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Stratigraphy, Sedimentology, and Deformational Significance of Cambrian and Early Ordovician Strata Along the Southeast Wisconsin Arch

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STRATIGRAPHY, SEDIMENTOLOGY, AND DEFORMATIONAL SIGNIFICANCE OF CAMBRIAN AND EARLY ORDOVICIAN STRATA ALONG THE SOUTHEAST WISCONSIN ARCH

by

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ABSTRACT

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A detailed study of the stratigraphic units in and around the Wisconsin Arch of central and southeast Wisconsin are presented to refine the sedimentologic record and the geologic implications within the Cambrian and early Ordovician strata. The Cambrian and early Ordovician sediments in central and southeast Wisconsin unconformably overlie a topographic high composed of Precambrian basement rocks, called the Wisconsin Arch, and consist of various clastic deposits, dolostones, and several horizons of deformation. Bedrock cores, made available through the Wisconsin Geological and Natural History Survey (WGNHS), were analyzed, to understand sedimentation in the Cambrian and early Ordovician. My analyses focused on: (1) lateral distribution of strata and changes in depositional environments, (2) the nature of deformation (e.g., soft sediment, karst collapse, tectonic, or glacial overriding) observed along significant erosional contacts, (3) the effect of the Precambrian Wisconsin arch on sedimentation, and (4) the presence of unconformities including incised valleys. This research analyzed a high-resolution imagery dataset of 22 cores from Columbia, Dodge, Fond du Lac, and Jefferson counties. Published literature describes the central Wisconsin Arch region, near Dane County, as having three unconformities that are situated between many fining upward sequences, areas of deformation, and multiple incised valleys. This study uses descriptions of newly

available cores to reevaluate literature and interpretations that address stratigraphy, facies description, depositional environment, deformation, and local unconformities in strata surrounding the Wisconsin Arch in southeast Wisconsin.

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Introduction

Problem

This study addresses the questions of what sedimentology, stratigraphy, and depositional environments are preserved in the Cambrian and Ordovician rock record of southeast Wisconsin, how the Precambrian Wisconsin Arch affected sedimentation, how these strata compare to the rest of the state, and what drove soft-sediment deformation. Answers to these problems will provide for a greater understanding of the Cambrian and Ordovician paleogeography of southeast Wisconsin, where comprehensive work is currently of high interest to the Wisconsin Geological and Natural History Survey (WGNHS.)

Objectives

The objectives of this research were to create comprehensive logs of available cores in Dodge, Jefferson, Colombia, and Fond du Lac counties that are complete with lithofacies and corresponding depositional environments, and to interpret what drove sedimentation and sediment deformation surrounding the Wisconsin Arch. There is broad interest by the WGNHS to map Precambrian surface topography, and overlying lower Paleozoic strata for lithology, deformation, and mineralization as it relates to groundwater studies. The findings of this study will provide the WGNHS with cross sections that interpret lower Paleozoic unit thickness and contacts as they relate to the paleotopography of the Wisconsin Arch, as well as detailed lithologic descriptions that include both primary and secondary features that may influence groundwater processes.

Previous Work

Lower Paleozoic strata (523 – 458 Myr) are exposed across much of the western and southwest areas of Wisconsin and within the Mississippi River Valley. These strata were studied extensively from 1970 into the 1990's to establish stratigraphic successions, and lithologic and depositional interpretations from the western flanks of the Wisconsin arch from Madison to the Mississippi River (e.g., Ostrom, 1970, Ostrom et al., 1978, Smith et al., 1993, Runkel, 1994, Runkel et al., 1998). However, across much of the rest of the state, lower Paleozoic strata are covered by Pleistocene glacial deposits and are only observable in cores and in well cuttings. Bedrock maps including deformational horizons have recently been published by the WGNHS for Dodge and Fond du Lac Counties (Batten, 2018; Stewart, 2021). A study by Kawa (2006) focused on developing an interpretation of time-equivalent deposits for the south-central region of the Wisconsin Arch and documented deformation horizons for south-central Wisconsin. These have been attributed to soft-sediment slumping or sliding, karst, tectonics, or glacial overriding, but the exact cause(s) of the deformations are still unknown.

Research Goals

Further description and interpretations of the Early Paleozoic strata are necessary in the south-eastern region of the arch to compare time-equivalent strata to surrounding regions and to determine what effects the Precambrian high had on sedimentation in and around the arch. The goal of this research was to complete in depth logging of cores from Columbia, Dodge, Fond du Lac, and Jefferson counties that defines the lithology, sedimentary structures, textures, and fabrics necessary to interpret depositional environments of the Lower Paleozoic strata in Wisconsin and to correlate strata and events across the area. Particular attention is paid to

unconformities and areas of deformation to define and provide hypotheses of processes that resulted in variations in thickness of the units.

Geologic Setting

Deep time paleogeographic reconstructions place present-day southeast Wisconsin along the continental margin of an equatorial shallow marine sea from the late Cambrian (501 Ma) to the middle Ordovician (461 Ma) (Scotese, 1992) (Figure 1). Understanding the paleogeographic setting provides insight into latitudinal climate implications for carbonate sedimentation, and tectonic implications for possible reactivation of cratonic Precambrian basement structures.

