A sequence stratigraphic synthesis of the Lower Pennsylvanian Pottsville Formation encountered in two drill cores in the Cahaba synclinorium, Alabama

by

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Abstract

The Lower Pennsylvanian Pottsville Formation is a classic clastic wedge of the Appalachian mountain system composed of interbedded sandstone, siltstone, claystone, shale, and coal beds with orthoquartzitic conglomerate at the base. The formation developed in response to thrust and sediment loading on the convergent margin of the Laurussian craton during the Alleghanian orogeny. The greatest preserved thickness of Pennsylvanian strata, more than 2500 m (8000 ft), accumulated in the Cahaba and Coosa coalfields of the greater Black Warrior Basin. The Carboniferous coalfield, which hosts the Pottsville Formation in the greater Black Warrior Basin, occurs in large synclinoria separated by anticlinoria where Cambrian-Ordovician rocks are exposed at the surface.

Eight lithofacies have been identified within two studied drill cores from the Cahaba basin on the basis of dominant rock types, color, grain size, and sedimentary structures. A transition from a tidal through delta-estuarine to fluvial environments has been identified with the aid of facies analysis. Conformable contacts indicate a gradual change in the depositional environments from delta front to the delta plain. Laterally extensive coal beds have been used to demarcate sequence packages in the terrestrial part, whereas a few localized flooding surfaces have been identified in the marine-dominated strata. Repetitive fining upward sequences show a wide array of prograding deltaic and alluvial facies in the highstand system tracts. Conglomerate layers associated with fluvial scour surfaces reflect the influence of eustacy on sedimentation.

Thin-section petrography shows incongruence between mudstone and conglomerate measures. Two distinct petrofacies assemblages have been identified within the sampled intervals of cores, and these may be indicative of changes in base level, depositional environment, climate, and possibly source terrain. The lower marine intervals of the studied core may have been sourced from the distal northern Appalachian Mountains via the Pennsylvanian mega-drainage system. The proximal southern Appalachian Mountains may have contributed for the deposition of the upper terrestrial section.

A combination of depositional and genetic sequence stratigraphic models has been applied to the Pottsville Formation in the study area. The depositional sequence model is better suited in the terrestrial-dominated upper part of the core due to abundance of major fluvial erosional discontinuities. The genetic sequence model is applicable to the marine-dominated lower part, which is characterized by the presence of marine flooding surfaces and associated condensed sections.

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CHAPTER 1: INTRODUCTION

1.0 INTRODUCTION

Sequence stratigraphy is important for understanding the genesis of basin fill (Posamentier et al., 1988; Posamentier and Vail, 1988; Van Wagoner et al., 1990; Hunt and Tucker, 1992). Stratigraphic surfaces are identified based on a chronostratigraphic framework. Identification of genetically related strata focuses on the correlation of basinwide coeval stratal units bounded by quasi-isochronous surfaces (Frazier, 1974; Mitchum, 1977; Galloway, 1989). Facies analysis leading to the interpretation of paleoenvironments is critical for sequence stratigraphy.

The nature of contacts between stratigraphic units, e.g., conformable vs. unconformable, and changes in facies across these contacts are the most important criteria used to identify the various type of sequence stratigraphic surfaces. These stratigraphic surfaces provide the framework for correlation necessary to construct sequence stratigraphic models.

The Pottsville Formation in the Cahaba synclinorium is a part of a thick clastic wedge that accumulated during the Lower Pennsylvanian in response to collisional tectonics (Pashin et al., 1995). Previous studies have established a general stratigraphic framework for the Pottsville Formation in the Cahaba synclinorium mostly based on surface exposures and subsurface core data (Pashin et al., 1995; Pashin and Carroll, 1999; Pashin and Raymond, 2004; Pashin, 2004; Greb et al., 2008). In spite of extensive studies on general stratigraphy, coal-bearing strata, and cyclic sedimentation of the Cahaba synclinorium, a complete sequence stratigraphic model has yet to be constructed for the Pottsville Formation.

Petrography reveals substantial information on the geochronology (Peavy, 2008; Uddin et al., 2010a,b; Moore et al., 2011a,b, 2012) and provenance of the Pottsville Formation (Schlee, 1963; Graham et al., 1976; Mack et al., 1983; Demirpolat, 1989; Liu and Gastlado, 1992; Peavy, 2008) as well as the tectonic and climatic controls (Pashin et al., 1995; Pashin and Carroll, 1999, Pashin, 2004) on sedimentation. Moreover, petrographic data also can be implemented to interpret mechanisms that create continental sequence-stratigraphic architecture (Lawton et al., 2003). A petrographic study by Lawton and others (2003) from southern Utah indicates that Upper Cretaceous alluvial successions in the southernmost part of the Cordilleran foreland basin were deposited by fluvial systems of contrasting drainage directions and provenance, and suggests different mechanisms governed their sequence architecture. This case study motivated the current research to identify petrographic changes between major marine and non-marine successions.

The main objective of the research is to establish a sequence stratigraphic framework for the studied section of the Pottsville Formation in the Cahaba synclinorium, Alabama, primarily based on facies analysis. An additional objective is to test the relationship, if any, between marine and non-marine depositional environments and sandstone petrofacies.

1.1 POTTSVILLE FORMATION

1.1.1 GENERAL STRATIGRAPHY

The Pottsville Formation is composed of shale, mudstone, siltstone, sandstone, extra- and intraformational conglomerate, and coal. This Formation developed in response to thrust and sediment loading on the convergent margin of the Laurentian craton during Appalachian-Ouachita orogenies (Thomas, 1976, 1995). Discrete depocenters developed along the Appalachian trend (Figure 1.1) cratonward of promontories on the continental margin in the Middle to Late Mississippian (Thomas, 1976, 1995; Quinlan and Beaumont, 1984). The base of the Pottsville Formation has been placed at Namurian C -Langsettian whereas the top is placed on Langsettian-Duckmantian boundary (Pashin, 2004). An ash layer in the younger strata in greater Black Warrior basin in Mississippi has been dated as 308.6±2.7 Ma (Uddin et al., 2010). The greatest preserved thickness of Pennsylvanian strata, more than 2500 m (8000 ft), accumulated in the Cahaba and Coosa coalfields of the greater Black Warrior Basin (Figure 1.2). These Carboniferous coalfields in the greater Black Warrior Basin now occur in large synclinoria separated by faults and anticlinoria (Figure 1.2) where Cambrian-Ordovician rocks are exposed at the surface (Figure 1.3). The Cahaba and Coosa coalfields are parts of the Appalachian thrust belt, in which thin-skinned folds and thrust faults are detached in Cambrian shale and come to the surface along frontal ramps.

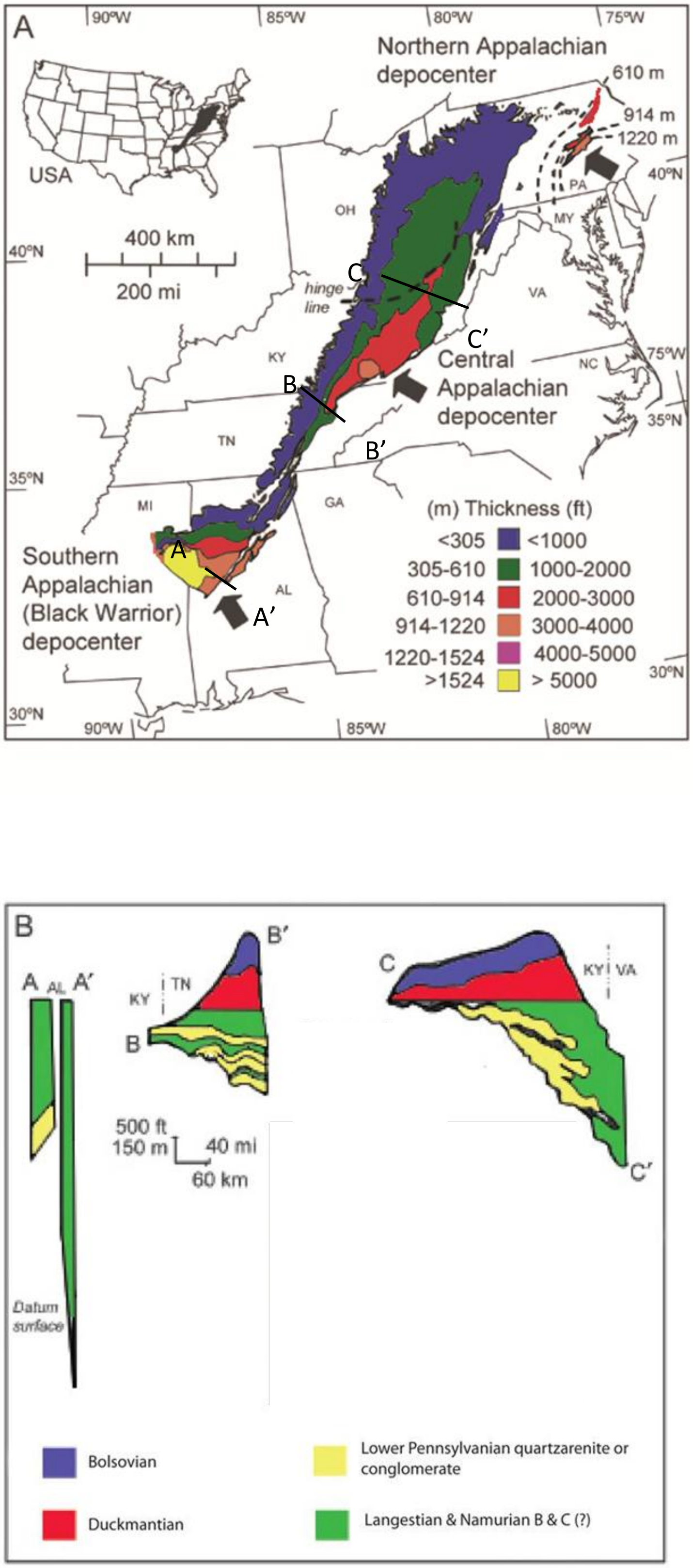


Figure 1.1 (A) Isopach map of Pennsylvanian strata in the greater Appalachian Basin (modified from Greb et al., 2008). (B) Generalized cross sections across the basin with subperiods of Pennsylvanian (A–A' modified from Wanless, 1975; B–B' and C–C' modified from Chesnut, 1991).

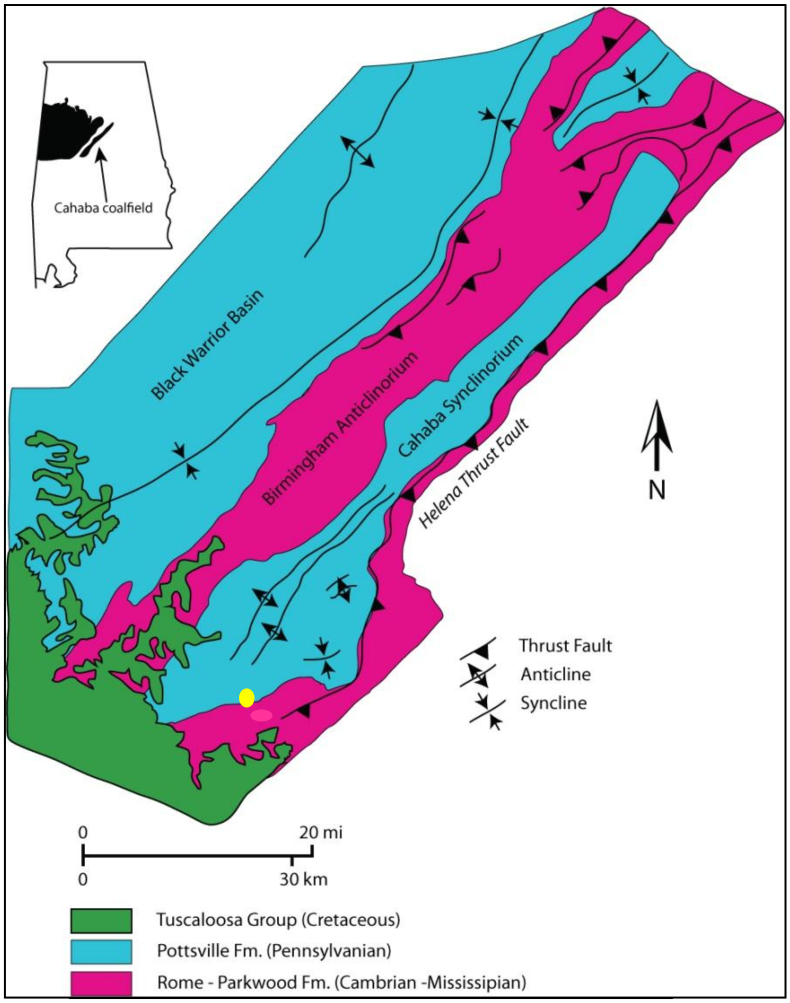


Figure 1.2: Geological map of foreland basins of the Southern Appalachian thrust belt (after Pashin et al., 2010). Yellow dot represents the position of the two studied cores (SWEPI 1 and SWEPI 2).

The Cahaba synclinorium, also referred to as the Cahaba coal field, is a synclinorium located in north-central Alabama (Figures 1.2, 1.3). The Cahaba synclinorium is bordered to the northwest by the Birmingham anticlinorium. It is separated from the Coosa synclinorium (also referred to as Coosa coal field; Figure 1.2) to the southeast by the regionally extensive Helena fault.

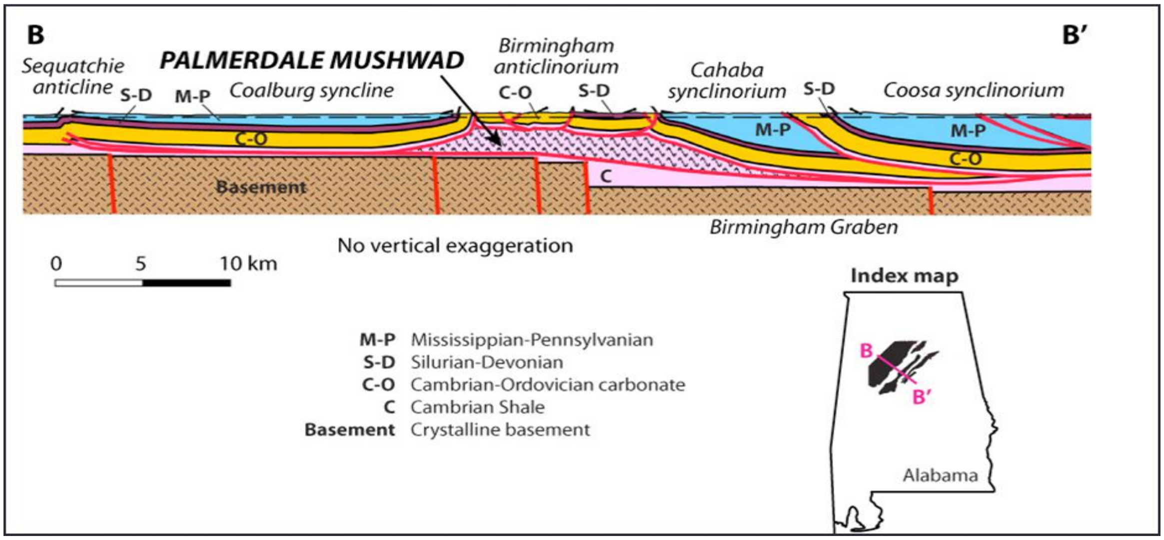


Figure 1.3: Restored structural cross section of Cahaba Basin and adjacent structures (modified from Thomas and Bayona, 2005; Pashin et al., 2010).

The Cahaba synclinorium is filled mostly with sedimentary rocks of the Lower Pennsylvanian Pottsville Formation. The formation contains 20 informal coal zones and overlies the Upper Mississippian-Lower Pennsylvanian Parkwood Formation throughout the basin (Pashin, 1997). The Pottsville Formation is the youngest unit in the Cahaba synclinorium. The formation is unconformably overlain by the Upper Cretaceous Coker Formation near the southwest end of the structure (Pashin and Carroll, 1999). The southeast part of the synclinorium has a thicker succession of sediment that reflects a greater rate of subsidence during deposition (Pashin and Carroll, 1999; Pashin, 2004).

The Pottsville Formation of the Cahaba coal field has been subdivided into three magnafacies (Pashin et al., 1995) (Figure 1.4). From bottom to top, they are (1) *quartzarenite,* (2) *mudstone*, and (3) *conglomerate* measures*.* Trough cross-bedded, light gray to white quartzarenite, along with minor bioturbated mud, dominate the *quartzarenite measures*. The *mudstone measures* contain marine mudstone, as well as numerous gray litharenite bodies and coal beds. The *conglomerate measures* are composed of litharenite, mudstone, coal and thick extraformational conglomerate units. This study focuses on the mudstone and conglomerate measures.

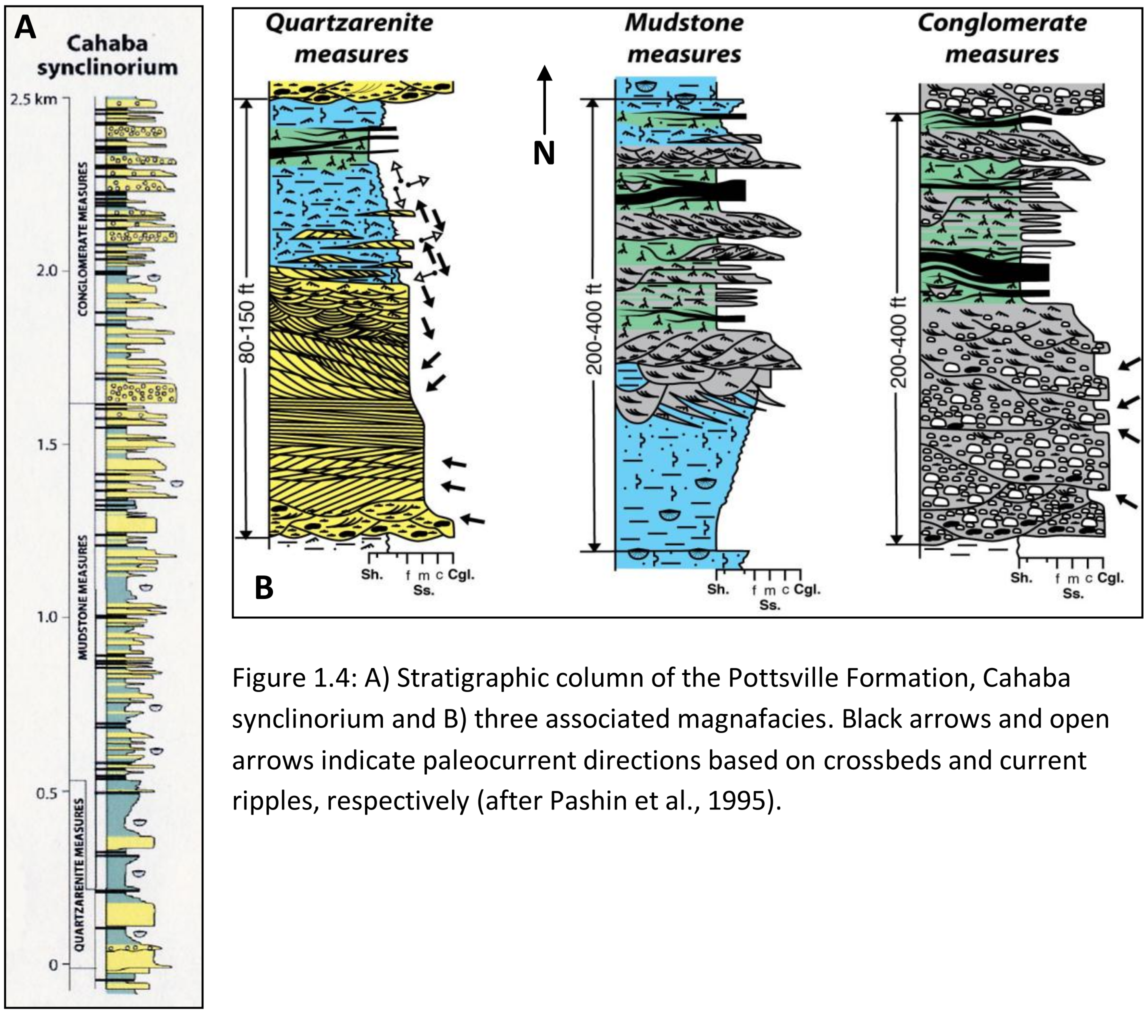


Figure 1.4: A) Stratigraphic column of the Pottsville Formation, Cahaba synclinorium and B) three associated magnafacies. Black arrows and open arrows indicate paleocurrent directions based on crossbeds and current ripples, respectively (after Pashin et al., 1995).

1.1.2 PENNSYLVANIAN DEPOSITIONAL CYCLES

Depositional cycles have been recognized in the Pennsylvanian strata of the Appalachian basin since the 1930s (Weller, 1930; Wanless and Weller, 1932). Weller (1930) attributed cyclicity to tectonics, whereas Wanless and Shephard (1936) attributed these cycles to global sea-level changes caused by fluctuations in the volume of Gondwanan ice sheets. Recent debate has focused on the tectonic and paleoclimatic implications of this cyclicity, which is thought to be a product of both basin subsidence associated with assembly of the Pangaea supercontinent and eustasy driven by Gondwanan glaciations (Ross and Ross, 1988; Heckel et al., 1998; Klein, 1990). Through the 1960s and 1970s, an increasing awareness of inherent behavior of alluvial and deltaic deposystems led many workers to reinterpret cyclothems previously distinguished in the Appalachian basin as autocyclic in origin (e.g., Ferm, 1970; Donaldson, 1979). Attempts to correlate mid-continent cycles with those in the Appalachian basin were inhibited by lack of a detailed biostratigraphic framework for the Appalachian basin, and by the prevailing view that eustasy would be masked or overshadowed by tectonic and/or autocyclic processes that were not prevalent in other cratonic basins.

Paleogeographic reconstructions indicate that the Black Warrior basin drifted through the southern tradewind belt into the equatorial rainy belt during Carboniferous (Figure 1.5) (Scotese and Golonka, 1992). A transition from red paleosols containing thick carbonate successions to a siliciclastic-dominated succession containing coal and underclay mark this migration (Pashin, 1994). This transition in lithology shows a change from a semi-humid or semi-arid climate to the everwet equatorial climate that prevailed in eastern North America during the Early Pennsylvanian (Cecil, 1990). Pashin (1994, 1998) defined 13 regionally extensive depositional cycles bounded by flooding-surface (FS) between the base of the Pottsville and the top of the Brookwood coal zone in the Black Warrior basin.

Figure 1.5: Paleogeography of the Cahaba and adjacent basins during Early Pennsylvanian (modified from Lacefield, 2000).

Marine-terrestrial depositional cyclicity is a characteristic feature throughout the Pottsville Formation. Sequence stratigraphy and facies analysis are particularly relevant to the study of processes responsible for cyclic sedimentation (i.e., cyclothems). These cycles appear to be the products of glacial-eustatic forcing associated with Milankovitch orbital eccentricity (Pashin and Raymond, 2004). Pashin (2004) delineated cyclothems and smaller scale packages in the Black Warrior basin. These idealized cyclothems (Figure 1.6) in the Black Warrior basin represent variable time spans

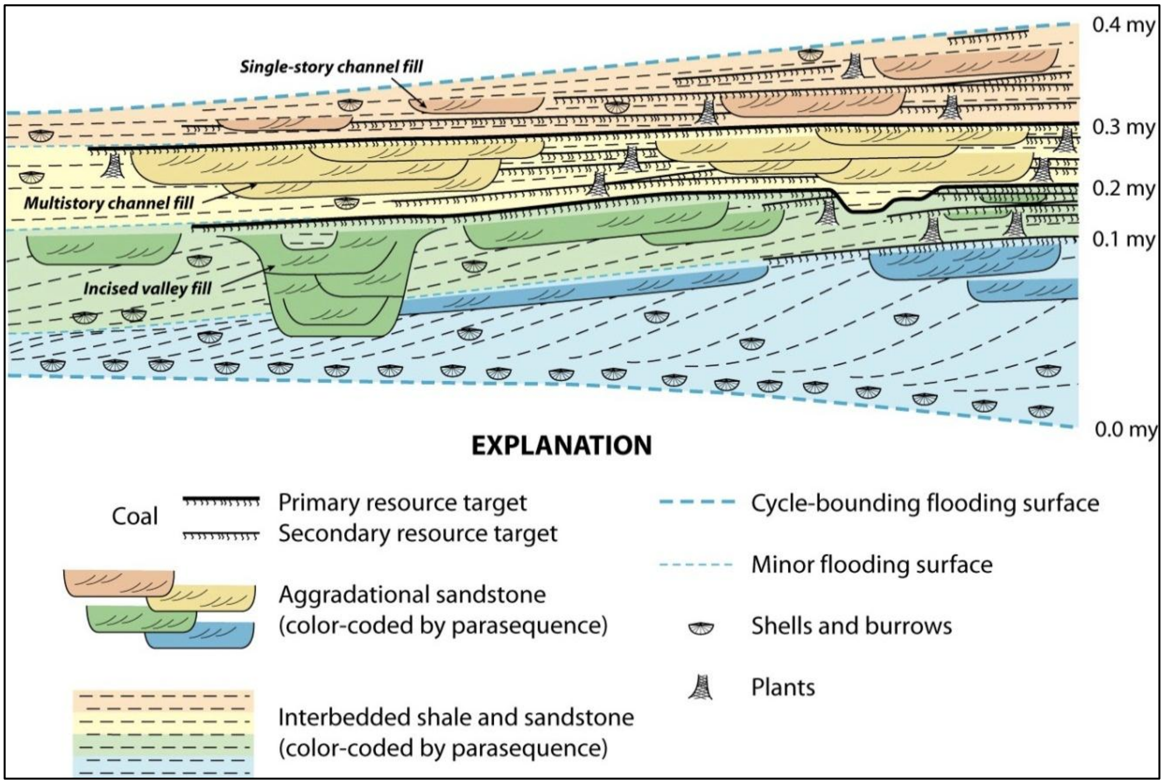


Figure 1.6: Idealized stratigraphic model showing facies relationships and flooding surfaces in upper Pottsville cyclothems of the Black Warrior coal-bed methane fields (after Pashin and Raymond, 2004).

ranging up to ~0.4 my using the timescale of Harland et al. (1989), which is equivalent to the period of the long orbital eccentricity cycle (Pashin and Raymond, 2004). Application of accurate timescales would suggest that the Pottsville represents less than 2 million years, and thus cycle periods may have been much lower (Pashin, 2004).

