All rights reserved. No part of this work covered by the copyrights herein may be reproduced or used in any form or by any means—graphic, electronic, or mechanical—without the prior permission of the publisher. Any request for photocopying, recording, taping, or reproducing in information storage and retrieval of any part of this book should be directed in writing to the Publications Department, Virginia Museum of Natural History, 21 Starling Avenue, Martinsville, VA 24112.

The Virginia Museum of Natural History (VMNH) is located in Martinsville, Virginia and is an affiliate of the Smithsonian Institution. VMNH, an agency of the Secretary of Natural Resources of the Commonwealth of Virginia, is accredited by the American Association of Museums, and is a member of the Association of Science-Technology Centers and the Virginia Association of Museums. For more information, please call 276-634-4141 or visit our Web site at www.vmnh.net.
## CONTENTS

Abstract.................................................................................................................................1

General Access And Logistics .................................................................................................2

Introduction...............................................................................................................................2

Geologic Setting.......................................................................................................................3

Methods...................................................................................................................................4

Results Of Photomosaic Mapping ............................................................................................6

Depositional Setting, Tidal Periodicities And Sedimentation Rates ........................................8

Discontinuities ..........................................................................................................................11

Geochemistry: Total Organic Carbon .....................................................................................12

Geochemistry: Major And Trace Elements ............................................................................12

Field Trip Stops.......................................................................................................................13

Stop 1 .......................................................................................................................................13

Stop 2 .......................................................................................................................................14

Stop 3 .......................................................................................................................................15

Stop 4 .......................................................................................................................................16

Stop 5 .......................................................................................................................................16

Stop 6 .......................................................................................................................................16

Stop 7 .......................................................................................................................................16

References.................................................................................................................................17
STRATIGRAPHY, SEDIMENTOLOGY AND GEOCHEMISTRY
OF THE UPPER MISSISSIPPIAN PRIDE SHALE IN THE
APPALACHIAN BASIN

Kenneth Eriksson ¹, Erik Kvale ², Ty Buller³

ABSTRACT

Key Themes: tide-dominated deltas, incised paleovalleys, tidal rhythmites, paleoastronomy

Tide-dominated or influenced coastal marine deposits form some of the most complicated and largest hydrocarbon fields in the world (Wood, 2004 and references cited therein). Good outcrop analogs can provide significant insight to geologists for recognizing tidal influence in core and interpreting petrophysical log data thus reducing uncertainty and risk when developing depositional models and planning for field development.

Despite the observation that 8 of the 12 largest deltas in the modern world are either tide-dominated or strongly tidally influenced (Middleton, 1991), many geologists fail to recognize tidal influence in the rock record, perhaps, in part, because of the influence of pre-existing paradigms.

While good ancient analogs of tide-dominated deltas exist (see summary table in Feldman, et al., 2014), many of these studies inferred tidal influence from the intercalation of sandstone and mudstone, an abundance of fluidized mud deposits, a dominance of structures formed from currents and the shoreline perpendicular orientation of elongate sandstone bodies. As noted by Feldman and others (2014), few studies have identified sedimentary structures in the delta front and prodelta settings that can be directly related to semimonthly tidal cycle deposition. This may reflect background interference from storms or variable fluvial discharge that disrupted tidal deposition and thus obscures evidence of fortnightly or longer tidal signals or it may reflect an absence of knowledge of what to look for when identifying such cycles.

The Pride Shale outcrops illustrated in these stops exhibit some of the most direct evidence of tidal influence within a deltaic succession found anywhere in the literature. They reflect the pervasive influence of tides found throughout the Upper Mississippian and Lower Pennsylvanian deposits in the Appalachian Basin and other basins in the southern and central U.S.A. As such, these outcrops offer geologists an opportunity for viewing excellent exposures of prodelta through delta plain facies associated with tide-dominated deltas. What makes the Pride Shale outcrops stand out above other outcrops that preserve tide-dominated facies is that they provide unrivaled examples of deposits that reflect hierarchic tidal cycles that span the semidiurnal through the ~19 lunar nodal cycles. The Pride Shale represents the thickest and aerially most extensive tidal rhythmite succession identified in the geologic record and it preserves a continuous annual tidal rhythmite record of hundreds of years of accumulation in individual exposures. This will be particularly significant for those scientists interested in paleoastronomy.

¹ Department of Geosciences, Virginia Tech, Blacksburg, VA, 24061, USA. Email: kaeson@vt.edu
² Devon Energy Corporation, Oklahoma City, OK, 73102, USA. Email: Erik.Kvale@dvn.com.
³ JPMorgan Investment Bank, 712 Main Street, Houston, TX 77002, USA. Email: ty.b.buller@jpmorgan.com.
GENERAL ACCESS AND LOGISTICS

The field trip area is easily accessed through Charlotte airport, North Carolina that is served by both domestic and international flights. The driving distance from the Charlotte airport to Princeton, West Virginia is 175 miles (280 km) along Interstate 77N (I-77). All stops on this field trip are accessible using a 2-wheel drive, regular automobile.

A number of the stops are located along I-77 north of Princeton (see field guide below) and it is necessary to get permission to stop along the interstate. Contact: West Virginia Parkways, 201 Pikeview Drive, Beckley, WV 25801, Tel: (304) 256-6924; FAX: (304) 254-2914 and request that orange vests be left at the rest stop near the junction of Rt. 460 and I-77 for use on the field trip. Hard hats are also recommended for use on the field trip.

In the event of an accident, contact the West Virginia State Police by dialing 911. The closest hospital is in Princeton which is within 30 minutes of all stops.

