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High-resolution Stratigraphy and Lithology of an Outcrop within the Grundy Formation (Pennsylvanian), Harlan County, Southeast Kentucky

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Abstract

Thick sequences of stratigraphically continuous exposures of rock occur within the Pennsylvanian section of the Appalachian Mountains that provide opportunities for detailed stratigraphic analysis. During uplift, large amounts of sediment were produced and transported into a foreland basin to the west of the rising Appalachians, and have since been uplifted. Pennsylvanian rocks are dominantly clastics, deposited in broad coastal plain, delta, and tidal systems. We examine a single roadcut near Coldiron, Harlan County, Kentucky within the Pine Mountain thrust sheet, along KY 119, to determine its high-resolution lithology, stratigraphic relationships, and depositional environments.

The outcrop is comprised of mudstone, siltstone, and sandstone with thin intervals of coal in the Grundy (formerly Hance) Formation (lower Pennsylvanian). We measured 81 meters of stratigraphic section using a Jacob's staff, and sampled pertinent rock units for detailed examination. The stratigraphic section shows several coarsening-upward sequences from 6 to 20 meters in thickness, capped by coal and/or organic-rich shale about a decimeter thick. Clastic lithologies pervasively exhibit lamination in mudstones and fine cross-lamination in siltstones and sandstones. Woody fragments and plant material are common in several units. The lithology and sedimentary structures of marine mudstone are consistent with deposition in shelf (prodelta?) depositional environments. Overlying sandstones were possibly deposited in deltaic and tidal systems, which are capped by coal and/or organic-rich mudstone that likely formed in coastal, freshwater environments.

Ultimately, contextual information, lithologic descriptions, the measured stratigraphic column, and photographs of key features and samples will be posted on the Kentucky Geological

Survey (KGS) website as a story map. Samples will be archived at the KGS Earth Analysis Research Laboratory (EARL).

Introduction

The Grundy (formerly Hance) Formation is found within the lower Breathitt Group located in the Eastern Kentucky Coal Fields. These rocks are of lower Pennsylvanian age and are exposed above and below the Pine Mountain thrust sheet. The study site is a road cut along US 119 through Harlan county (Figure 1), where recent road work expanded the road cut and exposed previously covered or heavily-weathered rocks of the Pine Mountain thrust.

This area of the Appalachians formed during the Alleghanian orogeny during the Carboniferous, eventually forming the Appalachian Mountains. During uplift, large amounts of sediment were produced and then transported into a foreland basin to the west of the rising mountain range. Pennsylvanian rocks here are exclusively clastics deposited in broad coastal plain, delta, and tidal systems (Ellsworth, 1977).

Methods

A site (36°49’48”N, 83°27’02”W) along US 119 in Harlan County near the community of Coldiron (Fig. 1) was selected due to ease of access and large amount of exposed stratigraphic section. The rocks are mapped as the Grundy Formation by Froelich (1972) and dip approximately 25 degrees west-southwest along the road cut.

The stratigraphic section is generally composed of mudrock, sandstone, organic-rich mudstone, and coal. The section was measured using a Jacob staff, recognizing lithology and lithologic changes upsection. Detailed descriptions were written in the field and representative samples of rock units were taken. Collected samples were slabbed and polished for examination.

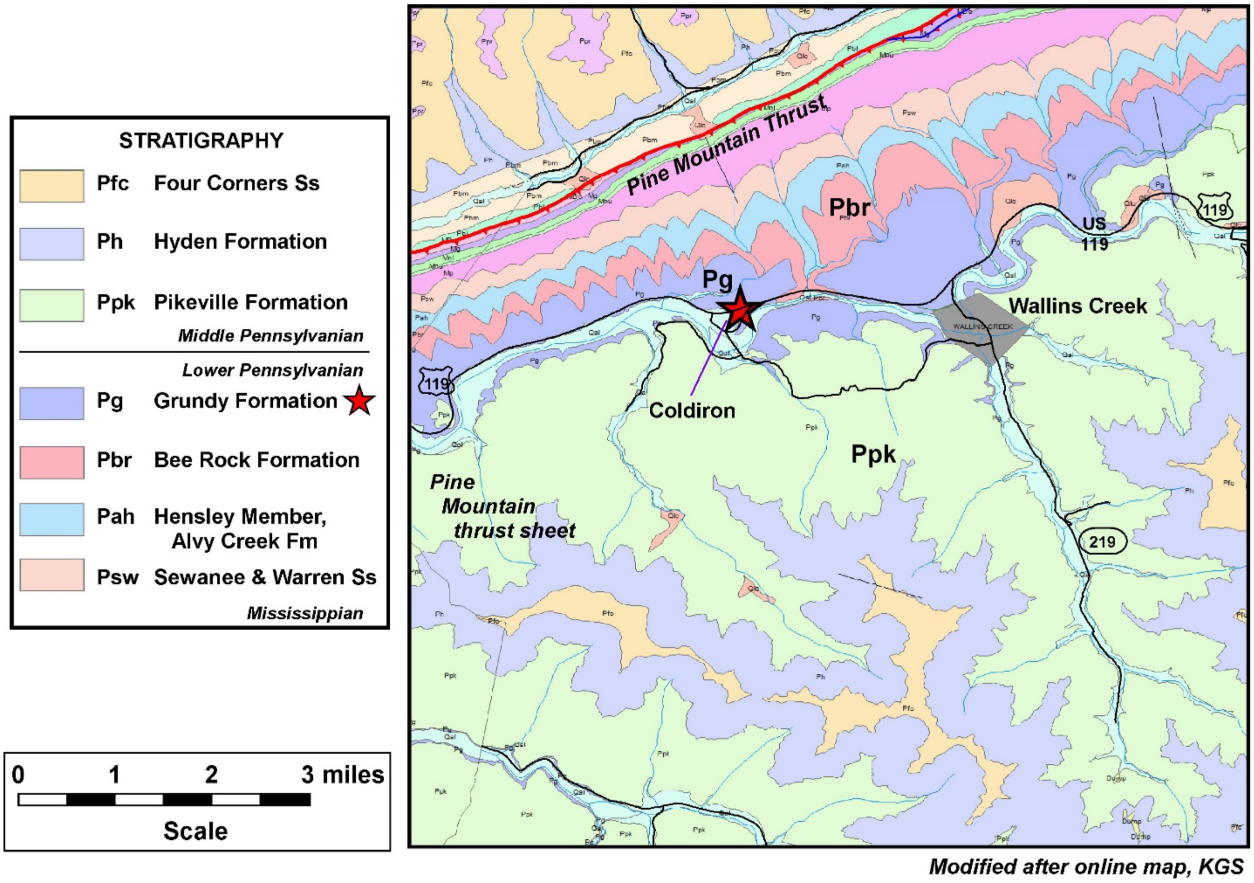

Figure 1. Geologic map of a portion of the Wallins Creek quadrangle, Harlan County, Kentucky (after Froelich, 1972). The outcrop location is marked with a star, where a portion of the Grundy Formation (Pennsylvanian) crops out.

Results

The measured stratigraphic section is 81 meters thick (Fig. 2). The rocks are comprised solely of clastic sedimentary rocks – mudstone, siltstone, and sandstone with some thin coal horizons. Five coarsening-upward sequences are observed throughout the stratigraphic column. These sequences appear to be genetically significant and are described and discussed below, from oldest to youngest.

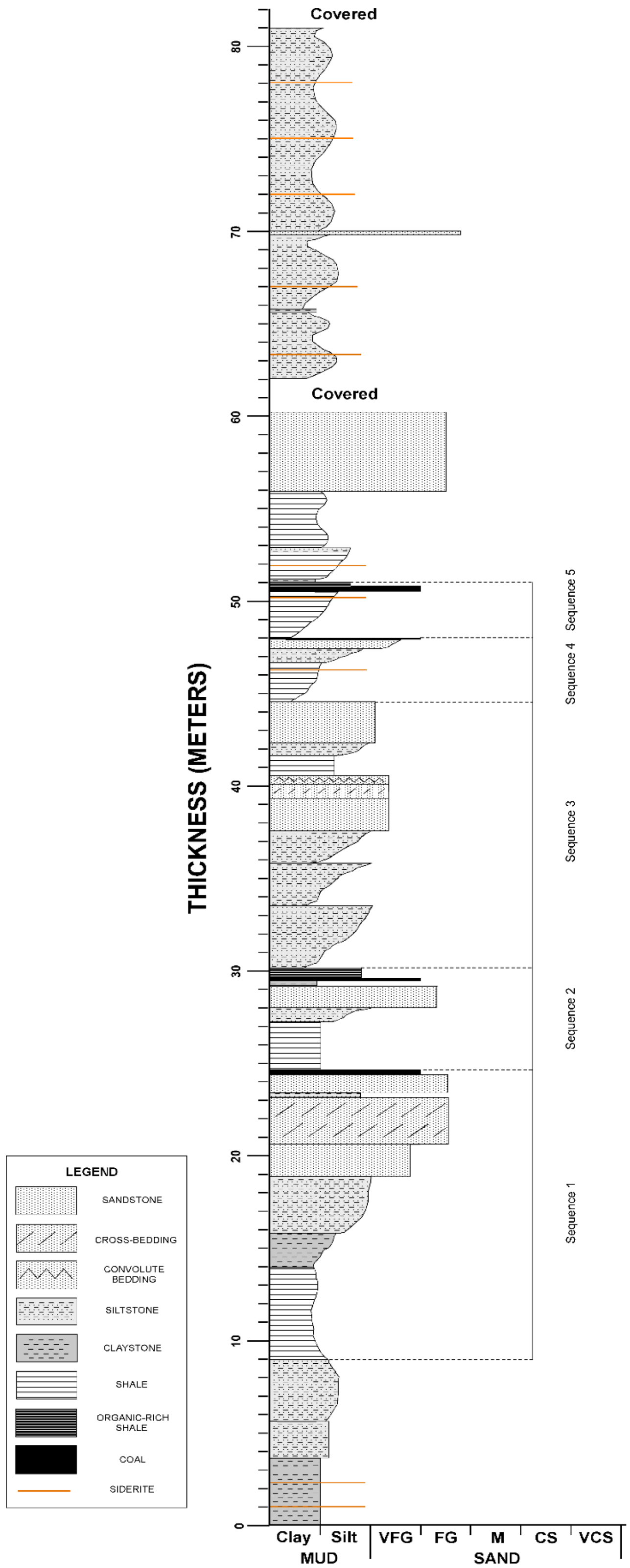

Figure 2. Stratigraphic column of the measured stratigraphic section. Note the location of several coarsening-upward sequences that are described and discussed in the text.

