6) Table displaying all facies identified in the Heath Formation during this investigation. All facies are color-coded into their respective Facies Association. This color-coding scheme is used throughout the remainder of this paper and is similarly displayed in figures 5 & 6. Additionally, this facies table utilizes a semi-quantitative parameter (Allochem Abrasion Index), introduced in this study, in order to assess the ratio of allochem fragmentation and reworking by wave energy. Coupled with observed sedimentary structures, fossil diversity/stress, and the relationship of abutting facies, this parameter helps to provide improved determinations of depositional environment. This is because grain abrasion is herein inferred to reflect depositional wave energy and distance from the loci of carbonate production. When considering the Allochem Abrasion Index with fossil assemblages, sedimentary structures, and the context of abutting facies, improved estimates of water depth and the relative influence of hydrographic (wave) barriers can be more accurately assessed.

Fig. 5) Detailed stratigraphic section of the *"33-3H Rock Happy"* cored interval of the Heath Formation. Color-coded Facies Associations are provided in addition to Paleowater Depth and Paleoclimate Curves. Sequence boundaries are labeled S.B.1-S.B.8. Note the humid to arid shift upwards in the Heath Formation, in addition to the Heath-Tyler unconformity.



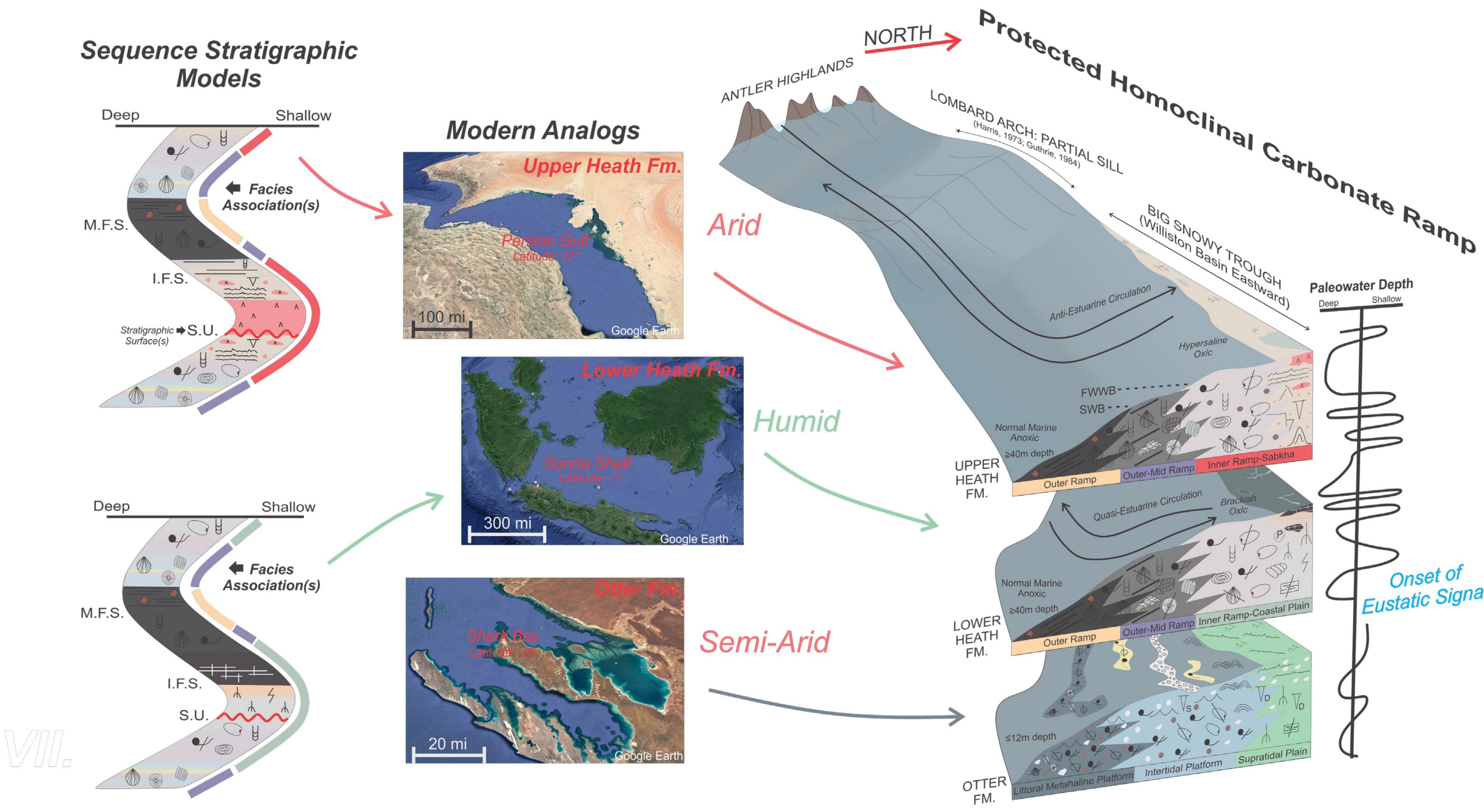


Fig. 6) Depositional block models with color coded facies associations, sequence stratigraphic models, and proposed modern analogs for the Otter Formation, in addition to the lower and upper portions of the Heath Formation. High frequency and high magnitude 4th-order relative sea-level oscillations are first recognized in the Heath Formation and are here interpreted to record the main eustatic signal of the LPIA. Modern analogs of the Otter and Heath Formations are supported by the works of Logan & Cebulski, 1970; Wagner & Van der Togt, 1973; and Roberts, 1987 among others. The depth constrains of sediments observed in these modern environments provide first-order approximations of the magnitude of sea-level shifts preserved in the Otter (< 12m) and Heath Formations (≥ 18- 36m).