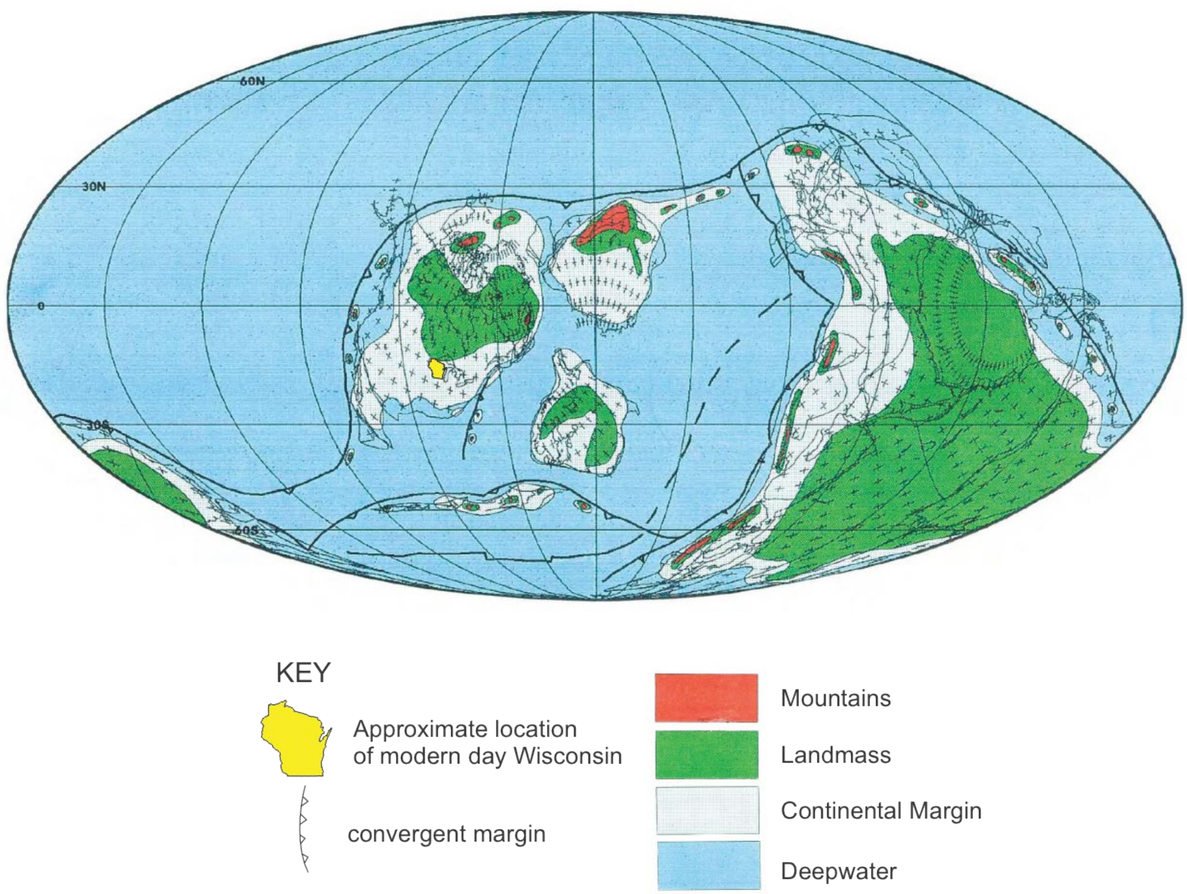


Figure 1. Paleogeography of North America in the middle Ordovician 548 Ma. Modified from Scotese, 1992.

The Wisconsin Arch is a Precambrian basement topographic high within the stable North American craton striking south-south-east through modern day central Wisconsin into northern Illinois. The Precambrian uplands separate major sedimentary basins including the Hollandale Embayment to the west from the Michigan Basin to the east (Figure 2).