Coarsening-upward Sequence 1 (24.66 m thick; Fig. 3)

Description

The measured section begins with a dark gray claystone with thick lamination to thin bedding characterized by splintery weathering (0 to 3.94 m). This claystone unit also exhibits siderite nodules and defined siderite layers 1-cm thick (1.03 m), and 3-cm thick (2.29 m). Upsection (3.62 to 5.62 m), the siltstone gradually transitions to a lithology showing consistent siderite nodule with spheroidal weathering (Plate 1) reflecting a unit (5.62 to 8.98 m) with higher silt content and slightly thicker bedding. The next stratigraphic change is to a silty shale unit (8.98 to 13.93 m) which initially becomes less silty upsection (until ~11 m) and then coarsens

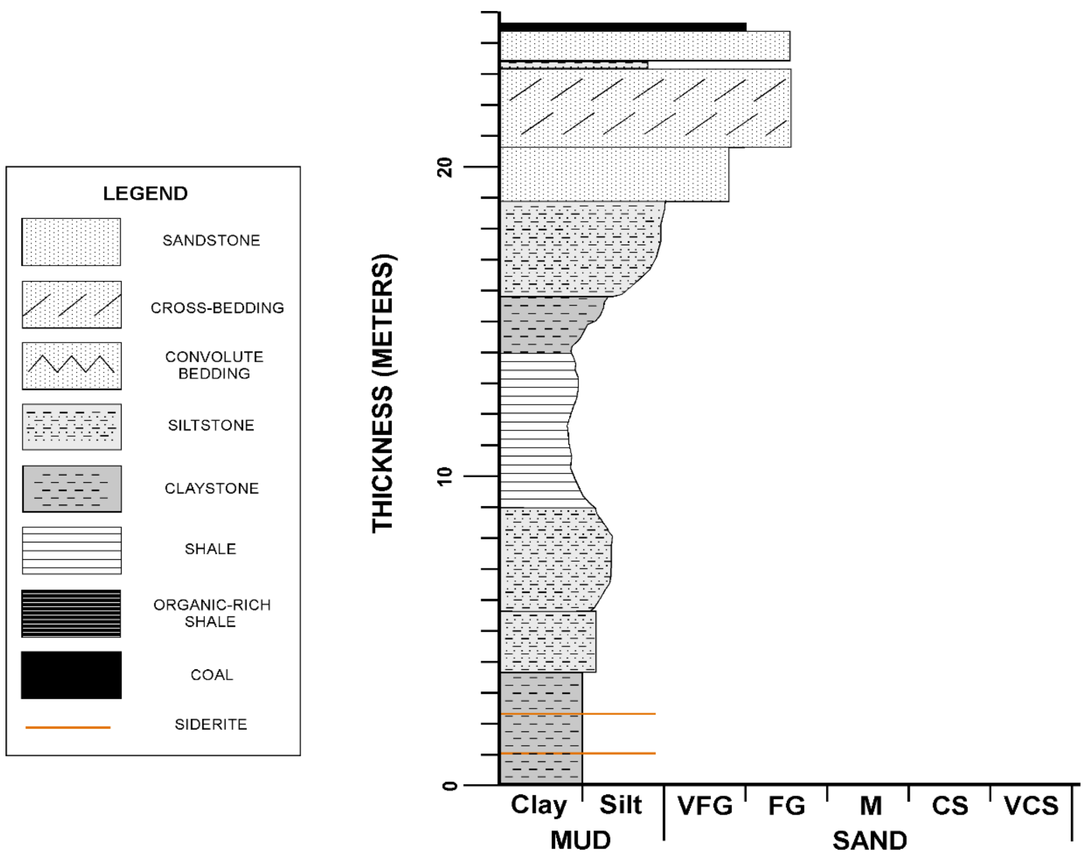

Figure 3. Coarsening-upward Sequence 1 of the measured section (0 m to 24.66 m).

again. A sample was taken at 13.21 m (CI-A, Plate 1) that shows dark gray, thinly laminated shale with good parting and stringers of lightly colored clay prominent throughout. The shale is succeeded by a dark gray claystone (13.93 to 15.70 m) with thick lamination to very thin bedding. The unit becomes siltier upsection to show tabular siltstone layers (15.70 to 18.81 m) with spheroidal weathering. These layers are thickly laminated to thinly bedded with fine, white silt layers, in contrast to its overall dark gray color. The next unit (18.81 to 20.64 m) is a medium to dark gray, micaceous, very fined grained sandstone. Bedding is tabular with thin to medium beds showing internal lamination. A sample was collected at 18.94 m (CI-B, Plate 1) that showed a medium gray, very fine-grained sandstone with thin to medium bedding and thick to thin internal cross lamination. Prominent mud drapes up to 3 mm thick were observed throughout the sample. A very fine- to fine-grained, cross-bedded sandstone of light gray color lies above (20.64 to 23.14 m) that possesses tabular, medium bedding with interior cross-lamination. A sample was taken at 21.64 m (CI-C, Plate 1) that shows cross lamination and interior cross lamination as well as mud drapes up to 1 mm thick. The sandstone unit is succeeded by coarse siltstone of dark gray color (23.14 to 23.30 m) that is thinly to thickly laminated with interior cross-lamination. Then a single, fine-grained, brown sandstone bed (23.30 to 24.45 m) occurs that has no internal structure and has an undulatory base with relief of 0.5 m to 1 m. The sandstone is then capped by a dark gray claystone layer (24.45 to 24.46 m) with an overlying, poorly developed coal bed (24.46 to 24.66 m) that has some blocky layers.

Interpretation

This portion of the stratigraphic section appears to demonstrate a full transition from marine to terrestrial depositional environments. The section begins with putative marine mudstones and siltstones which are most likely prodelta in origin due to their coarsening-upward nature. Layering is preserved within these rocks with little to no evidence of bioturbation, implying rapid sedimentation rates. The presence of siderite noules as well as preserved mud laminae within sample CI-A further support this interpretation. The overlying sandstone (18.81 m sample) is prhaps a tidal, littoral, or delta-front deposit, consistent with delta progradation and deposition in shallower water or delta progradation. This interpretation is supported by preservation of the sandstone's internal cross-lamination as well as mud drapes within. Upsection at 20.64 m, sandstones show increased coarsening with internal cross lamination and larger scale cross bedding, likely reflecting deposition in more turbulent, shallower water, as supported by the presence of preserved symmetrical mud drapes and internal lamination within sample CI-C. A thin siltstone layer and sandstone layer above exhibit no internal structure, a likely bioturbated fabric, consistent with tidal, littoral, or coastal plain deposits. This clastic sequence is then capped by a thin seam of coal, indicating a terrestrial, fresh-water swamp environment.

Coarsening-upward Sequence 2 (5.51 m thick; Fig. 4)

Description

This sedimentary package begins with a light gray shale containing a moderate amount of organic matter (24.66 m to 27.28 m) with moderate splintery weathering and no internal lamination. The unit then coarsens upsection into a light gray siltstone layer (27.28 to 28.01 m) that itself also coarsens upward; the layer is thinly bedded with no observable cross-bedding or cross-lamination. The next unit (28.01 to 29.20 m) is a very light gray, fine-grained sandstone

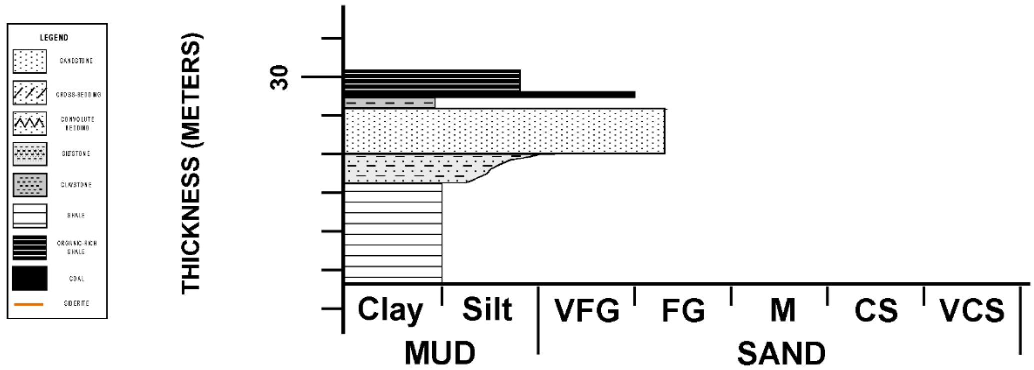

Figure 4. Coarsening upward Sequence 2 of the measured section (24.66 m to 30.17 m).

with internal lamination sometimes interrupted by burrows. This sandstone is also fractured from its base moving upward and is massively bedded. A sample was collected at the top of the sandstone (29.19 m, sample CI-D, Plate 2) showing internal lamination and thin external lamination. Thin mud drapes and discrete fossilized horizontal burrows ranging in size of 0.66 cm to 1.32 cm in diameter are prominent throughout sample. A layer of very dark gray to black, organic-rich mudstone (29.20 to 29.47 m) with very low silt content occurs upsection. A single seam of poor-quality coal (29.47 to 29.56 m) lies atop the organic shale, which in turn is overlain by dark brown, laminated, organic-rich shale (29.56 to 30.17 m, Plate 2) that is very thinly bedded.