INDIAN CAVE STATE PARK – 1, A NEW CORE THROUGH THE INDIAN CAVE SANDSTONE INTERVAL OF THE UPPERMOST PENNSYLVANIAN (VIRGILIAN)

Christopher R. Fielding[1*] and R. Matthew Joeckel[2]

[1]*Department of Earth & Atmospheric Sciences, 126 Bessey Hall, University of Nebraska-Lincoln, NE 68588-0340.*

[2] *Conservation and Survey Division, School of Natural Resources, Department of Earth & Atmospheric Sciences & University of Nebraska State Museum, University of Nebraska-Lincoln, 615 Hardin Hall, Lincoln, NE 68583-0996.*

**e-mail: cfielding2@unl.edu*

The Nebraska Conservation & Survey Division's Indian Cave State Park-1 hole was drilled in the summer of 2018 on the southwestern edge of the Indian Cave State Park (ICSP) reserve (Fig. 1) in order to provide control on the lateral extent of the Indian Cave Sandstone, which crops out 3.7 km to the east of the drillhole location. The hole spudded in Quaternary materials (soils, loess) and commenced coring at 120 feet below surface in Pennsylvanian strata. The hole terminated at 186 feet below surface within the Pennsylvanian section (Fig. 2). The cored succession comprises multiple intervals of mudrocks (many horizons preserving invertebrate fossils and bioturbation), thinly interbedded to interlaminated sandstone and siltstone (heterolithic) facies, thin sandstones, and several discrete beds of bioclastic to sandy limestone. Some intervals show evidence of pedogenic overprinting (penetration by carbonaceous root traces, strong coloration and color mottling, ped structure, destratification). Correlation with the local cyclothemic stratigraphy was achieved by reference to the section exposed at the surface nearby. Given the negligible structural dip, elevations in the drillhole could be matched to those of outcropping beds to good effect. Accordingly, the basal limestone encountered in the hole at 276-278 feet (84 m) is correlated to the Nebraska City Limestone, and the next limestone at 248-250 feet (76 m) is believed to be the Brownville Limestone, which in the ICSP outcrop underlies the erosional base of the Indian Cave Sandstone. The next limestone at 202-205 feet (62 m) is correlated to the Aspinwall Limestone, which is erosionally removed by the Indian Cave Sandstone in ICSP. An unnamed limestone and a thin coal occur at 182 and 167 feet (55 and 51 m, respectively), and near the top of the core a composite limestone comprising two beds at 141-150 Feet (43-45 m) is correlated to the Forest City Limestone, which typically overlies the Indian Cave Sandstone at outcrop. The topmost part of the core is heavily pedogenically modified, probably reflecting processes active both during the Pennsylvanian and also later during its geological history.

No direct representative of the Indian Cave Sandstone was encountered in the drillhole. Furthermore, limestone beds and other strata known to have been excised by erosion of the Indian Cave Sandstone paleovalley in the ICSP area are present in the core. Given the correlations, we identify the horizon of the Indian Cave Sandstone as a pedogenically-modified heterolithic interval at 153-160 feet (46-49 m), which we interpret to record an elevated "interfluve" facies outside of the incised paleovalley. The ICSP-1 core therefore provides the opportunity to examine stratigraphic relationships from paleovalley to interfluve in coeval, latest Pennsylvanian strata of SE Nebraska.

Acknowledgements

We thank Matt Marxsen, John Seamann, and Michele Waszgis of the Conservation and Survey Division (CSD) for drilling the core hole described herein. Justin Ahern drafted Figure 2.

