Analysis of the Depositional Environment of the Cretaceous Menefee Formation: Southeastern Flank of the San Juan Basin, New Mexico

By

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Abstract

The depositional environment of the Upper Cretaceous Menefee Formation within the San Juan Basin was examined in detail using both outcrop and subsurface data. The Menefee Formation consists of five lithofacies: a thick sandstone lithofacies, interpreted to represent channel deposits; a thin-bedded sandstone lithofacies that represents crevasse splay deposits; a grey mudrock lithofacies, representing overbank deposits; and coally mudrock lithofacies representing backshore peat swamp deposits. A sixth lithofacies is also described; the flaser-bedded sandstone lithofacies. This lithofacies is part of the Cliffhouse Sandstone, and represents a lag bed remnant of the beach facies of a transgressive shoreline system. This lithofacies is included because of its close association with the Menefee Formation depositional system.

The elemental composition of siderite concretions associated with the channel facies indicates an early diagenetic freshwater environment for that lithofacies. In addition, the sulfur content of the Menefee coals is relatively high, which indicates formation in a marine-influenced brackish water environment.

The proposed depositional model for the Menefee Formation is a lagoon and swamp dominated coastal plain that is intersected by an anastomosing fluvial system. This system is interpreted to be situated adjacent to a barrier-island dominated shoreline.

Introduction

The San Juan Basin is one of the most important natural gas basins in the United States. To date, recovered gas exceeds 29 trillion cubic feet, with another 50 TCF of producible reserves believed to be in-place (Huffman, 1989). One of the more prolific and economically important reservoir systems within the San Juan Basin is the Mesaverde Group. Current natural gas production from the Mesaverde Group alone is 23 Bscf/mo, with a cumulative total of 9.37 Tscf (as of July 2000; Engler et al., 2001). In 1992, Mesaverde reserves (proven developed and undeveloped) were estimated at 12.3 Tscf, primarily within unconventional tight sandstone and coal seam reservoirs (Engler et al., 2001).

This study focuses on the Menefee Formation, the middle formation within the Mesaverde Group. The unconventional reservoir system within the Menefee Formation is a possible prolific source of tight-gas and coalbed methane; however it is often by-passed by operators due to the highly complex and poorly understood geologic framework of the formation (Engler, 2001; Brister and Peabody, 2002). As a result, production from the Mesaverde Group is generally restricted to specific intervals within the upper Cliffhouse Sandstone and the upper Point Lookout Sandstone (Fassett, 1977; Choate, 1984; Huffman, 1989).

The objectives of this thesis are to characterize the complex geologic framework and depositional environment of the Menefee Formation through description and interpretation of lithofacies, and to interpret the depositional system responsible for the mid-Cretaceous Mesaverde Group stratigraphy within the San Juan Basin. By better understanding the Menefee Formation, operators may be able to more accurately assess the potential for unconventional gas production from the unit. In addition, this project will attempt to fill an apparent lack of published literature regarding the Menefee Formation. Only a few publications include a detailed study of the depositional environment of the Menefee Formation. The papers that do describe the Menefee Formation do so as a secondary topic, as the publications' primary topic involves either the depositional environment or oil and gas potential of the Cliffhouse and Point Lookout Sandstones (e.g., Donselaar, 1989; Wright-Dunbar and Ridgley, 1999). Donselaar (1989) discusses the Menefee Formation briefly, but only in relation to the depositional environment of the Cliffhouse Sandstone. Wright-Dunbar and Ridgley (1999) incorporated many of the same methods and interpretations as this thesis; however, their study focused more on the sequence stratigraphic framework of the entire Mesaverde Group, to better understand potential hydrocarbon reservoirs throughout the Mesaverde Group, primarily in the Cliffhouse and Point Lookout Sandstones.

Study Area

The San Juan Basin is located in northwest New Mexico and southwest Colorado, near the four corners area (Fig. 1). The field portion of the study focuses on the eastern and southeastern margins of the basin, near the town of Cuba, New Mexico (Fig. 2). Along this flank, there is an outcrop belt that exposes Mesaverde Group strata in near entirety and stretches for tens of miles. This outcrop belt is subdivided into two areas, a northern area and a southern. The outcrop belt is heavily eroded and poorly exposed throughout the middle section. The northern

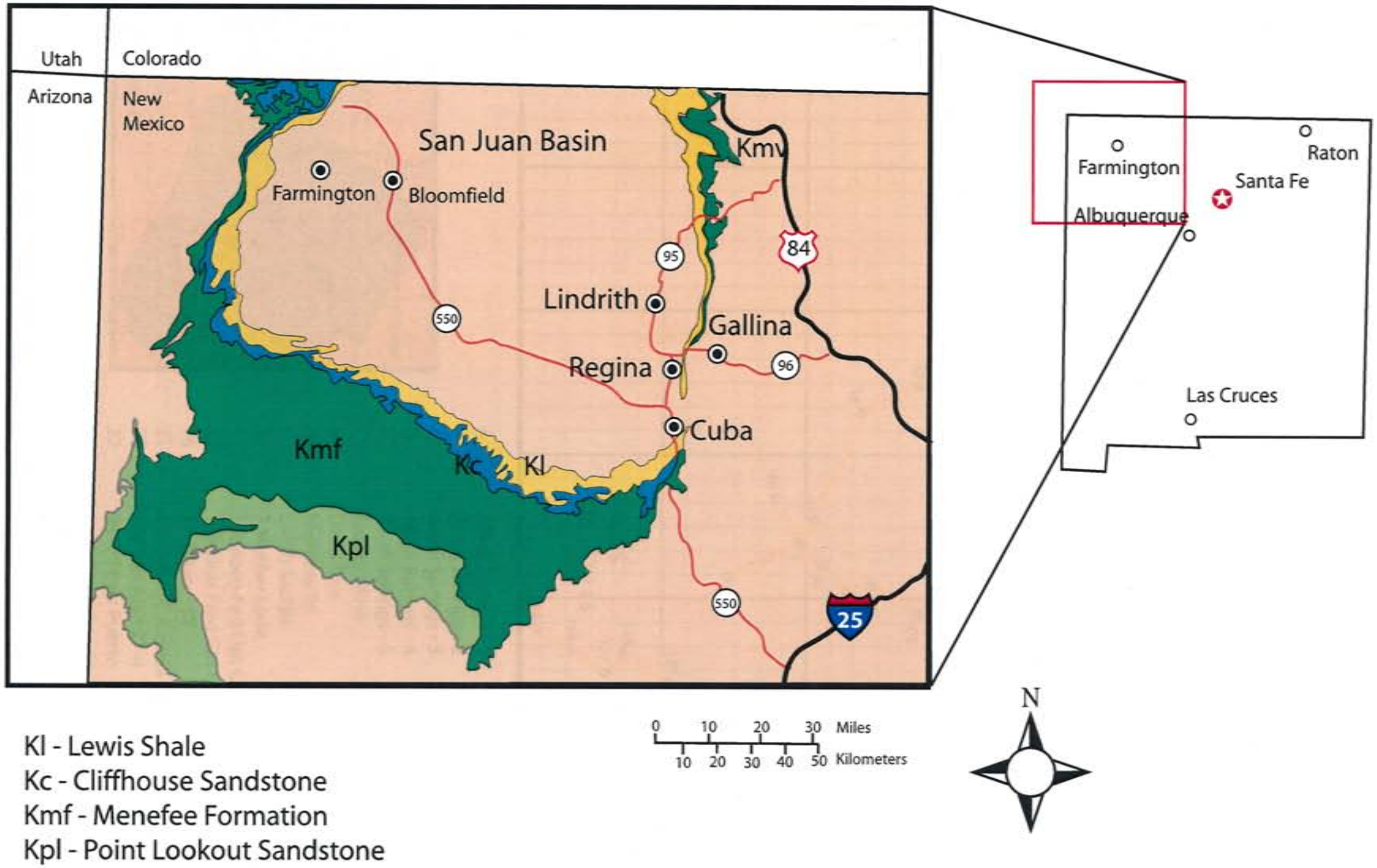


Figure 1. Location of the San Juan Basin in northwest New Mexico. The Menefee Formaton serves as the unoffical boundaryfor the basin.

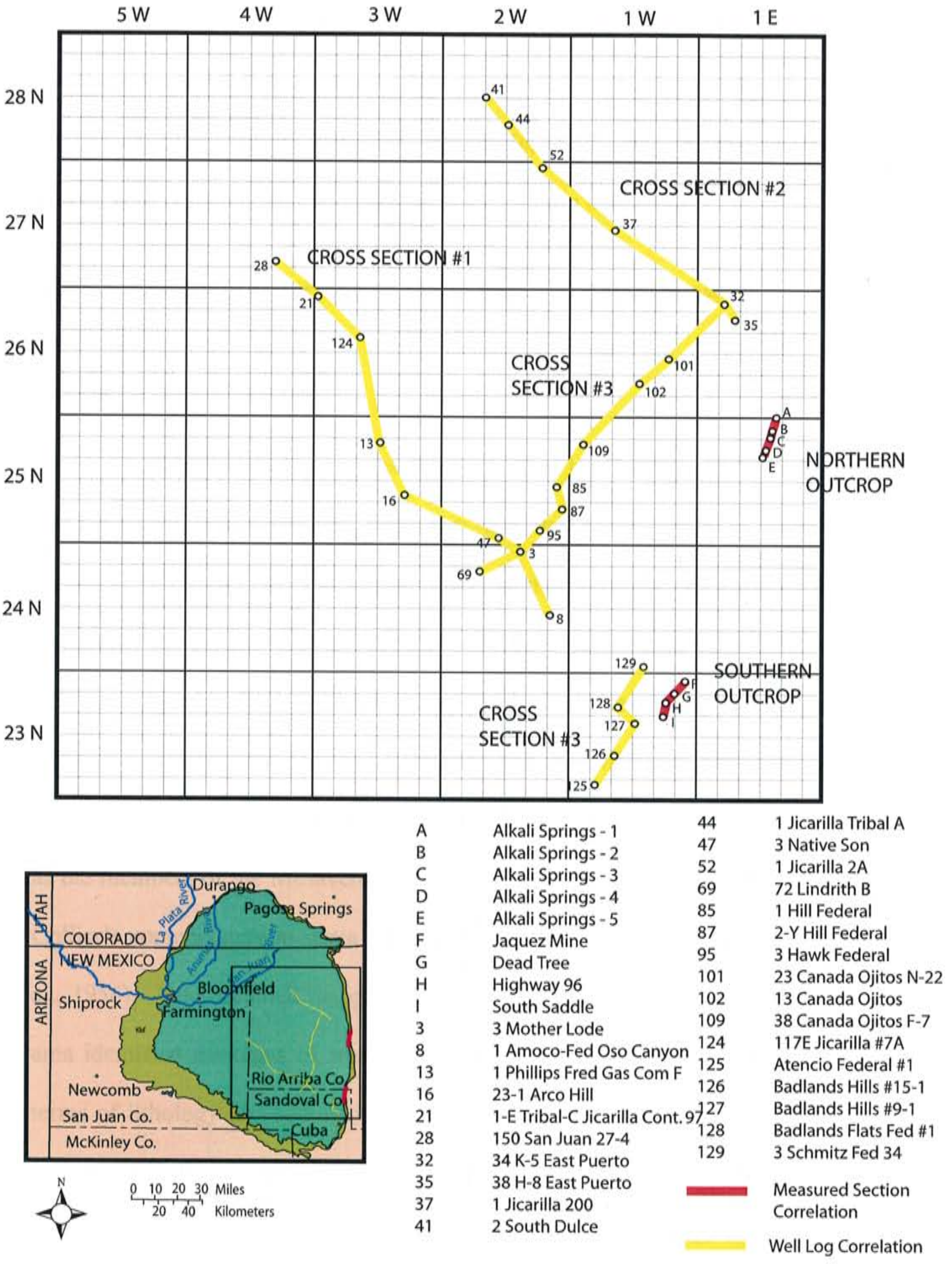


Figure 2. Basemap showing locations of measured sections and well logs used for cross sections.

area is situated near the center of the Santa Fe National Forest. The southern area lies just north of Cuba, where Highway 96 intersects the outcrop belt. The subsurface study encompasses most of the basin, and includes several cross sections that lie both perpendicular and parallel to the outcrop belt (Fig. 2).

Mesaverde Group and Related Formations

General Setting

The Mesaverde Group was first described by Holmes (1877), referring to the sandstone and associated beds that cap the Mesa Verde in southwestern Colorado. Holmes (1877) identified three distinct divisions: the lower escarpment sandstone, the middle coal group, and the upper escarpment sandstone. Collier (1914) assigned names to these three divisions, in ascending order, the Point Lookout Sandstone, the Menefee Formation and the Cliffhouse Sandstone (Fig. 3). Keeping with Holmes original division, Collier (1914) described these formations as the members of the Mesaverde group. In the early 20's workers began to apply Collier's nomenclature to strata located in northwestern New Mexico (Beaumont et al., 1956). Later detailed mapping by USGS workers throughout the four corners area identified packages of strata that matched the findings of Holmes (1877) in terms of lithology and sedimentary structures (Collier, 1914). The workers noted that the strata that compose the Mesaverde Group in New Mexico are considerably thicker than those found in the original type area in Colorado as described by Holmes (1877) and Collier (1914).

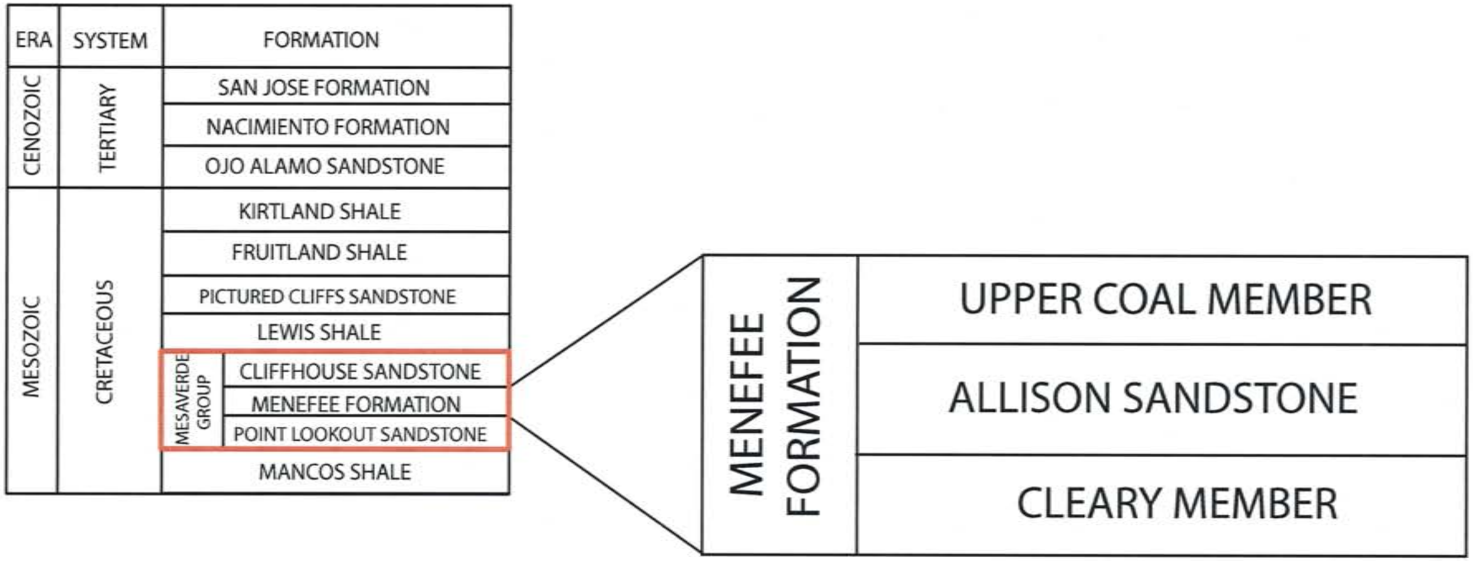


Figure 3. Stratigraphic column showing Mesaverde Group and surrounding formations.

The Mesaverde Group strata consist of intertonguing terrestrial and marine sediments, believed by many workers to be the product of a regressive-transgressive cycle of the Cretaceous Interior Seaway during the Campanian (Sabins, 1964; Young, 1973; Landis et al., 1974; Molenaar, 1974; Fassett, 1977; Donselaar, 1989; Devine, 1991; Molenaar and Baird, 1992). The Cretaceous Interior Seaway had a NW-SE trending shoreline. Therefore, during these cyclic shifts of the Interior Seaway, the shoreline migrated to the SW-NE, resulting in the Mesaverde Group forming a wedge-shape across the basin, thickening landward toward the southwest (Molenaar and Baird, 1992).

Three factors are believed to control the dynamics of a transgressing or regressing system: sediment supply into the system, local tectonic activity, and eustatic changes in sea level (Sabins, 1964; Haun and Kent, 1965; Kraft and John, 1979; Donselaar, 1989; Devine, 1991). Subsidence of the basin would cause the dip angle of the seaway slope to increase. As a result, the shoreline would migrate landward at a quicker rate despite a constant rate of sea level rise. Periods of low sedimentation allow the coast to readily retreat landward over the coastal plain (Donselaar, 1991). Finally, the rate of transgression was also influenced by a eustatic rise in the Cretaceous Interior Seaway (Hancock and Kaufman, 1979). A period of a eustatic-rise in sea level would cause the strandline to migrate landward, and vice-versa. In order for a regression or transgression to occur, there must be some imbalance between one or more of the 3 factors. If all 3 are in balance, then the result will be a stable shoreline of the seaway.

Mancos Shale

The Mancos Shale is a marine mudrock that underlies the Mesaverde Group. The Mancos Shale consists of gray to brownish-gray shale, with increasing interbeds of fine to very fine-grained sandstones near the upper contact with the overlying Point Lookout Sandstone. This formation is present throughout the San Juan Basin, and is thickest toward the northeastern flank of the basin near Shiprock, NM, where it is roughly 430 m thick (Young, 1973). Across the basin, the Mancos Shale thins toward the southeast as it intertongues with the overlying Mesaverde Group (Young, 1973).

Point Lookout Sandstone

The lowermost formation of the Mesaverde Group is the Point Lookout Sandstone. It is interpreted to represent a regressive cycle of the Cretaceous Interior Seaway (Young, 1973; Landis et al., 1974; Devine, 1991), and is composed of clastic sediment deposited as the shoreline advanced basinward (Devine, 1991). It is a massive sandstone composed of two or more sandstone units separated by thin units of sandy mudrock (Young, 1973). The Point Lookout Sandstone is widely interpreted as a marine unit deposited along the shoreline of the Cretaceous Interior Seaway (Sabins, 1964; Young, 1973; Landis, 1974; Devine, 1991), representing a coastal beach facies (Young, 1973; Devine, 1991). The thickness of the formation varies across the basin, with a maximum of 90 m (Young, 1973). East of Gallup, NM, the Point Lookout is separated into two parts by the Satan Tongue of the Mancos Shale. The upper part is referred to as the Point Lookout

Sandstone, and the lower part is considered a separate unit, and referred to as the Hosta Tongue of the Point Lookout Sandstone (Allen and Balk, 1954; Sabins, 1964). The lower contact of the Point Lookout Sandstone is transitional., consisting of frequent intertonguing beds of sandstone and silty-mudrock as it grades into the Mancos Shale (Young, 1973). The upper part of the formation is generally clean and massive, with occasional beds of carbonaceous mudrock present near the uppermost contact with the Menefee Formation (Young, 1973).

Menefee Formation

The Menefee Formation is the middle formation in the Mesaverde Group, and is thought to represent a non-marine environment with abundant backshore swamps and lagoons (Young, 1973; Landis, 1974; Molenaar, 1974; Fassett, 1977; Choate et al., 1984; Donselaar, 1989; Devine, 1991, Wright-Dunbar and Ridgley, 1999). The Menefee Formation consists of three members: the basal Cleary Member, the middle Allison Sandstone, and an unnamed upper member, commonly referred to as the upper coal member (Beaumont et al., 1956; Molenaar, 1977). It is present throughout the basin, and ranges in thickness from 130 to 930 m (Young, 1973). The Menefee Formation thins toward the northeast as it intertongues with the Point Lookout Sandstone and the overlying Cliffhouse Sandstone. As a result, the Menefee Formation forms a wedge shape that thickens toward the southwest (Young, 1973; Molenaar, 1977; Wright-Dunbar and Ridgley, 1999). It eventually pinches out into the Mancos Shale near Pagosa Springs, CO (Fassett, 1977). The upper coal bearing unit is not discussed much in the literature, but is generally described as resulting from the same depositional environment as the Cleary Member (Young, 1973; Fassett, 1977; Donselaar, 1989; Devine, 1991).

The upper and lower members of the Menefee Formation consist primarily of carbonaceous mudrocks and coal seams, and are believed to have formed in a lagoonal., swampy or floodplain type environment in proximity to the shoreline of the epicontinental seaway (Young, 1973; Fassett, 1977; Landis, 1974; Molenaar, 1974; Choate et al., 1984; Donselaar, 1989; Devine, 1991). The Cleary Member is associated with the backshore setting behind the Point Lookout Sandstone, with the environment repeating behind the Cliffhouse Sandstone (Donselaar, 1989; Wright-Dunbar and Ridgley, 1999). The middle Allison Member is described by many workers as a sandstone unit of fluvial origin encased in overbank non-marine floodplain mudrocks (Young, 1973; Molenaar, 1974; Fassett, 1977; Choate et al., 1984; Donselaar, 1989; Wright-Dunbar and Ridgley, 1999).

Cliffhouse Sandstone

The Cliffhouse Sandstone was deposited during a transgression of the Cretaceous Interior Seaway, and consists of a series of linear sandstone complexes representing the beach facies (Hollenshead and Pritchard, 1961; Fassett, 1977; Donselaar, 1989). It is the transgressive equivalent of the Point Lookout Sandstone (Fassett, 1977; Donselaar, 1989). The Cliffhouse Sandstone is found throughout most of the basin, and is exposed around most of the perimeter, particularly along the southern and eastern margins (Donselaar, 1989). The thickness averages about 90 m, except for an area south of Cuba, NM, where it is around 240 m thick

(Donselaar, 1989). Here, there are a series of intertonguings within the overlying Lewis Shale that are referred to as the La Ventana Tongue of the Cliffhouse Sandstone (Fassett, 1977; Donselaar, 1989). Throughout the basin, the Cliffhouse Sandstone is composed of numerous linear sandstone complexes that measure between 5 km wide and 15 to 25 m thick (Donselaar, 1989). Each body is connected by a thin sheet of sandstone, causing the formation to exist not as a continuous blanket, but more as a series of migrated stacked sandstone bodies (Fassett, 1977; Donselaar, 1989).

Methods of Study

This study occurred in two phases: a field study that examined the rocks in outcrop, and a subsurface study, which examined the stratigraphy from wells and logs. The main objective of the field component was to obtain a detailed understanding of the rocks, and also to collect samples necessary for laboratory examination. The subsurface part of the study was designed to examine and interpret changes in the stratigraphy as it extends into the subsurface across the basin. When used in conjunction, the detailed observations made in the field section allow for interpretation of the subsurface data at a much higher resolution than previously possible.

Measured Sections

Nine outcrop sections were measured, with four located in the southern field area and five in the northern (Fig. 4). The locations were picked based on which formations were exposed, as well as the quality and accessibility of the exposure.

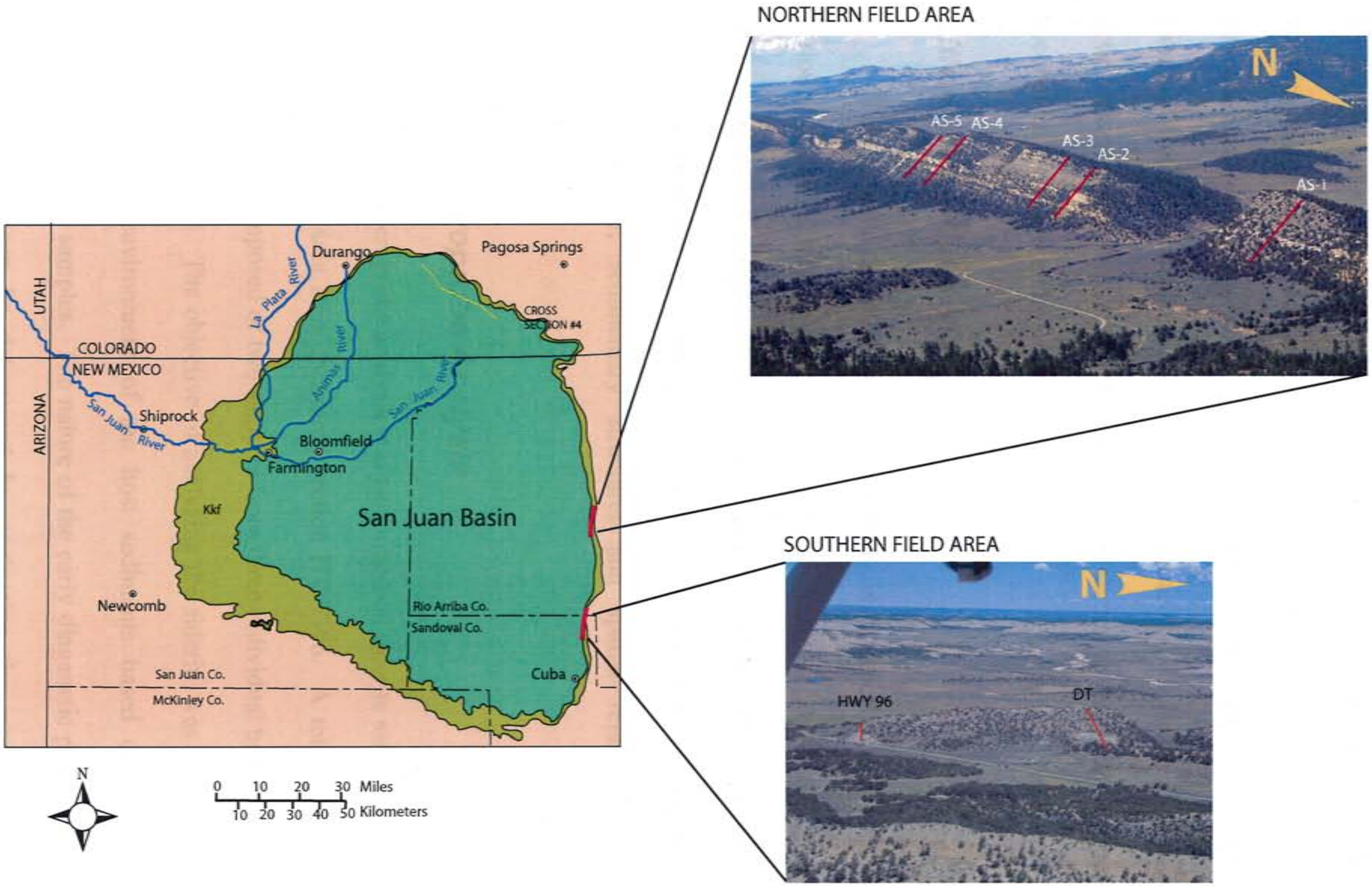


Figure 4. Locations of the measured sections across the northern and southern field areas.

Each section was measured at a 10 cm scale in order to best record the considerable vertical variation of the strata. The information described in each section includes bed thickness, lithology, color, grain size, presence of sedimentary structures, nature of bedding contacts, ichnofossil information, and if observed, paleocurrent data. A stereonet was used to apply structure correction to the paleocurrent data to account for the regional dip of the strata.

Lithofacies Differentiation

The primary objective of the field study is to describe and interpret the various lithofacies present within the Menefee Formation. By understanding the lithofacies, interpretations can be made regarding the specific environment the rocks were deposited in (Boggs, 2001). The main criteria for identifying lithofacies included lithology, sedimentary structures and spatial relationships of the lithofacies.

Electron Microprobe Analysis

Electron microprobe analysis was performed on siderite samples collected in the southern field area from measured section HWY-96. A total of six samples were collected, composed of two samples from three individual beds that contained siderite concretions. The objective of analyzing the siderite was to help determine the depositional environment of the host sediments based on the elemental composition of the samples. The nature of the early diagenetic pore waters, either marine or fresh, can be determined by comparing the amount of calcium, magnesium, manganese and iron (in mol %, normalized) of the siderite on ternary diagrams (Mozley, 1989).

The microprobe used for this analysis is a Cameca SX-100, located at the New Mexico Bureau of Geology and Mineral Resources. Back-scattered electron imaging was used to locate analysis sites on polished 1" rounds. The sample current used for spot analysis was 10 nanoamps, the accelerating voltage was 15kV, and the beam size was 20 um. The totals accepted for each spot varied between 102% and 93%. Some of the siderite samples exhibited rather high porosities, which resulted in low total counts for those samples.

Cross Sections

Cross sections were created throughout the basin using lithostratigraphic correlations in order to understand the stratigraphy of the Mesaverde Group in the subsurface, as well as document the variation of the lithologies across the basin. These subsurface cross sections were correlated with the outcrop, in order to show changes in the strata from the margins to the basin center. Four cross sections were constructed across the basin; two falling in a NW-SE direction, and two in a NE-SW direction. Each of the cross sections was created using well logs from throughout the basin, found at the New Mexico Bureau of Geology and Mineral Resources, as well as the online database provided by the New Mexico Tech Petroleum Research and Recovery Center (http:\\octane.nmt.edu).

Subsurface correlations were made using gamma ray, resistivity and bulk density logs. Gamma ray logs are a measurement of the natural gamma ray emissions from the rocks. Resistivity logs indicate the resistivity (which is the inverse of conductivity) of the rocks, which allows for identification of the fluids present in the pore spaces. The density log is a measurement of the combined density of the rock and pore space. Because each type of log measurement has certain shortcomings, a combination of all three log types was used to identify the separate formations as well as lithologies within the formations.

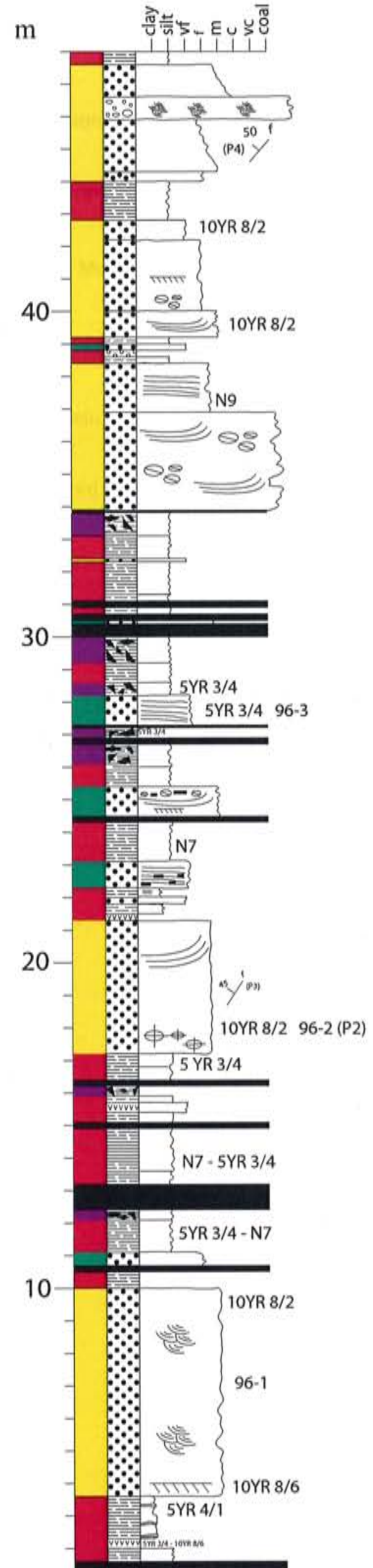
Core Descriptions

Core samples from three wells that include sections of Menefee Formation were described to better assist with the subsurface lithology and lithofacies differentiation from the well logs. The core samples were marked with depth indicators, which allowed direct comparison of the sample to the corresponding well logs that were corrected for depth. By making this direct comparison, the log response to each lithology as well as the resolution of the logging tool could be determined, which makes subsurface lithologic differentiation more accurate.

The three cores were provided by Burlington Resources located in Farmington, NM, and include wells 4C Howell D 2R, San Juan Unit 29-7 102A, and San Juan Unit 28-6 #3 ST. Because the well operators took core samples in very specific intervals, they do not contain complete sections of the Menefee Formation.

Lithofacies Descriptions

From the nine measured sections (Appendix A), six primary lithofacies were identified. A complete measured section is included (Fig. 5a, b) to illustrate the



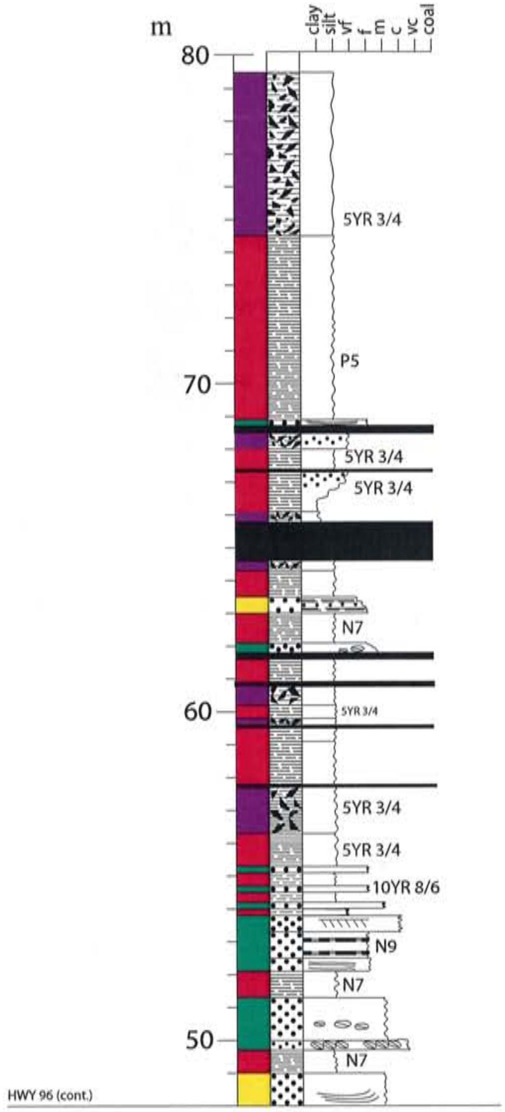


Figure 5a. Measured section Highway 96 illustrating the vertical relationships among the lithofacies in the Menefee Foramtion. Explanation of colors and symbols are shown in Fig. 5b.

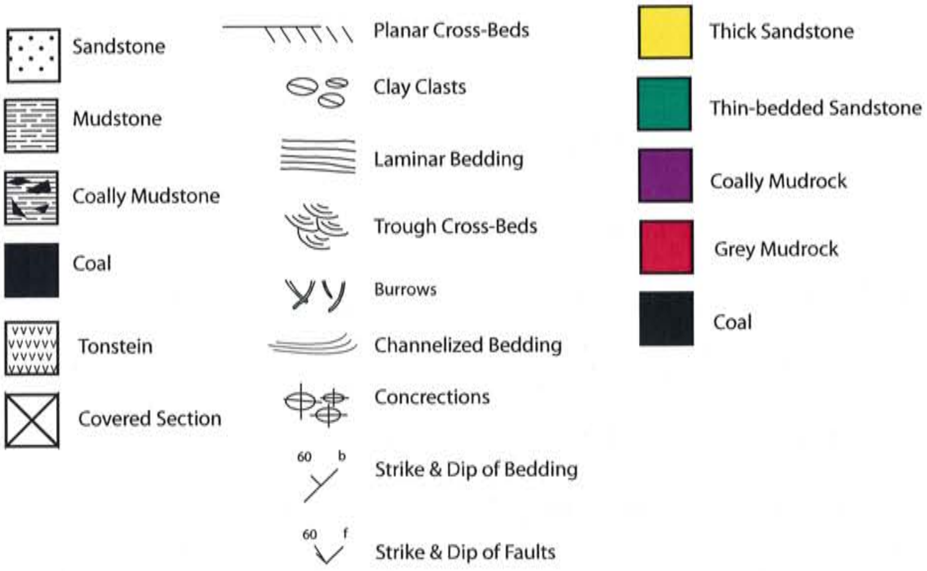


Figure 5b. Explanation of colors and symbols for measured section Highway 96 shown in Fig. 5a.

vertical relationships of the various lithofacies for the entire thickness of the Menefee Formation.

Thick Sandstone (Menefee Formation)

The thick sandstone lithofacies is a significant component of the Menefee Formation. In an economic sense, it is viewed as a potential reservoir unit for coalbed methane (Engler et al., 2000). In addition, the sandstone was believed to exhibit evidence that would contribute to the overall interpretation of the depositional environment. Because of this, the locations of the measured sections were chosen to maximize the amount of this lithofacies that would be intersected. Looking only at the measured section data, it would appear that one or more package of thick sandstone lithofacies would be intersected by any vertical transect of the outcrop. This is a misrepresentation of the distribution of this lithofacies, as the thick sandstones are sparsely spaced throughout the formation. The thick sandstone lithofacies is characterized by clean sandstone units that measure greater than 1 m in thickness (Fig. 6). The measured thickness of these units varies between 1 and 15 meters. In cross section, they are isolated, lenticular bodies (Fig. 7). This facies often exhibits stacked packages of sandstone with uniform grain size, with the grain-size for each package ranging from very fine to medium (Fig. 8). In a few cases, packages of coarse grained sandstones are present locally. These sandstone units contain thin mud deposits (< 5 cm thick) located along the contact between each bedset. The sandstones commonly exhibit scour surfaces (Fig. 9) along their basal contact with abundant mud rip-up clasts from the bedding below

Figure 6. Thick sandstone lithofacies at measured section Highway 96. Section shown in picture is located near base of the Menefee Formation. Red line represents 1.5 meter measuring staff.

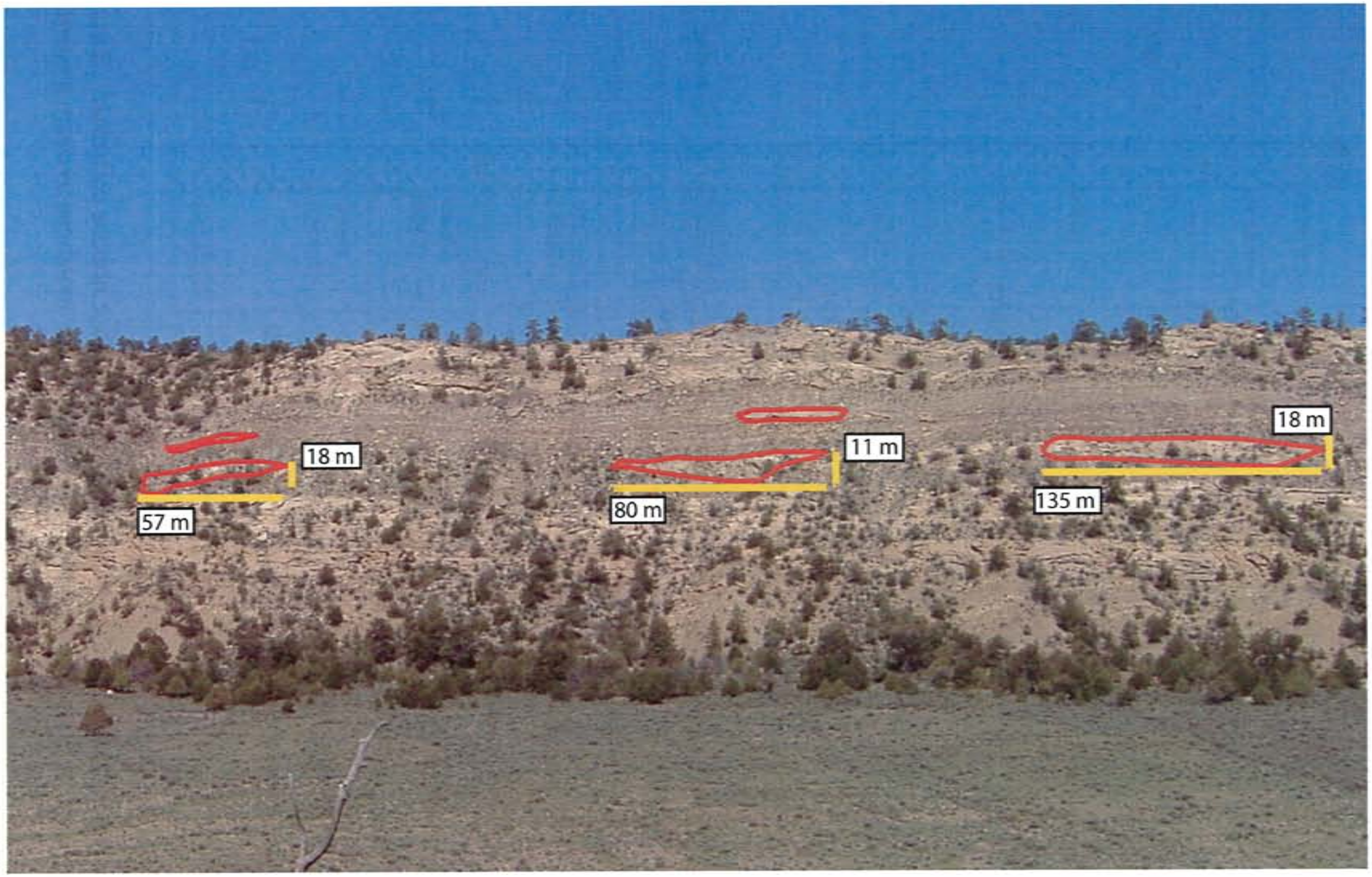


Figure 7. Cross sectional view of thick sandstone lithofacies across northern outcrop belt. Figure illustrates the isolated, lenticular nature of the sandstone bodies highlighted in red. Dimensions of the features in meters.

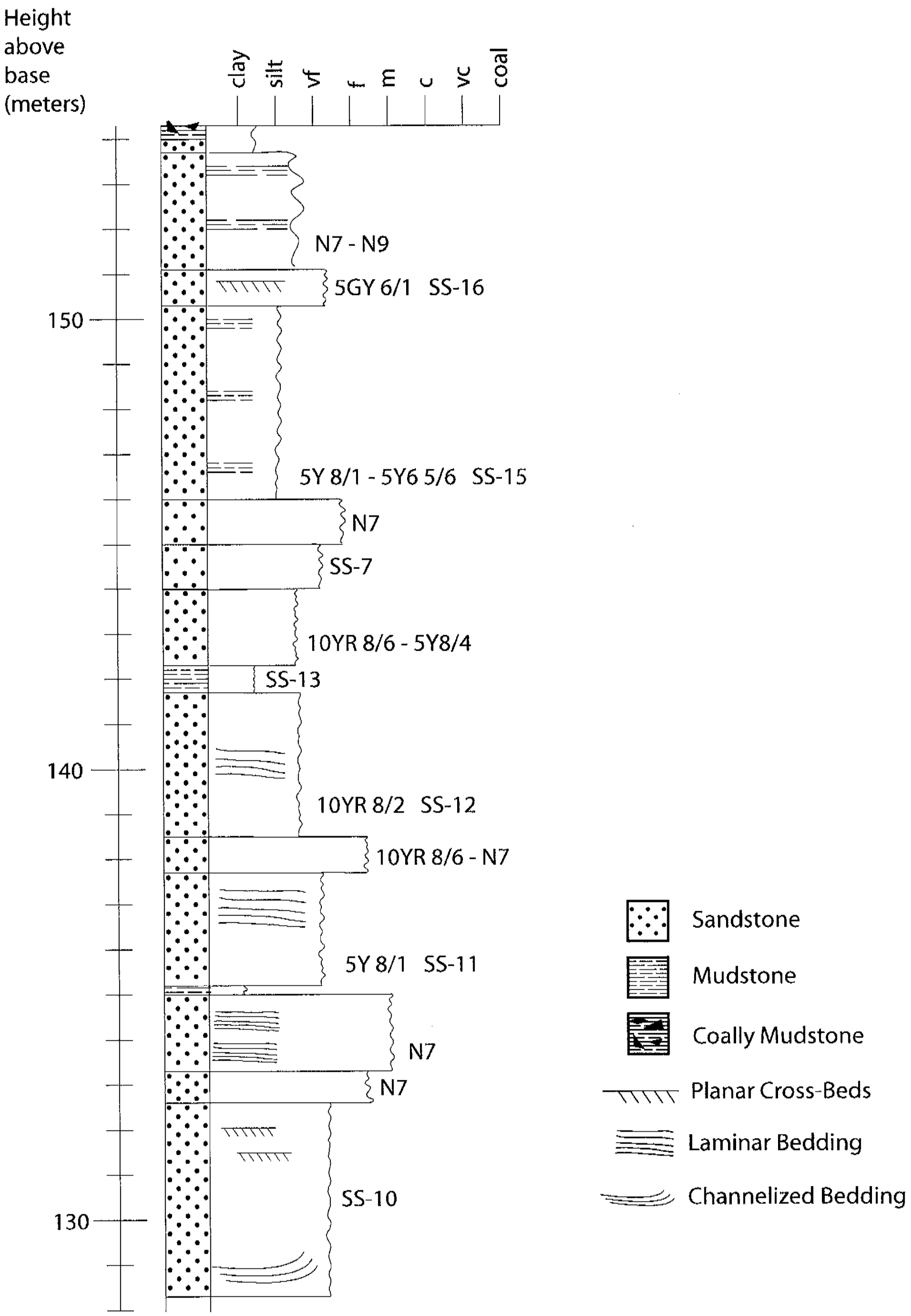


Figure 8. Measured section south Saddle showing a series of stacked bedsets that compose a massive sandstone lithofacies. Complete sections are found in Appendix A.

Figure 9. Erosive lower contact of thick sandstone facies at measured section Highway 96. Section shown in picture is located near base of the Menefee Formation. Yellow lines indicate lower strata intersected by base of thick sandstone. Rock hammer is 12 inches long.

(Fig. 10). The sandstone bedsets are usually adjacent to a mudrock lithofacies, and occasionally found adjacent to coal seams. Many of the bedsets contains large-scale trough (Fig. 11) and tangential cross stratification (Fig. 12). Measurement of the cross beds reveals a flow direction towards the northeast, at about N30°E. More commonly, asymmetrical ripplemarks indicate a current direction toward the northeast varying between 0 and 80° northeast (Fig. 13).

Siderite is common within this lithofacies as large concretions (30-60 cm diameter; Fig. 14). In outcrop, the siderite weathers to a reddish color. On fresh surfaces, the rock has a medium-dark grey color speckled with an unidentified white mineral. The siderite concretions are generally located within a sequence of the coally and grey mudrock lithofacies, but most often found directly adjacent to either a thick or thin-bedded sandstones lithofacies,.

Thin-bedded Sandstone (Menefee Formation)

The dominant feature of this lithofacies is thin to medium bedded sandstones interbedded with a variety of indurated mudrock deposits ranging from bedded siltstone to clayshale (Fig. 15; classification of Potter et al., 1980). The individual sandstone layers of this facies are approximately 2 to 10 cm thick, with the mudrock layers measuring less than 2 cm thick. The grain size of the sandstones ranges from very fine to medium (Fig. 16). The frequency of indurated mudrock beds typically increases upward throughout each package of this lithofacies (Fig. 15). Sedimentary structures observed include laminae (Fig. 17a) and ripplemarks (Fig. 17b). The orientations of the ripplemarks are similar to the

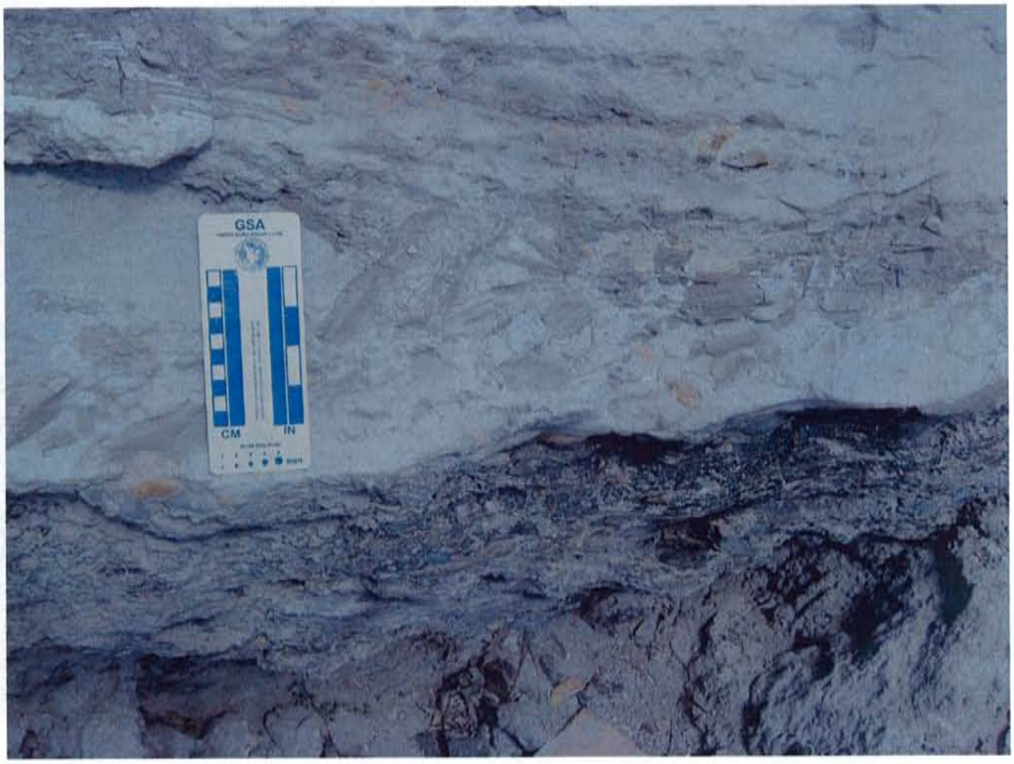


Figure 10. Rip-up clasts near base of thick sandstone lithofacies at measured section Highway 96. Section shown in picture is located near base of the Menefee Formation.

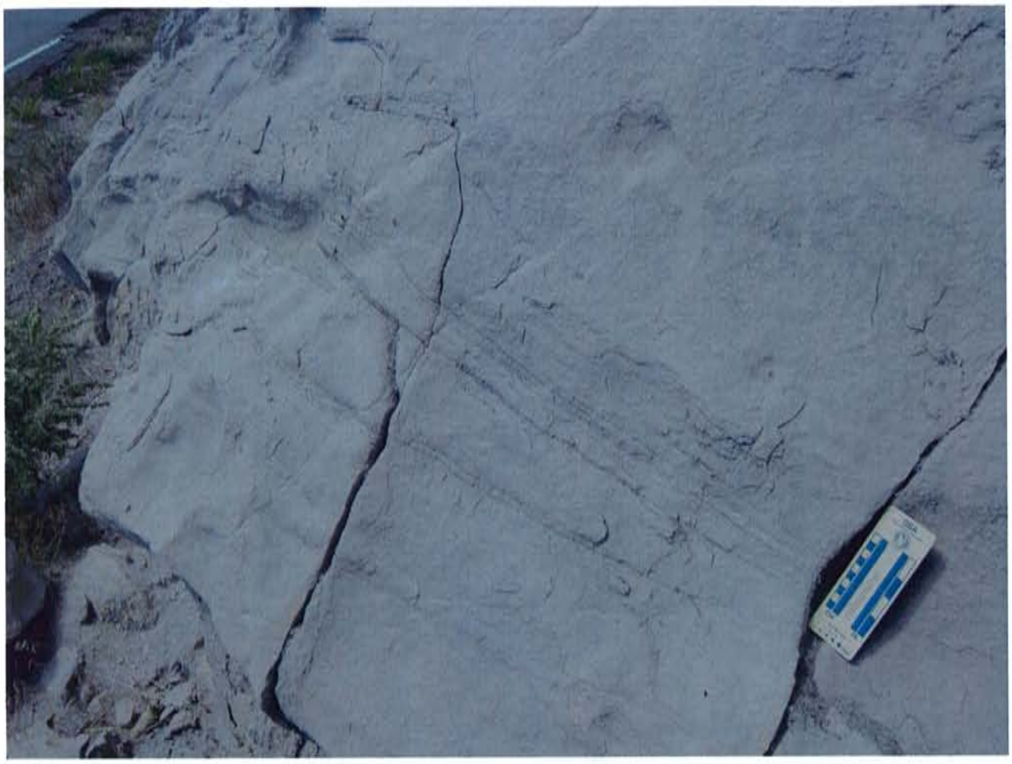


Figure 11. Trough cross bedding in a thick sandstone lithofacies at measured section Highway 96.

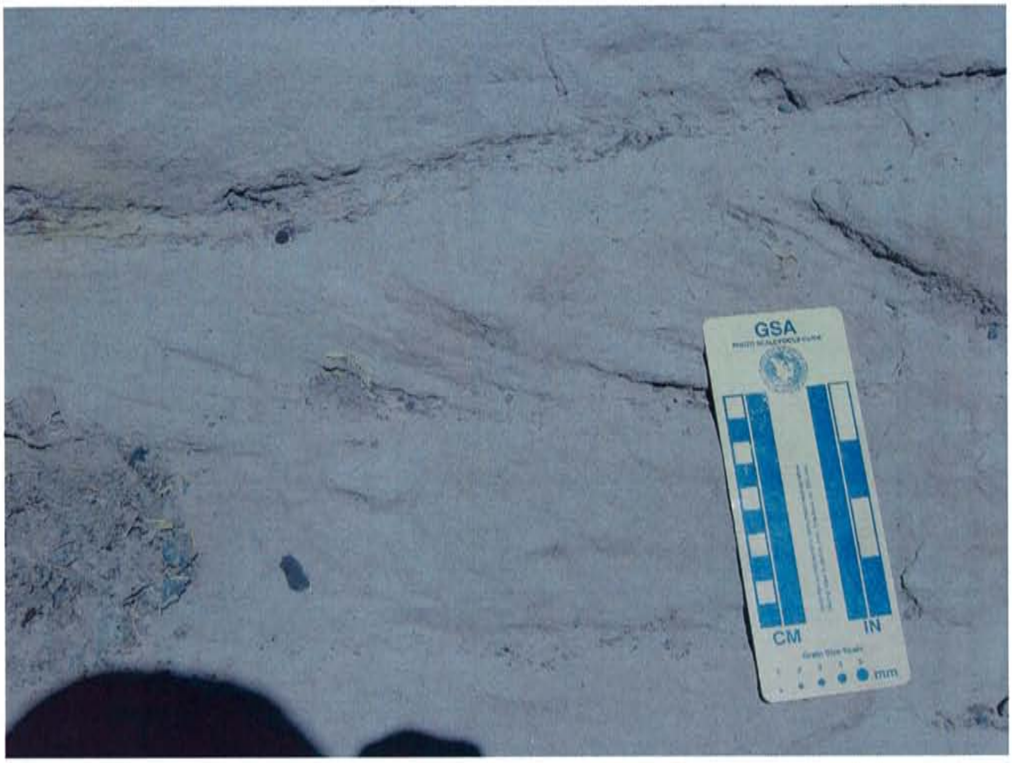


Figure 12. Tangential foreset cross bedding in thick sandstone facies at measured section Highway 96.

CROSS BEDDING

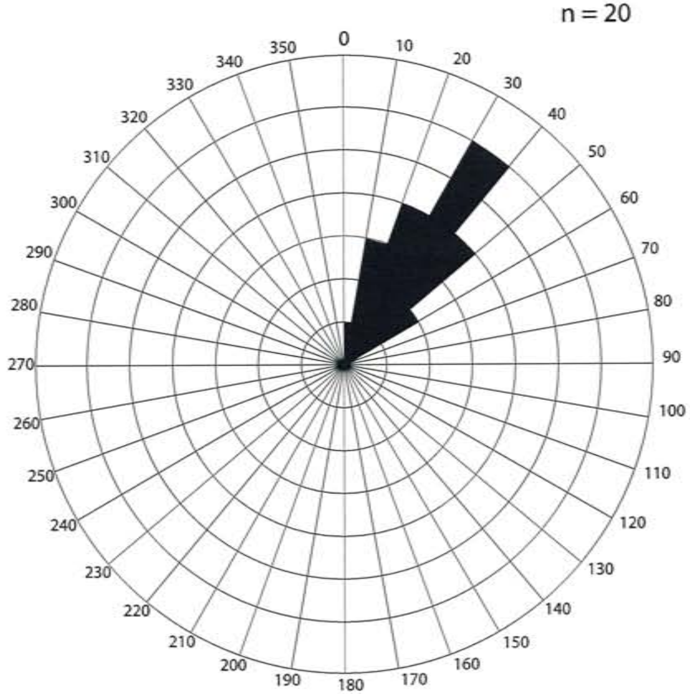


Figure 13a. Rose diagram showing paleocurrent data from thick sandstone lithofacies at Highway 96. Data set consists a total of 20 measurements of cross beds across entire exposure. A structure correction was applied to the data.