Interpretation

This sedimentary package again represents a transition from a marine to terrestrial environments of deposition. The basal shales have no internal bedding likely due to bioturbation and are consistent with offshore or littoral deposits. The overlying sandstones exhibit some wavy internal lamination and burrows, suggesting a low energy, marine, littoral, or tidal deposit. The overlying mudstone seems to indicate a freshwater environment due to its high organic content and partial coalification near the top of the unit. The overlying coal reflects deposition in a coastal swamp clearly indicating freshwater terrestrial environments. The capping organic–rich shale was perhaps deposited in a lagoon or lacustrine environment with low-oxygen content that excluded burrowing organisms.

Coarsening-upward Sequence 3 (10.42 m thick; Fig. 5)

Description

This section begins with mudrock (30.17 m to 33.55 m) that begins as claystone with relatively little silt that then transitions into siltstone, and eventually grades to a very-fine-grained sandstone. The mudrocks are a light gray color and is internally laminated. Bedding ranges from thin lamination to thin bedding, with bedding thickness increasing upsection. A sample was collected from this layer at 34.44 m (CI-E, Plate 3) showing internal cross-lamination and thin external lamination as well as mud laminae occurring in ripple troughs. From 33.55 m to 35.85 m we observe a similar coarsening-upward pattern (Plate 3), beginning with mudstones exhibiting splintery weathering and thin lamination for 93 cm, succeeded by siltstone showing thick lamination for 51 cm, then finally a very fine-grained sandstone with very thin bedding for 86 cm. Upsection is a third upward-coarsening series of mudrock from 35.85 m to 37.57 m (Plate 3), beginning with a splintery weathering claystone unit that is very thinly bedded and internally laminated. This unit extends for 55 cm then grades into a 1.72-m-thick layer of coarsening-upward siltstone with thin bedding (Plate 3). Both the claystone and siltstone are light gray in color and internally laminated. Above (37.57 m to 39.35 m), a medium gray, very fine-grained sandstone occurs with thin to thick bedding (Plate 3), and internal lamination, followed by a single bed of light brown, very fine-grained sandstone 80 cm thick (39.3 to 40.15 m,

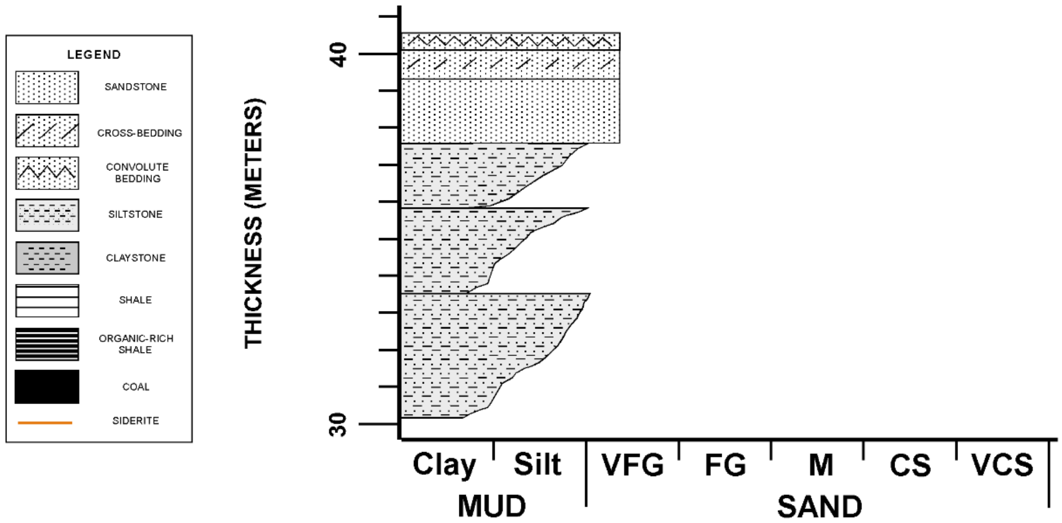

Figure 5. Coarsening upward Sequence 3 of the measured section (30.17 m to 40.59 m).

Plate 3). This sandstone exhibits tabular, decimeter-thick crossbedding and is capped by a 44-cm-thick bed of light gray to beige very fine grained sandstone (40.59 m) with distinctive convolute bedding (Plate 3).

Interpretation

The mudrocks of this sequence are consistent with littoral shelf and/or prodelta deposits in which bedding is preserved due to high sedimentation rates. The overlying sandstone contains cross beds generally larger than most observed at the Coldiron site, indicating higher turbulence in shallower water consistent with littoral shelf environments more exposed to waves. Convolute bedding in the upper sandstone is likely due to dewatering when sandy sediments were rapidly placed atop underlying sand with high water content. Thes capping sandstone are likely shallow water marine deposits.

Coarsening-upward Sequence 4 (7.4 m thick; Fig. 6)

Description

This sequence begins with a layer of shale 1.08 meters thick (40.59 m to 41.67 m) that is light gray and thinly laminated with very low silt content. Upsection (41.67 m to 42.29 m), a coarse-grained siltstone, similar to that of Sequence 3, that is medium gray, and exhibits very thin bedding and internal lamination. This is followed by a single, massively-bedded, 1.63-meter-thick layer of very fine-grained sandstone (42.29 m to 44.6 m). This sandstone is dark gray with internal lamination consisting of both darker- and lighter-colored siltstones. A sample was collected from this layer at 43.66 m (CI-F, Plate 4) showing a dark gray siltstone intermixed with very fine-grained sandstone with remnants of disturbed (bioturbated?) internal bedding. Above, a light gray, thinly-laminated shale (2.1 m thick; 44.6m to 46.7m) occurs containing interspersed siderite nodules and multiple siderite beds (less than 2-cm-thick). The shale coarsens upward to medium gray siltstone (74 cm thick; 46.7 m to 47.44 m) with thick lamination to very thin

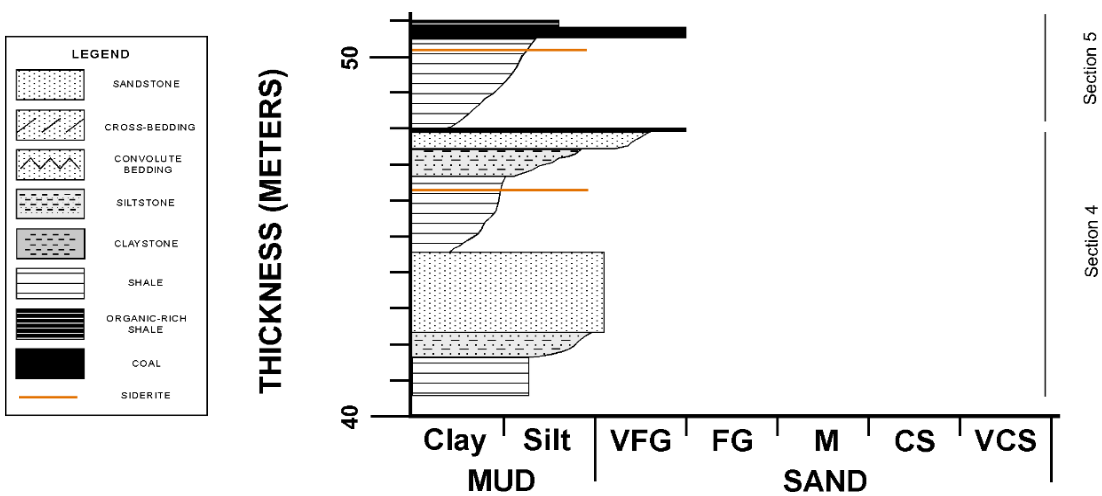

Figure 6. Coarsening-upward Sequence 4 (40.59 m to 47.99 m) and 5 (47.99 m to 50.99 m) of the measured section.

bedding that exhibits some splintery weathering, and itself coarsens upward. Following the siltstone is a light gray, medium bedded, very fine-grained sandstone (54 cm thick; 47.44 m to 47.98 m) with tool marks along the exposed at the base (Plate 4). This sandstone also shows ripple- and dune-sized cross bedding capped by a 1-cm-thick coal layer (47.99 m). A sample was collected from the sandstone (47.91 m, sample CI-G, Plate 4) that showed internal cross-lamination.

Interpretation

This sequence is similar coarsening-upward Sequence 1. It begins with internally laminated mudrocks, consistent with deposition in prodelta or offshore environments with higher sedimentation rates and fine grain size. The upsection transition from mudrocks to internally laminated siltstone and sandstone is consistent with progressive shallowing and prograding prodelta depositional environments, capped by deposits representing littoral environments or perhaps tidal deposits. Bioturbation exhibited in Sample CI-F suggests lower sedimentation rates with less turbulent conditions.

The sequence then appears to shift back to more distal, offshore depositional environments, perhaps prodelta, coarsening to siltstone that are likely more proximal. The overlying sandstone unit shows tool marks on its underside showing bedload transport. The transition above to a laterally continuous, but thin (1 cm) coal layer necessitates deposition from marine to swamp environments without preservation of transitional depositional environments capped ny environments representing littoral or perhaps tidal deposition. An alternative explanation is that the sandstone at ~42 m is fluvial, but no diagnostic evidence is present.