Pottsville cyclothems contain three subordinate marine flooding surfaces that define 5th - order parasequences (Pashin and Raymond, 2004). These may be products of relative sea-level changes associated with short orbital eccentricity cycle period (0.1 my, according to Harland et al., 1989)) (Figure 1.6). The lowermost parasequence in each cyclothem tends to be dominated by progradational deltaic deposits. The second and third parasequences contain a higher proportion of aggradational deposits and include incised valley fills as thick as 33 m overlain by widespread reservoir coal beds as thick as 3 m. The uppermost parasequences commonly contain transgressive tidal deposits.

CHAPTER 2: METHODS

2.0 INTRODUCTION

Sequence stratigraphy is a revolutionary paradigm in the field of sedimentary geology. The concepts embodied by this discipline have resulted in a fundamental change in the way geologists approach facies and stratigraphic analysis. In this study, sequence stratigraphic analysis started by describing core leading to lithofacies analysis. After lithofacies identification, depositional environments were recognized, bounding discontinuities were identified, and genetic sequences were delineated. In the end, a sequence stratigraphic model for the study area was formulated.

2.1 CORE DESCRIPTION

Two cores named SWEPI (Shell Western Exploration and Production Inc.) 1 (T24N-R9E Sec.29) and 2 (T24N-R9E Sec.30) (Figure 1.2) were provided for study in the core repository of the Geological Survey of Alabama in Tuscaloosa, Alabama. Both cores were drilled near the southeastern corner of the Cahaba synclinorium in Shelby County, Alabama. Core SWEPI 1 contains a continuous 1030-ft section (140 to 1170 ft subsurface), whereas core SWEPI 2 is a ~4009-ft section (500 to 4509 ft subsurface). Initially, dominant rock types, sedimentary structures and textures were documented to produce a graphic log of each core. Due to a large number of missing intervals in core SWEPI 1, only SWEPI 2 was used to produce complete graphic log (Figure 2.1). Later, more detailed observations (grain-size variations, fossil content) were added to facilitate facies analysis.

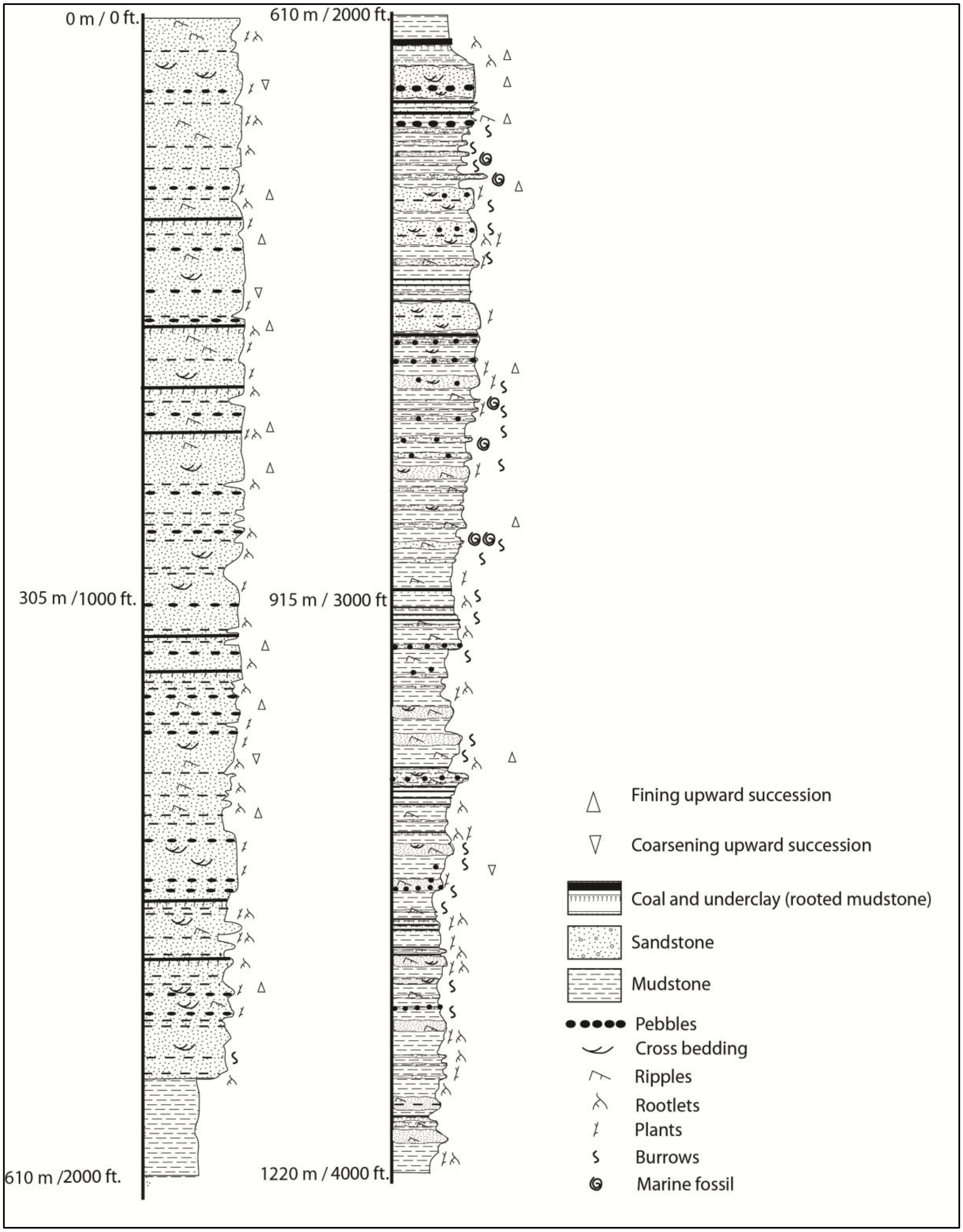


Figure 2.1: Graphic log of the Pottsville Formation in SWEPI 2 core in the Cahaba synclinorium.

2.2 FACIES ANALYSIS

Facies analysis is a fundamental sedimentological method of characterizing bodies of rocks with unique lithological, physical, and biological attributes relative to all adjacent deposits (Walker, 1984; Catuneanu, 2003). Lithofacies in the two cores were identified on the basis of dominant rock types, colors, bedding styles, sedimentary structures, and fossil content. Eight lithofacies were identified from the two cores using these criteria.

2.3 DEPOSITIONAL ENVIRONMENT ANALYSIS

Each of the eight lithofacies records either one or several environments of deposition. Paleoenvironments were interpreted based on the review of relevant publications (McCabe, 1977; Miall, 1978; Middleton, 1978; Walker, 1984; Reineck and Singh, 1986; Shanley and McCabe, 1991; Reading, 1996; Nichols, 1999) as well as case studies from the Appalachian basins and areas with similar geological settings (Gastaldo, 1994; Mars, 1995; Pashin, 1997; Pashin and Carroll, 1999; Gastaldo et al., 2006; Thomas, 2007, Greb et al., 2008).

2.4 SANDSTONE PETROGRAPHY

Sandstone petrography was used to identify provenance of source rocks as well as to test Lawton's (2003) approach to deciphering major changes in depositional environments. Twenty-six intervals were selected for sampling based on visible changes in textural and sedimentological character through the sections. Twenty-one samples were collected from the conglomerate measures, whereas five were collected from the underlying mudstone measures. Most samples are medium-grained sandstone collected from upper sandstone-dominated parts of core SWEPI 2. Thin sections were commercially prepared and were studied with a petrographic microscope (Olympus BH-2 BHTP). Grains were counted with the aid of the software Nikon Elements. At least 300 grains were counted for each slide by using the Gazzi-Dickinson method, which minimizes the control by grain size on sand composition (Dickinson and Suczek, 1979). Careful attention was paid to the classification of lithic fragments and feldspar types (Pettijohn et al., 1973; Uddin and Lundberg, 1998).

Compositional parameters (Table 1) distinguished during point counting include: Qt = total quartz; Qm = monocrystalline quartz grains; Qp = polycrystalline quartz grains, including chert grains; F = total feldspar grains; P = plagioclase feldspar grains; K = potassium feldspar grains; L = total lithic fragments; Lt = total unstable lithic fragments; Ls = sedimentary lithic fragments; Lv = volcanic lithic fragments; Lm = metamorphic lithic fragments.

All twenty-six samples were collected from various sandstone lithofacies. Petrofacies assemblages were studied to see if there are significant systematic changes that can be linked to major changes in depositional environments. Petrographic studies also were used to emphasize grading trends (fining- vs. coarsening-upward). Vertical profiles were studied to distinguish progradational and retrogradational trends in marine successions, and to outline fluvial depositional successions in non-marine deposits.

Table 1: Modal parameters of sand and sandstones determined in this study (Dickinson and Suczek, 1979; Dorsey, 1988).

Qt = Qm + Qp, where

Qt = total quartz grains

Qm = monocrystalline quartz (>0.625 mm)

Qp = polycrystalline quartz (or chalcedony)

Recalculated

Feldspar Grains (F = P + K)

F = total feldspar grains

P = plagioclase feldspar grains

K = potassium feldspar grains

Recalculated

Unstable Lithic Fragments (Lt = Ls + Lv + Lm)

L = total lithic fragments

Lt = total unstable lithic fragments (L + Qp)

Lv = volcanic/metavolcanic lithic fragments

Ls = sedimentary/metasedimentary lithic fragments

Lm= metamorphic lithic fragments

Recalculated

CHAPTER 3: LITHOFACIES DESCRIPTIONS

3.0 INTRODUCTION

Eight distinct lithofacies were identified in the two cores based on rock types, colors, bedding styles, sedimentary structures, and fossil content (Table 2). Some of these eight lithofacies were further subdivided into sub-lithofacies, which aid in identifying relevant depositional environments. In addition, an attempt has been made to distinguish key stratigraphic elements and surfaces/horizons based on lithofacies descriptions. These elements and surfaces/horizons have been described in detail in chapter 6. The eight lithofacies are as follows:

3.1 CONGLOMERATE LITHOFACIES

This lithofacies is composed of variegated pebbles within dark to light gray, massive, planar laminated or cross-bedded sand matrix (Figure 3.1). The dominant rock type of this lithofacies is clast- and matrix-supported litharenitic conglomerate with abundant extraformational and intraformational lithoclasts. The former include chert, granite, basalt, and volcanic clasts. The latter include siderite nodules, shale rip-up clasts, coal spur, and sandstone.

Extraformational conglomerates form the bases of major fining-upward successions. These successions have numerous smaller-scale fining-upward sequences that are composed of clast-supported conglomerate at the base and matrix-supported conglomerate at the upper part (Figure 3.2). Matrix-supported conglomerates (paraconglomerates) lack internal bedding but locally show clast imbrication. Individual paraconglomerate beds vary from 3 to 10 cm in thickness. In contrast, clast-supported conglomerates (orthoconglomerates) show horizontal stratification and clast imbrication. Some beds are lenticular and exhibit erosional bases. These beds are 3 to 6 cm in thickness and contain tabular cross-bedding. Matrix between clasts in both types of conglomerates is medium to coarse grained, light gray to medium dark gray sand.

Table 2: Summary of the identified lithofacies descriptions and architecture.

No.	Lithofacies	Sublithofacies	Major rock types	Sedimentary structures	Fossils	Biogenic activity	Underlain by	Overlain by
LF 1	Conglomerate	1.Orthoconglomerate 2.Paraconglomerate	Lithoclasts, Sandstone matrix	Massive, horizontal lamination in sandstone	No	No	LF 3	LF 2
LF 2	Sandstone	1. Trough and planar-tabular cross bedded 2.current-ripple cross-laminated 3.massive sandstone with lamination, 4.thinly interbedded with mudstones.	Sandstone	Massive, horizontal laminations, current ripple cross lamination	No	No	LF 1/LF 3/LF 5/LF7	LF1/LF 3 LF 5/ LF7
LF 3	Rooted mudstone and siltstone		Mudstone and gritty siltstone	Fissile, horizontally laminated mudstone Massive thin bed of sandstone	No	Rootcasts	LF 2	LF 2/LF 4
LF 4	Coal	1.Thin, extended 2. Thick, local	Coal	Massive to horizontally laminated	Plant	Rootcasts	LF 3/LF 7	LF 2
LF 5	Wavy bedded shale and sandstone		Shale and lithic arenite	Wavy, lenticular, and flaser bedding	Plant	Burrows	LF 2/LF 7	LF 2/LF 7
LF 6	Graded sandstone and shale		Sandstone and shale	Graded bedding, horizontal lamination, cross bedding	No	Rootcasts	LF 2	LF3/LF 4
LF 7	Burrowed mudstone		Mud, thin sandstone	Horizontal lamination	Marine	Burrows (very few).	LF 2	LF2/LF 3
LF 8	Shelly sandstone and shale		Shale and Sandstone	Massive to horizontal lamination in shale. Minor cross lamination in sandstone	Marine	Burrows	LF 2	LF 5

Figure 3.1: Clast-supported conglomerate from 784 ft (left) and 3819 ft (right). Clasts are dominated by siderite (brown), shale (gray), basalt (black), and sandstone (light gray). Coins are used for scale.

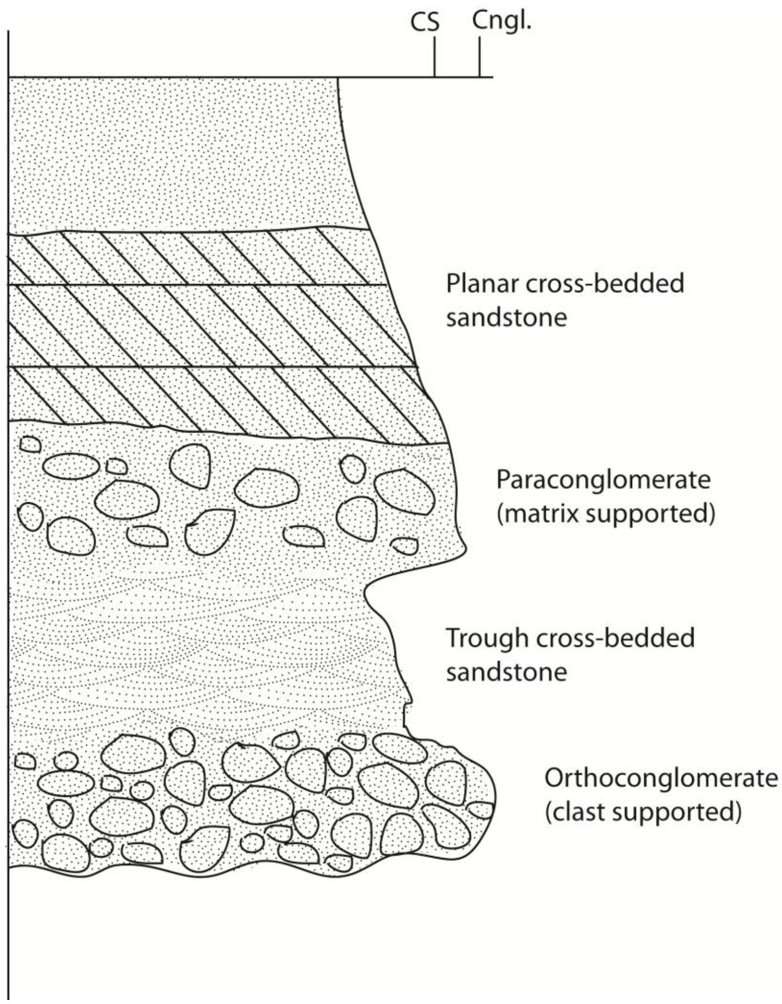


Figure 3.2: Schematic diagram illustrating the general distribution of different conglomerate sublithofacies in typical fining upward succession (not scaled).

3.2 SANDSTONE LITHOFACIES

The sandstone lithofacies is characterized by dark to light gray, coarse to fine-grained lithic sandstone. Bed thickness varies from 6 to 25 ft. Siderite occurs as isolated nodules and pebbles. Rip-up clasts composed primarily of shale are also present. Coal spar occurs locally throughout the lithofacies (Figures 3.3, 3.4). Grains are angular to subrounded, and moderately sorted. This lithofacies is divided into following four sublithofacies based on sedimentary structures.

(1) Trough and planar-tabular cross bedded sandstone- This sublithofacies is found at the bases of channel-fill deposits associated with conglomerate lithofacies.

(2) Current-ripple cross-laminated sandstone - Sandstones of this sublithofacies are composed of fine-grained sand that is comparatively more micaceous and carbonaceous and typically exhibits reactivation surfaces and mud-draped foresets.

(3) Massive sandstone with minor horizontal lamination -This sublithofacies contains thin layers (3-5 cm) of intraformational conglomerate dominated by siderite nodules and shale pebbles.

(4) Sandstones thinly interbedded with mudstones – In this sublithofacies, sandstones are medium grained and show grading, parallel lamination and in some cases lenticular bedding. Interbedded mudstones are commonly rooted.

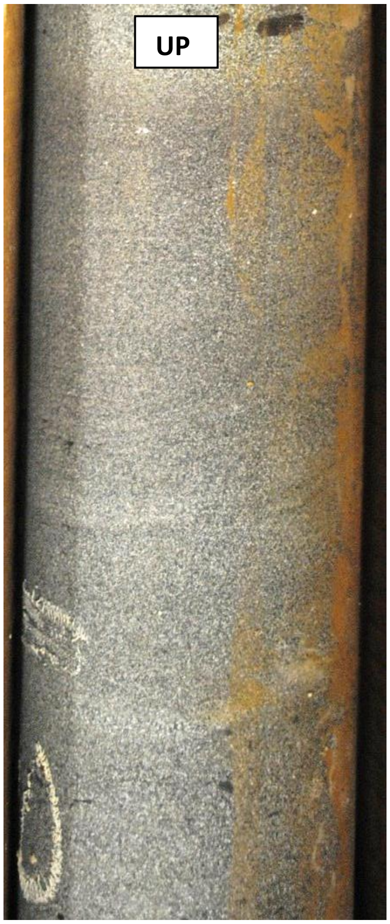


Figure 3.3: Trough cross-bedded coarse-grained sandstone from 2729 ft (left, core length is 6 inches) and massive sandstone from 1189 ft (right). Organic material and/or opaque minerals appear as dark spots.

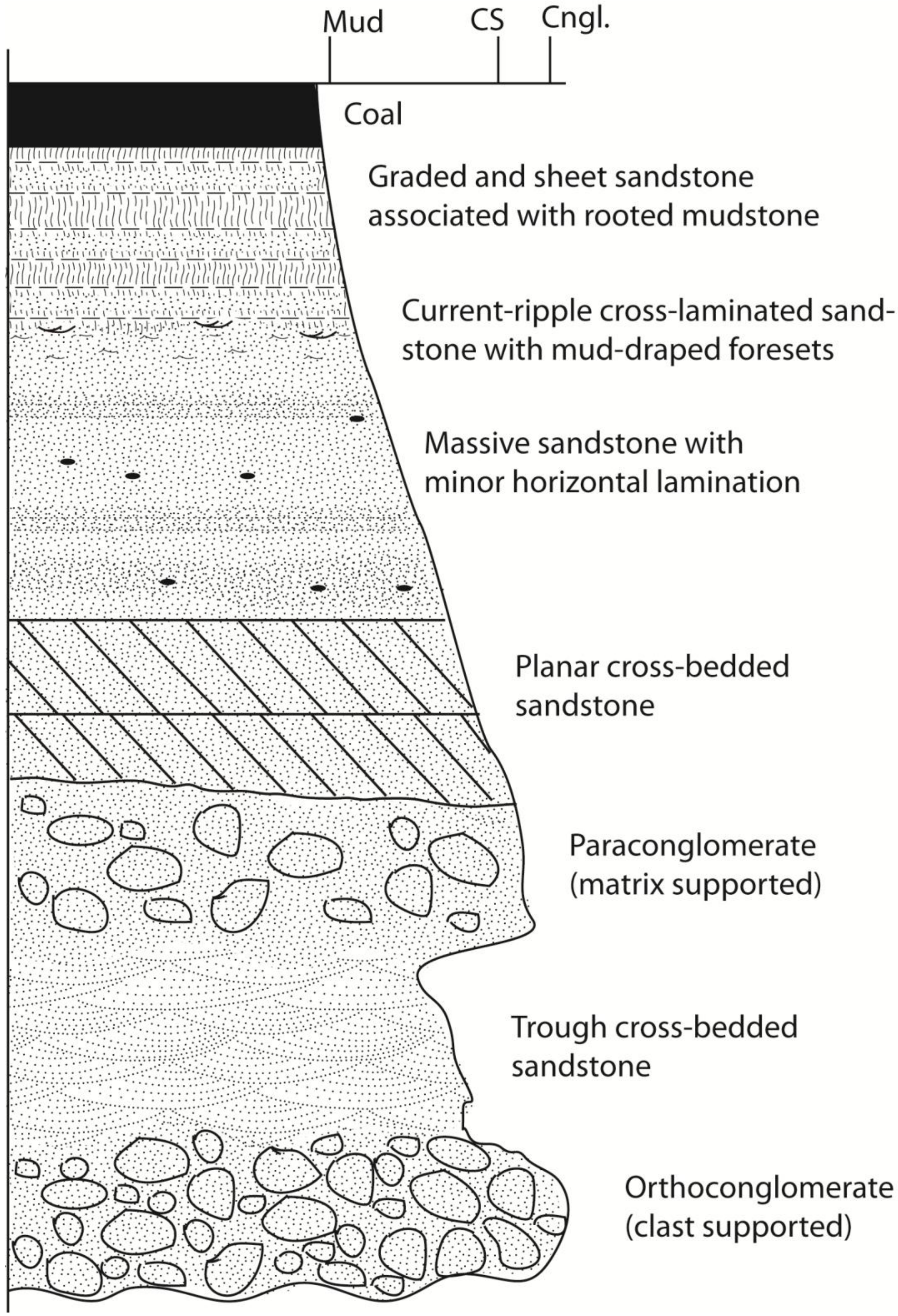


Figure 3.4: Schematic diagram of different sublithofacies of sandstone lithofacies in a typical fining-upward succession (not scaled).

3.3 ROOTED MUDSTONE AND SILTSTONE LITHOFACIES

This lithofacies, which varies from 0.5 to 3 feet thick, includes fissile, mottled, horizontally laminated dark to light gray, organic rich, rooted mudstone (underclay) (Figure 3.5) with thin interbeds of light gray siltstone. Rootcasts are a prominant character of this lithofacies. Erect plant fossils, leaf impressions, coal spar, and isolated bedded or nodular siderite are also common (Figure 3.6). This lithofacies is overlain most commonly by coal layers and underlain by sandstone. Root casts are more prominent and abundant, and siltstones are less common, immediately below the coal layers. Slickensides found along several planes in the lithofacies may indicate compaction related to pedogenesis.

Figure 3.5: Underclay with rootlets from 2527 ft (left, core length is 6 inches) and horizontally laminated coal from 1228 ft (right, core length is 5.2 inches).

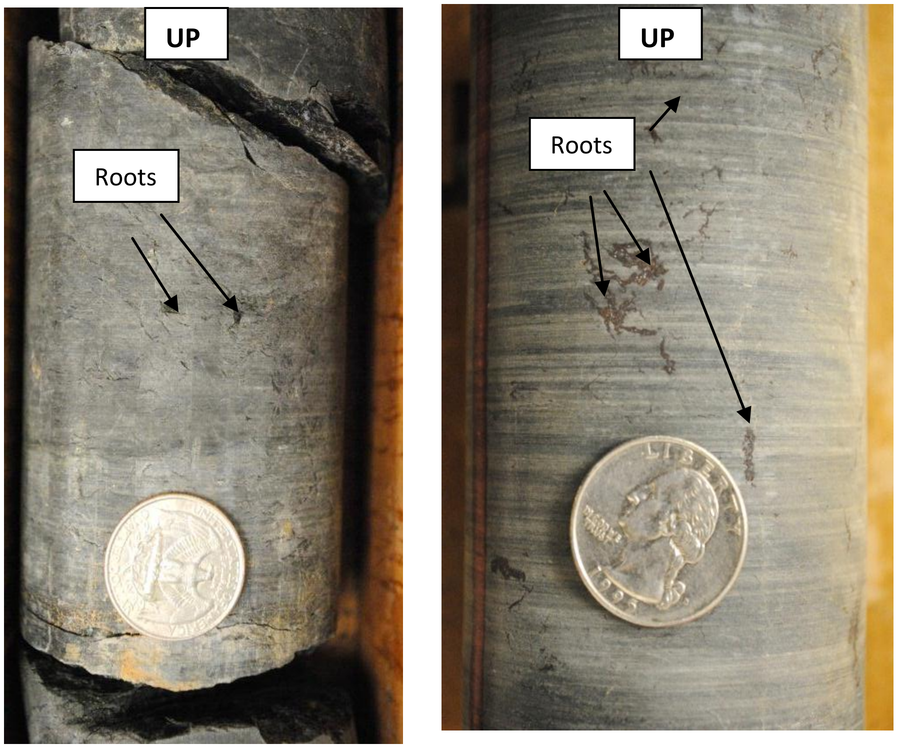


Figure 3.6: Rooted mudstone and siltstone (left, 1811 ft.). Rooted mudstone (right, 3619 ft.).

3.4 COAL LITHOFACIES

This lithofacies refers to black to dark gray, massive to horizontally laminated coal with rootlets. Coal lithofacies can be found throughout the cored depth with thicknesses ranging from 2 to 5 feet. Although coal beds were removed from the core for desorption testing, their positions in the core are noted in core logs and supporting geophysical well logs. Log data shows some thin discontinuous as well as regionally extensive coal beds in the Cahaba synclinorium. Coals may be underlain by burrowed shale lithofacies in deeper part of the core. However, they are usually underlain by rooted mudstone and siltstone lithofacies.

3.5 WAVY BEDDED SHALE AND SANDSTONE LITHOFACIES

This lithofacies is characterized by thinly interbedded dark gray mudstone and light gray, structureless to horizontally laminated, current-ripple cross-laminated or convolute laminated, fine- to medium-grained lithic sandstone (Figure 3.7). Thickness of this lithofacies varies from 8 to 14 ft. Lithic arenite and mudstone are evenly distributed and form flaser and lenticular bedding. Bedding within the lithofacies changes upsection from lenticular to wavy and to flaser bedding. Localized burrows and root casts similar to those in the rooted mudstone and burrowed shale lithofacies occur throughout this lithofacies. Siderite nodules occur in isolated horizontal layers. This lithofacies is usually overlain by rooted mudstone and underlain by the sandstone lithofacies.