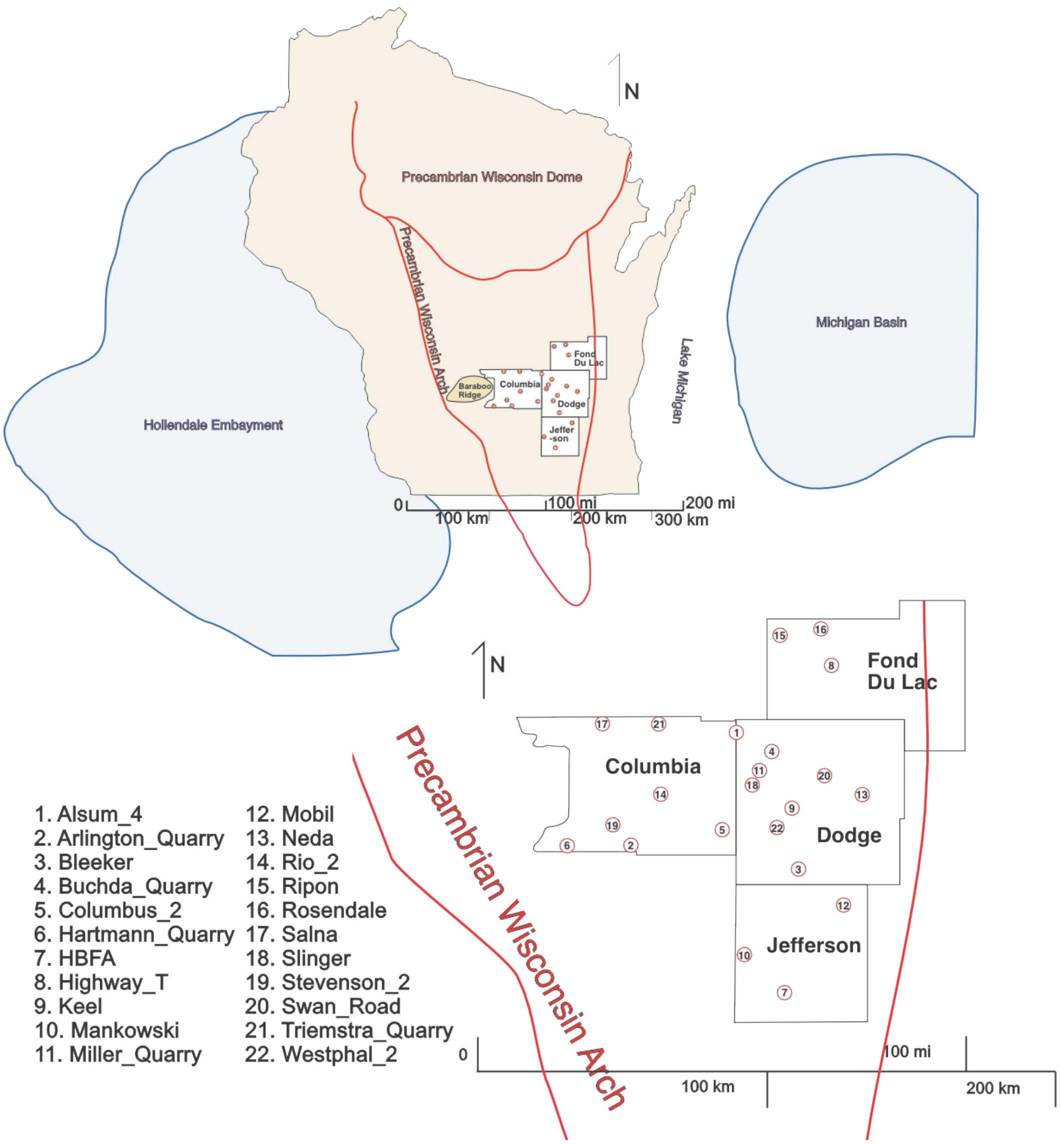


Figure 2. Approximate location of Precambrian Wisconsin Arch in relation to cores (red circles) of Columbia, Dodge, Fond du Lac and Jefferson Counties. The Precambrian topographic high known as The Wisconsin Arch, and Wisconsin Dome are uplands. Michigan Basin and Hollendale Embayment are lowlands. Modified from Runkel, 1998.

There are multiple areas from which bedrock core and exposed outcrop were analyzed for this research, which together represent a broad region of the southern Wisconsin Arch. Twenty-two cores from this study, ranging in thickness from 100 to 900 feet, are housed at the Wisconsin Core Repository in Mount Horeb, Wisconsin and managed by the WGNHS. These cores are distributed across Columbia, Dodge, Fond du Lac, and Jefferson counties and represent coverage of the southeastern arch region (Figure 2). Strata are described as a series of clastic and carbonate lithologies from the Mount Simon Formation (Late Cambrian), which represents the base of the Cambrian strata in Wisconsin, to the upper Sinnipee Group (Middle Ordovician). Figure 3 shows the stratigraphic relationships of the lower Paleozoic strata.