Coarsening-upward Sequence 5 (3 m thick; Fig. 6)

Description

This thinner sequence begins with a medium gray, thinly-laminated shale (2.65 m thick; 47.99 m to 50.64 m, Plate 5) with interbedded thin (<1 cm thick) siderite beds. This unit coarsens upward, as silt content increases, and then is succeeded by a unique layer resembling an underclay (4 cm thick; 50.64 m to 50.68 m, Plate 5). This shale layer is very dark gray that weathers with crumbly to powdery consistency; the unit is organic rich containing woody fragments and fine organic material. Directly above is a coal seam (18 cm thick; 50.6 8m to 50.86 m, Plate 5) that is crumbly at its base and becomes blockier upsection. This coal layer is then topped by a dark gray to black, organic-rich shale (13 cm thick; 50.86 m to 50.99 m, Plate 5) with thick lamination.

Interpretation

The base of this sequence is composed of laminated shales containing siderite that are consistent with offshore marine / prodelta depositional environments. This marine(?) unit is overlain by a possible underclay, classically interpreted as floodplain deposits with varying degrees of soil development. The coal unit here is relatively thick, like the coal of Sequence 1, and is indicative of a coastal swamp environment. The organic-rich shale likely reflects deposition in lagoon or lacustrine environments, both of which contain potentially large amounts of organic matter.

The sharp transition from presumably marine depositional environments to that of terrestrial environments without the evidence of a hiatus is puzzling. However, the siderite-containing, basal shale could be floodplain deposits although these rocks are identical to basal rocks of prior sequences interpreted as marine.

Uppermost measured section (30 m thick; Fig. 7)

Description

The first portion of the remaining stratigraphic sequence has a 11-m-thick coarsening-upward sequence but does not appear to be capped by rocks deposited in terrestrial environments

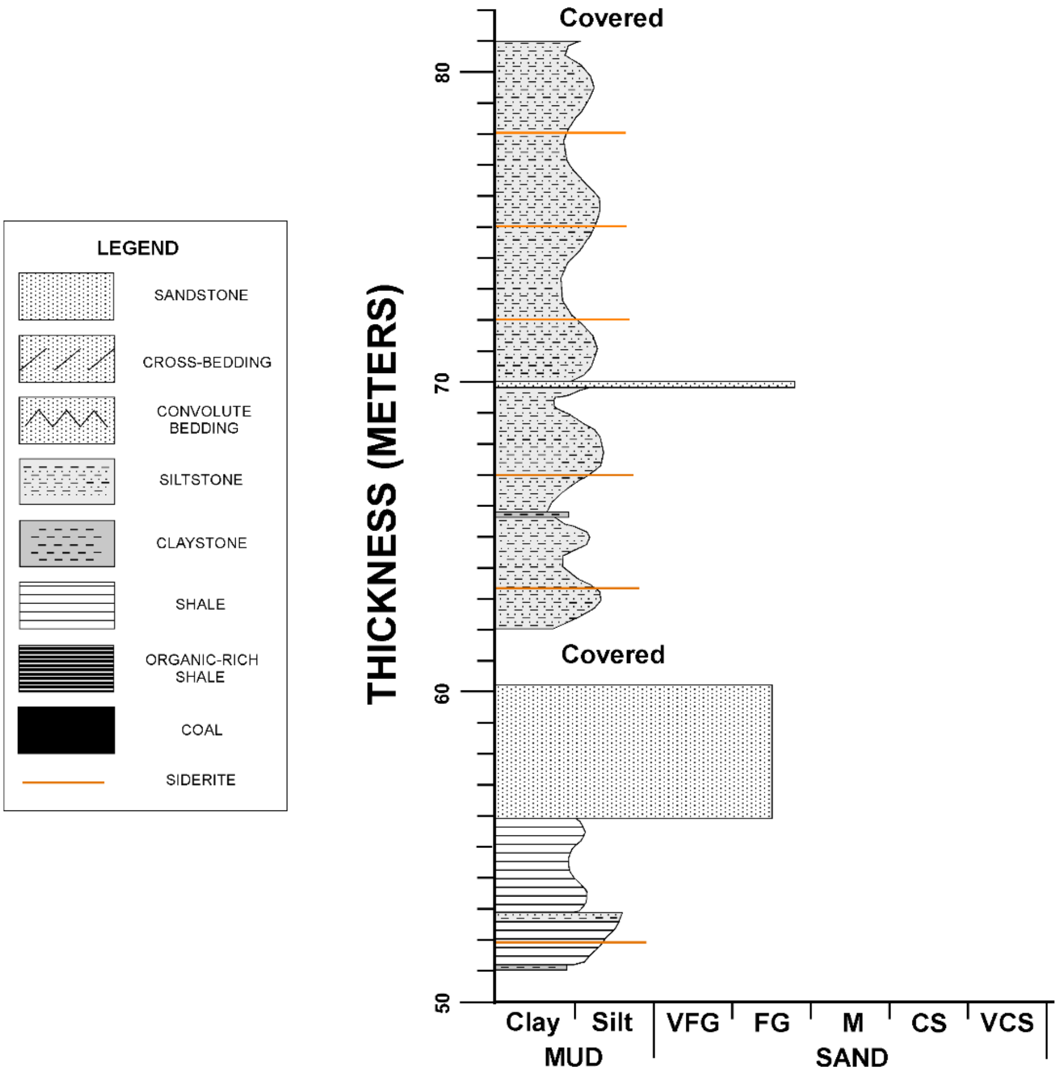

Figure 7. The uppermost portion of the measured section (51 m to 81 m).

as in Sequences 1 through 5. This section begins with a medium gray, thinly-laminated mudstone cm thick; 51 m to 51.1 m) with moderate silt content. Upsection, a medium gray, thickly laminated shale (1.56 m thick; 51.1 m to 52.66 m) occurs that contains <2-cm-thick siderite layers interspersed throughout the section . Next is 21-cm-thick unit of medium gray siltstone (52.66 m to 52.87 m) that is thinly laminated and contains internal laminations of claystone alternating with layers of silt. Upsection lies a medium gray to beige, thinly laminated, interbedded mudstone and shale (3.07 m thick; 52.87 m to 55.94 m) with internal laminations.

These mudrocks are succeeded by a beige to medium gray, fine-grained sandstone (4.3 m thick; 55.94 m to 60.24 m). The sandstone exhibits internal bedding and contains a lenticular coal layer less than 1 cm thick about 1 meter below the top of the sandstone body (Plate 6). A sample from this sandstone was taken at 55.99 m (CI-H, Plate 6) that shows internal and external, thin cross-lamination as well as preserved pieces of coalified, woody organic matter. The top of the unit is obscured by a rock slide, which covers the next 1.8 meters of the stratigraphic section (60.24 m to 62.04 m).

The rocks above the covered interval are a series of interbedded mudstones and siltstones that span 97% of the remaining 17-m-thick stratigraphic section (62.04 m to 81.04 m, Plate 6). These intercalated mudstones and siltstones are typically medium to dark gray in color, range from thin lamination to thin bedding, and are internally layered. Siderite interbeds <2-cm-thick are common (Plate 6). At 65.67 m, there is a 10 cm layer of medium gray mudstone (65.67 m to 65.77 m) that is thin to medium bedded. Above this layer at 69.81 m, a 39-cm-thick stringer of beige colored sandstone occurs. The sandstone bed is a single layer, approximately 2.7 m long that changes in thickness laterally, and has no internal lamination. It has a sharp base and cuts into the underlying mudrocks (Plate 6).

Interpretation

The lower portion of this stratigraphic sequence coarsens upward from mudrocks to a thick-bedded sandstone with internal lamination. These lithologies are consistent with littoral marine environments with sedimentation rates exceeding the rate of any bioturbation such as a delta-front environement. The lone sandstone body (69.81 m) was likely formed in a marine setting near a terrestrial source for woody material that ultimately formed the lens-shaped coal stringer and coalified organic matter throughout the layer. Bar-mouth or littoral sand bars are possible depositional environments. The final series of internally-laminated mudrocks are consistent with marine environments below the wave base.

Discussion

Stratigraphic position of the Coldiron section

Presently, we are uncertain of the exact or general stratigraphic position of this study's Coldiron section within the Grundy Formation, which can be in excess of 300 m thick (Froleich, 1972). However, portions of the Cedarville section (120 m to 200 m; Pike County, Kentucky), also within the Grundy Formation, closely resemble the Coldiron section. Although the Coldiron section exhibits different thicknesses of respective lithologies, the overall order of the stratigraphic section shows similarity. Both 80-meter sections have sequences of shallowing-upward depositional environments moving from probable prodelta or offshore deposits; then coarsening upward and moving shoreward to shallower marine deposits; then further upward-coarsening to sandstone deposits. Le Cotonnec et al. (2019) interpret other deposits within the Grundy as coastal plain and fluvial-estuarine in origin. Multiple coal units of the Grundy also appear in the Coldiron, Cedarville, and Wolfpit sections (Le Cotonnec et al., 2019), and the type section described by Chesnut (Pike County, Kentucky; 1992), as well within Harlan County, Kentucky (Froleich,1972).

From the examination of the findings of Le Cotonnec et al. (2019), Ruppert et al. (2010), Rice and Hiett (1994), and the geologic map composed by Froleich (1972), we very tentatively place the Coldiron section between the Molus shale and Mason coal beds (Glamorgan within Pike County; Le Cotonnec et al., 2019; Ruppert et al., 2010; Rice and Hiett, 1994).