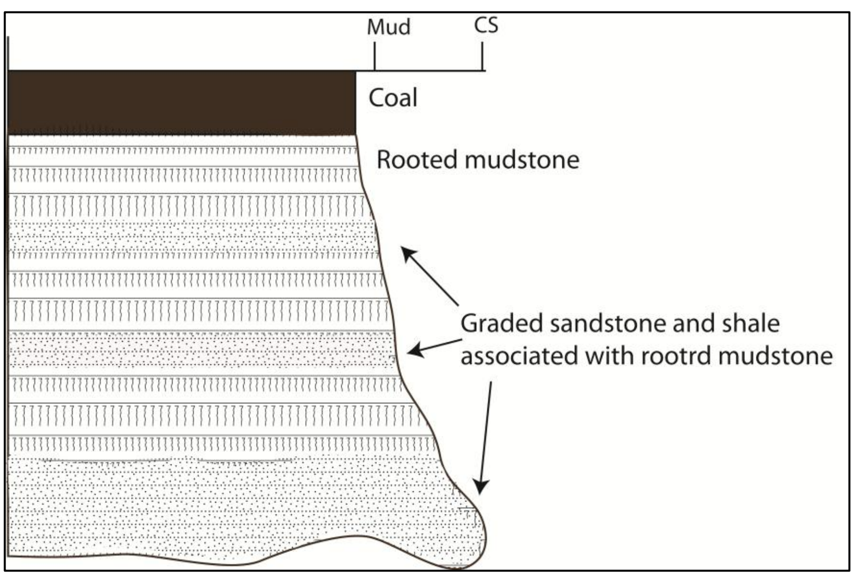
Figure 3.7: Sand lenses within wavy bedding (left core, 3934 ft), sand lenses within flaser bedding (middle core, 4336 ft), and typical wavy bedding with load casts (right core, 4386 ft).

3.6 GRADED SANDSTONE AND SHALE LITHOFACIES

This lithofacies contains graded sandstone-to-shale beds (Figure 3.8). These beds resemble wavy beds, but grading is obvious and the beds tend to be planar. This lithofacies is relatively rare in the SWEPI cores but when it occurs it is mostly associated with rooted mudstone (Figure 3.9).

Figure 3.8: Graded sandstone and shale (4446 ft). Core length is 7 inches. Arrows indicate coarsening upward successions.

Figure 3.9: Schematic diagram of graded sandstone and shale associated with rooted mudstone and coal.



3.7 BURROWED MUDSTONE LITHOFACIES

This lithofacies is characterized by fissile, horizontally laminated, black to dark gray and light gray, locally burrowed mudstone with marine fossils and thinly interbedded sandstone. Sandstones commonly exhibit unidirectional current-ripple cross lamination and/or convolute lamination. Localized siderite bands and nodules, rip-up clats, and coal spar are characteristic of this lithofacies (Figure 3.10).

This lithofacies contains vertical and horizontal burrows with lengths of 2 to 3 cm and diameters of 0.2 to 0.5 cm. Burrows are filled mostly by fine-grained light gray sand. This lithofacies is usually overlain by the rooted mudstone and siltstone lithofacies, but rarely is overlain by coal.

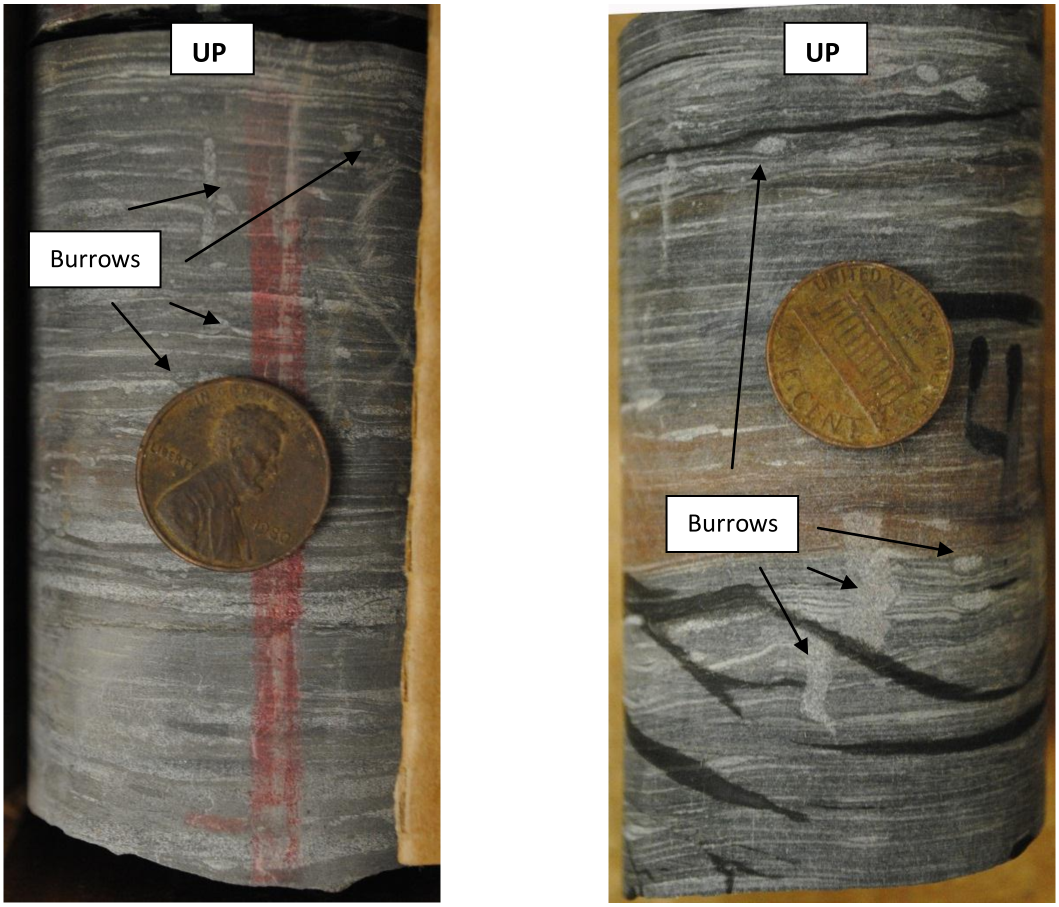


Figure 3.10: Horizontally laminated mudstone and thin interbeds of sand with burrows (left, 4227 ft, right, 4240 ft).

3.8 SHALE AND SHELLY SANDSTONE LITHOFACIES

This lithofacies is characterized by thinly laminated, fissile, dark gray to very dark gray shale with very thin sandstone interbeds, siderite bands, and layers of marine skeletal remains. At the first glance, this facies looks similar to the wavy bedded shale and sandstone lithofacies. However, sand layers are very thin and isolated within massive dark shale and mudstone (Figure 3.11). The absence of intense burrowing differentiates this lithofacies from burrowed mudstone lithofacies. This lithofacies usually is overlain by wavy bedded shale and sandstone and underlain by the sandstone lithofacies. Strata representing this lithofacies are 5 to 11 ft thick.

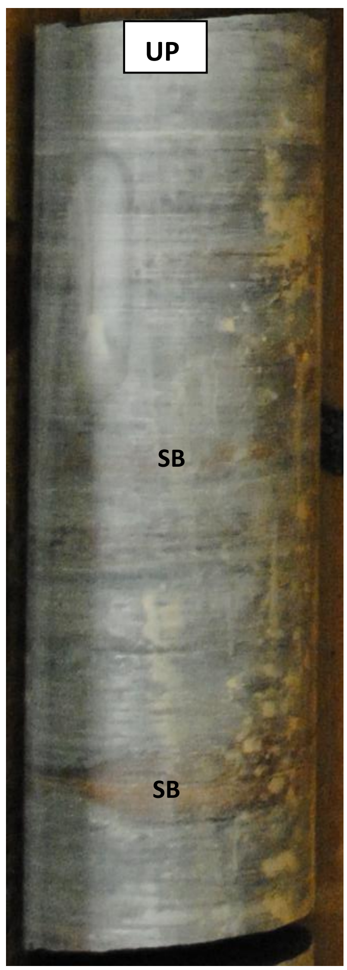


Figure 3.11: Laminated, very dark shale with thin layers of isolated sand. Brown siderite banding (SB) and some burrows are present. Core is from 3208 ft.

This lithofacies contains marine invertebrate body fossils, including brachiopods (e.g., *Productus semireticulatus*) (Figure 3.12), localized small-scale load casts, slump structures, syndepositional faulting, and burrows. Burrows are filled with fine-grained sand.

Fine- to very fine-grained sandstone mostly occurs as very thin layers encased within shale. Although the sandstones are mostly structureless, some isolated lenses contain unidirectional cross-lamination.

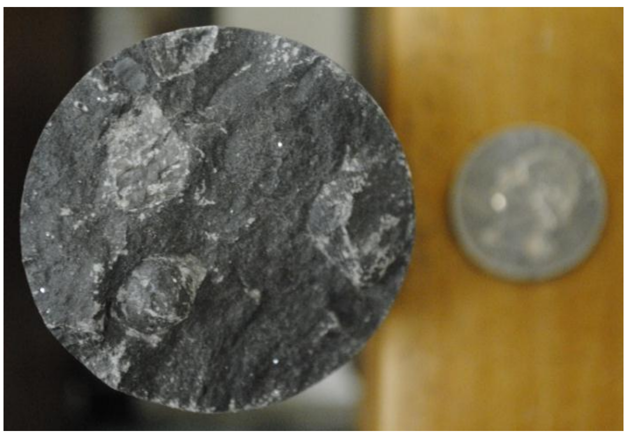


Figure 3.12: *Productus semireticulatus* fossil in shale and shelly sandstone lithofacies. The core is from 2730 ft.

Based on identified lithofacies in core SWEPI 2, a graphic log showing vertical distribution of lithofacies is provided in figures 3.13 and 3.14.

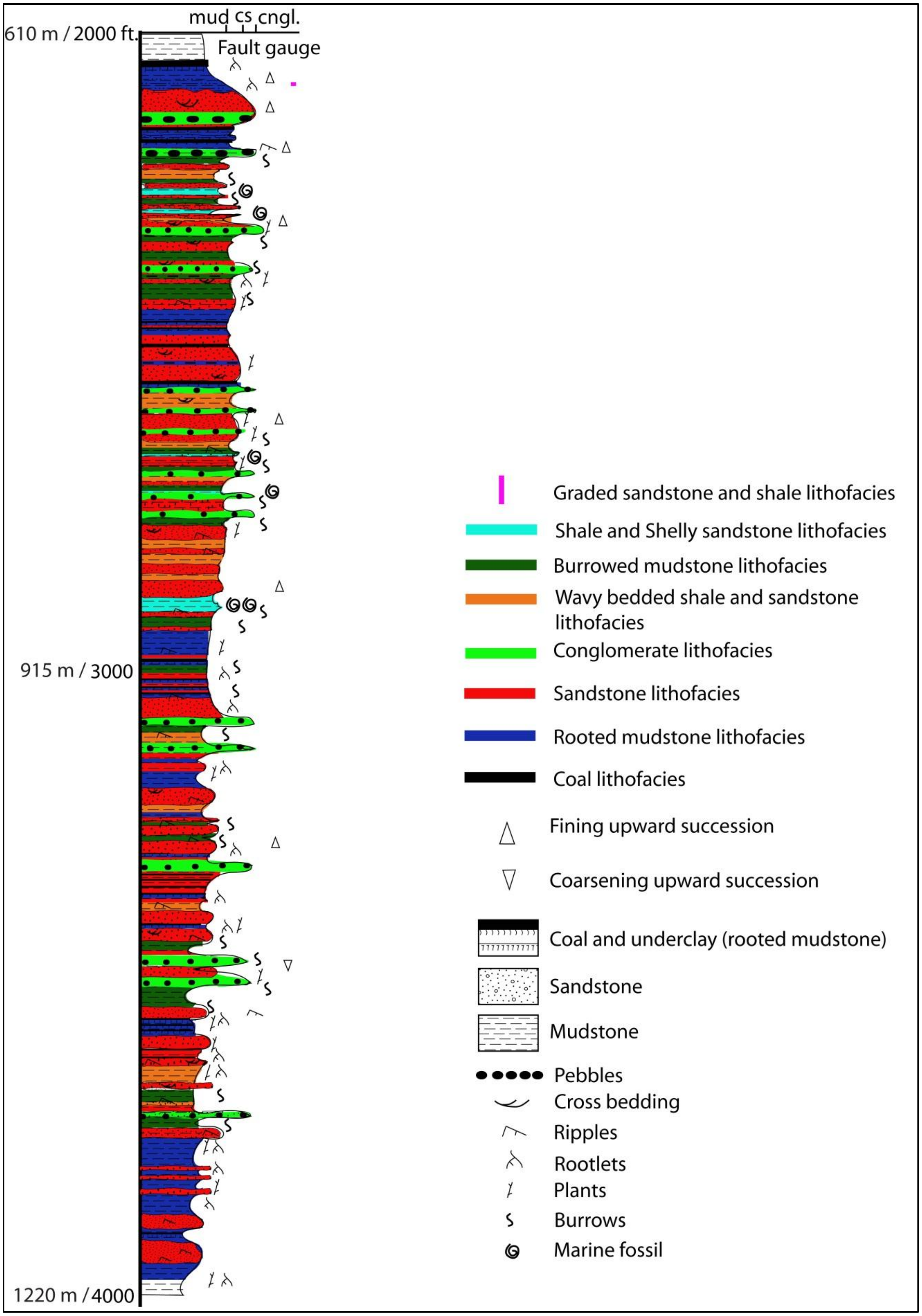


Figure 3.13: Identified lithofacies in the lower part of core SWEPI 2.

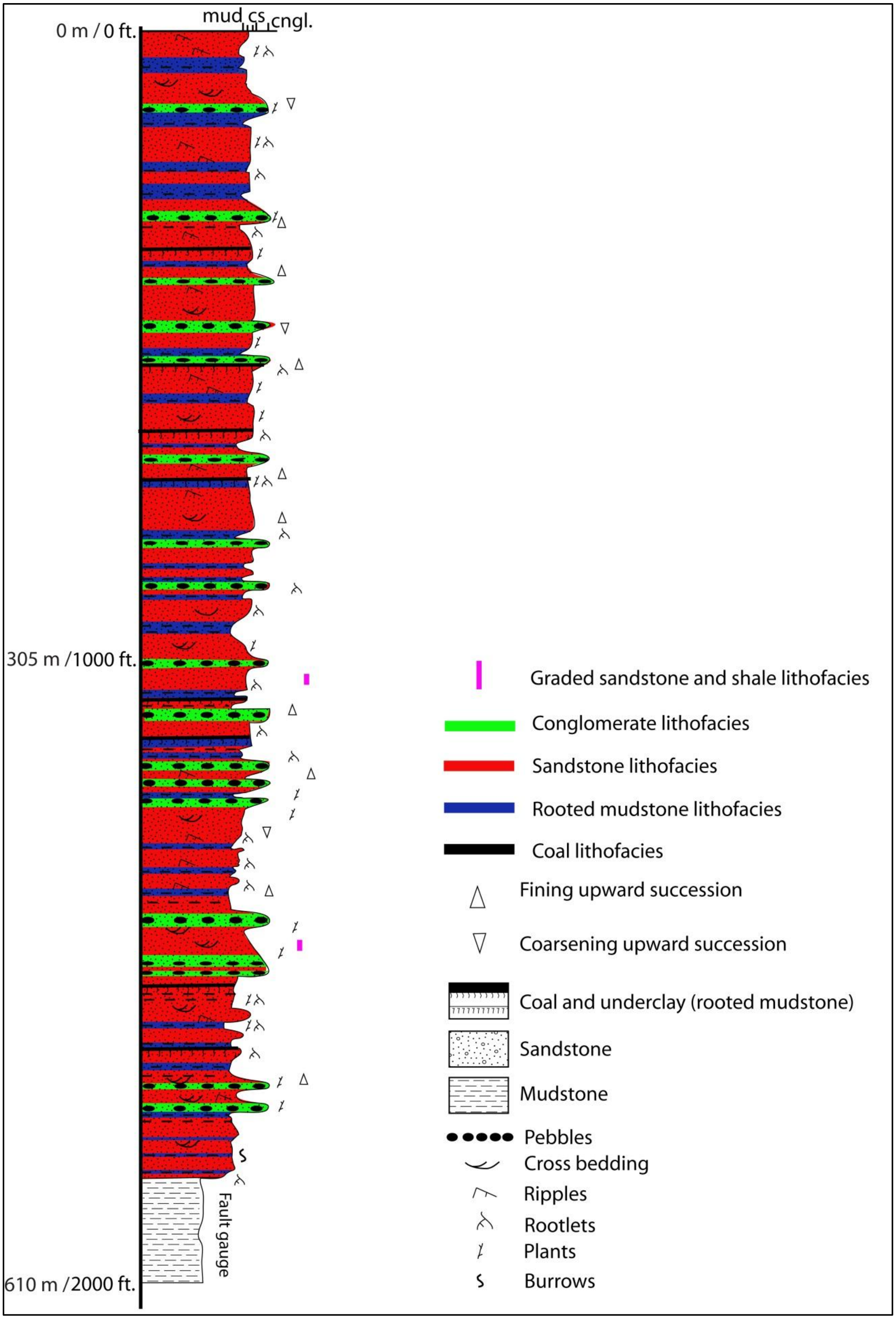


Figure 3.14: Identified lithofacies in the upper part of core SWEPI 2.

CHAPTER 4: PETROGRAPHY

4.0 INTRODUCTION

The modal composition of the studied Pottsville sandstone samples is $Q_{63}F_{11}L_{26}$ (Tables 3, 4). According to Folk's (1980) classification, the sandstones examined in this study are dominantly feldspathic litharenites and litharenites (Figure 4.1). Quartz grains are subrounded to subangular, and both monocrystalline (Figure 4.2 A) and polycrystalline grains (Figure 4.2 B) are common along with detrtital chert. Both plagioclase and K-feldpar are observed in significant amounts, and plagioclase feldspar is more abundant than K-feldspar (Tables 3, 4). Sedimentary lithic fragments are dominant. Metamorphic rock fragments (Figure 4.3 B) are predominantly schistose. Volcanic fragments are least common among the lithic fragments and are particularly uncommon in samples from the lower part of the core (Tables 3, 4). Muscovite is a relatively abundant accessory mineral, ranging from 2 to 4% of the total sandstone.

Based on modal composition, two out of four distinct petrofacies proposed by Lawton et al. (2003) have been identified in the studied core (Figure 4.4). The lower 600 feet are identified as the quartzolithic (mean $Qt_{77}F_6L_{17}$) petrofacies and the top 2300 feet are identified as the quartzofeldspatholithic (mean $Qt_{60}F_{12}L_{28}$) petrofacies (Figure 4.4).

4.1 QUARTZOLITHIC PETROFACIES (mean $Qt_{77}F_6L_{17}$)

The quartzolithic petrofacies identified in the lower 600 feet of the studied section (part of mudstone measures) is generally more quartzose (Figures 4.5-4.7). This section includes significant amounts of sedimentary lithic fragments; feldspar and volcanic lithic fragments are rare (Figures 4.6, 4.8) (Table 3, 4). This petrofacies contains mostly monocrystalline quartz with abundant chert. Feldspar contents average 6 percent of the framework population and both plagioclase and K-feldspar occur roughly in equal amounts (except in sample 26). Sedimentary lithics (e.g., argillites) dominate over metamorphic lithics, and volcanic lithic grains are rare or absent.

4.2 QUARTZOFELDSPATHOLITHIC PETROFACIES (mean $Qt_{60}F_{12}L_{28}$)

The upper 2300 feet of the core (conglomerate measures) is identified as the quartzofeldspatholithic petrofacies. While dominated by quartz, the quartzolithic petrofacies contains comparatively more feldspars and lithic fragments (Figures 4.5-4.7) (Table 3, 4). Like the quartzolithic petrofacies, quartz grains are dominated by monocrystalline types. Plagioclase feldspar is more abundant than K-feldspar. Metamorphic and sedimentary lithic grains (including argillite, siltstone, and phosphatic grains) are relatively more abundant then volcanic lithic grains (mostly basaltic). Chert grains contain rare recrystallized fossils originally composed of calcium carbonate, indicating an origin by replacement of carbonate rocks.

Ternary diagrams of the major components (monocrystalline grains and fine-grained lithic fragments) indicate that all sandstones were derived from a recycled orogen (Figures 4.9). The high proportions of quartz and limited feldspars (Tables 3, 4) in the quartzolithic petrofacies show high sediment maturity, which is an indication of longer distance from the source terrane and/or intense reworking. The less mature quartzofeldspatholithic petrofacies, with higher feldspar and lithic contents reflects less reworking and a different source area close to the basin.

Difference in compositional maturity between the petrofacies may indicate that the basin was at downstream or distal end of a transportation system during deposition of the lower section whereas the upper section received sediments from a proximal source.

Table 3: Raw point-count data of sandstones from two measures of the Lower Pennsylvanian Pottsville Formation (green samples from conglomerate measures, red ones from mudstone measures) from core SWEPI 2.

Sample	Depth (ft)	Qm	Qp	P	K	Ls	Lv	Lm
SN1	89	156	15	25	5	50	10	39
SN2	100	141	36	28	6	56	8	26
SN3	200	129	54	42	0	41	15	18
SN4	230	153	27	32	1	30	9	49
SN5	280	150	27	35	4	42	9	33
SN6	355	147	30	13	17	56	6	32
SN7	380	144	24	43	5	43	8	34
SN8	440	156	24	24	9	30	14	44
SN9	510	135	36	21	9	30	12	57
SN10	800	150	21	26	8	39	18	38
SN11	960	135	42	26	7	26	24	40
SN12	1050	162	21	24	0	38	28	27
SN13	1120	174	12	42	0	53	7	12
SN14	1210	171	12	37	5	31	22	23
SN15	1257	168	9	52	5	18	15	33
SN16	1300	156	24	20	10	34	37	19
SN17	1400	156	12	28	14	43	18	29
SN18	1500	150	21	26	16	30	26	30
SN19	1584	162	24	18	4	20	25	48
SN20	1734	144	51	21	3	26	11	45
SN21	2097	150	51	25	11	9	9	45
SN22	2110	174	57	4	2	34	3	26
SN23	2398	216	21	5	10	43	0	5
SN24	2512	234	12	11	4	23	9	7
SN25	2634	216	9	5	19	37	6	8
SN26	2845	174	30	30	6	36	2	22

Table 4: Normalized modal compositions (in %) of sandstones from two measures of the Lower Pennsylvanian Pottsville Formation. Green samples (SN1 to SN21) are from conglomerate measures and red samples (SN22 to SN 26) are from mudstone measures.

Sample	Qt	F	L	Qm	F	Lt	Qm	P	K	Ls	Lv	Lm
SN1	57	10	33	52	10	38	84	13	3	51	10	39
SN2	59	11	30	47	11	42	81	16	3	62	9	29
SN3	61	14	25	43	14	43	75	25	0	56	20	24
SN4	60	11	29	51	11	38	82	17	0	34	10	56
SN5	59	13	28	50	13	37	79	19	2	50	11	39
SN6	59	10	31	49	10	41	83	7	10	60	6	34
SN7	56	16	28	48	16	36	75	23	3	51	9	40
SN8	60	11	29	52	11	37	83	12	5	34	16	50
SN9	57	10	33	45	10	45	82	13	6	30	12	58
SN10	57	11	32	50	11	39	82	14	4	41	19	40
SN11	59	11	30	45	11	44	80	16	4	29	27	44
SN12	61	8	31	54	8	38	87	13	0	41	30	29
SN13	62	14	24	58	14	28	81	19	0	74	10	16
SN14	61	14	25	57	14	29	80	18	2	41	29	30
SN15	59	19	22	56	19	25	75	23	2	27	23	50
SN16	60	10	30	52	10	38	84	11	6	38	41	21
SN17	56	14	30	52	14	34	79	14	7	48	20	32
SN18	57	14	29	50	14	36	78	14	8	35	30	35
SN19	62	7	31	54	7	39	89	10	2	21	27	52
SN20	65	8	27	48	8	44	86	12	2	32	13	55
SN21	67	12	21	50	12	38	81	14	6	14	14	72
Mean	60	12	28									
SN22	77	2	21	58	2	40	97	2	1	54	5	41
SN23	79	5	16	72	5	23	94	2	4	90	0	10
SN24	82	5	13	78	5	17	94	5	2	60	23	17
SN25	75	8	17	72	8	20	90	2	8	73	11	16
SN26	68	12	20	58	12	30	83	14	3	60	3	37
Mean	76	6	18									
Mean	63	11	26	54	11	35	83	13	4	16	16	37
St. Dev.	7	4	6	8	4	8	6	6	3	18	10	15

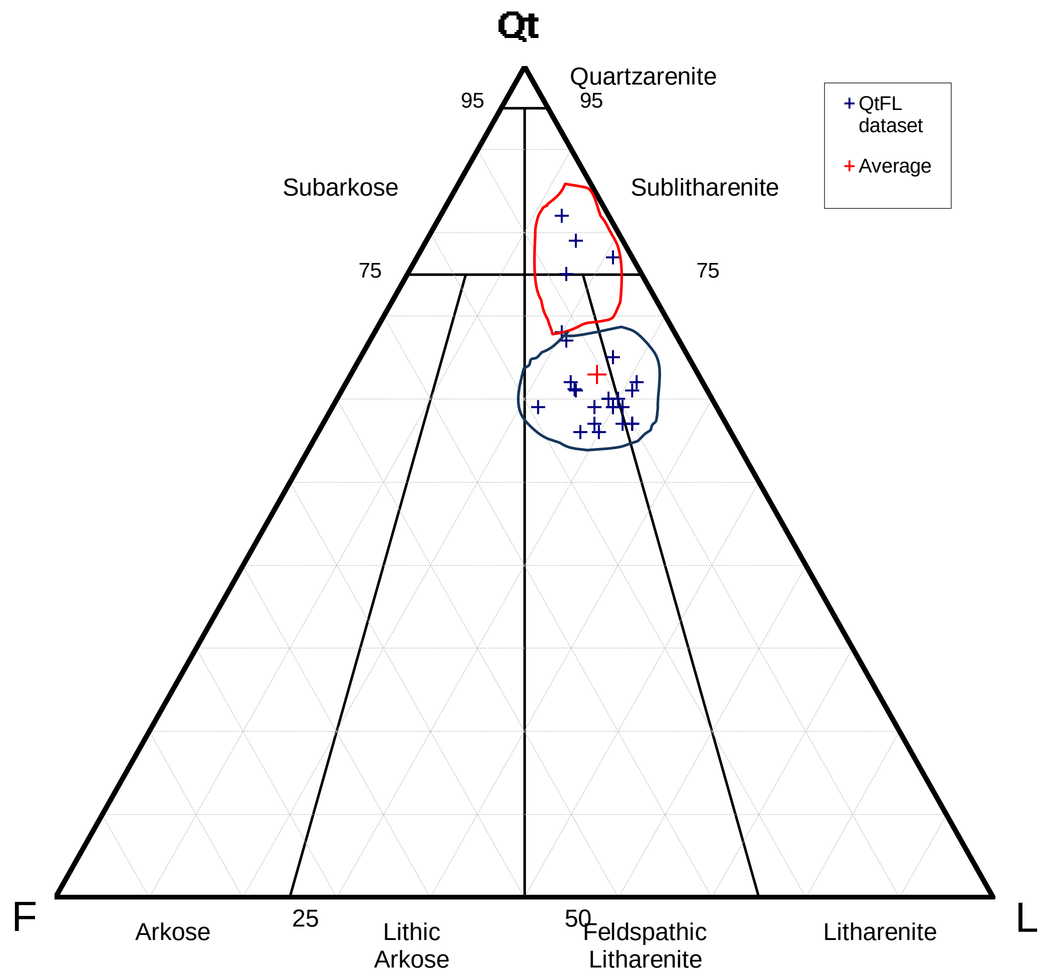
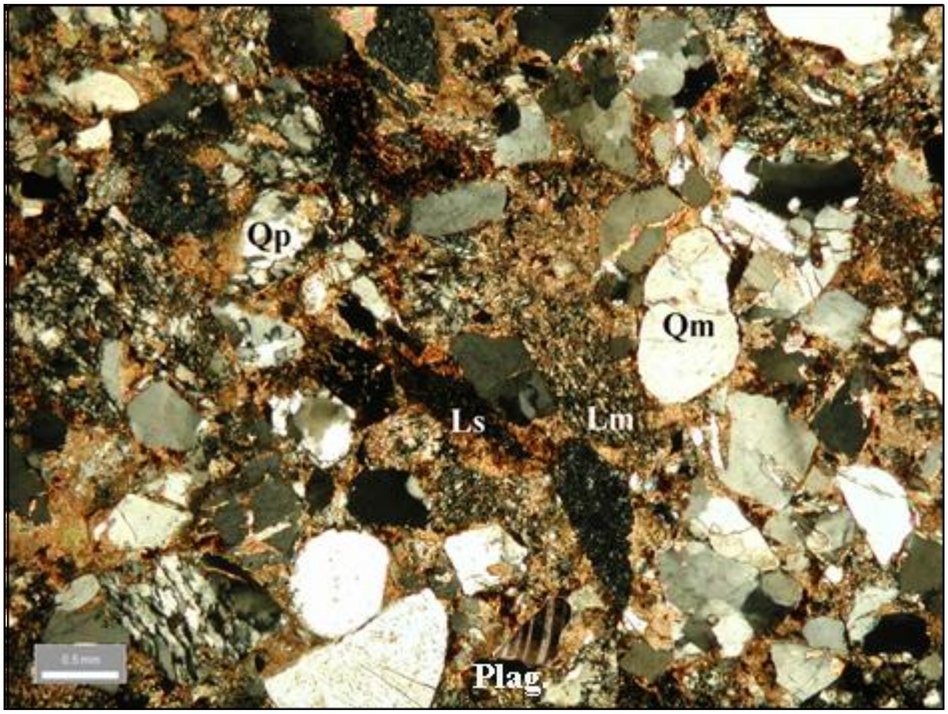


Figure 4.1: Composition of Pottsville sandstone based on Folk's (1980) classification scheme. Red and blue fields represent quartzolithic and quartzofeldspatholithic petrofacies, respectively.