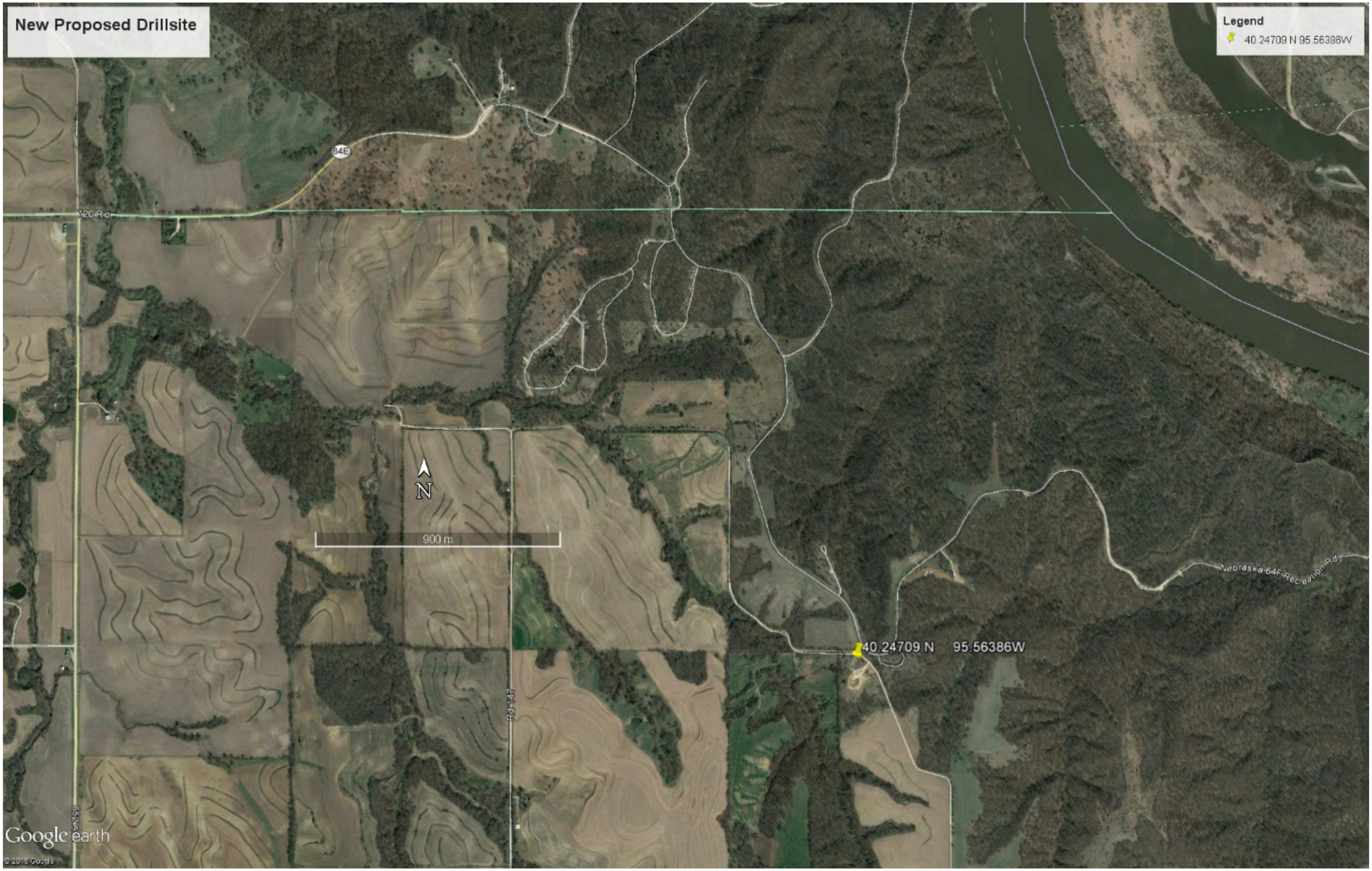


Figure 1. Aerial image from Google Earth showing the location of the ICSP-1 drillhole on the southwestern limit of the Indian Cave State Park.