Depositional Environments

We cannot determine specific depositional environments for sandstones at this locality, because we have no information about the lateral extent and shape of sand bodies. Observations at outcrop- and hand-sample scales suggest possible depositional environments that span the range of siliciclastic tidal, littoral, and deltaic settings.

The most interesting aspect of this work is the presence of multiple, coarsening-upward regressive sequences. These sequences show a transition from offshore marine environments to littoral marine to terrestrial environments represented by capping organic-rich shale and coal.

Coarsening- and shallowing-upward sequences

The Coldiron stratigraphic section shows five coarsening-upward sequences (Sequence 1, 0 to 24.66 m; Sequence 2, from 24.66 to 30.17 m; Sequence 3, from 30.17 to 40.59 m; Sequence 4 from 40.59 to 47.99 m; Sequence 5 from 47.99 to 50.99 m) and an overlying thick section of interbedded siltstone and mudstone containing a sandstone unit that are all presumably marine in origin.

The coarsening-upward sequences are of particular interest as they appear to document environments of deposition that shallow upward from shelf clastics to terrestrial fresh-water settings that result in the deposition of organic-rich shale, underclay, or coal tentatively interpreted as lacustrine, floodplain, and swamp deposits, respectively.

A hypothetical ideal sequence demonstrating this shoaling is Sequence 2 (from 24.5 m to 30 m, Fig. 4). This sequence begins as a marine shale that over the course of 3 meters coarsens upward into siltstone, consistent with distal marine shelf or prodelta deposits. The siltstone then coarsens upward into a 1.2-meter-thick fine grained sandstone, perhaps reflecting deposition in a low-energy littoral deposit. Overlying the sandstone is a 30-cm-thick, organic-rich claystone containing fossilized woody debris. This lithology is consistent with underclay, which are often interpreted as terrestrial floodplain deposits. The sequence is topped by a 7-cm-thick coal layer, overlain by organic rich shale that likely formed in swamp and lacustrine environments, respectively. Marine sedimentary rocks overlie these putative freshwater deposits without any recognizable hiatus in outcrop.

Stratigraphic Cyclicity

The origin of the cyclicity of Pennsylvanian clastics in general, and those in the Grundy Formation in particular, is problematic. Extensive studies by Greb et al. (2008) in the southern Appalachian, Black Warrior Basin of Alabama may assist in determining the origin of Grundy Formation cyclicity. Upper portions of the Pottsville Formation there are age-equivalent to the Grundy Formation and have similar lithologic and stratigraphic features as those observed near

Coldiron. Greb et al. (2008) propose tide-dominated, deltaic systems as the likely depositional setting. They also hypothesize a strong influence of tectonic subsidence as the chief sedimentary control that accommodate marine deposits with similar cyclicity as the Grundy.

Le Cotonnec et al. (2019) also posit that tectonic controls seem most important in controlling subsidence rate and thus accommodation space within the Grundy Formation. Sediment supply or mechanisms affecting eustatic sea level seem less important, especially in the lower portion of the Grundy Formation.

Conclusion

The stratigraphic position of the studied Coldiron section within the Grundy Formation is unknown and further study is necessary to determine its exact position. Our interpretations of depositional environments of the Coldiron section are tentative, because we lack lateral information required to make stronger interpretations. The Coldiron section exhibits strong cyclicity within the Grundy formation.

Multiple upward-coarsening sequences within the Coldiron section of the Grundy Formation, document at least five sedimentary cycles. These cycles represent a shallowing-upward trend of depositional environments with mud-rich, distal marine facies overlain by littoral/fluvial? deposits that are sand prone, and capped by coal and/or organic-rich shale likely deposited in freshwater environments. The cause of the cyclicity is in question, but studies elsewhere implicate tectonic control as the main factor.

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APPENDIX

MEASUREMENT CONVENTIONS

Grain size conventions are after Wentworth (1922). Terminology for bedding thicknesses is after McKee and Weir (1953) as modified by Ingram (1954).

Grain Size

Pebbles……………………………………………………………………4 - 64 mm

Granules…………………………………………………………………2 - 4 mm

Sand

Very coarse………………………………………………………1 - 2 mm

Coarse……………………………………………………………..1/2 - 1 mm

Medium…………………………………………………………1/4 - 1/2 mm

Fine……………………………………………………………1/8 - 1/4 mm

Very Fine……………………………………………………1/16 - 1/8 mm

Silt………………………………………………………………1/256 - 1/16 mm

Clay……………………………………………………………less than 1/256 mm

Bed Thickness

Very thick bedded……………………………………………greater than 1.0 m

Thick bedded…………………………………………………………0.3 - 1.0 m

Medium bedded………………………………………………………0.1 - 0.3 m

Thin bedded…………………………………………………………0.03 - 0.1 m

Very thin bedded…………………………………………………...0.01 - 0.03 m

Laminated………………………………………………………...0.003 - 0.01 m

Thin laminated………………………………………………less than 0.003 m

DETAILED STRATIGRAPHIC DESCRIPTIONS

UNIT	TK(m)	CUML.(m)	DESCRIPTION
1	5.62	5.62	Dark gray, siltstone. Thick lamination to very thin bedding. Unit experiences prominent splintery weathering. Notable siderite layers less than 3 cm thick at 1.03 and 2.32 m.
2	3.36	8.98	Dark gray siltstone with thick lamination to thin bedding. Unit experiences prominent splintery weathering transitioning into spheroidal weathering with siderite nodules up to 2 cm thick. PLATE 1
3	3.35	12.33	Dark gray mudstone with very thin to thin bedding. Unit experiences prominent splintery weathering transitioning into spheroidal weathering
4	1.6	13.93	Dark gray siltstone with thick clay lamination. Unit experiences prominent splintery weathering. SAMPLE: CI-A, PLATE 1
5	1.07	15	Dark gray micaceous siltstone with thin lamination. Unit experiences prominent splintery weathering.
6	0.7	15.7	Very dark gray mudstone with minor silt content and thick lamination. Apparent higher organic carbon content.
7	3.11	18.81	Very dark gray siltstone with thick lamination to very thin bedding. Visible horizons of fine white silt layers. Apparent higher organic carbon content.
8	1.83	20.64	Medium dark gray very fine grained micaceous sandstone with thin to medium bedding. Prominent internal lamination. SAMPLE: CI-B, PLATE 1
9	2.5	23.14	Medium gray fine grained sandstone with medium bedding. SAMPLE: CI-C, PLATE 1
10	0.26	23.3	Medium gray silty mudstone with thin to thick lamination. Prominent internal cross-lamination.
11	1.15	24.45	Brown fine grained sandstone with massive bedding. No notable internal bedding.
12	0.01	24.46	Light gray mudstone. Single very thin bed.
13	0.21	24.66	Coal, single medium bed of varying quality.
14	2.62	27.28	Light gray shale with thick lamination. Layer rich in fossilized woody debris.
15	0.73	28.01	Light gray siltstone with thick lamination coarsening upward.
16	1.19	29.2	Light gray very fine grained sandstone with massive bedding. Prominent internal cross lamination as well as fossilized horizontal burrows. SAMPLE: CI-D, PLATE 2
17	0.27	29.47	Dark gray claystone with thick lamination. Large amounts of preserved organic matter that is partially coalified. Appearance similar to an underclay.
18	0.09	29.56	Coal, single thin bed of varying quality.