A



B

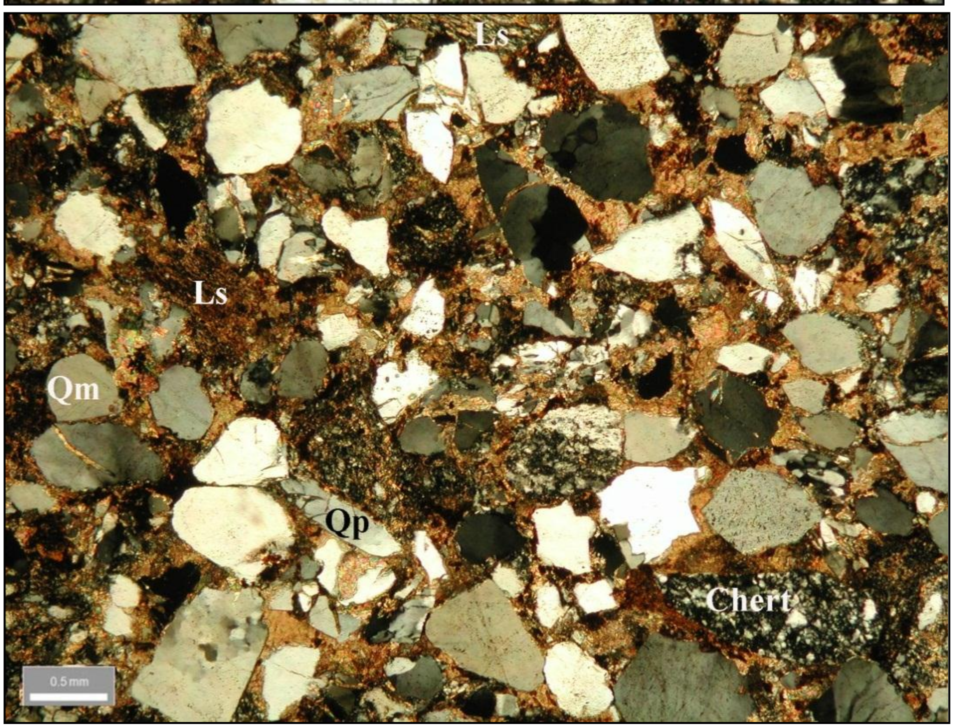
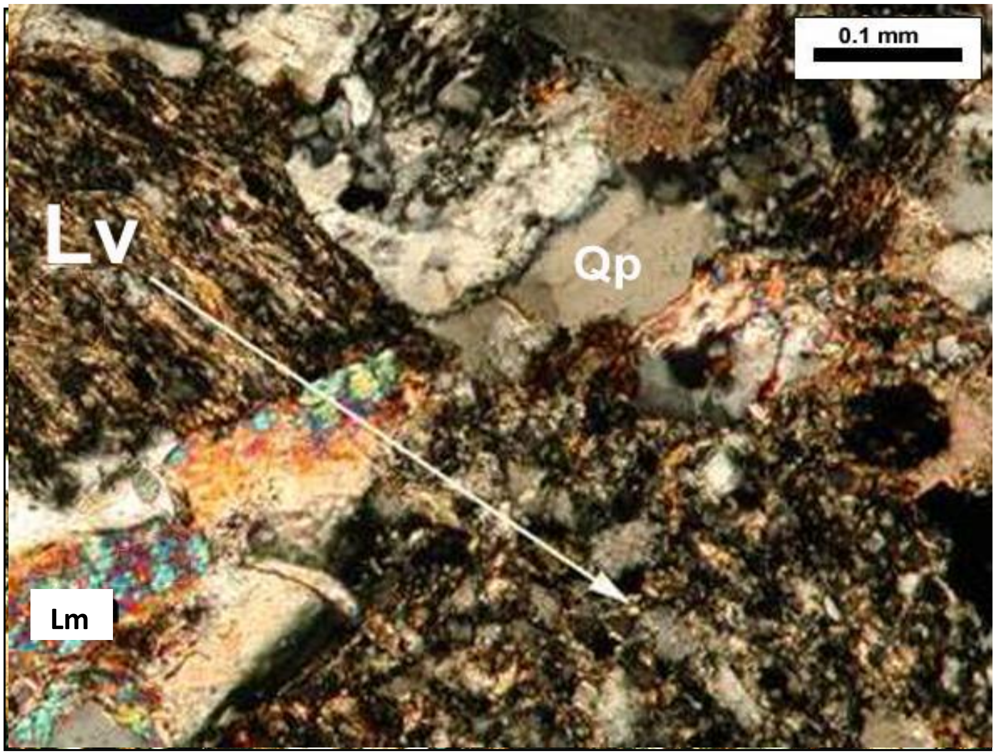


Figure 4.2: Representative photomicrographs of Pottsville sandstone (A) with rounded to sub-angular monocrystalline grains (Qm), polycrystalline quartz (Qp), plagioclase feldspar (Plag), sedimentary (Ls) and metamorphic lithic (Lm) fragments (sample SN-4 from quartzofeldspatholithic petrofacies, crossed polars) and (B) with detrital chert and polycrystalline quartz grains (Qp) among lithic grains (Ls) (sample SN-22 from quartzolithic petrofacies, crossed polars).

A



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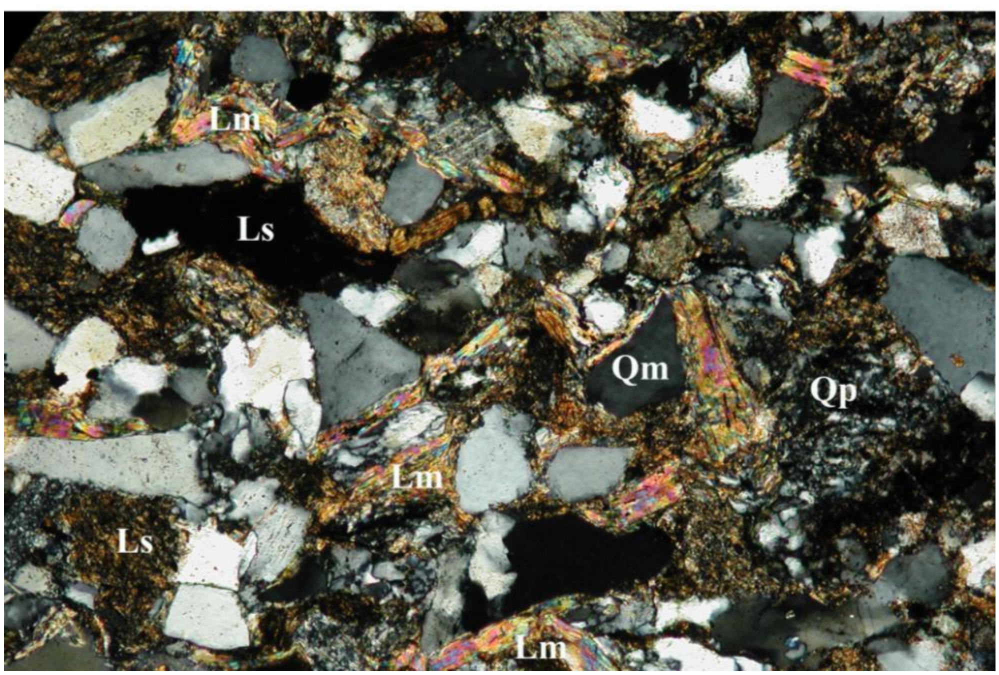


Figure 4.3: Representative photomicrographs of Pottsville sandstone (A) with volcanic clast (Lv), low-grade metamorphic clast (Lm), and polycrystalline quartz (Qp) (sample SN 16 from quartzofeldspatholithic petrofacies, crossed polars) and (B) with very low- to low-grade metamorphic fragments (Lm) (sample SN-14 from quartzofeldspatholithic petrofacies, crossed polars).

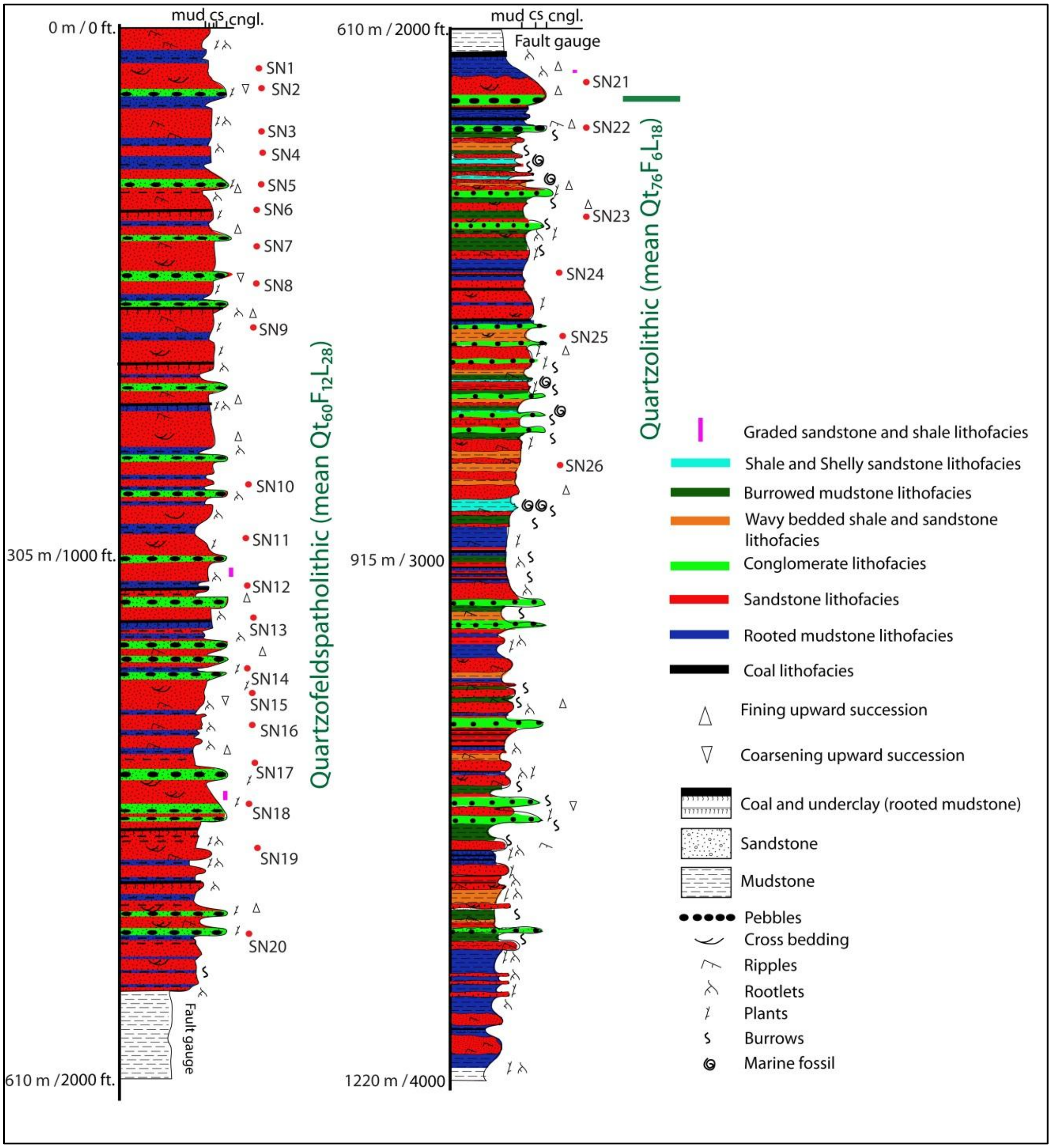


Figure 4.4: Distribution of petrofacies assemblages. The quartzolithic assemblage and the quartzofeldspatholithic assemblage correspond to the mudstone and conglomerate measures, respectively. Red dots represent sample-collection levels.

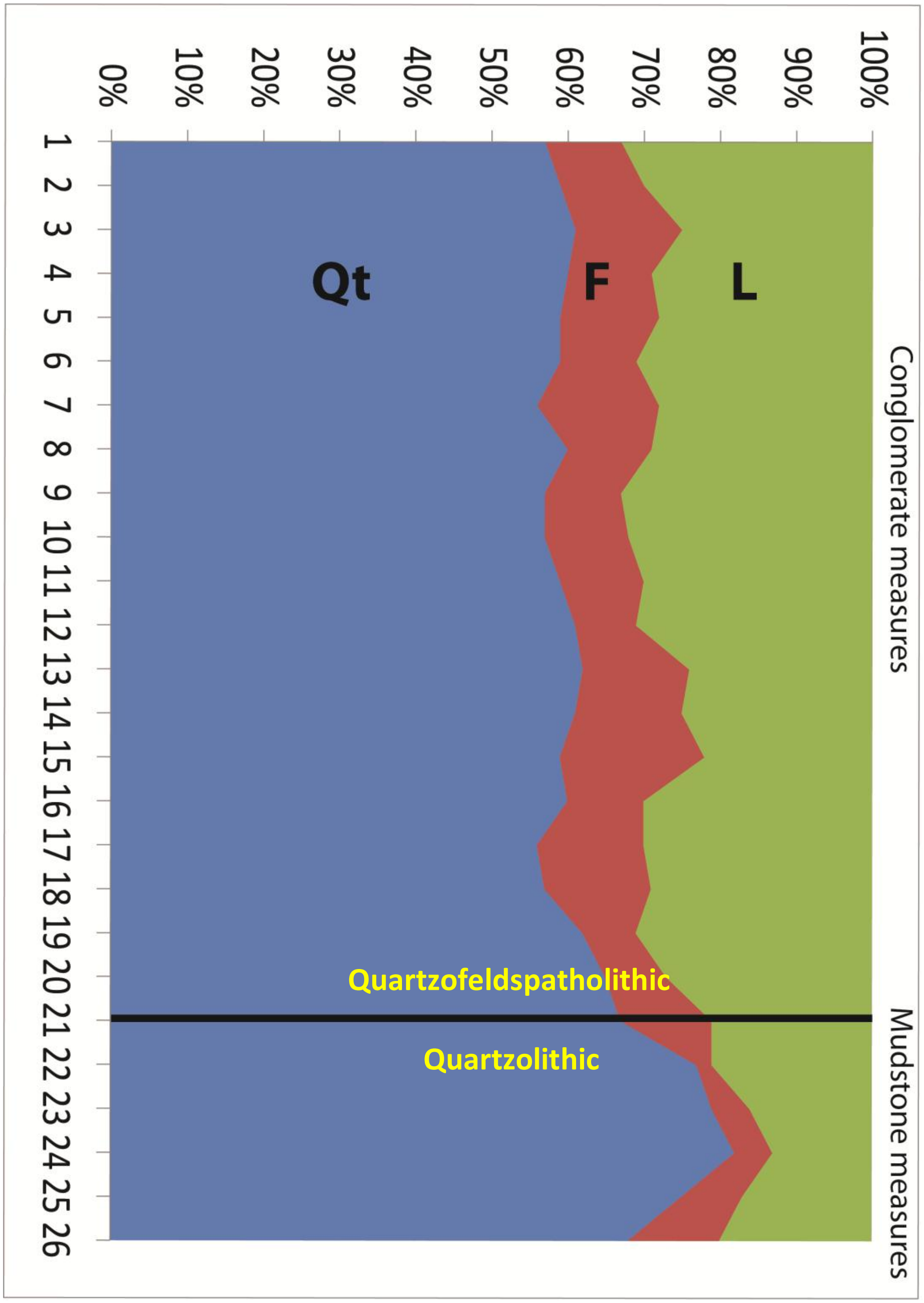


Figure 4.5: Profile plot of changes in percentages of total quartz (Qt), feldspar (F), and lithic fragments (L) through the Pottsville Formation in the Cahaba Basin.

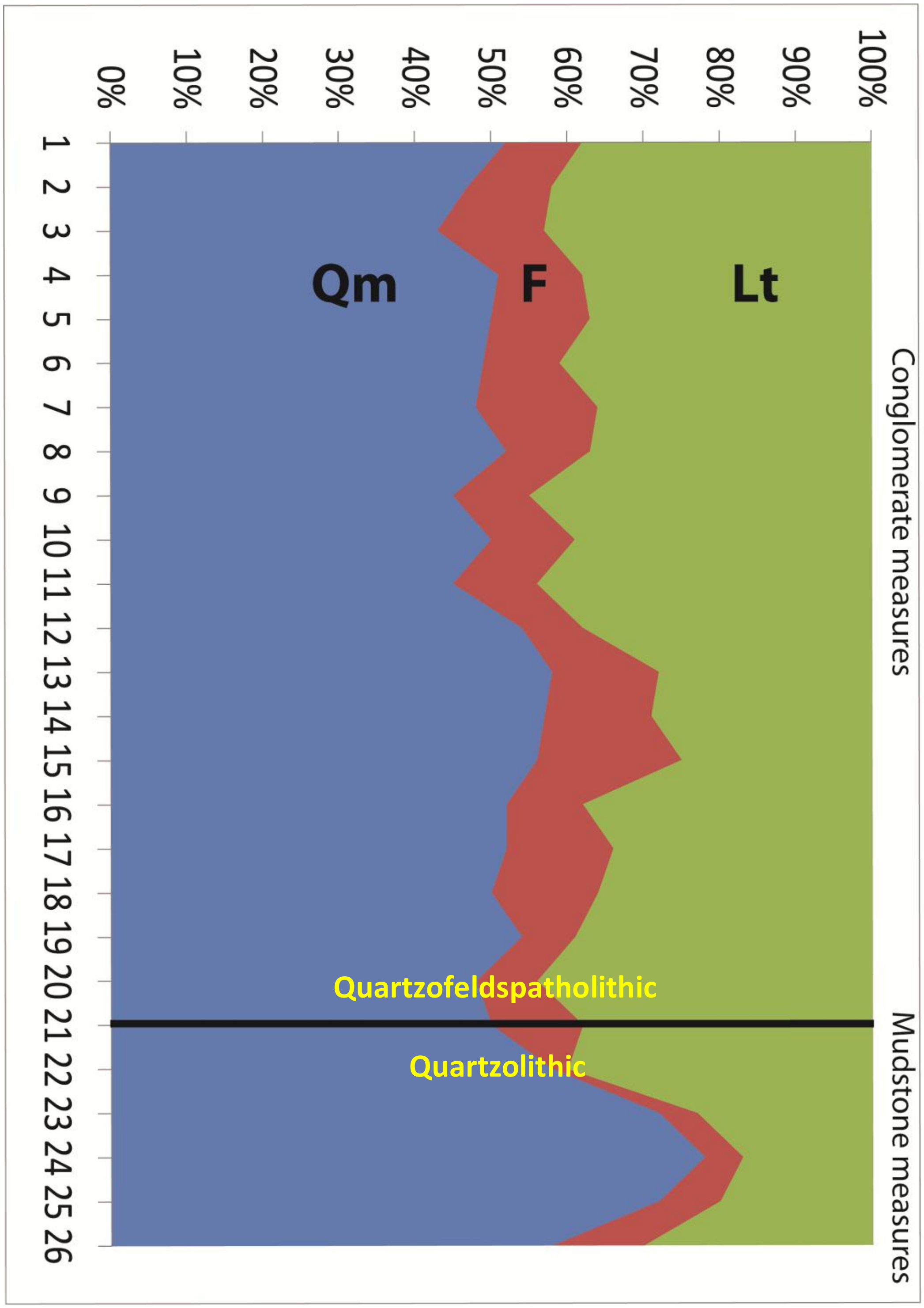


Figure 4.6: Profile plot of changes in percentages of monocrystalline quartz (Qm), feldspar (F), and total lithic fragments (Lt) through the Pottsville Formation in the Cahaba Basin. Chert and polycrystalline quartz are included in total lithic fragments.

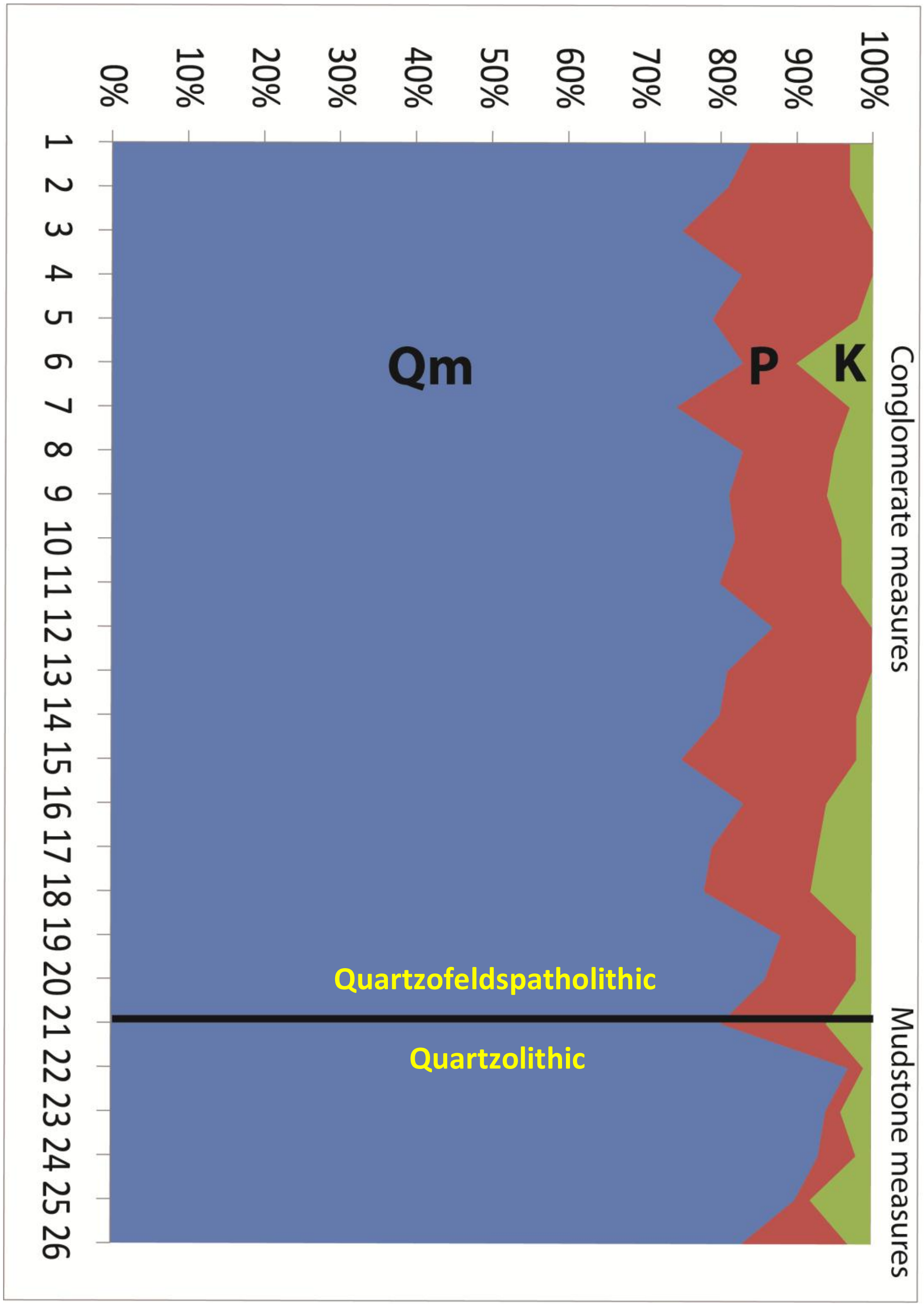


Figure 4.7: Profile plot of changes in percentages of monocrystalline quartz (Qm), plagioclase feldspar (P), and potassium feldspar (K) through the Pottsville Formation in the Cahaba Basin.