INTRODUCTION

Tidal facies in both the modern and the geologic record are preserved either as cross-bed foreset bundles, products of down-current accretion, or as thinly laminated to thickly bedded, fine-grained sediments (tidal rhythmites), products of vertical accretion (e.g. Dalrymple et al., 1991; Williams, 1991; Tessier, 1993; Greb et al., 2011, Kvale, 2012). Both modes of preservation may display thick-thin pairs, reflecting diurnal inequality of tidal current velocities (e.g. de Boer et al. 1989), and rhythmic thickening and thinning of laminae, reflecting fortnightly neap-spring-neap cyclicity (e.g. Visser, 1980; Kvale et al., 1999). In addition, alternating thicker and thinner neap-spring-neap bundles are inferred to record perigean and apogean effects (e.g. Kvale et al., 1999; Greb et al., 2011).

Holocene/Anthropocene tidal deposits are known from both open and embayed settings (see summary in Daidu, 2013), many associated with mud-dominated coastlines, tide dominated deltas, or drowned valleys (estuaries), such as the Bay of Fundy in Canada (Dalrymple et al., 1991) and Mont-Saint-Michel Bay in France (Tessier, 1993) as a result of amplification of the tides. Similarly, tidal facies preserving pervasive tidal signatures in the geologic record are developed and preserved in incised-paleo-valley fills (e.g. Dalrymple et al., 1992; Miller and Eriksson, 2000). Incised-valley fills most commonly developed during icehouse times in Earth history such as the late Paleozoic and Neogene. Less commonly, tidal rhythmites are developed in deltaic settings distal from shelf margins that are characterized by high sediment supply related to strong ebb-current retreat (e.g. Jaeger and Nittouer, 1995; Zaitlin et al., 1995; Dalrymple et al., 2003; Chen et al., 2014).

The Upper Mississippian Pride Shale in the Central Appalachians is fully exposed in two large road cuts along interstate highway I-81 and in a road cut west of I-81 in southern West Virginia (Fig. 1). Upwards of 60 m thick, the Pride Shale is an upward-coarsening, prodeltaic deposit of predominantly dark grey mudstone with subordinate fine-grained sandstone and siltstone. Lithologies are interlaminated at various scales ranging from sub-millimeter to meter. The Pride Shale locally contains major surfaces of discontinuity, lacks evidence of bioturbation and records a spectrum of tidal periodicities including semi-diurnal, fortnightly and multi-year, as well as annual climatic cycles (Miller and Eriksson, 1997). It preserves a continuous annual record of hundreds of years of accumulation in individual exposures. The Pride Shale represents the thickest and aerially most extensive tidal rhythmite succession identified in the geologic record. Unique preservation of tidal and climatic signals in the Pride Shale permits reconstruction of a hierarchy of tidal periodicities and thereby absolute sedimentation rates based on high-resolution tidal chronometers. The thickness, organic content and proximity to gas-bearing sandstones highlight the utility (proven or conceptual) of the Pride Shale as a source bed, seal, or even a shale gas reservoir.

Outcrops described for this field trip span a complete lowstand-transgressive systems tract (Stops 1 and 2) and highstand systems tract (Stops 3, 4, 5 and 6) both within a single fourth-order (~400 kyr) sequence. Specifically, the field trip will examine: 1) incised valley deposits of the Princeton Formation consisting of basal fluvial deposits overlain by estuarine facies that include tidal rhythmites; 2) the transition from incised valley-fill to deltaic facies across a ravinement deposit that is capped by a condensed section at the base of the Pride Shale; 3) a spectrum of tidal and climatic periodicities spanning daily to the approximately 18.6 year

![Figure 1. Map showing the regional mapped extent of the Pride Shale and the study area in southern West Virginia and southwestern Virginia. The Pride Shale crops out locally in the eastern part of the study area (gray shaded area) and is mapped in the subsurface over a larger area (dashed line). The Pride Shale is particularly well exposed in the central part of Mercer County, West Virginia.](image-url)
nodal cycle preserved in tidal rhythmtes of the Pride Shale; 4) discontinuities in the Pride Shale and evaluate their origin; 5) the vertical transition from the prodeltaic Pride Shale into distributary mouth bars and tidal sandridges (?) of the Glady Fork Sandstone; and 6) the abrupt and erosional contact between the Pride Shale and overlying distributary channel deposits of the Glady Fork Sandstone.

GEOLOGIC SETTING

The Upper Mississippian Mauch Chunk Group outcrops in southern West Virginia and southwestern Virginia and includes the Pride Shale that extends into the subsurface over an area of 15,000 km² (Fig. 1; England and Thomas, 1990). The Mauch Chunk Group is underlain by carbonates of the Greenbrier Formation and overlain by the Lower Pennsylvanian coal-bearing Pocahontas and New River Formations (Fig. 2; England and Thomas, 1990). The Chesterian-age Mauch Chunk Group thins westwards where it is truncated by the Mississippian-Pennsylvanian unconformity (Fig. 3). Upper Mississippian strata in southern West Virginia consist primarily of fluvial channel and floodplain sandstones and mudstones that display extensive evidence for pedogenesis under monsoonal climatic conditions in the form of Vertisols (Miller and Eriksson, 2000). The Pride Shale is a formally named member of the Bluestone Formation (Fig. 2) and consists predominantly of mudstone although the proportion of sandstone and siltstone increases upwards.