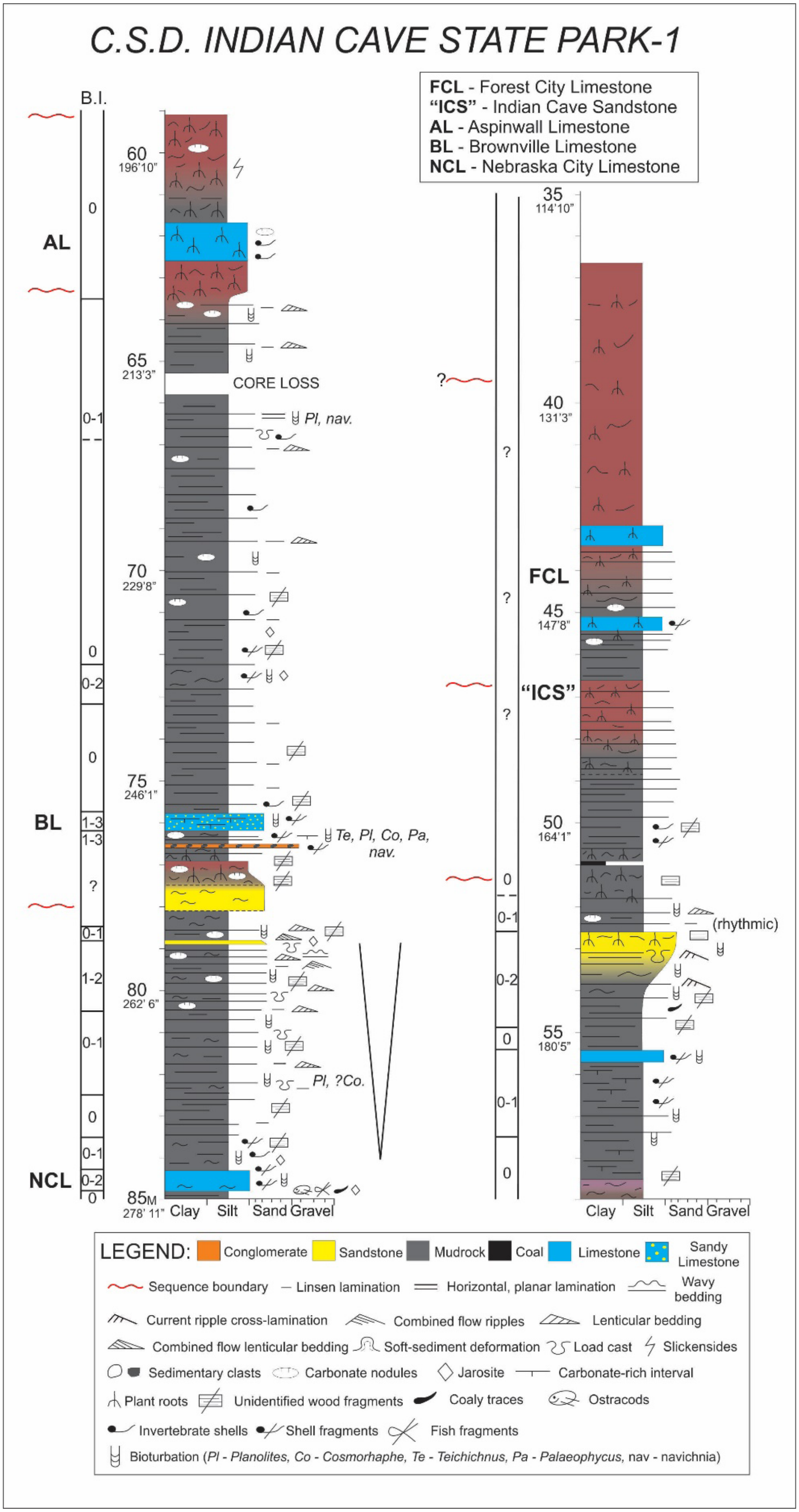


Figure 2. Graphic log of the succession penetrated by ICSP-1, with key to symbols and abbreviations used.

STRATIGRAPHY AND SEDIMENTOLOGY OF THE PENNSYLVANIAN CASEYVILLE AND TRADEWATER FORMATIONS, ILLINOIS –

EXAMPLES FROM CORE

N. D. Webb[1,*], J. L. Best[2], C. R. Fielding[3]

[1]*Associate Research Scientist, Petroleum Geologist, Illinois State Geological Survey, Prairie Research Institute,*

University of Illinois at Urbana-Champaign, 615 E. Peabody Dr., Champaign, IL, USA

[2] *Jack and Richard Threet Professor of Sedimentary Geology, Department of Geology, Natural History Building,*

University of Illinois at Urbana-Champaign, 1301 West Green Street, Urbana, IL 61801, USA.

**e-mail: ndwebb2@illinois.edu*

[3] *Professor, Coffman Chair, Department of Earth & Atmospheric Sciences, University of Nebraska-Lincoln,*

214 Bessey Hall, Lincoln, NE 68588, USA.

Pennsylvanian sandstone reservoirs account for 15% of the total oil production in the Illinois Basin. Main and Lawrence Oil Fields in Crawford and Lawrence Counties (respectively), southeastern Illinois constitute the largest areas of Pennsylvanian oil production in the state (Figure 1). The fields were discovered and largely developed, starting in the 1900s, by Marathon Oil Company, (formerly the Ohio Oil Company). The intense, "pre-law" development of the area helped Illinois become the third largest oil producing state in the USA between 1907 and 1914[1], but resulted in rapid depletion of reservoir pressure with much of the oil remaining in place. By the 1930s, there were attempts to increase recovery by air and gas repressuring[2]. By the 1960s, Marathon began using area as test pilots for innovative enhanced oil recovery techniques, thermal recovery (in-situ combustion or "fire flooding")[3,4,5,6], and chemical flooding using micellar-polymer[7,8]. Though Marathon divested its Illinois interests in the 1990s, succeeding operators have continued EOR attempts with methods such as alkaline-surfactant-polymer (ASP) flooding[9].

Marathon researchers were some of the first to recognize the importance of understanding geologic heterogeneity to design successful enhanced oil recovery programs. As such, the company initiated extensive coring in their pilot areas to characterize the geology of the reservoir sandstones throughout southeastern Illinois. The result is a valuable collection of core, most of which has been donated to the ISGS for perpetual storage in the Geologic Samples Library. The most recent donation of a large number of cores occurred in the 2010s when Rex Energy, a Marathon successor, divested their interests in the Illinois Basin.

The cores from this collection are in the process of being re-described as part of research to understand the filling of the Basin during the Early Pennsylvanian. Caseyville and Tradewater Formation strata preserve a record, deposited along the systemic sub-Absaroka unconformity surface, which reflects varied autocyclic and allocyclic processes: intraplate tectonics and differential subsidence related to the Alleghenian Orogeny; and the far-field record of climate change and eustatic sea-level fluctuations related to Gondwanan glaciation. The Caseyville and Tradewater Formations consist primarily of sandstone, siltstone, and shale. A number of coal seams exist in both formations, although most are lenticular and not regionally extensive. Limestones are rare in the Caseyville Formation but a handful are known to occur in the Tradewater Formation and some have been correlated at different points along the ILB margin based on biostratigraphic markers; however none have been correlated in the subsurface over any significant distance.

Creating the geological conceptual model required the development of a stratigraphic framework with a detailed understanding of dimensions and architecture of the sedimentary bodies, the sedimentology, and associated reservoir properties. Though most cores were collected only through the reservoir sandstone in a given area, allowing for detailed sedimentological study within a given sandstone body, a few longer cores were collected that document the variety of lithologies typical of the lower Pennsylvanian succession in the study area. Together these longer cores allowed the construction of a composite section through the Caseyville Formation in Lawrence and Crawford Counties, Illinois, providing the basis for developing a stratigraphic framework for the study area. The composite stratigraphy can be broadly broken down as follows:

Caseyville Formation – The Caseyville Formation is dominated by a succession of fluvial to fluvial-tidal sandstones encased in estuarine central basin mudstones. The Caseyville Formation primarily consists of sandstone, siltstone, and shale (Figure 2). The sandstones are generally composed of quartz with common quartz granules and pebbles that occur either scattered throughout the sandstone unit, or as conglomeritic beds within the sandstone. The sandstones contain relatively minor amounts of clay and mica. Sandstone bodies up to 30 m thick are common, with tabular cross bedding being the predominant sedimentary structure. Depositional trends of these fluvial sandstones are highly influence by the topography created by the unconformity surface; they are often vertically amalgamated and thicken into and downstream along the paleovalleys (Figure 3). The isolated nature of these sandstones and their high porosity and permeability make them significant oil reservoirs. Thinner, more lenticular sandstone bodies also occur in isolated bodies encased in thick successions of mudstone and usually reach thicknesses up to 8 m or so with ripple cross bedding being the most common sedimentary structure. A few coals are present, but rare, and no limestones have been observed in the study area. Because of the lack of regionally-extensive marker beds in these strata, and the fact that deposition is localized to individual paleovalleys, regional scale correlation is difficult. Correlations are most straightforward.

Tradewater Formation (Lower) – The lower part of the Tradewater Formation is lithologically similar to the Caseyville Formation in that it is dominated by sandstone and shale with relatively minor coals and is almost devoid of limestones (Figure 2). However, the filling of the paleovalleys largely with Caseyville Formations strata led to a subdued paleotopography with deposits becoming less confined and influenced by paleovalley walls. Sandstone bodies in general are thinner, more pervasively medium grained, lacking the coarse grains and quartz granules common in the Caseyville, and exhibit a greater degree of lateral amalgamation. A few thick, ribbon-shaped sandstone belts occur within this part of the succession and trend generally to the southwest, though they do not always reoccupy the buried paleovalleys (Figure 3), indicating the waning influence of the unconformity paleotopography. In most cases the sandstones are interpreted as fluvial, overlying estuarine central basin deposits along sharp erosional bases. Rip-up clasts, cross bedding and ripple bedding, and fining upwards grain size trends are typical. Tidal modulation becomes apparent near the top of these sandstones with the occurrence of mud drapes on foresets. The most prolific oil reservoirs occur within these sandstones. Thin coals commonly cap these sandstone which are in turn overlain my lenticular bedded sandstone or siltstone with tidal rhymites.

Tradewater Formation (Upper) – The upper part of the Tradewater Formation diverges lithologically from the underlying strata in that sandstones become relatively sparse, fine grained sediments dominate, and thin, widely traceable coals and limestones become common (Figure 2). The recurrence of these strata are also decidedly cyclic and mimic the style of the “Illinois type” cyclothems common in the younger Pennsylvanian units. The few sandstones in this part of the succession are thin, very-fine grained, lenticular, and exhibit pervasive tidal indicators including rhymithic shale laminations, tidal couplets, and diminutive low diversity bioturbation. A few thick, ribbon-shaped fluvial sandstones occur in the study area, incise through some of the cycles (Figure 3). The lateral continuity of marker beds indicates the filling of the underlying unconformity paleovalley topography and the development of a low relief coastal plain setting. The occurrence of limestone indicates that region experienced periodic inundation of the sea.

The Emma Fry example core will be shown to highlight some the variety of lithology and facies of these formations. The core spans the upper Caseyville to lower Tradewater Formation and shows the nature of incised valley fill estuarine central basin facies overlain by tidally influenced fluvial deposits. Detection of significant stratigraphic surfaces within the core, including a marine flooding surface, are key for interpreting subtle inflections on geophysical logs and correlating the features to other wells (Figure 4).