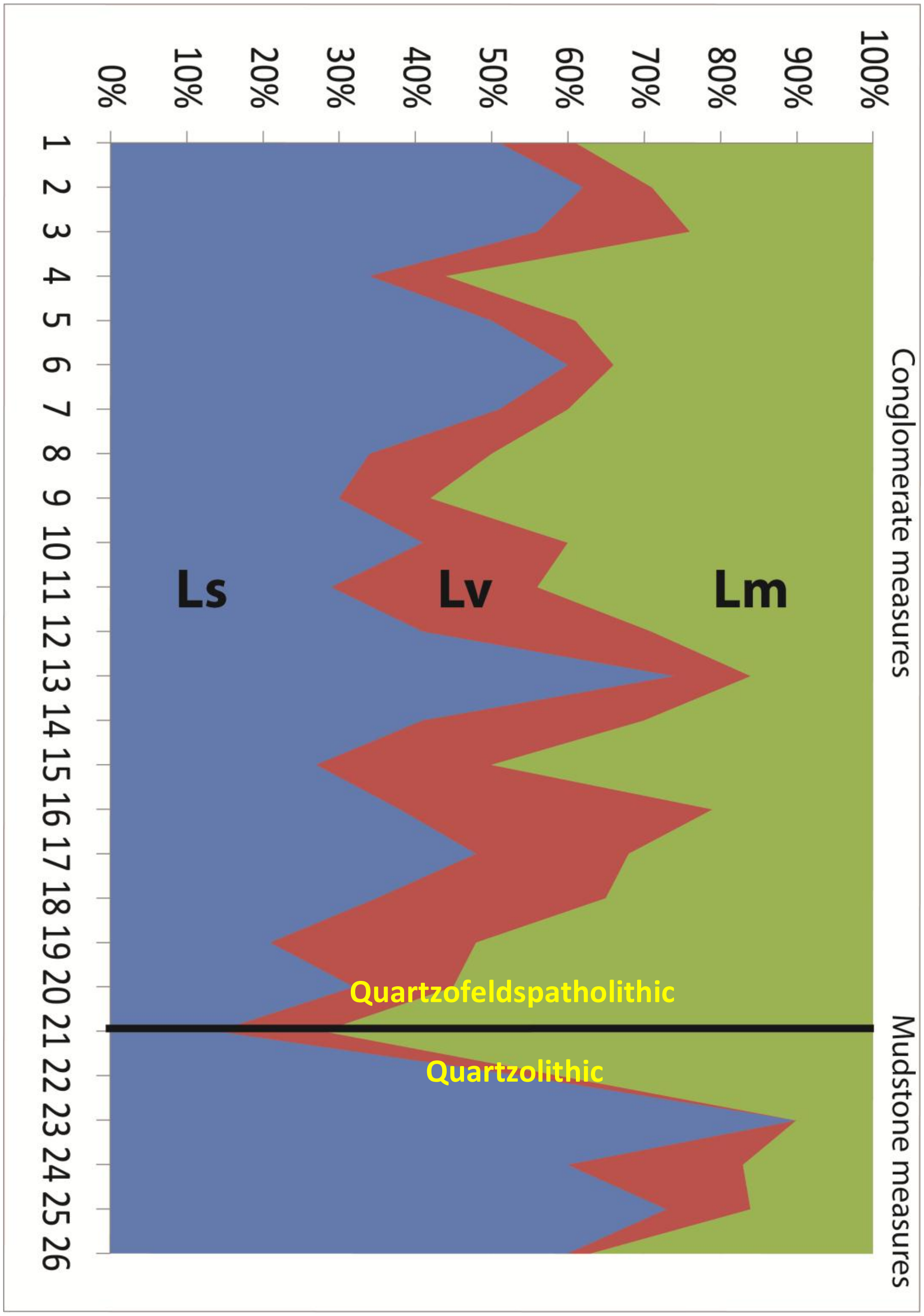


Figure 4.8: Profile plot of changes in percentages of sedimentary (Ls), volcanic (Lv), and metamorphic (Lm) lithic fragments through the Pottsville Formation in the Cahaba Basin.

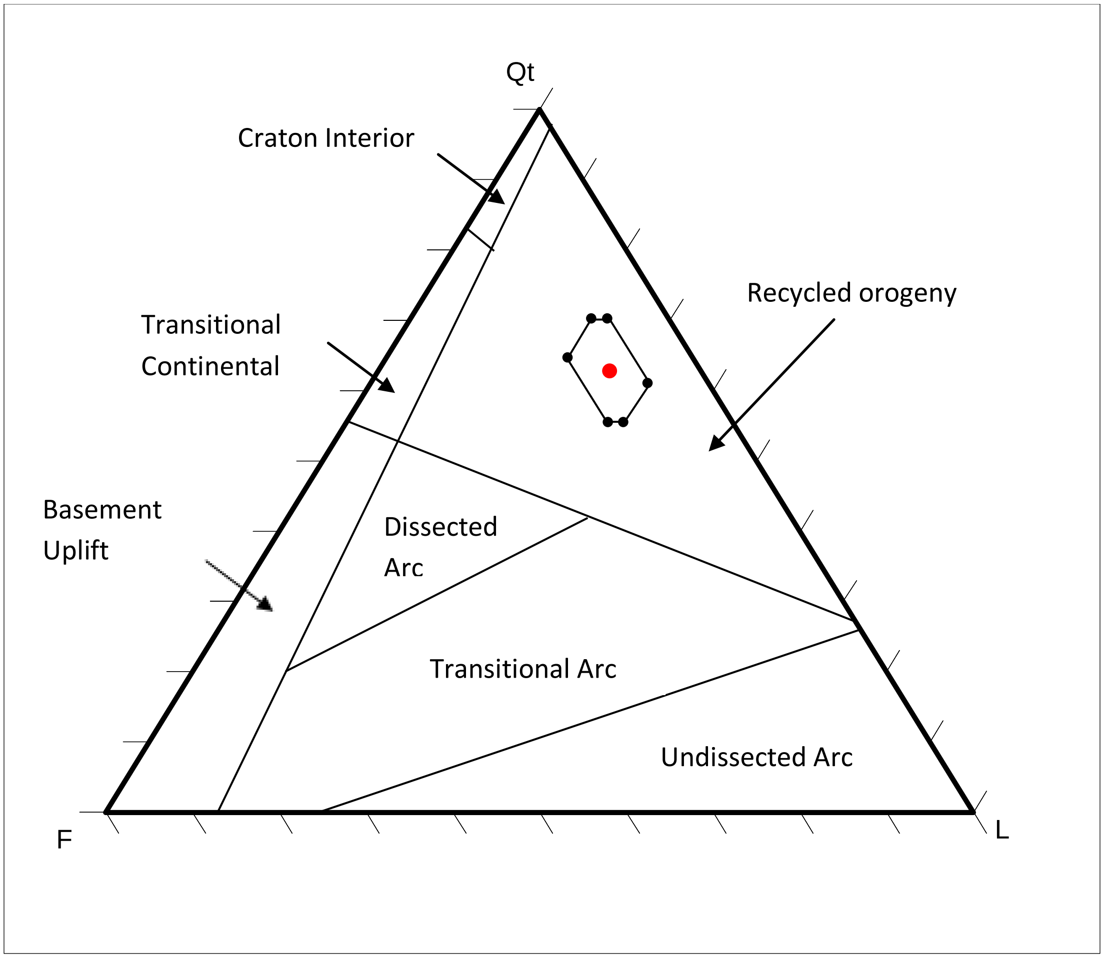


Figure 4.9: QtFL plot showing modal composition of Pottsville sandstones from the SWEPI 2 core of Cahaba Basin. Provenance fields are from Dickinson (1985). Standard deviation polygon is drawn around the mean (shown as a red dot). Qt=total quartz; F=feldspar; L=lithic grains.

CHAPTER 5: ENVIRONMENTS OF DEPOSITION

5.0 INTRODUCTION

Depositional environment plays a vital role in defining the physical characteristics of a facies. A subjective attempt is made here to interpret the depositional environments (Figure 5.1, Table 5) of the identified lithofacies and sublithofacies, based on previously published criteria (Miall, 1978; Reineck and Singh, 1986; Pashin et al., 1995; Reading, 1996; Pashin and Carroll, 1999).

5.1 CONGLOMERATE LITHOFACIES

Conglomerate lithofacies in the upper and lower conglomerate measures have been interpreted to represent bedload-dominated fluvial deposits (Osborne, 1988, 1991; Demirpolat, 1989) (Figure 5.1). Matrix-supported conglomerates (paraconglomerate) with minor clast imbrication suggest hyper-concentrated sheet floods, especially where the units are tabular and interbedded with finer sediments. Clast-supported conglomerates (orthoconglomerate), especially lenticular units with erosive bases, are stream bedload deposits (Reading, 1996). Horizontal stratification and prominent clast imbrication indicate near-horizontal pavement deposition either on top of braid bars or as channel-floor lags (Nemec and Postma, 1993). Intraformational clasts are associated with erosion of overbank floodplain deposits during channel migration (Reading, 1996). Extraformational clasts are concentrated in lags on scoured surfaces or on bar tops (Reineck and Singh, 1975). Extraformational conglomerates in the conglomerate measures indicate continued unroofing of the Appalachian orogen and development of an extensive alluvial plain at the end of Pottsville deposition (Osborne, 1991; Pashin et al., 1995). Internally stacked fining-upward sequences, along with greater thicknesses of the conglomerate lithofacies are suggestive of a composite multistory and multilateral fluvial deposit. Bases of internally stacked fining-upward sequences associated with considerable thickness of the conglomerate lithofacies have been identified as erosional surfaces.

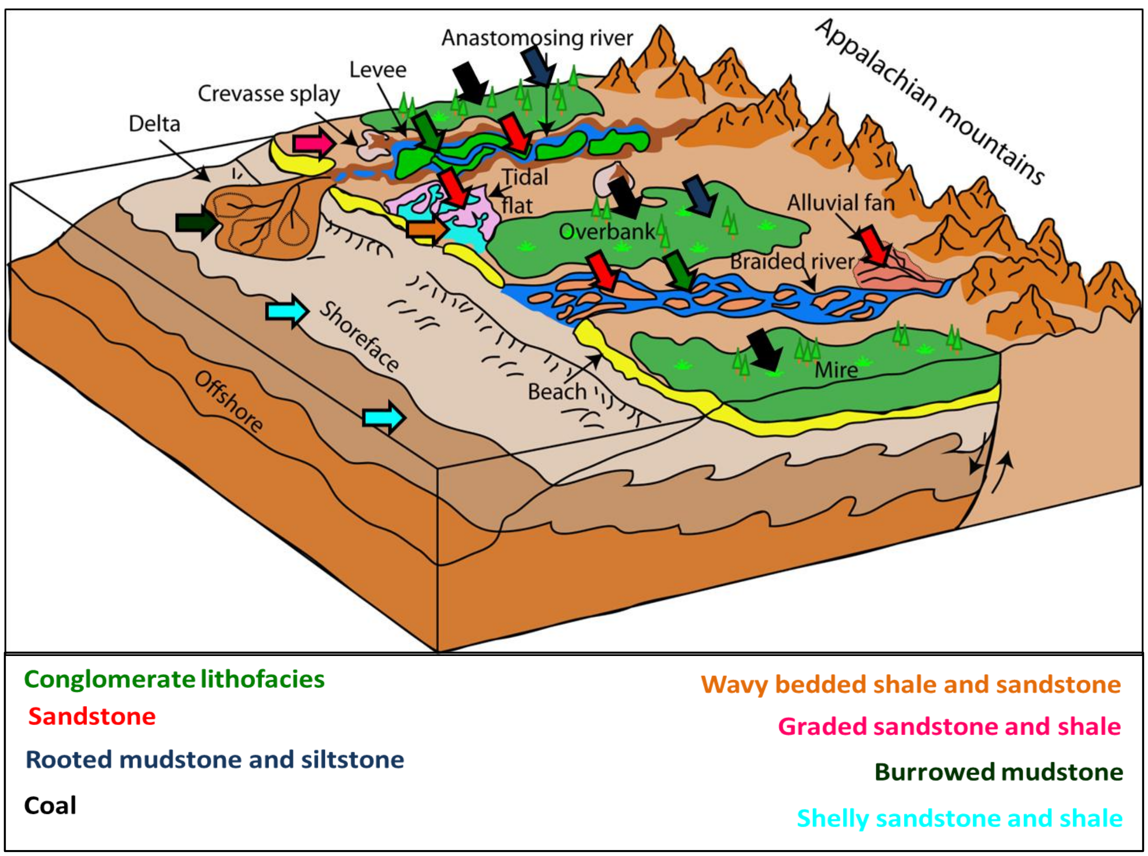


Figure 5.1: Reconstruction of the clastic depositional environments of Lower Pennsylvanian Pottsville Formation in Cahaba synclinorium, Alabama. Different colored arrows represent depositional environments for associated lithofacies.

Table 5: Summary of the identified lithofacies and inferred depositional environments.

No.	Lithofacies	Sublithofacies	Major rock types	Sedimentary structures	Fossils	Biogenic activity	Environment of deposition
LF 1	Conglomerate	1.Orthoconglomerate 2.Paraconglomerate	Lithoclasts, Sandstone matrix	Massive, horizontal lamination in sandstone	No	No	1.Hyper-concentrated sheet floods 2. Stream bedload deposits
LF 2	Sandstone	1. Trough and planar-tabular cross bedded 2.current-ripple cross-laminated 3.massive sandstone with lamination, 4.thinly interbedded with mudstones.	Sandstone	Massive, horizontal laminations, current ripple cross lamination	No	No	1. Anastomosed fluvial system 2. Weak currents as well as high rates of bed aggradation 3.Floodplain 4. Intertidal flats
LF 3	Rooted mudstone and siltstone		Mudstone and gritty siltstone	Fissile, horizontally laminated mudstone Massive thin bed of sandstone	No	Rootcasts	Clastic swamp
LF 4	Coal	1.Thin, discontinuous 2. extensive	Coal	Massive to horizontally laminated	Plant	Rootcasts	1.Localized swamps 2. Widespread flooding
LF 5	Wavy bedded shale and sandstone		Shale and lithic arenite	Wavy, lenticular, and flaser bedding	Plant	Burrows	Tidal-flat deposits
LF 6	Graded sandstone and shale		Sandstone and shale	Graded bedding, horizontal lamination, cross bedding	No	Rootcasts	Crevasse splays and associated flood basin
LF 7	Burrowed mudstone		Mud, thin sandstone	Horizontal lamination	Marine	Burrows	Delta-front slope or prodelta
LF 8	Shelly sandstone and shale		Shale and Sandstone	Massive to horizontal lamination in shale. Minor cross lamination in sandstone	Marine	Burrows	Deep water

5.2 SANDSTONE LITHOFACIES

The sandstone lithofacies is associated with both fluvial and tidal environments (Pashin, 1999) (Figure 5.1). Different sublithofacies based on internal sedimentary structure reflect a range of depositional process within fluvial, deltaic, and tidal settings.

Trough and planar-tabular cross-bedded sandstone: Trough cross beds are product of migrating three-dimensional bedforms (Reading, 1996), whereas tabular cross-bed sets are formed by straight-crested bedforms (e.g., dunes and less commonly scroll bars and chute bars) (McCabe, 1977). Association of these sandstone units with bed-load dominated fluvial deposits (conglomerate lithofacies) suggests an anastomosed fluvial system (Rust and Legun, 1983, Pashin et al., 1995).

Current ripple cross-laminated sandstone: Ripple cross-laminated sandstones reflect relatively weak currents as well as high rates of bed aggradation (Stear, 1985). The presence of reactivation surfaces as well as mud-draped foresets indicates water-stage fluctuations in a tidal channel (Rust and Jones, 1987).

Massive sandstone beds with minor horizontal lamination: These deposits are usually associated with rapid deposition from suspension during floods. These beds may form in both channel-bar and channel-bank settings. The association of massive sandstones with prominent ripple cross-laminated sandstones can be interpreted as anastomosed river deposits (Smith and Smith, 1980; Rust, 1981; Nadon, 1994; Reading, 1996).

Sandstones thinly interbedded with mudstones: Sandstones with parallel lamination and lenticular structure are interpreted to represent intertidal flats (Pashin, 1993; 1999). Graded sandstones interbedded with rooted mudstone probably represent crevasses splays and associated floodplain environments (Allen, 1965). The contact between this sublithofacies and coal lithofacies represents erosional surface in interfluves.

5.3 ROOTED MUDSTONE AND SILTSTONE LITHOFACIES

Rooted mudstone and siltstone lithofacies usually designate clastic swamp environments (Pashin, 1993; Diessel et al., 2000) (Figure 5.1). Although this lithofacies can form in channels, it is mostly confined to floodplains as overbank deposits (Ékes, 1993).

Laminated mudstone and siltstone were deposited under reducing conditions, which is evidenced by their dark color. The laminated mudstone, which contains banded and layered siderite, is believed to be deposited from suspension on a floodplain or in abandoned channels such as oxbow lakes (Reading, 1996). Gray massive siltstones are the result of rapid deposition by flooding (Fielding, 1984). Floodplain deposits contain plant debris (leaf imprints) and roots. Well-preserved organic matter reflects water-logged conditions. As a part of repetitive fining-upward sequences, combined coal and rooted mudstone lithofacies may be overlain by sandstone lithofacies. In these cases, tops of this lithofacies represent interfluvial erosional surfaces.

5.4 COAL LITHOFACIES

The Pottsville coal belt in Alabama formed as a widespread system of equatorial peat swamps (Phillips and Peppers, 1984) (Figure 5.1). High detrital ash content records dominantly low-lying swamps. However, some low-ash coal has been attributed to doming (Eble et al., 1994). Sulfur content is higher than 2% in coal with marine roof strata (Williams and Keith, 1963; Casagrande, 1987), and a wide range of sulfur contents reveals that coals were preserved below marine through terrestrial roof facies. The variable thickness and extent of Pottsville coal beds further points to diverse origins (Pashin and Gastaldo, 2009). Many of the thin, discontinuous beds are interpreted to be the products of localized swamps. These beds were prone to erosion or pass laterally into contemporaneous siliciclastic facies. In contrast, regionally extensive coal beds provide evidence for widespread flooding and water-clogged environments (paludification) in the coastal plain (Diessel, 1998). Bases of this lithofacies represent correlative surfaces on interfluves for the basal erosional discontinuity of major channel fill deposits.

5.5 WAVY BEDDED SHALE AND SANDSTONE LITHOFACIES

This lithofacies is typical of tidal-flat deposits (Figure 5.1). Tidal flats form along stretches of shoreline and their extent depends on tidal range, sedimentary supply and shoreline gradient (Nichols, 1999).

The combination of mud and relatively fine-grained sand records a mixed intertidal flat environment for this lithofacies. Relatively fine-grained sediments are retained here by the process of flocculation and settling (Reading, 1996). Mixed mud and sand reflect roughly equal contributions of suspension and bedload deposition. So, with decreasing mud proportion upsection, lenticular bedding changes to wavy bedding and wavy bedding changes to flaser bedding (Reineck and Wunderlich, 1968).

Lenticular bedding is composed of isolated ripples of sand completely surrounded by mud. These are produced when sand ripples are formed on muddy substratum and preserved as a result of deposition of the next mud layer (Reineck and Singh, 1975). Flaser bedding is characterized by isolated drapes of mud within cross-laminated sand. Sand is deposited during periods of current activity, while mud is deposited during current pauses in ripple troughs or completely covering the ripples (Nichols, 1999). During the next tidal cycle, ripple crests are eroded away and more sand is deposited as ripples, burying and preserving ripple beds with mud flasers in the troughs. Bifurcated flasers form when previously and newly formed flasers are in contact, indicating stronger intermittent reworking than simple flaser bedding (Reineck and Singh, 1986). Intermediate forms called wavy bedding, made up of approximately equal proportions of sand and mud, reflect equal contributions of suspension and bedload deposition (Reineck and Singh, 1975). In association with burrowed mudstone, this lithofacies demarcates ravinement surfaces.

5.6 GRADED SANDSTONE AND SHALE LITHOFACIES

The graded sandstone and shale associated with rooted mudstone are interpreted as crevasse splays and associated floodplain deposits (Figure 5.1). Graded beds are common in Pottsville delta-front deposits (Pashin, 1999; Greb et al., 2004) but are relatively rare in the SWEPI cores.

5.7 BURROWED MUDSTONE LITHOFACIES

This lithofacies is interpreted to be the product of slow deposition of suspended sediments in areas unaffected by wave or tidal processes, such as a delta-front slope or prodelta (Figure 5.1). Prodelta environments are closely associated with prograding delta systems. They comprise relatively stable zones where fine-grained river sediments carried in a buoyant plume are deposited from suspension to form well-laminated sediments (Reading and Collinson, 1996). Thinly interbedded sands are believed to reflect short pulses of terrestrial sediment input. This lithofacies, in association with wavy bedded shale and sandstone, defines ravinement surfaces.

5.8 SHELLY SANDSTONE AND SHALE LITHOFACIES

Interbeds of shale and very thinly laminated sand associated with localized bioturbation record slower sedimentation rates for this lithofacies. Usually, deep-water sedimentation is much slower than in shallower marine settings and results in much thinner beds (Loutit et al, 1988; Kidwell, 1989). Thus, shales in this lithofacies are interpreted as hemipelagic deposits that accumulated on a sediment starved shelf. Fossiliferous layers formed as a result of sea-level rise and condensation.

Based on the occurrence of hemipelagic sediments and layers of marine fossils, this lithofacies is inferred to represent marine condensed sections. Condensed sections usually form on the middle to outer shelf, slope, and basin floor during periods of maximum relative sea-level rise and maximum transgression of the shoreline (Loutit et al, 1988; Nichols, 1999) (Figure 5.1). Maximum flooding surfaces occur within the condensed sections.

5.9 VERTICAL DISTRIBUTION OF PALEOENVIRONMENTAL REGIMES

Inferred depositional environments from the Pottsville Formation encountered in the SWEPI2 core represent a progression from tidal/deltaic to terrestrial sedimentation. Stacked coarsening upward cycles in the lower part (mudstone measures) of core SWEPI2 represents dominantly tidal and deltaic environments. A few prominent marine zones record transgression of sea over tidal or deltaic deposits (Figure 5.2). The major shift from tidal/deltaic to dominantly terrestrial environments is indicated by the appearance of fluvial and clastic swamp deposits at the top (2000 to 2450 ft) of the lower part of the core.

The upper part of the core (conglomerate measures) mainly represents stacked fining-upward cycles deposited in fluvial and clastic swamp environments (Figure 5.3). Multistory channel fills with common amounts of unstable grains (feldspars) represent a terrestrial setting where the source was close and sediments were distributed through a bedload to mixed-load dominated fluvial system.

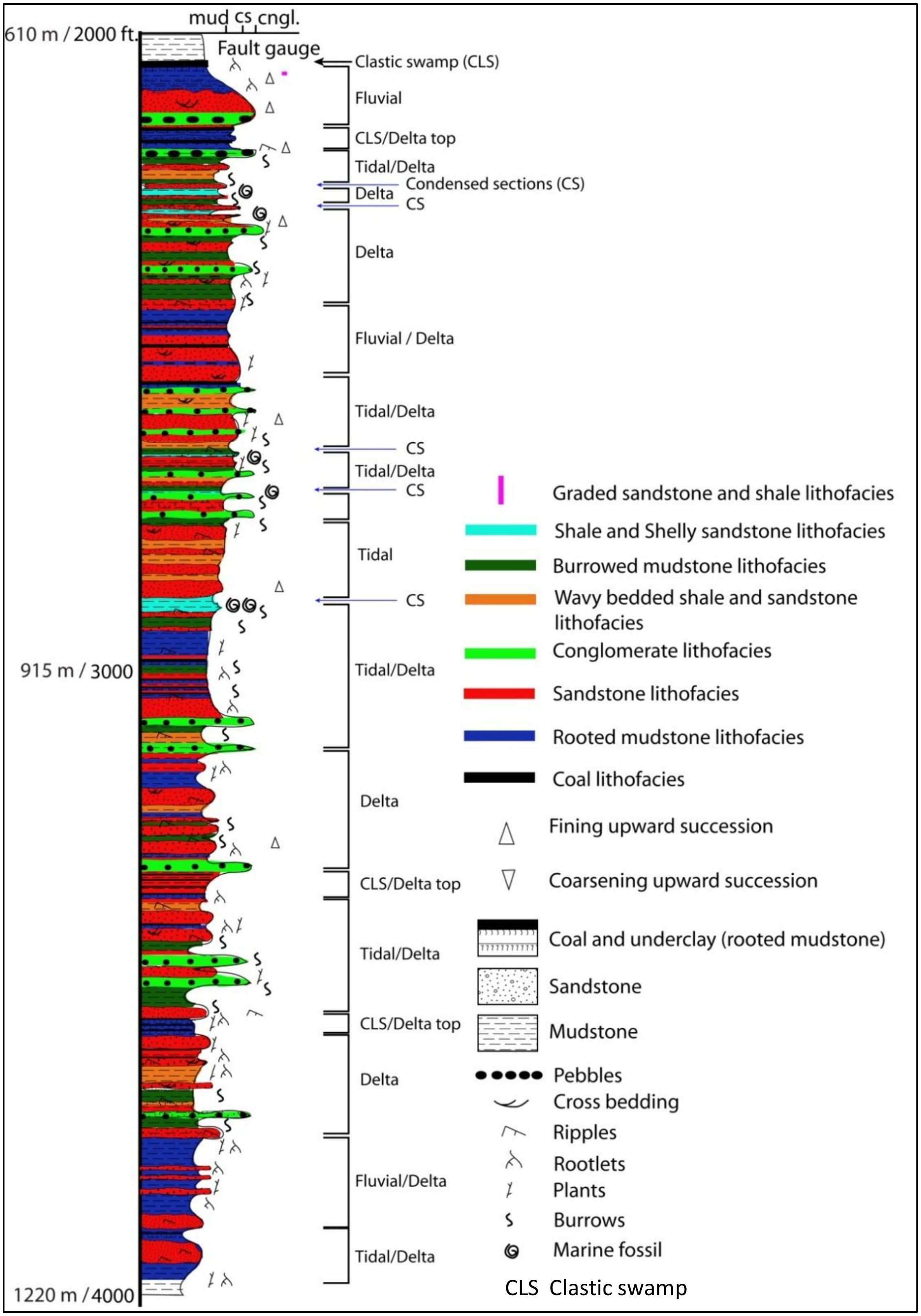


Figure 5.2: Interpreted depositional environments in the lower part of core SWEPI 2.