Based on a combination of outcrop and subsurface studies, the Mauch Chunk Group has been subdivided into two, third-order composite sequences of ca. 3 Myr duration that consist of fourth-order sequences of ca. 400 kyr duration (Miller and Eriksson, 2000). One of the fourth-order sequences consists of the Princeton Formation, Pride Shale and overlying Glady Fork Sandstone (Miller and Eriksson, 2000; Fig. 4). Incised-valley fill deposits of the Princeton Formation (Fig. 4) make up the lowstand and transgressive systems tracts whereas a condensed interval of black mudstone at the base of the Pride Shale that displays a distinctive high gamma ray signature, defines the maximum

<table>
<thead>
<tr>
<th>PERIOD</th>
<th>EPOCHS</th>
<th>STANDARD STAGES</th>
<th>AGE (Ma)</th>
<th>APPALACHIAN BASIN</th>
<th>CHESTERIAN TYPE SECTION</th>
<th>CONODONT ZONES</th>
</tr>
</thead>
<tbody>
<tr>
<td>CARBONIFEROUS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PENNSYLVIAN</td>
<td>BASHKIRIAN</td>
<td></td>
<td></td>
<td>POCAHONTAS</td>
<td></td>
<td>GROVE CHURCH</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>323.2</td>
<td></td>
<td></td>
<td>Gnathodus postbilineatus</td>
</tr>
<tr>
<td>SERPUKHOVIAN</td>
<td></td>
<td>CHESTERIAN</td>
<td></td>
<td>BLUESTONE</td>
<td>PRINCETON</td>
<td>Cavusgnathus monocerus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MAUCH CHUNK</td>
<td></td>
<td></td>
<td>HINTON</td>
<td>Cavusgnathus naviculus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GROUP</td>
<td></td>
<td>Little Stone Gap Mbr.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Stoney Gap Ss. Mbr</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MISSISSIPPIAN</td>
<td></td>
<td>CHESTERIAN</td>
<td>330.9</td>
<td>BLUEFIELD</td>
<td></td>
<td>WALTERSBURG</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MAUCH CHUNK</td>
<td></td>
<td></td>
<td></td>
<td>VIENNA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GROUP</td>
<td></td>
<td></td>
<td></td>
<td>TAR SPRINGS</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>GLEN DEAN</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GREENBRIER</td>
<td></td>
<td></td>
<td></td>
<td>Kladognatus mehli</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SERIES</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Alderson Ls.</td>
<td></td>
<td>HARDINSBURG</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Union Ls.</td>
<td></td>
<td>HANLEY</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pickaway Ls.</td>
<td></td>
<td>FRAILEYS</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Taggard Sh.</td>
<td></td>
<td>BEECH CR.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Patton Ls.</td>
<td></td>
<td>CYPRUS</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Sinks Grove Ls.</td>
<td></td>
<td>RIDEHNOWER</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>BETHEL</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>DOWNEYS BLUFF</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>YANKEETOWN</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>RENAULT</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>AUXVASES</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>JOPPA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>KARNAK</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SPAR MTN.,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FREDOMIA</td>
</tr>
</tbody>
</table>

Figure 2. Lithostratigraphy and biostratigraphy of Upper Mississippian strata of the Appalachian Basin of southeastern West Virginia and southwestern Virginia (adapted from Repetski and Stamm, 2009; Gradstein et al., 2012).
flooding surface. An incised-valley-fill model showing facies relationships within the Princeton Formation paleovalley in the eastern part of the study area is illustrated in Figure 5. The Pride Shale and Glady Fork Sandstone define the highstand systems tract of the fourth-order sequence and are interpreted as the deposits of a prograding, tide-dominated delta (Figs. 4 and 6; Miller and Eriksson, 1997).

The paleogeography of the basin is relevant to the development of tidal rhythmites that predominate in the Pride Shale. Tidal rhythmites are present throughout the Mauch Chunk Group but are subordinate to terrestrial red beds in units other than the Pride Shale (Miller and Eriksson, 2000). Sedimentation in the late Mississippian took place in a foreland basin to the west of the evolving Appalachian Orogenic Belt. The basin opened to the south but in the study area had the form of an embayment (Blakey, 2013) in which tides were amplified in response to the wide continental shelf and the shape of the basin.

Methods

Photomosaics were prepared from three large road cuts north of Camp Creek, WV and from a road cut/borrow pit near Spanishburg, WV. These are the only large-scale exposures of the Pride Shale in the Appalachians. Photomosaics were annotated in the field to demarcate major stratigraphic surfaces and, at Camp Creek, outcrop-scale discontinuities. Thin sections were prepared from oriented samples collected at Spanishburg which, combined with laminae thickness measurements from oriented and polished slabs and outcrop measurements, were used to document cyclicity in the Pride Shale. Details on methods used to recognize hierarchical bundling patterns within the Pride Shale are described in Miller and Eriksson (1997).

A total of 23 samples were collected for total organic carbon (TOC) determinations. An attempt was made to collect samples that were as fresh as possible through excavating weathered outcrops using a chisel and hammer. Three samples are from the basal Pride Shale and 10 pairs...
Figure 4. Stratigraphic section of the Princeton Formation, Pride Shale, and Glady Fork Sandstone from central Mercer County, West Virginia. The Pride Shale rests upon estuarine facies of the Princeton Formation incised valley fill, and is overlain by the Glady Fork Sandstone SB: Sequence Boundary; LST/TST: Lowstand/Transgressive Systems Tract; MFS: Maximum Flooding Surface; HST: Highstand Systems Tract (adapted from Miller and Eriksson, 1997).

Figure 5. Incised-valley-fill model showing facies relationships within the Princeton Formation paleovalley in the eastern part of the study area. Conglomeratic fluvial facies are overlain by estuarine sand-flat, marsh, and tidal creek facies. Tidally influenced, valley-fill deposits are truncated along a regional, flat ravinement surface represented by a lenticular, lag gravel that is overlain by black mudstones representing the marine condensed section at the base of the Pride Shale. Where the gravel is absent, grey mudstones of the Princeton Formation are overlain by black mudstones representing the marine condensed section at the base of the Pride Shale (adapted from Miller and Eriksson, 2000).