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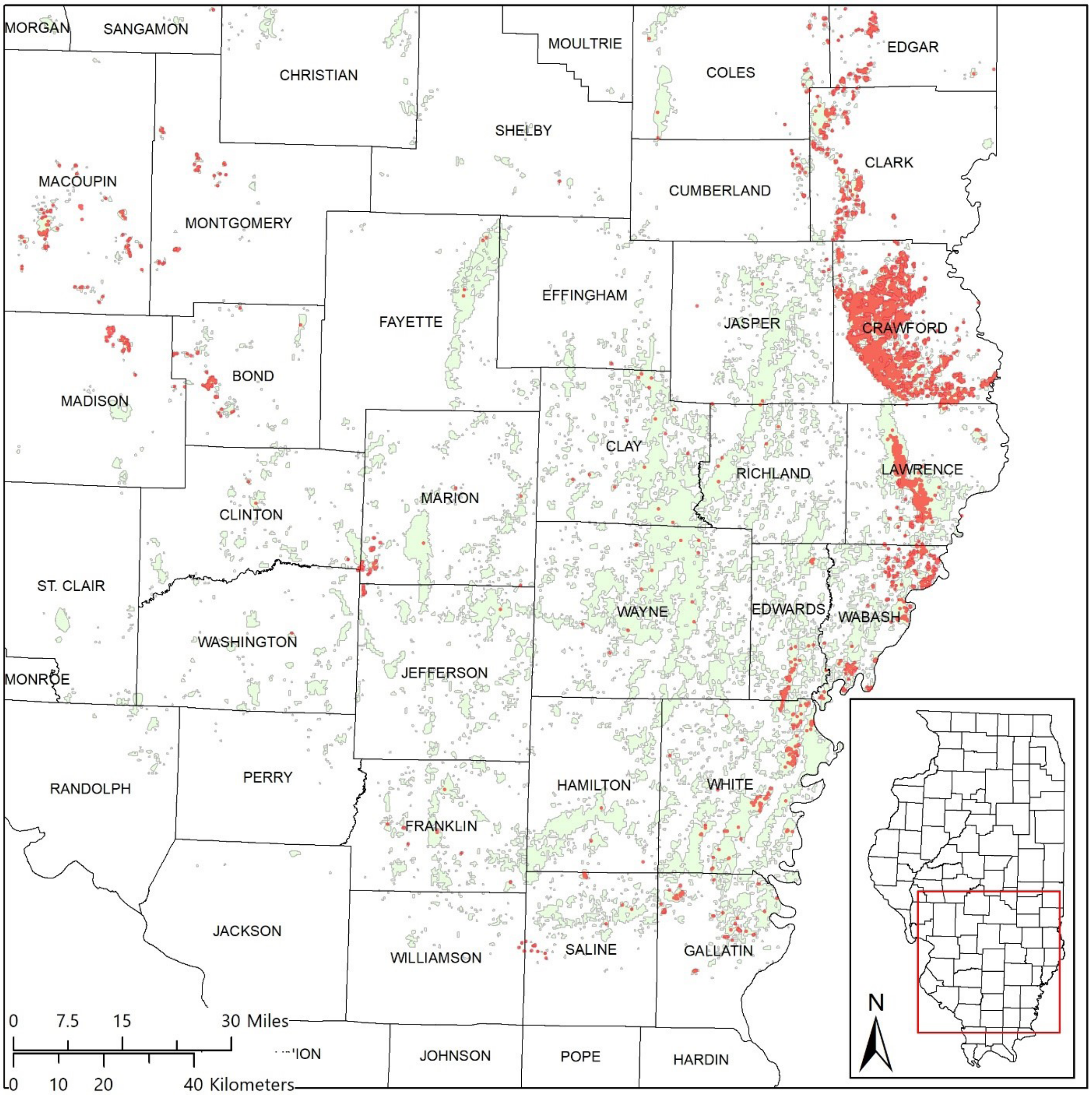

Figure 1. Map showing the distribution of oil fields in Illinois (green) overlain with the locations of Pennsylvanian oil producing wells (red). Main and Lawrence Oil Fields in Crawford and Lawrence Counties (respectively) in southeastern Illinois constitute the largest areas of Pennsylvanian oil production in the state.