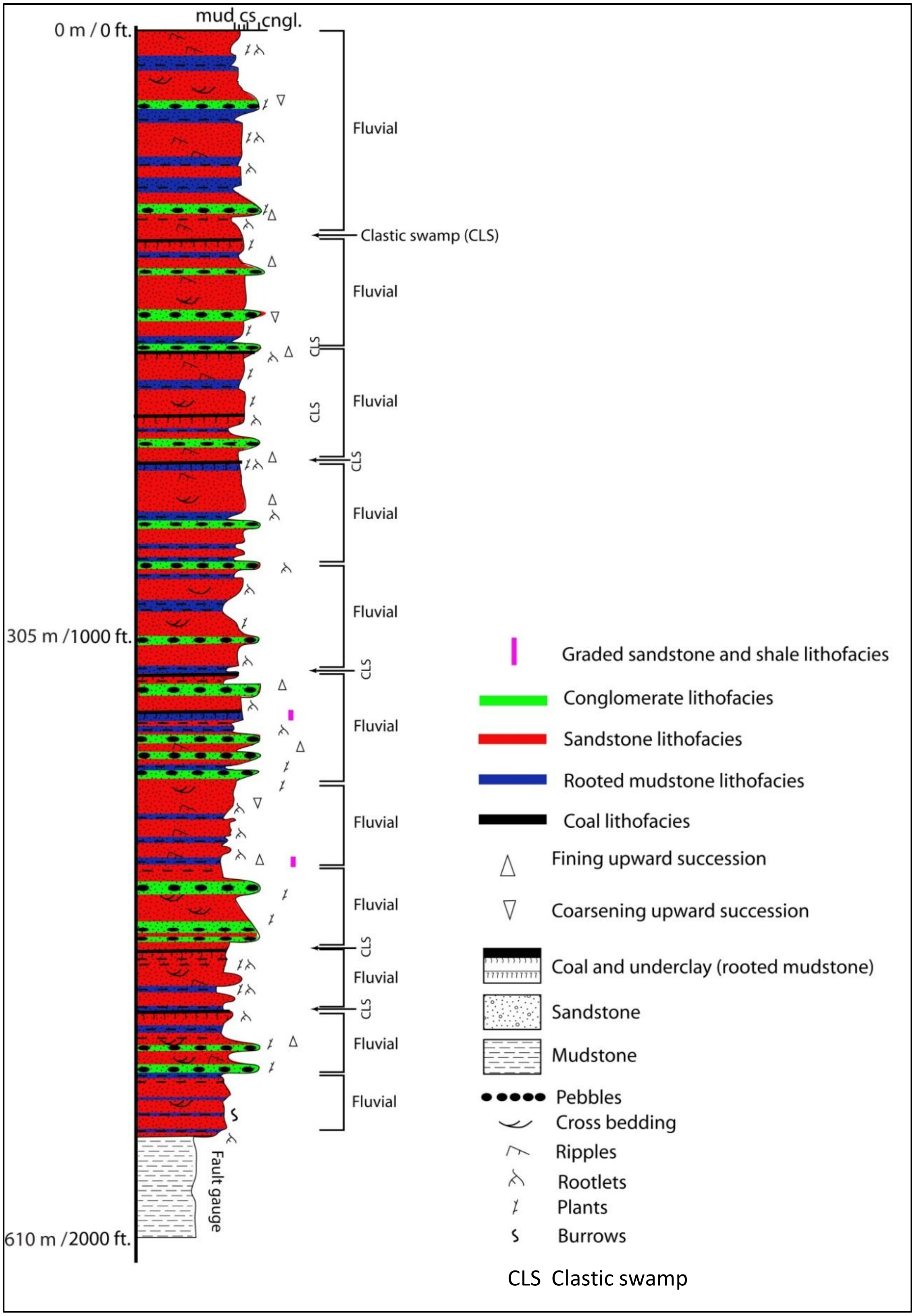


Figure 5.3: Interpreted depositional environments in the upper part of core SWEPI 2.

CHAPTER 6: STRATIGRAPHIC ARCHITECTURE

6.0 INTRODUCTION

Stratigraphic architecture is the result of a complex interaction of a wide variety of physical processes, e.g., rainfall, erosion, flood, ocean currents, waves, storms, seafloor failure, and tectonic deformation. Identification of key stratigraphic elements within the studied cores is crucial for the sequence stratigraphic analysis. The log and facies expression of identified surfaces (in chapter 3) varies considerably with the paleogeographic position in the synclinorium (Pashin, 1999, Greb et al., 2004). A combination of core, outcrop, well-log, and seismic data are used for a detailed analysis of both lithostratigraphically and chronostratigraphically significant surfaces and horizons (Posamentier et al., 1988; Van Wagoner et al., 1990; Bhattacharya, 1992). The analysis in the current research is based solely on core data. Hence, identified surfaces and horizons have only lithostratigraphic significance. Nonetheless, they at least provide an idea about the probable occurrence and nature of base-level changes.

Based on lithofacies descriptions, inferred depositional environments, and paleogeographic location of the studied cores, the following stratigraphic architectural elements have been identified: Progradational elements, aggradational elements, erosional surfaces, flooding surfaces, and condensed sections.

6.1 PROGRADATIONAL ELEMENTS

Upward coarsening successions represent progradational elements, which are typically the most common architectural elements in the deltaic/tidal portion (mudstone measures) of the Pottsville Formation (Pashin et al., 1995; Greb et al., 2004). Coarsening-upward successions overlie fining upward successions and are highly variable in thickness, ranging from 5 to 120 feet. Higher-frequency, coarsening-to-fining upward intervals within overall coarsening upward successions range in thickness from 1 to 50 feet (Figure 6.1). Lower-frequency successions consist of mudstone, sandstone, conglomerate, and coal. Bases are sharp and overlain by the shelly sandstone and shale lithofacies which is commonly succeeded by burrowed mudstone lithofacies. This transition in lithofacies records a shift from deep-water to pro-delta environments. The latter mudstone coarsens upward and intertongues with sandstone and merges into sublithofacies of sandstone which form thin interbeds with mudstones. Sand and mud interbeds form wavy, lenticular and flaser beddings under a tidal environment and are overlain by fluvial deposits consisting of trough and planar-tabular cross-bedded, ripple laminated, and massive sandstone sublithofacies and conglomerate lithofacies. Coal lithofacies usually cap the coarsening-upward successions and are laterally persistent independent of the extent of the underlying coarse-grained facies (Pashin and Carroll, 1999). Coarsening upward cycles are typical of fluvial-deltaic deposits. Bases are ravinement surfaces formed by shoreface erosion followed by prodelta deposition (burrowed mudstone). Interbedded tidal sand and mud and fluvial sandstone and conglomerate represent delta-front and delta plain deposits.

Coarsening-upward successions are interpreted as deposits of prograding deltas, formed during late stages of base-level rise through early stages of base-level fall in the Cahaba synclinorium (Pashin et al., 1995) and adjacent Black Warrior basin (Korus, 2002; Greb and

Martino, 2005). An overall coarsening-upward succession may be generated by channel avulsion, delta-lobe switching or growth faulting (Bodek, 2006). Sandstones, and in some cases conglomerate lithofacies, of these successions are believed to be anastomosed channel deposits (Coleman, 1976; Bhattacharya and Walker, 1992; Reading and Collinson, 1996).

These coarsening upward successions are overlain and underlain by upward-fining intervals which are also capped by coal. Upward fining deposits (graded sandstone, rooted mudstone, and coal lithofacies) are believed to be the product of crevasse-splay and overbank sedimentation followed by accumulation of peat in the delta plain (Coleman, 1976).

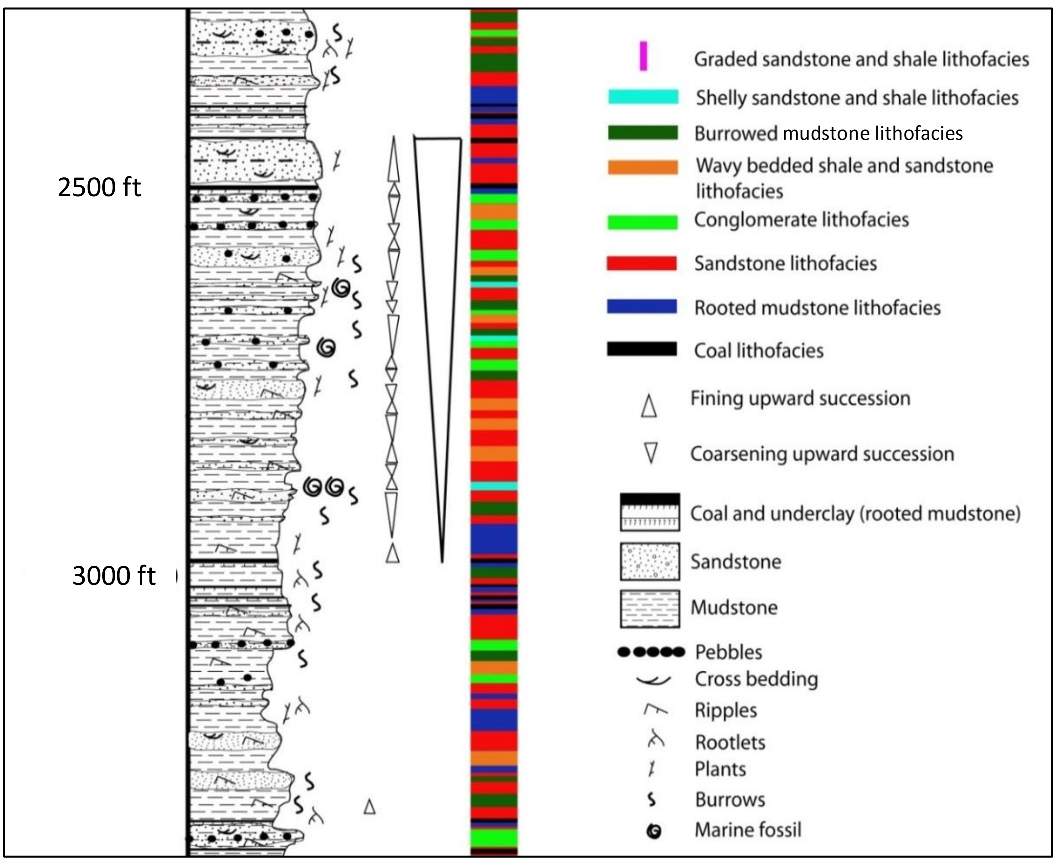


Figure 6.1: Overall coarsening upward succession with high frequency, small-scale coarsening-fining upward successions in the Pottsville Formation of Cahaba synclinorium representing progradational elements.

6.2 AGGRADATIONAL ELEMENTS

Fluvial sequences typically show fining-upward successions that reflect aggradation in energy-declining environments (Eberth and O'Connell, 1995; Hamblin, 1997; Catuneanu and Elango, 2001). Fining-upward aggradation elements are the most common stratigraphic elements in the fluvial-dominated upper part and locally in the marine-dominated lower part of core SWEPI2. Fining-upward successions are typically 10-30 feet thick. Extraformational conglomerates form the bases of these fining-upward sequences and grade upward to sandstone lithofacies, which in turn grade upwards into rooted mudstone and siltstone. In the lower part of core SWEPI2, such successions continue with the wavy bedded shale and sandstone lithofacies. Typically the succession is capped by rooted mudstone and coal lithofacies (Figure 6.2). Higher-frequency, coarsening-to-fining upward intervals occur within these overall fining-upward successions. Fining-upward successions directly underlie coarsening-upward successions.

Fining-upward successions indicate waning of flow conditions associated with base-level rise and decreased gradients. Continuous base-level rises initiate back-flooding of incised valleys and the formation of estuaries. The wavy bedded shale and sandstone lithofacies represents tidally influenced sedimentation and records marine invasion into fluvial environments (Greb and Martino, 2005). Widespread peat accumulation during stages of estuarine infill is recorded by capping coal layers. The coal layers suggest that marine invasions were sufficient enough to result in widespread coastal swamps (Shanley and McCabe, 1995).

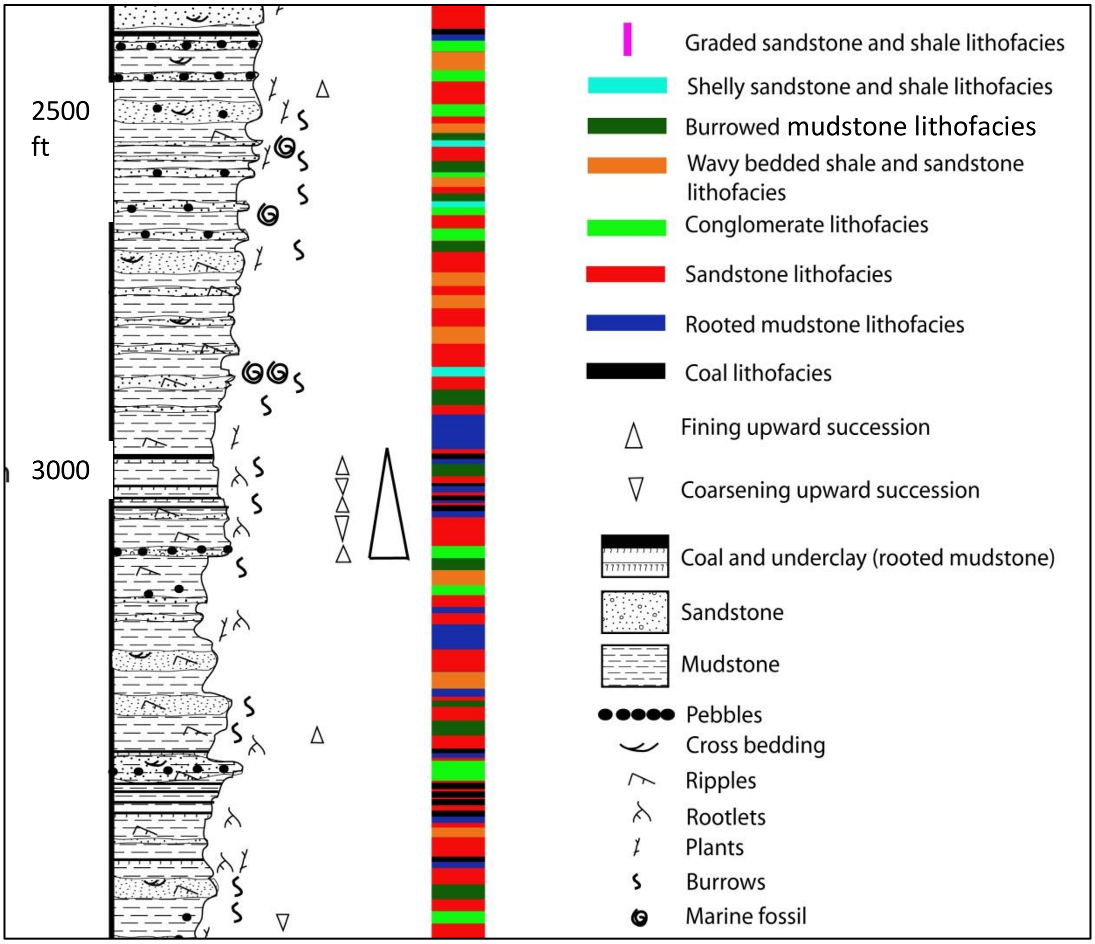


Figure 6.2: Overall fining-upward succession with small-scale coarsening-fining upward successions in the Pottsville Formation of Cahaba synclinorium representing aggradational elements.

6.3 BOUNDING DISCONTINUITIES

Bounding discontinuities in the studied cores are either erosional (unconformable) or depositional (condensed sections) (Walker, 1992). In addition to these two features, a few marine zones that contain flooding surfaces have been identified. Minor erosional discontinuities are common at the bases of isolated, lenticular sandstone bodies throughout most of the study interval. In contrast, major discontinuities are found at the bases of the widespread, conglomerate and amalgamated sandstone bodies.

6.3.1 EROSIONAL SURFACES

Erosional surfaces in the studied cores are mainly unconformable surfaces. These surfaces are commonly identified at the bases of channel-fill deposits (sandstone and conglomerate lithofacies) (Figure 6.3) in the fluvial dominated upper part of the section but also locally in the lower part of the section. Anomalously thick channel-fill deposits, and presence of multiple channel-fill deposits clustered within a relatively small vertical section, justify the identification of incised valleys in the studied cores. During the downward shift of the fluvial equilibrium profile, the alluvial system responded by down cutting and channel incision. Several factors, which include tectonic tilting, increased stream power due to increased discharge, and increased alluvial gradient due to sea-level induced exposure of a relatively steep surface may cause these downward shifts in equilibrium profile (Schumm, 1993; Posamentier and Allen, 1999). These surfaces are overlain by conglomerate lithofacies and underlain by rooted mudstone lithofacies.

In the interfluves (Figure 6.3) where these channel fill bodies pinch out laterally, these surfaces correspond with regionally persistent paleosols and coal layers (Aitken and Flint, 1995; Greb and Chestnut, 1996; Catuneanu, 2003). Simple discontinuities created by the shift of channels, including in some cases channel avulsion, create erosional surfaces on flood plains that are not associated with regional channel incision. These surfaces typically are overlain by graded sandstone sublithofacies or coal lithofacies and underlain by rooted mudstone lithofacies. The lack of channel clustering on top of these discontinuities differentiates these surfaces from incised valley bottoms.

Ravinement surfaces are another form of erosional surface that represent scour due to marine transgression. Most of the ravinement surfaces identified are in the lower part of the

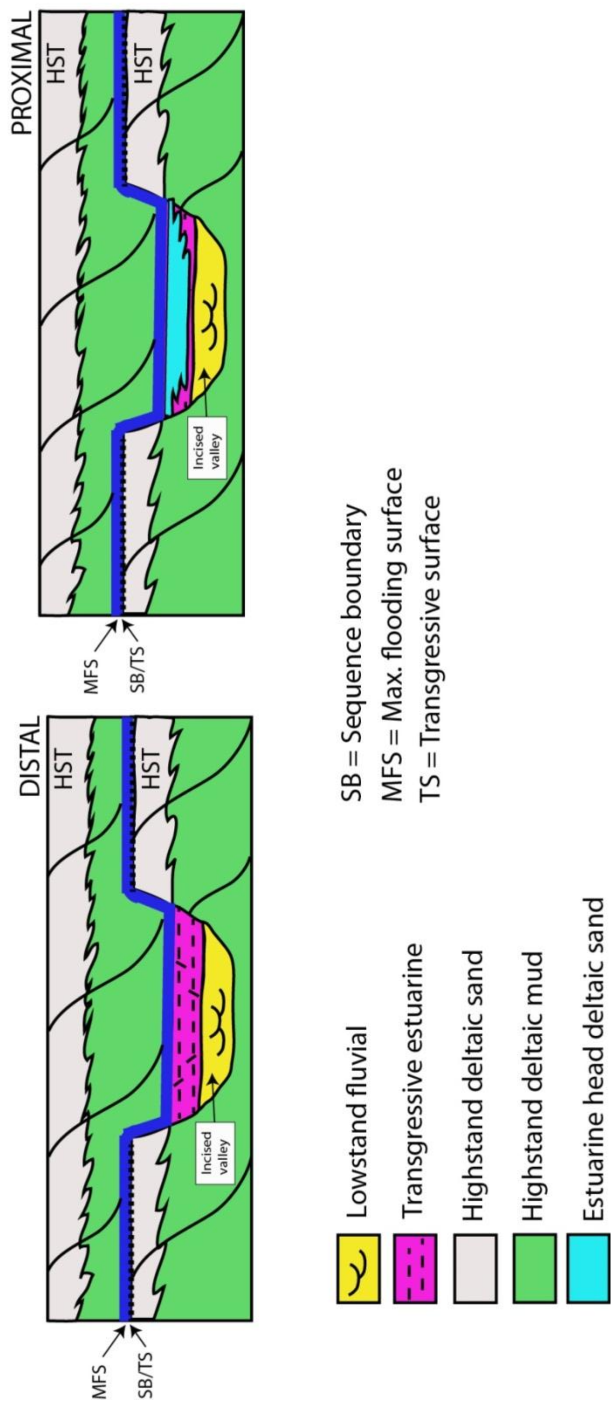


Figure 6.3: Hypothetical section across incised valley and interfluves representing key stratigraphic surfaces both distal and proximal part of the Cahaba basin during Early Pennsylvanian (modified from Posamentier and Allen, 1999).

studied core and those surfaces are overlain by shallow marine facies (burrowed mudstone and wavy bedded shale and sandstone lithofacies) (Figure 6.4). Ravinement surface formation is linked to subaerial exposure during relative sea-level fall and subsequent transgression. Such surfaces are characterized by deeply weathered soil horizons that were preserved if coastal and shelf energy was weak and minimal erosion took place during shoreline transgression across the area.

Transgressive ravinement may remove significant amounts of sediment, masking subaerial exposure surfaces that developed during earlier phases of sea-level fall. Deposits immediately upon these surfaces are called transgressive lag deposits. They are relatively coarse-grained deposits that typically contain wood fragments and rip-up clasts, all of which were derived from underlying deposits (e.g., rooted mudstone and siltstone as well as burrowed mudstone). Deeply penetrating burrows locally characterize ravinement surfaces.

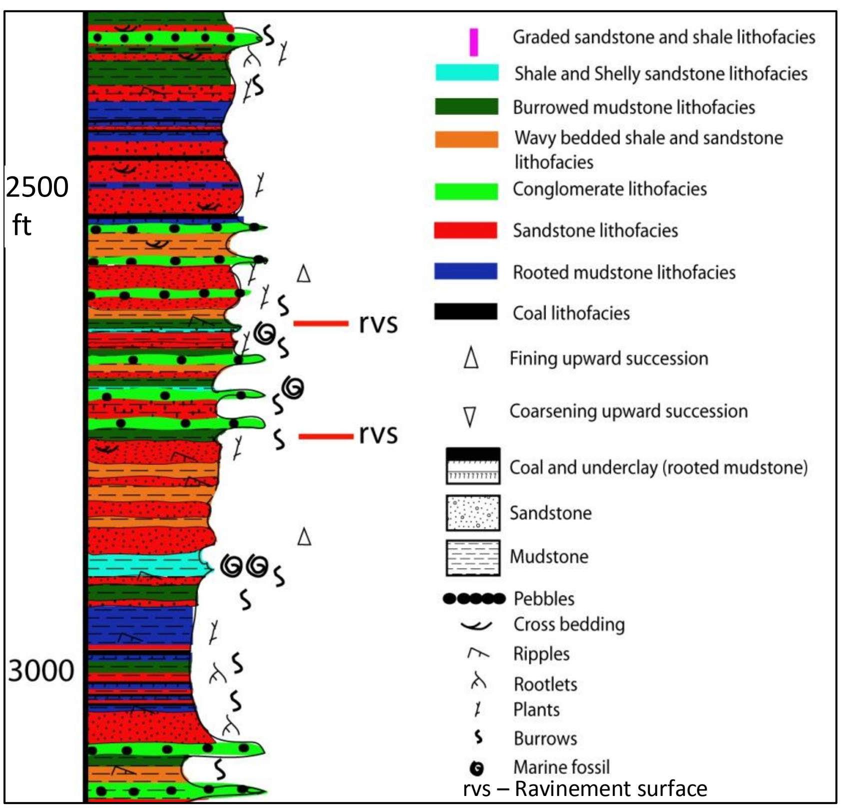


Figure 6.4: Ravinement surface (rvs) overlain by shallow marine facies in the lower part of the core.

6.3.2 FLOODING SURFACES AND CONDENSED SECTIONS

Flooding surfaces lie within the shale and shelly sandstone lithofacies, locally associated with wavy bedded shale and sandstone lithofacies and on top of rooted mudstone and extensive coal layers (Figure 6.5). Based on similar studies (Mars, 1995; Pashin et al., 1995; Bodek, 2006) of Lower Pennsylvanian sequences within the Appalachian basins, these zones and associated surfaces have been grouped into two categories; major and minor flooding zones and associated surfaces.

Major flooding surfaces are identified within the shale and shelly sandstone and locally on top of wavy bedded shale and sandstone lithofacies. Occurrences of the shelly sandstone and shale lithofacies are identified as condensed sections, which represent depositional bounding discontinuities (Walker, 1992). At the time of maximum transgression, coastal depocenters are located at their maximum landward position. Consequently, at these times relatively slow pelagic and hemipelagic sedimentation prevails on the middle to outer shelf and beyond. The resulting deposits are thin and represent relatively long periods of geologic time (Loutit et al., 1988). Condensed sections are relatively easy to identify as they are composed predominantly of fine-grained, hemipelagic deposits that accumulated during times when minimal continental sediments are delivered to shelf and deep-water environments (Figure 6.6). Marine flooding surfaces are typically found within the condensed sections (Figure 6.6). In the lower part of the core SWEPI 2, five condensed sections are identified based on the occurrence of the shelly sandstone and shale lithofacies. In the non-marine dominated upsection of the lower core, flooding surfaces are associated mostly with rooted mud with thinly laminated silt, barren of any marine fauna or trace fossils. Occurrences of rooted mud with thinly laminated silt signal tidal influences in estuaries. When identified atop wavy bedded shale and sandstone, flooding surface contains straight to slightly curve horizontal burrows (*Planolites*). These major flooding surfaces are laterally more extensive than their minor counterparts. Out of the five condensed sections, three major marine flooding surfaces have been identified at 2400, 2750, and 2900 ft based on the abundance of fossils.

Minor marine zones/flooding surfaces typically occur on top of fining-upward successions that contain either rooted mudstone or coal lithofacies. These deposits represent clastic swamp environment in interfluves. The minor flooding zones are thinner than their major counterparts.

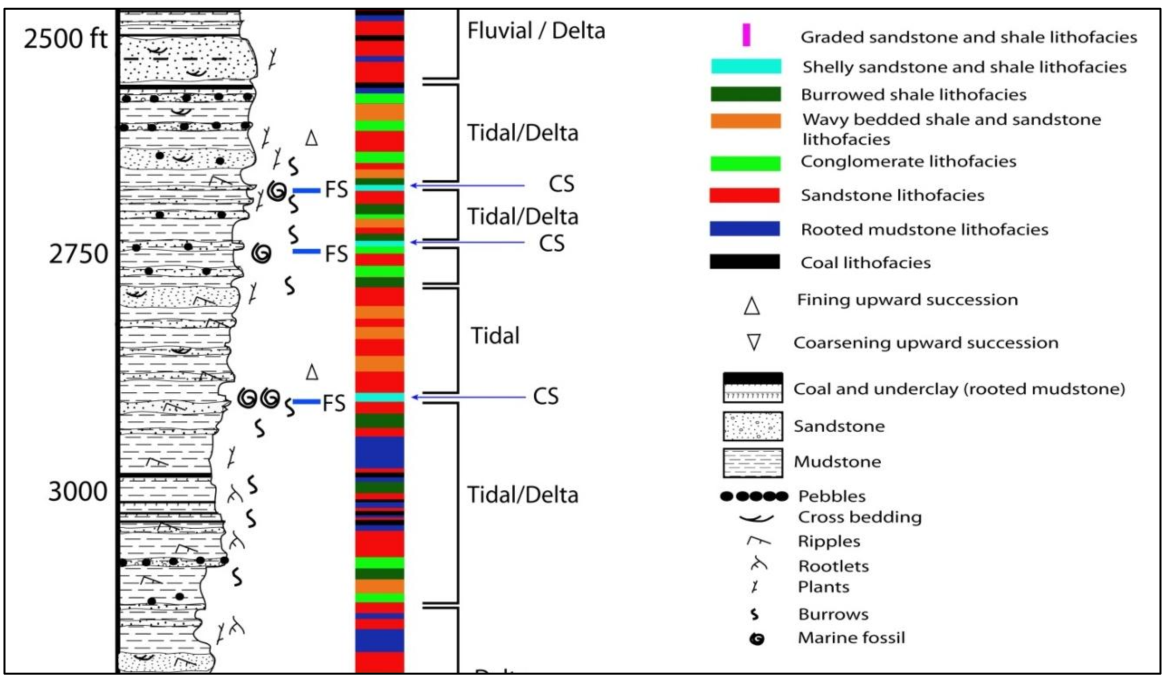


Figure 6.5: Flooding surfaces (FS) within condensed sections (CS). Condensed sections are identified by abundant fossil content within shale and shelly sandstone lithofacies.