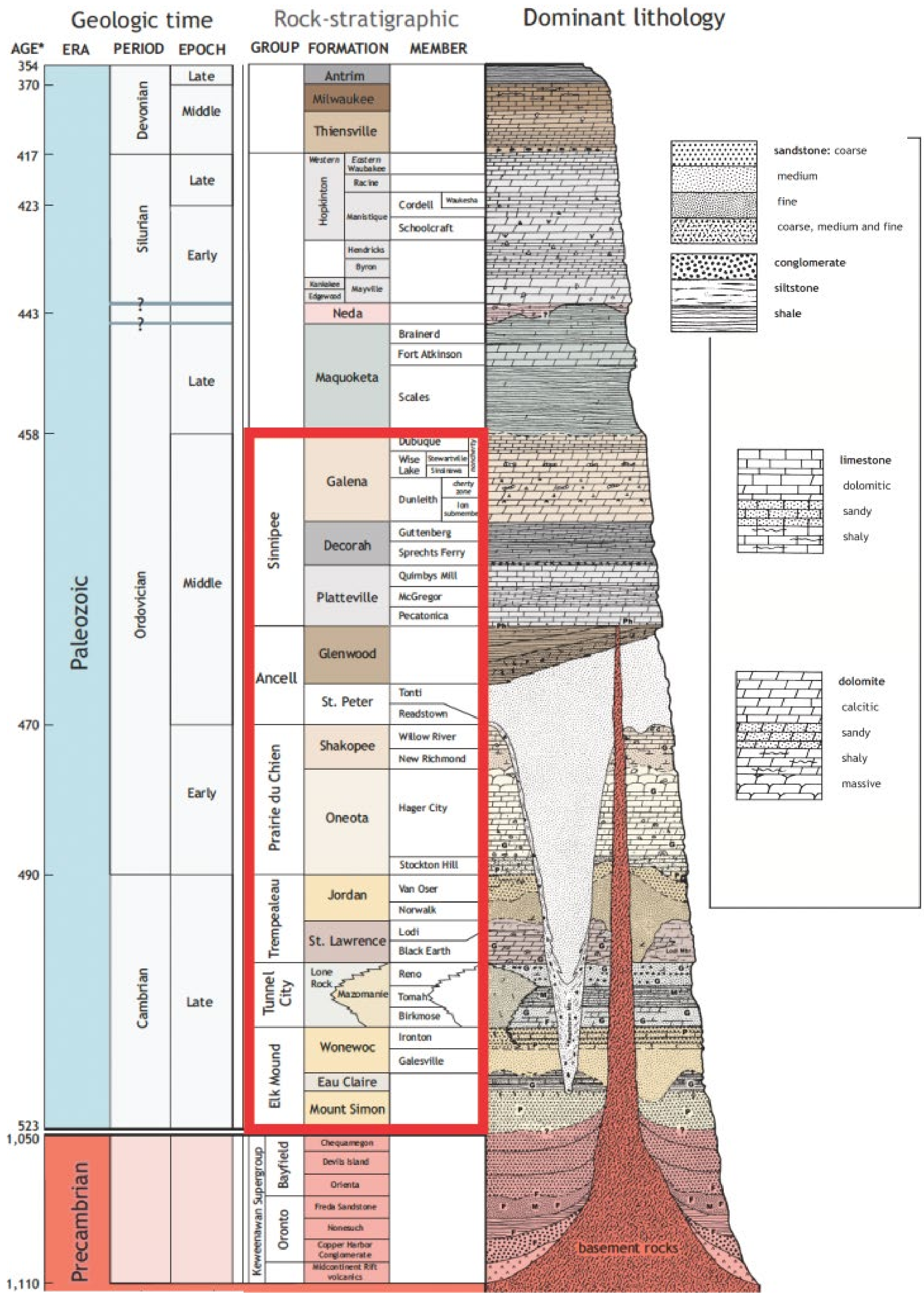


Figure 3. Bedrock Stratigraphy from the Wisconsin Geological and Natural History Survey, 2006. Strata of interest to this study are outlined in red.

Literature Review

A literature review of the lower Paleozoic strata from western and southwestern Wisconsin, where bedrock is at or near the land surface, provides a foundation to understand coeval strata in southeastern Wisconsin. Cambrian and Ordovician sediments spanning from 523-458 Myr were deposited in a terrestrial to shallow marine, equatorial, tropical setting on the present southern margin of the paleocontinent Laurentia, which was positioned about 90 degrees clockwise to the present-day position (Scotese, 1992). Subsidence of the Michigan Basin, thought to be driven by Appalachian orogenic events, began in the Late Cambrian and occurred episodically throughout the Paleozoic allowing for preservation of sediments (Hischke, 2018). The following descriptions are summarized from a literature review of sedimentological and stratigraphic studies completed in southwest, northwest, and northeastern Wisconsin.

A. Elk Mound Group

The Elk Mound Group (523-497 Myr) rests unconformably on top of Precambrian crystalline basement and makes up the oldest sediments found in Wisconsin (Twenhofel, 1935). The upper boundary of the Elk Mound Group is characterized by a disconformity with the overlying Tunnel City Group.

A1. Mt. Simon Formation

The Mt. Simon Formation is the oldest, lowermost formation of the Elk Mound Group and typically consists of a coarse-grained, porous, sandstone that contains fossils only in western Wisconsin (Aswasereelert et al., 2008; Attig and Clayton, 1990). The Mount Simon is described in the northeast part of the state as a very fine- to fine-grained, subangular, submature to mature quartz arenite sometimes with basal conglomerate and pebbly sandstone at the base (Hischke, 2018). The depositional environment of the

Mount Simon has been described as both fluvial, tidal, shallow marine, and eolian in origin based on sedimentary structures and the presence or absence of fossils (Driese et al., 1981; Attig and Clayton, 1990; Syverson and Havholm, 1998).

A2. Eau Claire Formation

The Eau Claire Formation is characterized as a fine- to medium-grained fossiliferous sandstone with variable amounts of sand, siltstone, shale, and dolomite (Aswasereelert et al., 2008; Hischke, 2018) with trace fossils from the *Cruziana* Ichnofacies (Kawa, 2006). The sandstone includes some feldspathic and glauconitic horizons and is commonly a succession of interbedded sands and shales (Aswasereelert et al., 2008; Kawa, 2006; Hischke, 2018). The Eau Claire is an important confining layer in most of the state but is absent toward the northeast (Hischke, 2018). The Eau Claire's depositional environment ranges from offshore below storm wave base to foreshore within the intertidal zone (Aswasereelert et al., 2008).

A3. Wonewoc Formation

The Wonewoc Formation is a classic cratonic sheet sandstone that developed over three distinct episodes of sea-level change (Runkel et al., 1998) and consists mostly of white to tan, medium to coarse-grained, sub-rounded, and well-sorted, sometimes poorly cemented quartz arenite (Hischke, 2018). The formation is separated into the Galesville and Ironton Members. The lower Galesville Member is a well-sorted, poorly lithified quartzose sandstone, similar to the Mount Simon Formation. In contrast, the upper Ironton Member is a fine- to medium-grained sandstone, yellowish to reddish in color, with common zones of bioturbation (Attig and Clayton, 1990; Kawa, 2006; Runkel,

1998). Most of the Wonewoc sands were deposited in a shoreface environment, while a lesser percentage is attributed to fluvial and eolian processes (Runkel, 1998).

A. Tunnel City Group

The Tunnel City Group (497-491 Myr) rests unconformably on top of the Wonewoc Formation of the Elk Mound Group and is conformable with the overlying Trempealeau Group. The Tunnel City Group is subdivided into two formations, the Mazomanie and Lone Rock Formation, which are laterally discontinuous (Attig and Clayton, 1990; Ostrom et al., 1978).

B1. Mazomanie Formation

The Mazomanie Formation is characterized as very fine- to medium-grained, well-sorted, non-glauconitic, interbedded feldspathic and quartzose sandstones and sandy dolomite with some cross stratification along with many zones of heavy bioturbation (Ostrom et al., 1978; Eoff, 2014; Kawa, 2006). The Mazomanie is laterally discontinuous and only occurs on and westward from the Wisconsin Arch (Ostrom, 1966). Directly atop the arch, the Mazomanie occurs below the Lone Rock, or occurs as a wedge within the Lone Rock west, east and south of the arch (Ostrom 1966, fig. 11). Within the four-county study area, the Mazomanie has only been observed in Colombia County. The Mazomanie was deposited in a shoreface environment above fair-weather wave base (Eoff, 2014).