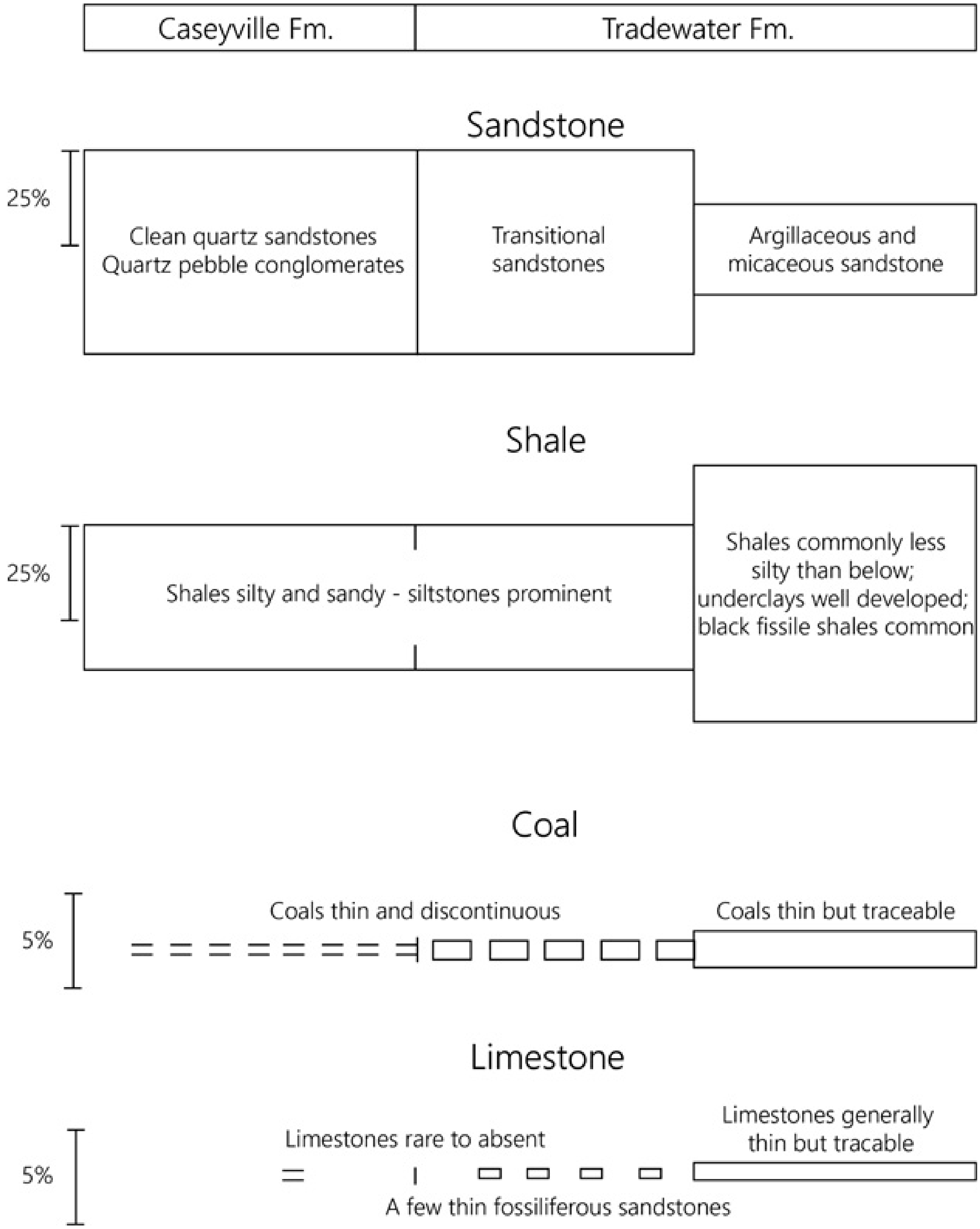

Figure 2. Diagram summarizing lithologic variability within the Caseyville and Tradewater Formations. Modified from Kosanke et al., 1960.

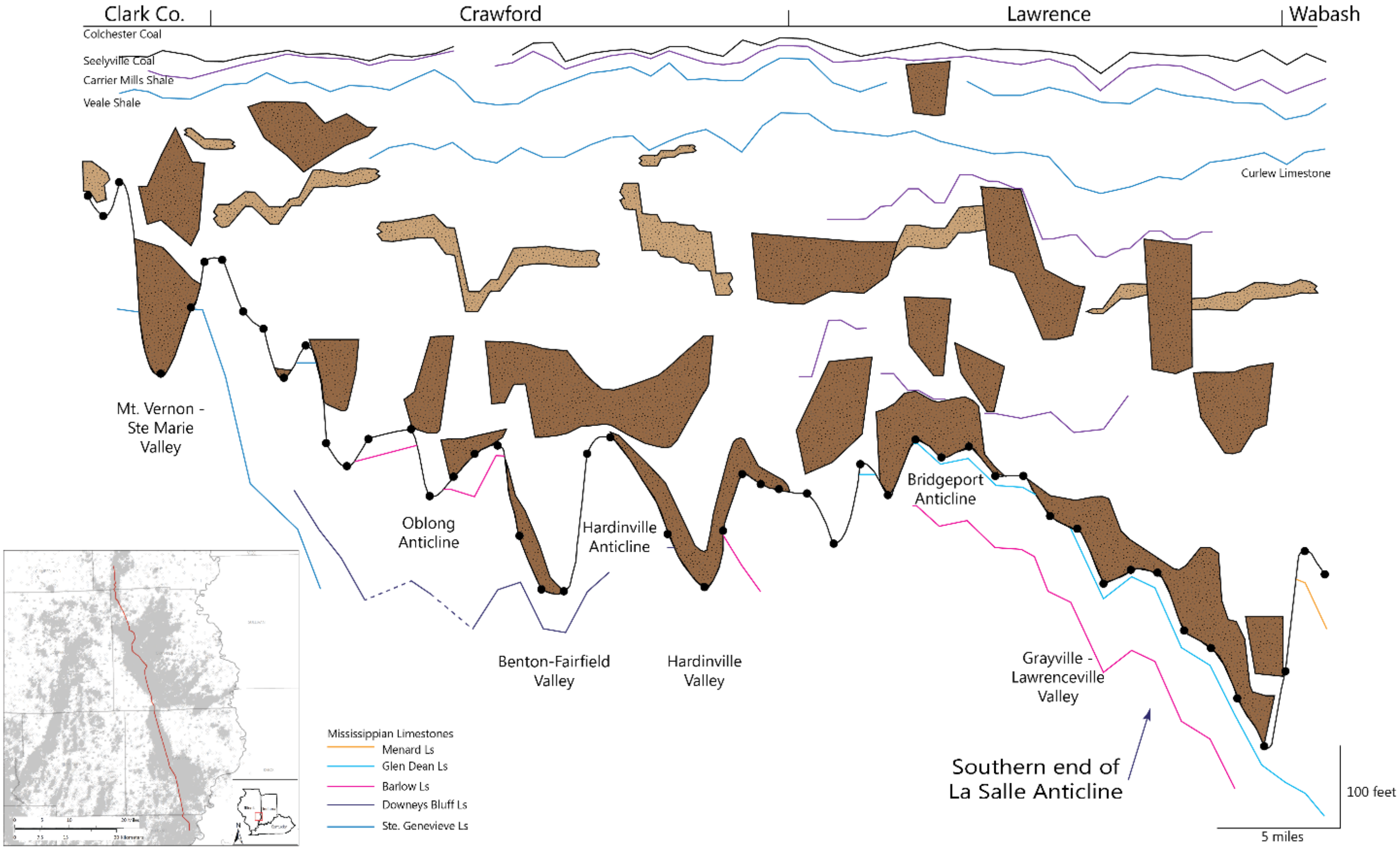

Figure 3. North-south regional diagrammatic cross section showing the occurrence of significant sandstone bodies in the lower part of the succession and the increasing ability to correlate shales, coals, and limestones regionally in the upper part of the succession.