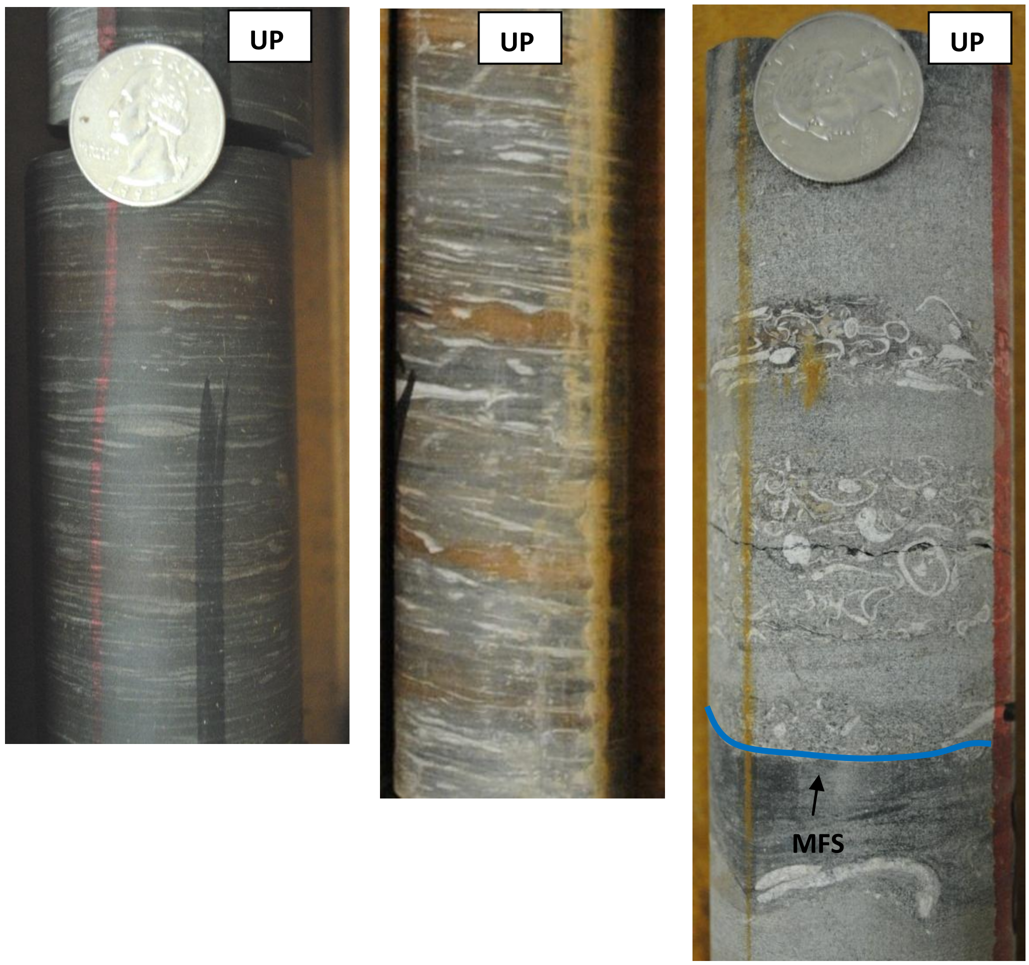


Figure 6.6: Typical condensed section in shelly sandstone and shale lithofacies containing minute burrows and sand lenses. Left core is from 3608 ft and middle core is from 3731 ft. The right core, from 2900 ft, depicts a fossil lag. The marine flooding surface (MFS) is at the contact between the shale and the shelly sandstone. Surfaces within the lag mark minor events associated with reworking during marine transgression and condensation.

CHAPTER 7: SEQUENCE STRATIGRAPHIC FRAMEWORK

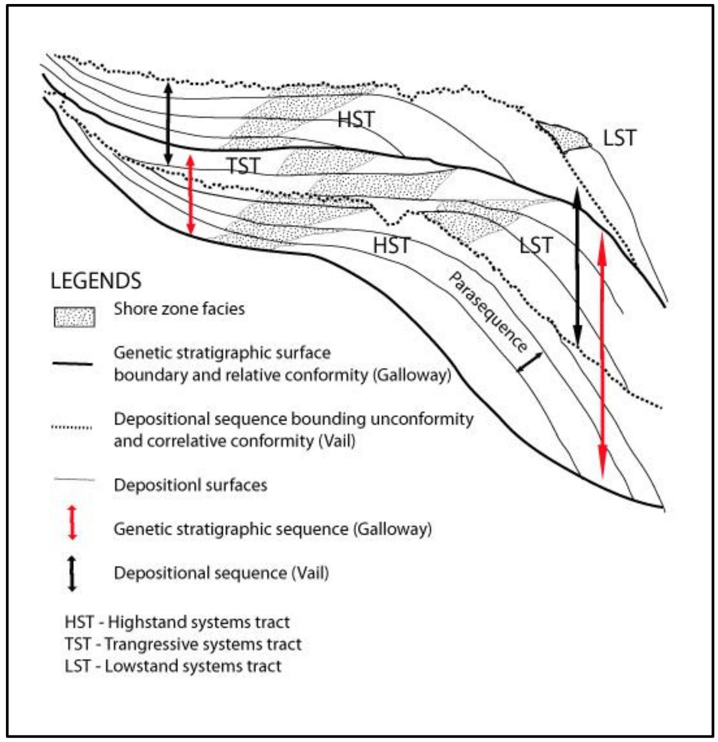
7.0 INTRODUCTION

Sequence stratigraphy deals with chronologically significant, genetically related, unconformity-bound intervals of sedimentary strata (Van Wagoner et al., 1988, 1990). Individual sequences, which are defined as relatively conformable, genetically related, and unconformity-bound successions of strata, are the basic building blocks of sequence stratigraphy (Mitchum, 1977). Lamina, laminasets, beds and bedsets, which are smaller-scale stratal units, comprise progressively larger-scale stratal units including parasequences (shallowing-upward successions bound by flooding surfaces) (Van Wagoner et al., 1988) and sequences.

This internal packaging of progressively thicker stratal units representing increasingly greater amounts of time ultimately defines a chronostratigraphic hierarchy (Van Wagoner et al., 1990; Mitchum and Van Wagoner, 1991). Lower-order sequences are stacked within higher-order sequences usually in a repetitive and anticipated way. Lower-order sequences, including parasequences, will predictably differ in facies-stacking patterns, sediment-body geometry, and position along depositional dip (Van Wagoner et al., 1988). Stacking patterns, distribution, and sediment-body geometry of lower-order stratal units within higher-order sequences provides some clues for identifying the controlling factors within a given depositional system. Depositional controlling factors (e.g., eustasy, tectonism, climate, sediment supply) influence base-level change, which ultimately dictates development of sequences.

Two different sequence models have been applied in this study (Figure 7.1). They are the depositional sequence (Vail-type sequence) and the genetic stratigraphic sequence (Galloway-type sequence) (Van Wagoner et al., 1988; Galloway, 1989). The primary difference between the two types is in the selection of sequence-bounding surfaces.

Figure 7.1: Schematic cross section of a Vail-type and a Galloway-type sequence (modified from Galloway, 1989).



The Vail-type sequence was developed as a basin-analysis tool to identify rock units that were deposited under varying conditions of eustatic sea-level change, tectonic subsidence, and sedimentation rates on Mesozoic and Cenozoic passive margins (Mitchum et al., 1977; Haq et al., 1988; Posamentier et al., 1988; Posamentier and Vail, 1988). A Vail-type sequence is bounded by unconformities that are interpreted as paleogeographic surfaces produced by basin- wide eustatic sea-level falls. Bounding surfaces or the sequence boundaries of a Vail-type sequence could be subaerial erosional surfaces, bases of incised valleys, or correlative surfaces on interfluves, and correlative conformities downdip.

Galloway (1989) identified and defined genetic sequences along the Cenozoic Gulf Coastal Plain using a sequence-bounding model to determine basin paleogeography and sediment dispersal patterns. A genetic stratigraphic sequence is defined as a rock or sediment unit that records a sequence of basin-margin outbuilding and filling (shoaling upward) followed by basin-wide flooding (Galloway, 1989). The boundaries between genetic stratigraphic sequences are identified as major marine-flooding surfaces, which occur within basin-wide condensed sections (thin, deep-water succession containing abundant marine fossils). Marine flooding surfaces separate sediments that were deposited in more landward depositional settings from overlying sediments that were deposited in more seaward depositional settings (Van Wagoner et al., 1990). Such vertical changes from landward to seaward facies are referred to as transgressive shifts in facies.

7.1 SEQUENCE STRATIGRAPHIC INTERPRETATION OF BOUNDING DISCONTINUITIES

The framework of major and minor discontinuities, including erosional (unconformable) horizons and marine zones, in the two cores provides a basis for evaluating the lower Pennsylvanian strata of Cahaba synclinorium in both a depositional and genetic sequence framework. In a genetic framework (e.g., Galloway, 1989), Pashin (1994, 1998) previously identified at least fifteen marine flooding surfaces within marine zones in the Pottsville Formation of the Black Warrior basin. These inferred sea-level cycles were attributed to glacial-eustacy but the apparent magnitude of flooding and condensation may have been controlled by subsidence rates. These marine zones separate the Pottsville Formation of the greater Black Warrior Basin into thirteen separate depositional cycles of variable thickness (Pashin, 1994, 1998).

Younger Pottsville strata of greater Black Warrior basin are 308.6±2.7 Ma based on dating of a volcanic ash bed at a drill core in Mississippi (Uddin et al., 2010a). Considering this age as near the upper boundary of the Pottsville Formation and using the timescale of Harland et al. (1990), the formation represents a span of 7 m.y. Recognizing the uncertainty in Pennsylvanian geochronology (Klein, 1990; Menning et al., 2000), correspondence of depositional cycles to orbital eccentricity may be superfluous. Still, estimates of cycle duration using the timescale of Harland et al. (1990) tend to be longer than estimates using other timescales, and the 7-m.y. span assigned to the Pottsville Formation is a conservative estimate. Therefore, cycles in the upper part of the Pottsville Formation were deposited almost certainly at the high frequencies attributed to the classic Pennsylvanian cyclothems of the North American mid-continent (Pashin, 2004). If the 13 Pottsville cycles are assumed to represent equal amounts of time, then each cycle was deposited in 0.5 m.y. using the timescale of Harland et al. (1990). As variations in cycle thickness would necessitate unreasonable changes of subsidence rates for an actively loaded foreland basin like the Cahaba basin, the assumed 0.5 m.y. time span for each cycle is almost certainly incorrect. The 13 cycles identified within the Pottsville Formation in greater Black Warrior basin represent a range of time spans (Pashin, 2004). A model generated by doubling the subsidence rates of the Black Warrior basin in different locations indicates an increase of time in earlier cycles, decrease in later cycles and no time variation in middle cycles (Pashin, 2004). The Pottsville cycles in the Black Warrior basin have been identified dominantly as 3^{rd}-order cycles by Pashin (2004), although studies show a transition to dominant 4^{th}-and 5^{th}-order cycles in the northwestern part of the basin (Pashin, 1997, 2004).

Following the criteria described in previous studies (Pashin, 1994, 1997, 1998, 2004), three major marine flooding surfaces (Figure 7.2 A) and associated condensed sections have been identified in core SWEPI 2 based on the occurrence of thinly laminated marine successions and abundance of associated marine fossils. These surfaces have been designated as 3rd-order *genetic* sequence boundaries, and the successions bounded by these surfaces are designated as 3rd-order *genetic* sequences.

Recognition of major marine flooding zones as 3rd-order maximum flooding surfaces leads to the interpretation of underlying major discontinuities at the bases of thick, amalgamated channel sandstone as third-order sequence boundaries in *depositional* sequence model (Figure 7.2). According to the depositional sequence stratigraphy perspective (e.g., Vail et al., 1977), amalgamated, thick channel sands based by conglomerate lithofacies are interpreted as incised valley fills in the fluvial dominated part and estuarine channel fill in the deltaic deposits. Bases of these channel bodies demarcate third-order *depositional* sequence boundaries. Seven 3rd-order *depositional* sequence boundaries have been identified throughout core SWEPI 2. Third-order marine flooding surfaces in the deeper part of the core are found stratigraphically above these major sequence boundaries, and differentiate the studied core into separate third-order *genetic* sequences.

Minor erosional discontinuities occur at the bases of isolated fluvial channel sandstone bodies. A recent (Bodek, 2006) sequence stratigraphic study of the Early Pennsylvanian Breathitt Group, West Virginia, deposited in a similar setting in the central Appalachian basin identified 400-k.y. duration for the sequences bounded by aforementioned minor erosional discontinuities at the base of isolated fluvial channel sandstones. The 400-k.y. interval for these sequences is comparable to the duration of long-term global eccentricity cycles (Plint, 1992; Read, 1995). These surfaces and the sequences they bound have been identified as 4th-order depositional sequence boundaries and 4th-order sequences, respectively. Similarities between the results of Bodek (2006) and the current study suggest that the twelve minor erosional discontinuities identified throughout the core could be interpreted as 4^{th}-order depositional sequence boundaries and the sequences bounded by those discontinuities could be interpreted as 4^{th} -order depositional sequences (Figure 7.2). The isolated fluvial sandstone bodies on top of these boundaries abruptly overlie muddy lithofacies such as rooted mudstone and wavy bedded shale and sandstone. Grain-size contrast across these discontinuities and regional extent of these surfaces based on previous studies (Pashin et al., 1995; Pashin, 1997, 2004; Greb at al., 2004) indicate origin from regional base-level falls and lead to their interpretation as *depositional* sequence boundaries (Aitken and Flint, 1994).

Minor flooding surfaces occur throughout the core at the tops of fining-upward successions within fourth-order depositional sequences. Usually these flooding surfaces occur in zones that contain successions of rooted mudstone and a regionally persistent coal that represent floodplain and clastic swamp environments (Figure 7.2). These flooding zones are thinner than the major flooding zones, which contain marine fossil and condensed sections. Based on sequence stratigraphic analysis and cyclic sedimentation of Lower Pennsylvanian rocks in southern (Mars, 1995, Pashin et al., 1995, Greb et al., 2004, Pashin, 2004) and central (Martino, 2004; Bodek, 2006) Appalachian basins, flooding surfaces within these thin flooding zones associated with coal and rooted mudstone lithofacies have been interpreted as 4^{th}-order sequence boundaries in the *genetic* sequence model. Eleven 4^{th}-order genetic sequence boundaries have been identified in the SWEPI 2 core (Figure 7.2).

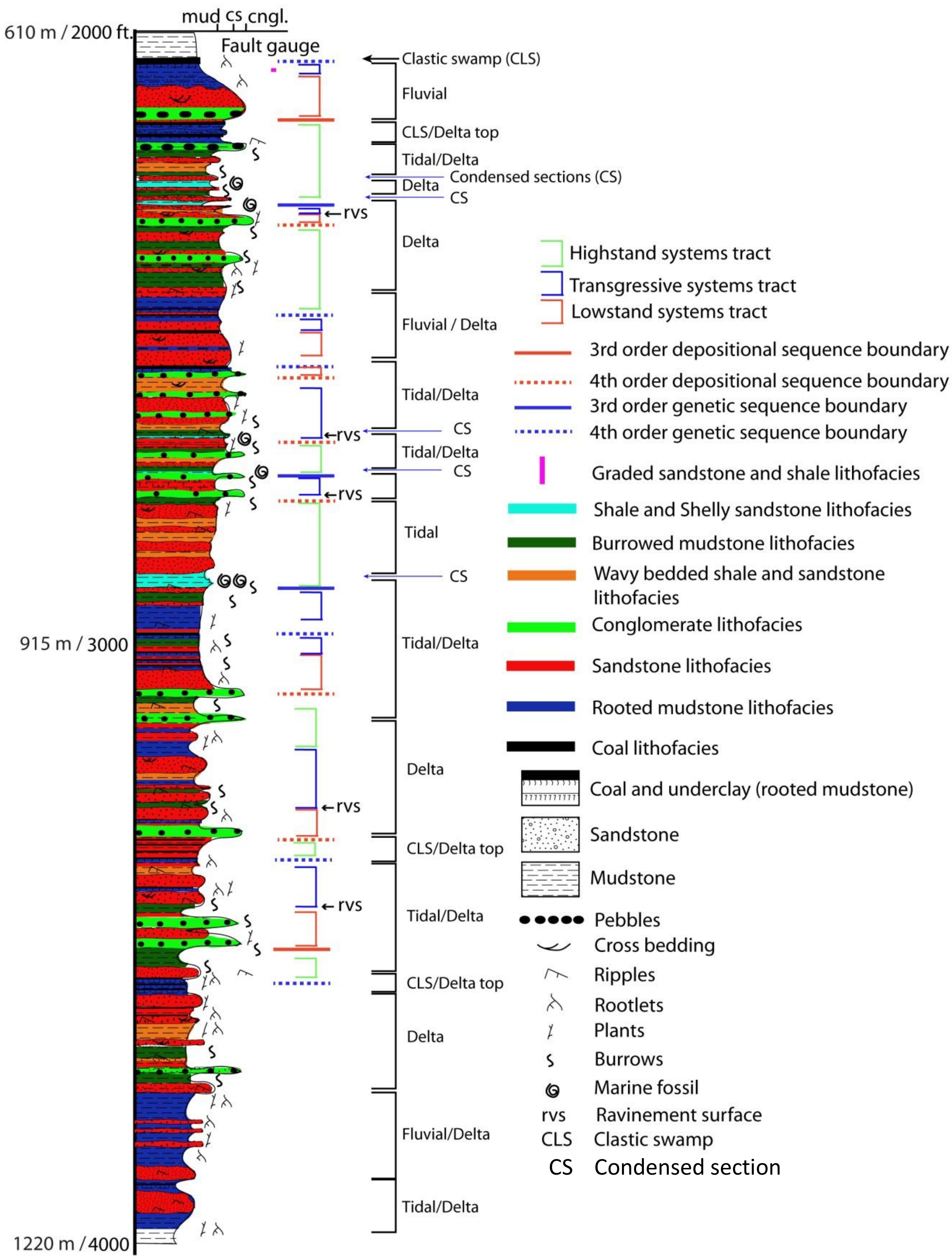


Figure 7.2(A): Proposed sequence boundaries and systems tracts in the lower-half of the graphic log at the SWEPI 2 well of Pottsville Formation in Cahaba synclinorium.

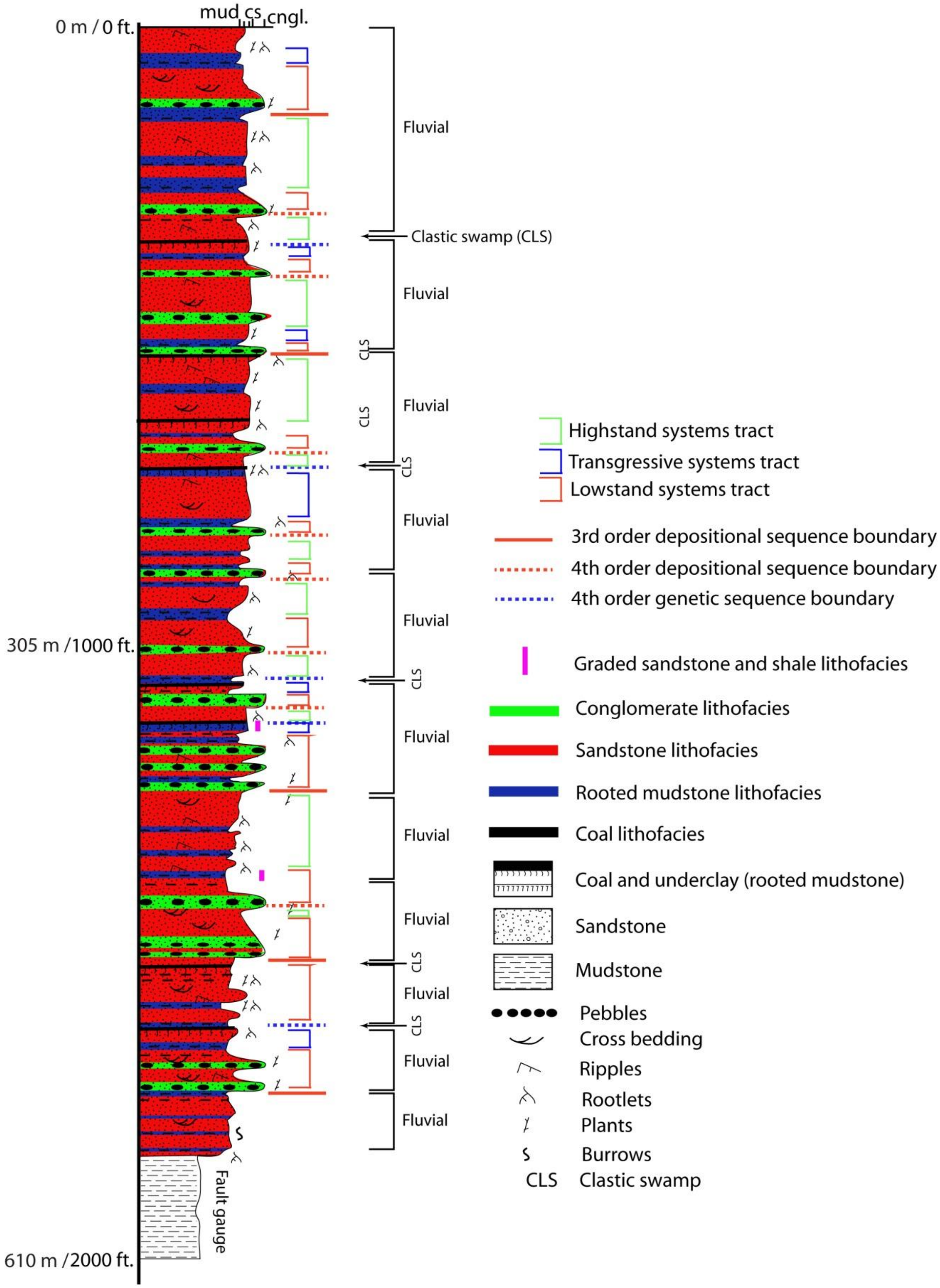


Figure 7.2(B): Proposed sequence boundaries and systems tracts in the upper-half of the graphic log at the SWEPI 2 well of Pottsville Formation in Cahaba synclinorium.

7.2 IDENTIFICATION OF SYSTEMS TRACTS

Fourth-order sequence and flooding surface-bounded successions comprise larger-third order sequences. A similar sequence hierarchy was recognized in correlative strata by Pashin (1997; 2004) in the greater Black Warrior Basin of Alabama, in the upper Mississippian of southern West Virginia by Miller and Eriksson (2000), and in the middle Mississippian by Smith and Read (2000). Additionally, fourth-order sequences have been recognized as comprising lowstand, transgressive, and highstand systems tracts within composite 3rd-order composite sequences, in the Middle Pennsylvanian of eastern Kentucky by Aitken and Flint (1994).

Sharp, erosional bases below incised valley-fill deposits of cross-bedded sandstone and conglomerate are interpreted as sequence boundaries that formed where the rate of eustatic fall exceeded basin subsidence at the depositional shoreline break (Vail et al., 1977; Van Wagoner et al., 1988). Coarse-grained incised valley fill and correlative interfluve areas are included within the lowstand systems tract (Van Wagoner et al., 1988; Aitken and Flint, 1995; Zaitlin et al., 1994; Petersen and Andsbjerg, 1996). Lowstand wedges are not observed in the Cahaba Synclinorium as they are probably developed along the distal shelf margin to the southwest in the Ouachita foredeep (Pashin, 2011, personal communication).

The lowstand systems tract is terminated at the transgressive surface, which probably occurs within the upper portions of alluvial incised valley fill (Posamentier and Jervey, 1988; Reading and Collinson, 1996). The upper boundary of lowstand systems tract is roughly equivalent to the transgressive surface (Posamentier and Allen, 1993; Zaitlin et al., 1994) and is expressed as a change from coarse fluvial facies to muddier estuarine facies (part of incised valley fills) (Greb and Martino, 2005). These fluvial to estuarine transitions are roughly correlative to down-dip marine flooding zones (Greb and Martino, 2005). In the studied core, these transitions are typically manifested as a vertical facies change from the current ripple cross-laminated sandstone to wavy-bedded shale and sandstone lithofacies with tidal indicators such as slack water-induced ripple bedding and tidal rhythmites. These transitions represent parts of fining-upward aggradational elements.

Aggradational fining-upward successions of conglomerate, sandstone and rooted mudstone lithofacies that are commonly overlain by a regionally persistent coal bed characterize transgressive systems tracts (Figure 7.3). Coal beds typically define the top of the transgressive systems tracts in dominantly alluvial settings. The maximum flooding surface caps the retrogradational transgressive system tracts in marine strata in the lower part of the core. Capping of transgressive system tracts by extensive marine flooding surfaces in the marine-dominated part is a characteristic feature of the Pottsville formation in southern Appalachian basins (Greb and Martino, 2005). A thick succession of burrowed mudstone overlying widespread coal beds is indicative of estuarine conditions developed with further transgression during maximum flooding. Similar estuarine deposits occur in the Pottsville Formation in both southern and central Appalachian basins (Zaitlin et al., 1994; Greb and Martino, 2005).

The bases of a relatively persistent burrowed mudstone lithofacies in the lower part (Figure 7.4) and dominantly rooted mudstone lithofacies in the upper part of the core mark the bases of highstand systems tracts. These mudstones continue to coarsen upward. Usually one or more coal beds also are encountered in the upper highstand systems tract especially within deltaic deposits. These coal beds have large spatial extent and typically cap small-scale fining-upward sequences in an overall coarsening-upward succession (Pashin, 1997; Pashin and Carroll, 1999). The highstand systems tract shows a complete coarsening-upward aggradational element and is terminated at the overlying sequence boundary.