B2. Lone Rock Formation

The Lone Rock Formation is the younger of the two formations of the Tunnel City Group and occurs as a discontinuous thin sheet in the areas surrounding the Wisconsin Arch (Ostrom et al., 1978; Kawa, 2006) but comprises most of the group in western,

southeast, and southern Wisconsin (Attig and Clayton, 1990; Ostrom, 1966). There are three primary lithologies in the Lone Rock Formation (Ostrom et al., 1978), corresponding to three members: the lower Birkmose, middle Tomah (present in the west), and upper Reno (present in the east) (Eoff, 2014.) The two dominant lithologies within the study area are the Reno which is a cross-stratified, feldspathic, shaley, fine-grained sandstone, and the Birkmose characterized as a fine-grained, poorly-cemented, glauconitic, feldspathic sandstone (Eoff, 2014, Ostrom et al., 1978; Kawa, 2006). All three members include heavily bioturbation of fine sands, referred to as "wormstone" in literature from across the Midwest (Twenhofel and Thwaites, 1919; and others) The Lone Rock depositional environment ranges from an off-shore setting near storm wave base, to a shoreface environment above fair-weather wave base (Eoff, 2014).

B. Trempealeau Group

(491- 485.4 Myr) The Trempealeau Group lies conformably on top of the Tunnel City Group, and is unconformable with the overlying Prairie du Chien Group. The Trempealeau Group consists of the St. Lawrence Formation, and the laterally discontinuous Jordan Formation.

C1. St. Lawrence Formation

St. Lawrence Formation is divided into two distinct members. The lower Black Earth Member is a dolomitic sandstone with stromatolites and flat-pebble conglomerates; whereas the upper Lodi Member consists of finely interlayered dolomites, siltstones, and very fine-grained sandstones (Attig and Clayton, 1990; Hughes et al., 1997; Kawa, 2006). This formation is consistently about 10 meters thick and is mostly comprised of the

yellowish Lodi dolomite in most locations west of the Wisconsin Arch (Attig and Clayton, 1990). The depositional environment of the St. Lawrence has been interpreted in various ways (Hughes, 1997) ranging from offshore marine (Runkel, 1994) to tidal (Hughes, 1997).

C2. Jordan Formation

The Jordan Formation is a well-studied cratonic sheet sandstone divided into 5 distinct members (Runkel, 1994). The Norwalk, Van Oser, Waukon, and Sunset Point Members are mostly homogeneous, very-fine to medium-grained sandstones (Runkel, 1994; Kawa, 2006). In contrast, the Coon Valley Member is a combination of dolomitic, quartzose sandstones, and sandy oolitic dolomites (Runkel, 1994; Kawa, 2006). The Van Oser and Coon Valley Members make up most of the Jordan Formation near the Wisconsin Arch (Kawa, 2006). The depositional environment of the Jordan sandstone is a prograding shoreface (Runkel, 1994).

C. Prairie du Chien Group

The Prairie du Chien Group (PDC; 485.4-470 Myr) makes up the oldest Ordovician sediments in Wisconsin and is unconformable with the underlying Trempealeau and overlying Ancell Groups. Macrofauna and midcontinent conodont fauna indicate the PDC was deposited in a shallow continental sea (Smith et al., 1993; Smith, 1991 Attig and Clayton, 1990).

G1. Oneota Formation

The Oneota Formation is the lower formation of the Prairie du Chien Group

and is typically divided into two distinct lithofacies: a sandy dolomite and a thickly bedded dolomite (Attig and Clayton, 1990; Kawa, 2006; Smith et al., 1993). The sandy dolomite facies commonly consists of sandy, oolitic packstones and grainstones (Smith et al., 1993; Kawa, 2006). The thick dolomite facies has stromatolite boundstones and oolitic grainstones and makes up most of the Oneota Formation (Smith et al., 1993). The Oneota is typically 25 meters in thickness west of the arch near Sauk County, and ranges in color from pale brown to light brownish gray (Attig and Clayton, 1990).

G2. Shakopee Formation

The Shakopee is the upper formation of the Prairie du Chien Group and is divided into two lithofacies; quartz arenite facies and silty dolomite facies (Attig and Clayton, 1990; Kawa, 2006; Smith et al., 1993). The quartz arenite sandstone facies is characterized by fine- to medium-grained feldspathic sand with planar and trough cross beds (Smith et al, 1993). The silty dolomite facies is a combination of wackestones and packstones with wavy to planar laminations of sand and shale (Smith et al., 1993).

D. Ancell Group

The Ancell Group (470-458 Myr) unconformably overlies the Prairie du Chien Group and underlies the Sinnipee Group. The Ancell Group consists of two formations: the St. Peter Formation, and the Glenwood Formation, which is discontinuous and has not been observed in southeastern Wisconsin.

D1. St. Peter Formation

The St. Peter Formation consists of a very clean, mature, sheet sandstone deposited on top of an extensive erosional surface that covers most of the central United States (Dott and Mai, 1985; Kawa, 2006). The St. Peter Formation is divided into two members: the

lower Readstown Member and the upper Tonti Member (Dott and Mai, 1985.). The Readstown Member, formerly known as the Kress Member, is a conglomeratic mixture of chert, shale, and sandstone (Dott and Mai, 1985; Kawa, 2006). The Tonti Member consists of clean, friable, white, pink, tan, and yellow quartzose sands (Dott and Mai, 1985; Kawa, 2006). The St. Peter has been interpreted as either eolian or marine based on who described the unit or at what locality it was described from (Dott and Mai, 1985).

E. Sinnipee Group

The Sinnipee Group (458-541 Myr) rests unconformably on top of the Ancell Group and is overlain conformably by the Maquoketa Formation. The Sinnipee dolostones consists of 3 formations: the Platteville, Decorah, and Galena (Ostrom et al., 1978). The depositional environment of the Sinnipee Group ranges from shallow marine to reef, to offshore marine (Ostrom et al., 1978).