ASYMMETRICAL RIPPLE MARKS

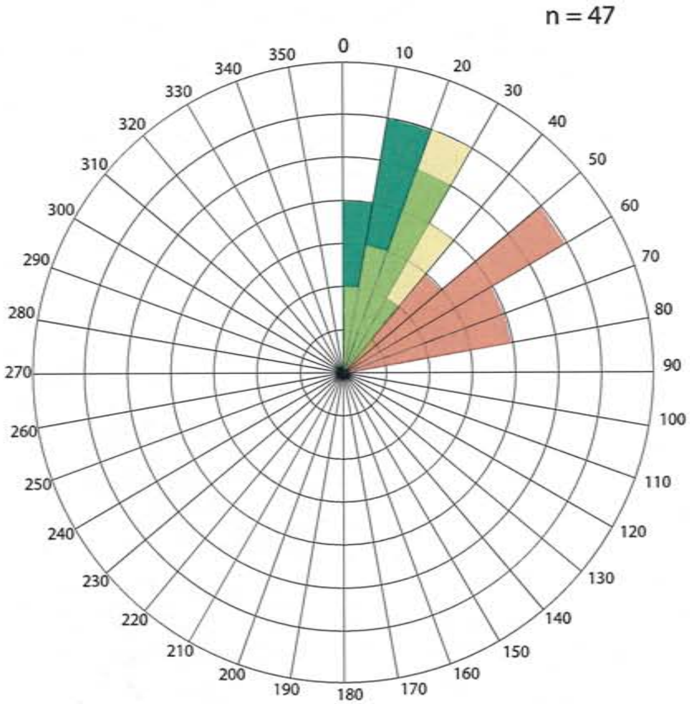


Figure 13b. Rose diagram showing paleocurrent data from thick sandstone lithofacies at Highway 96. Data set consists a total of 47 measurements of asymmetrical ripple marks collected from three seperate units. Green, yellow and red bars each indicate a seperate bed from which measurements were taken. A structure correction was applied to the data.

Figure 14. Siderite concretion in the Menefee Formation. This example is from measured section Highway 96. 19 cm notebook for scale.

Figure 15. Thin-bedded sandstone lithofacies. This example is from measured section Highway 96.

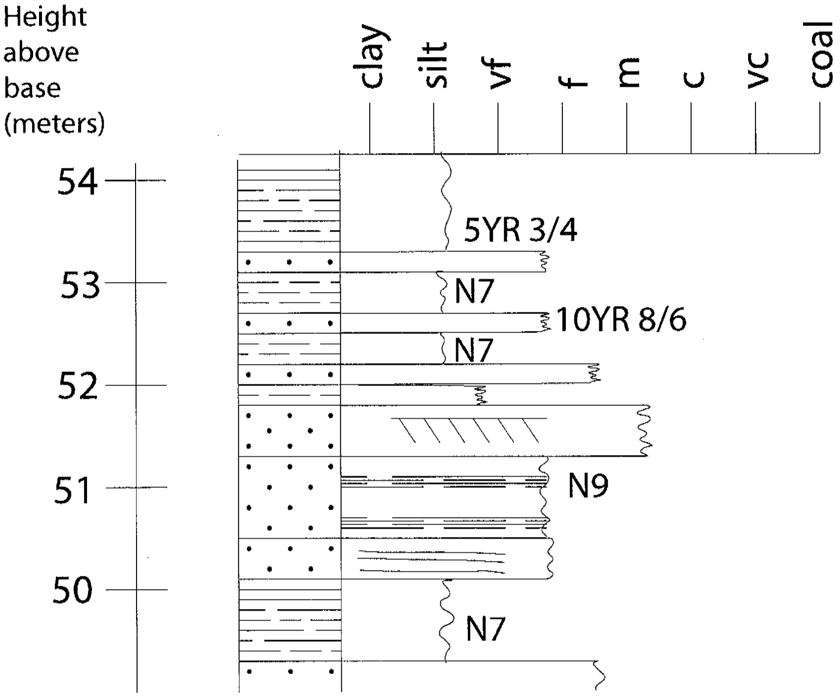


Figure 16. Measured section showing a series of interbedded sandstones and shales that make up the thin-bedded sandstone lithofacies.

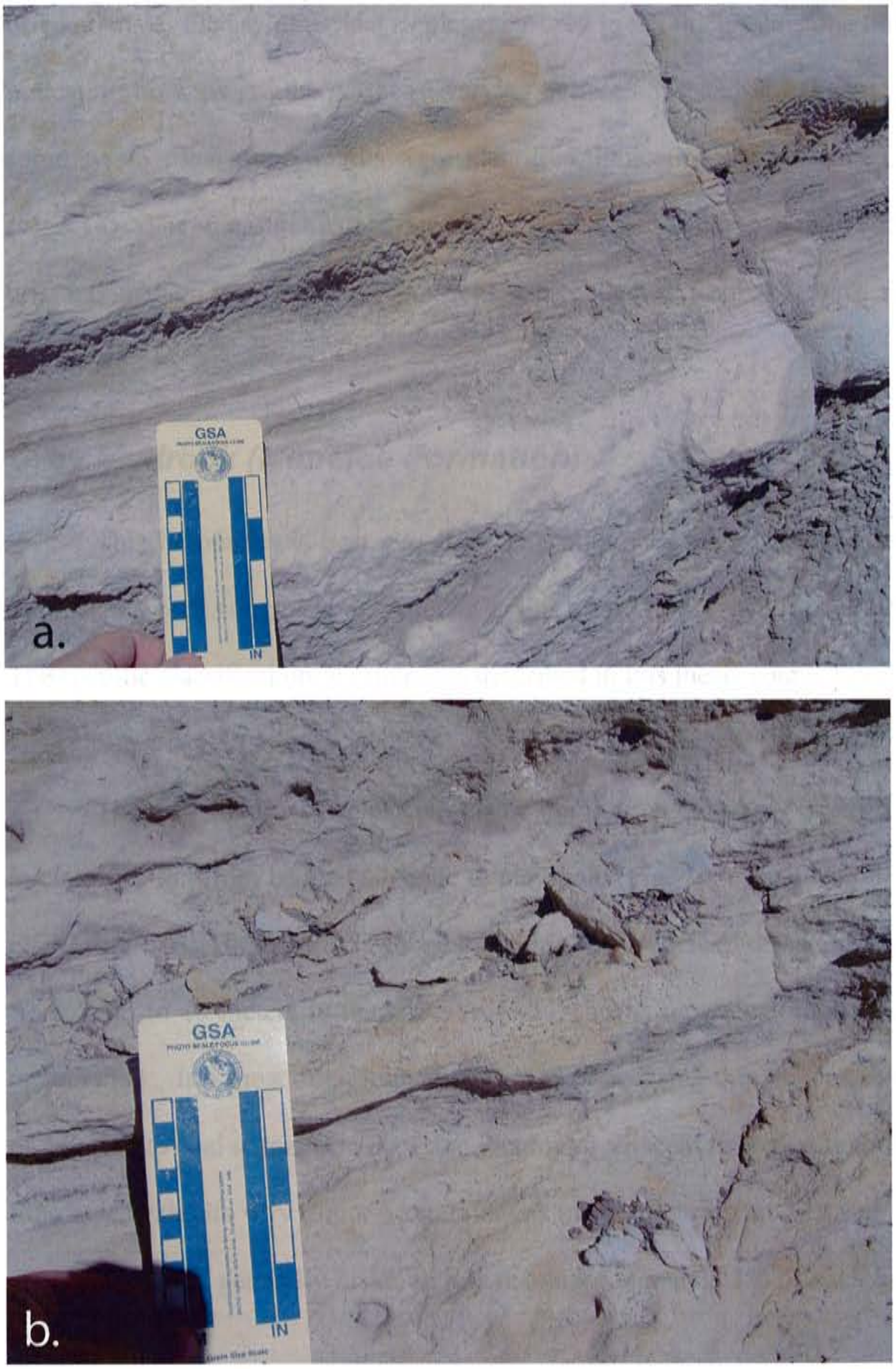


Figure 17. (A) Example of lamination found in thin bedded mudstone. (B) Ripple structures found in same lithofacies. Both examples are from measured section Highway 96.

orientations of the asymmetrical ripples measured in the thick sandstone lithofacies, indicating flow toward the northeast varying between 350 and 80° (Fig. 18). Also, some symmetrical ripple marks were identified, indicating the presence of waves (Fig. 18). The measurement from these structures revealed a more east-west orientation than any of the paleocurrent data collected from the thick sandstone lithofacies.

Grey Mudrock (Menefee Formation)

This lithofacies is best classified as a mudrock, a term used to describe a sedimentary rock composed of sediment grains smaller than sand (i.e., <0.062 mm). The specific classification of mudrocks described in this thesis comes from Potter et al. (1980).

The grey mudrock facies consists of light to medium grey deposits ranging in classification from bedded siltstone to clayshale (Fig. 19; classification of Potter et al., 1980). This lithofacies is abundant within the Menefee Formation, and ranges from 5 cm to 10 meters in thickness (Fig. 20), but is most commonly less than 3 meters thick. It is most often found adjacent to or encasing thin-bedded sandstones, or adjacent to coal seams. On occasion it is found adjacent to coally mudrock. This lithofacies exhibits very minor accumulations of coal debris, but the accumulations are localized and generally make up less than approximately 1% of each bed where found.

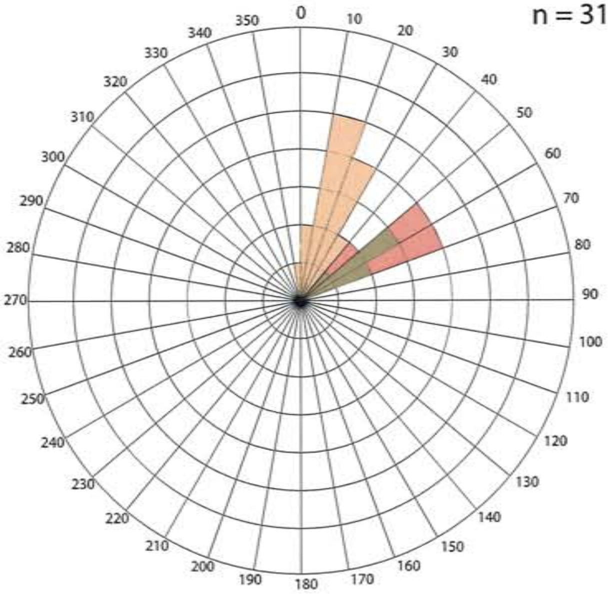

ASYMMETRICAL RIPPLEMARKS

Figure 18a. Rose diagram showing paleocurrent data from thin-bedded sandstone lithofacies at Highway 96. Data set consists a total of 31 measurements of asymmetrical ripplemarks from three seperate units. Orange, green and red bars each indicate seperate beds from which measurements were taken. A structure correction was applied to the data.

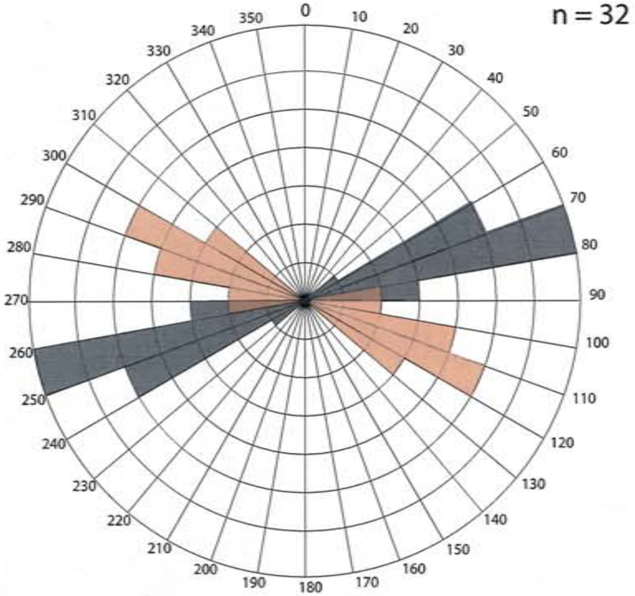

SYMMETRICAL RIPPLEMARKS

Figure 18b. Rose diagram showing orientation data from thin-bedded sandstone lithofacies at Highway 96. Data set consists a total of 32 measurements of symmetrical ripple marks collected from two seperate units. Orange, and blackbars each seperate beds from which measurements were taken. Measurements are shown perpendicular to crest. A structure correction was applied to the data.

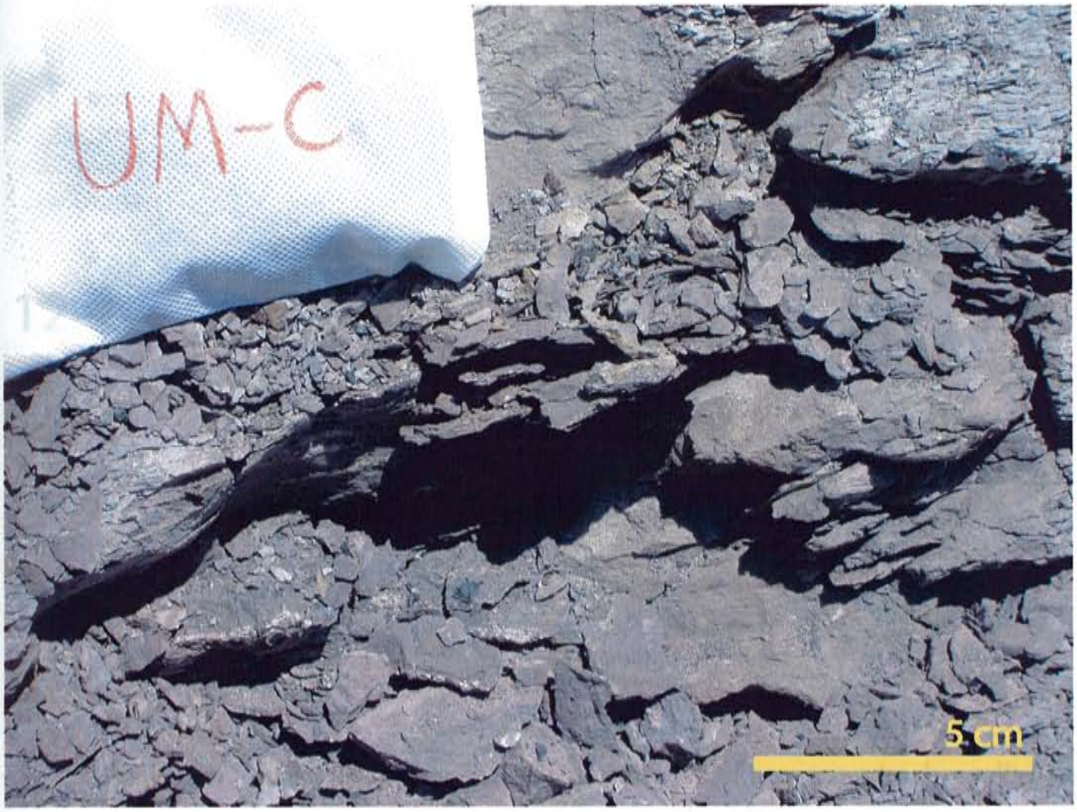


Figure 19. Grey mudrock lithofacies. From measured section Highway 96.

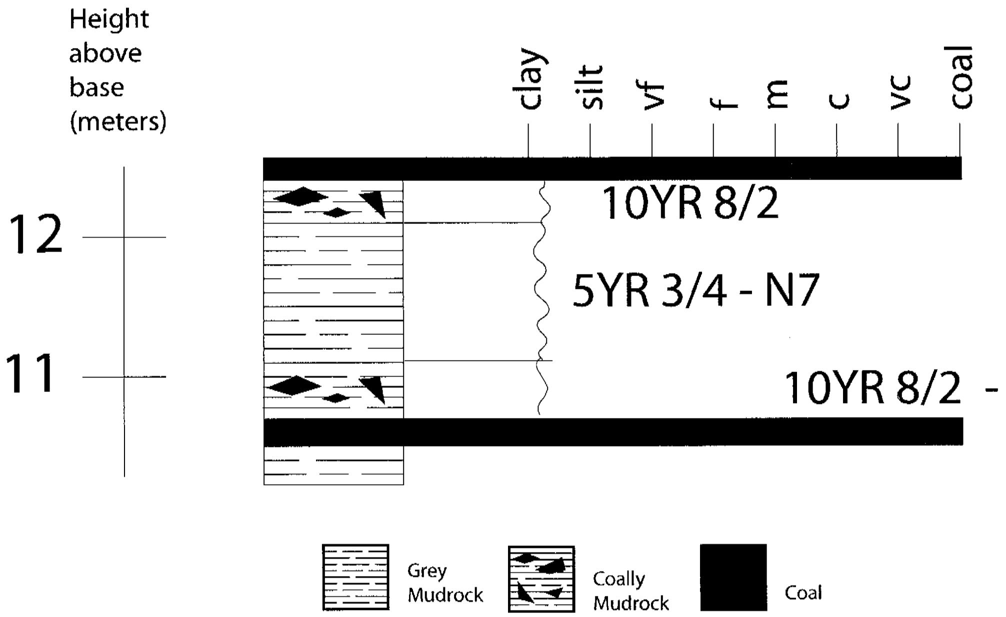


Figure 20. Measured section showing an example of a grey mudrock, coally mudrock and coal seam lithofacies. From measured section Highway 96.

Coally Mudrock (Menefee Formation)

The coally mudrock lithofacies makes up a large percentage of the Menefee Formation. It contains varying amounts of coally clasts and silt-sized sediment (Fig. 21). Because of the variable amounts of silt-sized particles the mudrocks range in classification between bedded siltstone, mudstone and claystone (Fig. 20). The coal clasts are angular, and measure about 1 to 3 mm in diameter. Thickness of this lithofacies varies between 5 cm and 10 meters. Color of the mudrock matrix varies from brown to dark brown/black. Coally/organic material is black, and consists of angular coal fragments and/or leaf and/or wood fragment imprints less than 5 mm across. Coally mudrock beds commonly contain laminations and very thin beds of planar siltstone and very fine grained sandstone, coal-free grey mudstones, and coal seams. Coally mudrocks have sharp upper and lower contacts with grey mudrock lithofacies, but are occasionally also in contact with a coal seam lithofacies. Like the grey mudrock facies, this lithofacies exhibits both strong and weak induration.

Coal Seam (Menefee Formation)

Some coal seams are observed in the Menefee Formation (Fig. 22). The thickest coal seams are about 2 meters thick, and only occur in a few measured sections (Hwy 96: 12 m, 65 m; JM: 83 m, 167 m; AS1: 72 m; AS2: 92 m; AS3: 85 m; AS4: 188m; AS5: 83 m). In addition, the thicker coal seams are not pure, as they contain numerous pockets of coally mudrock. The vast majority of the pure coal seams are sparsely distributed and measure less than 20 cm thick (Fig. 20). The

Figure 21. Coally mudrock lithofacies. From measured section Highway 96.

Figure 22. Coal seam lithofacies. From measured section Highway 96.

coals found within the Menefee Formation are dark black and rank as sub-bituminous A (Hoffman, 1991). The seams are commonly found encased in coally mudrocks. Hoffman (1996) presented compositional data for the coal., which were collected from the La Ventana coal field located along the southeastern edge of the basin, just south of the southern field area. The average sulfur content for the Cleary Member is 1.01 vol %, whereas the sulfur content of the upper coal member was found to be 1.36 vol %. These values are higher than the average sulfur content for San Juan Basin coals, which is 0.92% (Hoffman, 1996). In much of the literature, the Menefee Formation is referred to as a coal-abundant unit, but when inspected in outcrop the pure coal seams are actually found to be a very minor component of the strata, between 1 and 5% (AS1 2.8%; AS2 3.4%; AS3 3.5%; AS4 1.9%; AS5 2.5%; DT 4.9%; JM 3.7%; HWY 96 4.8%; SS 2.9%) .

Flaser-Bedded Sandstone Lithofacies (Cliffhouse Sandstone)

Although this lithofacies is actually a part of the Cliffhouse Sandstone, it is included in this thesis because its interpretation may help to better understand the depositional environment of the Menefee Formation. Both the Point Lookout and Cliffhouse Sandstone were examined in the measured sections; both exhibited cross bedding in some places, but in general consist of massive sandstone bedding. Unlike the Point Lookout Sandstone and the rest of the Cliffhouse Sandstone, this unit exhibits distinctive sedimentary structures and trace fossils, therefore it was examined more closely and included in the list of lithofacies. This lithofacies is believed to be an integral part of the depositional environment of the Menefee Formation as well as the entire Mesaverde Group. By applying Walther's Law, the facies interpretation of this unit may provide insight into the adjacent facies, which includes the Menefee Formation.

Across the northern and southern outcrop belts, this distinctive package of flaser bedded and wood debris abundant sandstone (Fig. 23) is present and marks the contact between the Menefee Formation and overlying Cliffhouse Sandstone. This sandstone is well exposed throughout the northern field area, and fairly well exposed in the Jaquez Mine and Dead Tree measured sections. The thickness of this lithofacies varies between 3 and 6 meters with no discernable trends in thickness across the outcrop. The grain size varies between fine and medium (Fig. 24). The color is mostly a yellowish grey, with localized areas of light olive grey. This lithofacies exhibits abundant wood debris imprints that measure 10 cm long and less. The wood debris exhibits extensive boring casts, identified as *Teredolites* (Fig. 23a). This lithofacies also exhibits localized zones of flaser bedding (Fig. 23b).

Core Descriptions

Most of the lithofacies described in outcrop were also identified in the core. In many of the cores, only partial sections were available, and it was common for sections of the core to be missing or severely broken, making lithologic description difficult. The descriptions of the three cores allow a direct comparison with their associated well logs. The three wells used for this analysis include San Juan Unit

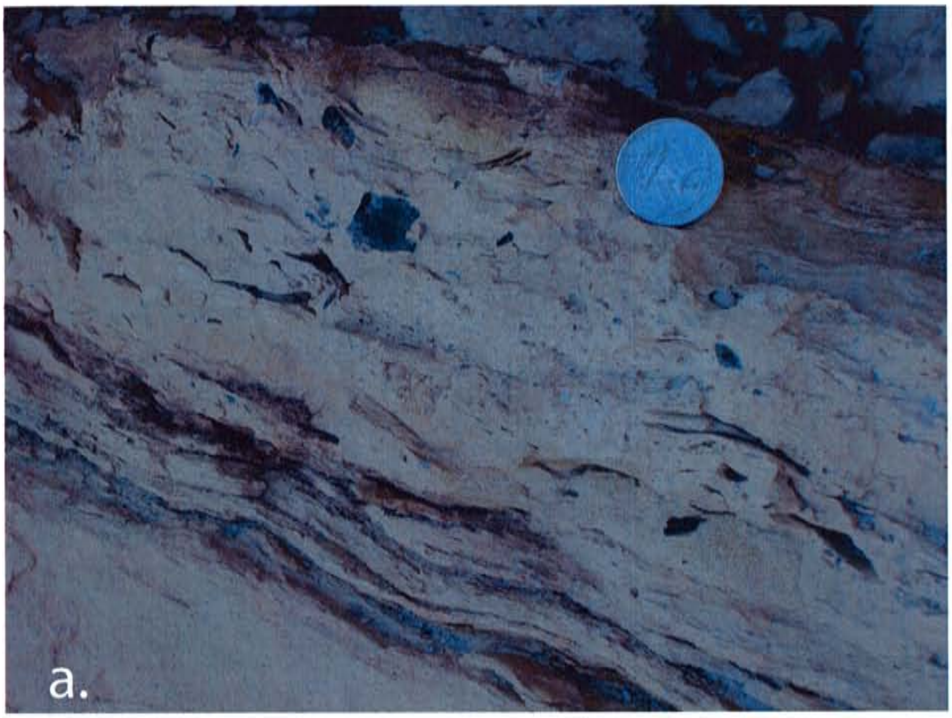


Figure 23. (a) Flaser bedding found within heavily-bioturbated sandstone lithofacies. (b) Bioturbation in heavily-bioturbated sandstone lithofacies. This example is from measured section AS-3. Coin diameter is 2.5 cm.

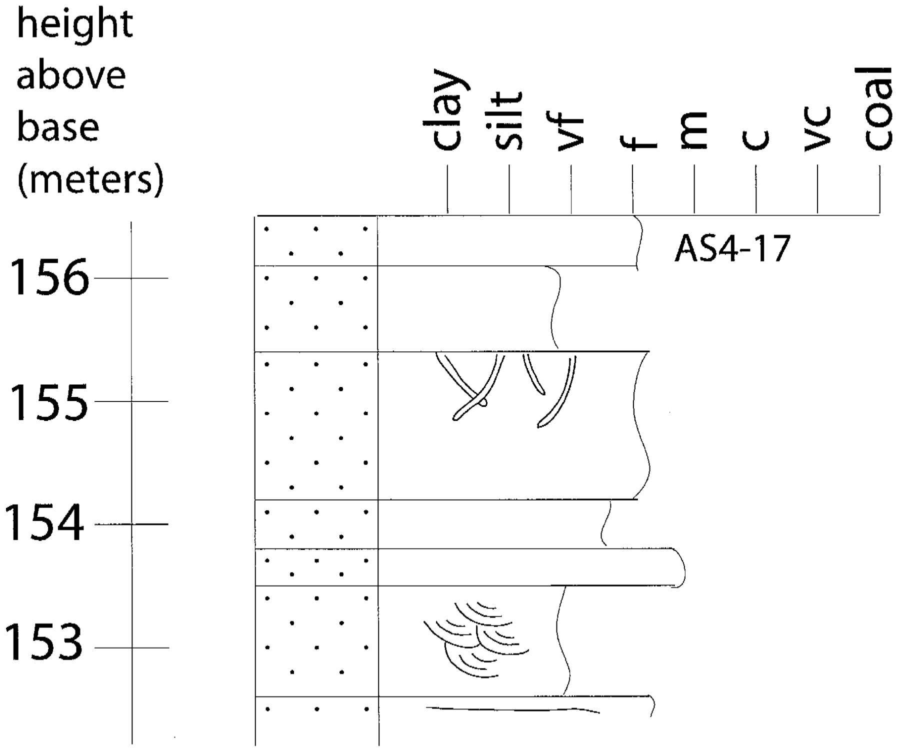


Figure 24. Measured section showing an example of heavily bioturbated sandstone lithofacies from measured section AS-5

28-6 #3ST (Fig. 25), 4C Howell d 2R (Fig. 26), and San Juan Unit 29-7 102A (Fig. 27).

The thick sandstone lithofacies is present in each of the three cores (Fig. 28). The sandstones observed in core are identical to those in outcrop except for color. The sandstones in outcrop are whitish yellow to orangish-yellow due to weathering of the surface exposures, whereas the core samples retain their original grayish appearance. Other than color, the lithofacies in outcrop and core match in lithology and sedimentary structures.

The grey mudrock (Fig. 29) and coally mudrock lithofacies (Fig. 30) are both present in the cores, and have the same appearance as the mudrocks in outcrop. Some core samples of both mudrock lithofacies remain intact, whereas some sections of seemingly identical material are completely shattered within the core box. Possible explanations for this include variable drilling rates when extracting the samples, poor handing after collection, samples were taken from a zone of natural fractures, or there may in fact be extremely subtle differences in the rocks that alter their strengths, such as variation in clay content.

Only one example of a pure coal seam was found, and no example of the thin-bedded sandstone lithofacies was observed. This is most likely due to the fact that a complete section of Menefee Formation core was not available. Collecting a core sample is an expensive process; therefore operators are often very selective in which intervals are sampled. Because they are not present, it is likely that the thin-bedded sandstone and coal lithofacies were not considered significant to the operators of cored wells examined in this thesis, therefore not sampled in the cores.

San Juan Unit 28-6 #3 ST
300390722
28N 6W 32

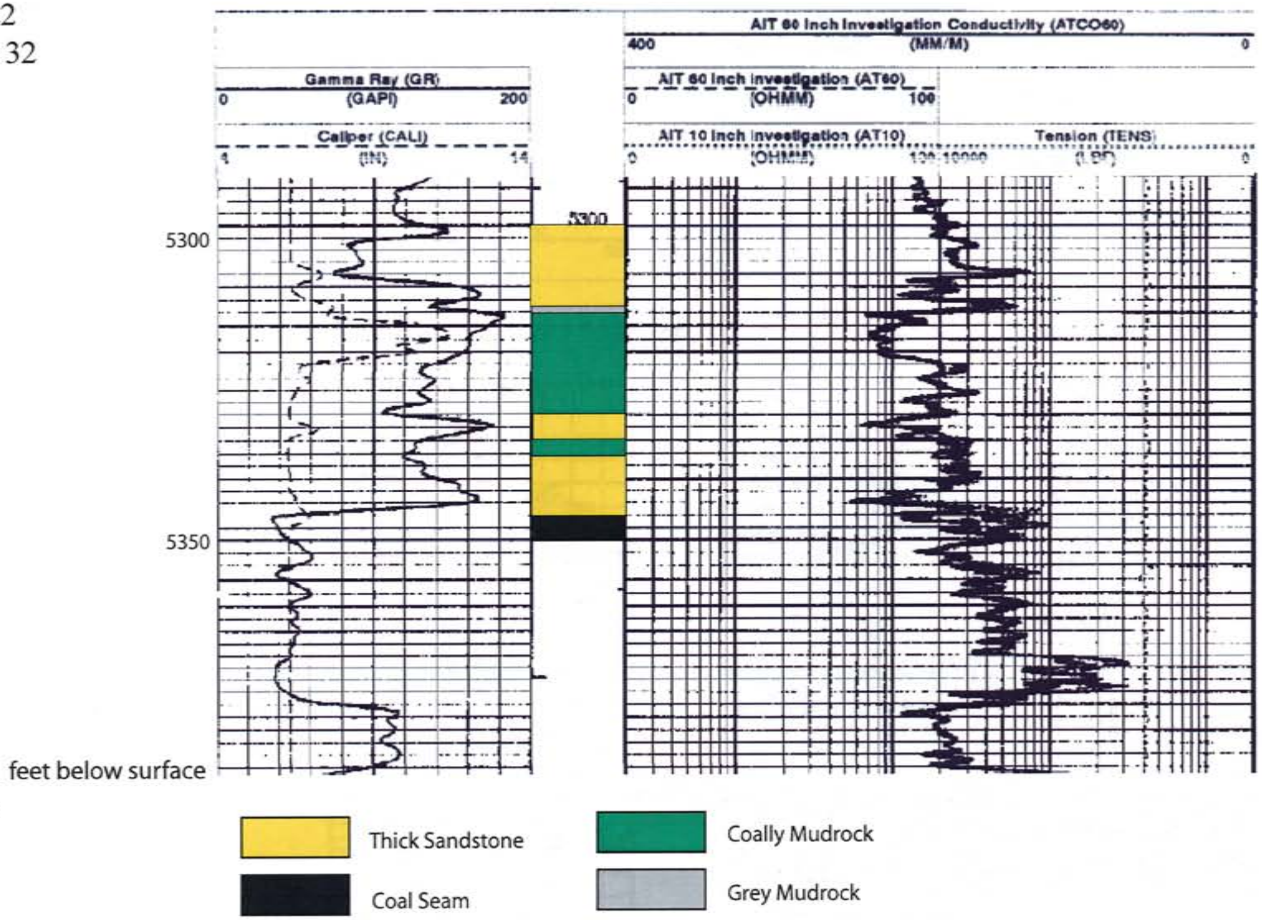


Figure 25. Well log and core description for well San Juan Unit 28-6 #3 ST. Log scale is 5" = 100'.

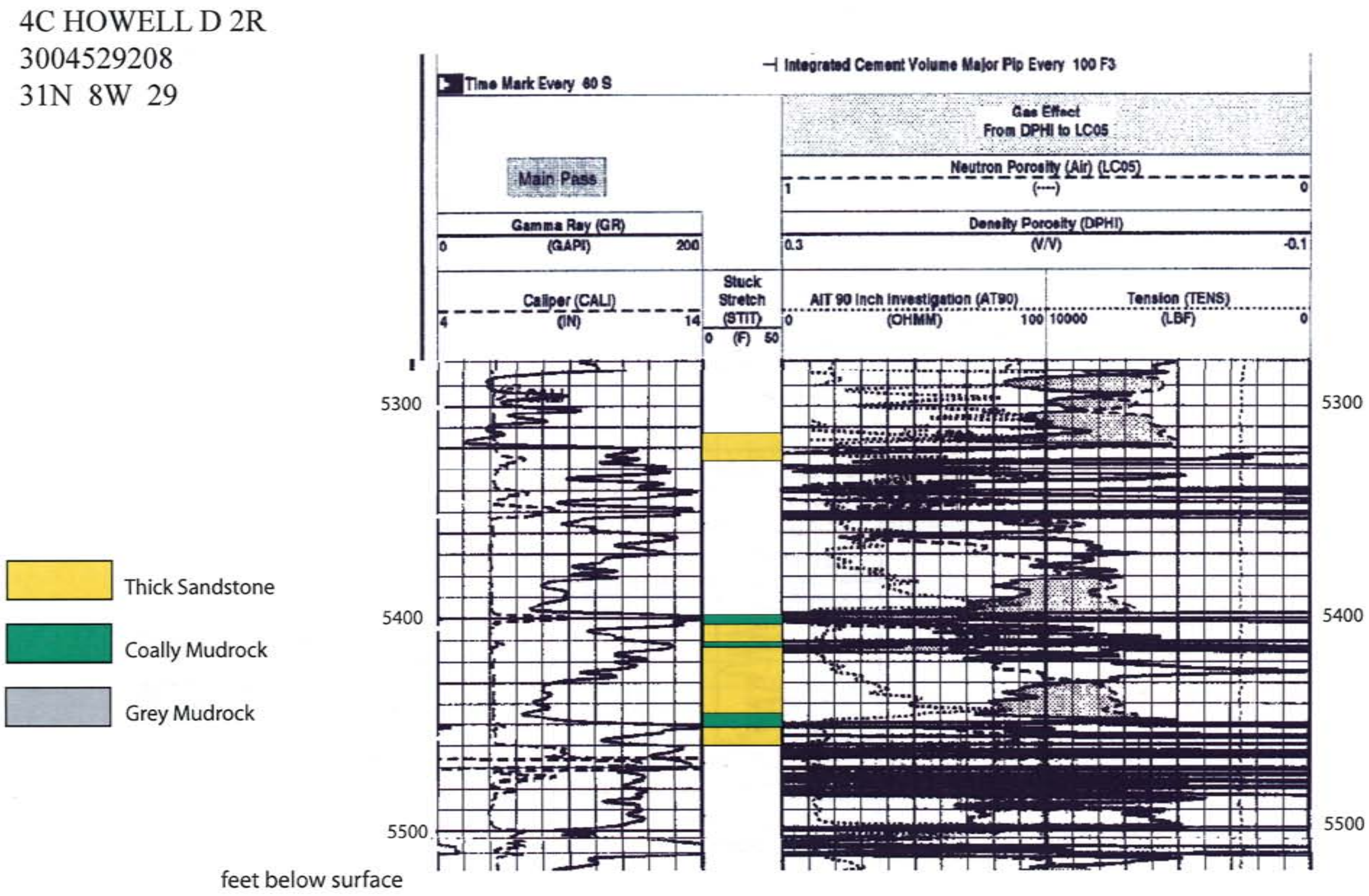


Figure 26. Well log and core description for well 4C Howell D 2R . Log scale is 2" = 100'.

San Juan Unit 29-7 102A
300392544
29N 7W 15

🟨 Thick Sandstone
🟩 Coally Mudrock
⬜ Grey Mudrock

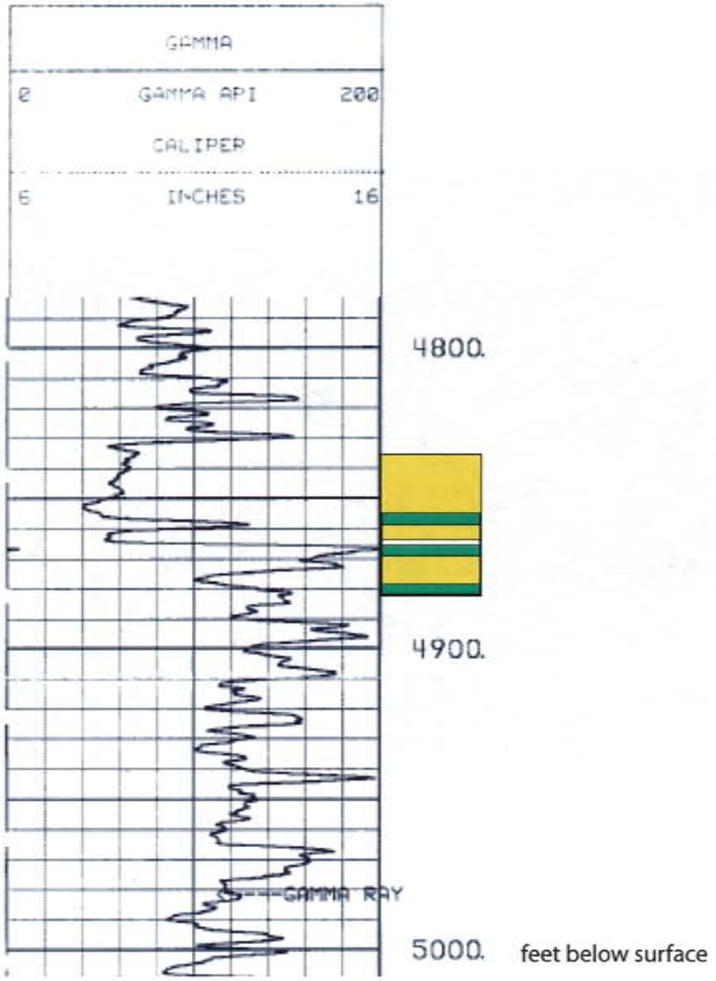


Figure 27. Well log and core description for well San Juan Unit 29-7 102A. Log scale is 2” = 100’.

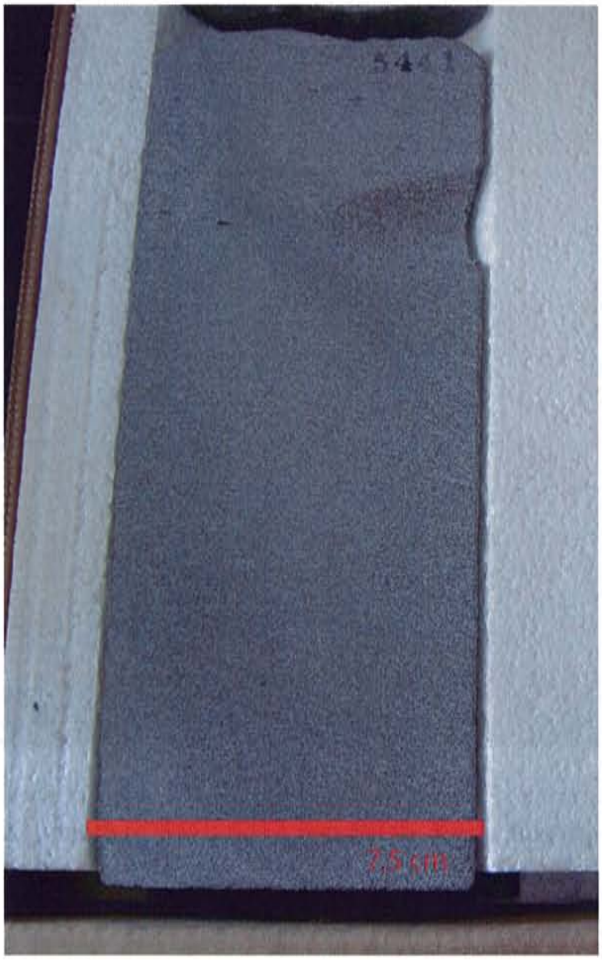


Figure 28. Thick sandstone lithofacies in a core sample. Sample is from well 4C Howell D2R, depth of 5441 feet below Kelly Bushing level.

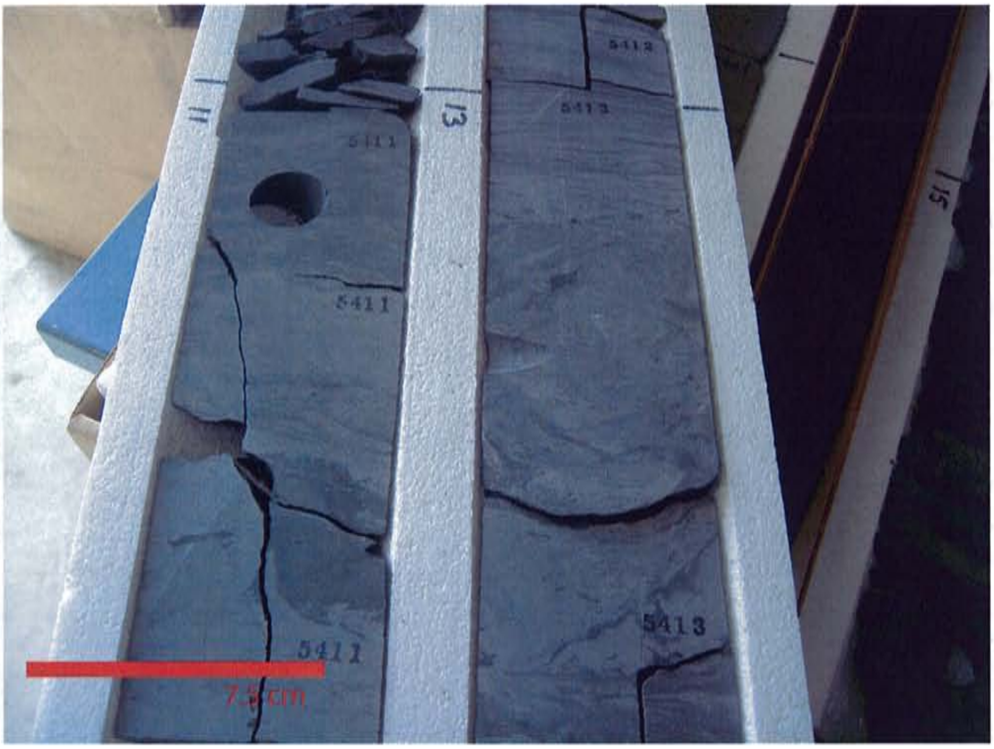


Figure 29. Grey Mudrock lithofacies in a core sample. Sample is from well 4C Howell D2R, depth of 5410-5413 feet below Kelly Bushing level.

Figure 30. Coally mudrock lithofacies in a core sample. Sample is from well 4C Howell D2R, depth of 5414-5418 feet below Kelly Bushing level.

A primary objective of the core description was to allow for a more accurate interpretation on the logs. Due the low resolution of the logs and the high vertical variability, this could not be done to a satisfactory degree. The lithologies in the outcrop vary on a scale of 10's of cm, which is too small a scale for the down-hole measurement devices to resolve. Also, the responses on the well logs for the matching sections of core often were very different than expected. Similar lithologies with minor differences in coally material will produce vastly different log responses. An example of this can be seen in Fig. 27 at depth 5345'. The actual amount of coally material is less than 5%, yet the log curve infers the lithology has a much higher coal content. The primary problems here seem to be the high variability of the strata and low resolution of the measurement tools; therefore both the high vertical variability of the strata in the Menefee Formation and the low resolution of the logging tools make it extremely difficult to pick individual beds from the well logs.

Cross Sections

Several cross sections were constructed using outcrop data and subsurface data from well logs to illustrate changes in the stratigraphy of the Mesaverde Group throughout the southeast San Juan Basin. The method of illustrating these changes is correlating the strata using lithostratigraphy.

Two cross sections were built across the field areas: one across the northern field area and one across the southern (Fig. 2). Across the northern area the Mancos Shale, the Point Lookout Sandstone and the lower Menefee Formation are relatively uniform in thickness (Fig. 31). The only exception is in the middle of the field area, near section AS-3, where the Point Lookout Sandstone thickens and then thins to the north and south. The contact between the Point Lookout and the overlying Menefee Formation is sharp and planar to undulating across the outcrop, and is adjacent to either a Menefee mudstone or coal seam lithofacies. Within the Menefee Formation, the lithofacies are not continuous across the outcrop belt. This is observed in photographs of the outcrop, as the massive sandstones that comprise the Allison Sandstone Member are a series of lenticular sandstone bodies of varying size, present mainly as isolated pods (Fig. 6). Due to extensive surface cover, it was not possible to trace the lateral continuity of the more easily eroded mudstone and coal lithofacies over a distance of more than 10 meters.

In sections AS-3 and AS-4, there is an intertonguing of Menefee Formation and Cliffhouse Sandstone deposits, which results in a situation where the end result is an additional ascending sequence of Menefee Formation and Cliffhouse Sandstone (Fig. 31). Within these sections, the heavily-bioturbated sandstone facies is observed twice, marking two contacts between the Menefee Formation and the Cliffhouse Sandstone (Fig. 31). When constructing the cross section for this area, the lower contact is used as the datum. Because of extensive vegetation cover and variability of the exposed rocks, the specific point at which the Menefee Formation tongue pinches out could not be located. Based on the correlations, it is expected to pinch out to the north, between measured sections AS-2 and AS-3. Although no example of this intertonguing is documented in any of the previous literature, it likely represents a minor regressive-transgressive shift within the larger scale

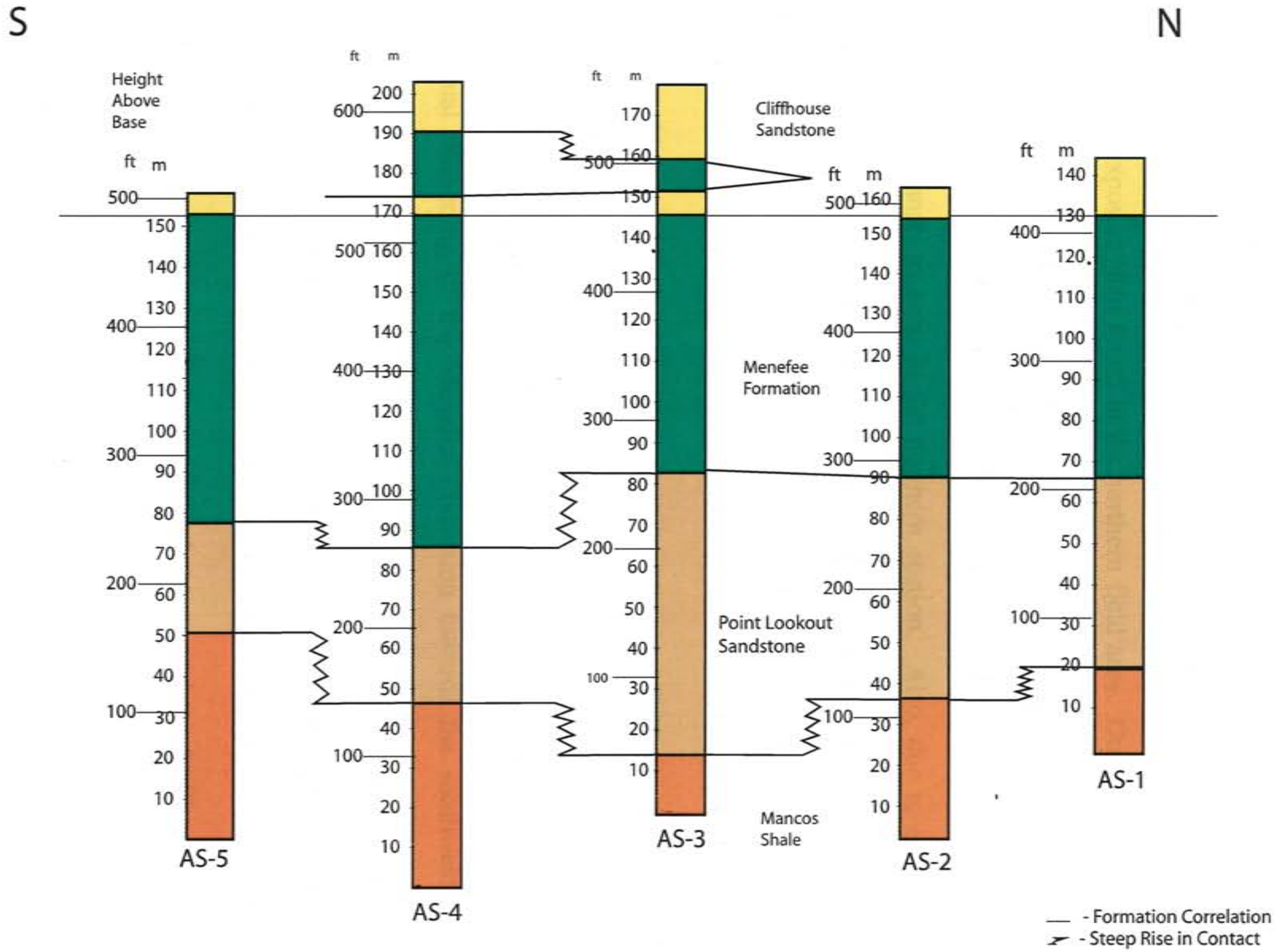


Figure 31. Cross section across northern field area. Datum: top of Menefee Formation.

regressive-transgressive depositional system of the Mesaverde Group that is discussed in the previous literature (Young, 1973; Fassett, 1974; Molenaar, 1974; Donselaar, 1989; Devine, 1991; Molenaar and Baird, 1992).

Across the southern field area, the correlation (Fig. 32) is less complete due to poorer exposure than found in the northern field area. Due to surface cover the Point Lookout Sandstone is not exposed in sections Highway 96 or DT. When observed, the contact between the Point Lookout and the Menefee Formation is sharp and planar, as seen in the northern section. Also, due to more extensive surface cover in the southern field area, the flaser-bedded sandstone lithofacies can only be observed in sections JM and DT. Across the outcrop belts, the southern area is similar to the northern area as the strata are relatively parallel, exhibiting minor thickness changes between sections SS and HWY 96 and also between section DT and JM.

In the subsurface, several general trends can be identified. The first is a gradual thickening of the Menefee Formation towards the southwest. This is illustrated in cross section #4 (Figs. 33 a, b), where the thickness of the Menefee doubles from less than 2000 ft to in excess of 4000 ft towards the southwest. The Point Lookout Sandstone exhibits a gradual thinning towards the northeast, as does the Cliffhouse Sandstone. Both the Point Lookout and the Cliffhouse Sandstones exhibit an occasional steep rise of their contacts, illustrated by steep rises on the cross sections. Cross section #1 (Fig. 34) shows that the stratigraphy has minimum variation along a northwest/southeast trend. In cross section #1, there is a slight thickening of the strata between wells #124 and #13, and a thinning of the strata

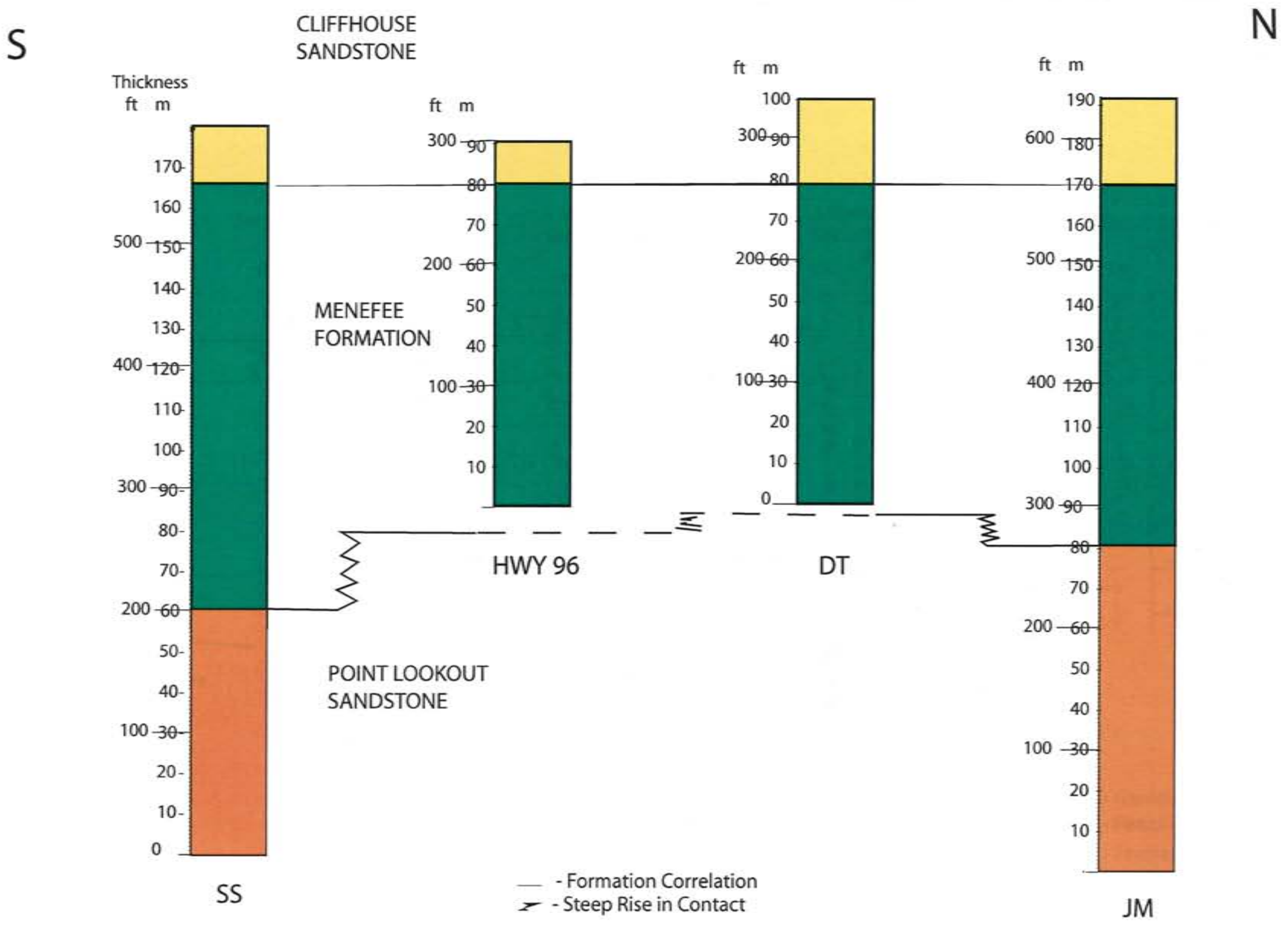


Figure 32. Cross section across southern field area. Datum: Top of Menefee Formation.