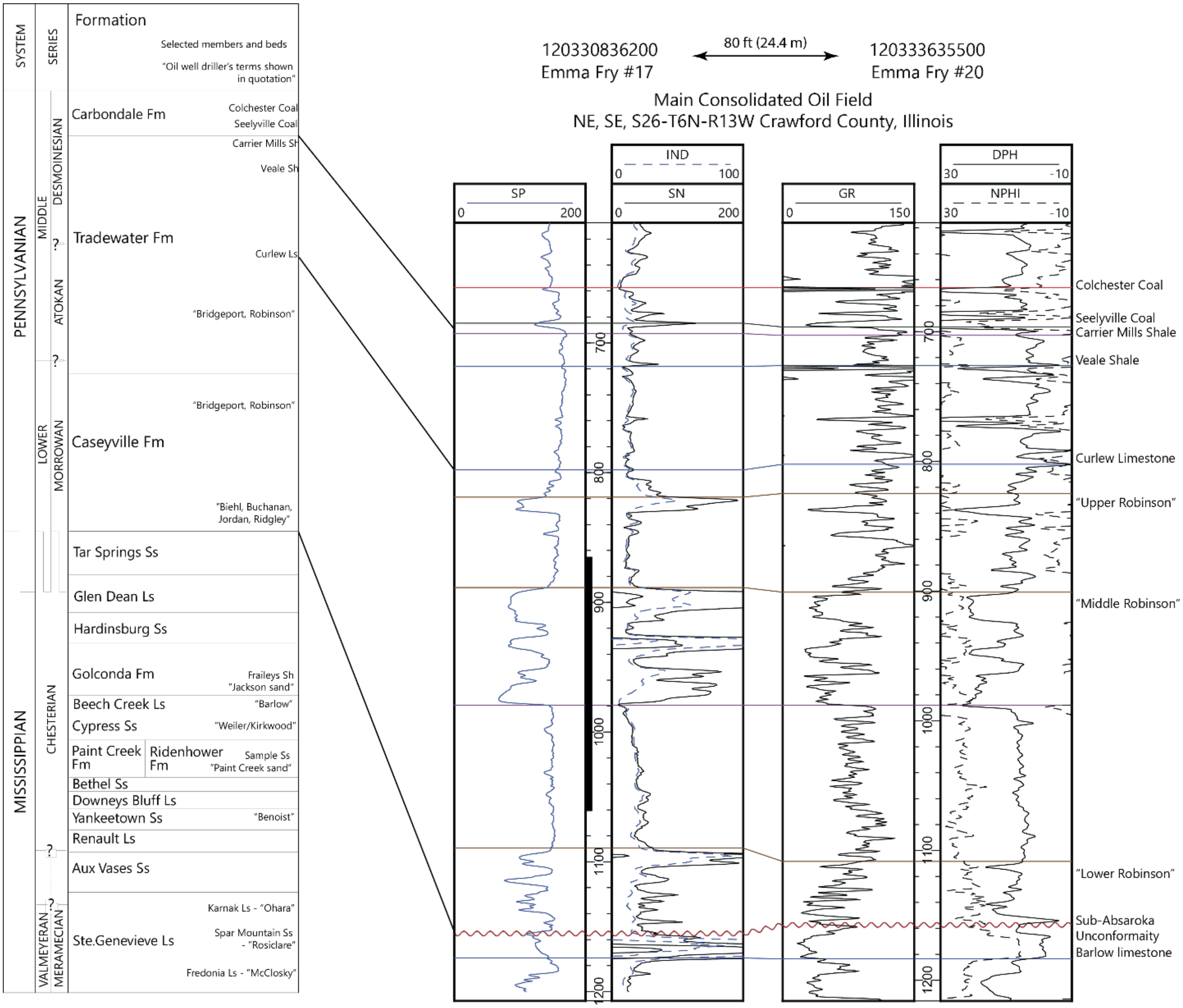

Figure 4. Stratigraphy and logs corresponding to the Emma Fry core which exhibits a range of tidally influenced fluvial and estuarine facies characteristic of the Caseyville Formation. The cored interval is indicated by the black bar on the Emma Fry #17 log. A modern gamma-ray/porosity log is also provided for an adjacent well.

"PAPER CORES": ELECTRICAL BOREHOLE IMAGE LOGS OF THE OREAD LIMESTONE FROM SOUTHERN KANSAS

John H. Doveton

Kansas Geological Survey, University of Kansas

Lawrence, Kansas 66047 USA

e-mail: doveton@kgs.ku.edu

The Oread Limestone is named for Mount Oread in Lawrence, Kansas, where its puny outcrop expression is dwarfed by thick developments in southern Kansas. This has been known for many years from log correlation studies and descriptions based on drill-cuttings. However, geological observations from cores are rare because the Oread is not a prime oil exploration target.

Two boreholes were recently drilled close to the Oklahoma border in Sumner County as part of a DOE carbon dioxide sequestration project and logged by an extensive suite of tools, including FMI borehole electrical imaging. The two boreholes are approximately two miles apart, but show dramatic changes of the Plattsmouth Limestone where it nearly doubles in thickness from about sixty feet to an impressive mound development that can be seen on 3-D seismic.

The image logs have a resolution of less than a quarter of an inch, so that distinctive lithology structures in the Oread section are shown crisply. Although the images are electrical conductive rather than optical, it is easy to see commonalities with outcrop expressions. The two Oread image logs will be shown in the core workshop together with associated descriptions of geological features and results from data analysis. Freeware image processing software was applied for feature enhancement and statistical analysis such as Fourier analysis of limestone bedding patterns and tidalites in the overlying Kanwaka Shale.

Conservation and Survey Division
School of Natural Resources
Institute of Agriculture and Natural Resources
University of Nebraska–Lincoln

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