F1. Platteville Formation

The Platteville is described as dolostone and shaly dolostone (Ostrom et al., 1978, Brown, 1999) and consists of five members based on clay content and bedding characteristics (Brown 1999). The formation thins and becomes less shaley moving from southern Wisconsin into the north-central parts of the state (Brown 1999).

F2. Decorah Formation

The Decorah has only been identified in southwest Wisconsin west of Jefferson County and consists of a thin argillaceous carbonate layer (Brown 1999).

F3. Galena Formation

The Galena is continuous across Wisconsin and is characterized by a gray-blue dolomite with green shale partings that are dominant in the lower members (Ostrom et al., 1978,

Brown, 1999). The upper Galena is generally pure carbonate in southern Wisconsin but become shaly to the northeast (Brown 1999).

Methods

Twenty-two cores covering various study areas in Columbia, Dodge, Fond du Lac, and Jefferson counties (Figure 4) are available as high-resolution images and for physical in-person study at the WGNHS bedrock core repository in Mount Horeb, WI. Log sheets were used to document unit thickness, unit contacts, lithology, mineralogy, bedding contacts, sedimentary structures, fossils, bioturbation, grain-size distributions, secondary mineralization, and deformation styles. Thickness measurements and depths were documented in feet as that is the designation for cores from WGNHS. Stratigraphic columns were produced from viewing both physical samples, and high-resolution images of cores. Four cross sections were developed to represent subsurface lateral trends. Computer software ArcGIS Pro was used to locate all core holes and form spatial relationships between surface and subsurface data. Core descriptions and cross sections were used to interpret depositional environments and construct a regional facies model that addresses the lateral distribution of lithofacies associations as they occurred along the slope margin. A regional stratigraphic column complete with site-specific stratigraphy, lithology, thickness, and sedimentary structures was constructed alongside an interpretation of regional sea level developed from the facies model. Drafting of stratigraphic columns, maps and figures was completed using a computer drawing software program (CorelDRAW, version 24, 2022).

Results

Twenty-two cores were described in detail noting lithology, sedimentary structures, stratigraphic contacts, unit thicknesses, and deformation. A facies model was created to describe common lithofacies and their corresponding facies association based on interpreted facies environment. Common characteristics of stratigraphic units and contacts were then described by county to account for variability across the study area. Parasequences and major contacts observed in core were used to identify five depositional sequences driven by relative sea level. Four cross sections across the study area were created to display lateral trends in thickness, elevation, and lithology across the study area.

Lithofacies and contact descriptions of core across a four-county distribution were used with understanding relative time constraints to interpret a likely depositional model that explains the environments that produced primary sedimentation and the forces that drove deformation across a 40-million-year period from 501-461 Ma. This depositional model (Figure 4) outlines the facies associations from a shallow marine, intercontinental shelf environment from a nonmarine, terrestrial environment to offshore marine. Table 1 describes the common lithology, grain size, sedimentary structures and bioturbation observed in each facies association as well as the stratigraphic units that display their characteristics.