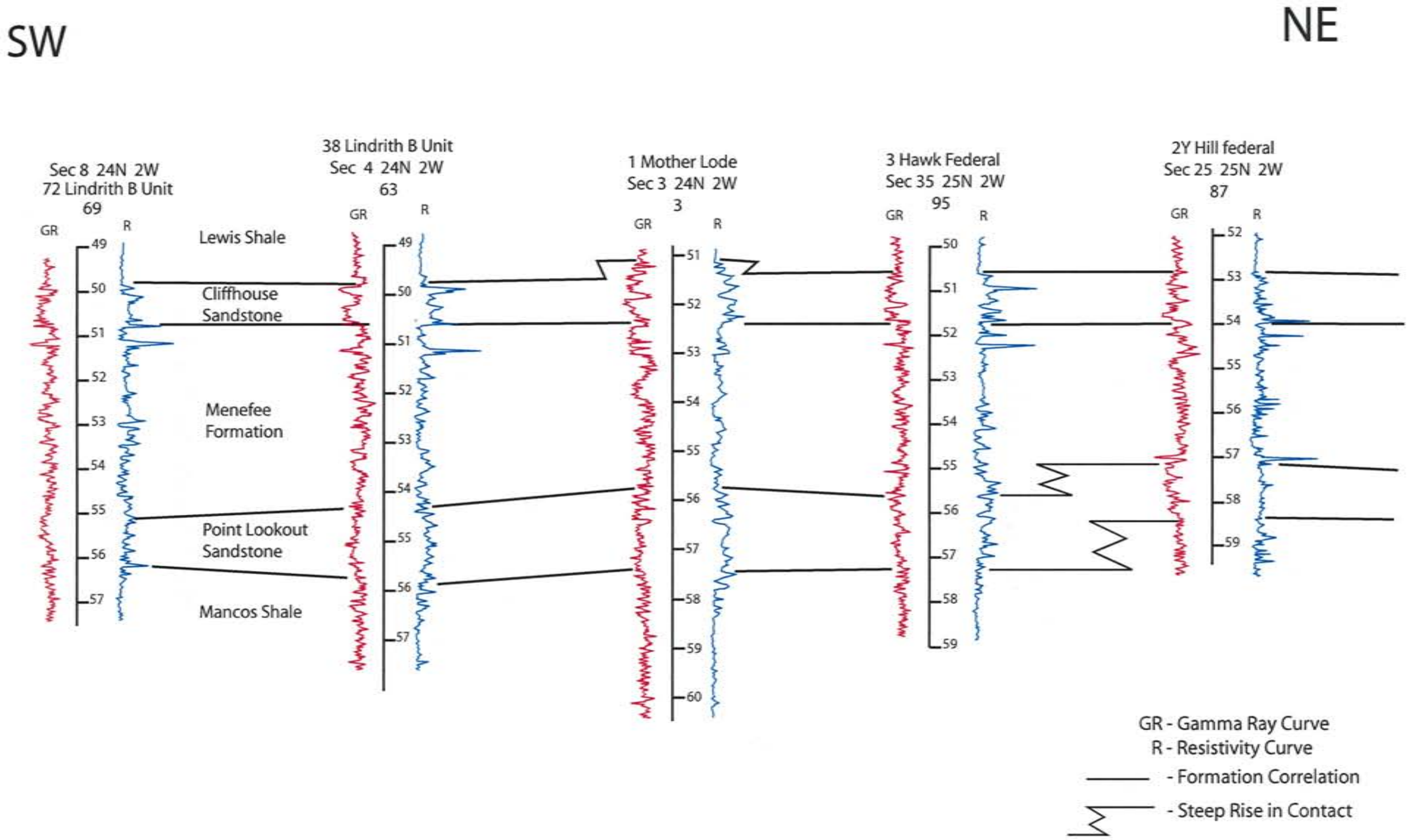


Figure 33a. Cross Section #4. Depth x100 from KB. Continued on next page.

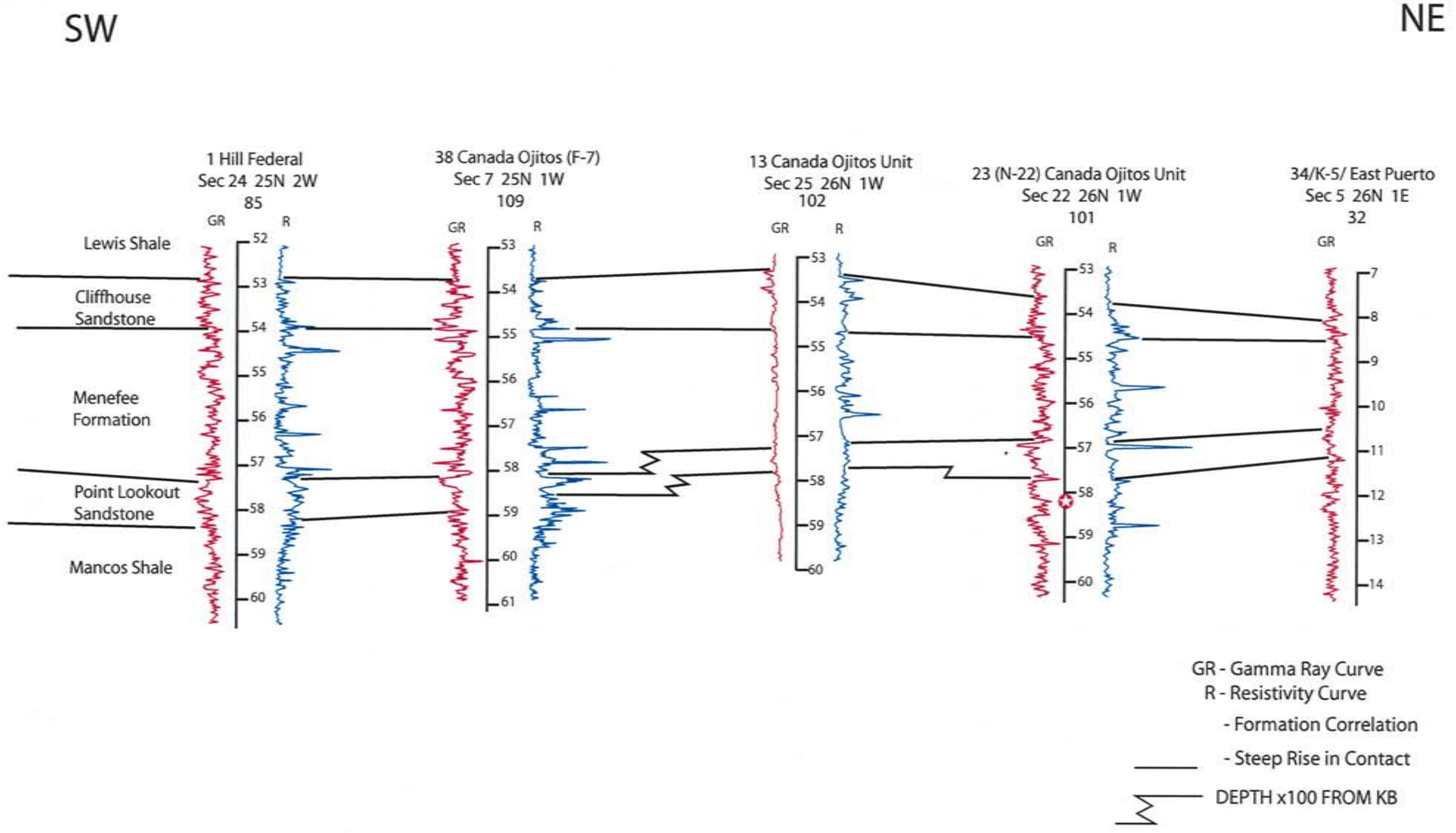


Figure 33b (cont.). Cross Section #4. Continued from previous page. Datum: Top of Menefee Formation. Depth x100 from KB.

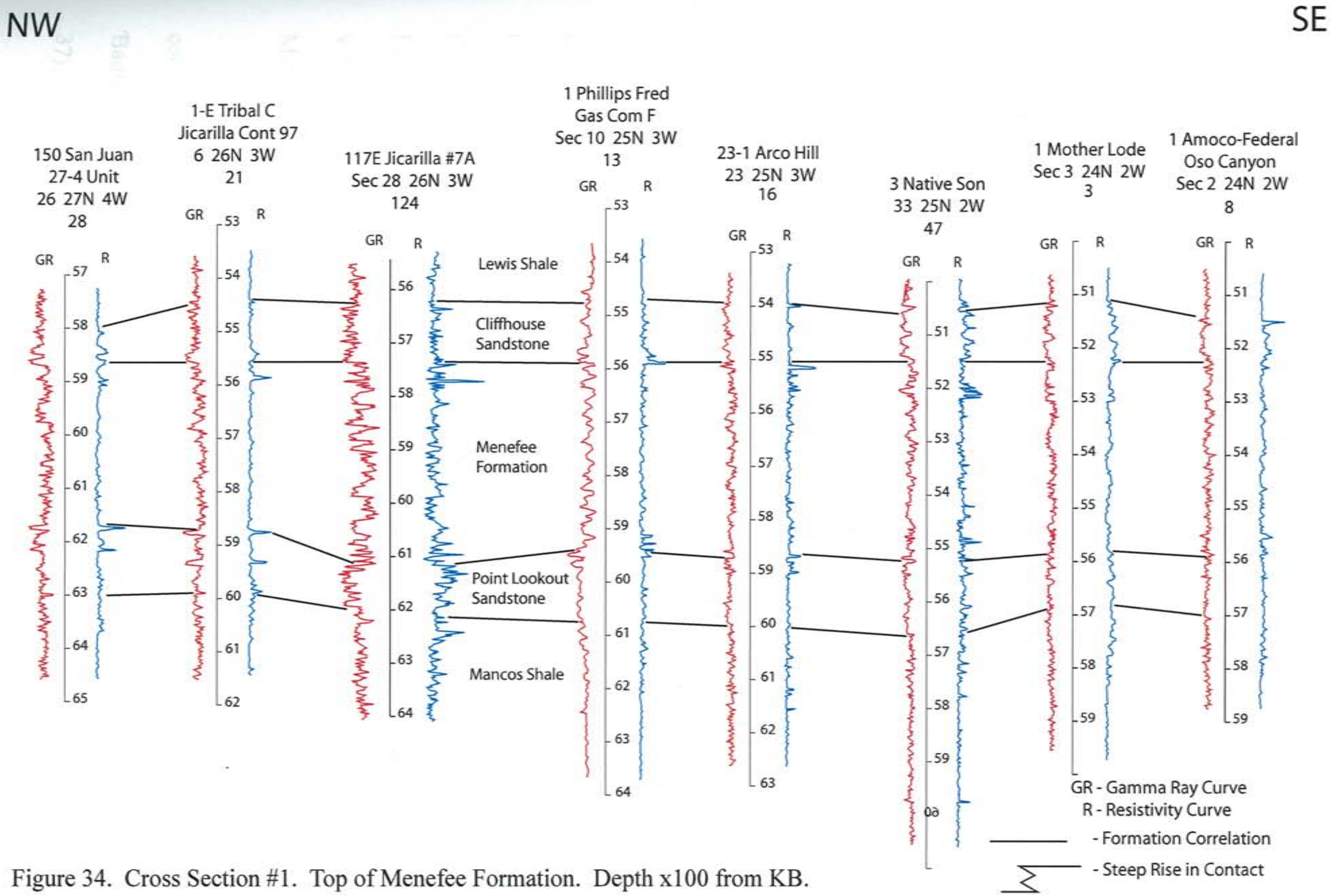


Figure 34. Cross Section #1. Top of Menefee Formation. Depth x100 from KB.

between wells #16 and #3. The thickening and thinning in these locations is attributed to the fact that the cross section is not completely straight in the northwest/southeast direction, showing the changes in stratigraphy in a more NNW direction. Cross section #2 (Fig. 35) is parallel to cross section #1, but maintains a straighter line of section. As a result, the changes in thickness within the cross section are not as great, as cross section #2 does show the Point Lookout Sandstone thickening slightly towards the southeast. Cross section #2 is situated further towards the northeast, whereas cross section #1 is more centrally located within the basin. As a result, the thickening of the Mesaverde Group towards the southwest observed in cross section #4 can also be seen by comparing the relative thickness change from cross section #1 across the basin to cross section #2.

Cross section #3 (Fig. 36) is placed in a position that allows for comparison of the subsurface nearest to the basin margin, and also lies directly adjacent to the southern field area. In cross section #3, the strata exhibits the gradual wedge-thickening towards the southwest found in each of the other sections. The Cliffhouse Sandstone maintains a relatively constant thickness, as does the Point Lookout. Across wells 1 Atencio Federal., Badland Hills #15-1 and Badland Hills 9-1, the Point Lookout Sandstone is separated by a minor intertonguing of the Mancos Shale that can also be correlated into the southern area cross section.

The stratigraphy of the Mesaverde Group exhibits a smooth transition when correlated from outcrop into the subsurface (Fig. 37). Wells 1 Atencio Federal and Badland Hills 15-1 are located in a line with the southern field area correlation (Fig. 37), therefore are easily correlatable. Because of the quality of exposure of the

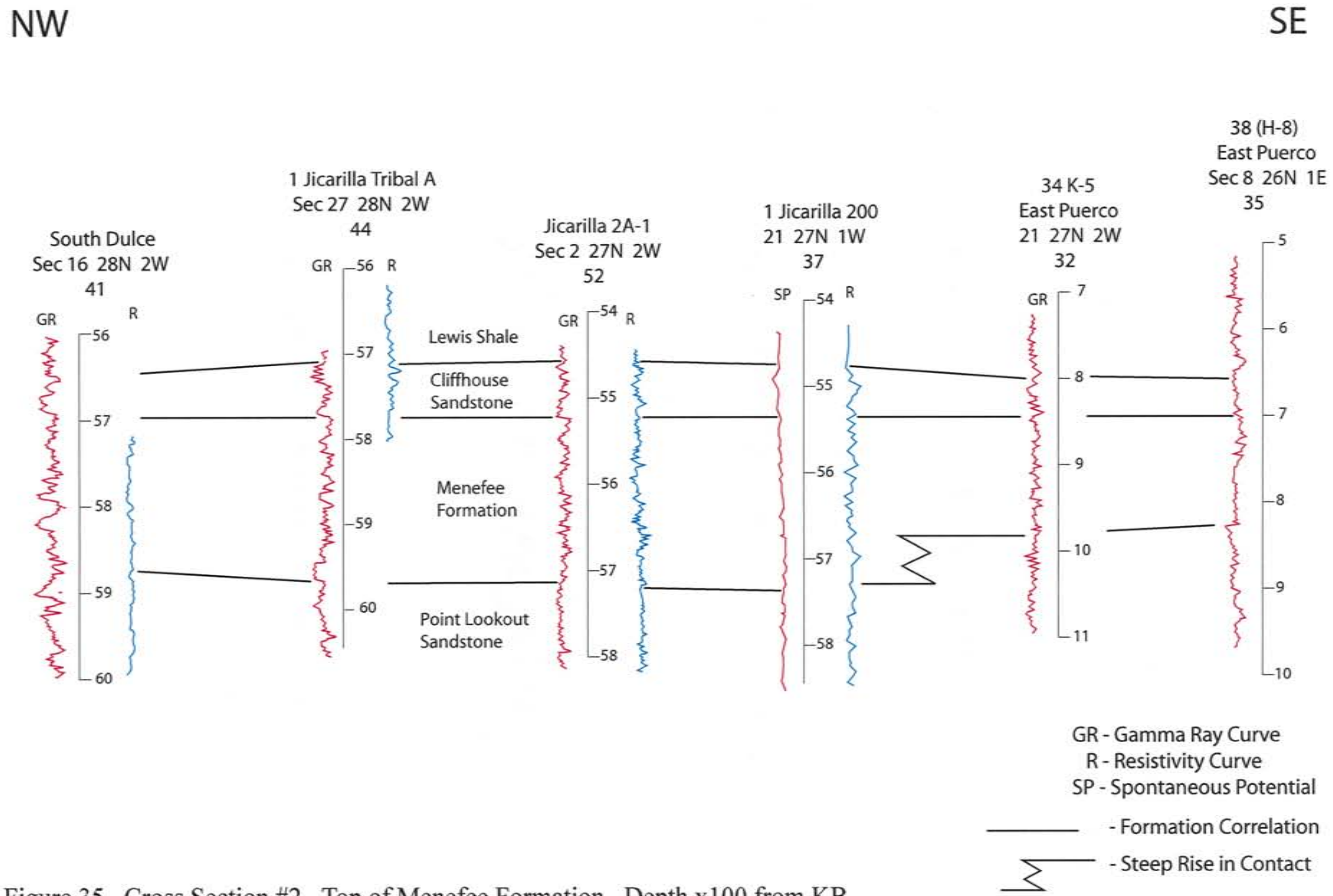


Figure 35. Cross Section #2. Top of Menefee Formation. Depth x100 from KB.

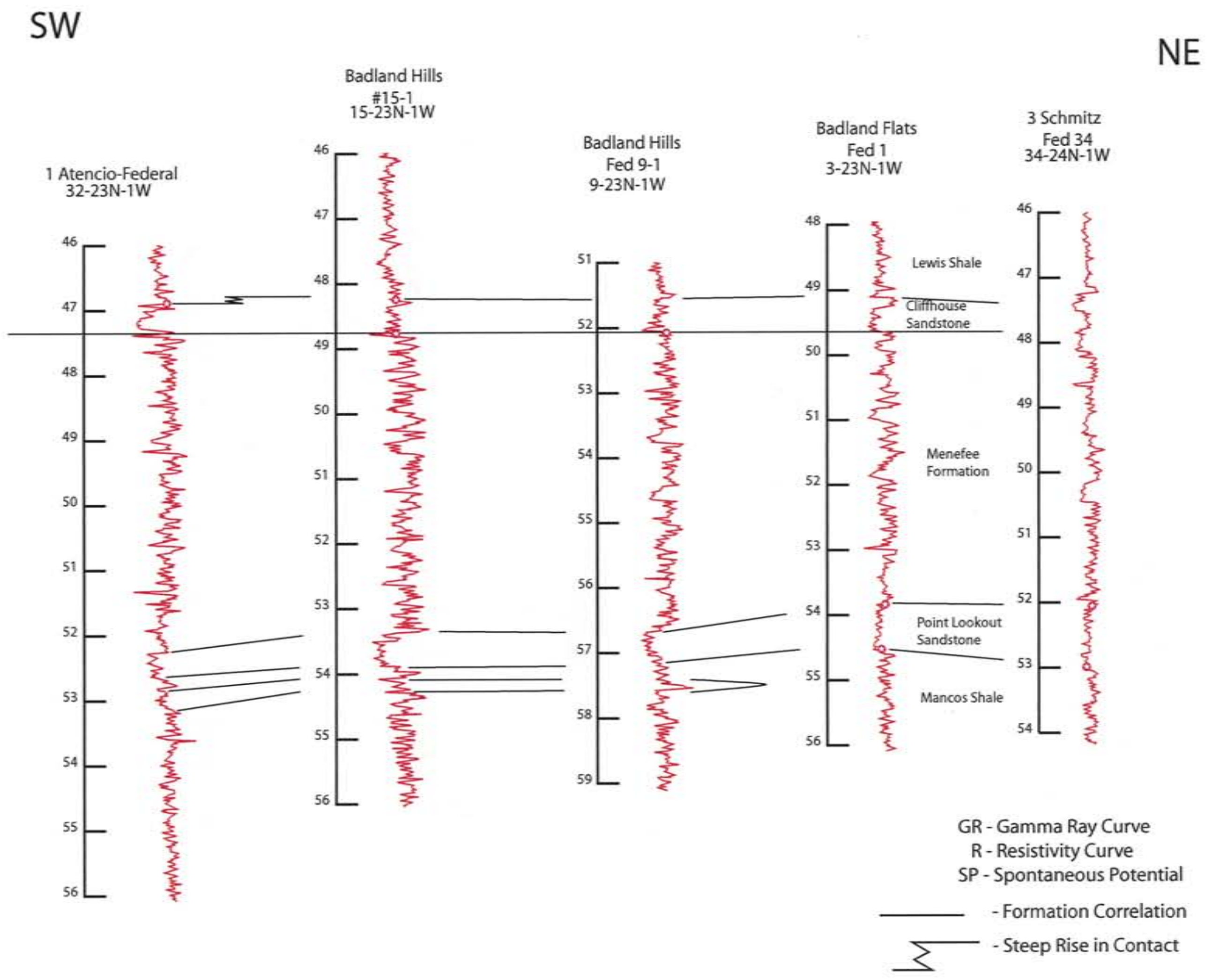


Figure 36. Cross Section #3. Top of Menefee Formation. Depth x100 from KB.

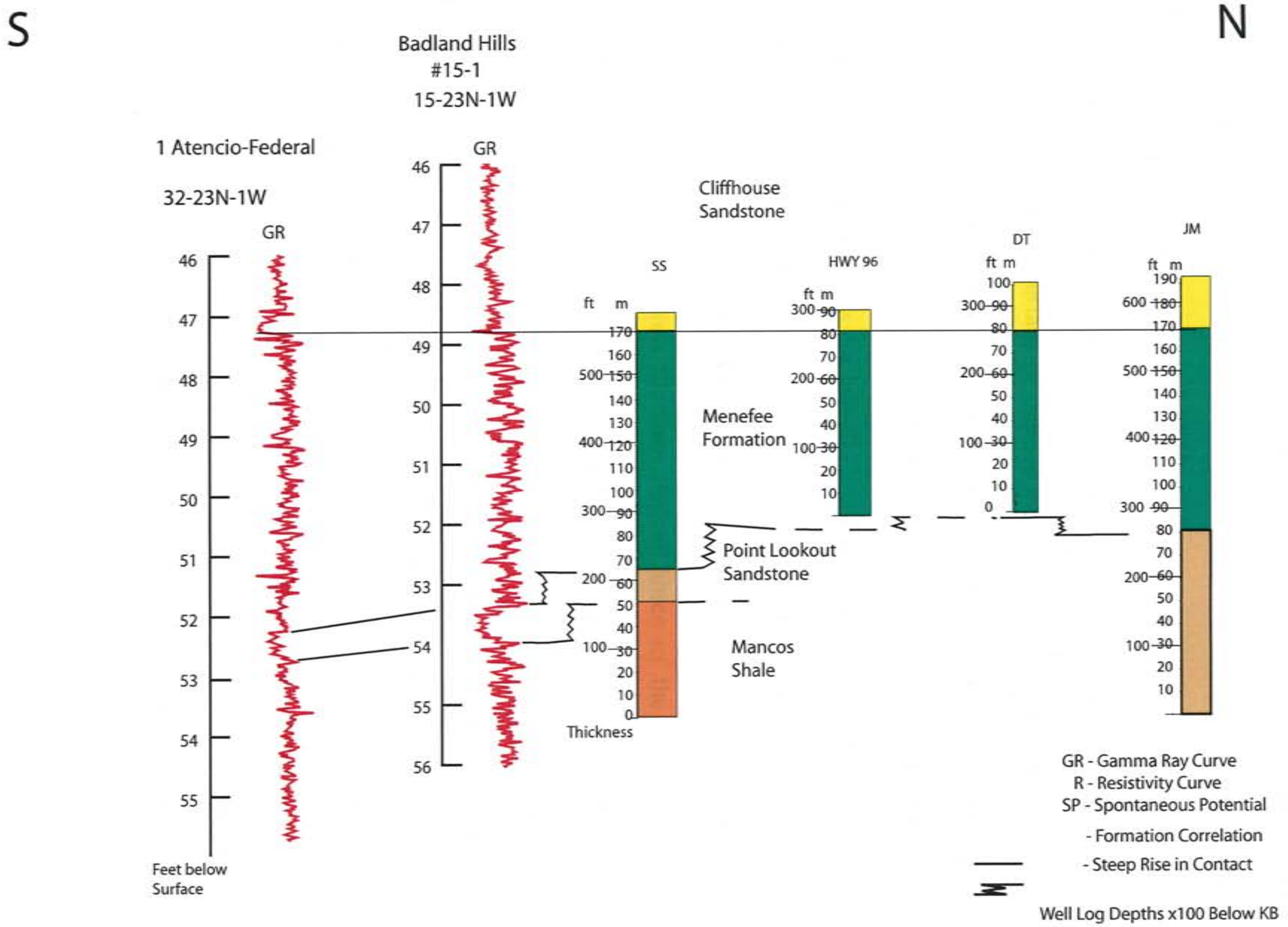


Figure 37. Subsurface to outcrop belt correlation. Datum: Top of Menefee Foramtion.

outcrop belt and accessibility, the formations cannot be correlated continuously from the subsurface across the outcrop. The Menefee Formation exhibits a general thinning towards the northeast until some point between measured sections HWY 96 and DT, where it begins to thicken. Measured Section JM, the northernmost section in the southern field area, has the thickest section of Menefee Formation found in either subsurface or outcrop data. Also, the lower contact of the Point Lookout Sandstone was not exposed in this field area. In the southern part of the cross section, the Point Lookout is separated into two units by an intertonguing of the Mancos Shale. It is not laterally continuous, as it is not observed in measured section South Saddle. It is likely that the Mancos Shale tongue also pinches out directly to the southwest of well 1 Atencio Federal.

The cross sections illustrate that all three of the formations within the Mesaverde Group gradually thin toward the northeast margin of the San Juan Basin. There are local fluctuations within each of the formations, causing random thickening and thinning throughout the basin. The local fluctuations are minor, on the scale of around 50 ft, whereas large scale thinning of the strata is on the order of 200 to 300 ft. Of the three formations, the Menefee Formation exhibits the most extreme thickness changes across the basin. From the northeast to southwest, the formation thickness varies by 220 ft. From the northwest to southeast, the strata maintain a relatively constant thickness of 350 ft. Cross section #2, which is situated parallel to cross section #1 but closer to the northeast margin of the basin, also exhibits a relatively constant thickness of around 200 ft.

Siderite Geochemistry

The elemental composition of the siderite was examined on an electron microprobe. A total of six concretions were sampled, two each from three beds that contained the siderite. Samples L1 and L2 were collected from the middle of the Cleary Member, M1 and M2 were collected from the Upper Cleary Member, and U1 and U2 were collected from the Allison Member (Fig. 38).

When the mol % of Ca, Mg, and Fe are plotted for each set of samples, the results are very similar (Fig. 39 a, b). All samples are relatively pure, exhibiting high concentrations of Fe, almost to the point of end-member compositions. When the composition of the samples are plotted to show Ca-Mg-Mn ratios, the results from each sample are relatively similar as well. Each set of samples from the same bed appear to have a somewhat similar composition, but the match is not as strong from bed to bed. The points from samples L1 and L2 do not lie in as tight a cluster as the other two sample sets; however the points do still fall in a field that reflects a dominantly Fe composition. The points on the Mn-Mg-Ca plot for samples U1 and U2 are slightly more concentrated near the Mn end member than samples L and M. Samples M1 and M2 are similar to L1 and L2, plot with a fairly mixed composition, exhibiting an overall centralized point cluster on a Mn-Mg-Ca plot.

When the results of Mozley (1989) are overlain on the ternary plots, the siderites primarily plot within a freshwater setting (Fig 39 a, b). The data collected from the samples taken from the Menefee Formation show relatively high Fe and Mn contents, supporting the hypothesis that the siderites formed in freshwater. It should be noted that in general., the results on the Ca-Mg-Fe plot are more

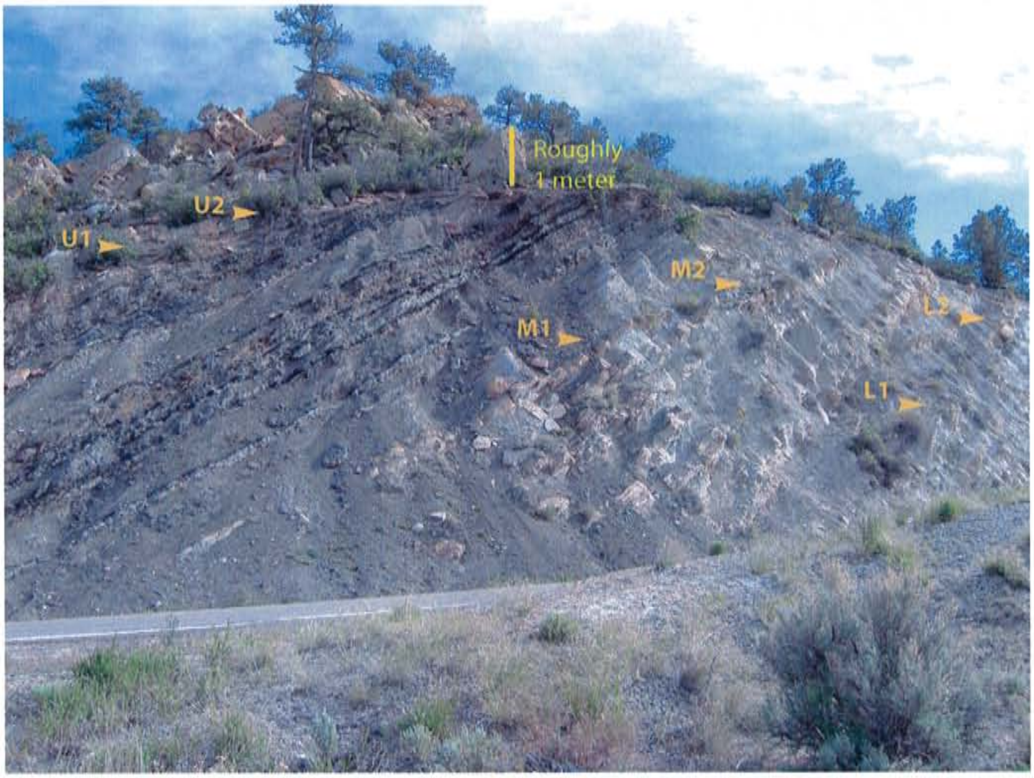


Figure 38. Measured section Highway 96, showing locations where the siderite samples were collected. View to the north.

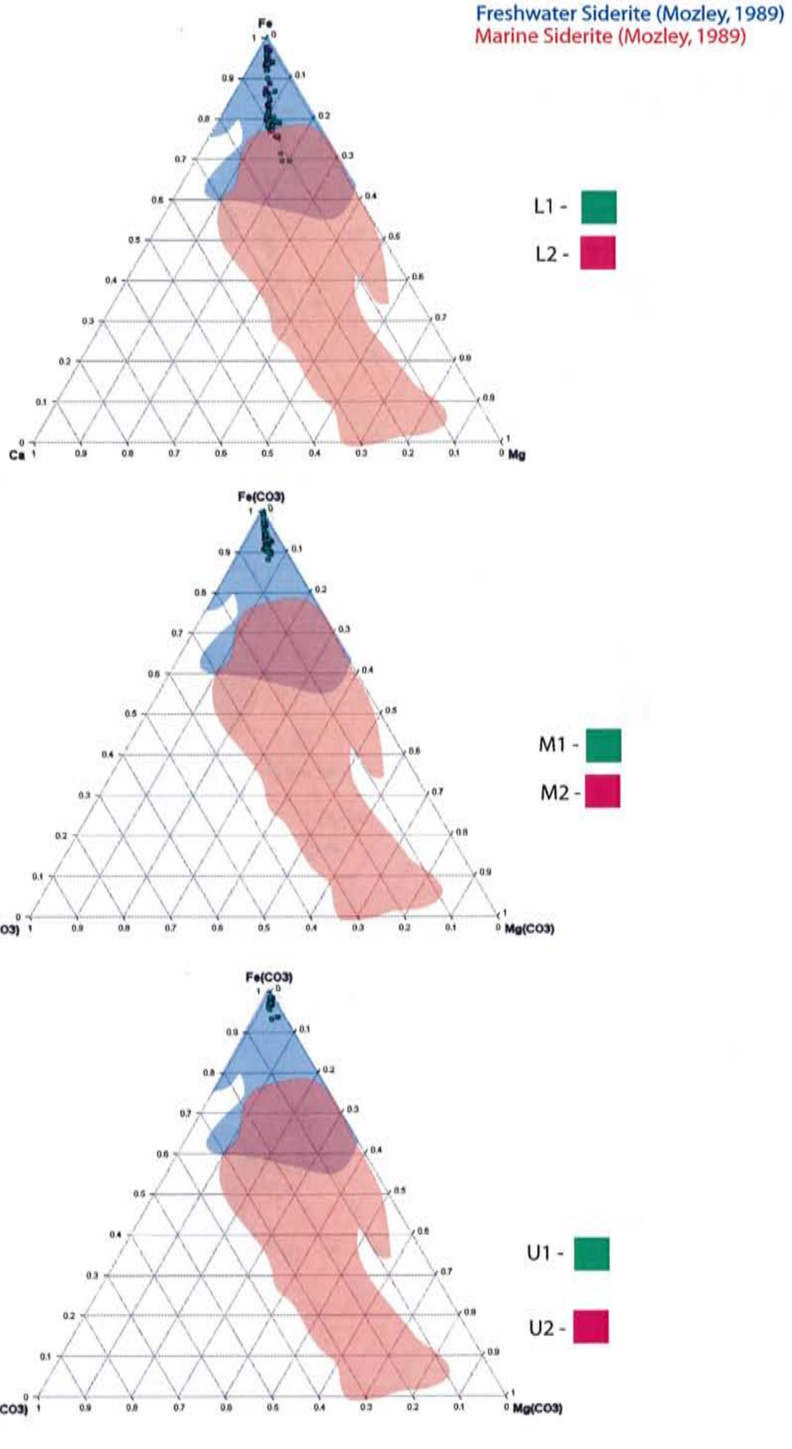


Figure 39a. Ca-Mg-Fe plots comparing the compositional data from the siderite concretions collected from the Menefee Formation outcrop and the results of Mozley (1989).

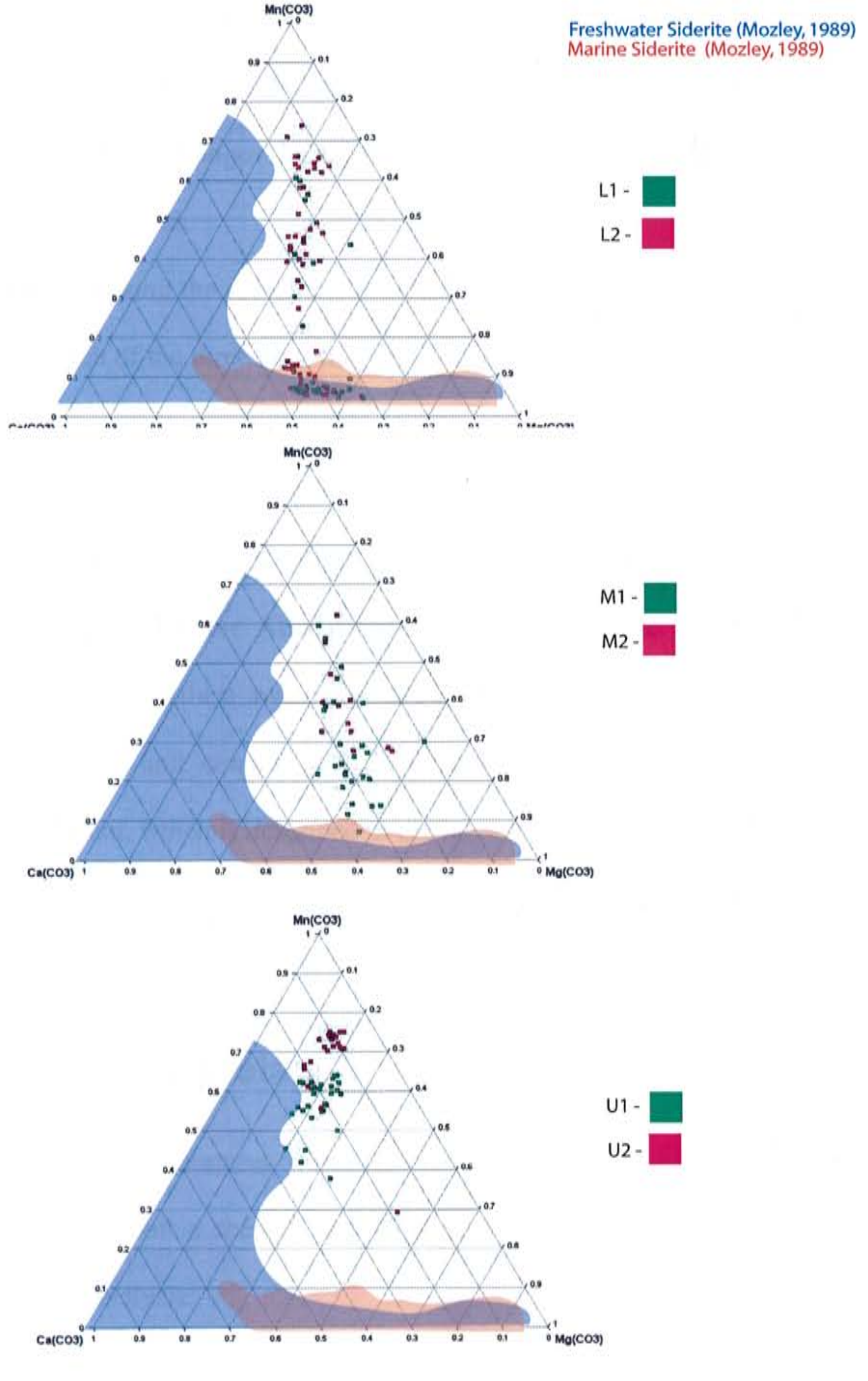


Figure 39b. Ca-Mg-Mn plots comparing the compositional data from the siderite concretions collected from the Menefee Formation outcrop and the results of Mozley (1989).

conclusive than the Ca-Mg-Mn plot (Mozley, 1989; Mozley, personal communication, 2005). This is due to the fact that the Fe is the most abundant component. As a result, a plot that does not include the Fe content is likely to vary widely based on minor changes in the percentages of the other elements, which may or may not be significant.

When analyzing the results for the Ca-Mg-Fe compositional data, a trend is identified for each of the three beds that the samples were taken from. Of the three, bed U had the highest Fe content, bed M had the second highest, and bed L was the lowest. Bed L is situated near the lower Menefee contact, closest to the Point Lookout Sandstone, which is described in the literature as a marine sandstone unit. Bed U is located within the Allison Sandstone Member, near the center of the Menefee Formation, furthest away from the Point Lookout. Thus, samples taken nearest the marine unit contain less than those taken from further within the Menefee Formation, which is described in the literature as a non-marine unit. Thus, the siderite data suggest an increasing degree of marine influence as marine strata are approached.

Lithofacies Interpretation

Based on the features observed in outcrop, each lithofacies can be interpreted to represent a specific depositional environment. Table 1 provides a summary of this analysis.

Lithofacies	**Grain Size**	**Thickness**	**Bedding**	**Sedimentary Structures**	**Organic Material**	**Depositional Environment**
Massive Sandstone	fine - coarse	>60 cm	clean, massive	cross beds	occasional rip-up clasts	Anastomosing river system
Thin-Bedded Sandstone	fine - very fine	20 - 50 cm	planar sandstone - mud interbeds	ripple marks	occasional coally mudstone interbeds	Crevasse splay
Grey Mudstone	mud - silt	5 cm - 10 m	planar siltstone mudstone intrrbeds	–	very few coally clasts	Lagoon / tidal flat/ overbank
Coally Mudstone	mud - silt	5 cm - 10 m	planar siltstone mudstone intrrbeds	–	varying amounts of coally/organic clasts	Swamp / lagoon/ floodplain
Coal Seam	–	>2 m	interbedded coal seams / coally mudstone	–	coal / coally clasts	Peat bog / swamp
Heavily-bioturbated Sandstone	medium-coarse	3 - 6 m	Flaser	casts, bioturbation	mud interbeds, coal clasts	Transgressive lag bed, representing beach facies

Table 1. Lithofacies identification and interpretation chart.

Thick Sandstone (Menefee Formation)

Based on the sedimentary structures observed, it can be argued that this lithofacies represents a channel facies. The presence of cross-bedding found in early each example of this lithofacies indicates that currents were present in the environment. Often near the basal contact of this lithofacies, a zone of rip-up clasts and accumulations of pebbles are observed, which are common in high-energy environments, such as channels. Also, the basal contact is erosive, cutting into the surrounding and underlying strata. This type of contact provides additional evidence that this depositional facies had a flow regime with enough energy to erode surrounding sediments. Finally, when observed in cross section across outcrop, this lithofacies exhibits a lenticular geometry, consistent with the cross-sectional appearance of a channel.

A variety of environments have the potential to have deposited this lithofacies, including tidal channel, braided fluvial., meandering fluvial., anastomosing fluvial and deltaic distributary channel.

A braided river system does not serve as the most likely model for several reasons. Braided rivers exhibit numerous low-sinuosity, closely spaced channels separated only by small sand bars or islands (Cant, 1982). In outcrop, the channels are sparsely distributed and are separated by thick accumulations of mud, silt and coal. Braided rivers typically exhibit high water discharge and a high sediment load with an abundance of coarse-grained material. As a result, clay, mud and silt-sized sediment are a minor component of braided river deposits (Blodgett and Stanley, 1980; Cant, 1982; Rust and Jones, 1986). This does not hold true for the Menefee

Formation, as it is composed dominantly of mud-sized sediment. In fact, the channels are generally composed of very fine to medium-grained sandstone, suggesting low flow energies. Braided rivers are generally found within unstable substrates that are unable to confine the channel; as a result, their deposits will reveal that the channel has migrated laterally by exhibiting lateral accretion features and/or have steep banks that form a wedge shape (Blodgett and Stanley, 1980; Rust and Jones, 1986). The sediment of the Menefee channels is somewhat uniform in structure and the overall geometry of the channels is clearly lenticular, suggesting that the channels experienced minimal lateral migration. Braided rivers are most commonly associated with mountain river systems or distal outwash plains from glaciers or alluvial fans (Blodgett and Stanley, 1980; Cant, 1982), and neither of these options fit well with the paleogeographic descriptions of the San Juan Basin during the late-Cretaceous. Commonly, braided channels are dominated by lobate linguoid bars, reflecting periods of high flow and sediment loads (Blodgett and Stanley, 1980; Rust and Jones, 1986). Within these same channels, periods of low-flow are marked by eroded tops of the high-flow linguoid bars, sets of planar, cross and parallel stratified sands and mudstones (Blodgett and Stanley, 1980). Although minor sets of planar, cross and parallel stratified sands and mudstones are commonly found across the outcrop, no observed examples of linguoid bars or prograding lobes are observed.

Tidal channels are channels that intersect the shoreline, connecting the seaway and backshore environment. They are dominated by tidal activity, experiencing bi-directional currents as tide waters rise and fall (Weimer et al., 1981;

Cloyd et al., 1990). As a result, tidal channel deposits exhibit distinct bi-directional current indicators, such as opposing sets of cross bedding and ripplemarks (Weimer et al., 1981). Within the thick sandstone lithofacies, cross bedding and ripple marks are found showing only unidirectional flow. If the thick sandstone lithofacies did represent a tidal channel system, it would likely be the case that cross bedding of opposing direction would be a dominant feature found in the rocks across the outcrop. Also, the evidence indicating that the channels are of freshwater origin (inferred from the siderite geochemical data) eliminate the notion that the channels served primarily as tidal inlet channels.

Although it is not evident in the orientation of the cross beds, evidence for tidal influence can be found elsewhere in the rocks. Each instance of thick sandstone lithofacies is generally composed of stacked bedsets separated by mud drapes, which indicate intermittent periods of flow, possibly from tidal activity. Also, the coal geochemistry implies the behind-shore region was a brackish water environment. Therefore, marine water was being introduced into the backshore, possibly by tidal processes. Donselaar (1989) observes lenticular sandstones that exhibit bimodal cross bedding that measures 10-30 cm thick, which he interprets as tidal-channel fills. Based on the characteristics observed in outcrop, it is being suggested that the channels observed in the measured sections are not of tidal origin, but did experience some depositional influence from tidal activity. However, based on the observations of Donselaar (1989), it is likely that tidal channels were present in the Menefee Formation depositional environment, and may in fact be present elsewhere in the outcrop.

Another possible facies model is a meandering river system. For this model, the channel structures would exhibit point bar and cut-bank features in a lateral accretion sequence (Cant, 1982; Kastens and Shor, 1985; Miall and Mohamud, 1987). Lateral accretion in this type of environment produces a fining-upwards, vertical sequence of channel deposits including a scour base, lag bed base, dune and cross bedded structures (Cant, 1982). This process can produce large-scale cross stratification, known as epsilon cross bedding, that is produced by the lateral movement of the point bar (Shukla et al., 1999). This type of distinct depositional record is not observed in any of the sections measured.

The model that best fits this lithofacies is an anastomosing river system. Anastomosing rivers are classified as a type of meandering river system that is composed of multiple channels that are unable to migrate due to a more stable, vegetation- rich interchannel area (Smith and Smith, 1980; Smith, 1983; Miall and Mohumad, 1987; Nadon, 1994). They often appear as ribbon channels and have extensive floodplain deposits associated with them (Smith, 1983; Miall and Mohumad, 1987). The steady flow of these low-gradient fluvial systems would accumulate uniform grain sizes as seen in outcrop, and the exposures fit the description of these units as ribbon channels. Also, the channels sit at approximately the same height (roughly 20 meters) within the strata as measured from the contact between the Menefee Formation and the Point Lookout Sandstone (Fig. 40). This would be expected of numerous channels simultaneously flowing through a common area.

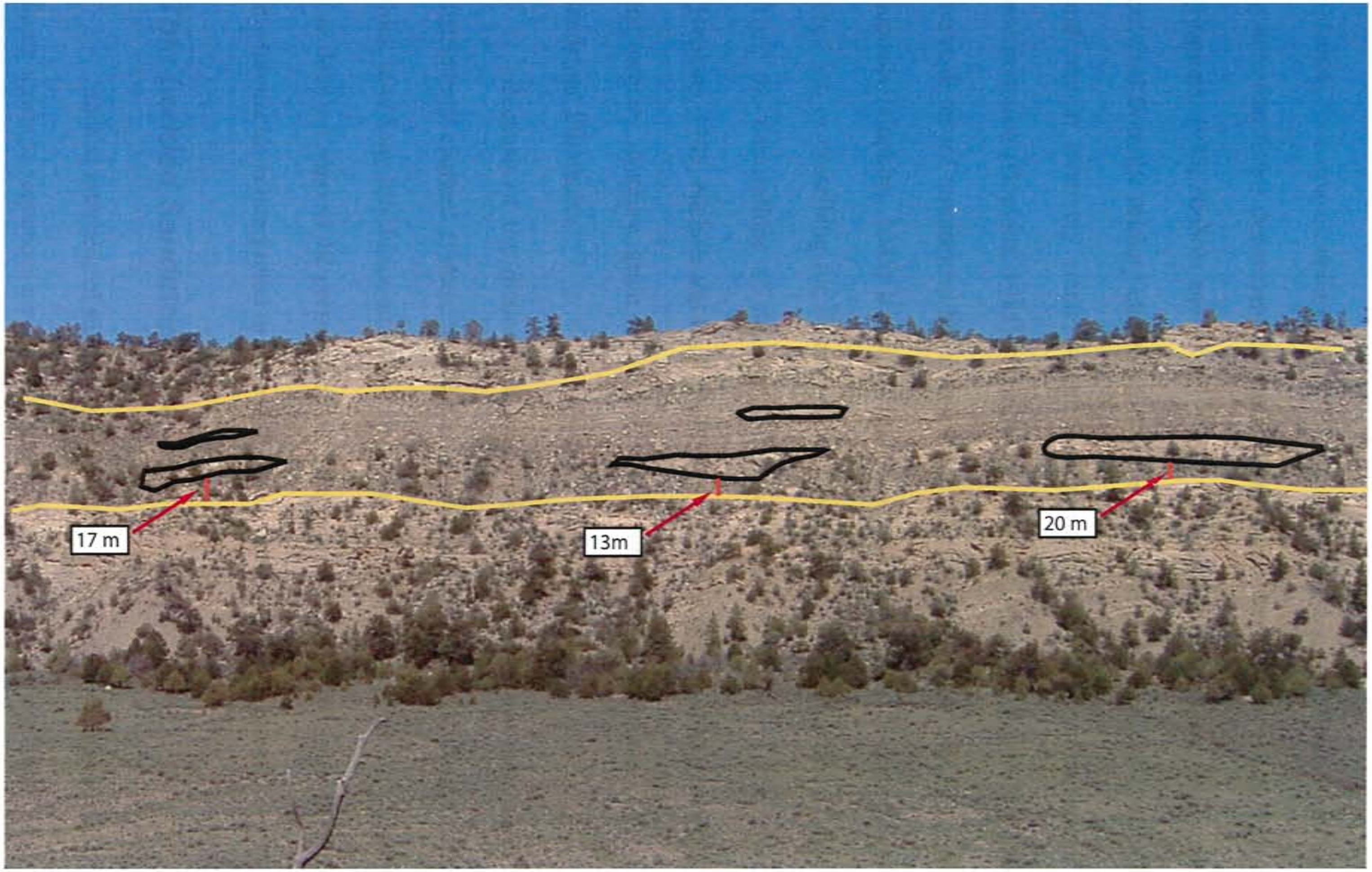


Figure. 40. View of the northern outcrop belt. Figure illustrates the relative heights of some of the more prominent thick sandstone lithofacies. Heights are in meters above contact with the Point Lookout Sandstone.

It is also a possible that the channel facies represents a series of distributary channels for a coastal delta system. Distributaries make up the branching channel system that forms downstream, generally flowing toward the distal end of a delta (Hopkins, 1985; Nichols and Hirst, 1998). Distributary channels generally branch outward from the primary channel as they intersect the muddy coastal environment and remain relatively stable, which is congruent with the anastomosing river interpretation (Hopkins, 1985). Also, distributary channels are generally found in the rock record represented by scour-base channel fill bodies encased in overbank deposits (Hopkins, 1985; Kirschner and Bouma, 2000). This description does a good job of describing the thick sandstone lithofacies of the Menefee Formation. Also, the descriptions of the distributary channel fill bodies in the literature (Hopkins, 1985; Nichols and Hirst, 1998; Kirschner and Bouma, 2000) in regards to sedimentary structure, grain size and geometry match the descriptions of the thick sandstone lithofacies.

Because of the distinct similarities between an anastomosing river and distributary channel system, it is difficult to determine which of these facies the thick sandstone lithofacies actually represents. However, based on additional data that does not support the presence of a deltaic system (discussed later in the thesis), this lithofacies is interpreted to represent an anastomosing river system.

Thin-bedded Sandstone (Menefee Formation)

Stacked interbeds of sandstone and mudrock, asymmetrical ripplemarks, and fining upwards sequences are used to help with the interpretation of this lithofacies.

The presence of asymmetrical ripplemarks suggests that the deposition of this lithofacies occurred in a flowing environment. These features are rather distinct in a few of the sandstone beds, allowing for the collection of paleocurrent directional data. The presence of interbedded mudrock and sandstone deposits indicate that the flow environment was variable, alternating between periods of high and low energy. Although both exhibit similar features, this lithofacies is classified separately from the thick sandstone facies based on its decreased thickness and also because the interbedded mudrock beds in this lithofacies are significantly more frequent.

An unlikely interpretation for the thin bedded sandstone facies is a washover fan deposit. A washover fan results from coastal sediment being washed into the lagoon region directly behind a barrier island though either storm or tide events (Price, 1947; Deery and Howard, 1977; Boyd and Penland, 1981; Orford and Carter, 1982; Maynard and Suter, 1983). The structures that are most commonly observed in this type of deposit include grain size grading upwards from medium to very fine grained, planar bedding and landward dipping foreset beds (Price, 1947; Deery and Howard, 1977; Orford and Carter, 1982; Maynard and Suter, 1983). The ripplemarks observed in outcrop are asymmetrical., the general orientation of the ripples (perpendicular to the crests) is toward the northeast. If this lithofacies were a washover fan, asymmetrical ripplemarks would show flow toward the west, indicating a landward flow direction which is opposite to the direction of flow in the channel facies. In addition, this lithofacies is observed closely associated with the mudrock lithofacies. If the thin-bedded lithofacies were in fact washover deposits, it would be expected that they would be found in nearly all cases either adjacent to or to have a strong association with a sand-dominated beach or shore facies, such as the Cliffhouse Sandstone.

A more likely interpretation for this lithofacies is that they are crevasse splay deposits. Crevasse splays form adjacent to the river channel as overbank flow breaks through a levee deposit (Smith, 1983). They can be either short-lived depositional events, or more permanent if the main channel becomes abandoned and the crevasse splay becomes the new channel (Smith, 1983; Nadon, 1994). Crevasse splays are generally lobate (Smith and Smith, 1980; Nadon, 1994) therefore many of the thin-bedded lithofacies observed in outcrop may actually be minor lobes from the splay. As a lobe dies out shortly after being deposited, it is often overlain by overbank muds. This is supported by the overall fining upward pattern of the sandstone beds that make up this lithofacies. An example of this is shown in Fig. 15, as each of the multiple layers of sandstone beds within this lithofacies exhibit a finer-grained composition that the ones adjacent and below. This reflects the type of temporary crevasse splay deposit that would form during repeated flooding events.

The symmetrical ripples help support the crevasse splay interpretation. As mentioned before, as a crevasse splay forms, it is eventually flooded by water within the floodplain and overlain by mud deposits. Wind action will often create wave activity in this flood water producing symmetrical ripples, influencing the sediment of the crevasse splays. It is likely this is the process that created the symmetrical ripplemarks that are preserved and observed in this lithofacies.

Grey Mudrock and Coally Mudrock Lithofacies (Menefee Formation)

Because the structure of the grey mudrock lithofacies and the coally mudrock lithofacies is very similar (except for the brownish color and coally particles), they likely accumulated in a similar environment. Both lithofacies are dominantly composed of mud-sized sediment and have laminar bedding. Because these lithofacies are composed of laminated mud-sized sediment, they are interpreted to have accumulated in calm, protected water. The presence of the coally material and debris indicates that extensive vegetation accumulation was present within this environment. The coally mudrock probably accumulated rather slowly during periods of low energy. The coally mudrock that has a high coal debris content is proposed to have accumulated during higher energy conditions, with the coally particles representing rip-up clasts of coal-forming material already deposited in the calm environment, which integrates into the accumulating mud. This is supported by the fact that the coal clasts are extremely angular and randomly oriented, and is often more concentrated near the base of the beds, and are most commonly found adjacent to a coal seam lithofacies. During these high energy events, it is also possible for coarser sediment that usually could not be transported into this environment to be deposited, which explains the presence of the occasional silty mudstone seams.

For the organic-free grey mudrock lithofacies to accumulate within an organic rich setting, the deposition of the sediment would likely have been rapid. This sedimentation would have exhibited higher energy levels, which would have exceeded the rate of organic accumulation. This process would have likely produced the grey organic-free mudrock as well as the silt-sized sediment accumulations observed in outcrop. This type of rapid sedimentation could have occurred in several ways. Frequent flooding of channels in a vegetation rich environment would explain the alternating bands of grey mudrock and coally mudrock beds throughout the strata. Tidal processes transporting coastal sediment into the backshore may also contribute to the accumulation of organic-free mudrock. Also, storm events may rapidly increase the sedimentation in this setting by transporting the material from the coastline.

Common environments that promote the type of sedimentation observed in both the grey mudrock and coally mudrock lithofacies include floodplains, tidal flats, swamps, and lagoons.

This lithofacies could have been deposited in a floodplain environment. The grey mudrock may be floodplain deposits, representing the mud- and clay-sized sediment that is deposited distally from the crevasse splays or mud-sized overbank deposits originating from the flooding of the anastomosing channels. The coally mudrock lithofacies could have been deposited in more vegetation-rich interchannel areas.

Alternatively, this lithofacies could have been deposited in a tidal flat environment. As discussed in the thick sandstone lithofacies section, tidal influence is likely to be a part of the Menefee Formation depositional system. Mud- and clay-sized sediment may be transported and deposited in a clam, low gradient tidal flat (Cloyd et al., 1990). This sediment would be organic free, representing the grey mudrock. However, this sediment could infiltrate throughout the entire coastal plain, allowing for the accumulation of organics in more protected areas. Also, tidal flats are commonly associated with coastal swamps. The influx of coastal sediment into a vegetated swamp would likely exhibit the type of sedimentation exhibited with these lithofacies.

Potential environments that produce this type of sedimentary history also include lagoons and swamps landward of a barrier-dominated coastline (Kraft and John, 1979; Donselaar, 1989; Devine, 1991). Lagoons are typically quiet water settings dominated by mud-sized particles (Kraft and John, 1979; Donselaar, 1989). This depositional setting would periodically be affected by sedimentation from storm, tide and wind blown processes (Leckie and Walker, 1982; Devine, 1991). Also, because lagoons are protected and poorly drained, vegetation would be abundant in this environment, accounting for the abundant organic material (Boyd and Penland, 1981; Maynard and Suter, 1983).