Figure 6. Upward-coarsening and upward-thickening trend in the Pride Shale along I-77 at Camp Creek. Note the distinct corrugations on outcrop related to interbedded sandstone-rich and mudstone-rich facies. White scale is 1m long.
RESULTS OF PHOTOMOSAIC MAPPING

Photomosaics of the outcrops document the stratigraphic context of the Pride Shale as well as internal discontinuities. The on-ramp to I-77 North at Camp Creek exposes the contact between estuarine facies at the top of the Princeton Formation and the condensed section at the base of the Pride Shale (Fig. 7). Carbonate concretions up to 0.5 m in diameter and a fossil detritus lag define the base of the Pride Shale which is capped by organic-rich black fissile shale a few meters thick. The large road cuts along I-77 north of the Camp Creek on-ramp expose the coarsening-upward transition from the Pride Shale into the overlying Glady Fork Sandstone as well as two surfaces of discontinuity that traverse the outcrops (Figs. 8, 9A). Only a portion of the Pride Shale is exposed at Spanishburg (Fig. 9B) where neither the basal condensed section nor the overlying Glady Fork Sandstone is present. Samples for TOC analyses were collected at the same location as 11C on Figure 8 but over a thicker interval. The vertical black bar (annotated with an “X”) in the middle right of the lower panel demarcates the location of the slab sample in the Larksins (2009) study.

Figure 7. Photomosaics from the I-77 Camp Creek, WV exit of the contact between estuarine facies of the Princeton Formation and the overlying Pride Shale defined by a condensed section.
Figure 8. Photomosaics of eastern outcrop of Pride Shale and overlying Glady Fork Sandstone along I-77 at Camp Creek, WV (vertical exaggeration 2:1). Discontinuities are annotated in red. Locations of Figures 6 and 11C are shown on the middle panel. Samples for TOC analyses were collected from a ~1.1 m-thick, continuous section at same location as Figure 11C but over a thicker interval of alternating sandstone-rich and mudstone-rich strata. The vertical black bar in the middle right of the lower panel (annotated with an “X”) demarcates the location of slab sample in the Larkins (2009) study.

Figure 9. Photomosaics of: a) western outcrop of the Pride Shale and overlying Glady Fork Sandstone along I-77 at Camp Creek, WV (vertical exaggeration 2:1). One major discontinuity is preserved and is projected to extend below road level. Rotated blocks are developed along the discontinuity. b) Pride Shale at Spanishburg, West Virginia which represents a more distal paleoenvironment than at Camp Creek. Finer-grained, thinner annual cycles are developed at this location. Scale bar is 100 cm long. Note locations of Figures 12, 13A and 13B on upper panel and Figures 11 A, B and D on lower panel.
DEPOSITIONAL SETTING, TIDAL PERIODICITIES AND SEDIMENTATION RATES

Description

In outcrop, the Pride Shale displays a distinctive corrugation pattern in which the thicknesses of the corrugations increase upwards related to an upward increase in proportion of sand (Fig. 6). Bioturbation is noticeably sparse to absent in the Pride Shale.

The Pride Shale preserves a hierarchy of submillimeter to meter-scale cycles (Fig. 10; Miller and Eriksson, 1997). The lowest level of the hierarchy consists of submillimeter-thick (0.01 and 1 mm), normally graded, fine-grained sandstone and black mudstone or siltstone and black mudstone couplets; thick-thin pairs of laminae are preserved rarely (Fig. 11A). Within both the coarse- and fine-grained components of the couplets, dark clotted textures are evident in thin section (Fig. 11A). Up to 17 couplets are stacked into systematically upward-thickening and thinning millimeter-to centimeter-scale cycles (Figs. 11B, 12A). Locally, these cycles are alternately thicker and thinner. Up to 18 of these cycles are arranged in upward-thickening and thinning decimeter-scale cycles (Fig. 11B) that are manifested as the corrugations in outcrop (Figs. 6 and 13). These cycles consist of interbedded, positive-weathering, more arenaceous facies and negative-weathering, more argillaceous facies (Fig. 11C). Meter-scale cycles are weakly developed in some outcrops (Fig. 11D) and are comprised of 17-21 decimeter-scale cycles (Fig. 11D). Plant fossils are common within the Pride Shale as generally small fragmented remains, but include *Stigmaria stellate*. Invertebrates in the rhythmic beds include small, thin-valved bivalves (*Sanguinolites, Modiolus sp.*) that are confined to a few horizons, and rare carbonized impressions of shrimp-like arthropods (Miller and Eriksson, 1997). Except for a few horizons, the Pride Shale lacks bioturbation.

![Figure 10](image)

*Figure 10.* Hierarchy of tidal cycles in the Pride Shale. Five orders of laminae bundling are interpreted to reflect tidal and climatic controls on prodeltaic sedimentation (adapted from Miller and Eriksson, 1997).
The Pride Shale is gradational into the overlying Glady Fork Sandstone Member (Figs. 8, 9A) that, at the I-77 outcrops, consists of a 10 to 20 m-thick succession of flaser- and wavy-bedded, fine-grained sandstone and mudstone. Along Rt. 460, south of Princeton, WV, the Glady Fork Sandstone Member is expressed as a multi-story/multi-channel sandstone that is incised into the Pride Shale and along its basal contact contains large-scale, ball-and-pillow and flame structures.

**Interpretation**

The overall upward coarsening of the Pride Shale and gradationally overlying Glady Fork Sandstone Member (Figs. 8 and 9A), coupled with the upward increase wave thickness of the corrugations (Fig. 6), is interpreted to be a result of progradation of a tide-dominated delta (Miller and Eriksson, 1997). The Glady Fork Sandstone Member is dominated by tidal bedding and is interpreted as a distributary mouth-bar deposit. The multi-story/multi-channel expression of the Glady Fork Sandstone Member is interpreted as a distributary channel deposit. Holocene examples of tide-dominated deltas include the Fly River, Yangtze and Amazon where ebb tidal currents supply sediment to delta front/prodelta settings (Jaeger and Nittrouer, 1995; Dalrymple at al., 2003; Hori et al., 2002; Harris et al., 2004).