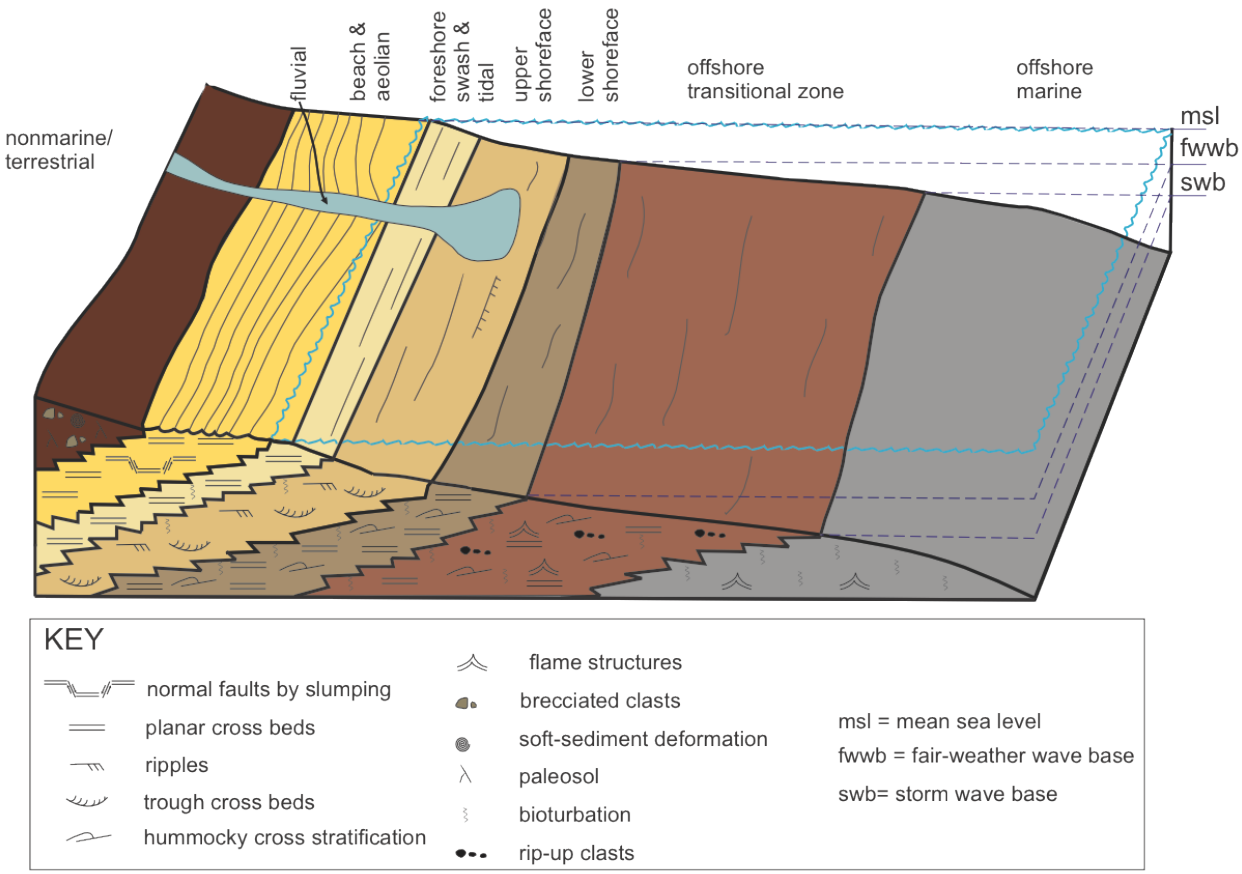


Figure 4. Schematic facies model of the intercontinental shallow marine slope of southeast Wisconsin from the late Cambrian to middle Ordovician showing distribution of principal facies associations described in this study. Inspired by models from Howell and Flint (2003) and Runkel (2007).

Table 1. Principal lithofacies associations, their signature characteristics, and common stratigraphic units in which they are described.

Lithofacies association	**Nonmarine terrestrial**	**Beach & aeolian**	**Foreshore swash & tidal**	**Upper Shoreface**	**Lower shoreface**	**Offshore Transitional**	**Offshore marine**
Lithology	variable depending on bedrock	Quartz sand	Quartz sand	Clean quartz sand	Quartz sand and fossil fragments, shallow water carbonate platforms	Fine clastics, storm beds, hummocky cross-stratification, glauconite, and carbonate wackestones and packstones	Fine clastics and mudstones
Grain size	variable. weathering of bedrock	fine to medium	fine to medium	fine to medium	medium to coarse	fine to silt	very fine, silt and clay
Sedimentary structures	paleosol, brecciated clasts, secondary alternations, soft sediment deformation	planar beds, aeolian dunes and soft sediment slumping and sliding	planar cross beds	planar and trough cross beds, migrating dunes, wave and current ripples	Planar cross laminations and hummocky cross-stratification, rip-up clasts	Planar cross laminations, hummocky cross-stratification, flame structures, rip-up clasts, sediment-starved	Laminated fine beds, flame structures, sediment-starved
Bioturbation	little to none.	rare vertical burrows	rare vertical burrows	vertical burrows	vertical and horizontal burrows	intensely bioturbated	intensely bioturbated
Common stratigraphic units	Conglomerates overlying Precambrian Arch, Karsting of Prairie du Chien Gp, deformation of Readstown Mbr, Paleosols along unconformities	Mount Simon Fm, Wonewoc Fm, Jordan Fm, Saint Peter Fm	Mount Simon, Wonewoc Fm, Jordan Fm, Saint Peter Fm	Mount Simon Fm, Wonewoc Fm, Mazomanie Fm, Jordan Fm, Saint Peter Fm	Eau Claire Fm, Jordan Fm, Saint Lawrence Fm, Prairie du Chien Gp	Eau Claire Fm, Lone Rock Fm, Saint Lawrence Fm, Prairie du Chien Gp, Sinnipee Group	Eau Claire Fm, Sinnipee Group

Twenty-five specific lithofacies are noted in descriptions throughout the four-county study area. Table 2 describes the lithological characteristics of each, their corresponding facies association, depositional interpretation, and common units of occurrence.

Table 2. Specific lithofacies descriptions, corresponding facies associations and interpretation, and common units of occurrence.

Lithofacies	Lithological Description	Facies Association and Interpretation	Common units of occurrence
Paleosol	Dark brown, light brown to light green sand, silt, and clay lacking internal structure, with common brecciated clasts and soft sediment deformation	Nonmarine: terrestrial exposure and weathering of bedrock and surficial deposits	Jordan Fm (lower) Prairie du Chien Gp (upper)
Brecciated silcritic sandstone	white medium to coarse quartz sand with 1–2-inch angular clasts of sandstone, dolomite and chert, with white silcrete filled pore space and 1–2-inch angular silcrete nodules and bands	Shallow Marine: primary deposition in upper shoreface, foreshore, or beach Nonmarine: secondary subaerial exposure and accumulation of silcrete, weathering, brecciation, and deformation of unstable sediments along a slope of valleys or underlying karst	Readstown Mbr
Conglomerate	1-4-foot-thick layers of 1-2 in diameter granite and quartz clasts in a sand and mud matrix	Nonmarine: terrestrial erosion and incorporation of angular bedrock clasts into earliest shallow marine Cambrian sedimentation during subsequent transgression	Mount Simon Fm Jordan Fm
Karst-mottled dolomite	gray dolomite with broken dolomite clasts, and a sand and mud matrix, some soft sediment deformation seen in matrix, calcite and silcrete accumulation in fractures and pore space	Shallow marine: primary deposition in lower shoreface to transitional zone Nonmarine: secondary near-surface exposure, groundwater and rainwater mixing allow for karst development	Prairie du Chien Gp
Soft sediment deformed strata	dark brown mud, silt, and sand with 0.25 cm clasts, low to high angle soft sediment deformation	Nonmarine: soft sediment slumping and sliding related to changes in topography	Prairie du Chien Gp Saint Peter Fm