All of these possible environments provide a reasonable interpretation for the grey and coally mudrock lithofacies. Based on the depositional model of the Menefee Formation presented later in this thesis, it is a likely scenario that the floodplains, tidal flat, swamp and lagoon environments are all present within this environment, although some may be more influential than others. Based on the distribution of the anastomosing channels and crevasse splays, it is likely that the mudrocks most commonly represent overbank deposits within the inter-channel floodplain regions. Also, because it is believed that a barrier-dominated coastal plain is present, it is likely that lagoons and swamps are present landward of the shoreline. Finally, tidal activity may promote the accumulation of the mudrocks on tidal flats also located directly behind the shoreline.

Coal Seams

The formation of coal requires a specific combination of chemical and biologic factors, and a reducing environment (Flores, 1993; Hoffman, 1994). Generally the environment must provide ample vegetation and organic matter that is allowed to accumulate. It must also be poorly drained, allowing for the constant presence of standing water. In addition, it must be somewhat protected from high energy events such as tidal and storm events, to allow the organic material to accumulate.

An isolated coastal swamp peat bog would provide a good environment for coal formation including lush vegetation, and a poorly drained environment. Peat bogs are reducing environments, and generally accumulate thick packages of organic material (Flores, 1993). Although storm and tide activity near the coast would occur, peat bogs are slightly more isolated from the shoreline and immediate backshore region and therefore witness only extreme flooding and tidal events. This explains the lack of thick coal seams observed in outcrop and also the abundance of coally mudstone and siltstone interbeds within the coal seams.

Additional support for this environment comes from the compositional data presented in Hoffman (1996). The sulfur content data is relatively high for coals throughout the San Juan Basin. As discussed in Phillips and Bustin (1996), sulfur contents such as these suggest a brackish, marine-influenced depositional environment.

Flaser-bedded Sandstone Lithofacies (Cliffhouse Sandstone)

This lithofacies may represent a lag bed which represents the beach facies of the Cretaceous Interior Seaway that was reworked during a marine transgression (Kraft and John, 1979; Donselaar, 1989). Based on this interpretation, this lithofacies is actually a part of the Cliffhouse Sandstone. This formation would represent the beach facies of the environment, which is not a part of the Menefee Formation.

This lithofacies is interpreted as forming in a coastal environment based on several features observed in the outcrop. The presence of debris-rich, flaser bedded wavy sandstones is often associated with a sand-dominated lower shoreface/offshore facies of a coastal environment (Donselaar, 1989). The flaser bedding is significant, as this bedding type is most commonly associated with tidal and wave activity either on tidal flats or nearshore environments. There are zones of accumulated woody debris, found as either carbonized chunks of wood or more commonly imprints of logs and branches. The presence of trace fossil boring casts within the wood imprints, classified as *Teredolites,* help to support the interpretation of this depositional environment. *Teredolites* are interpreted to be the result of a type of wood-boring worm that is generally associated with marine environments (Hasiotis et al., 1991).

This lithofacies exhibits an erosive base where it is in contact with the Menefee Formation. These are both traits of a transgressive barrier-island dominated shoreline as it migrates landward over the shoreline facies (Kraft and John, 1979; McCubbin, 1981; Donselaar, 1989). The wave action will re-work and erode the existing beach facies, leaving little evidence of the previous facies. The only evidence of a previous beach facies is usually left in the form of a debris bed. The interpretation that this lithofacies represents a lag bed of a transgressing barrier-dominated shoreline is in agreement with other authors who discuss the nature of this lithofacies (Kraft and John, 1979; Donselaar, 1989).

Depositional Model

As discussed earlier, the thick sandstone lithofacies is thought to have been deposited by an anastomosing river system. During the wet season, flow and discharge from the channels would be higher, with deposition from the channels being dominantly uni-directional toward the shoreline. However, during drier times of the year, tidal and storm activities may have more effect, causing the channels to experience some bidirectional flow, particularly in their lower reaches. During times of extremely high discharge, flood waters will overtop the channel levees and locally form crevasse splays.

The backshore region presented in this model could best be described as lagoon and peat swamp dominated, located directly landward from the beach facies. This region would be significantly restricted, poorly drained, and heavily vegetated. Within this environment, the abundance of organics would promote the formation of coal deposits and incorporation of organic rip-up clasts within mud deposits deposited during storm events.

This depositional model includes the presence of a barrier island complex. Barrier islands are linear marine sand accumulations that are situated parallel to the coastline. Because of their location, the islands provide protection and isolation for the backshore environment, allowing the peat swamps and lagoons to develop. Being directly adjacent to the seaway, these islands would also represent the beach facies. These islands also would provide the shallow marine offshore environment where *Teredolites* burrows could form. During the transgressive phase of the seaway, this beach facies would migrate landward and be re-worked to form the transgressive lag that is found in outcrop as the lowermost section of the Cliffhouse Sandstone, directly in contact with the Menefee Formation strata.

Based on the data collected in this report, a possible depositional model for the Menefee Formation within the San Juan Basin is a lagoon and swamp dominated coastal strand-plain intersected by an anastomosing channel system along a barrier-dominated shoreline of the Cretaceous Interior Seaway (Fig. 41). This model is proposed because it adequately incorporates each of the identified lithofacies and their respective depositional interpretations.

The Menefee Formation is represented by the non-marine backshore environment that includes the coastal swamp, lagoon, tidal flat, crevasse splay, and overbank deposits, as well as the anastomosing channel system that intersects the region. The Menefee Formation depositional environment does not include the

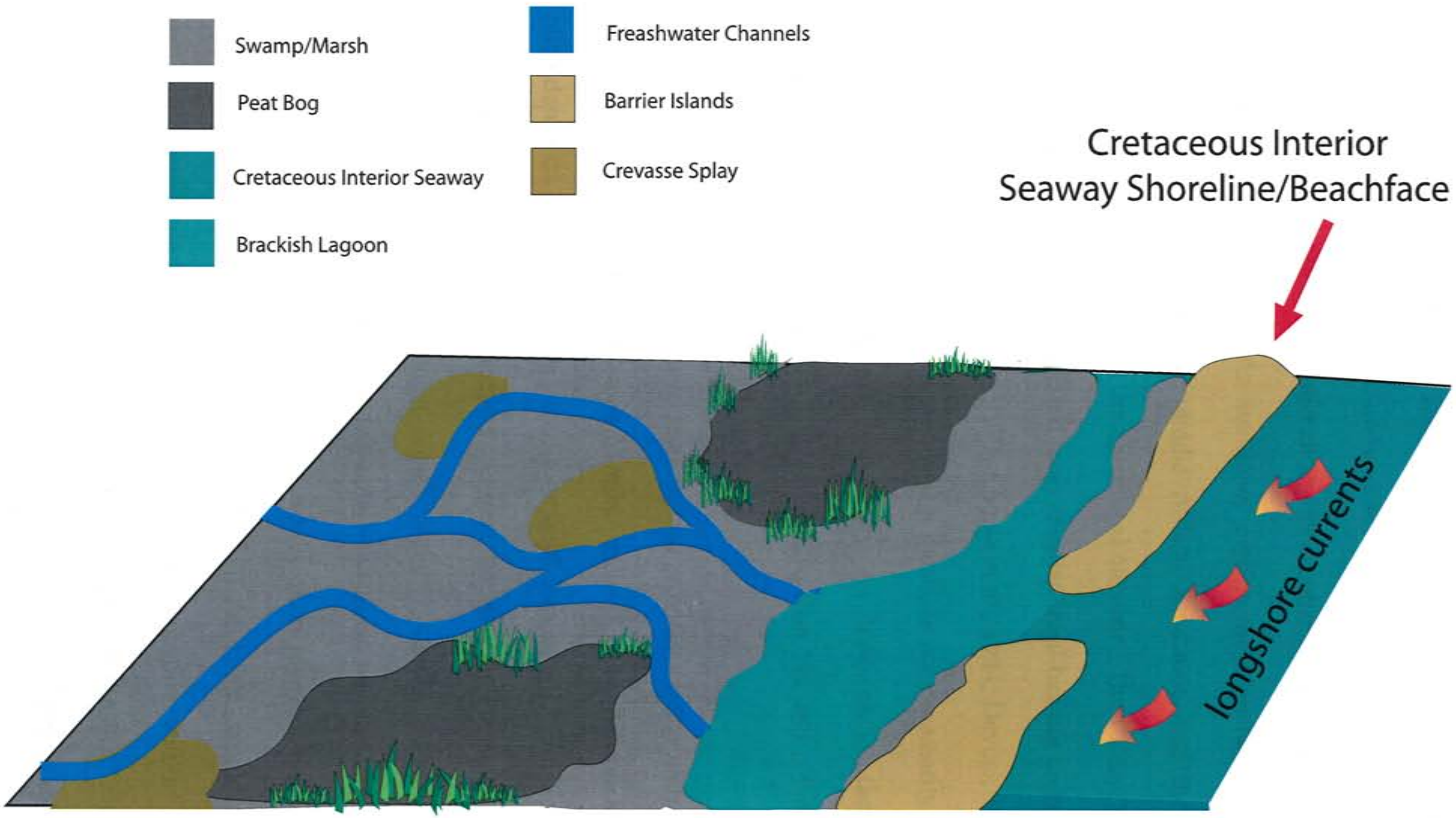


Figure 41. Barrier-dominated coastal plain with an anastomosing river system along the the shoreline of the Cretaceous Interior Seaway. This diagram represents the proposed model for the depositional environment of the Menefee Formation.

barrier island complex, which is represented in the mid-Cretaceous stratigraphy by the Point Lookout and Cliffhouse Sandstones.

The results of this thesis also allows for a better description of the members of the Menefee Formation. As mentioned earlier, the Menefee consists of the lowermost Cleary Member, the middle Allison Sandstone, and the uppermost unnamed member, referred to as the upper coal member. The Cleary Member and upper coal member are often referred to as abundant coal-bearing units (Beaumont et al. 1956; Sabins, 1964; Fassett, 1977; Choate et al., 1984; Devine, 1991; Brister and Peabody, 2002), which illustrated in this thesis, is not necessarily true within the southeastern section of the San Juan Basin. As shown earlier, the actual coal content of the Menefee Formation is generally less than 5%, and is broken up into numerous beds usually less than 20 cm thick.

The data from the measured sections also provides a better understanding of the nature of the Allison Sandstone Member as well. The Allison Sandstone is often described as a "coal-barren, sandstone unit" Beaumont, 1956; Young, 1973). Based on the data from the measured sections, the Menefee Formation in this part of the basin does not exhibit a clearly defined middle sandstone member. Throughout much of the basin, the lenticular sandstones are concentrated near the midsection of the formation. Operators would often intersect these sandstones when drilling wells, which, during correlation of the strata, would appear as a continuous sandstone body (Brister, personal communication, 2003). It is clearly shown in this thesis that within the southeastern region of the San Juan Basin, the Allison Sandstone is not a continuous sandstone unit. Therefore, in this section of the basin, the subdivision of the Menefee Formation is not a particularly accurate description of the formation strata.

It may be asserted that the Menefee Formation represents a non-deltaic coastal plain. The three primary types of deltas include river-dominated, wave-dominated and tide-dominated. Of the three listed, the Menefee Formation most resembles a wave-dominated delta system, but there is little evidence to support this.

A river-dominated delta is unlikely for several reasons. First of all, the energy of the water feeding the delta would be too high to result in Menefee Formation deposits. The sediment load associated with this delta system is high, resulting in extensive, prograding deposits at the mouth of the river system, dominated by lobate prodelta deposits (Miall, 1984). A classic fluvial-dominated prodelta deposit would consist of offshore deposits overlain by a deltaic complex, including, in ascending order, offshore shales overlain by transitional offshore siltstones and shales, prodeltaic silty sandstones and muddy siltstones, overlain by crossbedded distributary mouth bar, ultimately capped by thick delta plain coals (Miall, 1984; Gingras et al., 1998; Mattson and Chan, 2004). This entire suite of deposits is usually extensively bioturbated (Miall, 1984; Gingras et al., 1998; Mattson and Chan, 2004). Such deposits are not present in the Menefee Formation. Finally, a common trait of this delta system is paleocurrent indicators that exhibit a radial pattern of measurements (Miall, 1984; Morgan, 1970). Although this pattern was not observed in the paleocurrent data collected, many more measurements would be required to properly determine whether or not a radial pattern is present.

The tide-dominated deltaic model is also a poor option. Tide-dominated deltas generally have a higher tidal range; therefore deposition along the shoreline is strongly influenced by tidal activity (Leckie and Walker, 1982). They exhibit landward dipping foresets throughout the strata deposited by this type of delta. In addition, flood-dominated linear sand bars are common, which are situated perpendicular to shoreline forming extensive ridge and prominent tidal channel features (Leckie and Walker, 1982; Miall, 1984). The coastal environment that results from a tidal deltaic system exhibits much more distinctive influence from a marine environment (Miall, 1984). It was established earlier that tidal activity may be an influence on the deposition of the Menefee Formation, but likely plays a minor role. No landward dipping foresets are observed, which would be a dominant feature if the environment was in fact tide-dominated. The channels do not resemble the tidal channel and ridge features strongly associated with this type of delta. Finally, the siderite data and sulfur content of the coals indicate that marine waters within the environment were not a dominant influence on the Menefee Formation, which would be the case in a tide-dominated system.

Although there are many similarities between a wave-dominated delta system and the model proposed for the Menefee Formation, this type of deltaic model still does not properly describe the depositional model for the formation. Wave-dominated deltas produce extensive mud- and silt-dominated prodelta deposits (Horne, 1980). These deposits are extensively bioturbated by *Teichichnus, Chondrites* and *Planolites*, and exhibit slump folds, thin turbidite beds and extensive soft-sediment deformation features (Larue and Legarre, 2004). At the mouths of the distributary channels, curved mouth bar sandstones develop into linear beach ridges (Bhattacharya and Giosan, 2003). This environment is also dominated by widespread delta-front sheet sandstones that occupy the interchannel areas (Heward, 1981). These sandstones are a result of the higher wave energies associated with this type of depositional environment (Miall, 1984; Horne, 1980). The barrier island complex described in the depositional model for the Menefee Formation is too large in scale and dimension to have developed in a in a wave-dominated deltaic system. Also, the Menefee Formation does not exhibit the proper sedimentary structures, bioturbation and extensive interchannel sheet sandstones. Most of the Menefee Formation lithologies suggest a low-energy environment, which again conflicts with this deltaic model.

The interpretation presented in this paper that the Menefee Formation formed in a non-marine, lagoon/swamp dominated coastal environment is in agreement with the previous studies of the unit (Young, 1973; Fassett, 1974; Landis, 1974; Molenaar, 1974; Choate et al., 1984; Donselaar, 1989; Devine, 1991, Wright-Dunbar and Ridgley, 1999). The lagoonal backshore environment that is the depositional setting for the grey and coally mudrock and coal seams is described by Young (1973), Fassett (1974), Molenaar (1974), Choate et al. (1984), Devine (1991), Donselaar (1989), and Wright-Dunbar and Ridgley (1999). Most of these authors present this as the extent of their description of this environment, however Fassett (1974), Devine (1991), and Wright-Dunbar and Ridgley (1999) provide greater detail by mentioning the presence of lagoons, swamps floodplains and tidal flats.

In these same publications, a fluvial channel facies is described, which matches the description for the thick sandstone lithofacies. Each of the authors support the interpretation that the thick sandstone represents a fluvial channel facies. This thesis presents one of the few specific interpretations of the channels by describing them as anastomosing fluvial. Based on his observation of landward dipping foresets, Donselaar (1989) provides a more specific description of the channels by calling them tidal. As mentioned before, this thesis interprets tidal activity to be a minor influence on channel deposition, therefore disagrees with referring to this lithofacies as tidal channels. The strata that Donselaar (1989) examined were located in the southern region of the basin; therefore, it may be possible that tidal activity was more important in the southern area. The paper by Wright-Dunbar and Ridgley (1999) is in agreement with the interpretation that the channels are fluvial with a minor degree of tidal influence.

The interpretations of Donselaar (1989) and Wright-Dunbar and Ridgley (1999) match well for what is described as the heavily-bioturbated lithofacies in this report. Both authors identify the same basic structures in their studies, and also describe the unit as a part of the Cliffhouse Sandstone, consisting of a lag bed formed during the transgressive phase of the Cretaceous Interior Seaway. Both Donselaar (1989) and Wright-Dunbar and Ridgley (1999) observe that this unit is extensively bioturbated, and identify an abundance of broken shells and shark teeth. It is unclear as to why the section of the San Juan Basin examined in this thesis exhibits the bioturbation, but not the shark teeth and shell debris as described by

Donselaar (1989) and Wright-Dunbar and Ridgley (1999). This may have to do with the fact that their studies occur in different parts of the San Juan Basin.

Modern Analog

The South Padre Island region, located off the southeastern shore of Texas in the Gulf of Mexico, serves as a modern analog for the Menefee Formation depositional environment.

South Padre Island makes up the southern section of the Padre Island National Seashore, which is a barrier island-dominated shoreline that extends from Corpus Christi Bay to the Rio Grande delta (Fig. 42). South Padre Island is described as a microtidal barrier island, which is separated from the mainland of Texas by the Laguna Madre (Watson, 1971; Weimer, 1982; Prouty and Prouty, 1989; Morton et al., 2000). Laguna Madre is a protected back barrier environment situated landward of the Padre Island barrier complex (Watson, 1971; Prouty and Prouty, 1989). This type of environment is described as a barrier-dominated strand plain (Watson, 1971; Weimer, 1982; Prouty and Prouty, 1989; Morton et al., 2000).

The Laguna Madre back-barrier region represents a similar representation to the environment that is the modern analog for the Menefee Formation. The Laguna Madre environment is described as a complex of overlapping environments, including tidal flats, washover deposits, marshes, lagoons, and overbank deposits from the associated channels that intersect the environment (Watson, 1971; Weimer, 1982; Prouty and Prouty, 1989; Morton et al., 2000). These environments include broad, vegetated surfaces that are located near local sediment sources which

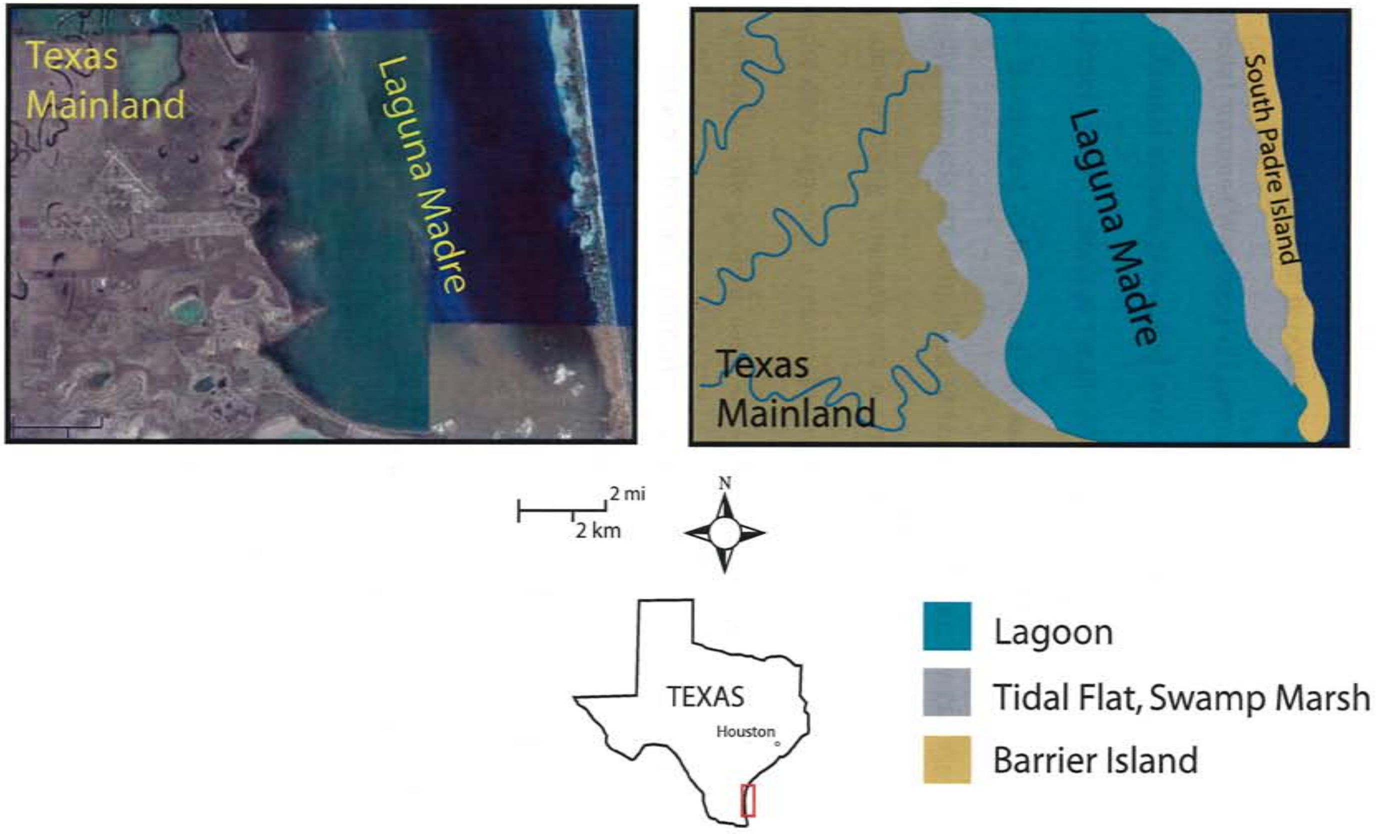


Figure 42. Illustration and aerial photographs of South Padre Island, located off the southeastern shoreline of Texas.

include coastal streams, tidal and storm activity, washover deposits and to a minor degree, eolian sediment from the barrier islands (Morton et al., 2000). Also within this environment, sedimentation is occurring from overbank and discharge deposits from the coastal streams (Watson, 1971; Prouty and Prouty, 1989).

The channel system associated with the Laguna Madre is slightly different from the channel system described for the Menefee Formation. Menefee Formation channels are interpreted to be part of an anastomosing river system, whereas the Laguna Madre channels are actually a series of meandering rivers. As previously discussed, anastomosing channels are a type of meandering river; therefore the Laguna Madre does represent a reasonable model. Also, the sediment from Laguna Madre is generally fine-grained sand or smaller, whereas the sediment of the Menefee Formation channels primarily ranges from fine- to medium-grained. Although these minor differences do exist, the Laguna Madre is still an excellent analog for the depositional model proposed for the Menefee Formation in this thesis.

The sedimentation that produced the barrier island complex of Padre Island involves a combination of accumulation of terriginous sediment and re-working of littoral longshore drift (Watson, 1971). Terriginous sediment is transported toward the coast via the numerous associated fluvial channels, which intersect the backshore environment and feed sediment into the island complex (Morton et al., 2000). This sediment is immediately reworked and redistributed into the barrier islands primarily by the process of longshore current wave run-up (Morton et al., 2000). This process is similar to the one proposed in this thesis that formed the barrier islands which are represented by the Cliffhouse and Point Lookout Sandstones.

Finally, the shoreline of South Padre Island is described as a transgressing system, as the shoreline is actively shifting landward over top the current coastal environment (Mazzullo and Sims, 1983). This is an exact analog for the shoreline of the Cretaceous Interior Seaway during deposition of the Cliffhouse Sandstone.

Regional Depositional Model

By examining the depositional model of the Menefee Formation, interpretations can be made regarding the depositional history of the entire Mesaverde Group and surrounding formations within the San Juan Basin. The interpretations presented in this paper regarding the large-scale depositional setting of the Mesaverde Group are consistent with the conclusions presented by other authors. In each of the publications referenced, deposition of the Mesaverde Group is primarily influenced by a regressive-transgressive history of the Cretaceous Interior Seaway (Sabins, 1964; Young, 1973; Fassett, 1974; Landis, 1974; Molenaar, 1974; Donselaar, 1989; Devine, 1991; Molenaar and Baird, 1992).

During the mid- to late-Cretaceous, the shoreline of the Cretaceous Interior Seaway was situated to the southwest of the modern day San Juan Basin (Young, 1973; Fassett, 1974; Donselaar, 1989). During this time, the four corners area was generally flat lying, as the San Juan Basin had not begun to subside until the late Campanian (Cather, 2004). The shoreline of the seaway was oriented along an overall northwest/southeast trend (Young, 1973; Donselaar, 1989; Fig. 43). During

Figure 43. Paleogeographic map showing the position of the Cretaceous Interior Seaway during the late-Cretaceous. (modified from Blakey, 1997).

time of regression, the shoreline and coastal facies migrate seaward, and in the case of the Mesaverde Group this would be towards the northeast. Similarly, during a transgression, the shoreline would have shifted landward back towards the southwest.

Features observed in outcrop and cross sections constructed for this thesis and also those published by other workers (Molenaar and Baird, 1992; Wright-Dunbar and Ridgley, 1999) illustrate the regressive-transgressive depositional history of the Mesaverde Group. As noted previously, the Cliffhouse Sandstone and Point Lookout Sandstone are interpreted as northwest-southeast oriented, linear sandstone bodies representing barrier islands. Barrier islands are often preserved in the rock record as a series of thick linear sandstone deposits, either overlain atop one another or separated by thin intervals of strata (Hollenshead and Pritchard, 1961; Donselaar, 1989; Devine, 1991; Wright-Dunbar and Ridgley, 1999). In the northern field area, the Point Lookout Sandstone exhibits an example of this (Fig. 44). Also, this study presents the interpretation of a cross sectional view of the southeastern margin of the basin that is consistent with this geometry (Fig. 45). This interpretation is consistent with a barrier island coastal environment, and also with the previous work on the depositional environment of the Point Lookout and Cliffhouse Sandstone (Fassett, 1977; Donselaar, 1989; Devine, 1991). In each cross section, these individual packages resemble shoestring sandstone bodies, oriented along a northwest/southeast trend. These thick packages are generally only visible in the cross sections with a northeastern/southwestern orientation. When viewed along a northwest/southeast cross section, the formation contact exhibits a uniform

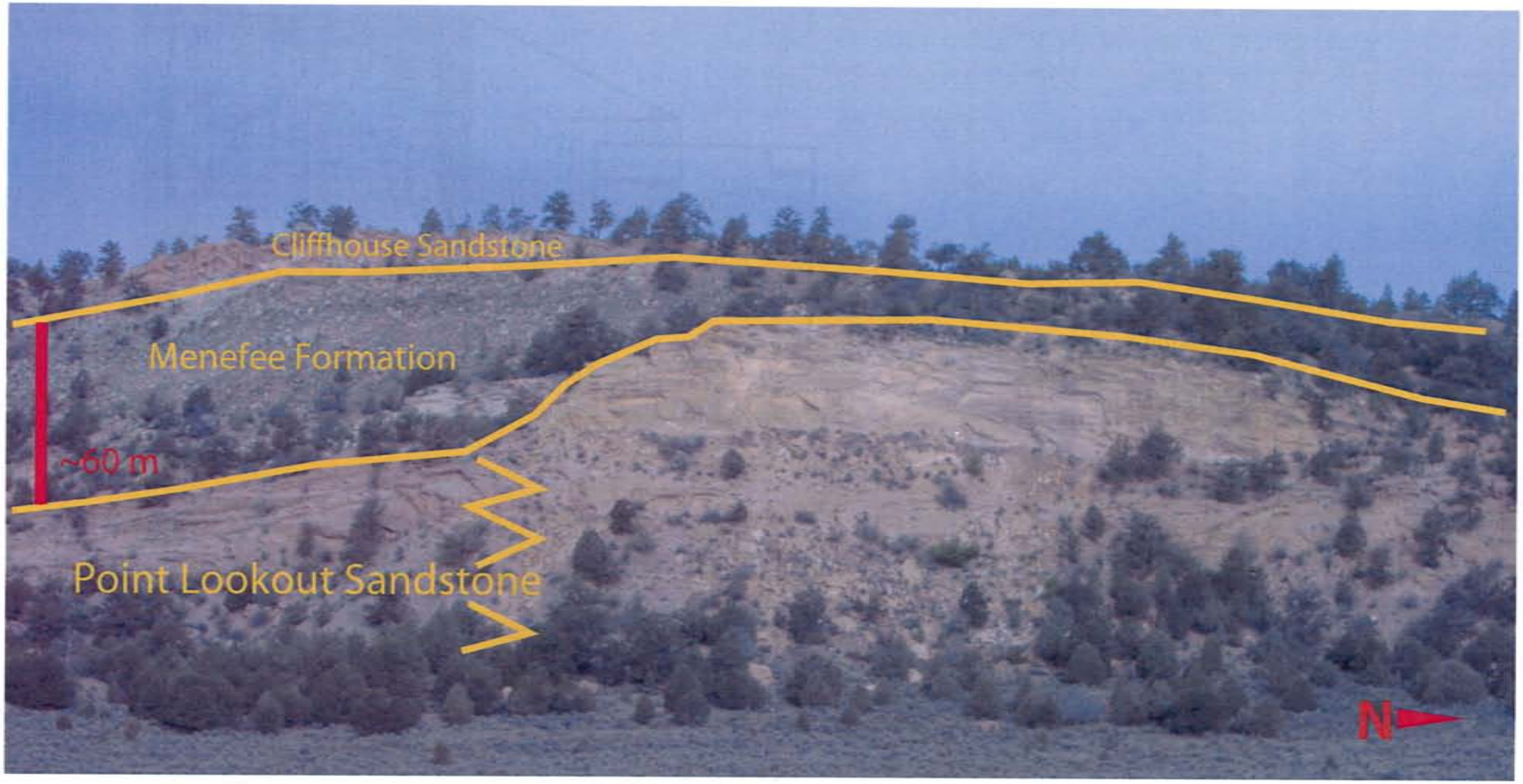


Figure 4□
composed of a series of lenticular sand bodies. Picture taken near the middle of the northern field area.

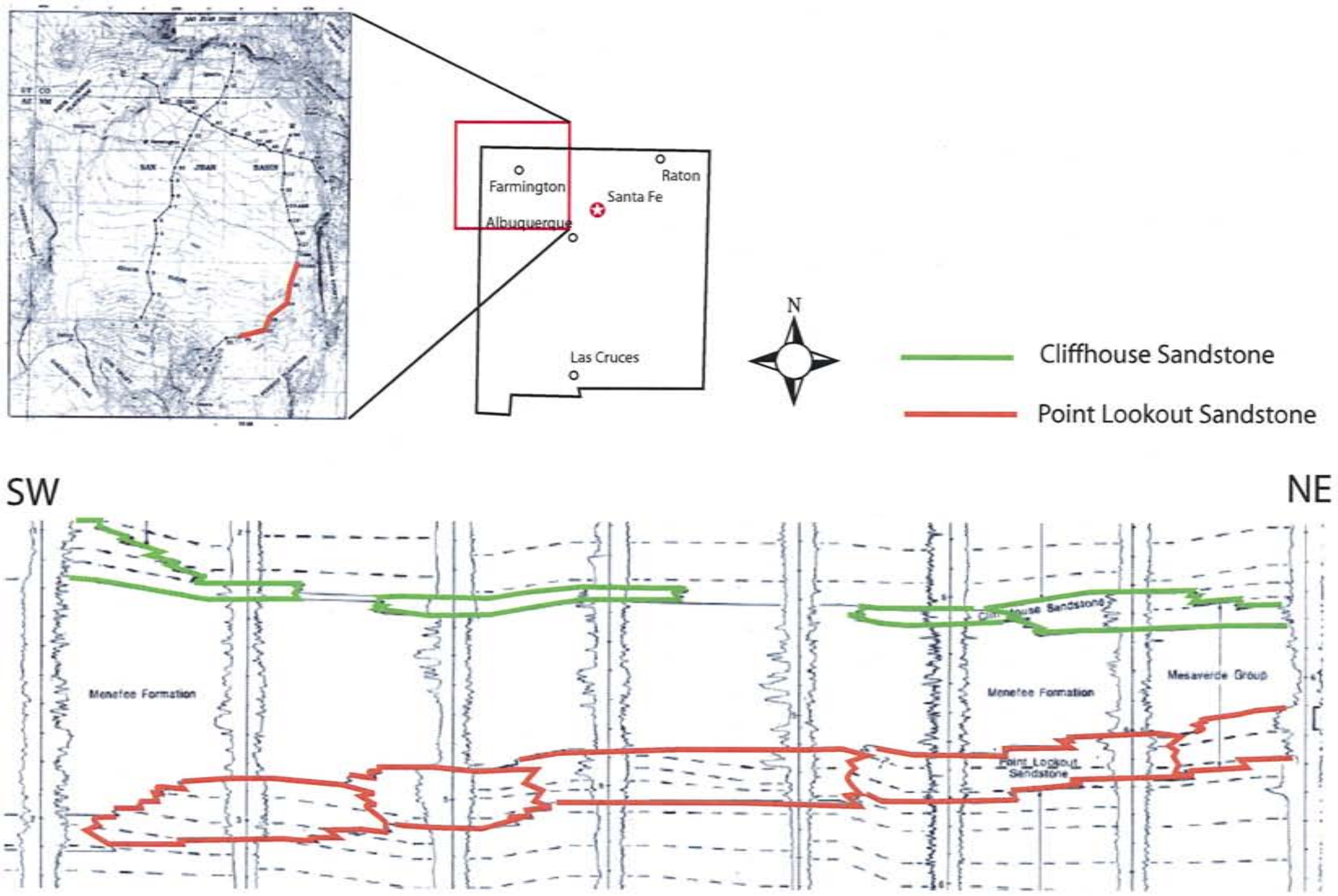


Figure 45. Northeast - southwest cross section through San Juan Basin used to illustrate the individual sediment packages that are interpreted in this paper to make up the Cliffhouse and Point Lookout Sandstone. (Cross section from Molenaar and Baird, 1992; interpretations of sediment packages on cross section by M. Iacoboni)

thickness. This observation is in agreement with the literature that examines this aspect of the strata (Hollenshead and Pritchard, 1961; Donselaar, 1989; Devine, 1991; Molenaar and Baird, 1992; Wright-Dunbar and Ridgley, 1999). As discussed earlier, the thick packages of sandstones found within the Cliffhouse and Point Lookout Sandstone are interpreted to represent barrier islands that make up the beach facies of the Cretaceous Interior Seaway (Donselaar, 1989; Devine, 1991). As a regressive-transgressive model, the two formations are depositionally equivalent, despite their different appearances in outcrop.

Because the Point Lookout unit is regressive, the beach facies is better preserved due to the fact that the shoreline deposits were not disrupted post-depositionally as the wave energy moved seaward, away from the newly deposited sediment (Devine, 1991). In addition, the beach deposits would be protected by the backshore Menefee Formation deposits following immediately behind. As a result, the Point Lookout retains more primary sedimentary structures.

Sedimentary structures are somewhat rare in the Cliffhouse Sandstone, except for flaser bedding observed near the basal contact. Also, the flaser-bedded sandstone lithofacies found in the Cliffhouse Sandstone is not observed in the Point Lookout Sandstone. As discussed earlier, the Cliffhouse Sandstone is described as being deposited during a transgressive phase of the Cretaceous Interior Seaway. Because of this, the sediment would be reworked and re-distributed immediately after deposition, removing most structures from the sediment (Kraft and John, 1979; Donselaar, 1989; Divine, 1991).

This model also helps to explain the thickening of the Menefee Formation towards the southwest as seen in the cross sections presented in this thesis. Because the sea was situated to the northeast, it is likely that the southern and western sections of the basin would have been exposed for a longer period of time, allowing for thicker accumulations of non-marine Menefee Formation deposits (Cather, 2004). As the shoreline migrates towards the northeast, the Menefee Formation continues to thin and eventually disappear as the seaway transitions from regressive to transgressive. This pinchout represents the point of maximum regression of the Cretaceous Interior Seaway. This is supported by Cather (2004), as he states that the Menefee Formation pinches out occurs directly northeast of the northeastern margin of the modern San Juan Basin, just past the Colorado/New Mexico border. The pinching-out of the Mesaverde Group strata is further supported by the fact that the Cliffhouse Sandstone and Point Lookout Sandstone also thin in the same direction as the Menefee Formation, towards this point of maximum regression (Fig. 46).

Conclusions

1. Five lithofacies are observed in outcrops of the Menefee Formation: a thick sandstone lithofacies, interpreted to represent channel deposits; a thin-bedded sandstone lithofacies, interpreted as crevasse splay deposits; a grey mudstone facies representing lagoon and overbank deposits; a coally mudstone facies, interpreted to form in a vegetation rich, swamp environment; and a coal seam lithofacies, representing a protected peat swamp environment. A sixth lithofacies of heavily-

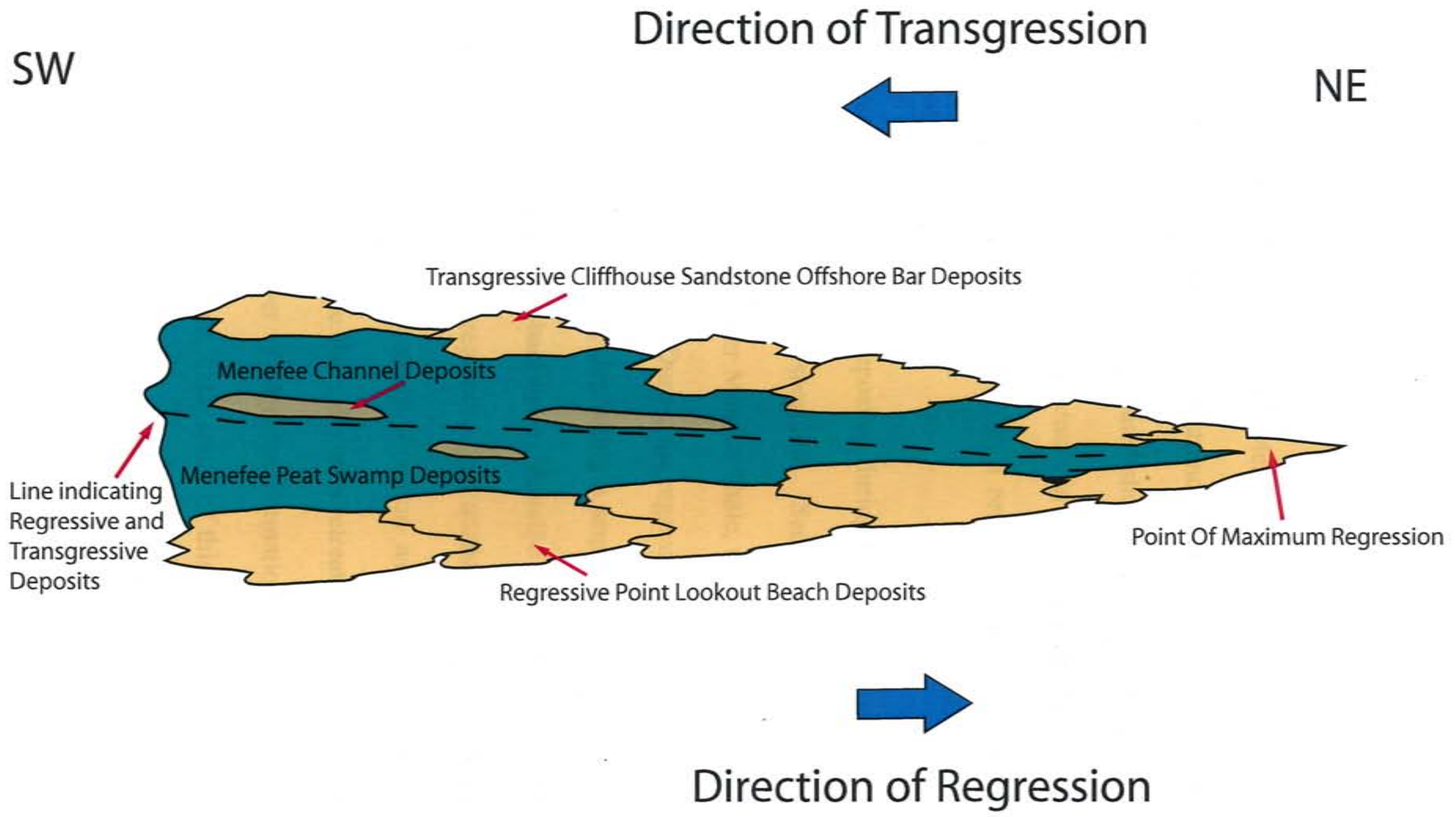


Figure 46. Schematic illustration showing the regressive-transgressive depositional history of the Mesaverde Group. Figure illustrates the nature of the individual bodies that compose the Cliffhouse and Point Lookout Sandstones as seen in cross section.

bioturbated sandstone is also observed, but is interpreted as a lag bed representing a barrier-island complex of a transgressing shoreline system. It is thought to be part of the Cliffhouse Sandstone.

2. The depositional environment of Menefee Formation is interpreted to be a lagoon and swamp dominated coastal strand-plain intersected by an anastomosing channel system along a barrier-dominated shoreline. The Menefee Formation was deposited in a very dynamic environment involving an intimate commingling of multiple depositional environments. As a result, the depositional facies overlap within the environment.

3. The Mesaverde Group was deposited during a regressive-transgressive shift of the Cretaceous Interior Seaway shoreline. Sedimentation during the regressive phase is represented by the upper Mancos Shale, the Point Lookout Sandstone and the lower Menefee Formation. During the regression, the shoreline of the seaway migrated towards the northeast, depositing a sequence of offshore Mancos Shale, coastal Point Lookout, and backshore Menefee Formation. As the shoreline reached a point of maximum regression just northeast of the northeastern modern San Juan Basin margin, it reversed direction as it shifted from regression to transgression. As a result, the shore deposits retreated back towards the southwest depositing an additional layer of Menefee Formation, followed by the Cliffhouse Sandstone and the Lewis Shale. The result of this transition from a regressive to transgressive system near the northeastern margin of the basin is a wedge-shaped Mesaverde Group that thickens towards the southwest.

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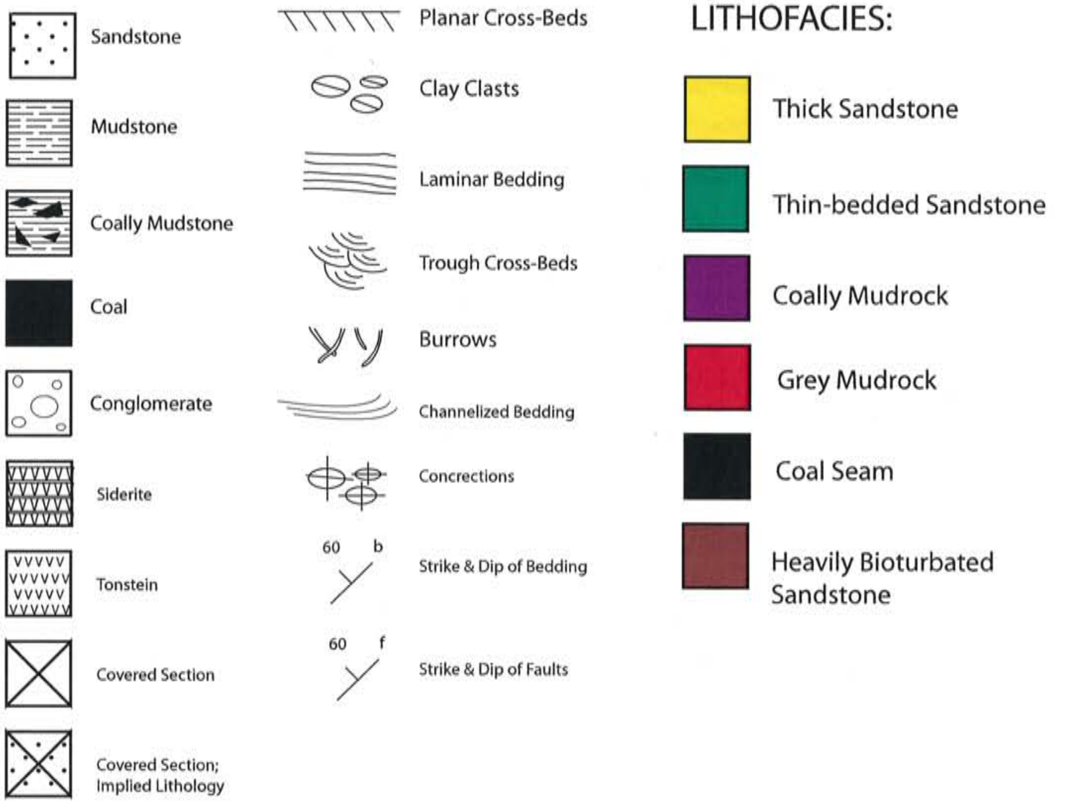
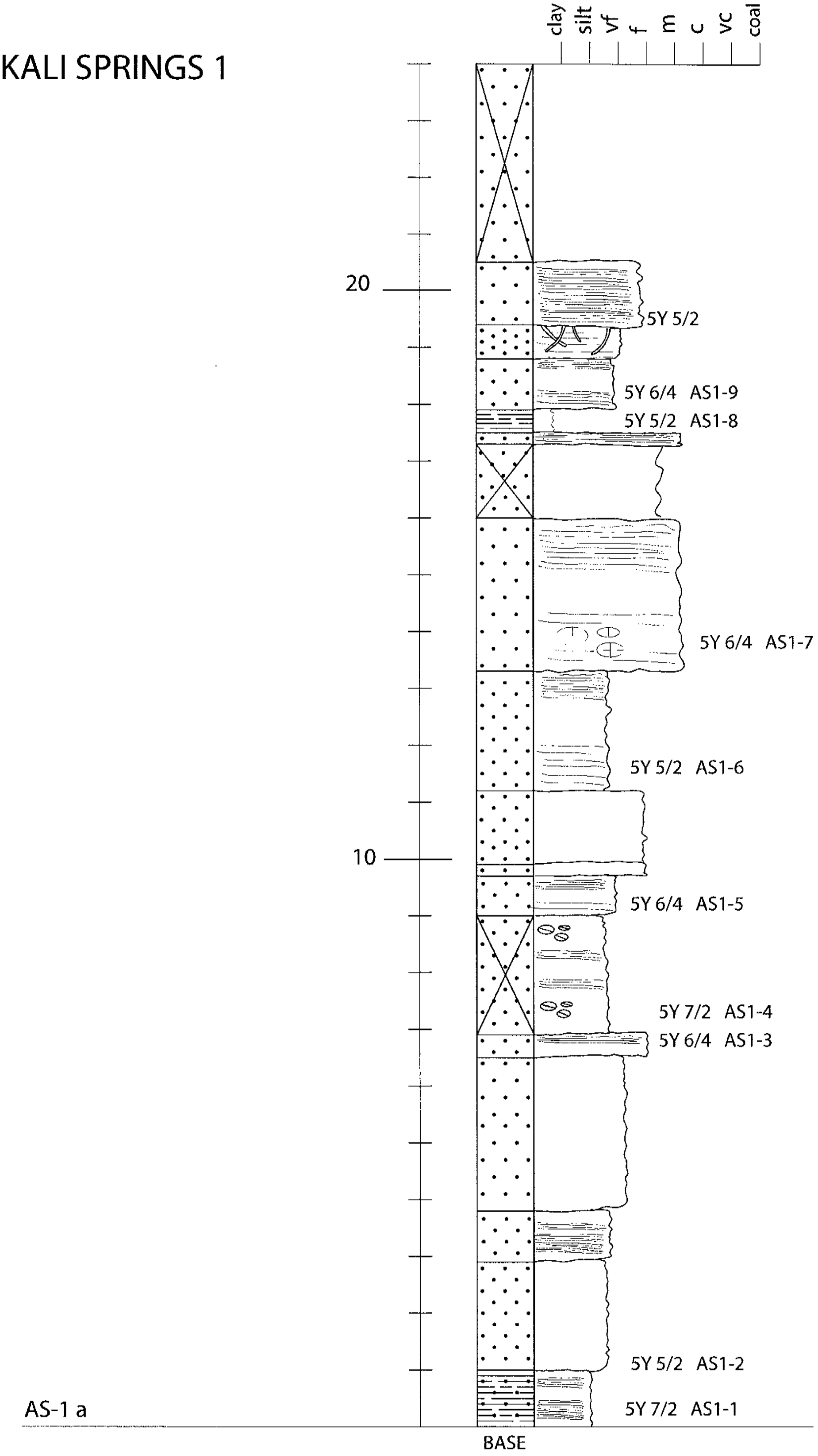
APPENDIX A: Drafted Measured Sections

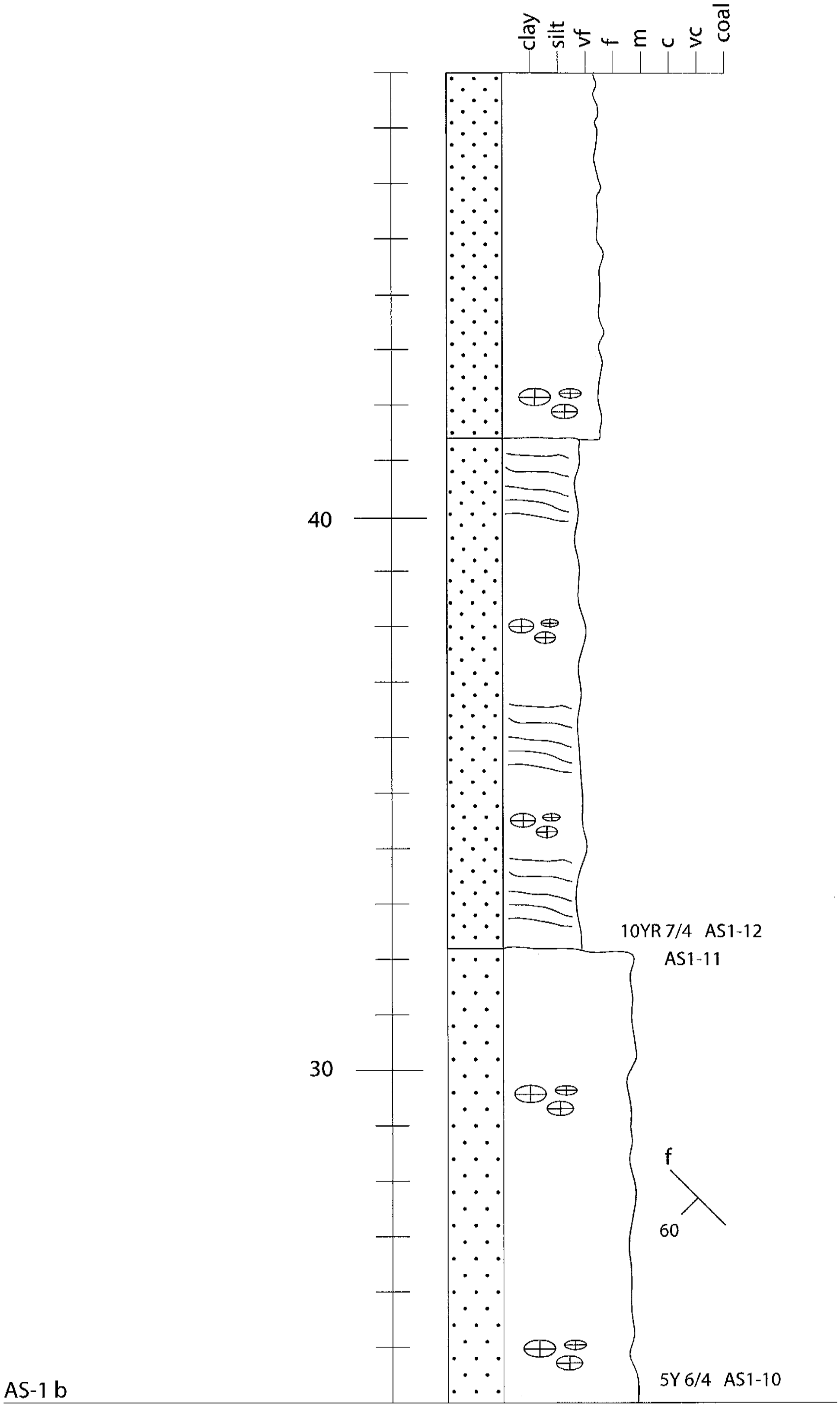
Appendix 1 consists of the nine measured sections across the northern and southern field areas. The measured sections included in this section are South Saddle, Highway 96, Dead Tree, Jaquez Mine, and Alakali Springs 1, 2, 3, 4, 5. Lithofacies are identified only within the Menefee Formation.



All measurements in meters above base of measured section.