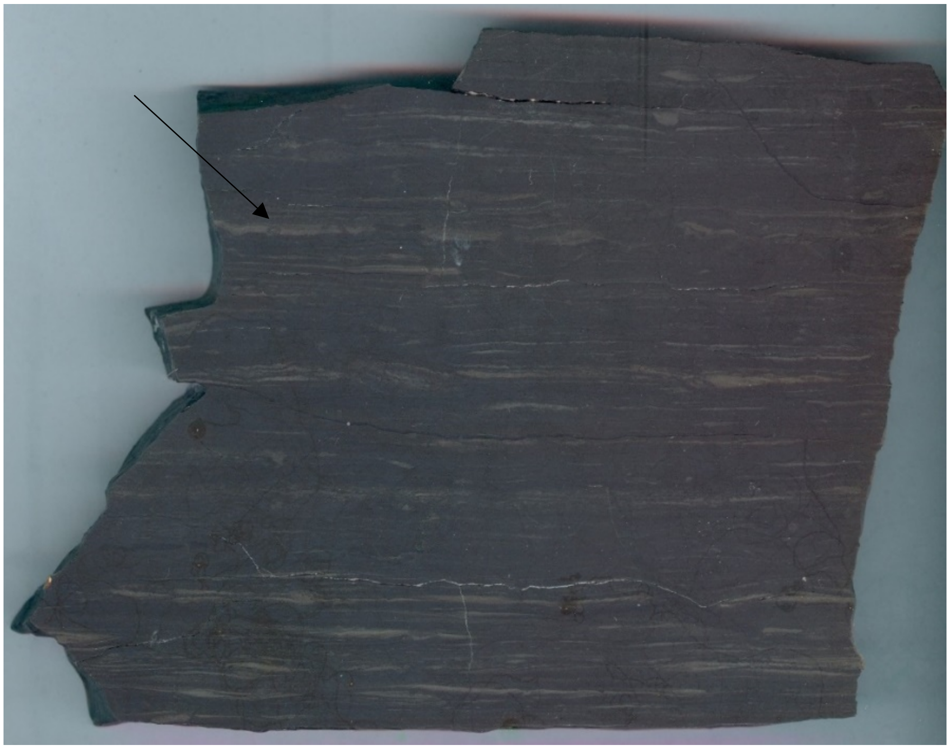
19	0.61	30.17	Black organic-rich shale. Separated layers have oily sheen and visible oxidization. PLATE 2
20	1.97	32.14	Light gray mudstone with thin lamination to thin bedding. Notable splintery weathering and upward layer thickening.
21	1.41	33.55	Light gray coarse siltstone interbedded with very fine grained sandstone with thin to thick lamination.
22	0.93	34.48	Light gray fine grain sandstone. Single layer of medium bedding size. Notable splintery weathering. Internal lamination with preserved mudstone layers. SAMPLE: CI-E, PLATE 3
23	0.51	34.99	Light gray fine grained sandstone with very thin bedding,
24	0.86	35.85	Light gray very fine grained sandstone with thin bedding,
25	1.72	37.57	Light gray siltstone with very thin to thin bedding. Notable splintery weathering and lateral increase in bedding thickness. PLATE 3
26	1.78	39.35	Light gray very fine grained sandstone with thin bedding. Notable internal lamination. PLATE 3
27	0.46	39.81	Light gray very fine grained sandstone with medium to thick bedding varying laterally. Notable internal lamination. PLATE 3
28	0.34	40.15	Beige very fine grained cross-bedded sandstone with medium bedding. Notable internal cross lamination. PLATE 3
29	0.44	40.59	Light gray to beige very fine grained convolutely cross bedded sandstone with medium to thick bedding that varies laterally. PLATE 3
30	1.08	41.67	Light gray shale, with thin lamination. PLATE 3
31	0.62	42.29	Light gray siltstone with thin bedding.
32	2.31	44.6	Light gray very fine grained sandstone with a single massive size bed. Partial internal cross lamination with preserved mud drapes. SAMPLE: CI-F, PLATE 4
33	2.1	46.7	Medium gray shale with thin lamination. Notable siderite beds <1 cm in thickness observed.
34	0.74	47.44	Medium gray siltstone with thick lamination laterally thickening to thin bedding. Notable splintery weathering.
35	0.47	47.91	Dark gray very fine grained sandstone with thick lamination to thin bedding. Notable tool marks on bed bottom as well as preserved dune-size ripples. SAMPLE: CI-G, PLATE 4
36	0.08	47.99	Coal layer of poor quality, single bed. PLATE 5
37	2.65	50.64	Light gray shale with thin lamination. Notable siderite beds <1 cm in thickness observed. PLATE 5
38	0.04	50.68	Dark gray claystone with thick lamination and notable splintery weathering. Large amounts of preserved organic matter that is partially coalified. Likely an underclay. PLATE 5
39	0.18	50.86	Coal layer of poor quality, single bed. PLATE 5

40	0.13	50.99	Black organic-rich shale. Separated layers have oily sheen and visible oxidization. PLATE 5
41	0.1	51.09	Medium gray claystone with thick lamination.
42	1.56	52.65	Light gray shale with thick lamination. Notable siderite beds <1 cm in thickness observed.
43	0.21	52.86	Light gray siltstone with thick lamination to very thin bedding.
44	0.69	53.55	Light gray claystone with thick lamination. Partial splintery weathering.
45	2.39	55.94	Light gray to beige interbedded claystone and shale with thin to thick lamination. Notable siderite layers <1cm thick and siderite nodules present through unit as well as notable internal lamination.
46	4.3	60.24	Beige, fine to medium grained sandstone with thin to thick bedding. Notable internal cross lamination and lamination. SAMPLE: CI-H, PLATE 6
47	1.8	62.04	UNEXPOSED
48	3.63	65.67	Light gray interbedded mudstone and siltstone with thin lamination to thin bedding. Notable siderite layers <1 cm present at various points throughout unit. PLATE 6
49	0.1	65.77	Medium gray mudstone with thin bedding.
50	4.04	69.81	Light gray interbedded mudstone and siltstone with thin lamination to thin bedding. Notable siderite layers <1 cm present at various points throughout unit.
51	0.2	70.01	Beige fine grained sandstone. Single layer of medium bed thickness.
52	11.21	81.02	Light gray interbedded mudstone and siltstone with thin lamination to thin bedding. Notable siderite layers <1 cm present at various points throughout unit. PLATE 6

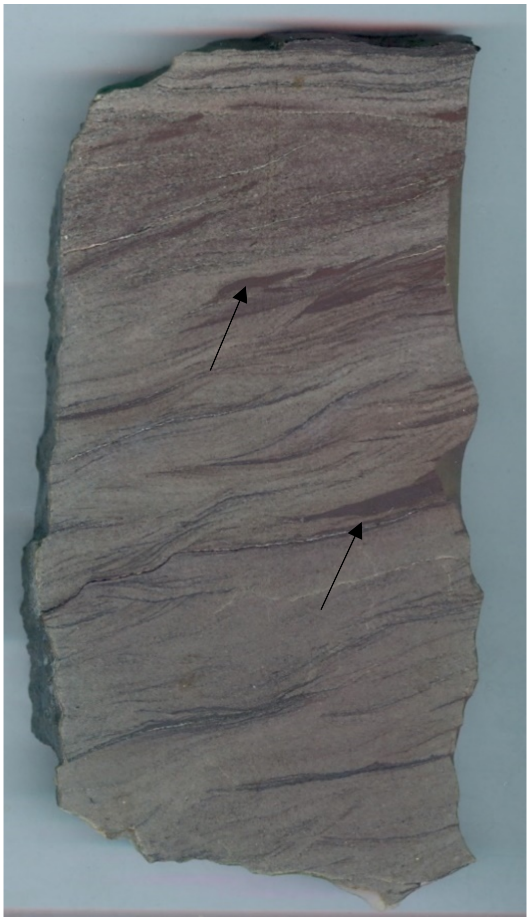
PHOTOGRAPH PLATES

PLATE 1

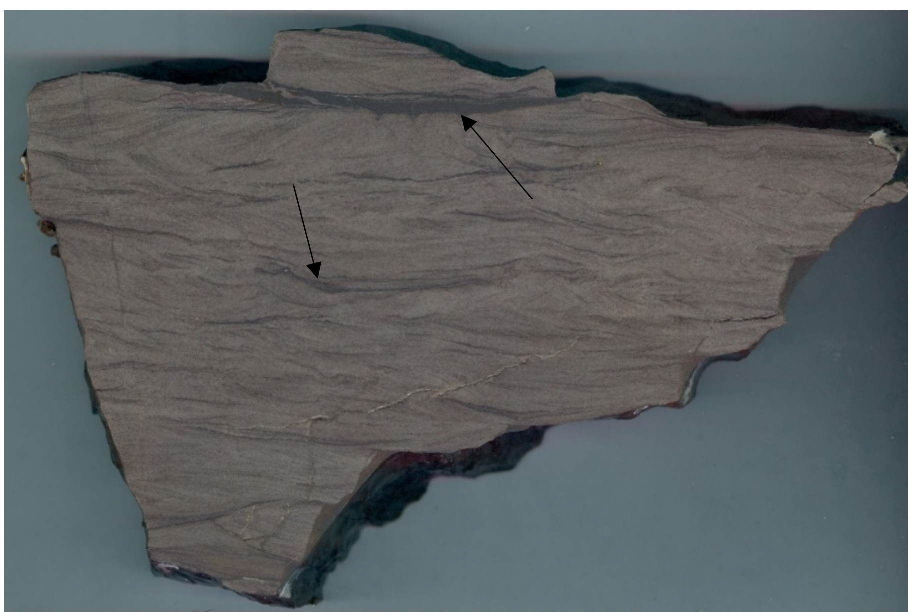
Coarsening-upward Sequence 1



CI-A: Dark gray siltstone sample collected at 13.21 m within Coarsening-upward Sequence 1 (lithologic unit 4). Note thick clay laminations.



CI-B: Medium gray sandstone collected from 18.94 m within Coarsening-upward Sequence 1 (lithologic unit 8). Note thick to thin internal cross lamination and prominent mud drapes up to 3 mm thick.