The hierarchy of cycles preserved in the Pride Shale is interpreted to record a spectrum of tidal and climatic periodicities (Fig. 10) that can be used as high-resolution
chronometers from which sedimentation rates can be deduced (Miller and Eriksson, 1997). Individual graded sandstone-siltstone laminae are interpreted as the deposits of suspension fall-out or hyperpycnal flows from tidally modulated river plumes generated by the dominant ebb tide. The rarely preserved thick-thin pairs of laminae are considered to represent the deposits of both the dominant and subordinate semi-diurnal ebb tides (cf. Kvale et al., 1989). Shale partings separating graded laminae are interpreted as slack-water deposits formed from flocculated muds as suggested by the clotted textures of the mudstone particles (Fig. 11A). Systematic alternations of relatively thick and thin sand-silt laminae are observed in modern tidal deposits and uniquely record the diurnal inequality of the tides from successive semi-diurnal tidal currents (e.g. de Boer et al., 1989; Dalrymple et al., 1991; Kvale and Archer, 1991). Similar rhythmic sand-mud alternations are present in the delta front/prodelta settings of the Fly River, Yangtze and Amazon deltas on millimeter to centimeter meter scales (Jaeger and Nittrouer, 1995; Dalrymple et al., 2003; Hori et al., 2002; Harris et al., 2004). Similarly, rhythmites of the Neoproterozoic Reynella Siltstone and parts of the Elatina Formation in South Australia similarly display laminae that are arranged in thick-thin pairs (Williams, 1989, 1991). Thickening and thinning, millimeter- to centimeter-scale cycles in the Pride Shale are considered to represent fortnightly neap-spring tidal deposits related to the semi-monthly inequality of the neap and spring tides (Kvale, 2006). These cycles are comparable to neap-spring cycles that occur in modern tidal deposits (Dalrymple et al., 1991; Tessier, 1993; Greb et al., 2011). A comparable neap-spring signal is discernable in the tidal laminites of the Amazon delta (Jaeger and Nittrouer, 1995). Similar thickening and thinning cycles in the Neoproterozoic Elatina Formation are up to 2 cm thick and contain 8-16 laminae. The abbreviated character of the neap-spring cycles in the Pride Shale is inferred to be a reflection of the distal, prodeltaic setting in which deposition took place and into which not only the subordinate daily but also the weakest
neap ebb flows were of insufficient strength to transport sand or silt. Alternating thicker and thinner neap-spring cycles are interpreted to be of perigean and apogean origin (Miller and Eriksson, 1997). Perigean tides form during a more proximal distance between the Earth and Moon at spring tide whereas apogean tides are associated with a greater distance between the Earth and Moon at spring tide (cf. Kvale et al., 1999; Greb et al., 2011). Decimeter-scale cycles in the Pride Shale are interpreted to record an annual climatic (monsoonal) signal in which thicker neap-spring cycles record the monsoon when voluminous sediment was supplied to the river mouth and the thinner cycles record the inter-monsoon when less sediment was supplied to the delta (Fig. 12B; Miller and Eriksson, 1997). Monsoons arise when the land is hot relative to the cool ocean; low pressure results in precipitation on the land causing higher fluvial discharge (Ruddiman, 2001). Maximum entropy spectral analysis on the decimeter-scale cycles reveals a strong peak at 16.7 neap-spring cycles (Fig. 12B; Miller and Eriksson, 1997). Annual cycles in the Pride Shale range in thickness from <3 cm at the base to as much as 50 cm at the top and average approximately 10 cm in thickness (Fig. 13). These data indicate that sediment accumulated at a (compacted) rate of 3-50 cm per year (Miller and Eriksson, 1997). Such rates are consistent with paleontological data (rare fossils and rare bioturbation) which suggests a turbid and perhaps sometimes brackish, nearshore environment of deposition. The weakly developed meter-scale cycles are interpreted by Miller and Eriksson (1997) to reflect the nodal (~18.6 year) tidal periodicity which results from the slow rotation of the lunar orbital plane with respect to the ecliptic (solar plane).

The preserved record of tidal hierarchies in the Pride Shale is inconsistent with a symmetrical ebb and flood tidal prism but, rather, implies that long-term sediment dispersal to the delta was dominated by ebb transport. Preservation of the near-continuous, 60 m-thick record of tidal sedimentation represented by the Pride Shale is attributed to the tectonic setting of the basin. The Pride Shale is an anomalous interval of marine deposits within the predominantly alluvial Mauch Chunk Group and likely reflects an increase in accommodation related to thrust loading in the foreland basin.

**DISCONTINUITIES**

**Description**

Multiple outcrop-scale discontinuities in roadcuts along I-77 in Mercer County, West Virginia consist of smooth to irregular, concave-upward troughs which extend for hundreds of meters, and commonly separate underlying fine-grained rhythmites from overlying sand-dominated rhythmites (Figs. 8 and 9A). In general, the discontinuity surfaces dip southwest and are characterized locally by several meters of relief (Fig. 14A). Where subhorizontal, the discontinuities appear conformable with underlying beds. Dipping portions (up to 20 degrees) clearly truncate older strata and are overlain by a zone of meter-scale, rotated/deformed blocks (Fig. 14B). The rhythmic sedimentary infills within the troughs lack a conglomeratic lag yet drape the deformed blocks. Sand-dominated neap-spring cycles thin from up to 50 cm at the discontinuity surface (Fig. 13) to less than 1 cm over a distance of several-to-tens of meters. The sandy intervals are commonly restricted to one side of the trough.