ALKALI SPRINGS 1

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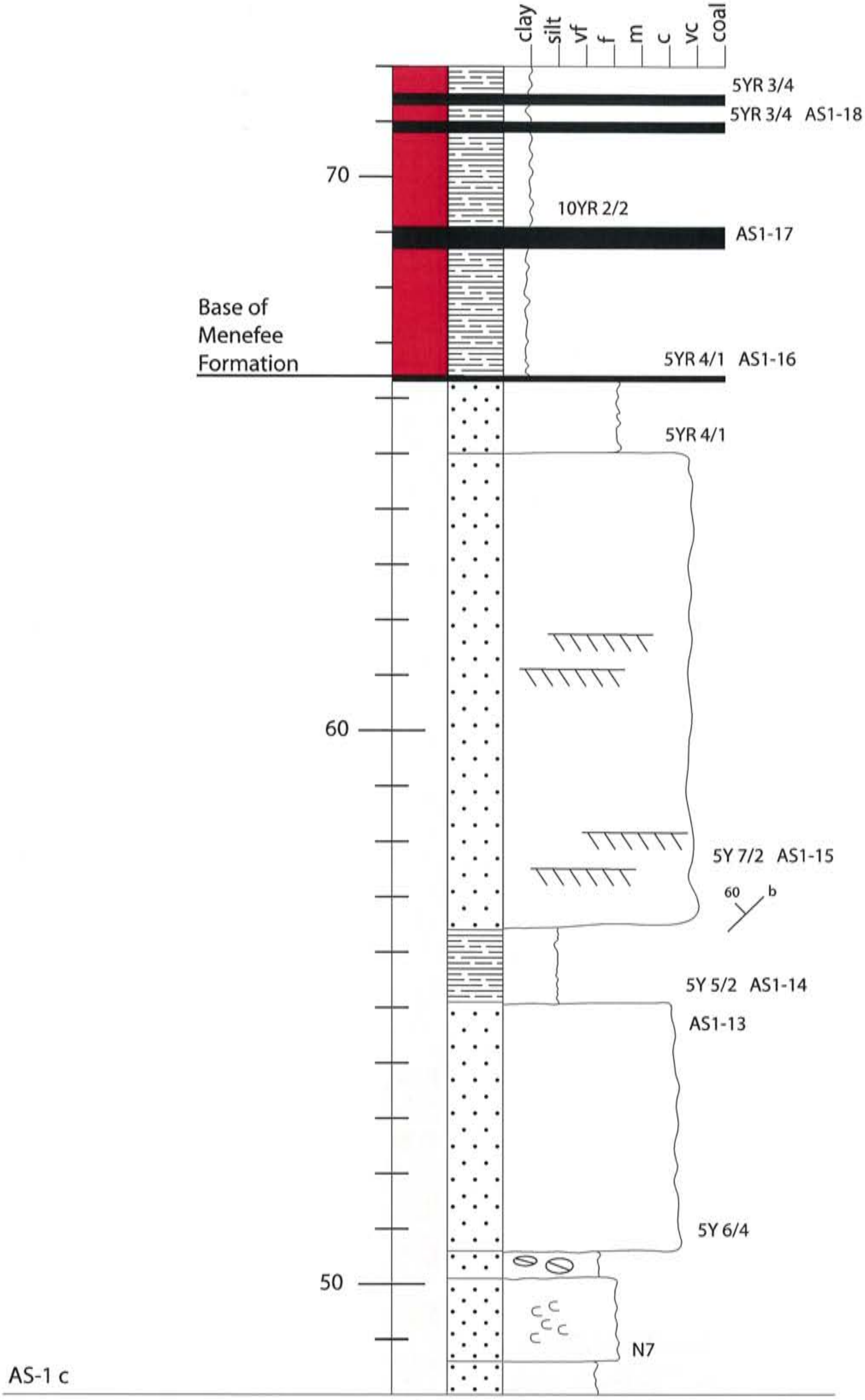
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AS1-13
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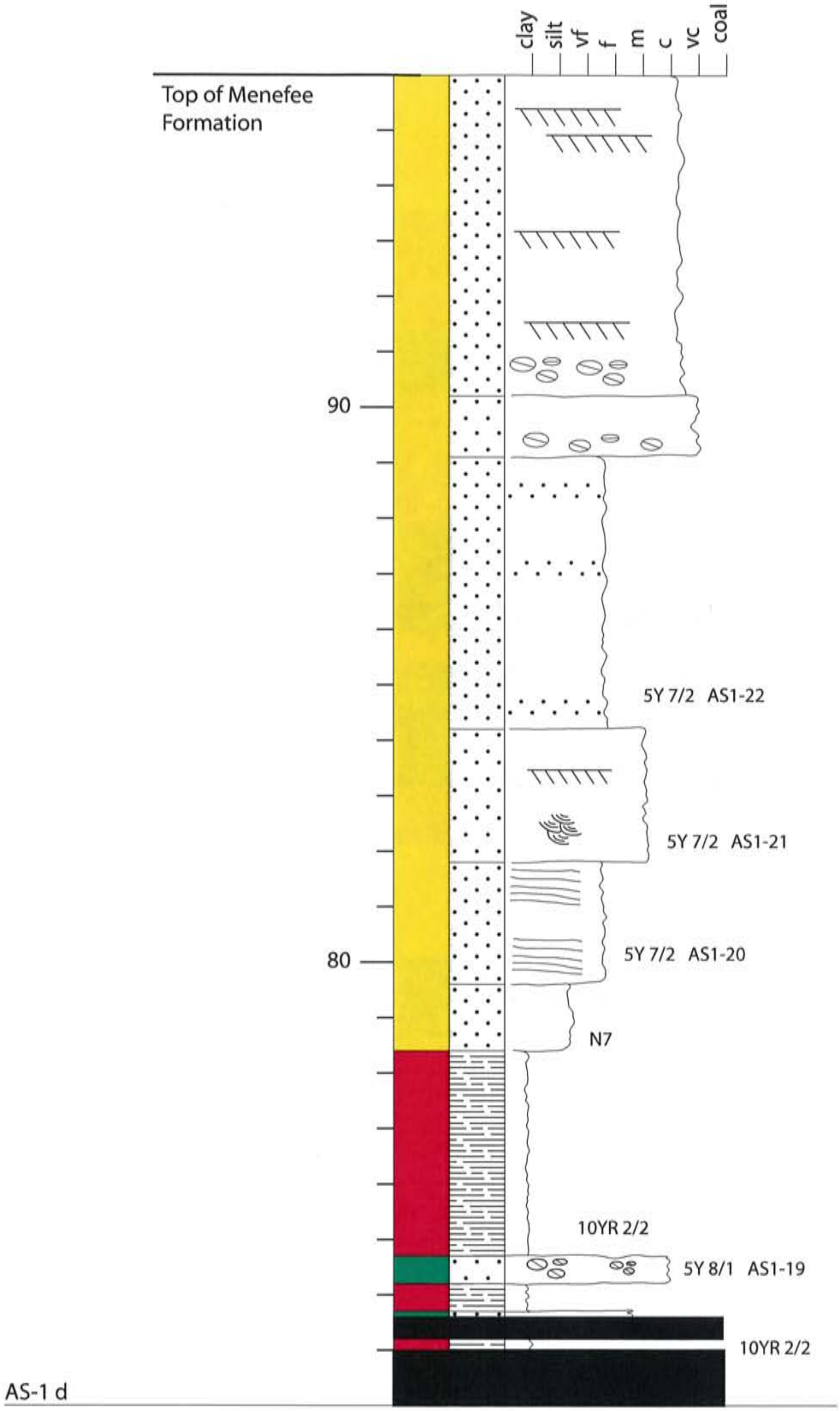
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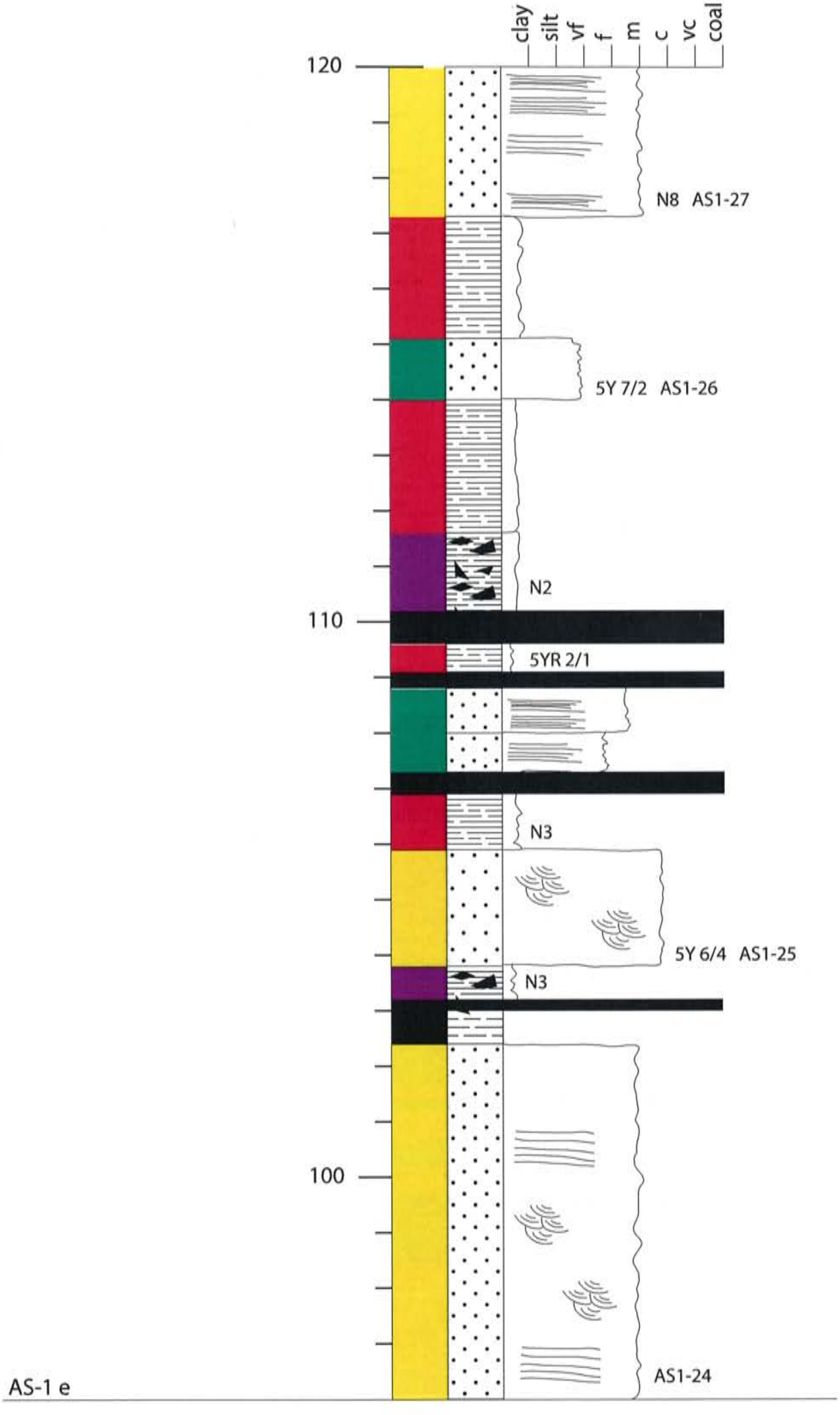
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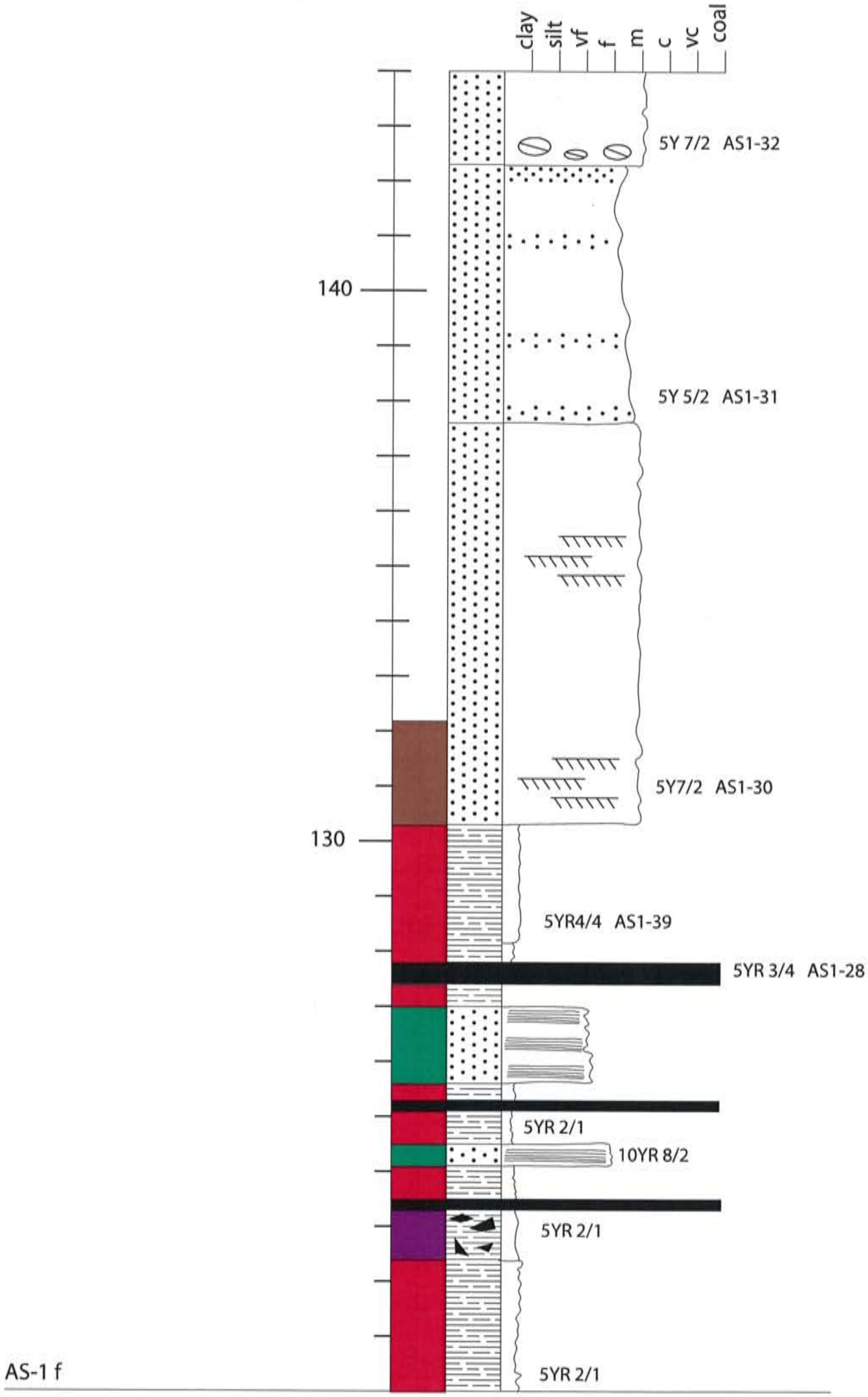
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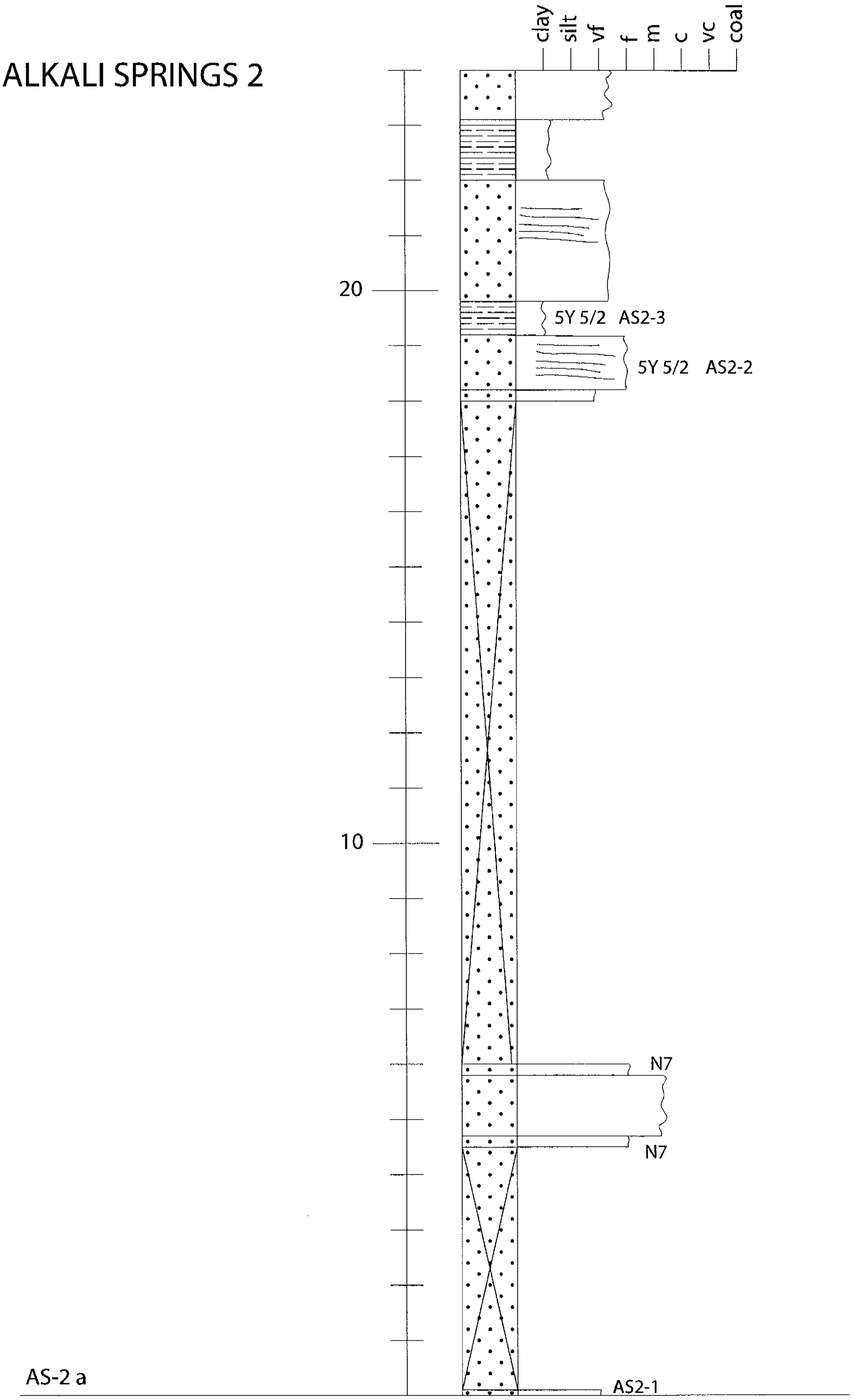
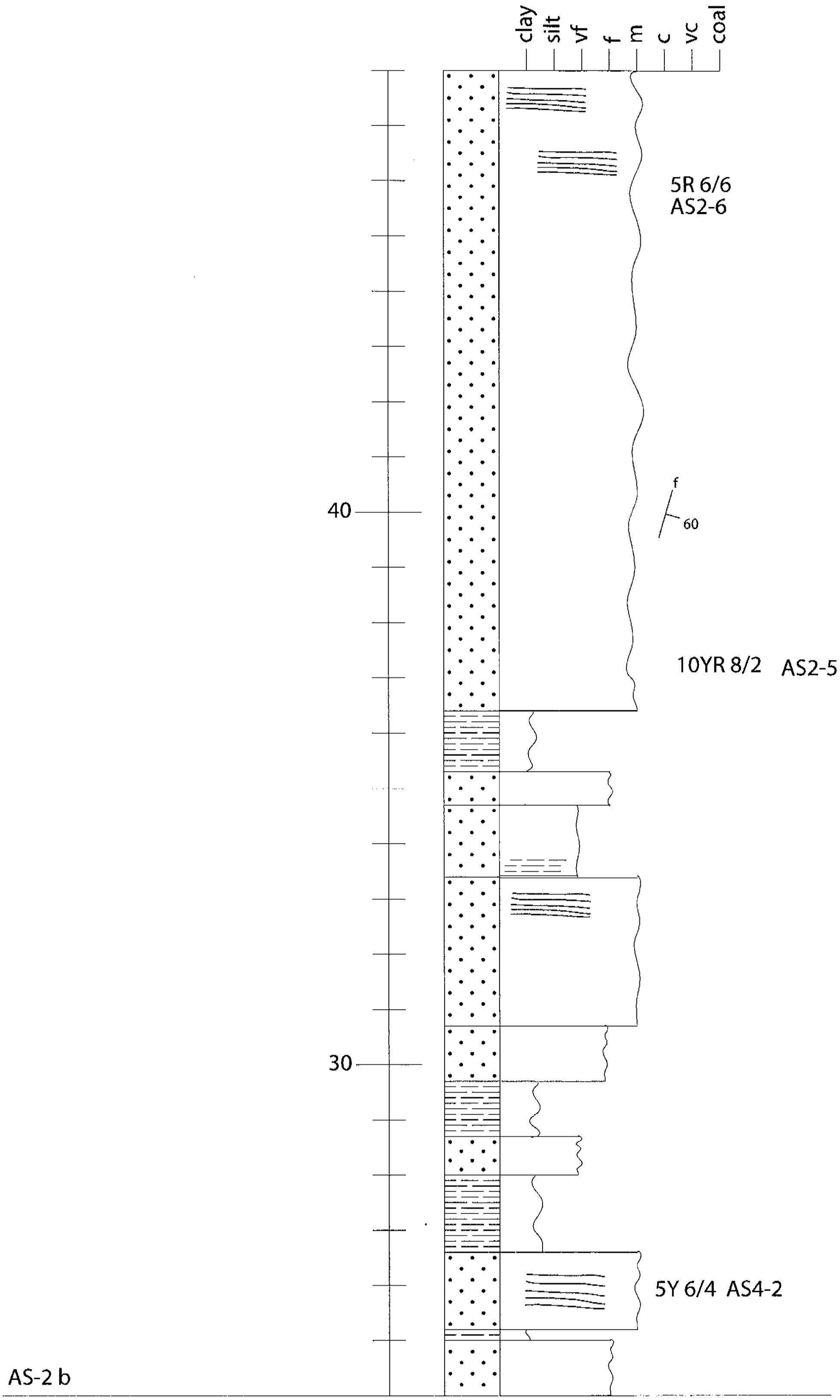
ALKALI SPRINGS 2

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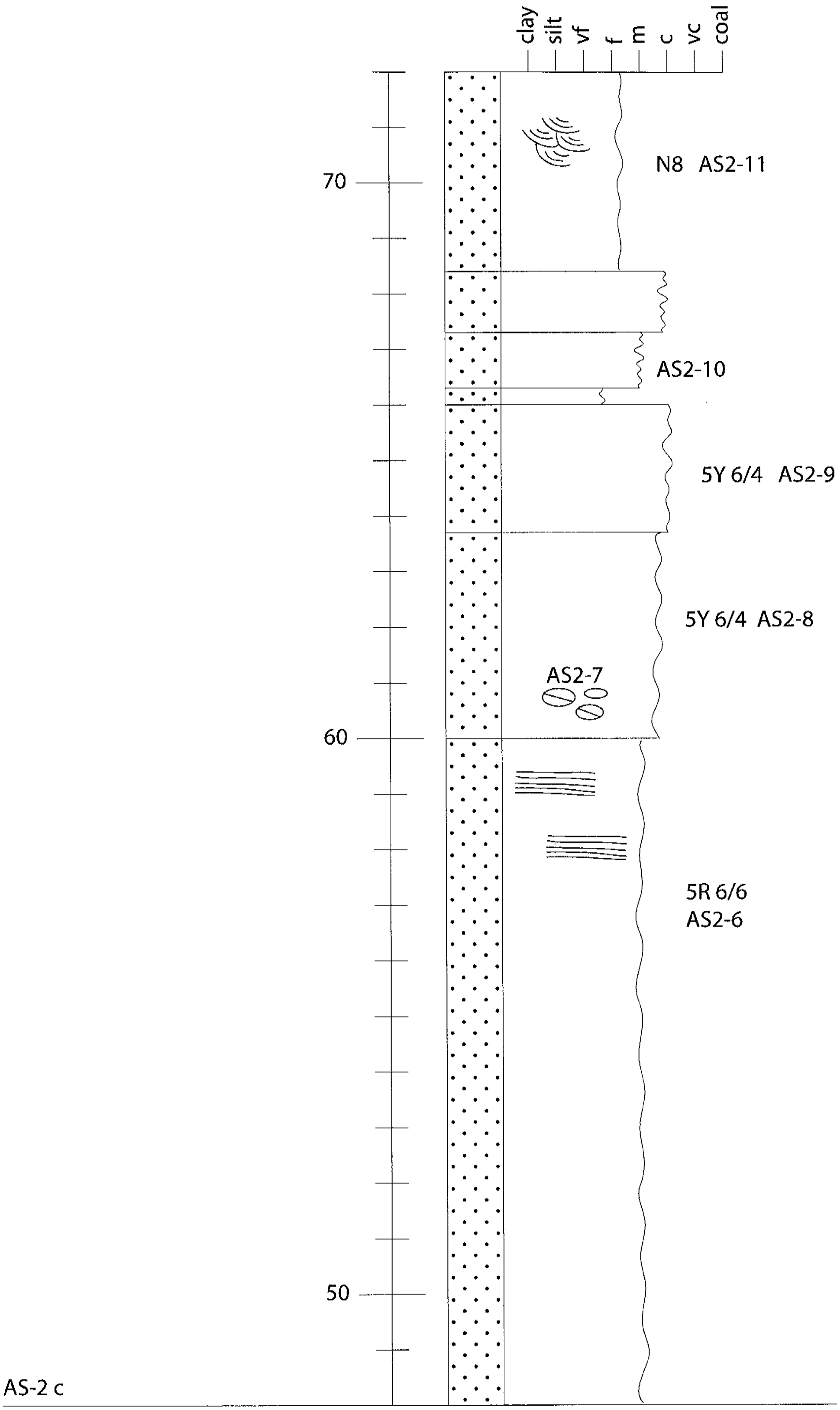
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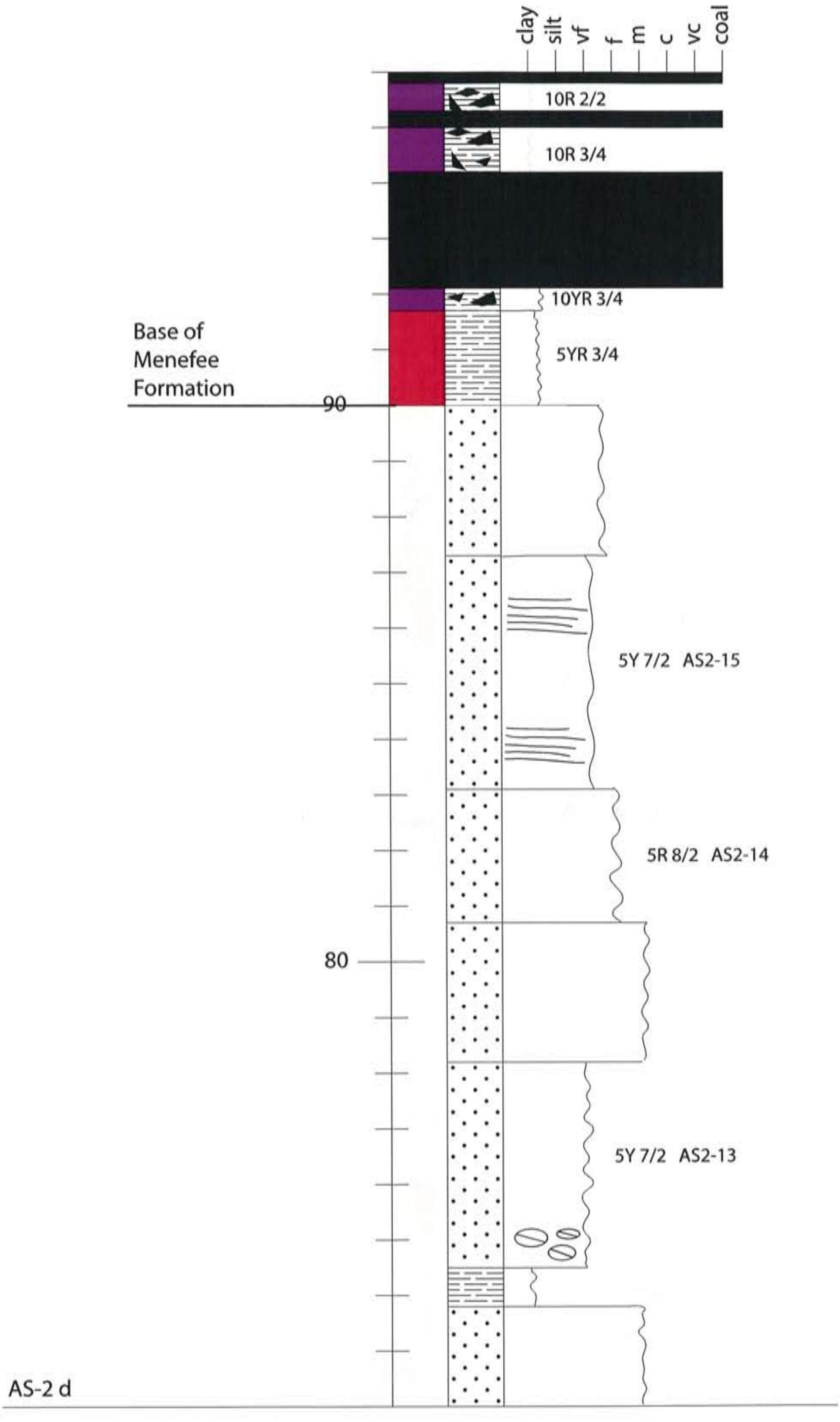
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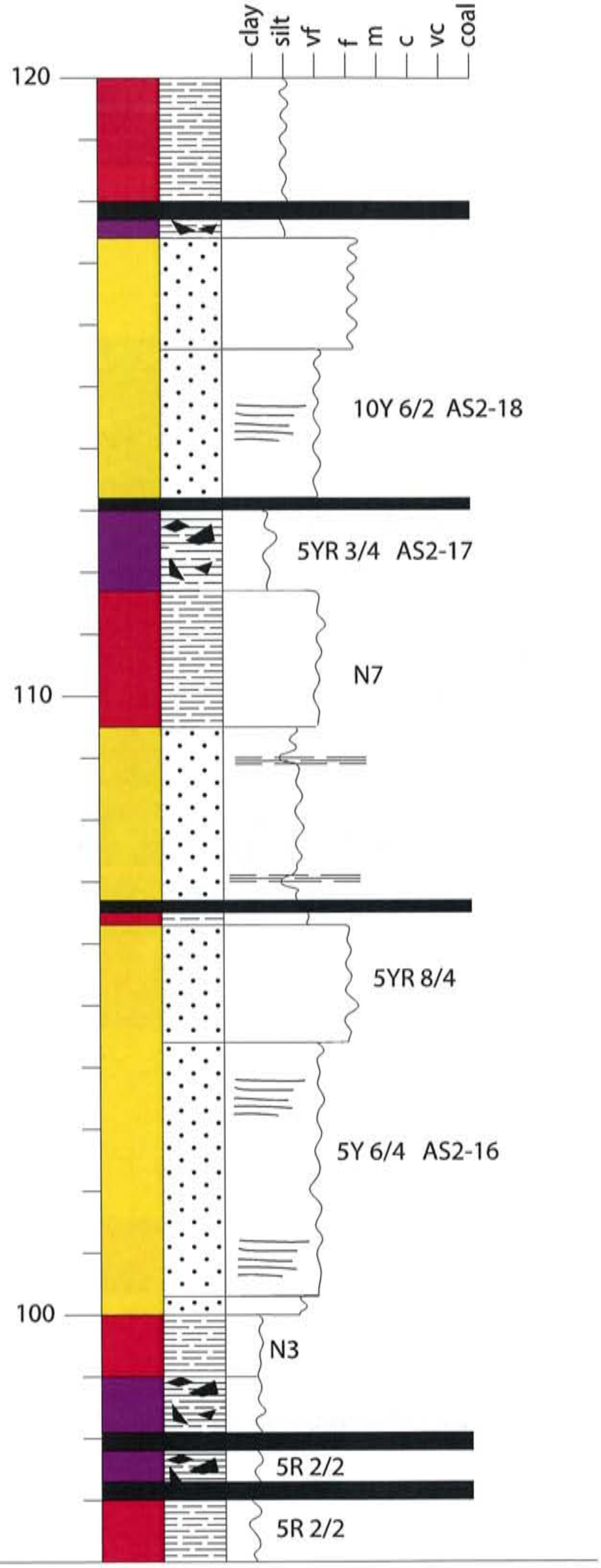
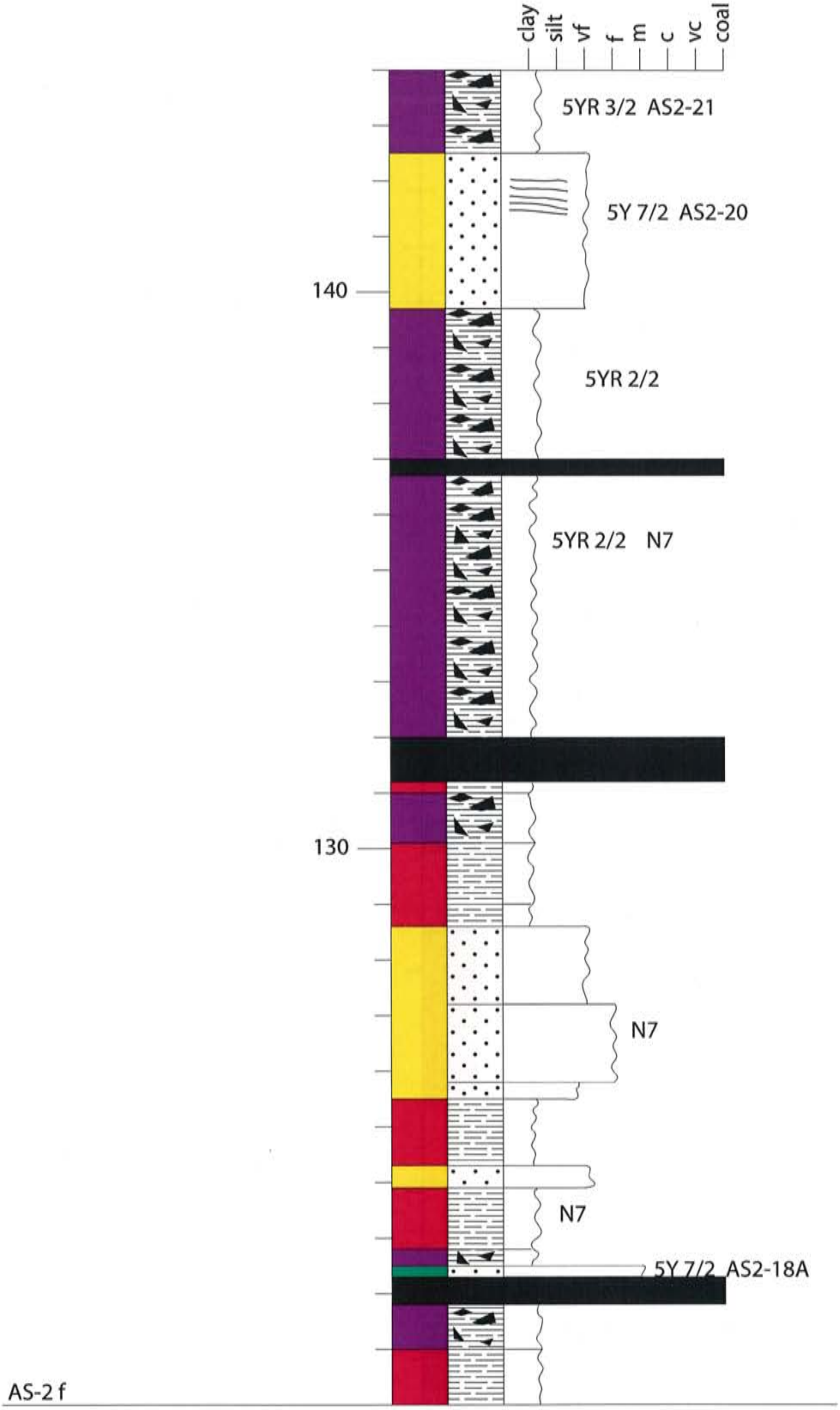
Base of Menefee Formation
90
5Y 7/2 AS2-15
5R 8/2 AS2-14
80
5Y 7/2 AS2-13
AS-2 d


clay
silt
vf
f
m
c
vc
coal
120
110
100
10Y 6/2 AS2-18
5YR 3/4 AS2-17
N7
5YR 8/4
5Y 6/4 AS2-16
N3
5R 2/2
5R 2/2

AS-2 e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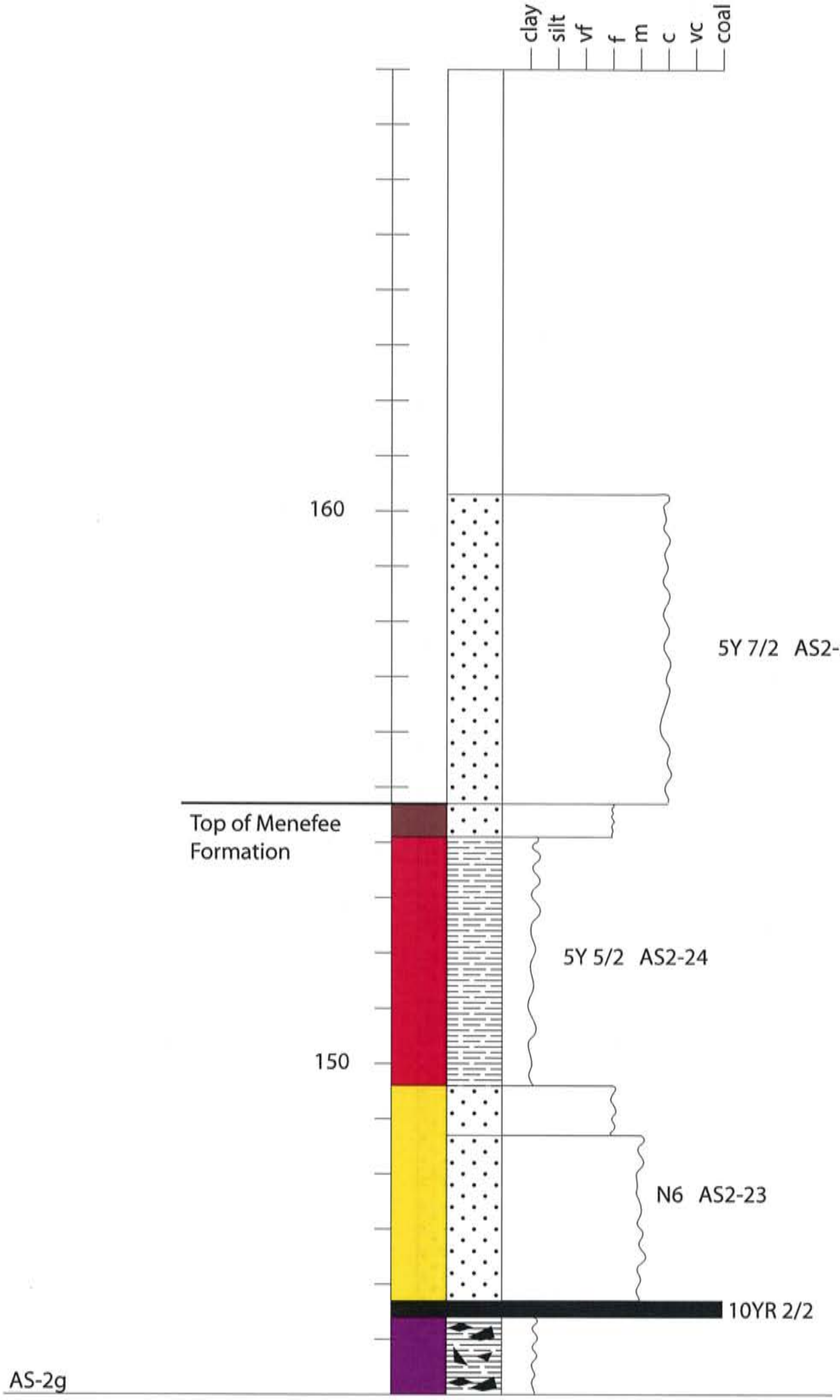
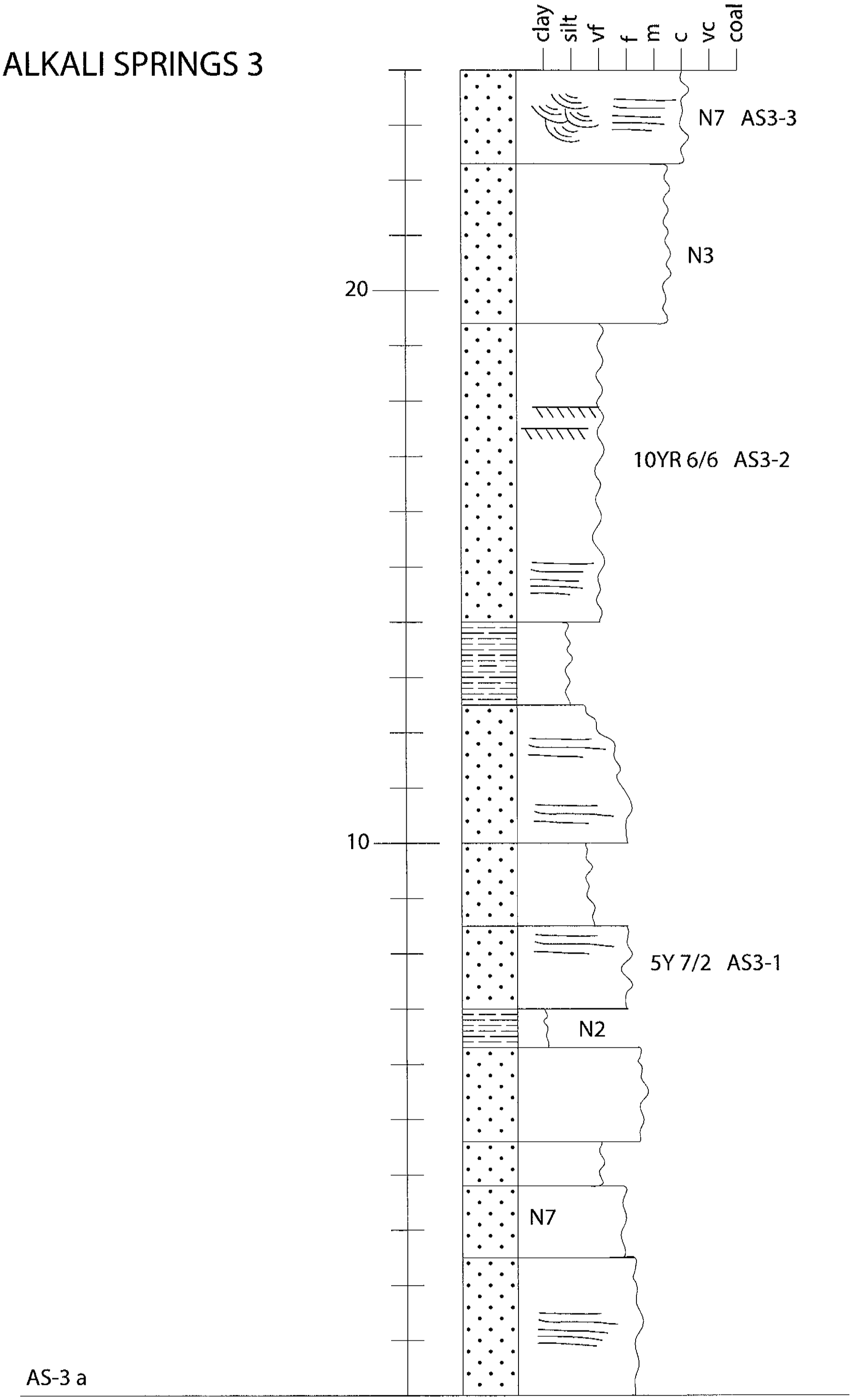
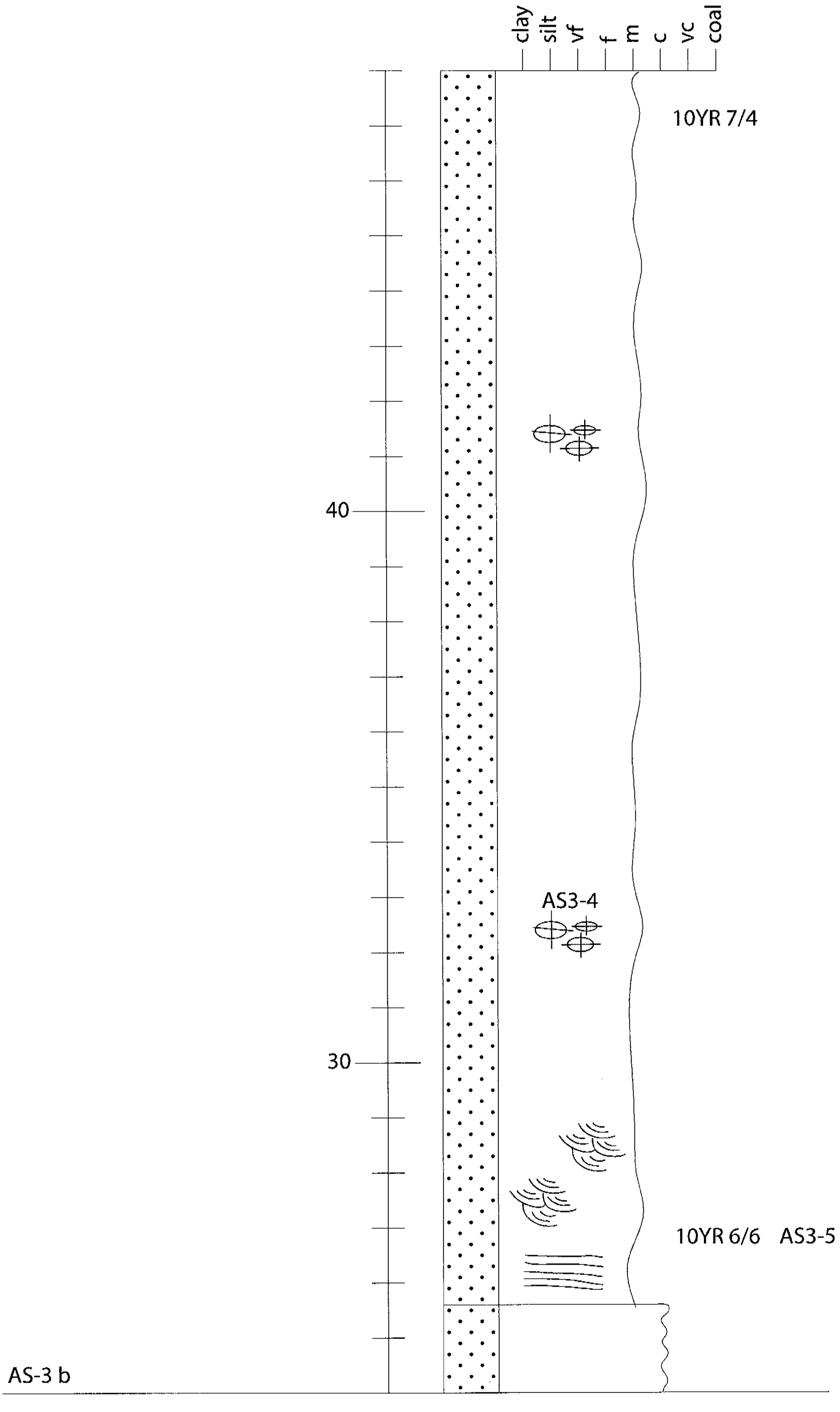
vf
f
m
c
vc
coal
5YR 3/2 AS2-21
5Y 7/2 AS2-20
140
5YR 2/2
5YR 2/2 N7
130
N7
N7
5Y 7/2 AS2-18A
AS-2 f


clay
silt
vf
f
m
c
vc
coal
160
5Y 7/2 AS2-25
Top of Menefee Formation
5Y 5/2 AS2-24
150
N6 AS2-23
10YR 2/2
AS-2g