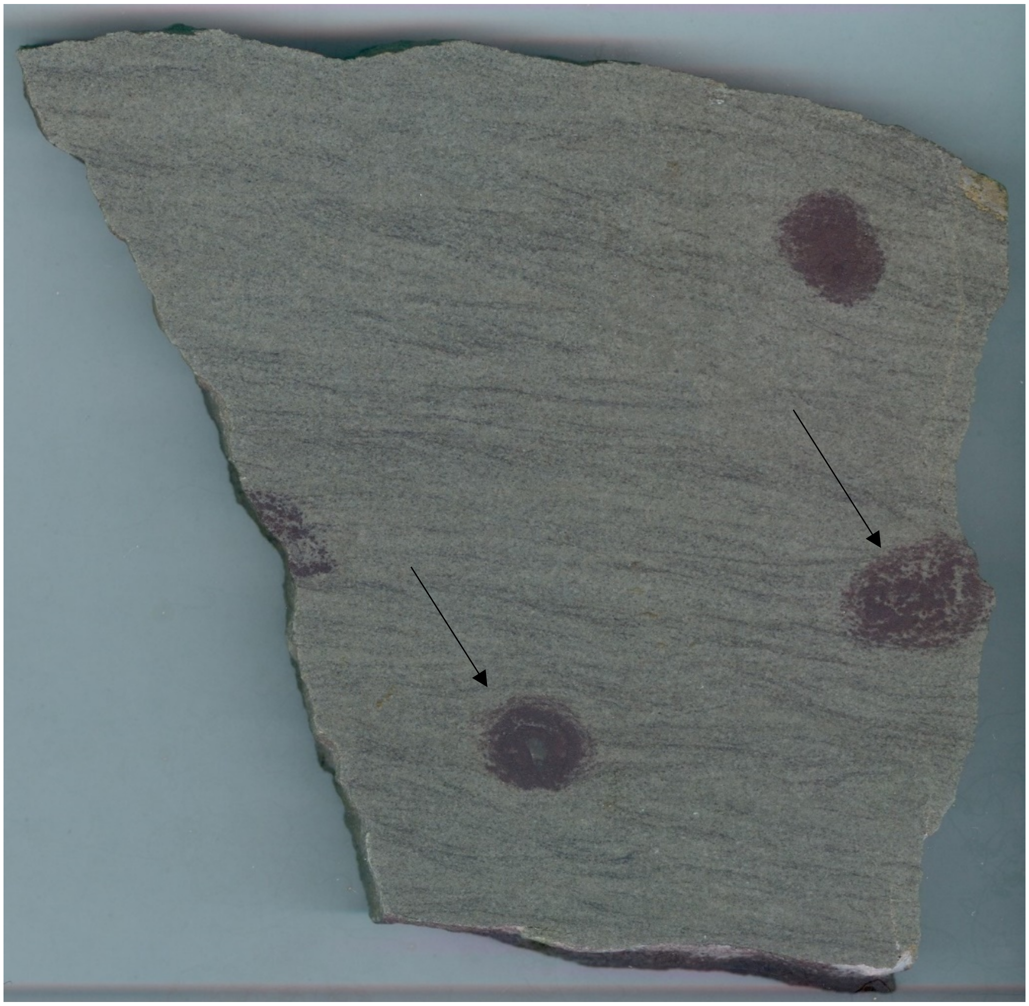


CI-C: Light gray sandstone collected at 21.64 m within Upward-coarsening Sequence 1 (lithologic unit 9). Exhibits interior cross lamination with mud drapes up to 1 mm thick.

FI-A: Siderite nodules observed at 7.92 m in lithologic unit 2 within Upward-coarsening Sequence 1.

PLATE 2

Coarsening-upward Sequence 2



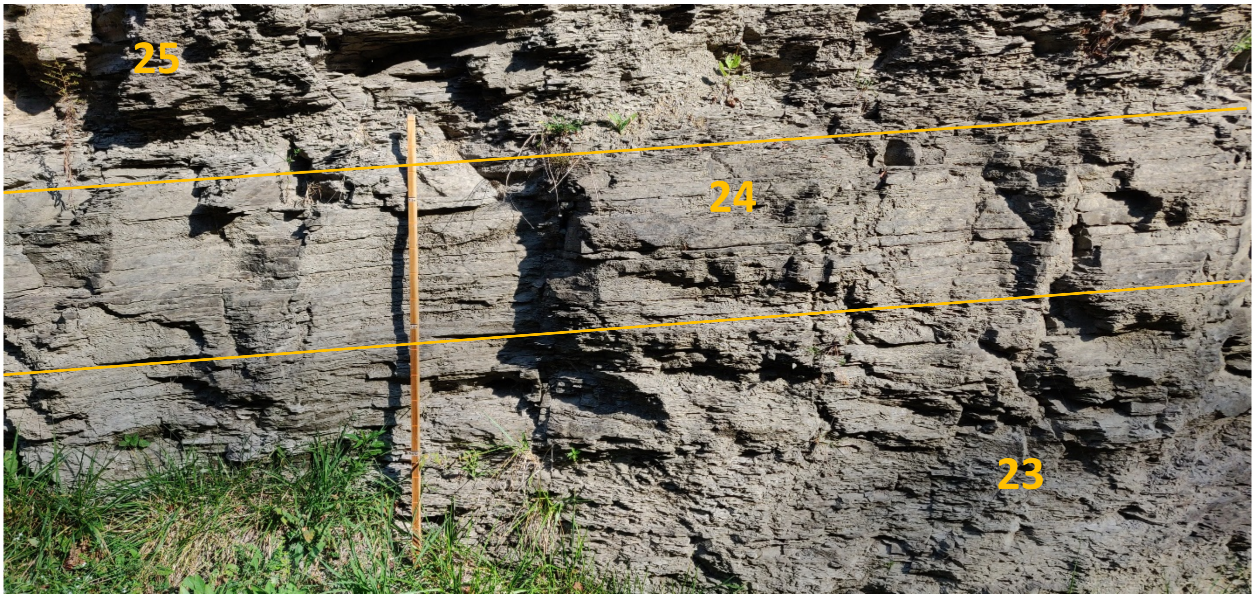
CI-D: Light-gray sandstone collected from 29.19 m within Upward-coarsening Sequence 2 (lithologic unit 16). Exhibits internal lamination with thin mud drapes and discrete horizontal burrows ranging in size from 0.6 cm to 1.3 cm in diameter.

FI-B: Organic rich shale layer at 30.17 m within Upward-coarsening Sequence 2 (lithologic unit 19).

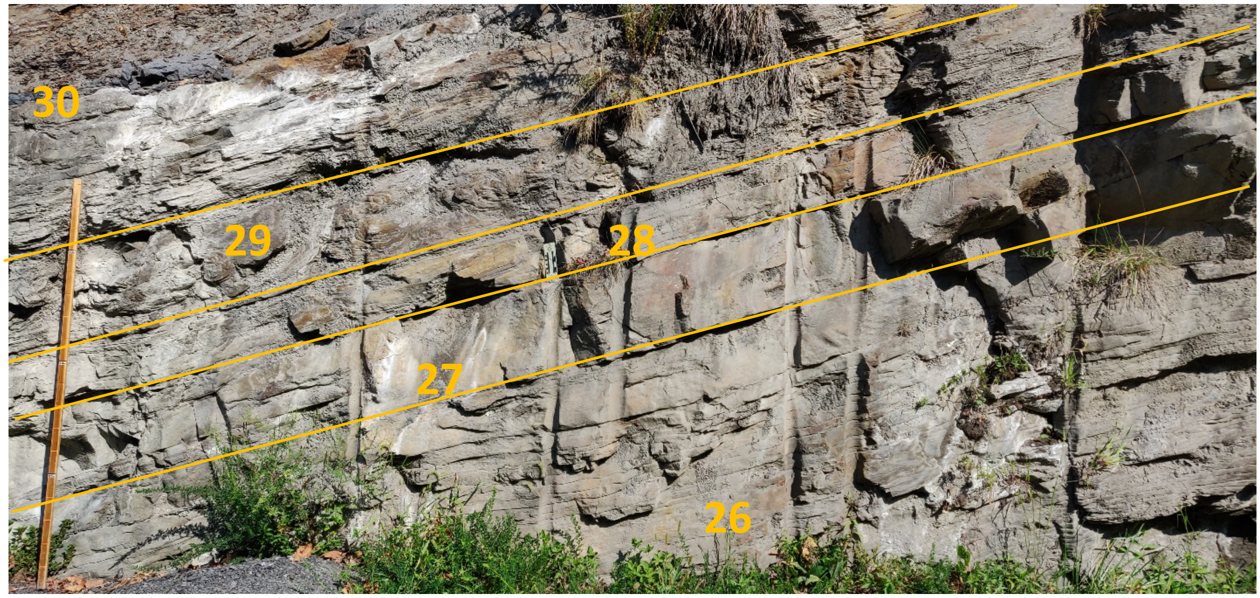
PLATE 3

Coarsening-upward Sequence 3

CI-E: Light gray sandstone collected from 34.44 m within Coarsening-upward Sequence 3 (lithologic unit 20). Shows internal cross-lamination with mud laminae occurring in ripple troughs.



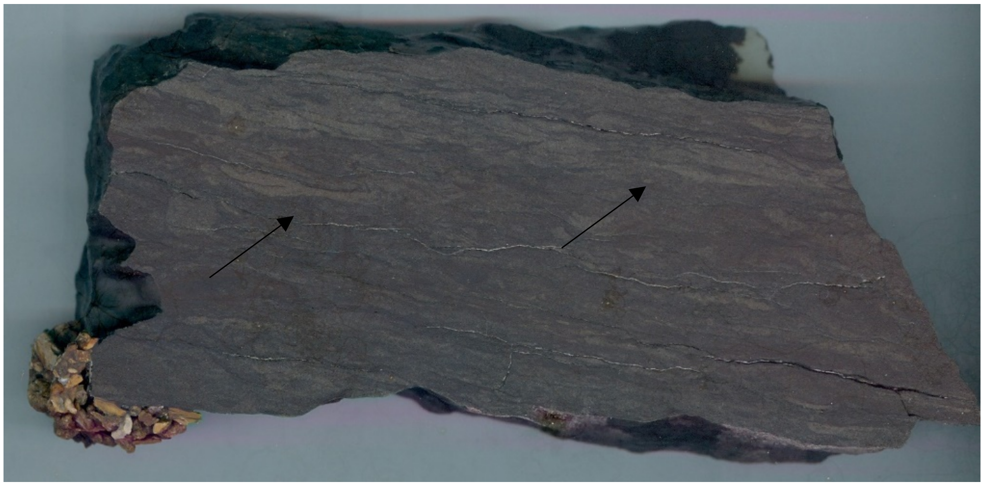
FI-C: Lithologic units 23, 24, and 25 within Coarsening-upward Sequence 3. Jacobs staff has divisions that are 10-cm thick.



FI-D: Outcrop photograph of lithologic units 26, 27, 28, 29, and 30 within Coarsening-upward Sequence 3 comprised of bedded sandstone. Jacobs staff has divisions that are 10-cm thick.