**Interpretation**

A channel-scour origin has been proposed for the discontinuities but does not adequately explain their irregular geometry and sedimentary fill. Similar discontinuity-bounded sedimentary packages in slope carbonates of the Sverdrup Basin were interpreted by Davies (1977) as the infills of large slump-scars. Such a slump-scar interpretation explains the features associated with the trough-like discontinuities in the Pride Shale, and provides an autogenic explanation for the variability in accumulation rate recorded by these rhythmites. This interpretation invokes gravity sliding of thick (to 15 meters) packages of semi-coherent sediment into deeper portions of the basin. Blocks derived from the
scar-margins or from the trailing edge of the slump block were left within the scar interior. Subsequent rapid rhythmite infill via tidal currents draped the blocks and filled the scar. The sandy rhythms reflect proximity to source and are clearly progradational into the axial mudstones (Miller and Eriksson, 1997). Sands cannibalized from the underlying sediments were confined to sites of high current velocities along the topographically high scar margins. Tidal currents were apparently of insufficient duration or strength to move margin-derived sands more than a few tens of meters. The irregular and asymmetrical distribution of sands along scar margins likely reflects local erosion/deposition via currents oblique to the slump direction (Miller and Eriksson, 1997). Thus, the discontinuities are interpreted as slump scars related to rapid sedimentation and oversteepening of deltaic clinoforms (Miller and Eriksson, 1997).

**GEOCHEMISTRY: TOTAL ORGANIC CARBON**

**Description**

TOC data are from the base of the Pride Shale (Fig. 7) and from a ~1.1 m-thick, continuous interval of alternating sandstone-rich and mudstone-rich strata (Fig. 8). The data reveal that sandstone-rich facies have an average TOC content of 1% and mudstone-rich facies have an average TOC content of 1.3% (Fig. 15). TOC% values for sandstone-rich and mudstone-rich facies fluctuate, respectively, between 0.8 to 1.3% and 1.0 to 1.7% (Fig. 15). One of three samples from the base of the Pride Shale has TOC content of 2.3%. TOC% in both sandstone-rich and mudstone-rich facies displays a systematic decrease upwards within the sampled interval (Fig. 15). All samples analyzed are from weathered outcrops and thus are probably lower values than would be exhibited by fresh samples. Variations between sandstone-rich and mudstone-rich facies are considered to be real because, on the scale of the sampled interval, all samples will have been skewed equally by weathering.

**Interpretation**

Highest TOC contents in the basal condensed section are consistent with lowest sedimentation rates associated with maximum flooding. The sandstone-rich and mudstone-rich facies are interpreted to represent monsoonal and intermonsoonal facies, respectively, and to record ten years of prodeltaic sedimentation. Within annual cycles, higher TOC values are associated with deposits of the intermonsoon at which times sedimentation rates are inferred to have been lowest resulting in higher concentration of organic carbon. In contrast, lowest values are associated with deposits of the monsoon at which times sedimentation rates are considered to have been highest resulting in dilution of organic carbon. The systematic decrease upwards within the sampled interval TOC% in both sandstone-rich and mudstone-rich facies (Fig. 15) is attributed to dilution of organic relative to inorganic sediments, the result of progradation of the delta. TOC variations within the Pride Shale are consistent with the findings of Ibach (1982) who observed that highest TOC weight percentages in black mudstones are associated with slow sedimentation rates and lower TOC weight percentages are associated high sedimentation rates. Ibach (1982) attributed lower TOC contents to clastic dilution. Similarly, Ricken (1996) attributed lower concentrations of organic carbon within rhythmically bedded deposits to high sediment yields and elevated concentrations of organic carbon to low sediment yields.

**GEOCHEMISTRY: MAJOR AND TRACE ELEMENTS**

**Description**

A 22 cm-long outcrop slab from the second road cut along I-77 at Camp Creek, WV (Fig. 8), and a 16 cm-long sample from a loose boulder at Spanishburg (Fig. 9B) were collected by Larkins (2009) to evaluate whether major and trace element geochemistry can be used as proxies for cyclicity in the Pride Shale. The outcrop was coated in layers of sodium silicate, rubber latex mold and foam sealant prior to using a concrete saw. Both samples were analyzed using an Avaatech XRF-scanner with a 0.5 mm step size and both a 10 kV/1000 μA scan for 60 seconds and a 30 kV/1000 μA scan with a Pd-thin filter for 120 seconds. The three palaeoenvironmental proxies selected were titanium, silicon/titanium, and sulfur, which were used as potential proxies for detrital, biogenic and authigenic processes, respectively. The XRF-scanning technique produced a continuous record expressed as counts rather than specific quantities.
Interpretation

Larkins (2009) proposed that the Pride Shale in the two samples collected preserves two dominant periods, an ~ 27 mm period expressed in total Ti contents and Si/Ti ratios, and interpreted to represent an annual cyclicity, and an ~2.27 mm period expressed in the S record and interpreted to represent a monthly cyclicity. High total Ti counts were interpreted to represent periods of enhanced precipitation when terrigenous sediment flux was elevated during the monsoon. Conversely, high Si/Ti ratios were interpreted to represent enhanced biogenic silica productivity during the intermonsoon. Higher sulfide contents within the sediments were attributed to an increase in marine organic matter in the surface sediments, and enhanced sulfate reduction during monthly spring tides.

FIELD TRIP STOPS

- **Note:** It is necessary to get permission to stop along I-77. Contact: West Virginia Parkways, 201 Pikeview Drive, Beckley, WV 25801, Tel: (304) 256-6924; FAX: (304) 254-2914 and request that orange vests be left at the rest stop near the junction of Rt. 460 and I-77 for use on the field trip.