ALKALI SPRINGS 3

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m
c
vc
coal
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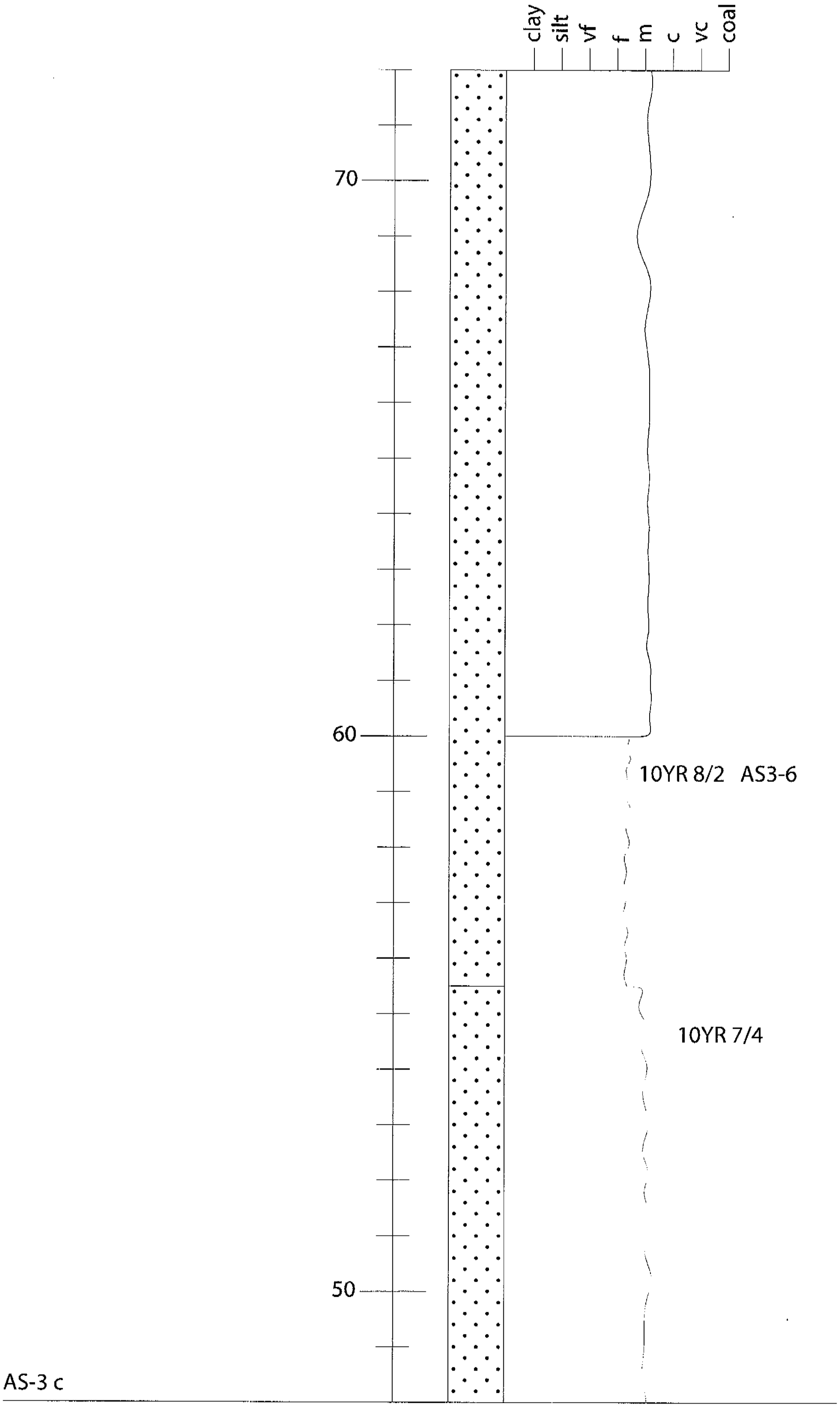
40
AS3-4
30
10YR 6/6
AS3-5
AS-3 b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m
c
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60
50
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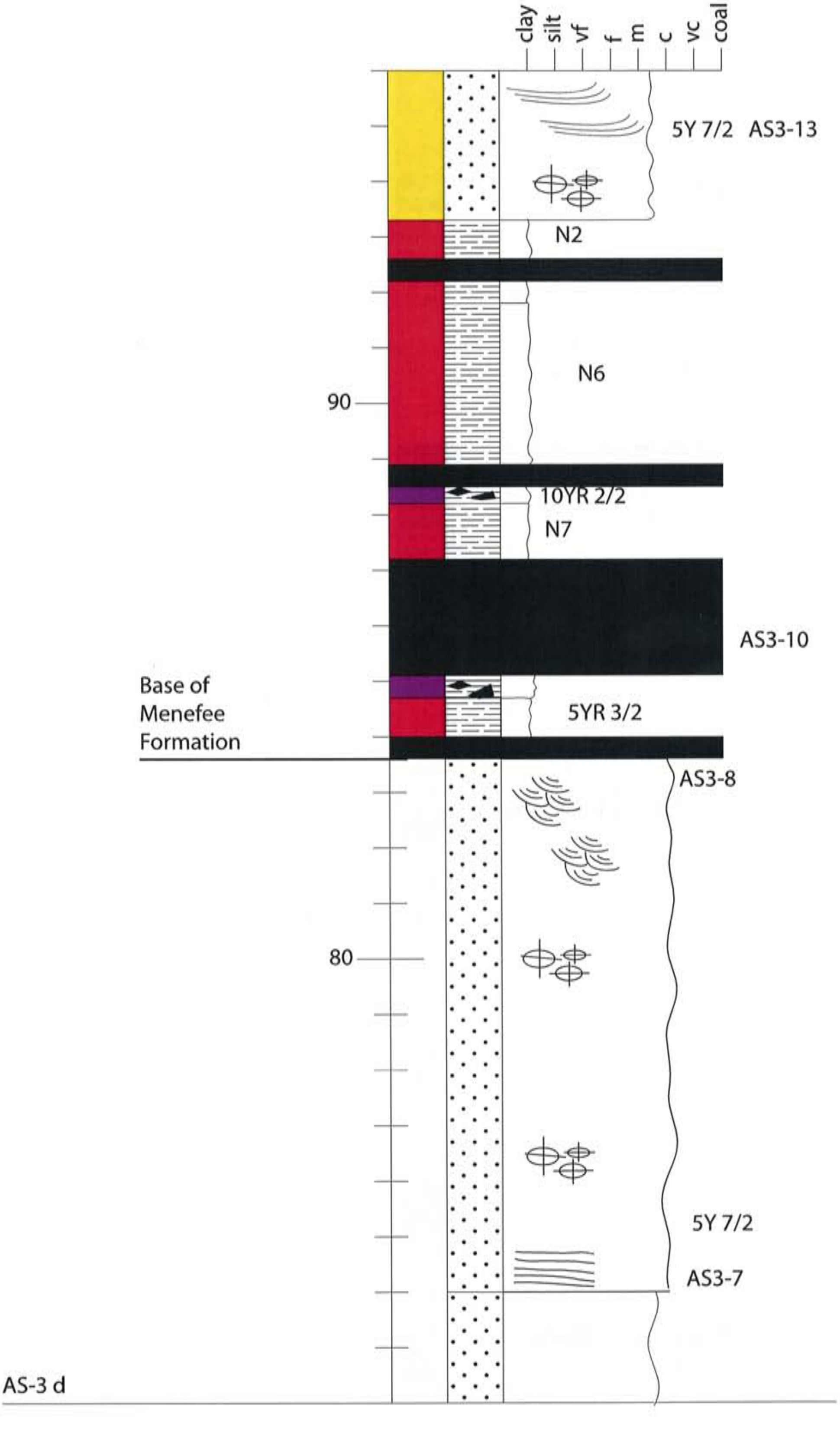
10YR 7/4
AS-3 c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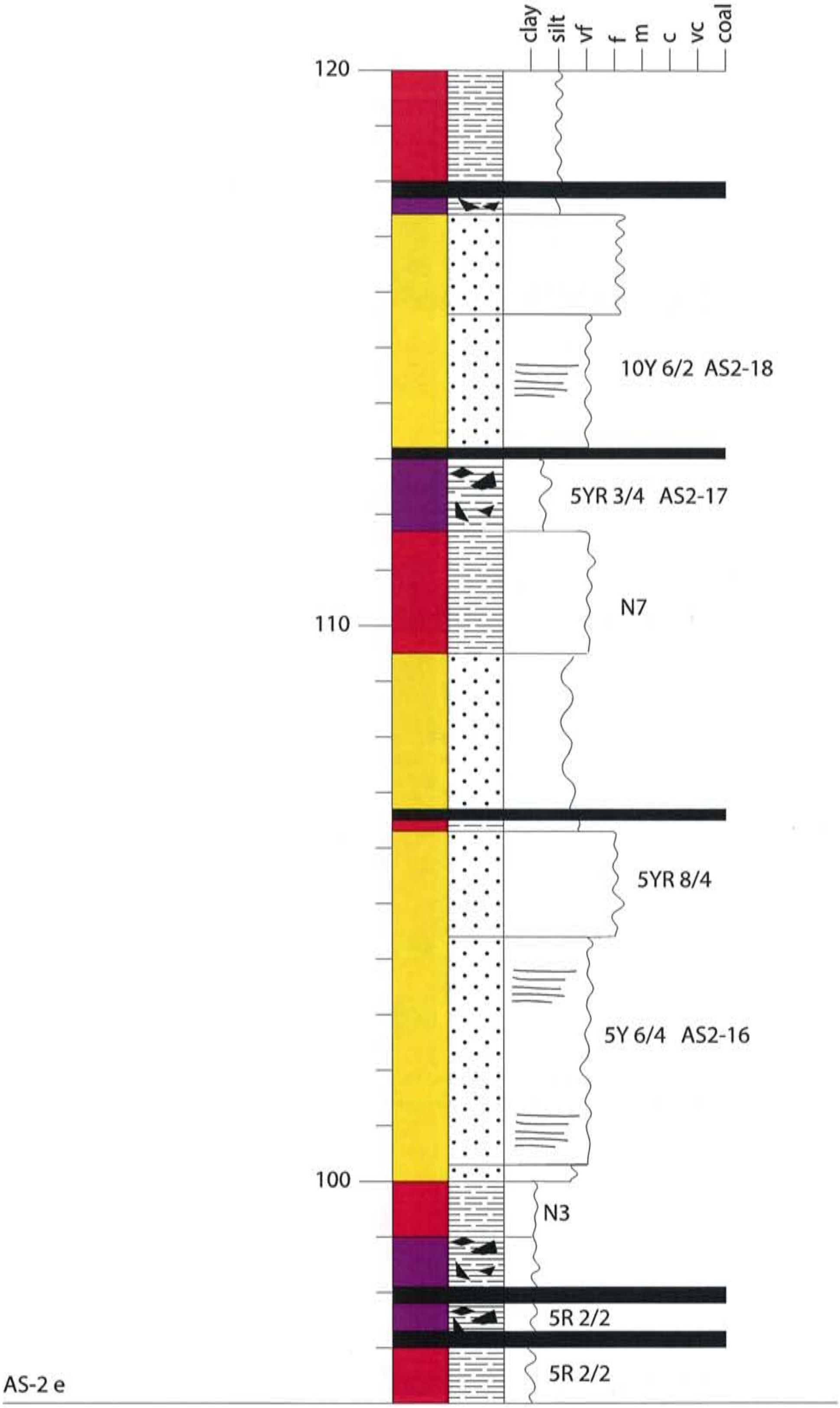
f
m
c
vc
coal
5Y 7/2 AS3-13
N2
N6
90
10YR 2/2
N7
AS3-10
Base of Menefee Formation
5YR 3/2
AS3-8
80
5Y 7/2
AS3-7
AS-3 d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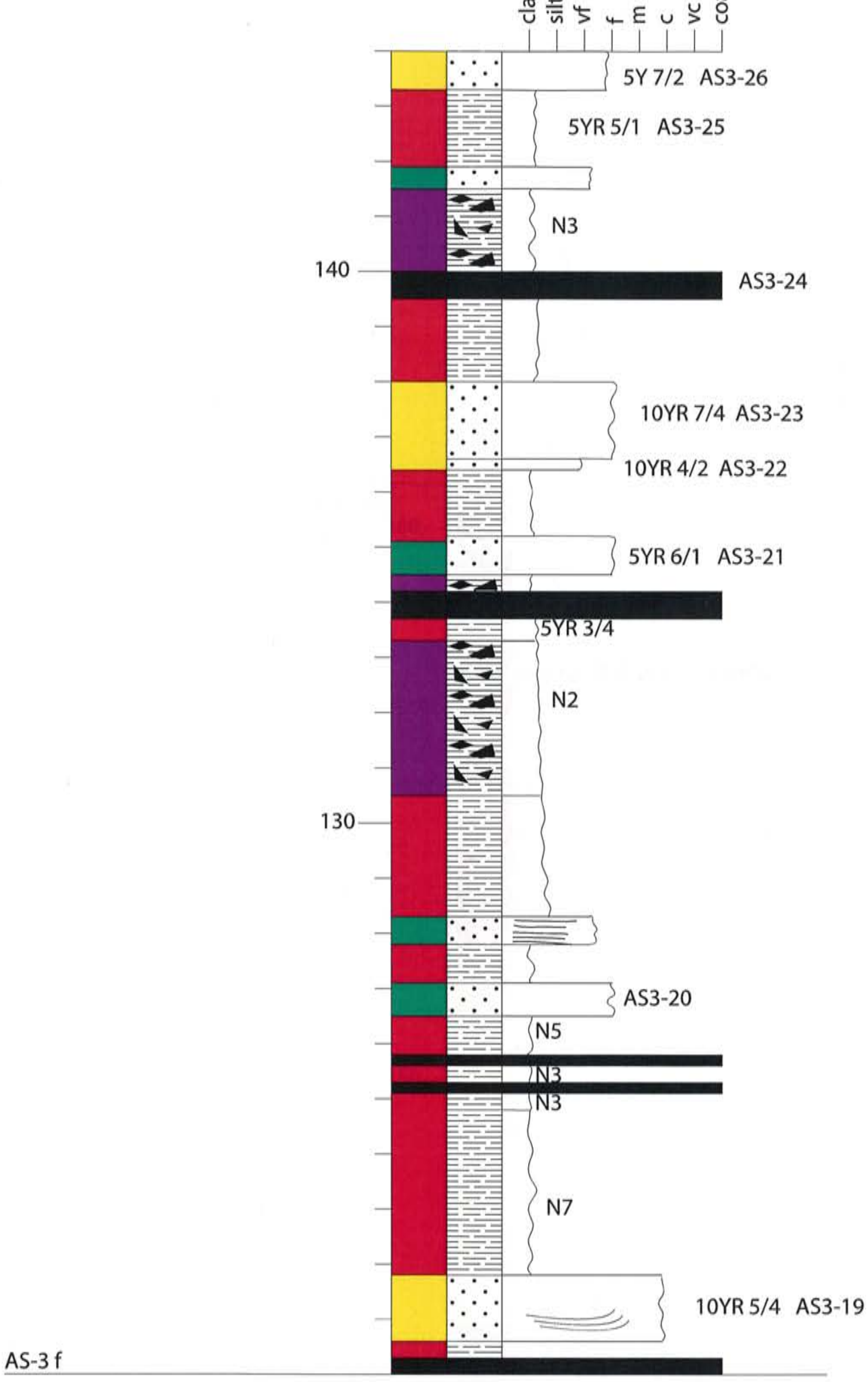
silt
vf
f
m
c
vc
coal
120
10Y 6/2 AS2-18
5YR 3/4 AS2-17
N7
110
5YR 8/4
5Y 6/4 AS2-16
100
N3
5R 2/2
5R 2/2
AS-2 e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vf
f
m
c
vc
coal
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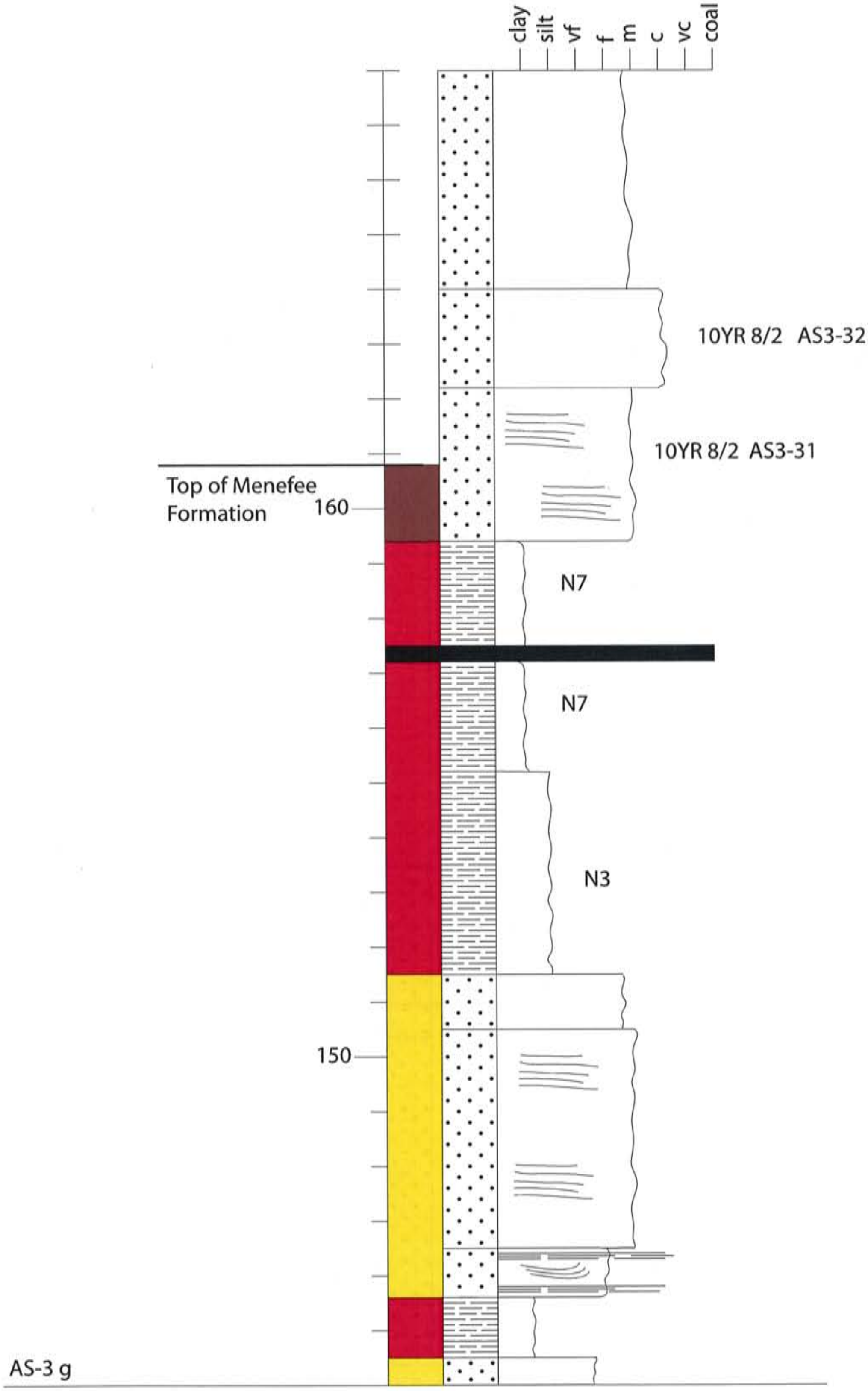
5YR 5/1 AS3-25
N3
140
AS3-24
10YR 7/4 AS3-23
10YR 4/2 AS3-22
5YR 6/1 AS3-21
5YR 3/4
N2
130
AS3-20
N5
N3
N3
N7
10YR 5/4 AS3-19
AS-3 f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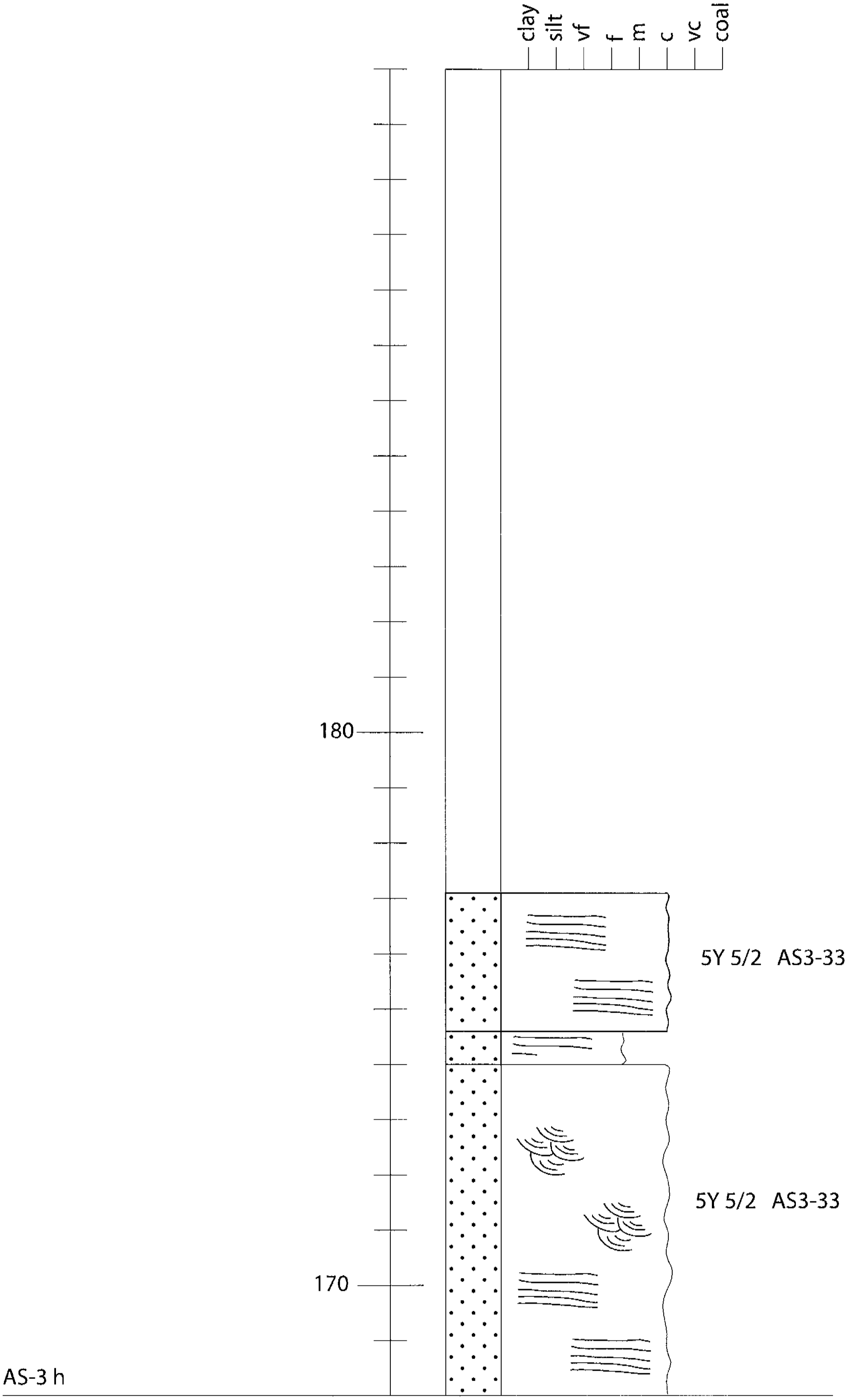
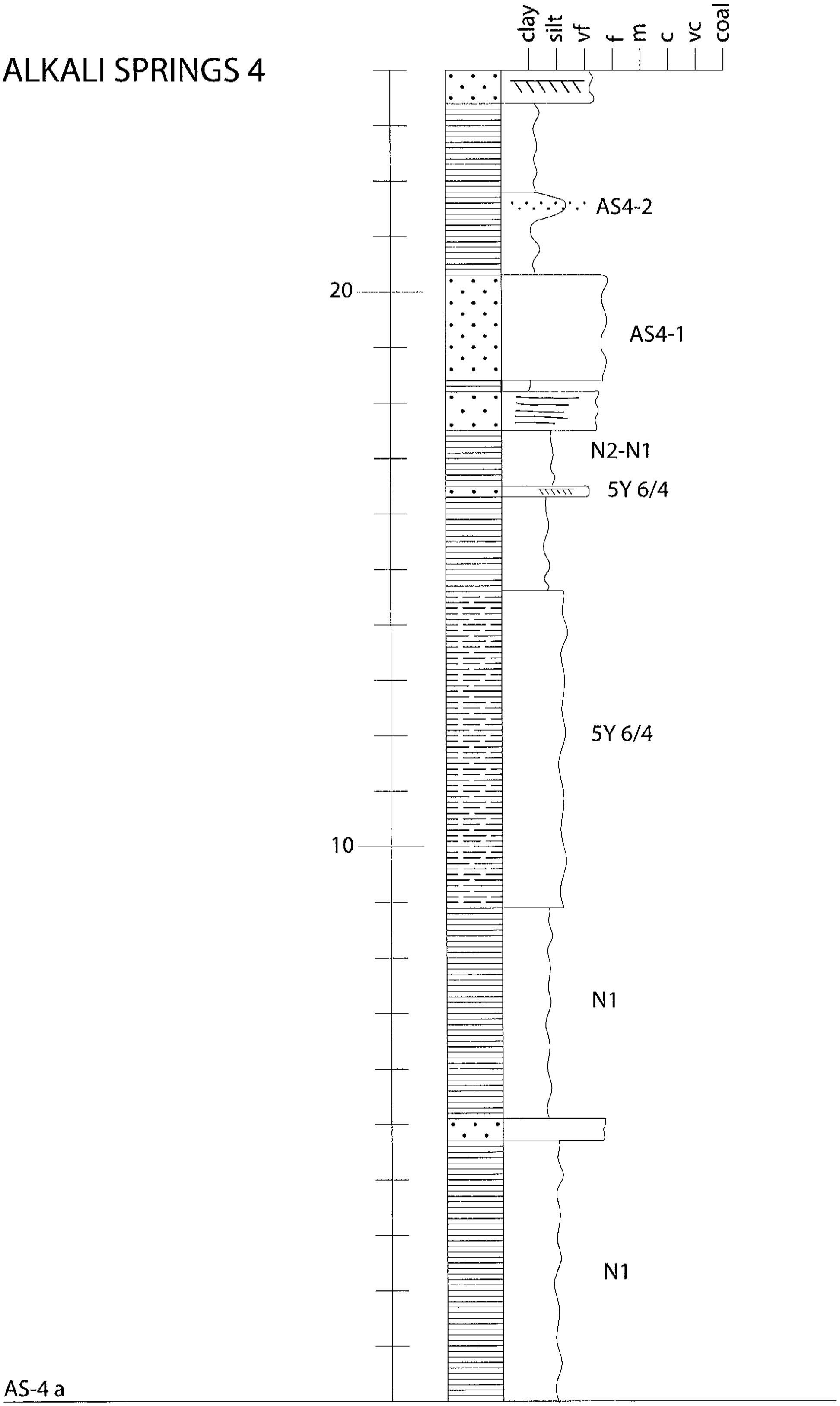
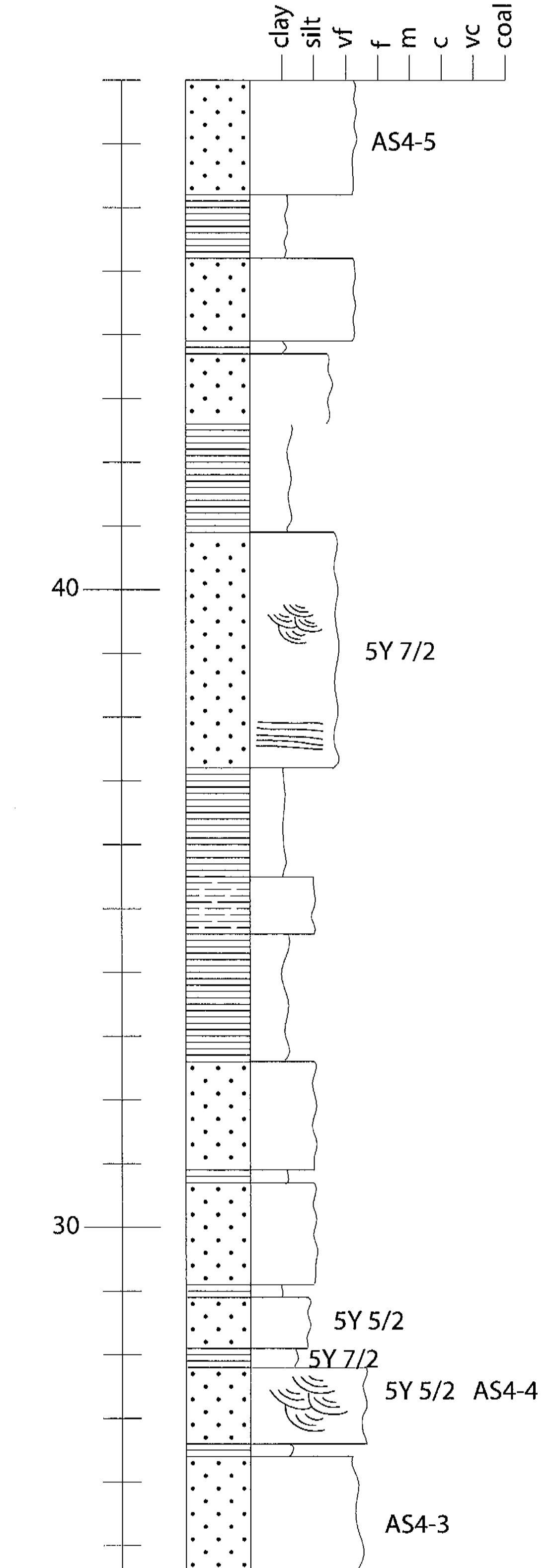
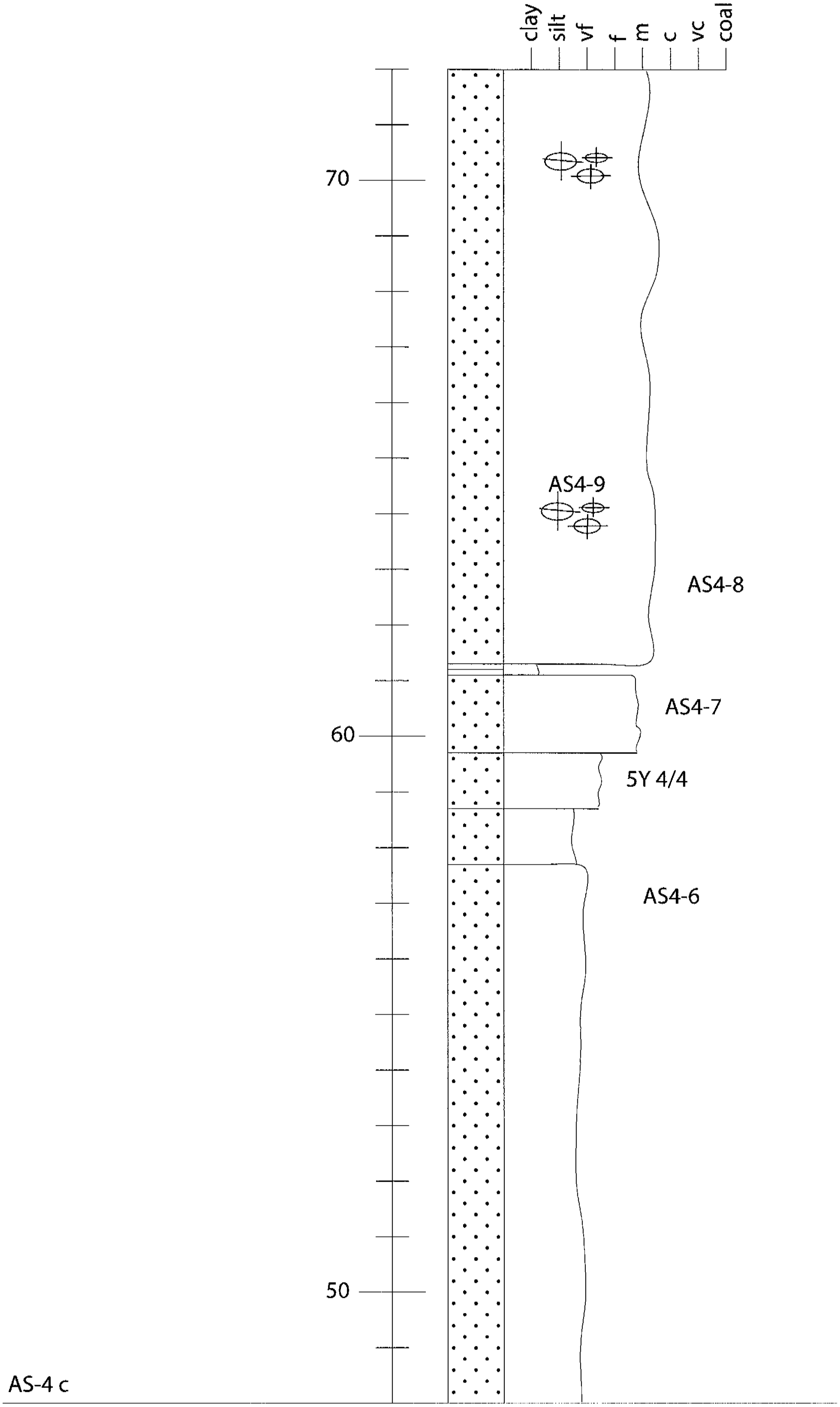
vf
f
m
c
vc
coal
10YR 8/2 AS3-32
10YR 8/2 AS3-31
Top of Menefee Formation
160
N7
N7
N3
150
AS-3 g

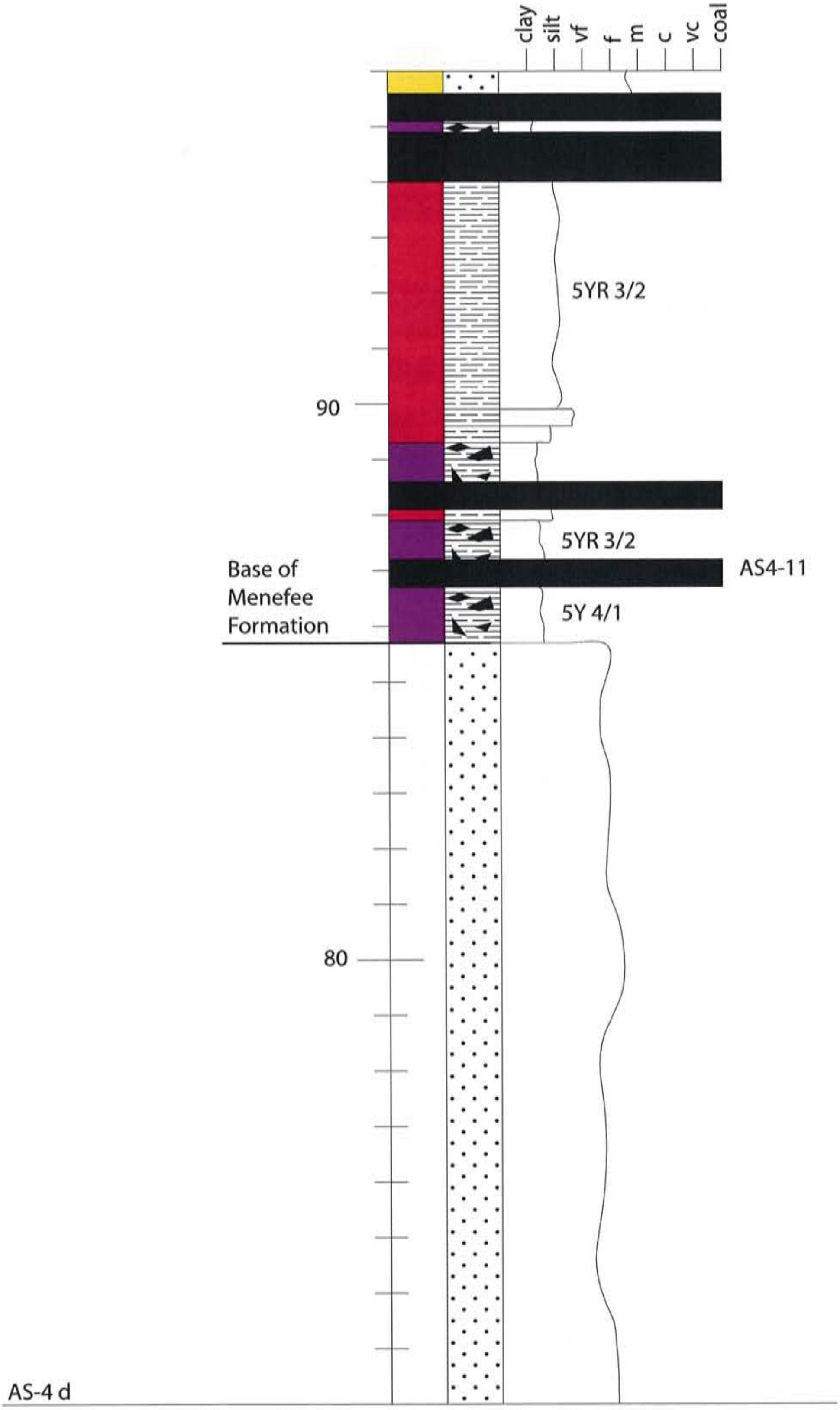

clay
silt
vf
f
m
c
vc
coal
180
5Y 5/2 AS3-33
5Y 5/2 AS3-33
170
AS-3 h

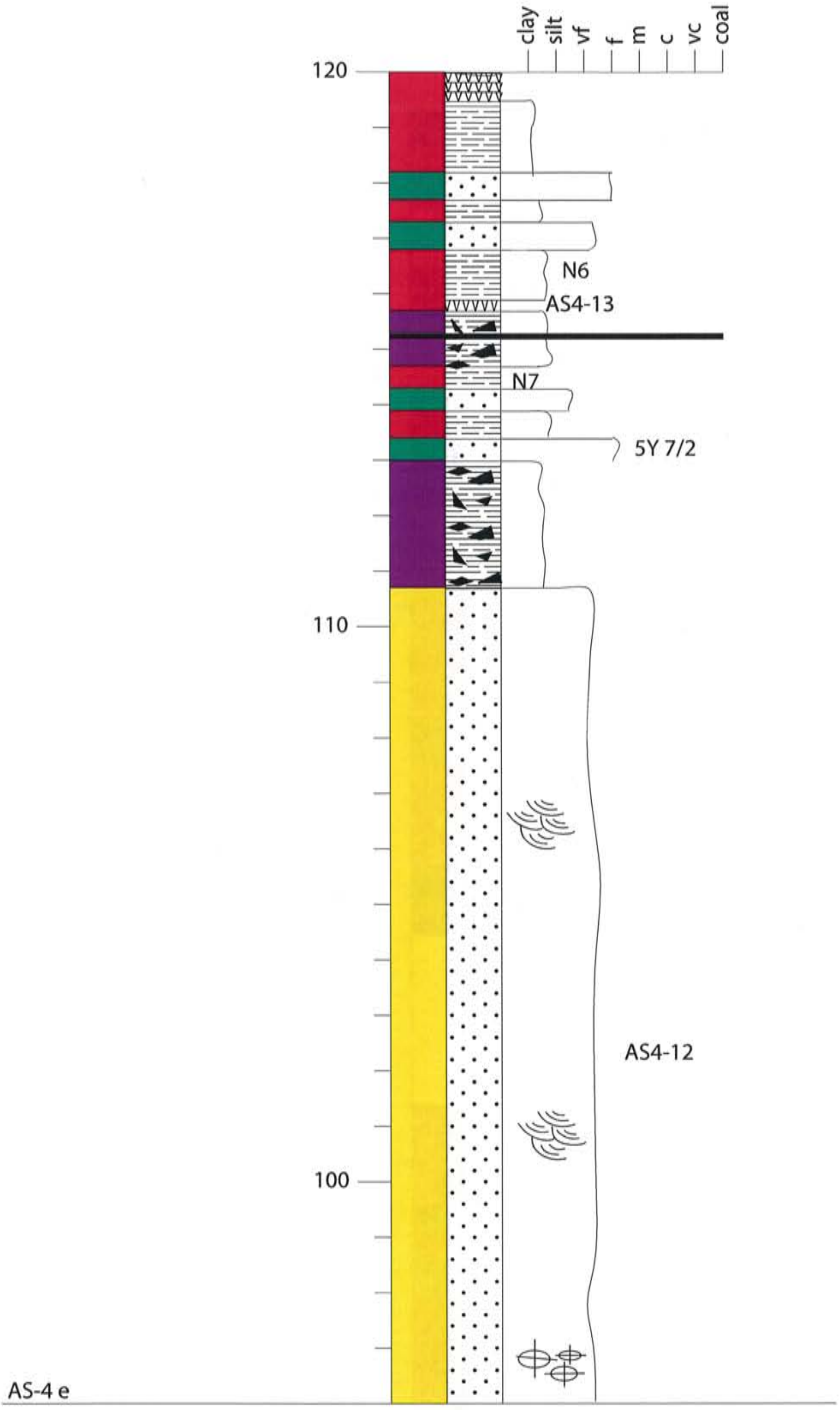
ALKALI SPRINGS 4

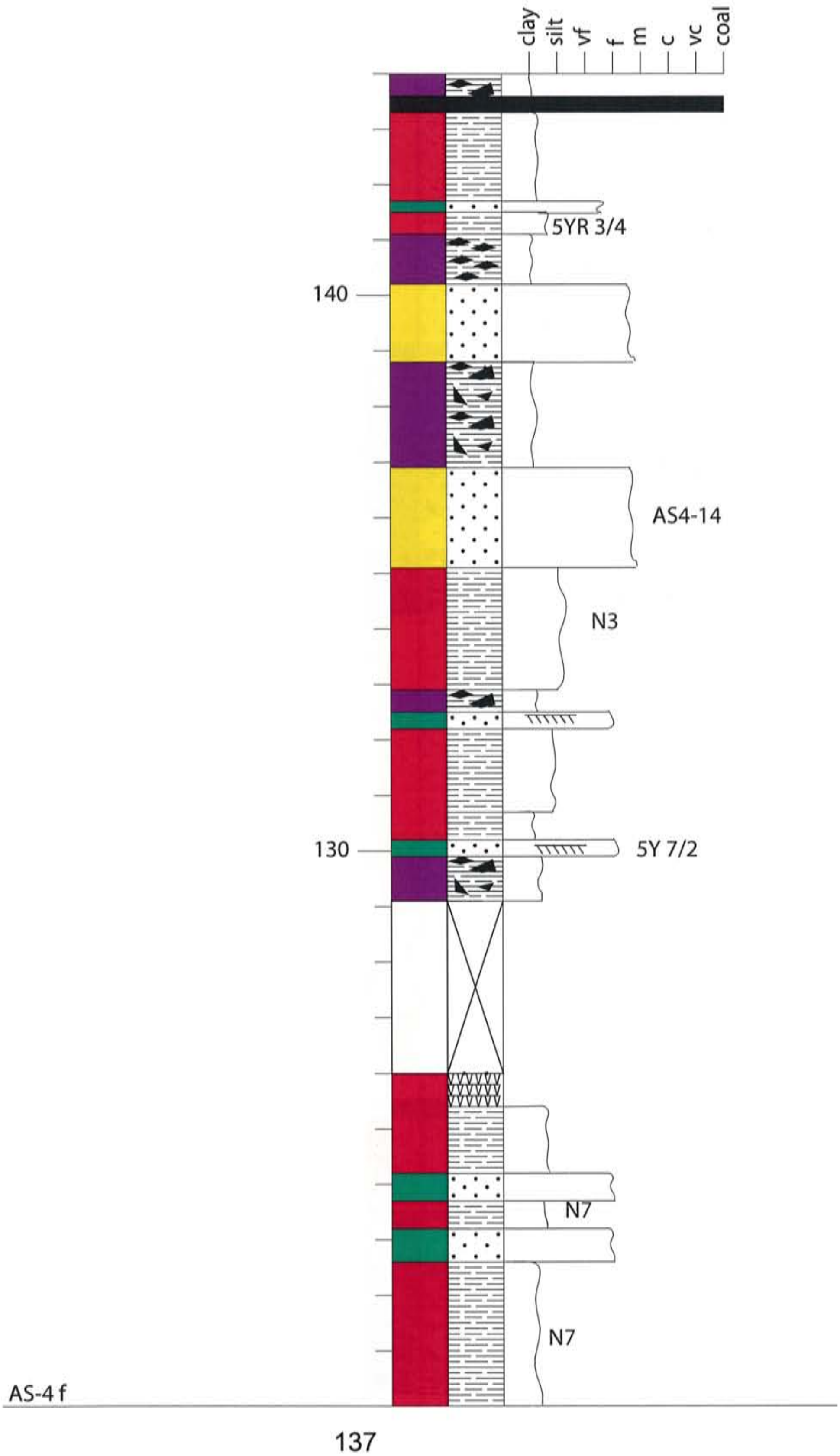


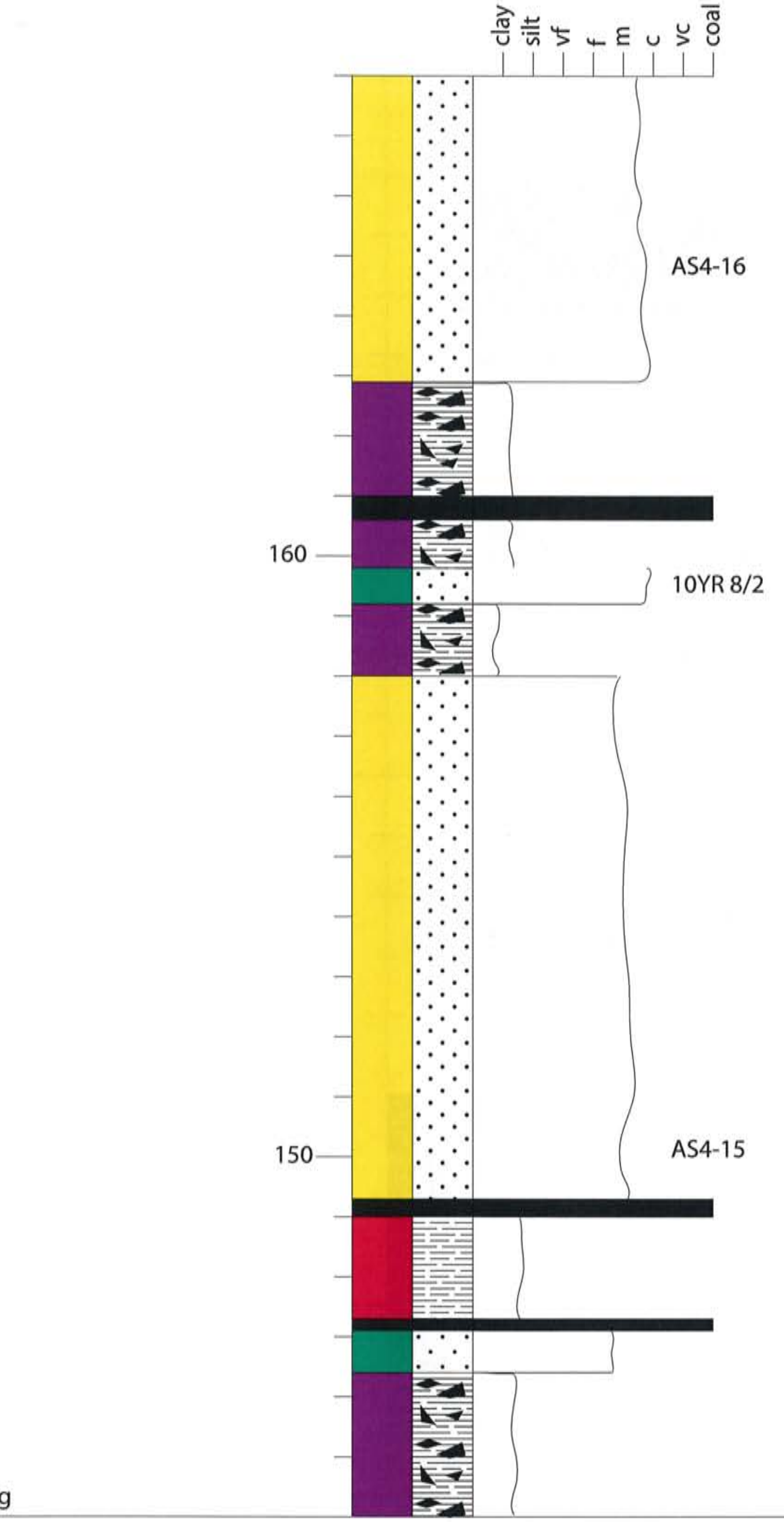

clay
silt
vf
f
m
c
vc
coal
AS4-5
40
5Y 7/2
30
5Y 5/2
5Y 7/2
5Y 5/2
AS4-4
AS4-3
AS-4 b


clay
silt
vf
f
m
c
vc
coal
70
AS4-9
AS4-8
AS4-7
60
5Y 4/4
AS4-6
50
AS-4 c


clay
silt
vf
f
m
c
vc
coal
5YR 3/2
90
5YR 3/2
AS4-11
Base of Menefee Formation
5Y 4/1
80
AS-4 d


clay
silt
vf
f
m
c
vc
coal
120
N6
AS4-13
N7
5Y 7/2
110
AS4-12
100
AS-4 e


clay
silt
vf
f
m
c
vc
coal
5YR 3/4
140
AS4-14
N3
130
5Y 7/2
N7
N7
AS-4 f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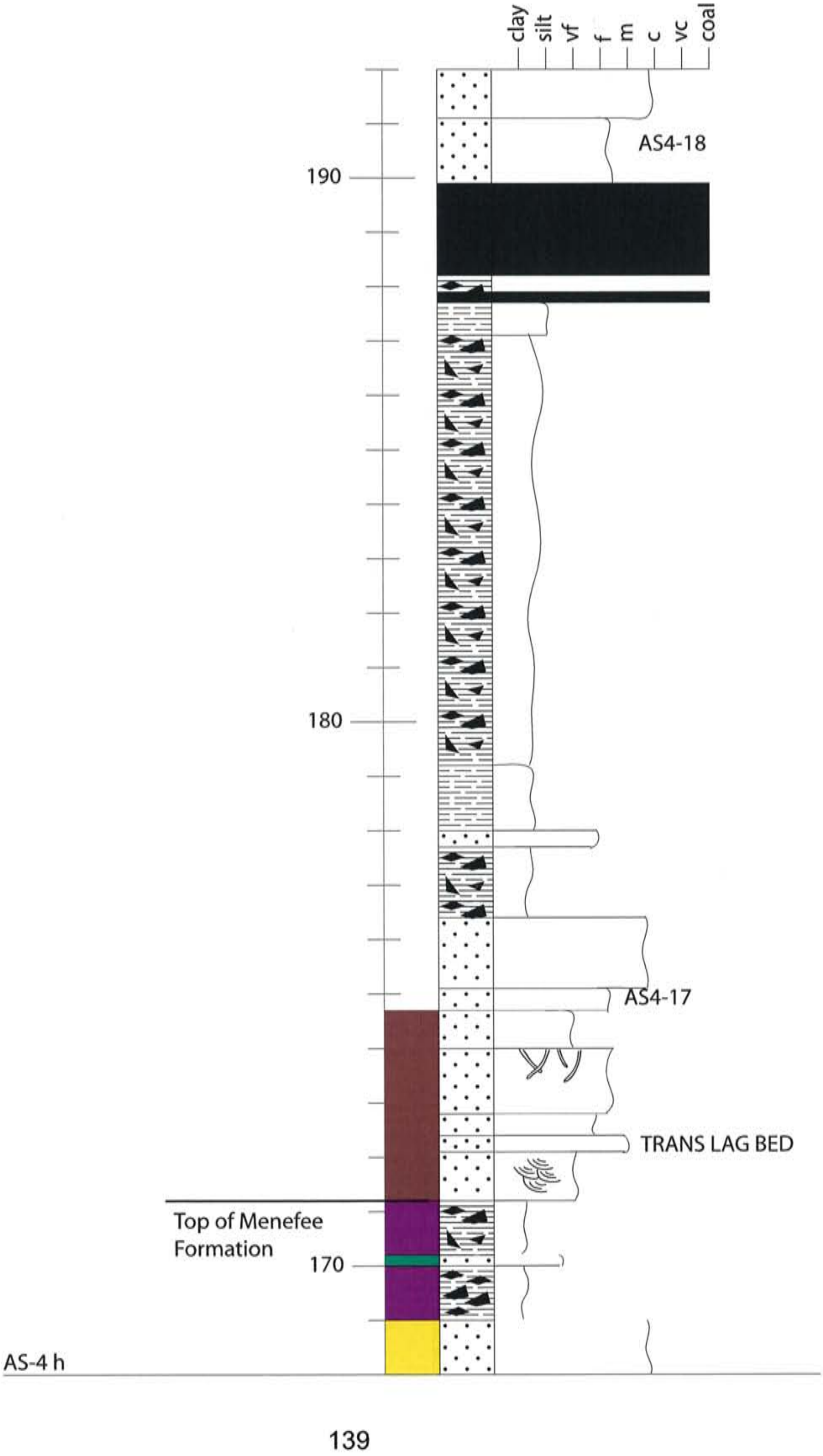
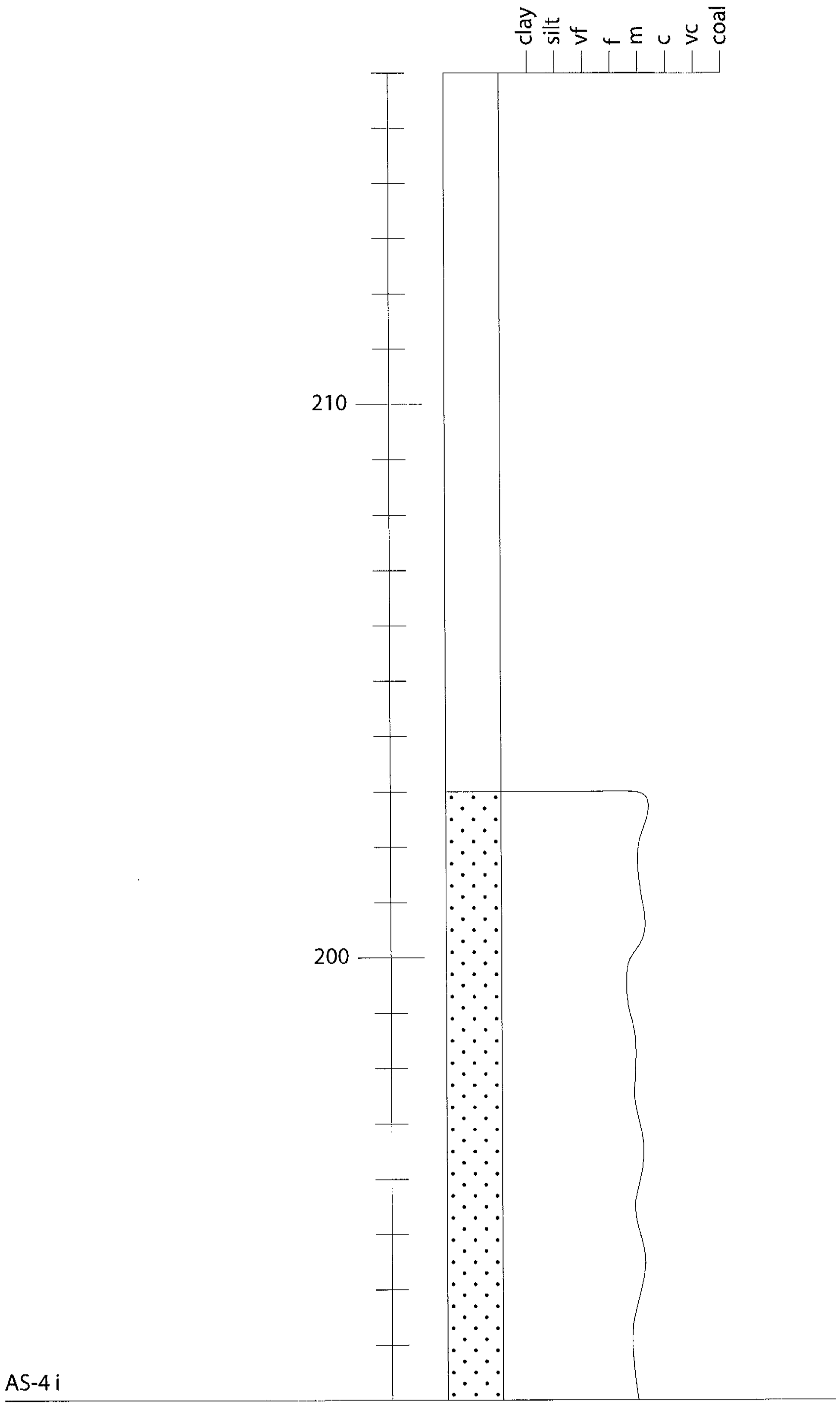
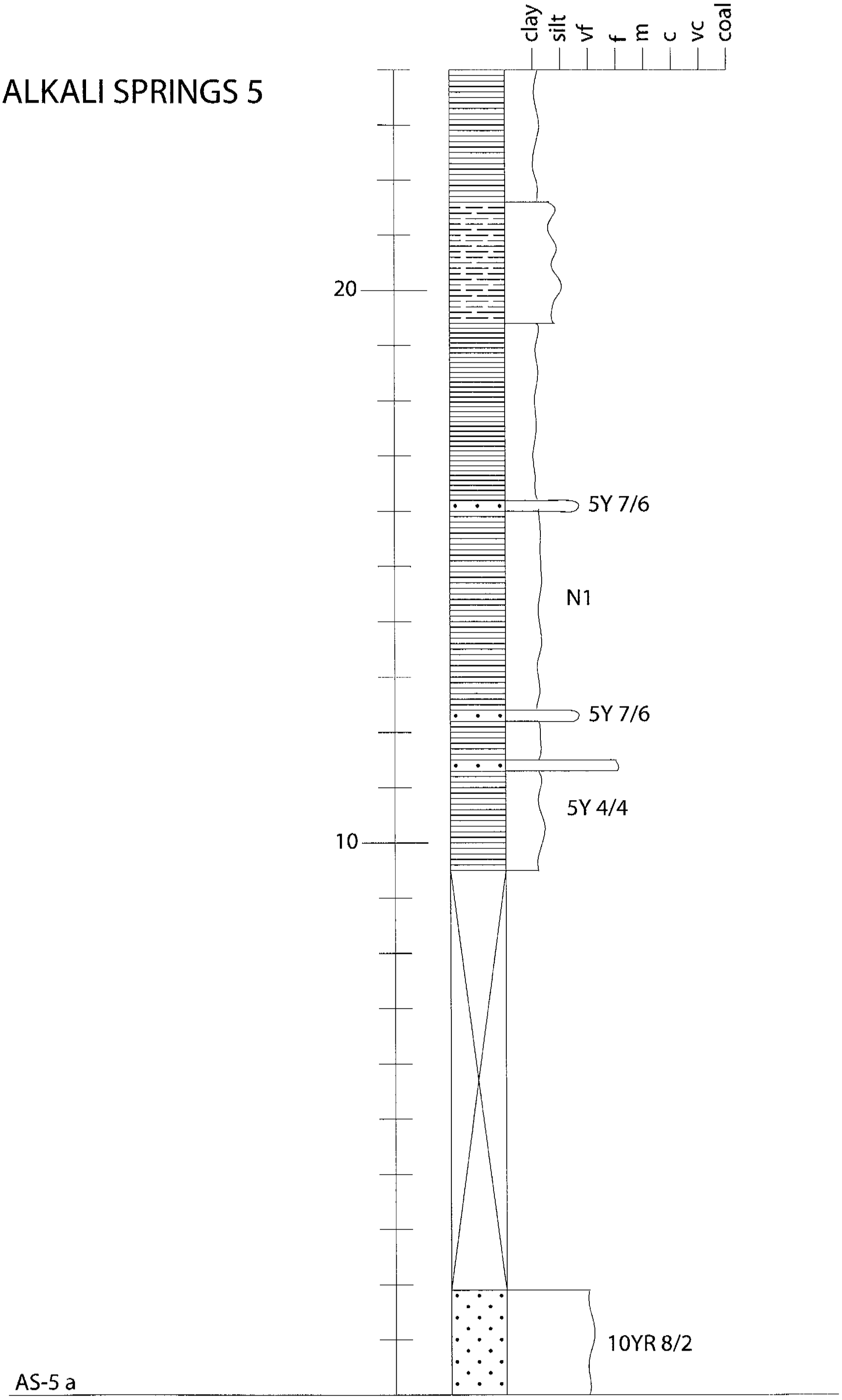
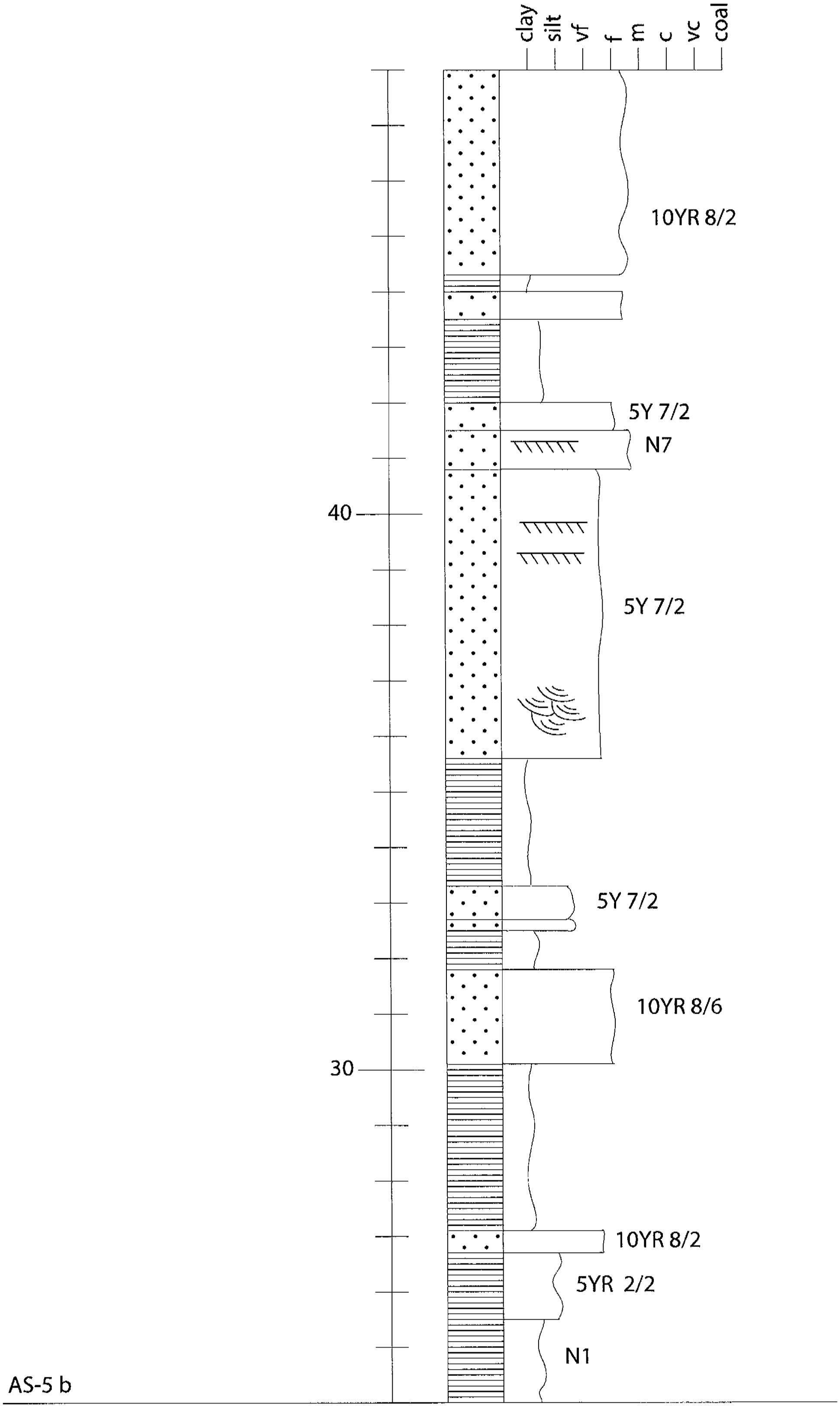
vf
f
m
c
vc
coal
AS4-16
160
10YR 8/2
150
AS4-15
AS-4 g

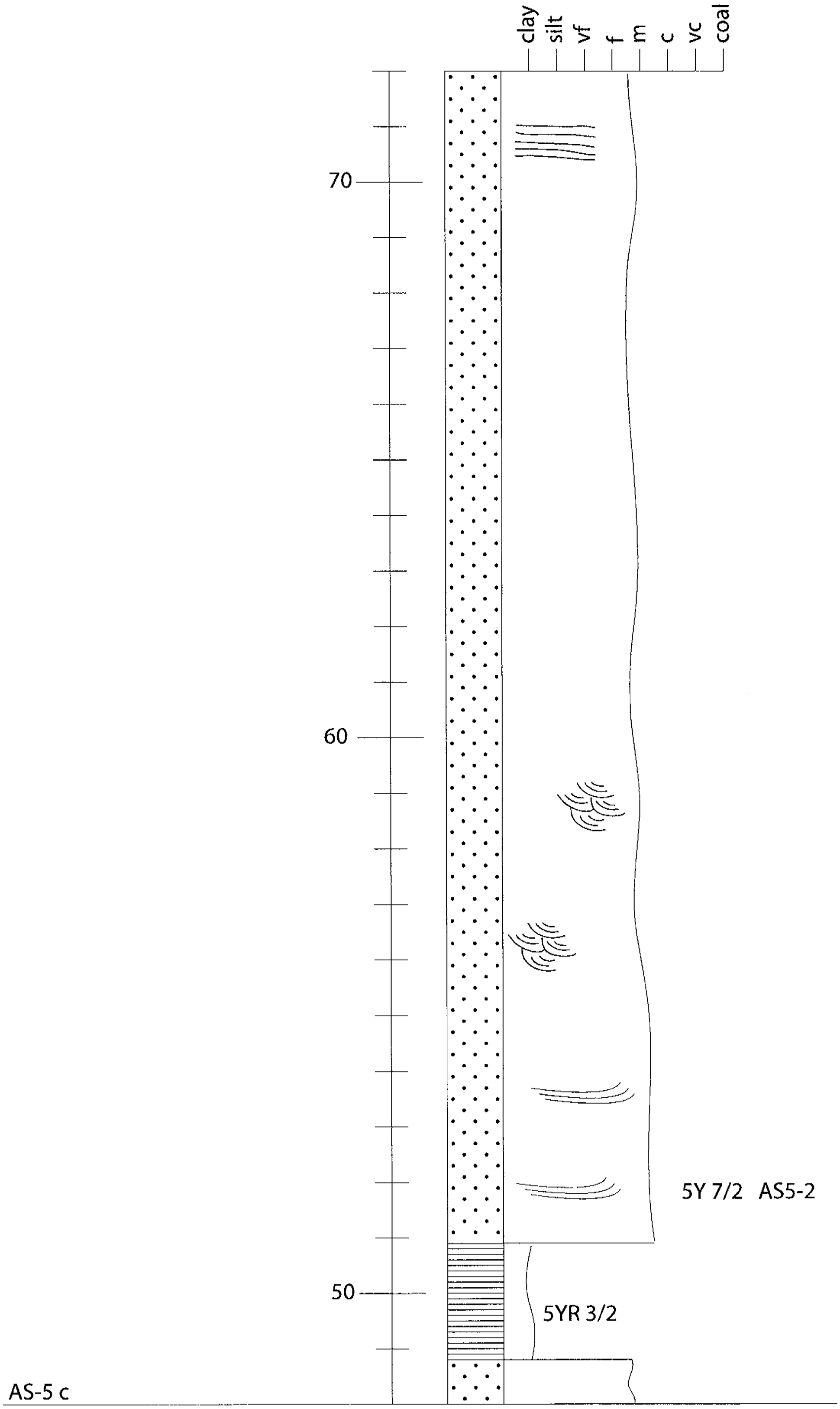

clay
silt
vf
f
m
c
vc
coal
AS4-18
190
180
AS4-17
TRANS LAG BED
Top of Menefee Formation
170
AS-4 h