PLATE 4

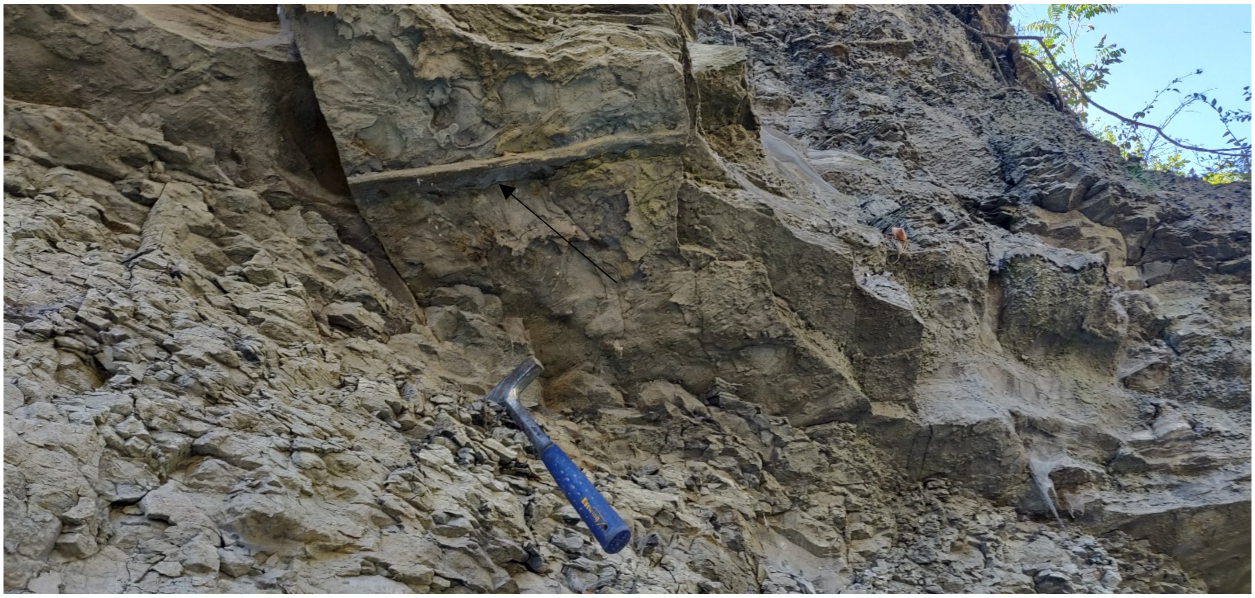
Coarsening-upward Sequence 2



CI-F: Dark gray siltstone intermixed with very fine-grained sandstone collected at 43.66 m within Coarsening-upward Sequence 4 (lithologic unit 32). Note remnants of disturbed (bioturbated?) internal bedding.

CI-G: Light gray sandstone collected from 47.91 m within Coarsening-upward Sequence 4 (lithologic unit 35).

FI-E: Probable tool marks on bed undersurface of lithologic unit 35 within Coarsening-upward Sequence 4. See FI-F for close-up of tool marks on underside of lower-right bed..

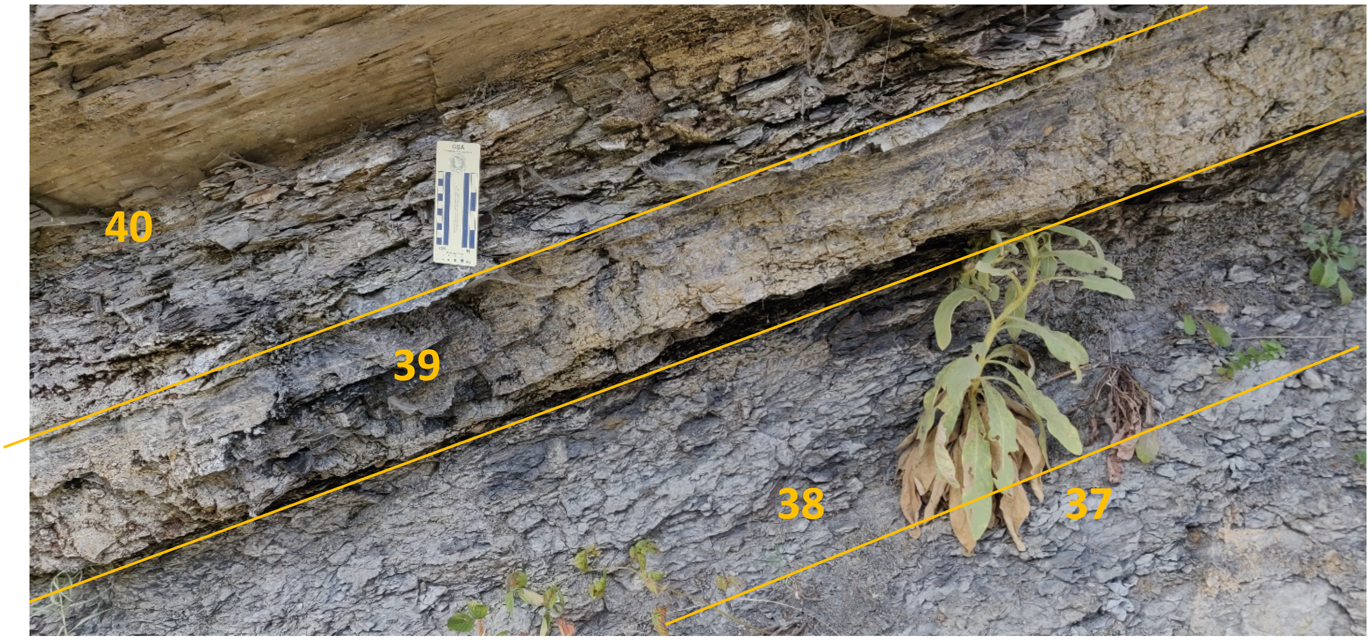


FI-F: Probable tool marks on underside of lithologic unit 35 within Coarsening-upward Sequence 4.

FI-G: Dune-sized ripples of lithologic unit 35 within Coarsening-upward Sequence 4.

PLATE 5

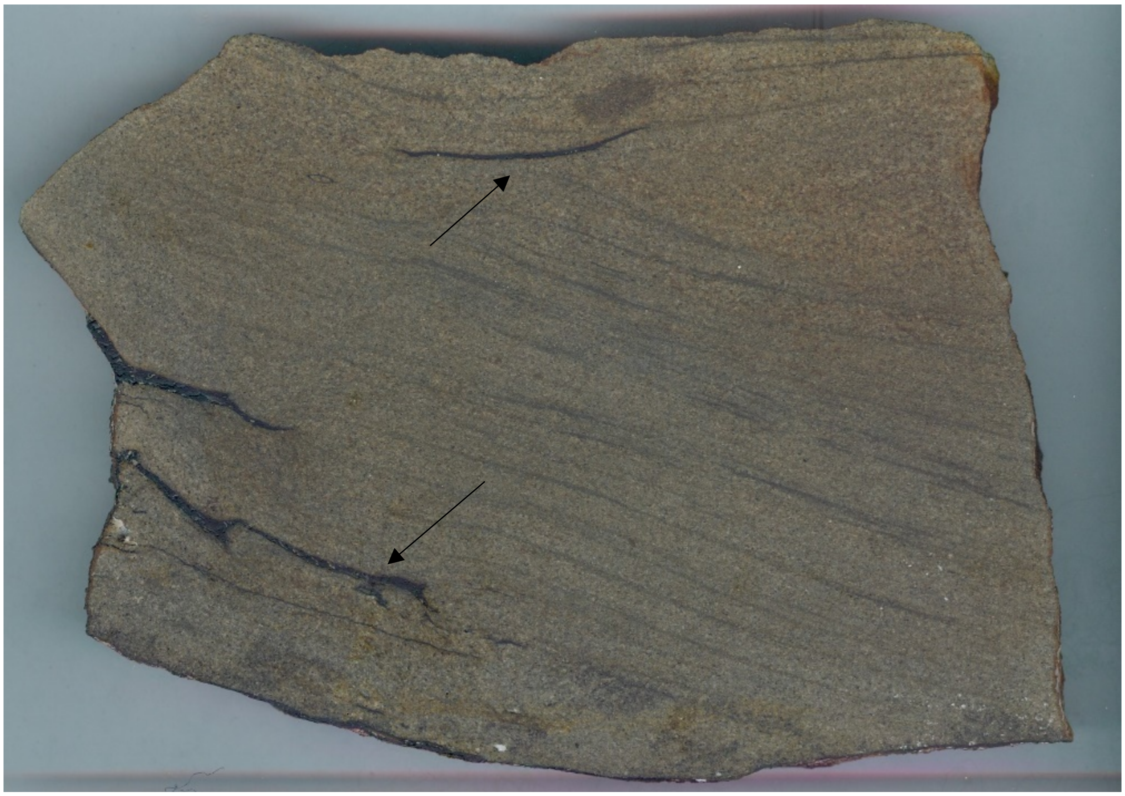
Coarsening-upward Sequence 5



FI-H: Lithologic units 37, 38, 39, and 40 within Coarsening-upward Sequence 5. Unit 37 is shale with siderite beds. Unit 38 is a claystone with large amounts of organic matter that is partially coalified; likely an underclay. Unit 39 is a poor-quality coal layer. Unit 40 is an organic-rich shale.

PLATE 6

Uppermost Measured Section



CI-H: Beige sandstone collected at 60.24 m of the Coldiron stratigraphic section (lithologic unit 46). Note strong internal cross lamination and coalified organic matter (arrows).

FI-I: Lenticular coal within lithologic unit 46, Coldiron stratigraphic section.

FI-J: Siderite layers in lithologic unit 48, Coldiron stratigraphic section.

FI-K: Lithologic unit 52 with single sandstone stringer (arrow)at ~ 70 m near top of Jacob's staff that has divisions that are 10-cm thick.

End