- **Field Trip departs from the Tourist Information Center immediately west of the intersection between Rt. 460 and I-77 near Princeton, West Virginia (Latitude: 37.36261N; Longitude: 81.04543W). Refer to Figure 16 for locations of field trip stops 1 through 7.

- **Drive out of the parking lot of the Information Center and turn left onto Rt. 219/2 North towards Rt. 460. Turn left at traffic light (0.1 miles) then turn right onto I-77 North (0.2 miles).**

- **Turn right onto Rt. 7 at Athens exit from I-77 and take next turn to right onto Rt. 14. Drive 0.3 miles up the hill and make a U-turn in parking lot on left. Drive back towards Rt. 7 and park vehicles on side of the road at intersection with Rt. 7 (6.5 miles). Walk into large exposure visible from road (Stop 1A). Return to vehicles and walk west along Rt. 7 for 400 yards underneath I-77. Exposure is located along on-ramp to I-77 South (Stop 1B) (Beware of traffic).**

STOP 1:
Latitude: 37.42496N; Longitude: 81.06334W

Lower Princeton Formation

The base of the Princeton Formation defines a sequence boundary recognized on the basis of subsurface and surface mapping of the Princeton incised valley fill (Figure 3; Miller and Eriksson, 2000). At **Stop 1A,** the Princeton Formation consists of multistory channel sandstones that are erosional into the Hinton Formation. Carbonaceous mudstone and an intercalated coal horizon are present at the top of the Hinton Formation. The overlying Princeton channel sandstone contains a diverse suite of clasts including pebbles of quartz,
metamorphic rock, intrabasinal mudstone, limestone, and caliche. The clasts imply uplift of an eastern source terrane containing crystalline rocks and older sedimentary components including the Greenbrier and Hinton formations. Clasts of coal are also present in the Princeton sandstone (Miller and Eriksson, 2000). At Stop 1B, Princeton Formation consists of multi-story/multi-channel elements. Individual channel elements are up to 2.0 m thick and up to 15 m wide (Fig. 17). A braided alluvial setting is inferred for the lower Princeton Formation (Miller and Eriksson, 2000).

STOP 2:
Latitude: 37.45659N; Longitude: 81.0676W

Upper Princeton Formation

Exposed at this locality are several facies that record a shift from braided-alluvial, lowstand systems tract deposits to transgressive systems tract, tidal-estuarine to maximum flood, black mudstones at the base of the Pride Shale. Hidden below the road are the conglomeratic quartz sandstones seen at Stop 1 which typify the lower Princeton Formation. Upper Princeton Formation facies seen here include a laterally variable package of tabular sandstones, heterolithic channel-fills, and dark mudstones with siderite concretions (Fig. 5). Plant fossils and/or root traces are common in all three facies.

The tabular sandstone body at road level contains plane beds, small-scale cross beds, ripples, and mm–to cm–thick, crude bundles of sandstone-mudstone couplets. This facies is interpreted as a tidal sand flat
deposit on the basis of inferred tidal bundles and associated ripples. In the absence of mudstone, evidence for subaerial exposure is lacking. Thus, this facies probably developed on a lower tidal flat. Minor (1-2 m thick) channel-fills are present on either side of the tabular sand body within the dark mudstones. The channel deposits are over steepened or folded as a result of syn-sedimentary slumping. Channel-fill sediments include cyclic rhythmites consisting of sand-mud couplets between 1mm and 1 cm thick (Fig. 18). A spectrum of tidal periodicities including is recognized on the basis of couplet bundling patterns including semi-diurnal, alternating thick and thin sandstone – mudstone couplets interpreted as dominant/subordinate diurnal pairs, and semi-monthly (neap-spring) cycles consisting of thickening and thinning couplets (Fig. 18). It is unclear whether individual sand-mud couplets were deposited by flood or ebb (or both) tidal currents. Most neap-spring cycles are comprised of fewer than 15 couplets, and record deposition via only the strongest tidal currents. A few thick neap-spring cycles consist of up to 28 individual couplets. Interpreted as tidal creek successions, these channel-fill facies provide strong evidence for a mixed, predominantly semi-diurnal tidal system. The dark mudstones with locally abundant siderite nodules, plant fossils and rhizoliths are interpreted as tidal marsh facies (Miller and Eriksson, 2000).

The marsh/tidal creek facies are truncated by a thin (less than 1 m) conglomeratic bed which contains rounded quartz pebbles and invertebrate fossils including gastropods, brachiopods. This horizon can be traced across much of the study area, where it is generally less conglomeratic and more fossiliferous and is interpreted as a ravinement bed produced via tidal scouring as the Princeton estuary was transgressed. The ravinement bed is overlain by a few meters of dark, fissile mudstone of the basal Pride Shale Member (Bluestone Formation). Where the gravel is absent, as on the northern edge of the cut on the western side of the road, grey mudstones of the Princeton Formation are overlain by black mudstones representing the marine condensed section at the base of the Pride Shale (adapted from Miller and Eriksson, 2000). This basal Pride Shale facies is interpreted as a condensed section deposit associated with maximum flooding, and represents the source for the hot gamma-ray spike seen in subsurface well logs (Fig. 3) throughout the study area. Regionally, the Pride Shale extends beyond the margins of the Princeton incised valley fill and overlies interfluve red beds of the upper Hinton Formation.