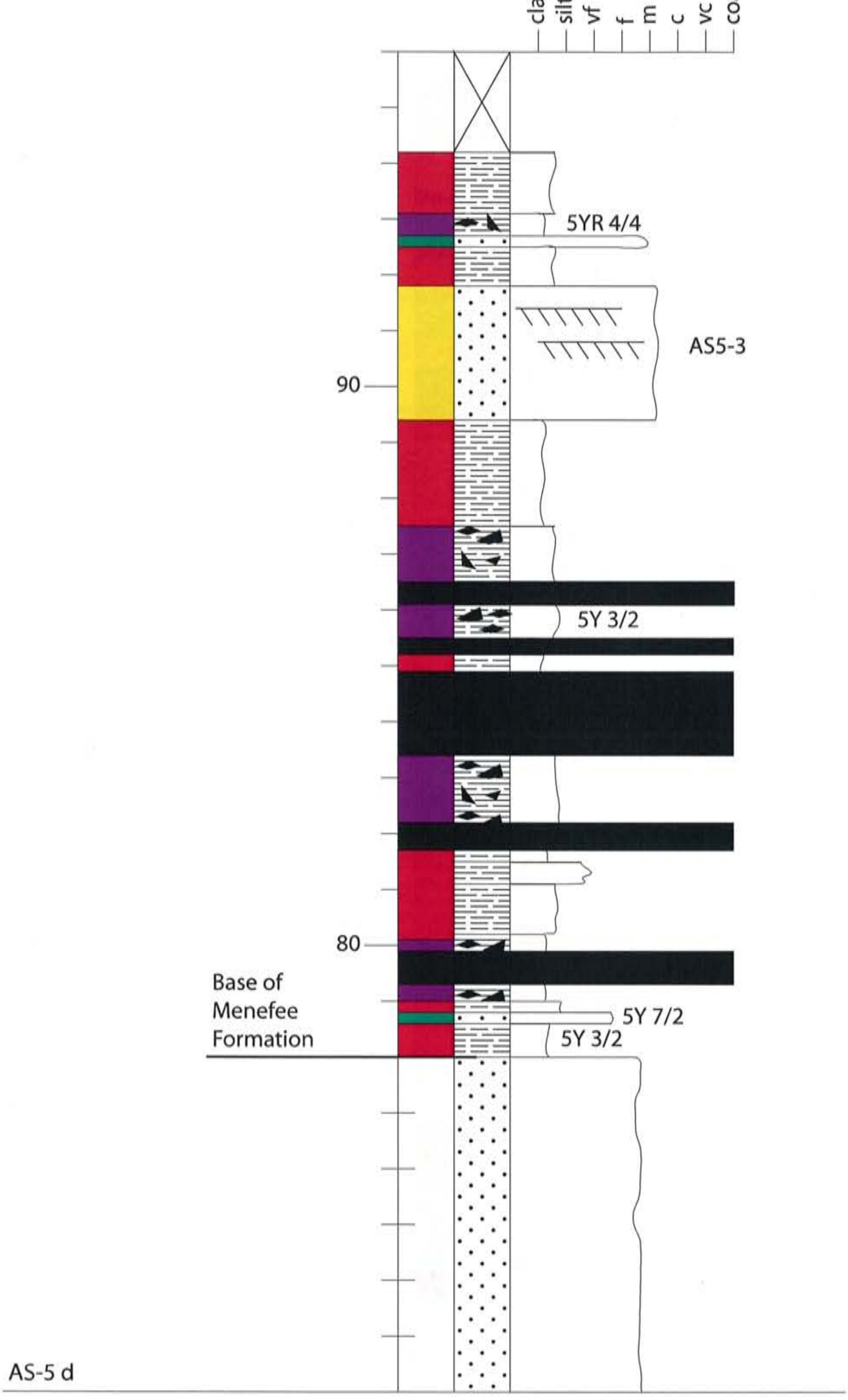

clay
silt
vf
f
m
c
vc
coal
210
200
AS-4 i

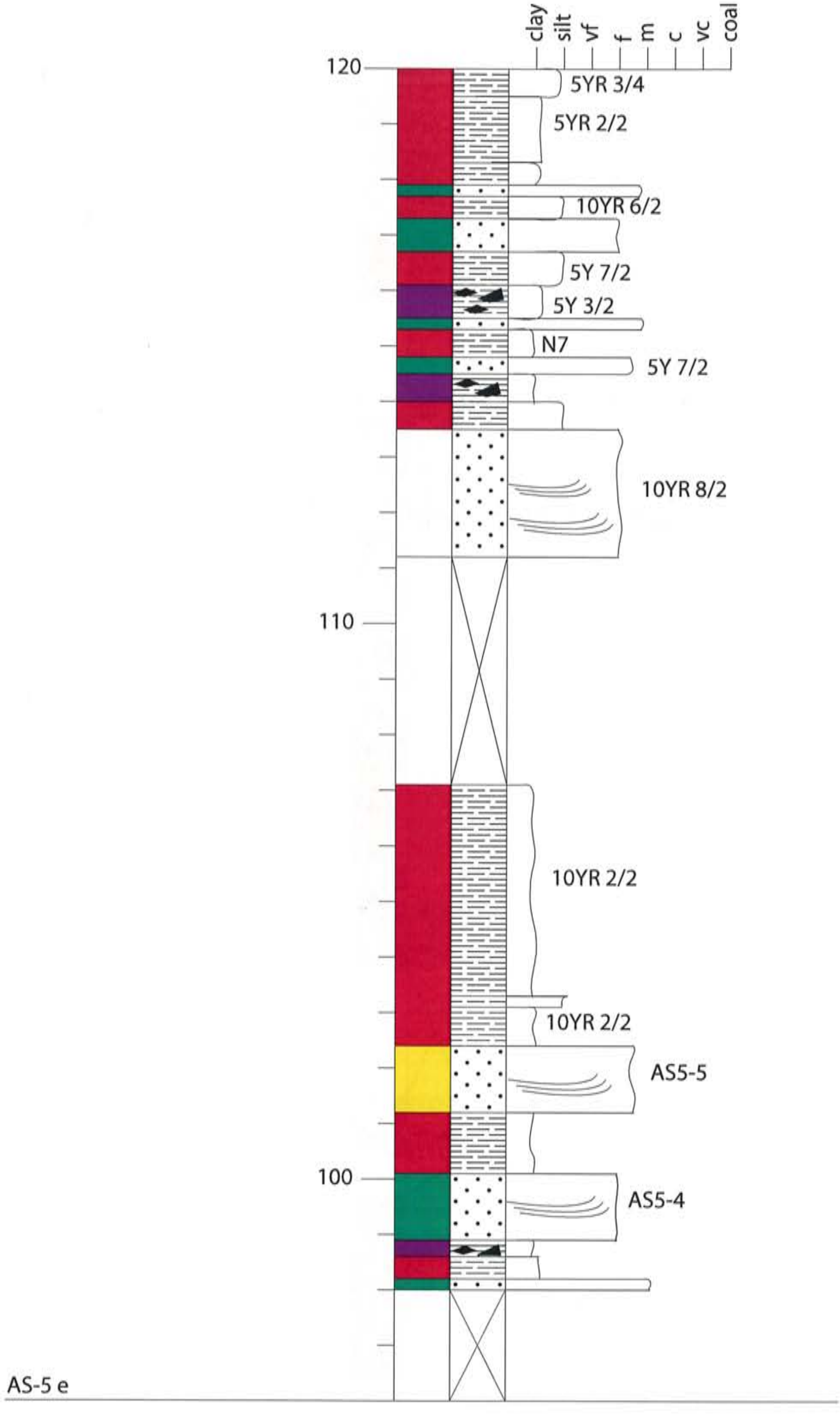
ALKALI SPRINGS 5




clay
silt
vf
f
m
c
vc
coal
10YR 8/2
5Y 7/2
N7
40
5Y 7/2
5Y 7/2
10YR 8/6
30
10YR 8/2
5YR 2/2
N1
AS-5 b


clay
silt
vf
f
m
c
vc
coal
70
60
50
5Y 7/2 AS5-2
5YR 3/2
AS-5 c


clay
silt
vf
f
m
c
vc
coal
5YR 4/4
AS5-3
90
5Y 3/2
80
Base of
Menefee
Formation
5Y 7/2
5Y 3/2
AS-5 d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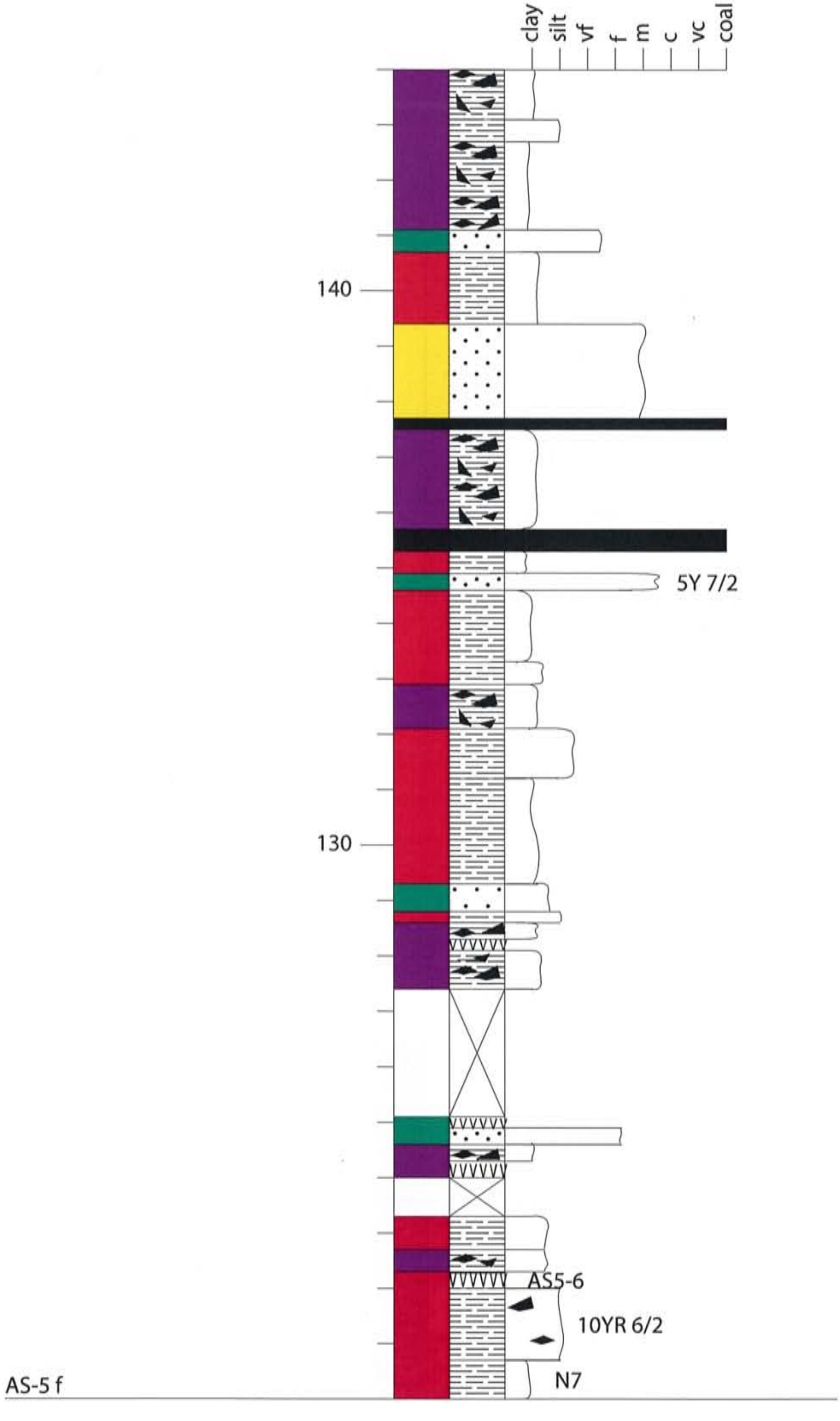
silt
vf
f
m
c
vc
coal
120
5YR 3/4
5YR 2/2
10YR 6/2
5Y 7/2
5Y 3/2
N7
5Y 7/2
10YR 8/2
110
10YR 2/2
10YR 2/2
AS5-5
100
AS5-4
AS-5 e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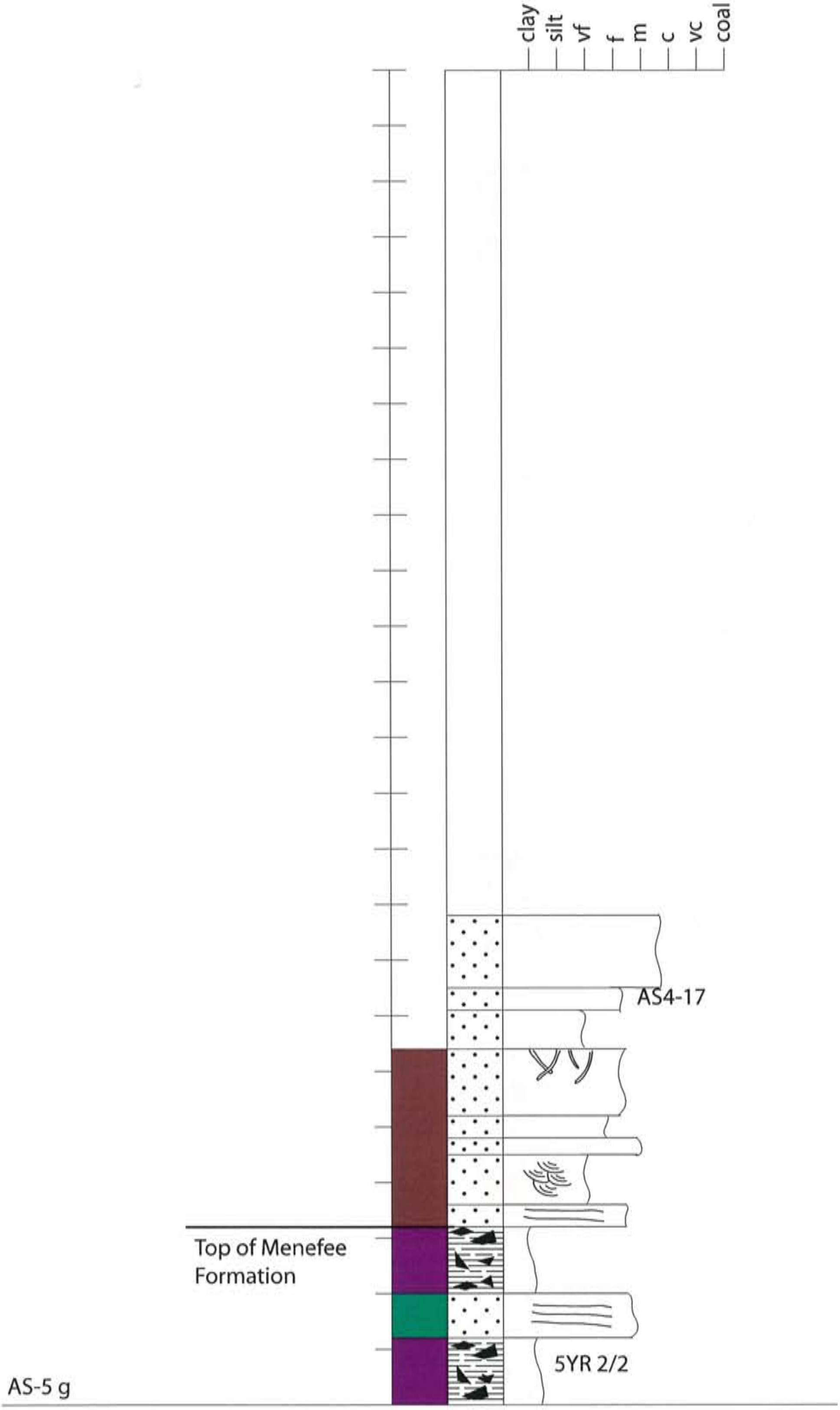
vf
f
m
c
vc
coal
140
5Y 7/2
130
AS5-6
10YR 6/2
N7
AS-5 f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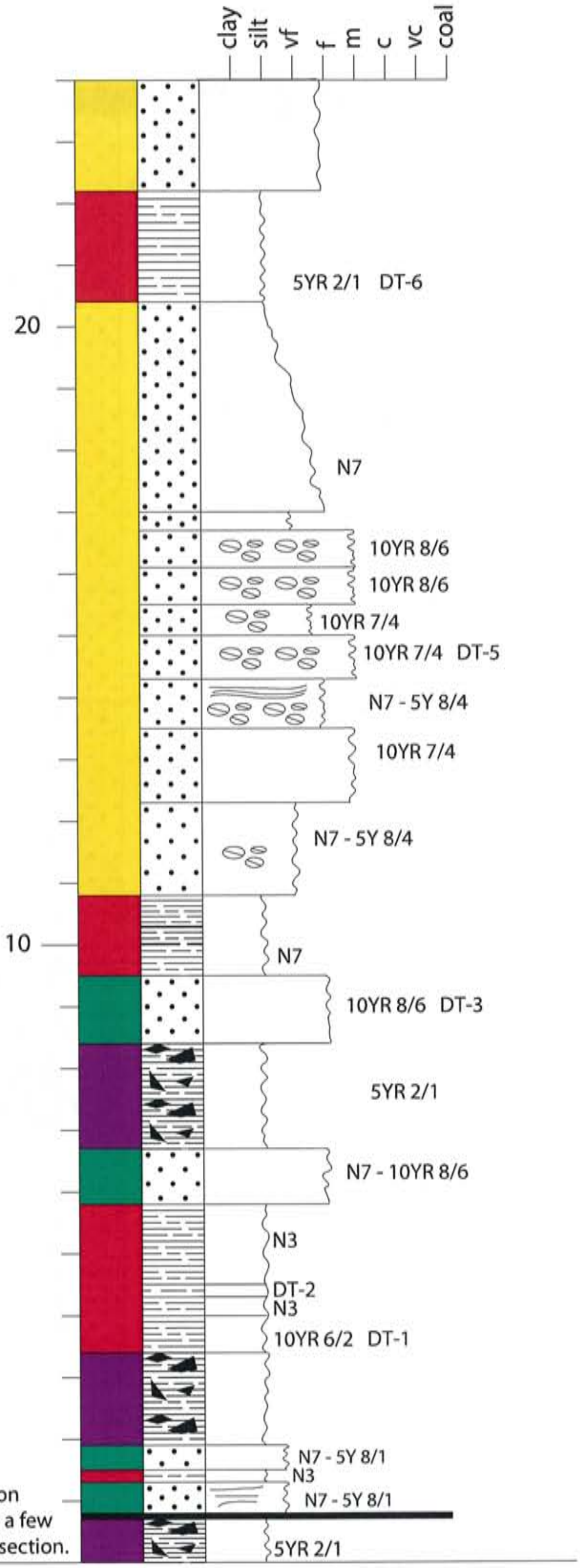
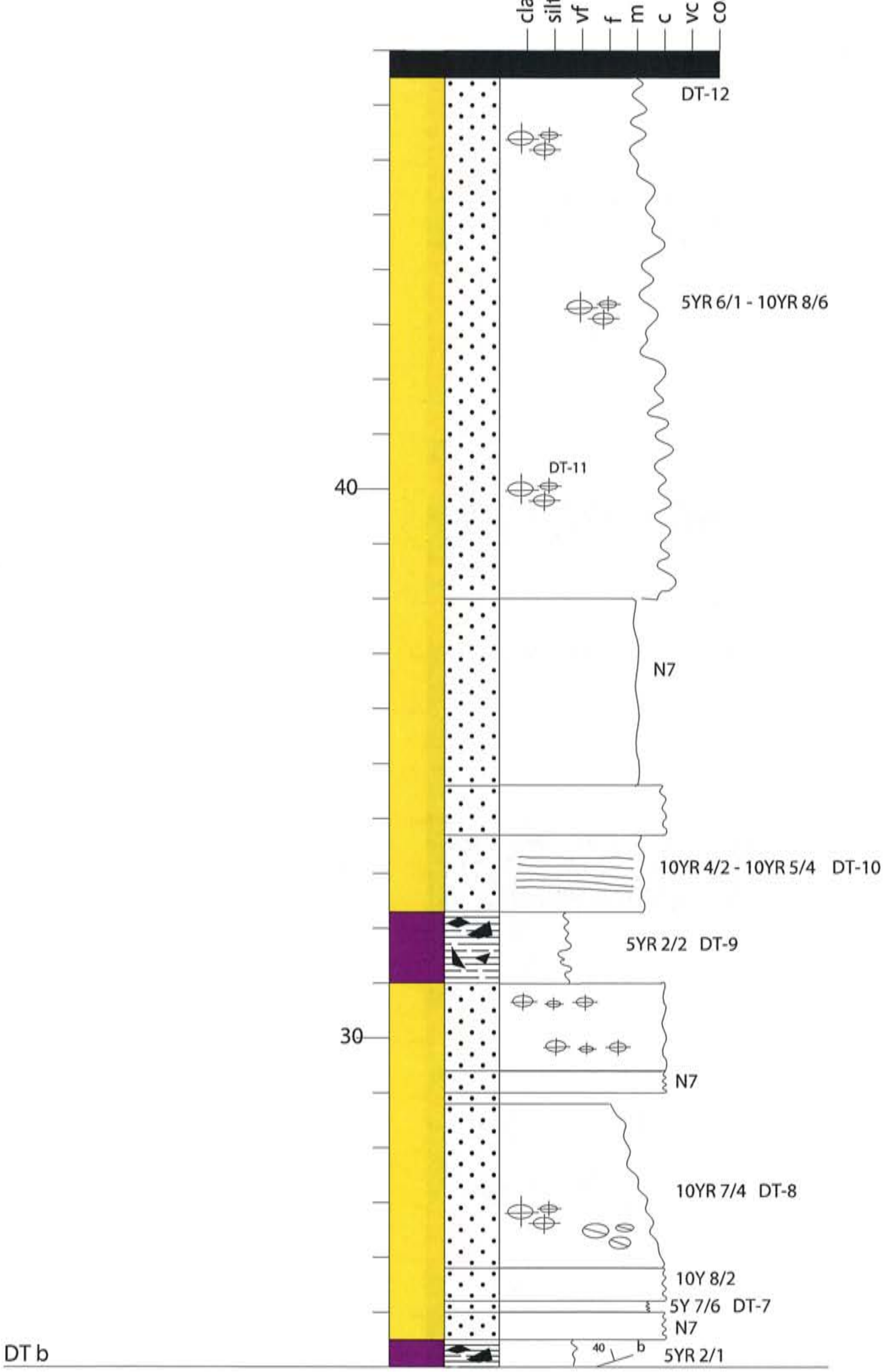
silt
vf
f
m
c
vc
coal
AS4-17
Top of Menefee Formation
5YR 2/2
AS-5 g

DEAD TREE



Base of Menefee Formation
covered; estimated to be a few
below base of measured section.

DT a


clay
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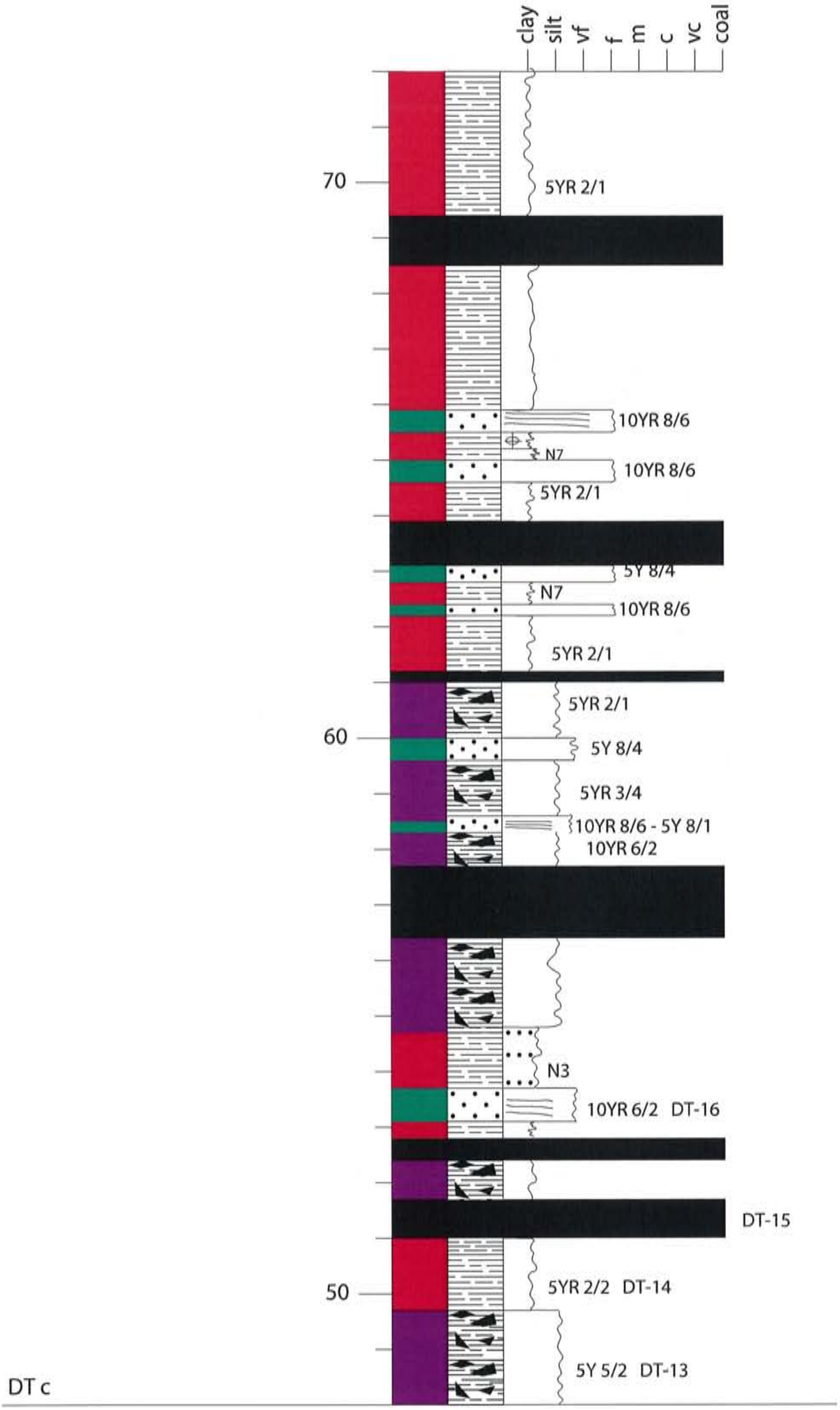
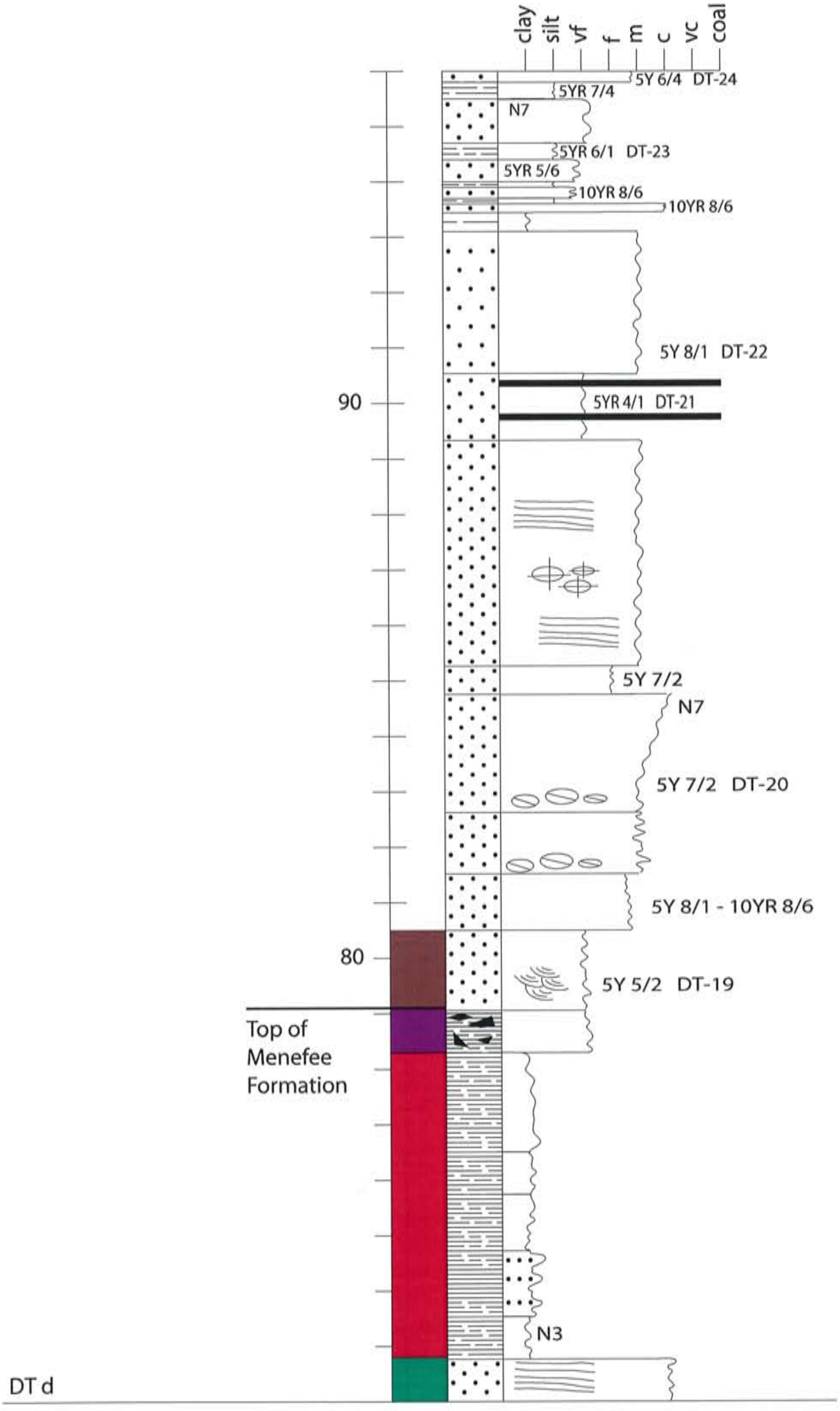
vf
f
m
c
vc
coal
DT-12
5YR 6/1 - 10YR 8/6
DT-11
40
N7
10YR 4/2 - 10YR 5/4 DT-10
5YR 2/2 DT-9
30
N7
10YR 7/4 DT-8
10Y 8/2
5Y 7/6 DT-7
N7
DT b
40
b
5YR 2/1


clay
silt
vf
f
m
c
vc
coal
70
5YR 2/1
10YR 8/6
N7
10YR 8/6
5YR 2/1
5Y 8/4
N7
10YR 8/6
5YR 2/1
5YR 2/1
60
5Y 8/4
5YR 3/4
10YR 8/6 - 5Y 8/1
10YR 6/2
N3
10YR 6/2 DT-16
DT-15
50
5YR 2/2 DT-14
5Y 5/2 DT-13
DT c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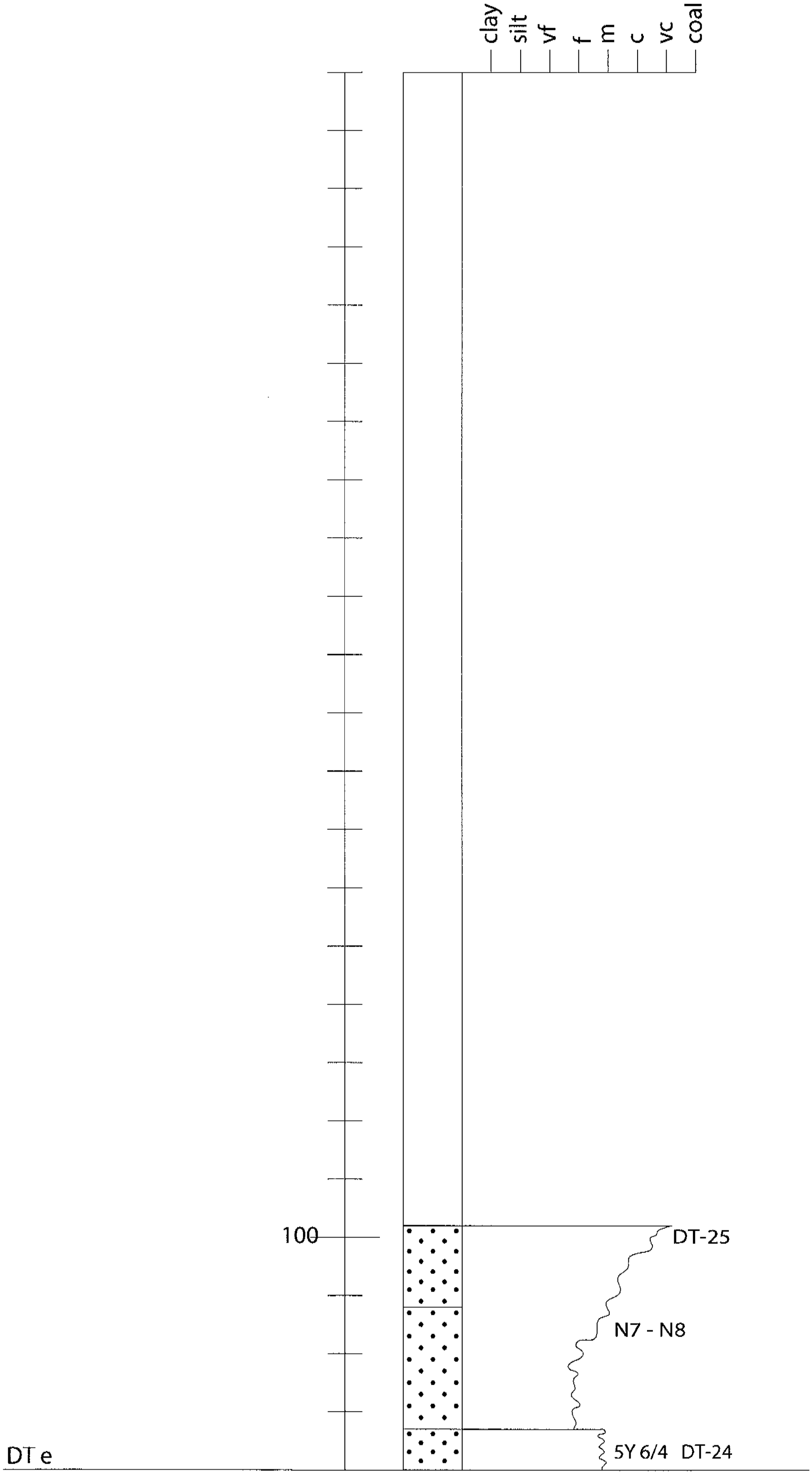
silt
vf
f
m
c
vc
coal
5Y 6/4 DT-24
5YR 7/4
N7
5YR 6/1 DT-23
5YR 5/6
10YR 8/6
10YR 8/6
5Y 8/1 DT-22
90
5YR 4/1 DT-21
5Y 7/2
N7
5Y 7/2 DT-20
5Y 8/1 - 10YR 8/6
80
5Y 5/2 DT-19
Top of Menefee Formation
N3
DT d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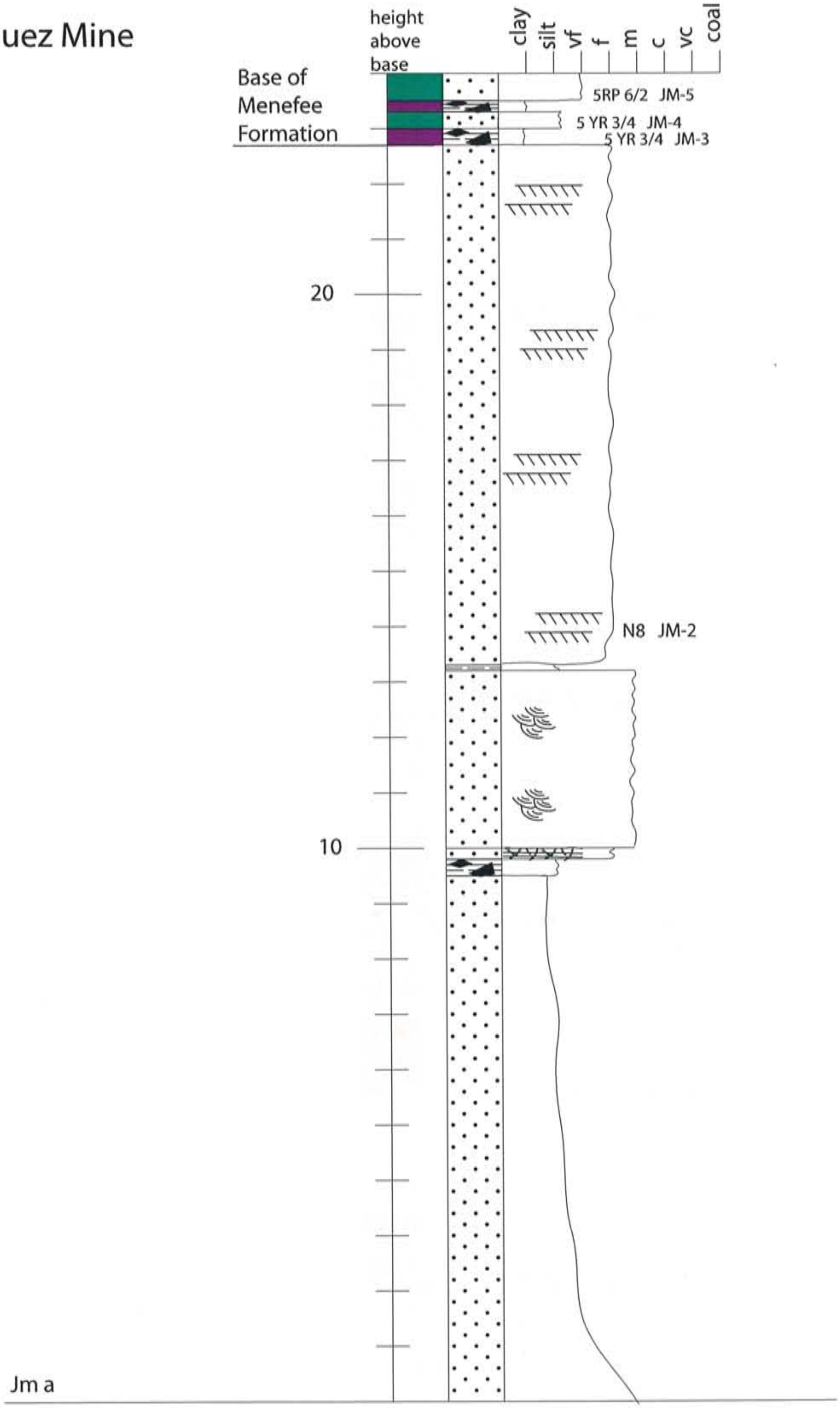
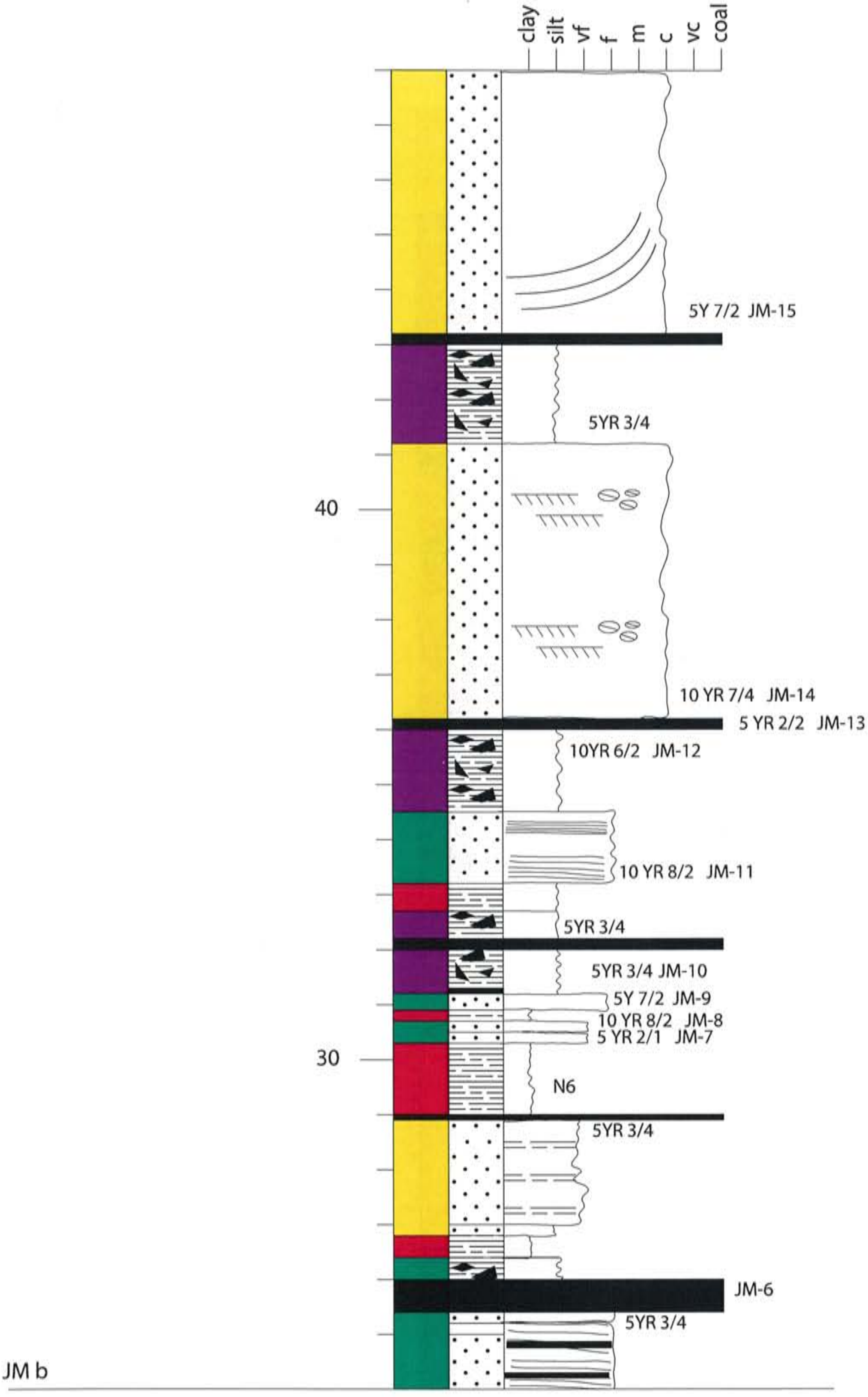
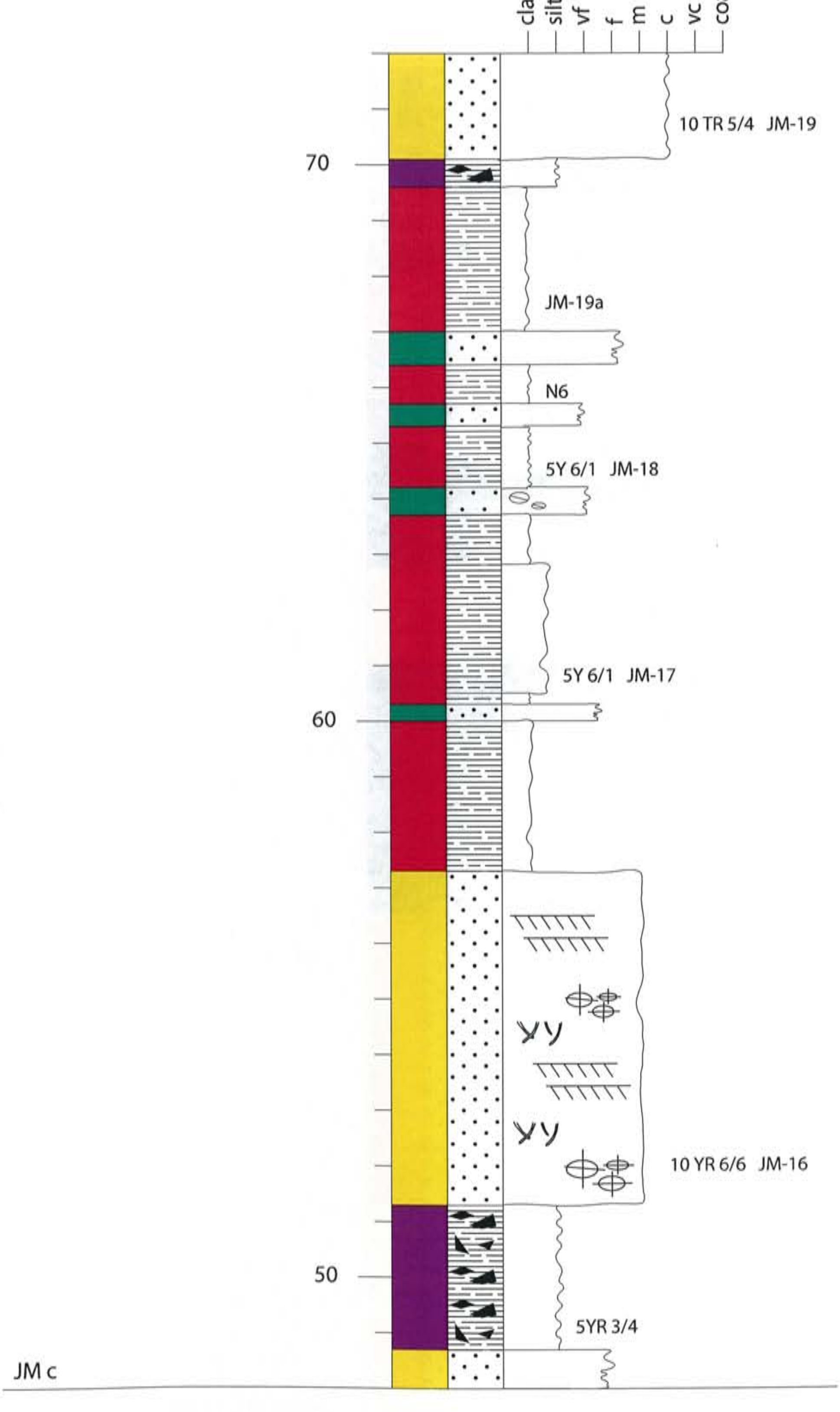
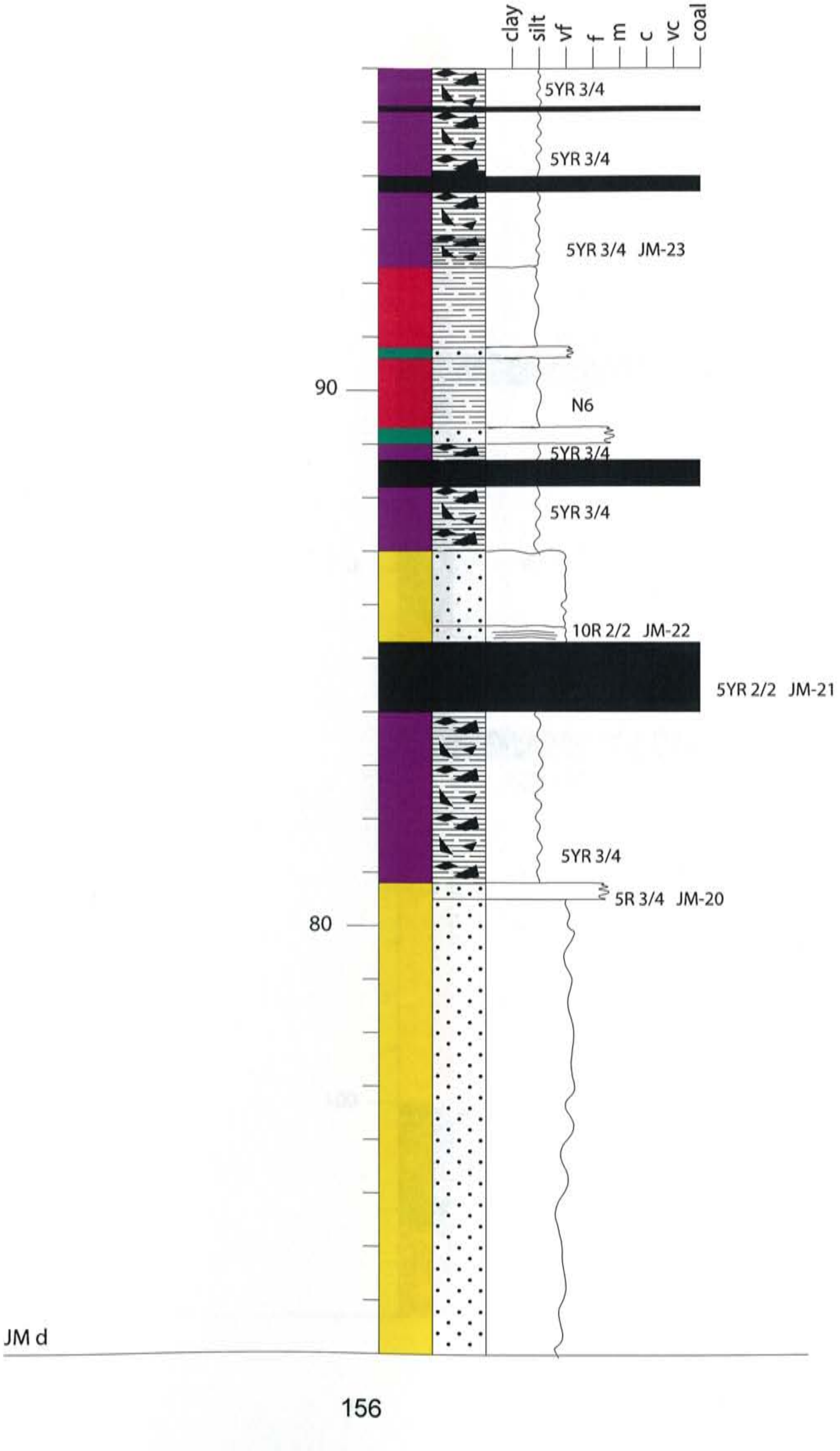
silt
vf
f
m
c
vc
coal
100
DT-25
N7 - N8
5Y 6/4 DT-24
DT e