In the central and southern Appalachian basin, both erosional (sequence boundaries) and condensed (marine flooding surfaces) bounding discontinuities have been recognized. In the studied core, erosional discontinuities have been identified dominantly in the non-marine upper section (conglomerate measures) of the core, whereas only a few are identified in the marine dominated lower section (mudstone measures). In contrast, marine flooding surfaces containing condensed sections have been identified only in the marine-dominated lower part (mudstone measures). This finding has led to both *depositional* (Vail et al., 1977) and *genetic* (Galloway, 1989) interpretations of sequence stratigraphic for the SWEPI 2 core.

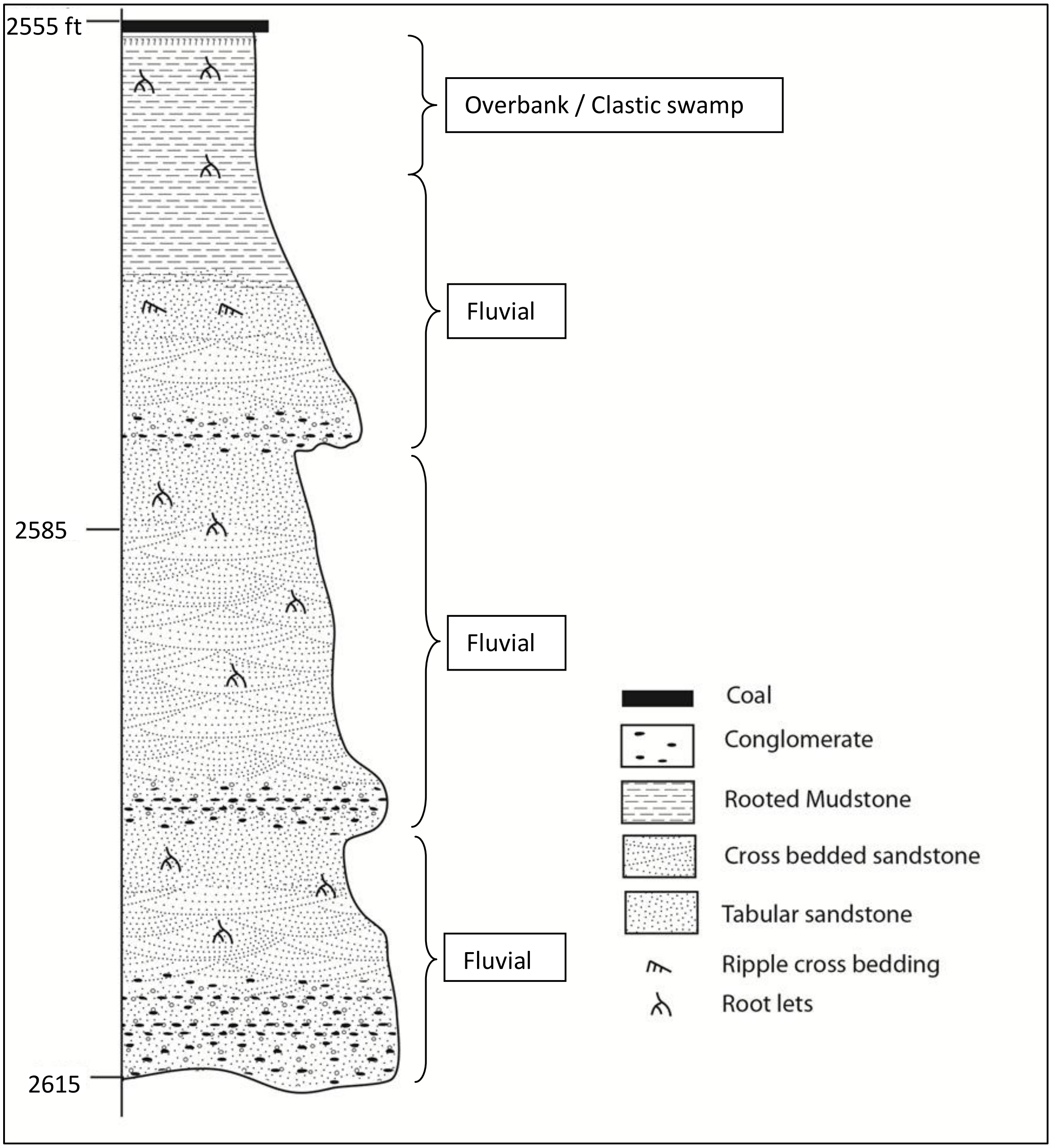


Figure 7.3: Vertical succession of a transgressive systems tract including depositional environments in SWEPI 2 recognized between 2555 to 2615 feet.

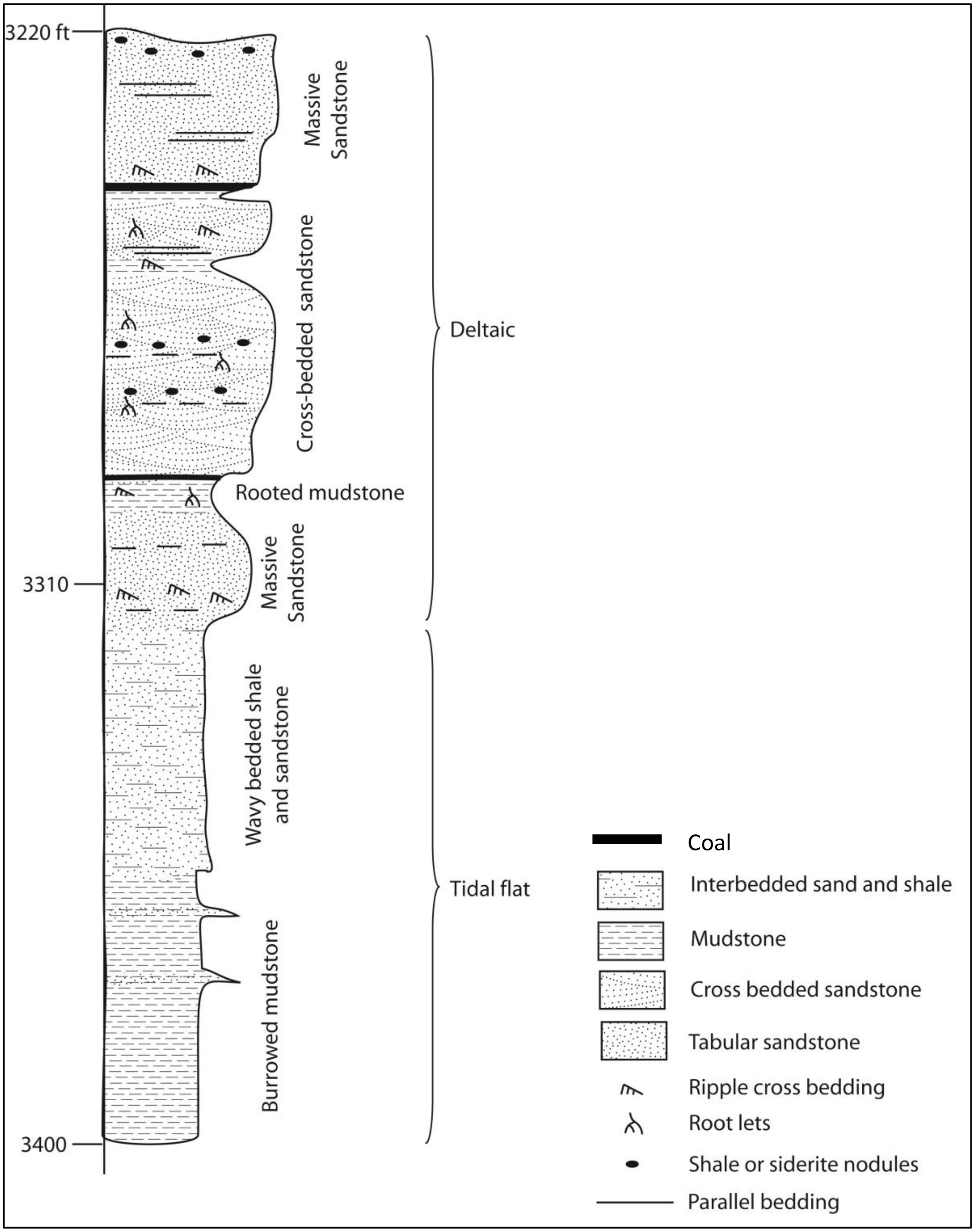


Figure 7.4: Inferred lithofacies and depositional environments within vertical succession of a highstand systems tract in SWEPI 2 recognized between 3220 to 3400 feet.

CHAPTER 8: DISCUSSION

8.0 INTRODUCTION

Sequence stratigraphic principles were developed to study shallow marine strata wherein marine flooding surfaces are readily observed and discrete genetically related, unconformity-bound depositional packages can be delineated (e.g. Galloway, 1989). Maximum flooding surfaces, recognized within condensed sections identified in the lower part of core SWEPI 2 (Figure 7.2), are interpreted as sequence boundaries in *genetic* sequence model. Marine flooding zones and *genetic* sequence boundaries are less prominent in the upper part of the studied section wherein the effects of marine processes are less evident. However, *depositional* sequence boundaries are often prominent beneath amalgamated fluvial sandstone bodies (Miall and Arush, 2001). In dominantly terrestrial strata, it is more difficult to develop a genetic sequence framework due to the absence of readily recognizable key flooding surfaces. In contrast, the depositional sequence model is more easily implemented.

8.1 SIGNIFICANCE OF MAJOR SEQUENCE STRATIGRAPHIC SURFACES

The Pottsville Formation in the studied section shows overall progression from marginal-marine to terrestrial sedimentation upsection (Figure 7.2). The upper part of the Pottsville Formation in the cores consists of mainly conglomerate, sandstone, rooted mudstone, and coal lithofacies representing exclusively terrestrial environments that include alluvial braidplain and mixed-load fluvial systems. Amalgamated fluvial channels in the upper part of the core are composed of multistory sandstone and conglomerate lithofacies. These amalgamated channel deposits are typically interpreted to represent deposition during lowstand to early transgressive conditions following a basinward shift of facies (Shanley and McCabe, 1995). Subsequent transgression is recorded by isolated sandstone lithofacies overlain by rooted mudstone and coal lithofacies. The succeeding highstand systems tract is marked by an up-section increase in multistory stacking of channel sandstone bodies and fluvial sheet sandstones. The overlying transgressive systems tract starts at the transgressive surface that is characterized by a distinct transition to floodplain facies. In contrast, transgressive surfaces are commonly ambiguous in terrestrial settings. Lowstand systems tracts in the study interval consist of conglomerate and sandstone lithofacies that formed as incised valley fills.

Wavy bedded shale and sandstone, burrowed mudstone, shale and shelly sandstone lithofacies are identified in the lower part of the core. In combination, these lithofacies along with conglomerate, sandstone, and coal form coarsening upward cycles that can be attributed to coastal plain environments, including fluvial systems, deltas, and estuaries. Widespread condensed sections, which contain maximum flooding surfaces were deposited during maximum stages of sea-level rise. Condensed beds mark times of maximum rate of transgression and maximum flooding, and the overlying deltaic deposits indicate subsequent shallowing. Deepening and regional flooding was a temporary source of accommodation space that was filled completely during highstand. Transgressions are believed to be related to glacial eustasy associated with the Milankovich orbital eccentricity cycles (Pashin, 1994; 1998). A gradual decrease of marine strata and increase of non-marine strata upsection indicates a transition to predominantly terrestrial sedimentation during the unroofing of the Appalachian (Pashin et al., 1995).

Key stratal surfaces of marine regimes, such as condensed sections and associated marine flooding surfaces, are absent in terrestrial sequences of conglomerate measures. In the absence of these isochronous discontinuities, laterally extensive coal beds have been used as proxies in non-marine sedimentary basins to identify flooding events. The formation of transgressive coals is usually attributed to eustatic sea-level rise driven by 4^{th}-order Milankovitch orbital eccentricity cycles (Chestnut, 1994; Pashin and Carroll, 1999; Pashin, 2004; Bodek, 2006). In the studied cores, coal beds occur within both fining-upward transgressive facies, and coarsening-upward highstand facies. A number of researchers have documented coal beds in a wide variety of sedimentary basins. These include foreland basins (e.g., Gastaldo et al., 1993; Aitken and Flint, 1994, 1995; Chesnut, 1994; Demko and Gastaldo, 1996; Bohacs and Suter, 1997; Hampson et al., 1999; Tibert and Gibling, 1999; Michaelsen and Henderson, 2000), rift basins (e.g., Petersen and Andsbjerg, 1996; Petersen et al., 1998; O'Mara and Turner, 1999; Van Heeswijck, 2001), intracratonic basins (e.g., Alves and Ade, 1996; Holz, 1998) and passive margins (e.g., Bohacs and Suter, 1997). Coal beds are found to form under conditions of both icehouse (e.g., Gastaldo, 1993; Aitken and Flint, 1994, 1995; Chesnut, 1994; Hampson et al., 1999; O'Mara and Turner, 1999; Tibert and Gibling, 1999) and greenhouse conditions (e.g., Cross, 1988; Kalkreuth and Leckie, 1989; Petersen and Andsbjerg, 1996; Bohacs and Suter, 1997; Petersen et al., 1998) and in a wide variety of tectonic regimes. However, prevailing climatic conditions during times of peat accumulation influences the occurrence, geometry, as well as ash and sulfur content of coal beds (Cecil et al., 1985; Cecil, 1990; Cecil et al., 1993; Holz, 1998). In shallow, nearshore environments, accommodation is dictated by relative sea-level change, which is controlled by the combined effects of tectonism, eustasy, and sedimentation rate (Plint et al., 1992). The most substantial accumulations of peat form where the rate of accommodation increase approximately equals the rate of peat production (Bohacs and Suter, 1997).

8.2 HIERARCHY OF SEQUENCE STRATIGRAPHIC SURFACES

In the genetic stratigraphic framework, Pashin (2004) identified a hierarchy of bounding discontinuities from dominant 3rd -order to 4th -and 5th-order flooding surfaces. Martino (2004) identified nine interfluvial sequence boundaries that divide the Glenshaw Formation in the central Appalachian basin into nine allocycles. Chesnut (1994) identified a hierarchy of marine zones within both 'coal-clastic' 4th-order cycles and 3rd-order composite tectono-cycles. Other workers (e.g., Aitken and Flint, 1994, 1995; Korus, 2002) have characterized Pennsylvanian strata in a depositional sequence stratigraphic sense (e.g., Vail et al., 1977) by identifying erosional disconformities at the bases of fluvial sandstone bodies interpreted as incised valley fill deposits.

Two orders of flooding surfaces and erosional discontinuities have been identified in the studied core. The highest order flooding surfaces correspond to 3rd-order maximum flooding surfaces have been identified in the marine-dominated lower section as major marine horizons. Due to the absence of marine influence in the upper part of the core, no 3rd-order maximum flooding surfaces has been identified there. The subordinate surfaces within the sequences bounded by 3rd-order maximum flooding surfaces have been designated as 4th-order flooding surfaces throughout the core. Transgressive coals are closely associated with 4th-order maximum flooding surfaces and consistently occur above fining-upward fluvial to estuarine transitions.

Sea-level change associated with 3rd-order marine flooding surfaces has been attributed to tectonoeustatic processes, including orogeny, changes in midoceanic ridge volume, and intraplate stress (Pitman, 1978; Cloetingh, 1986; Cathles and Hallam, 1991). Association of the Kaskaskia–Absaroka boundary with tectonic reorganization of the eastern Black Warrior Basin supports a component of tectonic forcing, although the precise causes of 3^{rd}–order cyclicity in the lower part of the Pottsville Formation are a matter for speculation (Pashin, 2004).

Valley incision was a temporary response to falling sea level and overfilling of the basin with sediment (Pashin, 2004). This filling of incised valleys initiated amalgamation of channel deposits beneath which lie 3^{rd}-order erosional discontinuities or depositional sequence boundaries. During the last phase of Pottsville deposition, unroofing of the Appalachian Mountains contributed a vast amount of terrestrial sediments, and accumulation exceeded basin subsidence (Graham et al., 1976; Pashin and Carroll, 1999). The resultant terrestrial-dominated deposits account for the multistory channel deposits within the incised valleys. Low magnitude regional sea-level falls initiated deposition of isolated channel deposits within fluvial to estuarine environments. Bases of these isolated channels represent 4^{th}-order depositional sequence boundaries. The average periodicity of similar 4^{th}-order sequences in central Appalachian basins is ~400-k.y (Bodek, 2006). This duration corresponds to the long-term Milankovitch orbital eccentricity cycle (Plint et al., 1992; Read, 1995, Bodek, 2006).

8.3 RELATION BETWEEN SANDSTONE PETROGRAPHY AND STRATIGRAPHIC ARCHITECTURE

Sandstone petrography has been utilized to correlate compositional variation with probable fluctuation in source area and associated sea-level and tectonic effects. The basal Pottsville Formation of the Cahaba synclinorium is composed of mature, recycled, quartzose sandstones, reflecting intense chemical weathering in an equatorial region (Pashin, 1997). A large-scale, integrated drainage system was formed across the eastern North America during the low sea-level stand during the Early Pennsylvanian (Archer and Greb, 1995). This megachannel was somewhat analogous to the Ganges and/or Brahmaputra river systems of the Himalaya (Uddin and Lundberg, 1998). A large drainage basin associated with this megachannel may have contributed to the reworking of sediments and the quartzose composition of the basal Pottsville Formation (Figure 8.1). Moore (2012) found similar inference from some sections of the Pottsville Formation based on detrital geochronology. Associated with the transition from the quartzarenite measure to the mudstone measure, sedimentary and metamorphic lithic fragments become more common, suggesting derivation from a recycled orogen. Repetitive appearances of tide-dominated deltaic sublitharenite in the mudstone measures are related to the onset of Alleghenian orogenic activity (Bement, 1976; Rice, 1984; Tankard, 1986; Chestnut, 1988). The mineralogical maturity of the basal sandstones may have been enhanced by multicycle reworking and storage in bifurcating fluvial systems similar to sands of the tropical rivers in South America (Savage and Potter, 1991; Archer and Greb, 1995; Greb and Chestnut, 1996).

The overall sandstone composition of the Pottsville Formation in the study interval indicates that sediments were derived from a recycled orogenic source with local change in source terrains (Figure 8.1). The predominance of sedimentary and metamorphic lithics over volcanic lithics is consistent with a principal origin from fold and thrust belts predominantly from the Appalachian mountain belt (Peavy, 2008; Uddin et al., 2010b). Petrofacies and architectural analyses nevertheless indicate that the isolated sand bodies at greater depth are quite different from the amalgamated sandstone units at the upper part of the core. Higher quartz contents and lack of unstable grains indicate more reworking of the sediments in marine-dominated depositional environments. Amalgamated channel sandstones in the quartzofeldspatholithic upper part of the core change very little in composition. These channel sands are believed to be deposited by rivers that flowed southwest along the basin foredeep (Archer and Greb, 1995; Pashin, 1995; Lawton, 2003). This compositional consistency has been termed *congruence* (Lawton et al., 2003) with respect to composition and dispersal direction. The upper quartzofeldspatholithic part of the core is compositionally and depositionally incongruent with the lower quartzolithic section.

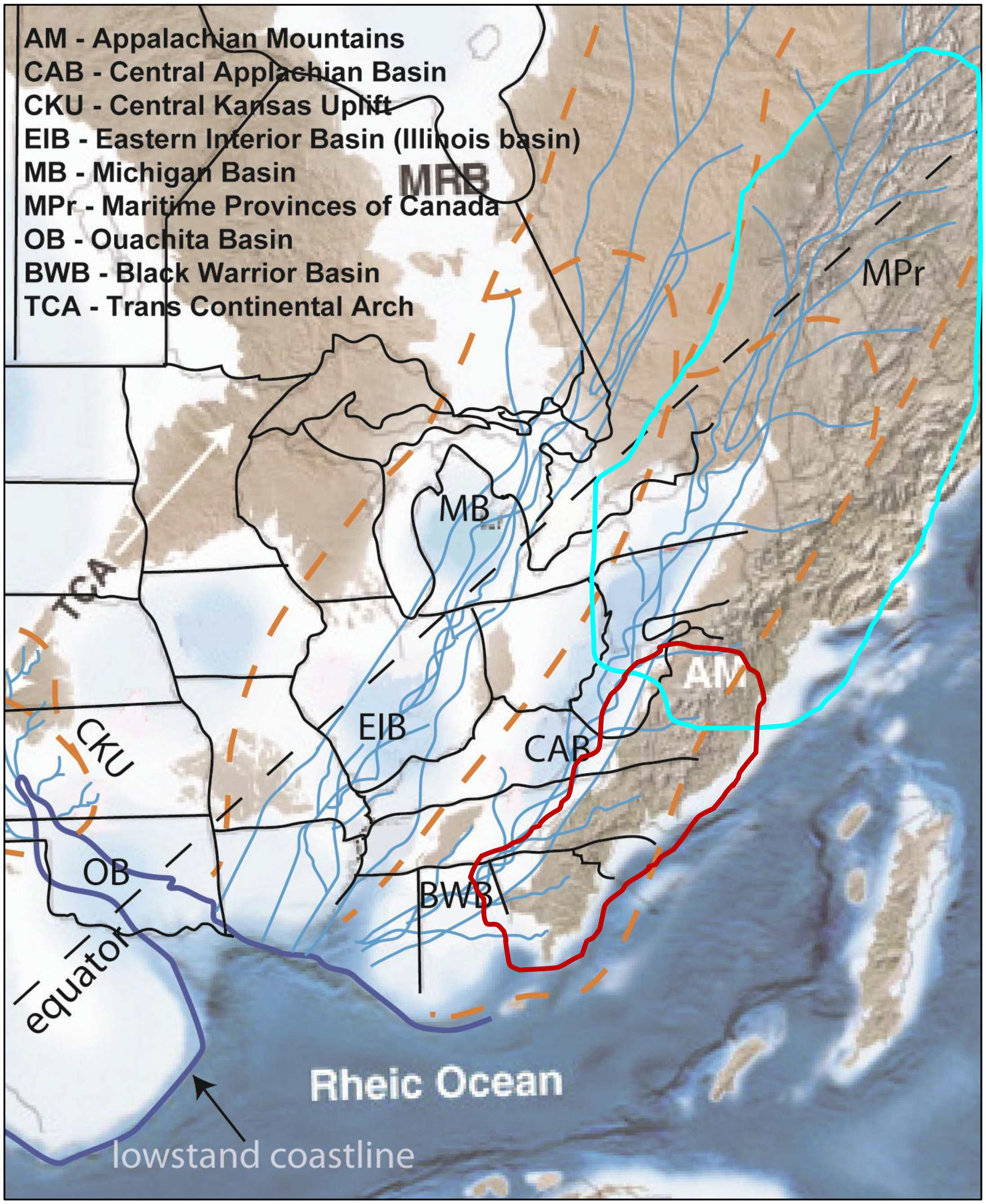


Figure 8.1: North American Pennsylvanian mega-drainage system influences the compositional diversity in the lower and upper part of the Cahaba synclinorium. Blue polygon represents the probable sediment source terrain for the more mature lower part of the core whereas the red polygon represents the source area for the less mature sediments in the upper part of the core (modified from Blakey et al., 1988; Archer and Greb, 1995).

8.4 RELATION BETWEEN SANDSTONE PETROGRAPHY AND DEPOSITIONAL ENVIRONMENTS

Higher quartz contents, low proportion of feldspar and lithic fragments in the lower part (quartzolithic petrofacies) of the core and the increase in feldspar and lithic contents in the upper part (quartzofeldspatholithic petrofacies) records a change in source rock type and/or transportation process. Samples from the quartzofeldspatholithic petrofacies were mostly taken from amalgamated fluvial channels, while samples of the quartzolithic petrofacies were from isolated sandstone bodies deposited in mostly shallow marine to marine depositional environments. Hence, the compositional variation in some way could be connected with change in paleoenvironment.

This relation between paleoenvironment and composition is similar to that recognized by Lawton at al. (2003) in their study of Late Cretaceous fluvial systems of southwestern Utah. In their study, quartzofeldspatholithic and feldspatholithic (not identified in current research) petrofacies were observed in two fluvial amalgamated sandstone bodies (Drip Tank Member of Straight Cliffs Formation and capping sandstone member of Wahweap Formation) bounded at their bases by major depositional sequence boundaries. Lawton et al. (2003) also identified isolated sand bodies characterized by quartzose (not identified in the current research) and quartzolithic petrofacies and representing tidal and alluvial plain deposits. Compositional differences or incongruence was used to delineate stratigraphic architecture.

In the current study, the petrologic incongruence between the mudstone measures and the conglomerate measures can be correlated a major shift from marine to nonmarine depositional environments. Integration of facies analysis and sandstone petrology with paleocurrent analysis will enhance the interpretation of the causes of facies shifts, changes in accommodation, and resultant sequence architecture.

CHAPTER 9: CONCLUSIONS

The following conclusions can be drawn from this research:

1) The Lower Pennsylvanian Pottsville Formation of the Cahaba synclinorium of southern Appalachian basin is characterized by conglomerate, sandstone, rooted mudstone, wavy bedded shale and sandstone, graded sandstone, burrowed mudstone, shale and shelly sandstone, and coal lithofacies.

2) High-magnitude sea-level fluctuations influenced the deposition of the Pottsville Formation. Incision and backfilling of incised valleys with sublithic sand occurred during relative sea-level lowstand to early transgression periods. Continued transgression formed estuaries with the back-flooding of incised valleys. During relative sea-level fall, progradational deltaic facies developed above estuarine and marginal marine facies.

3) Compositional incongruence between terrestrial and marine lithofacies has been identified between the mudstone and conglomerate measures, and this incongruence has been interpreted as major shift from marine to terrestrial depositional environment.

4) Major sea-level fluctuations have been attributed to both tectonic and eustatic mechanisms. 3^{rd}-order composite sequences identified by marine flooding surfaces and bases of incised valley fills are attributed to eustatic sea-level changes modulated by the lower-frequency orbital eccentricity cycle. High-frequency 4^{th}-order cycles represented by extensive coal layers may be linked to higher-frequency glacio-eustascy cycles. 4^{th}-order sequences contain fluvial to marginal marine facies that comprise lowstand, transgressive, and highstand systems tracts. Higher-

frequency autocycles in the lower part of the core are associated with deltaic facies within 4th-order highstand systems tracts.

5) Coal beds developed within late transgressive facies associated with 4th-order maximum flooding surfaces and in association with higher-frequency deltaic autocycles of 4th-order highstands. Hence, the formation of coal beds can be attributed to both glacio-eustatic and autocyclic deltaic mechanisms.

6) Quartz constitutes the dominant framework grain at the lower section. The increase in total feldspar and lithic fragment contents toward the top of the section could indicate a change in source terrains with greater contribution of sediments from a recycled orogen.

7) The lower marine sections of the studied core may have been sourced via the Pennsylvanian mega-drainage system from the northern Appalachian, whereas the upper terrestrial section received sediments from the adjacent southern Appalachian Mountains.

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