Stop 3:
Latitude: 37.49801N; Longitude: 81.10490W

Tidal Rhythmites in Mudstone and Princeton-Pride contact

Along the freeway entrance on-ramp, dark, siderite-rich mudstones of the Princeton Formation are exposed. Thin tidal rhythmite deposits and relatively intact plant fossils in this interval are suggestive of a tidal-estuarine marsh environment. A few centimeters of fossiliferous (w/gastropods, brachiopods) sandstone (equivalent to the ravinement bed at Stop 2) separate the Princeton Formation from the basal black mudstone (condensed section) of the Pride Shale Member. Large (up to 0.5 m) carbonate concretions at the base of the Pride Shale contain abundant microfossils and invertebrates (Weems and Windolph, 1986). A large (0.5 m) fish fossil was recovered (Weems and Windolph, 1986) from a carbonate concretion at the base of the Pride Shale. Plant fossils are common within the Pride Shale as generally small fragmented remains, but include Stigmaria stellate. Invertebrates in the rhythmic beds include abundant small, thin-valved bivalves (Sanguinolites,
Modiolus sp.) and rare carbonized impressions of shrimp-like arthropods (Miller and Eriksson, 1997).

- **Return to vehicles after Stop 3 and continue on I-77 North. Pull well off the road at sign “Speed Limit 70” for Stop 4 (13.8 miles). (Keep well away from the Interstate and beware of trucks in the inside lane).**

**Stop 4:**
Latitude: 37.50269N; Longitude: 81.11176W

Pride Shale

At this stop, the Pride Shale displays prominent annual cycles that are expressed as corrugations on the order of 5 to 15 cm thick (Fig. 11C). Using a combination of observations on outcrop and thin section photographs, a hierarchy of bundling patterns can be reconstructed. Within the positive-weathering elements of the corrugations, ~5mm to 1 cm-thick sandy layers thicken and thin upwards within the inferred annual cycles. Within individual sandy layers, sandstone-siltstone/mudstone couplets thicken and thin upwards in what are inferred to represent neap-spring cycles (refer to Fig. 11B). Individual couplets within the neap-spring cycles are interpreted as semi-diurnal deposits that rarely occur as thick-thin semi-diurnal pairs (refer to Fig. 11A). The exposure is dissected by major discontinuities in the form of broad, concave-up surfaces. The Pride Shale coarsens upward into the Glady Fork Sandstone Member that will not be visited at this stop.

- **Pull off at the parking place alongside I-77 North for Stop 5 (14.1 miles). Three vehicles can be accommodated at this location. At Stop 5, examine the Pride Shale above the first bench and then walk to the southern end of the exposure and climb two benches to examine the transition from the Pride Shale into the Glady Fork Sandstone (Keep well away from the Interstate).**

**STOP 5:**
Latitude: 37.50695N; Longitude: 81.11597W

Pride Shale and Glady Fork Sandstone

At this stop, the Pride Shale displays prominent annual cycles expressed as corrugations similar to those at Stop 4 but on the order of 5 to 50 cm thick. Towards the northern end of the road cut, ~50cm thick annual cycles consisting of up to 16 neap-spring cycles, are preserved above the level of the first bench (Fig. 9A and 13). Discontinuities are apparent on outcrop as broad concave-up surfaces with several meters of relief (Fig. 14A). The first bench above road level contains meter-scale, rotated/deformed blocks (Fig. 14B). The Pride Shale coarsens upward into the Glady Fork Sandstone Member. The Glady Fork is exposed as a 20 m-thick succession of flaser- and wavy-bedded, fine-grained sandstones which are interpreted as distributary mouth-bar deposits. Interbedded terrestrial mudstones and sandstones in the overlying Gray and Red members reflect a basinward shift in coastal plain sedimentation. The Red Member contains paleosol horizons with carbonate nodules and likely reflects a semi-arid climate (Miller and Eriksson, 2000).

- **Continue North on I-77 to Exit 28 at Ghent Interchange (22.1 miles). Take I-77 South to Exit 20 (31.4 miles) and take Rt. 19 West to Spanishburg exposure. Pull-off on wide shoulder on side of the road (38.7 miles) immediately before Hank Williams Sr. Memorial Bridge over Bluestone River.**

**STOP 6:**
Latitude: 37.439945N; Longitude: 81.12128W

Pride Shale

The Pride Shale at this locality is expressed as corrugations on the order of 1 to 5 cm thick interpreted as annual cycles. In addition, and different to Stops 4 and 5, a larger-scale corrugation (25 to 100 cm thick) is developed that is considered to reflect the 18.6 year nodal tidal periodicity (Fig. 11D). Internally, the annual cycles are comprised of 11-18, 1-2 mm-thick, neap-spring cycles (Fig. 11B). Compared to Camp Creek outcrops, overall grain size is finer with less sand and more mud-dominated intervals. This change in grain size reflects the more basinward location of Spanishburg compared to Camp Creek outcrops. The prominent annual cycles preserved at Spanishburg in comparison to Camp Creek most likely are due to less frequent disturbances from bottom currents and/or bioturbation at this more distal location (Larkins, 2009).

- **From the Spanishburg outcrop make a U-turn to drive back to I-77 Camp Creek exit. Take I-77 South to Exit 9 (45.6 miles) at intersection with Rt. 460/19 at Princeton. Turn right onto Rt. 460/19 (56.4 miles) to exposure of Glady Fork Sandstone (59.3 miles). Park on side on road along Rt. 460 to examine outcrop.**

**STOP 7:**
Latitude: 37.35487N; Longitude: 81.09878W

Pride Shale-Glady Fork Sandstone contact south of Princeton, WV

The Glady Fork Sandstone at this location is expressed as a multi-story/multi-channel sandstone body incised into...
the Pride Shale. Individual channel elements are 1.7 to 3.0 m thick and up to 15 m wide. Along its basal contact, the Glady Fork Sandstone contains large-scale ball-and-pillow and flame structures indicating that the Pride Shale was unconsolidated at the time of Glady Fork deposition. The Glady Fork Sandstone at this locality is interpreted as a distributary channel deposit of the Pride delta.

- **Continue on Rt. 460W and make U-turn at 60.2 miles. Return to Tourist Information Center (64.4 miles)**

**REFERENCES**