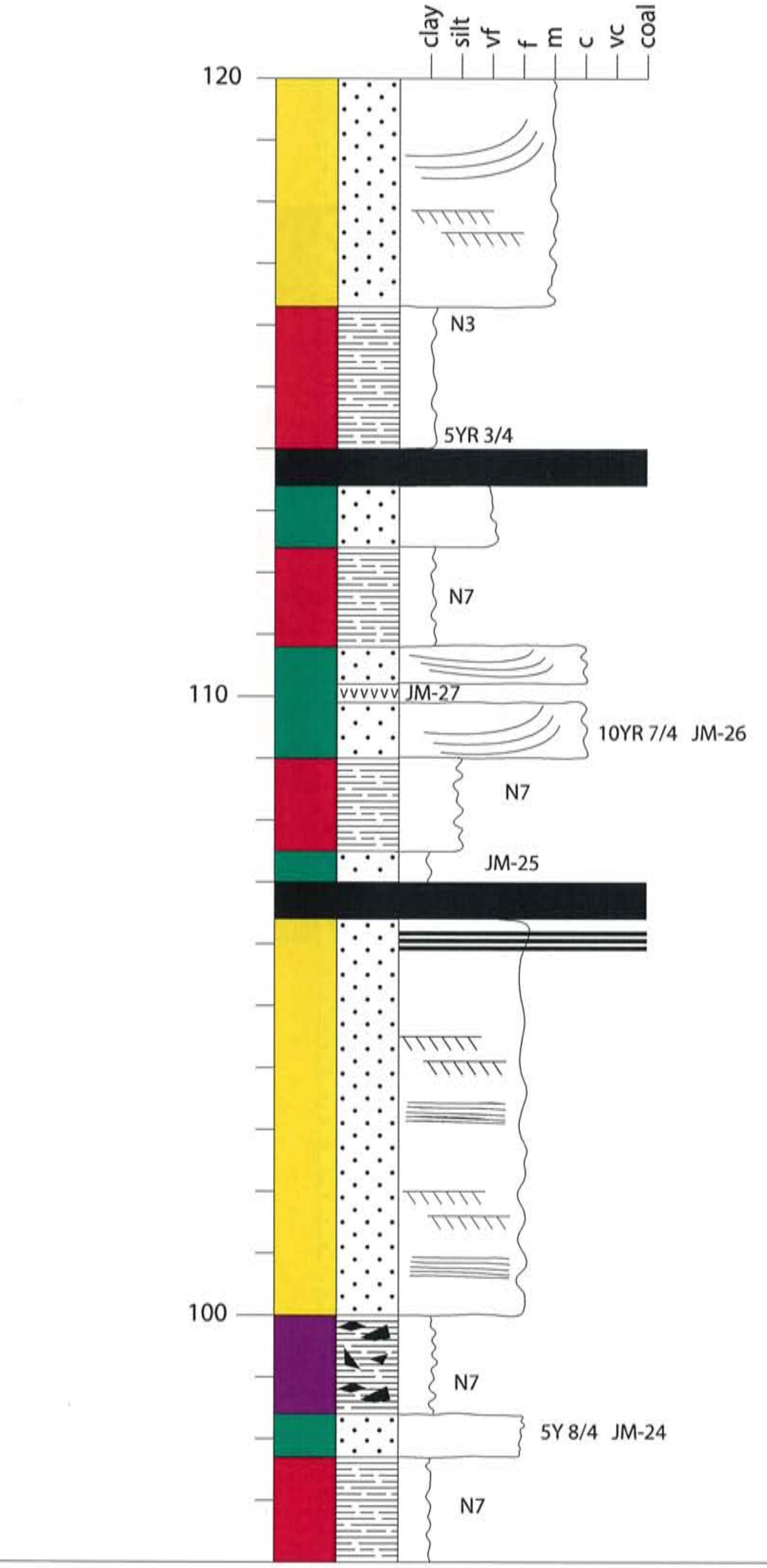
Juaquez Mine

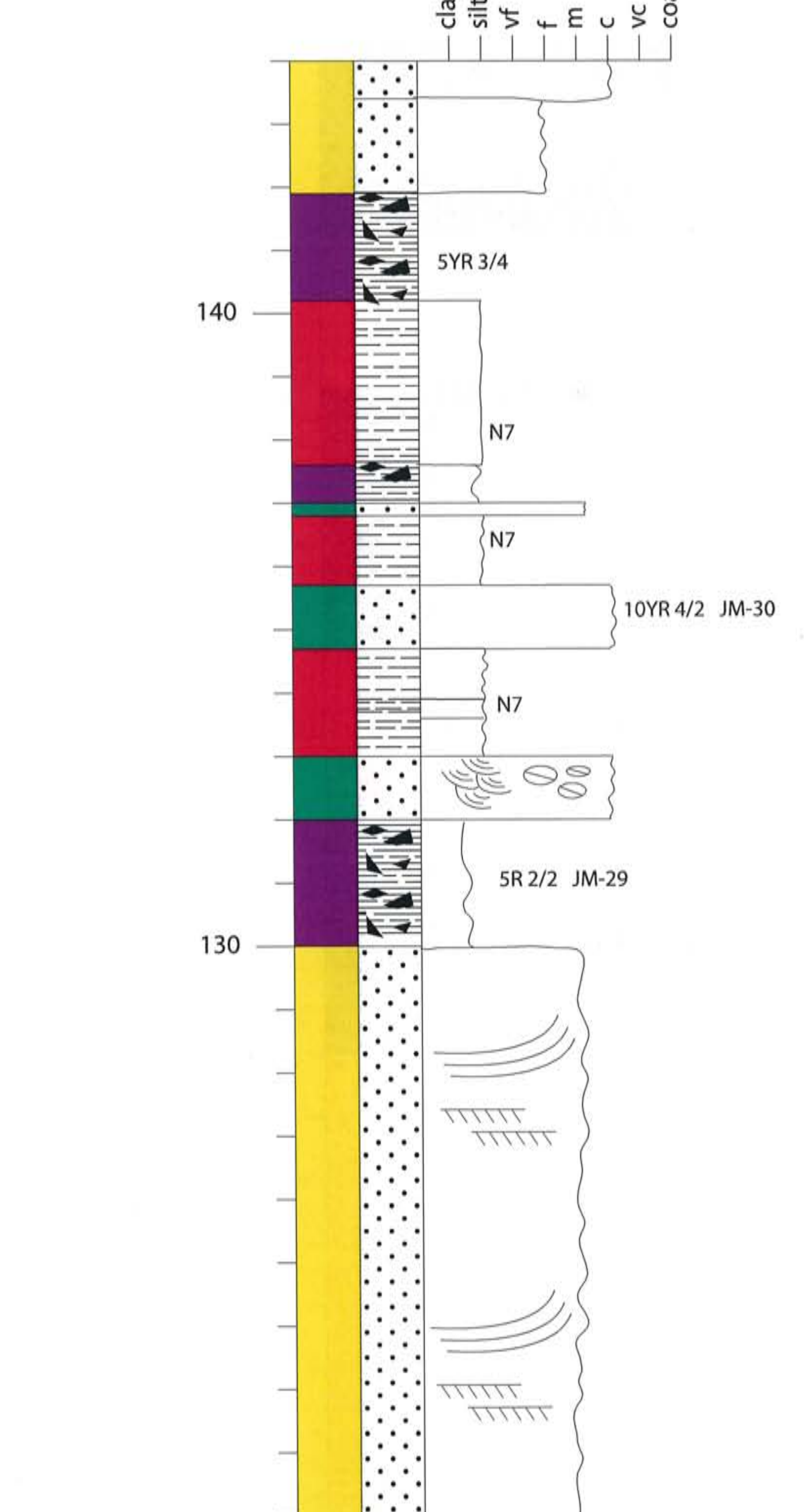


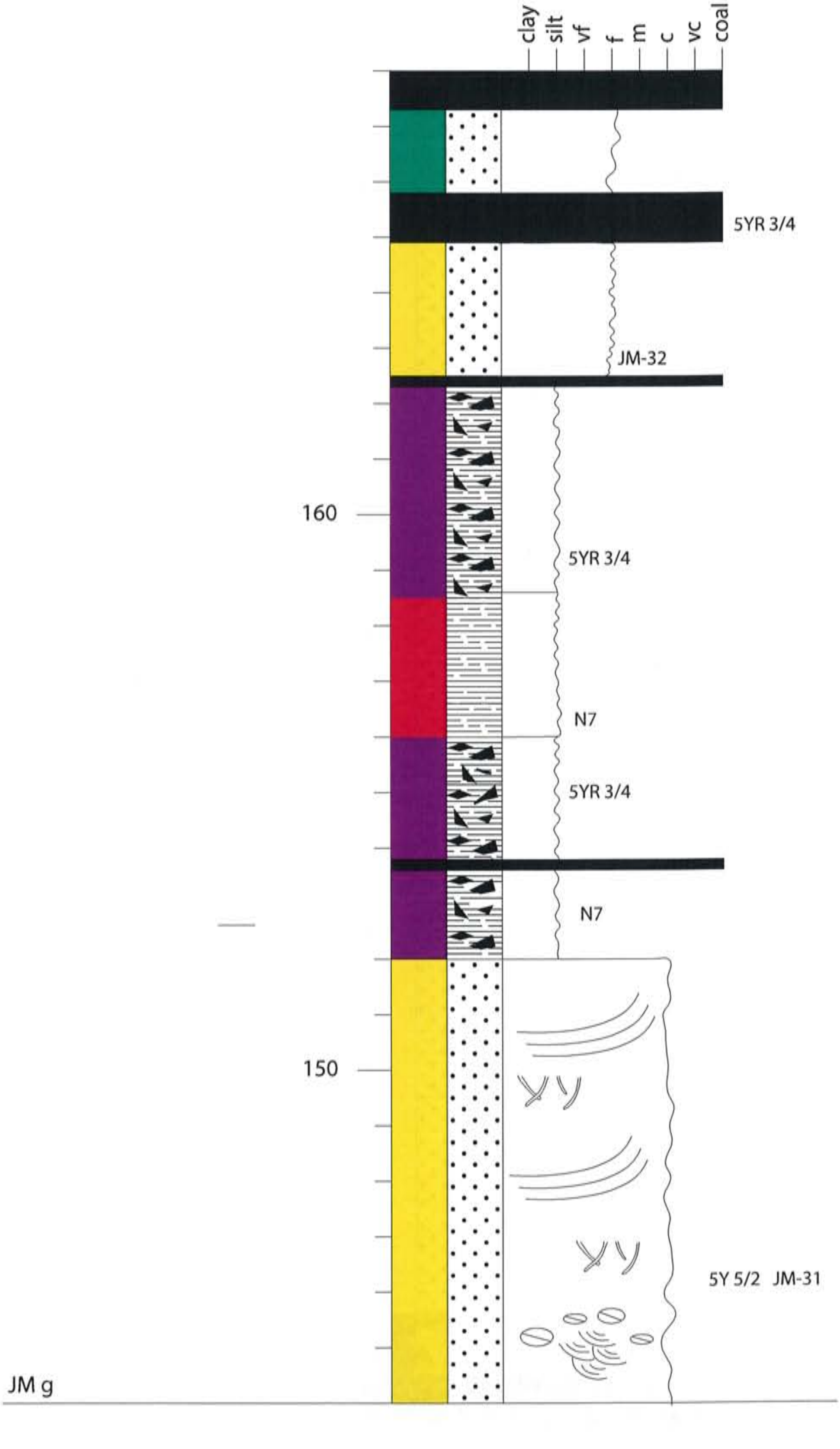

clay
silt
vf
f
m
c
vc
coal
5Y 7/2 JM-15
5YR 3/4
40
10 YR 7/4 JM-14
5 YR 2/2 JM-13
10YR 6/2 JM-12
10 YR 8/2 JM-11
5YR 3/4
5YR 3/4 JM-10
5Y 7/2 JM-9
10 YR 8/2 JM-8
5 YR 2/1 JM-7
30
N6
5YR 3/4
JM-6
5YR 3/4
JM b

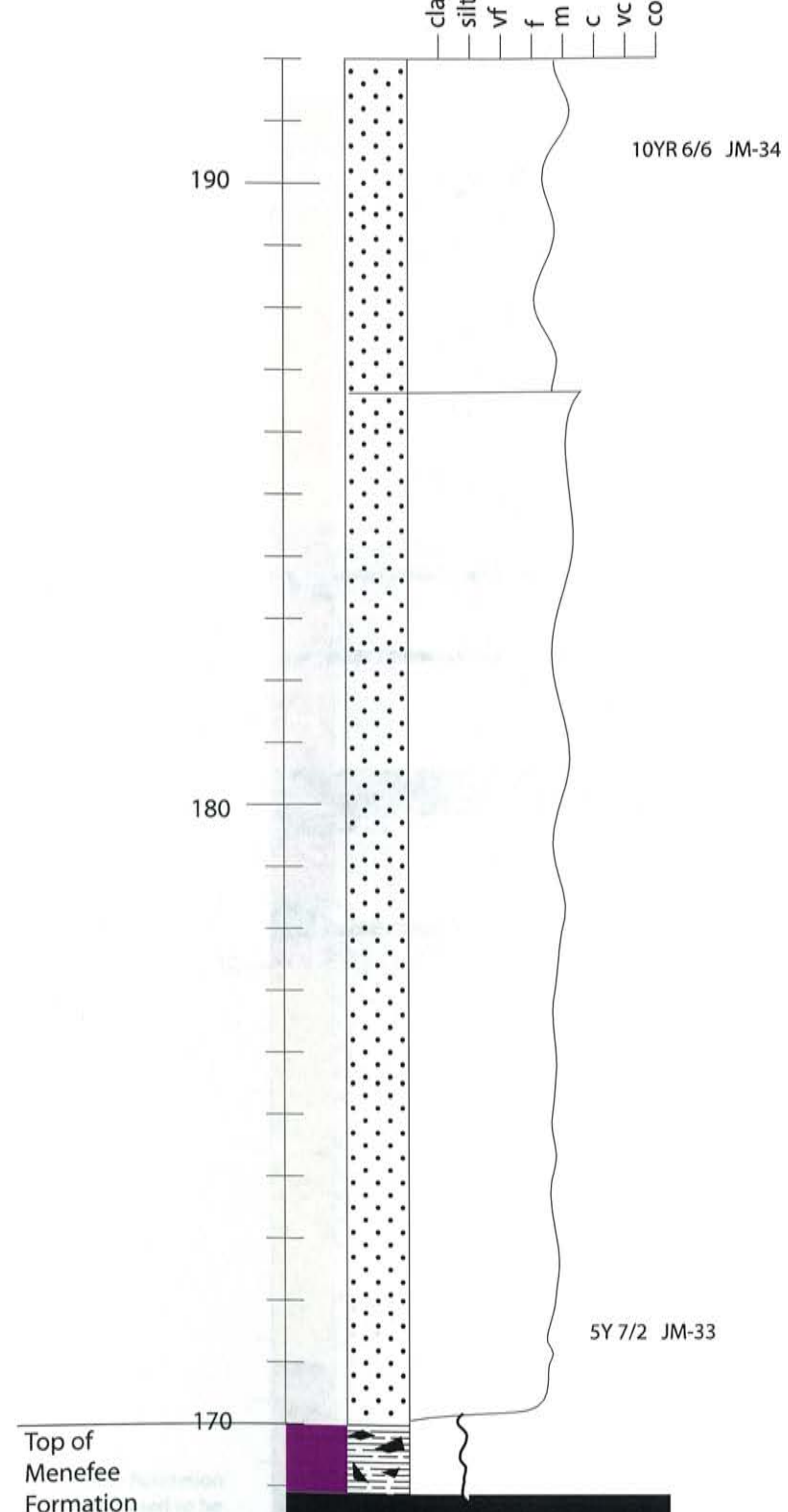

clay
silt
vf
f
m
c
vc
coal
10 TR 5/4 JM-19
70
JM-19a
N6
5Y 6/1 JM-18
5Y 6/1 JM-17
60
10 YR 6/6 JM-16
50
5YR 3/4
JM c


clay
silt
vf
f
m
c
vc
coal
5YR 3/4
5YR 3/4
5YR 3/4 JM-23
90
N6
5YR 3/4
5YR 3/4
10R 2/2 JM-22
5YR 2/2 JM-21
5YR 3/4
5R 3/4 JM-20
80
JM d

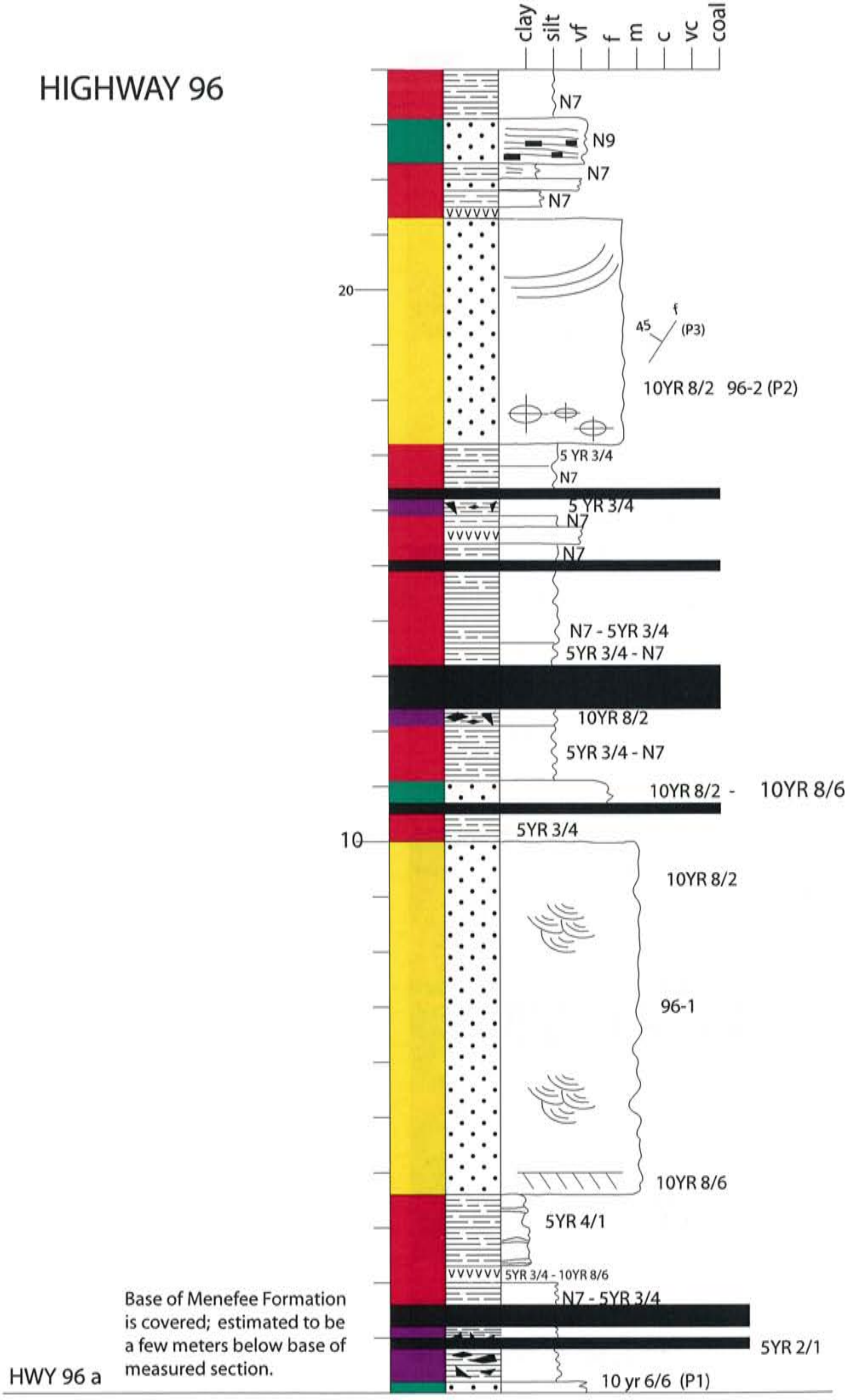

clay
silt
vf
f
m
c
vc
coal
120
N3
5YR 3/4
N7
110
JM-27
10YR 7/4 JM-26
N7
JM-25
100
N7
5Y 8/4 JM-24
N7
JM e


clay
silt
vf
f
m
c
vc
coal
5YR 3/4
140
N7
N7
10YR 4/2 JM-30
N7
5R 2/2 JM-29
130
JM f

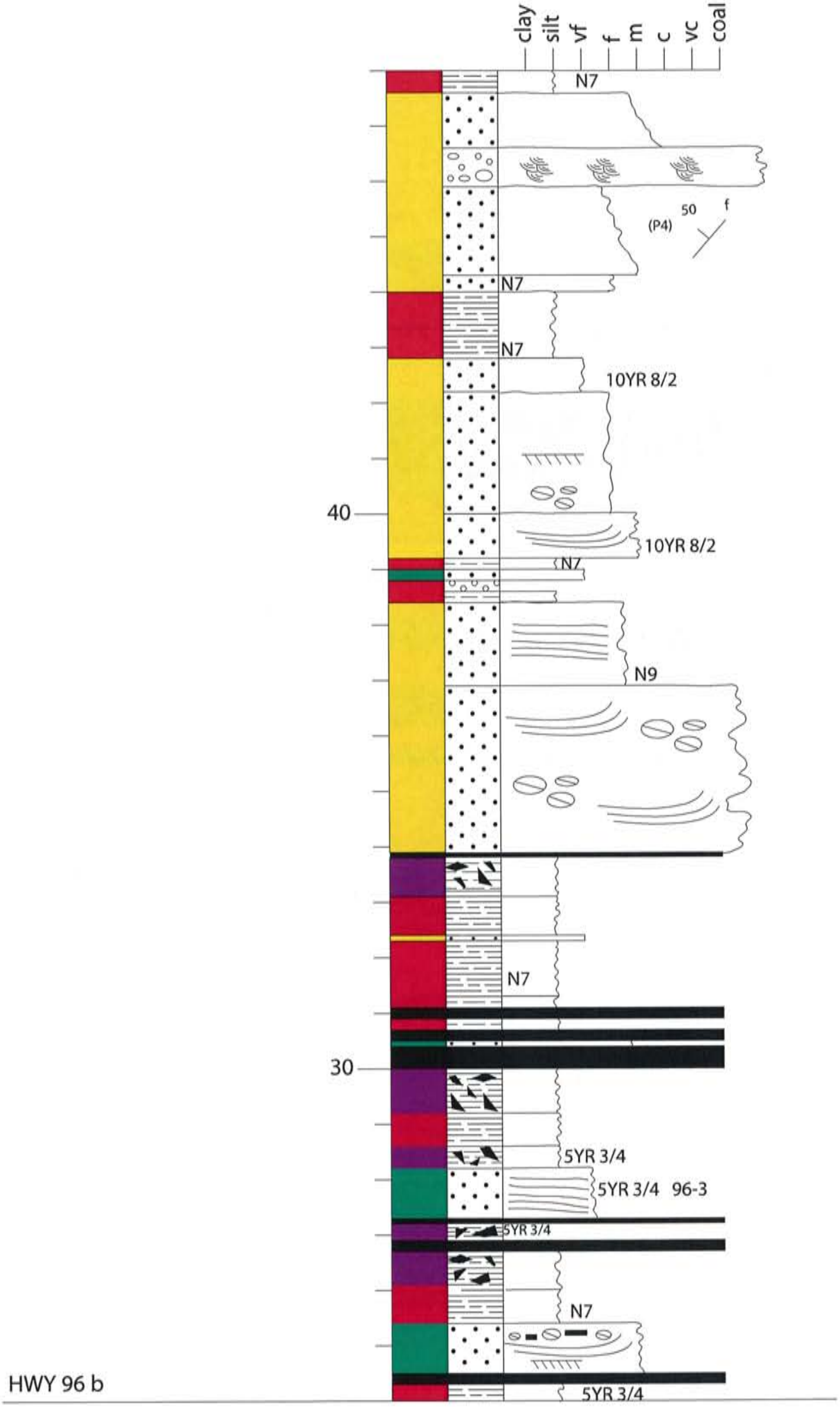

clay
silt
vf
f
m
c
vc
coal
5YR 3/4
JM-32
160
5YR 3/4
N7
5YR 3/4
N7
150
5Y 5/2 JM-31
JM g

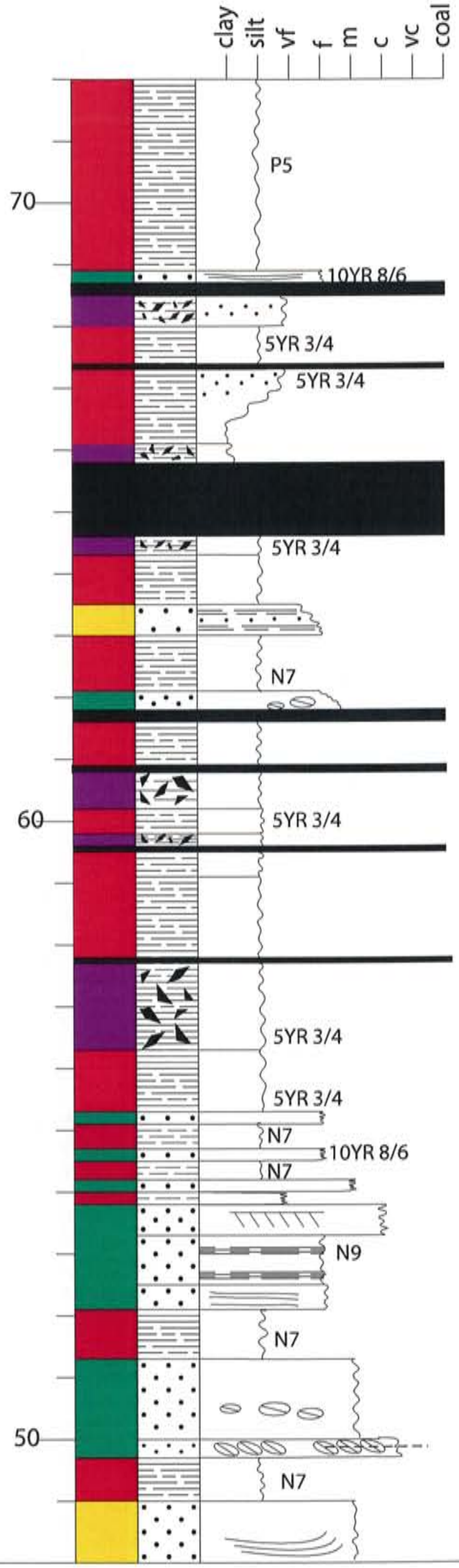

clay
silt
vf
f
m
c
vc
coal
190
10YR 6/6 JM-34
180
5Y 7/2 JM-33
170
Top of
Menefee
Formation
JM h

HIGHWAY 96

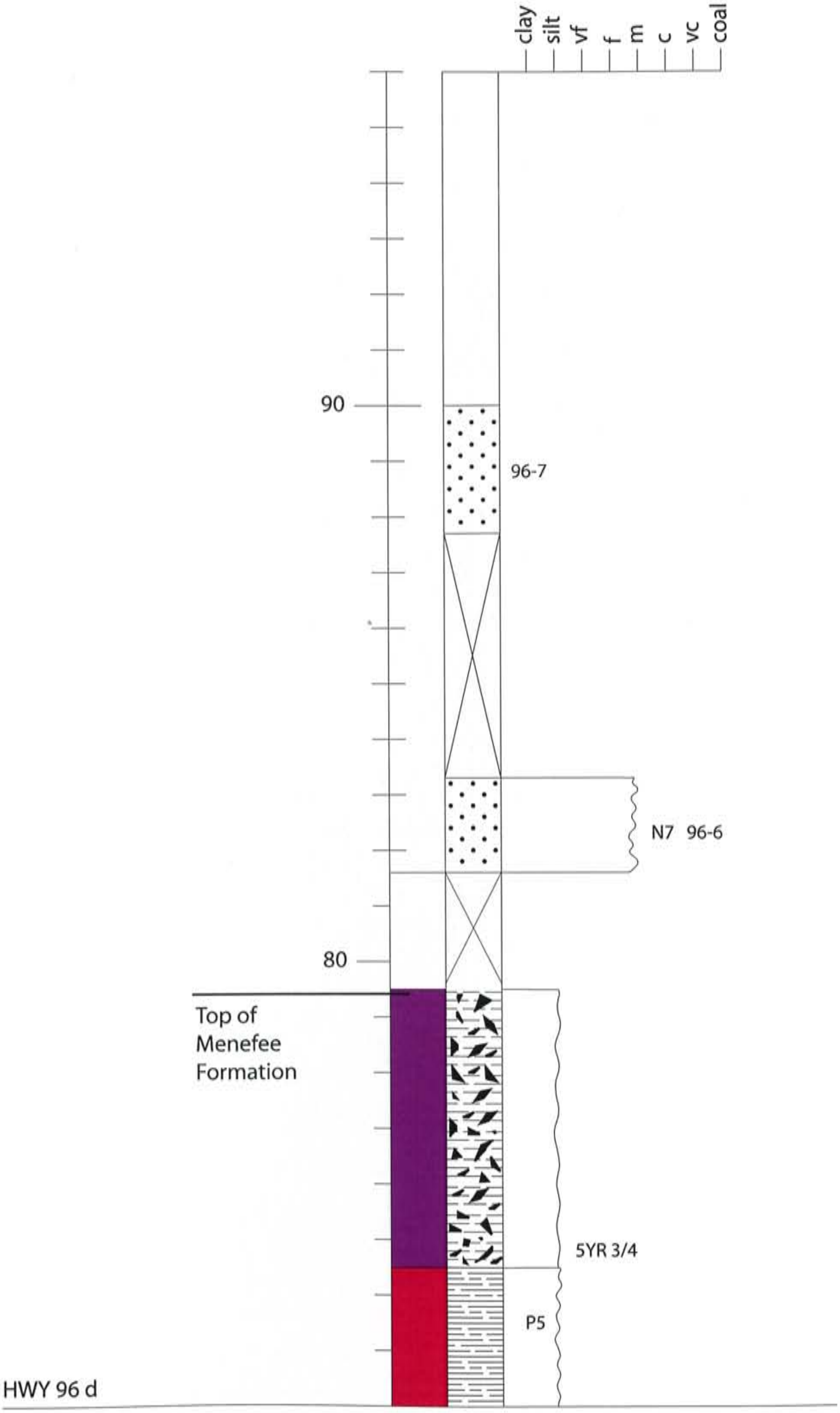


Base of Menefee Formation is covered; estimated to be a few meters below base of measured section.

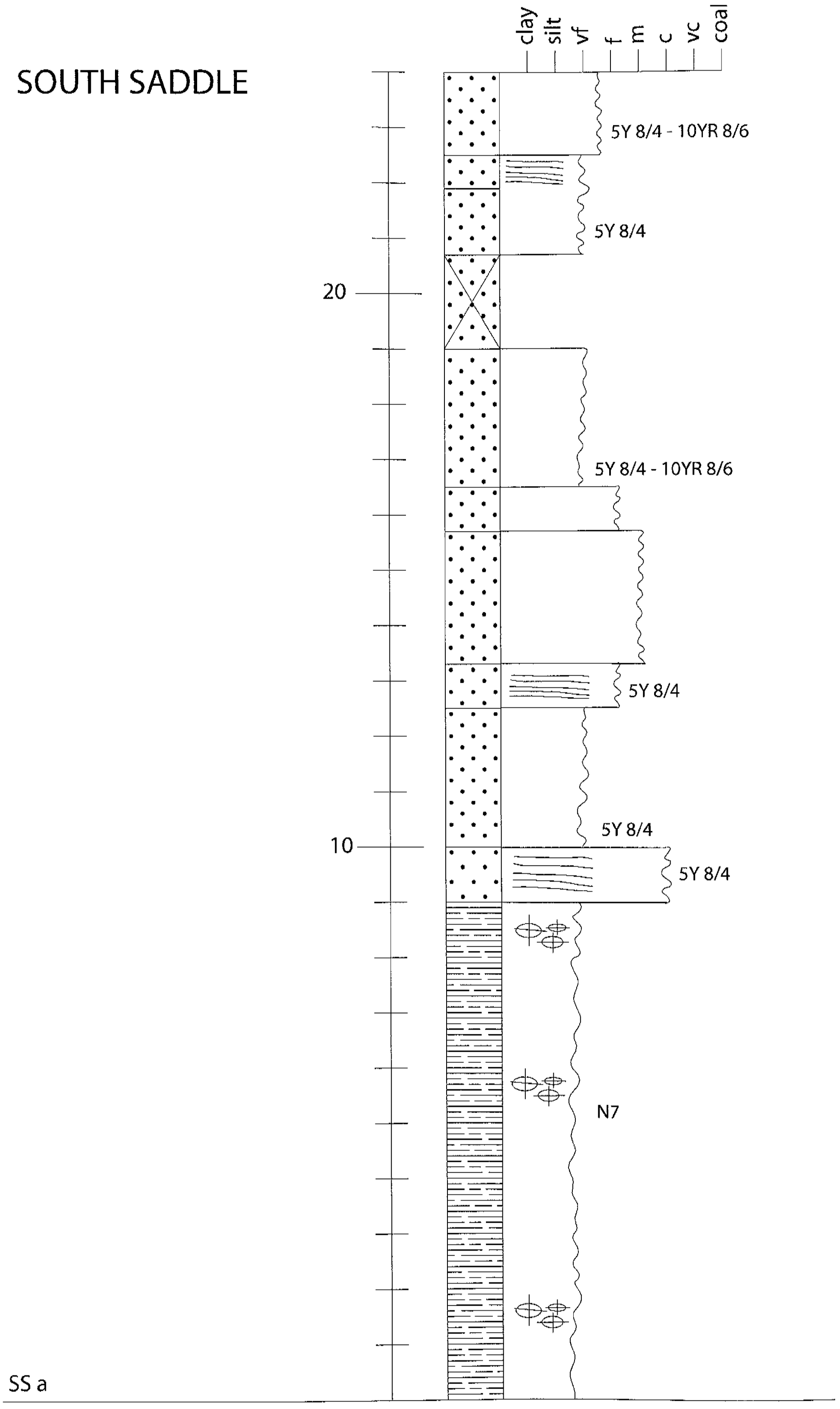

clay
silt
vf
f
m
c
vc
coal
N7
50
f
(P4)
N7
N7
10YR 8/2
40
10YR 8/2
N7
N9
N7
30
5YR 3/4
5YR 3/4 96-3
5YR 3/4
N7
5YR 3/4
HWY 96 b

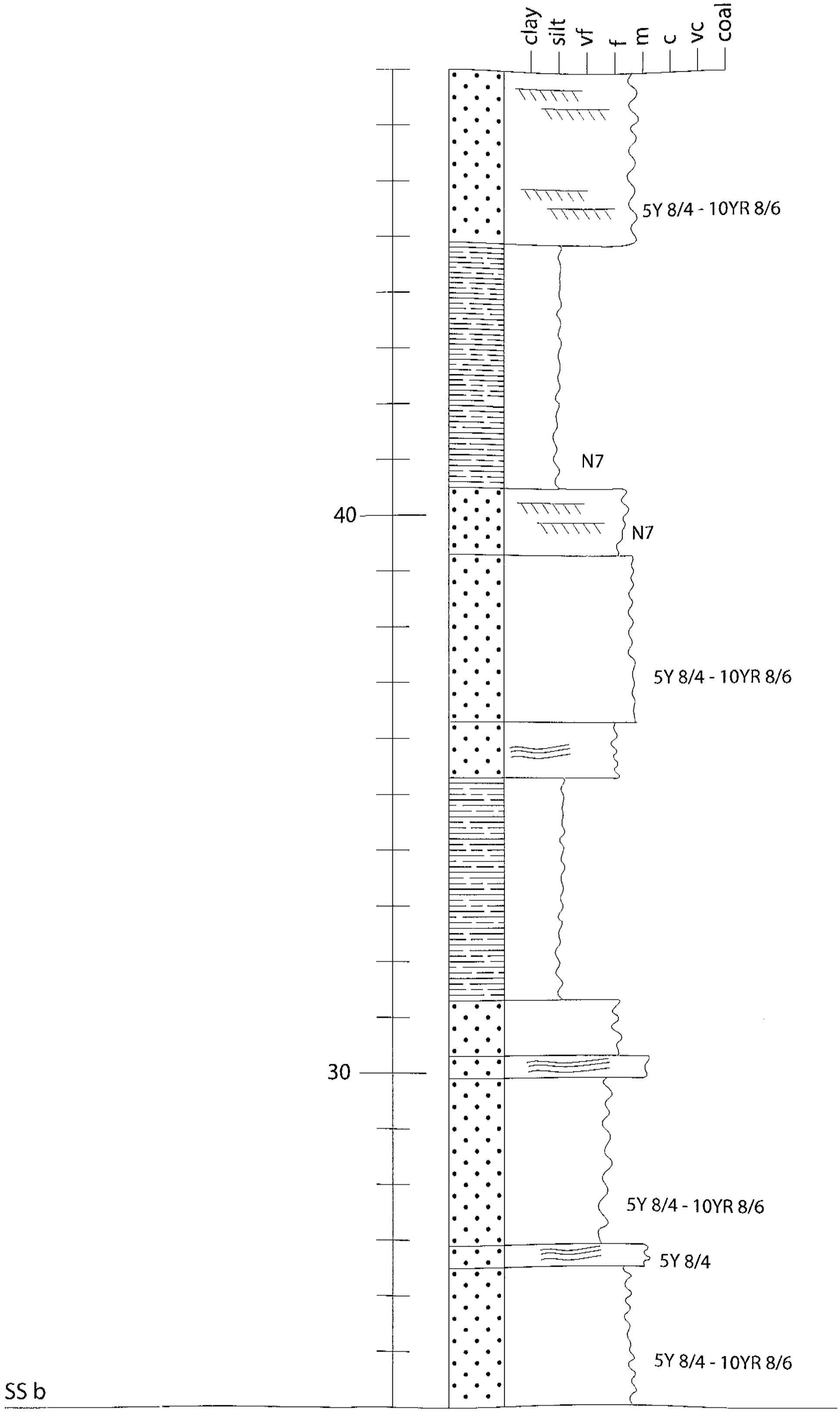

clay
silt
vf
f
m
c
vc
coal
70
P5
10YR 8/6
5YR 3/4
5YR 3/4
5YR 3/4
N7
60
5YR 3/4
5YR 3/4
5YR 3/4
N7
10YR 8/6
N7
N9
N7
50
N7

HWY 96 c


clay
silt
vf
f
m
c
vc
coal
90
96-7
N7 96-6
80
Top of
Menefee
Formation
5YR 3/4
P5
HWY 96 d

SOUTH SADDLE

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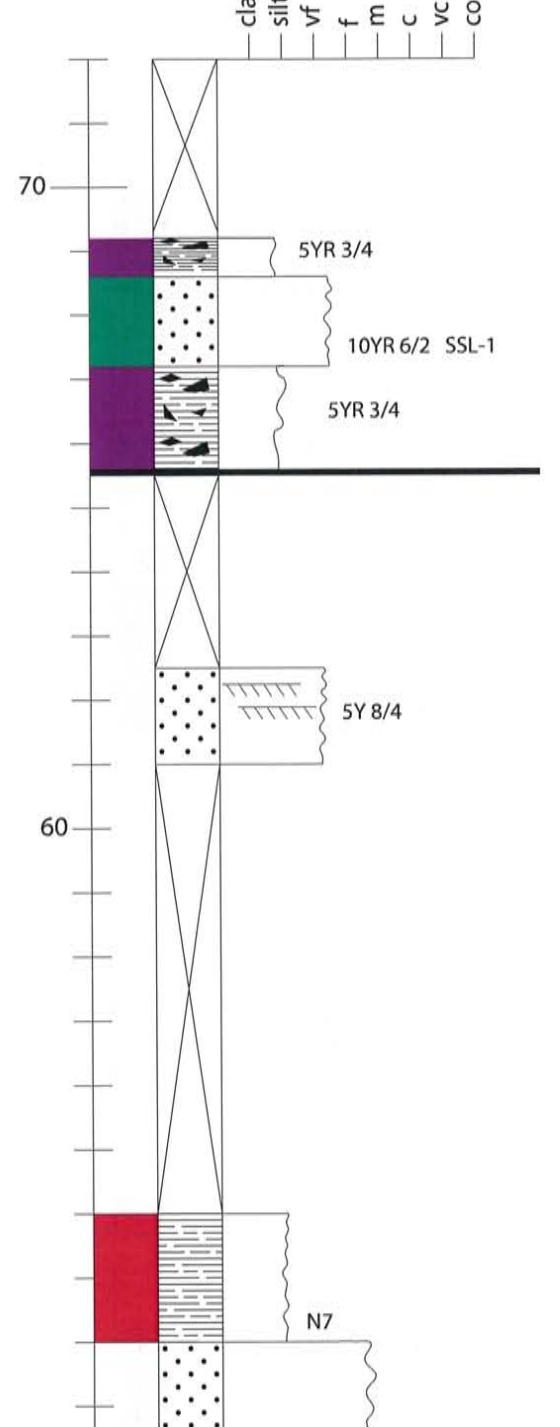
vf
f
m
c
vc
coal
5Y 8/4 - 10YR 8/6
N7
40
N7
5Y 8/4 - 10YR 8/6
30
5Y 8/4 - 10YR 8/6
5Y 8/4
5Y 8/4 - 10YR 8/6
SS b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silt
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m
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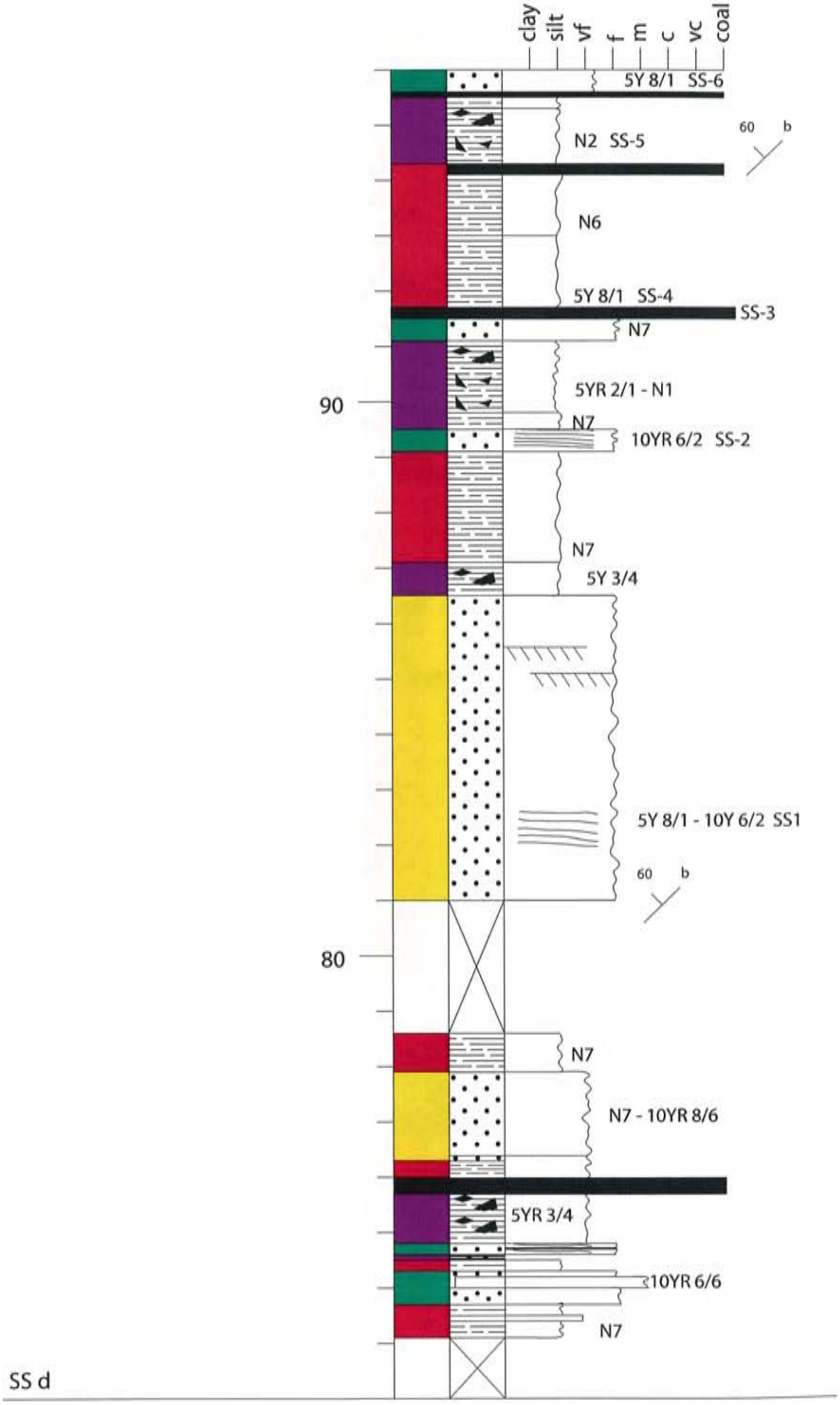
coal
70
5YR 3/4
10YR 6/2 SSL-1
5YR 3/4
5Y 8/4
60
N7
50
SS c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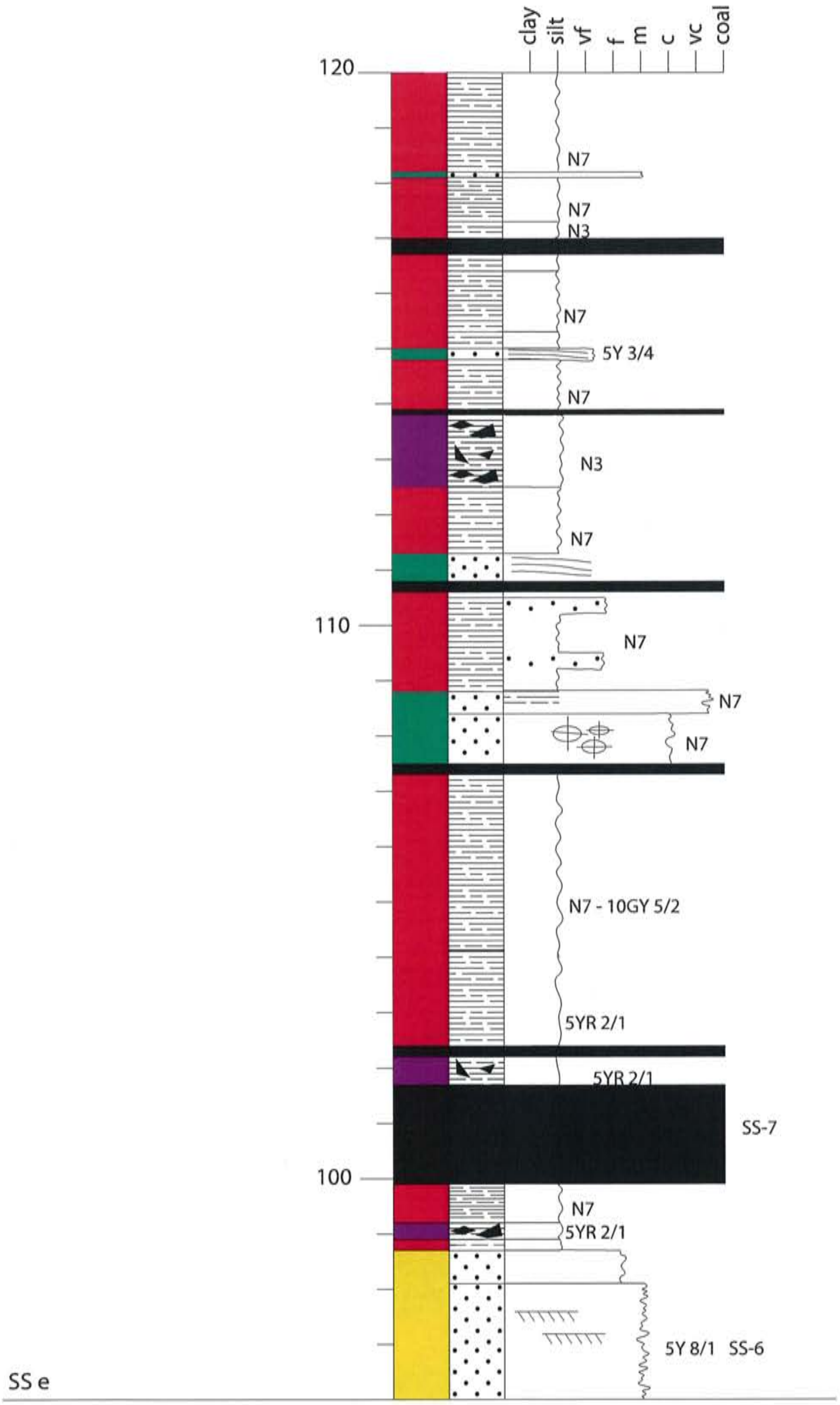
silt
vf
f
m
c
vc
coal
5Y 8/1 SS-6
N2 SS-5
60
b
N6
5Y 8/1 SS-4
SS-3
N7
5YR 2/1 - N1
90
N7
10YR 6/2 SS-2
N7
5Y 3/4
5Y 8/1 - 10Y 6/2 SS1
60
b
80
N7
N7 - 10YR 8/6
5YR 3/4
10YR 6/6
N7
SS d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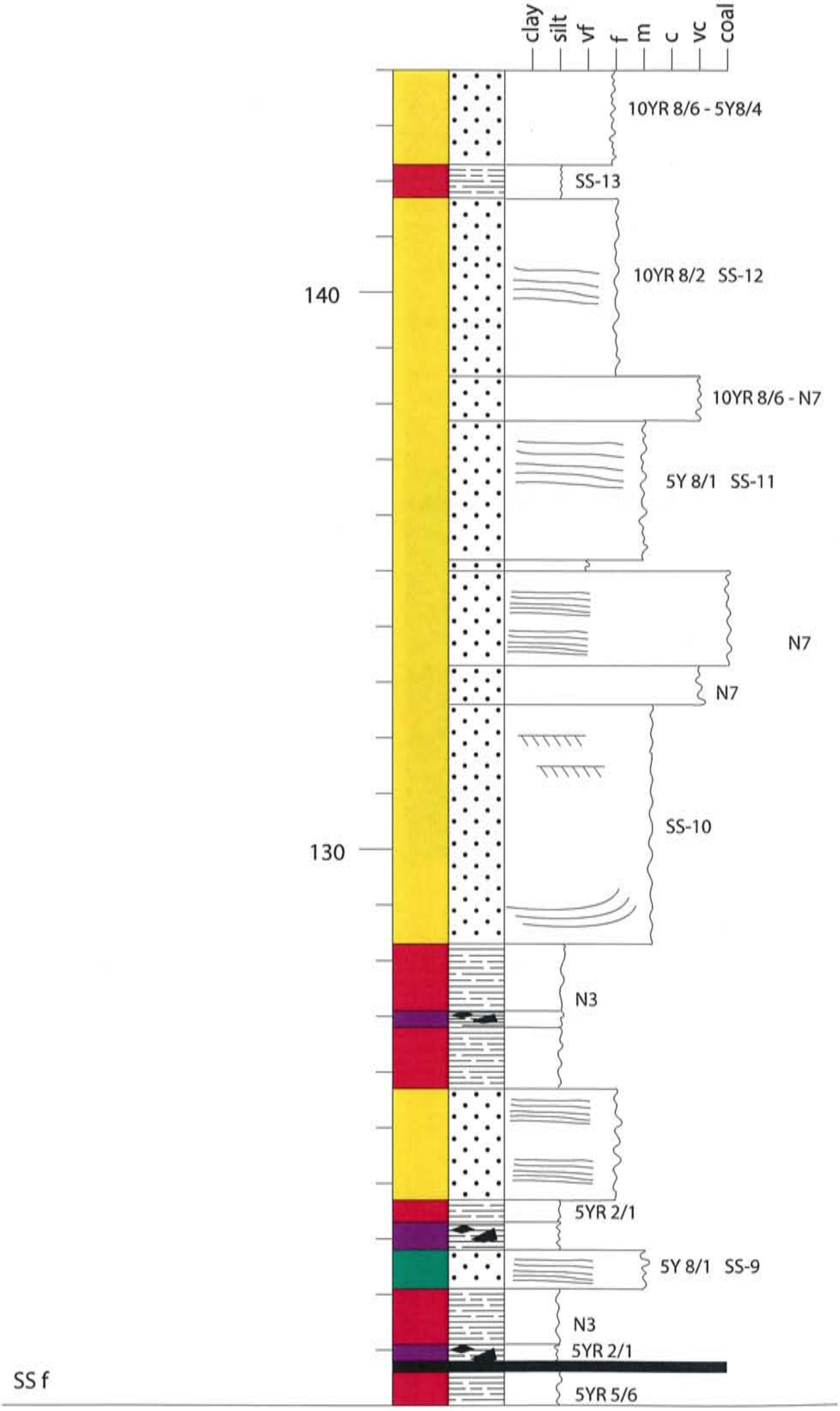
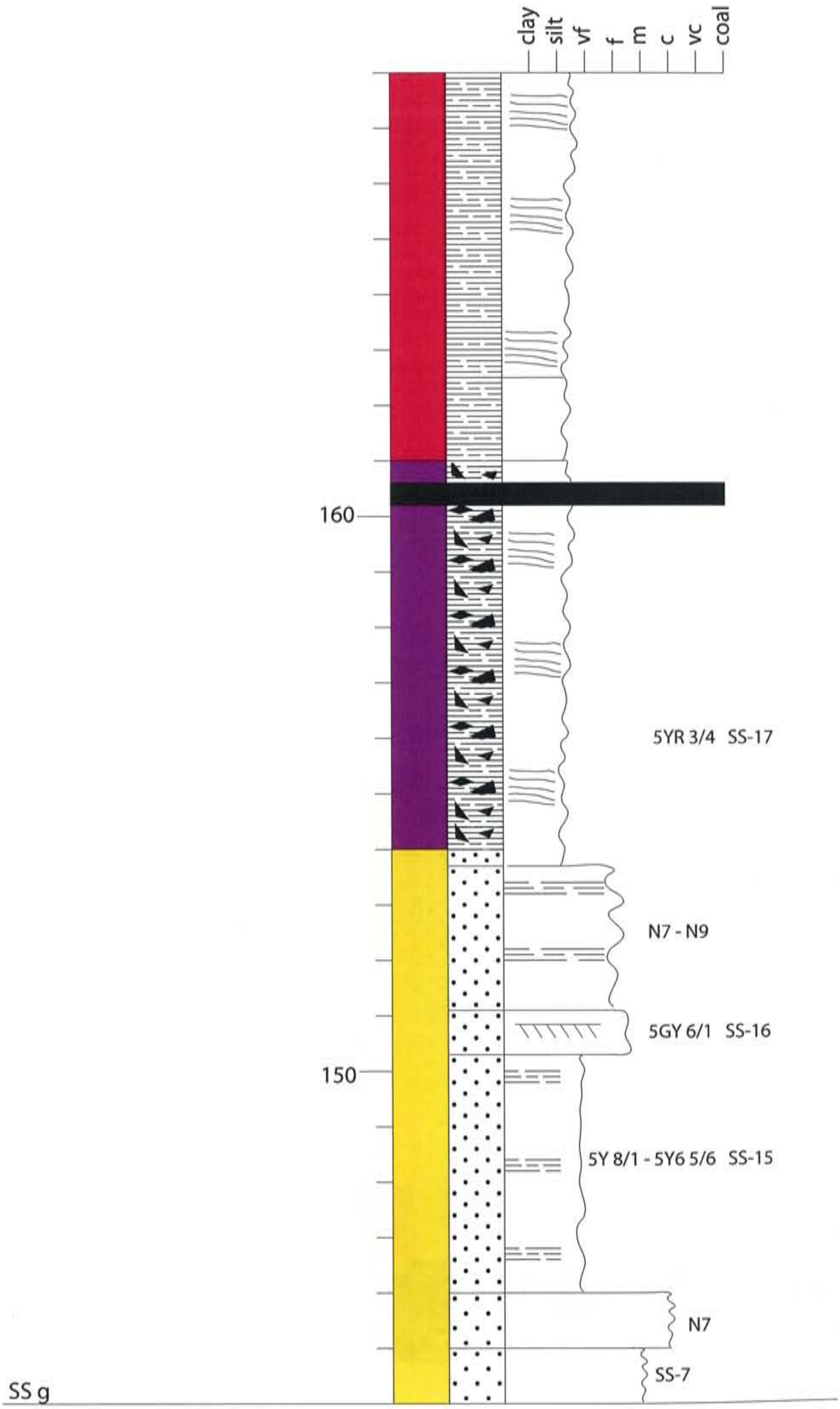
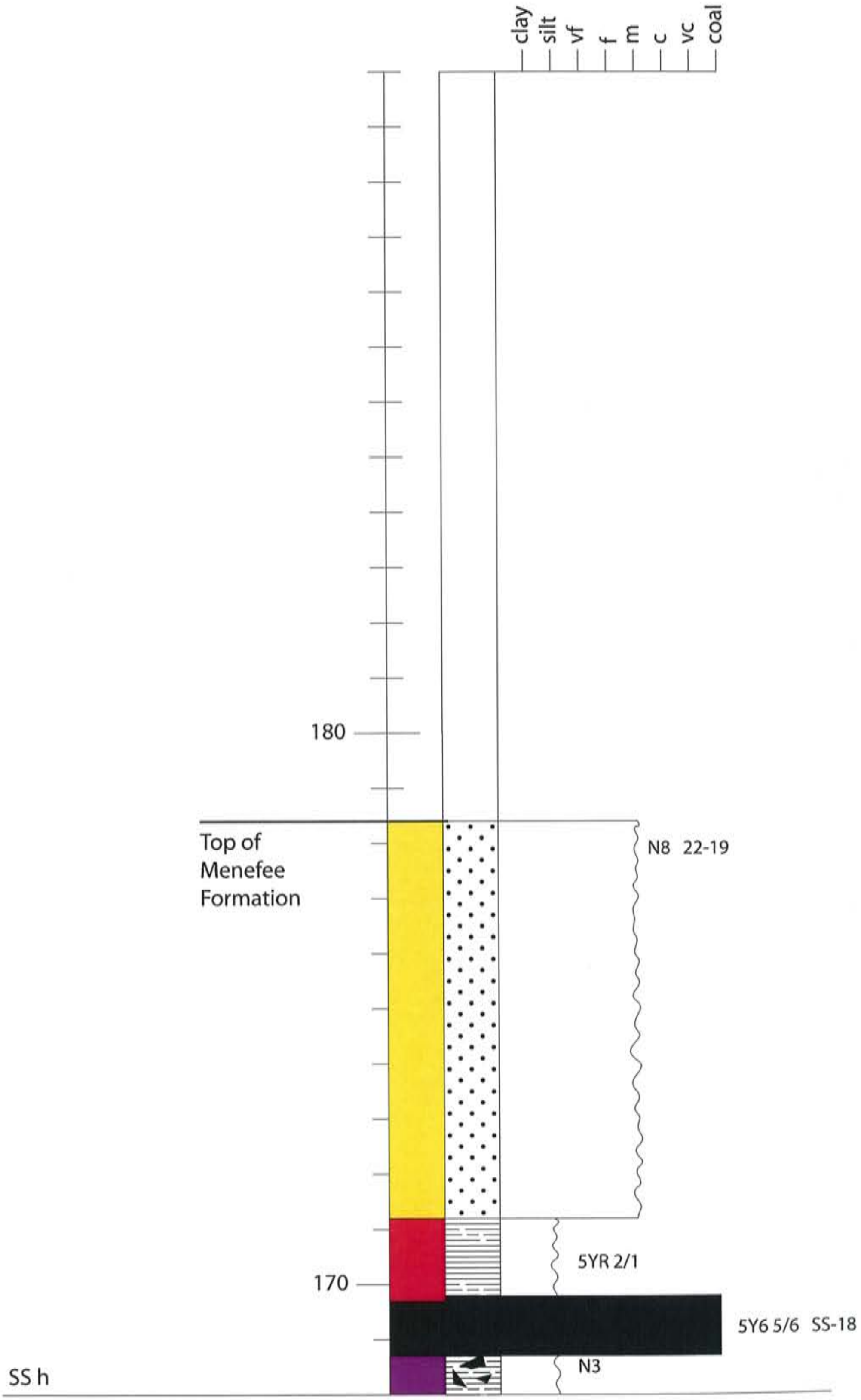
silt
vf
f
m
c
vc
coal
120
N7
N7
N3
N7
5Y 3/4
N7
N3
N7
110
N7
N7
N7
N7 - 10GY 5/2
5YR 2/1
5YR 2/1
SS-7
100
N7
5YR 2/1
5Y 8/1 SS-6
SS e


clay
silt
vf
f
m
c
vc
coal
10YR 8/6 - 5Y8/4
SS-13
10YR 8/2 SS-12
140
10YR 8/6 - N7
5Y 8/1 SS-11
N7
N7
SS-10
130
N3
5YR 2/1
5Y 8/1 SS-9
N3
5YR 2/1
SS f
5YR 5/6


clay
silt
vf
f
m
c
vc
coal
160
5YR 3/4 SS-17
N7 - N9
5GY 6/1 SS-16
150
5Y 8/1 - 5Y6 5/6 SS-15
N7
SS-7
SS g


clay
silt
vf
f
m
c
vc
coal
180
Top of Menefee Formation
N8 22-19
5YR 2/1
170
5Y6 5/6 SS-18
N3
SS h