		from incised valleys or karst collapse	
Fractured sandstone	medium to coarse quartz sandstone with brittle offset that looks like minor fracturing	Syndepostional deformation of sand such as slumping and sliding of unstable dunes	Wonewoc Fm Mazomanie Fm Saint Peter Fm
Fine bedded sandstone	fine, well-sorted, quartz arenite sands with planar cross beds and carbonate cement	Shallow marine: upper shoreface, foreshore or beach sands Nonmarine: aeolian dunes	Eau Claire Fm Tunnel City Gp Jordan Fm Saint Peter Fm
Cross-stratified sandstone	medium to coarse, well-sorted, quartz arenite sands with 1-3 inch planar and low angle cross bed sets, and carbonate cement, generally well-cemented with few 1–6-inch layers of weakly cemented sands	Shallow marine: upper shoreface, foreshore, or beach Nonmarine: aeolian	Elk Mound Gp Mazomanie Fm Trempealeau Gp Saint Peter Fm
Bioturbated sandstone	medium to coarse quartz arenite sands with sand, silt or mud-filled vertical burrows	Shallow marine: upper shoreface to lower shoreface (terrestrial organisms are not present in this time period so bioturbation is strictly marine)	Elk Mound Gp Mazomanie Fm Reno Mbr Saint Lawrence Jordan Fm Saint Peter Fm
Thrombolytic and stromatolitic dolomite	gray dolomite with tan dendritic thrombolytic fabric	Shallow marine: upper shoreface to lower shoreface (shallow waters and persistent wave energy allow stromatolites and thrombolites to form)	Prairie du Chien Gp
Sandy dolomite	gray to tan dolomite wackestones with 0.5-4-inch-thick massive quartz sand lenses, hummocky cross-stratification, with common 0.5-1-inch calcite filled vugs	Shallow marine: lower shoreface to transitional zone (low levels of clastic sedimentation rates allow carbonate to dominate, storm deposits bring pulses of sand from near shore into the	Eau Claire Fm St. Lawrence Fm Prairie du Chien Gp Sinnipee Gp

		carbonate-producing facies)	
Silty dolomite	gray to light brown dolomite with silty texture, 0.5-2-inch silcrete nodules and vugs	Shallow marine: lower shoreface to transitional environment more distal than the sandy dolomite facies (low levels of clastic sedimentation rates allow carbonate to dominate, storm deposits bring pulses of fine sediment from near shore into the carbonate-producing facies)	Sinnipee Gp
Dolomite wackestone	gray to tan dolomite with brachiopod, bivalve, crinoid, and stromatolite fossils with hummocks, 1-3-inch vugs	Shallow marine: lower shoreface to transitional zone (low levels of clastic sedimentation rates allow carbonate to dominate, storms deposit fossil fragments in coarser storm beds)	St. Lawrence Fm Prairie du Chien Gp Sinnipee Gp
Hummocky cross-stratified dolomite	Dolomite mudstone to wackestone with 0.5-6-inch wavy beds of fossil fragments overlain by finer beds	Shallow marine: lower shoreface and transitional zone within storm wave base	Saint Lawrence Fm, Prairie du Chien, Sinnipee Gp
Silcritic dolomite	gray dolomite with abundant white, 0–3-inch silcrete nodules and bands	Shallow marine: primary deposition in lower shoreface to transitional zone Nonmarine: secondary subaerial exposure and accumulation of silcrete	Prairie du Chien Gp Sinnipee Gp
Fine-grained glauconitic bioturbated sandstone (green wormstone)	fine-grained quartz and glauconite sand with few shale partings, and many vertical and horizontal burrows, and intense bioturbation, rip up clasts and hummocky cross-stratification	Shallow marine: lower shoreface to offshore, at or below storm wave base (sediment starvation and marine flooding cycles observed, deepest environment observed)	Birkmose Mbr Reno Mbr
Flat pebble conglomerate	fine to medium quartz sand with hummocky cross-stratification, sandstone and muddy	Shallow marine: lower shoreface (storm deposits with high energy local rip-up	Tomah Mbr Saint Lawrence Fm

	clasts with 0.5-1-inch diameter along long axis.	clasts grading up into hummocks and lower energy sands)	
Glauconitic flat pebble conglomerate	fine to medium quartz and glauconite sand with well-rounded sandstone clasts with 0.5-1-inch diameter along long axis. Commonly exists between green wormstone facies, truncating its basal contact and grading into its upper contact	Shallow marine: lower shoreface (sediment starved interval interrupted by storm deposits with high energy local rip-up clasts grading up into hummocks and lower energy sands)	Birkmose Mbr Reno Mbr
Laminated mudstone	0.25-3-inch layers of brown, yellow and light-green shale, and flame structures	Shallow marine: tidal or transitional zone to offshore (clastic sedimentation is dominant distally in which only silt and clay particles deposit out of suspension)	Tunnel City Gp
Dolomite mudstone/micrite	gray to light brown lime mud with 0.5-1-inch silcrete nodules and vugs	Shallow marine: transitional zone below storm wave base (low levels of clastic sedimentation rates allow carbonate to dominate)	Prairie du Chien Gp Sinnipee Gp

Stratigraphy, Lithofacies, and Depositional Interpretation by County

Results of the core study are organized first by county and then by unit to deliberately describe each unit as it appears in its respective county to more easily observe lateral facies trends across the study area. Members and formations of groups are described and interpreted individually where they are most distinguishable and display unique lithofacies trends that can provide a greater understanding to changes in environment than if the unit was described as a whole.

Columbia County

Precambrian

The Precambrian is intercepted in one Columbia County core: Triemstra Quarry at an elevation of 438 feet mean sea level (msl). The Precambrian basement is a porphyritic alkali feldspar red granite with biotite and hornblende phenocrysts (Figure 5).

Elk Mound Group

The Elk Mound Group directly overlies the Precambrian basement and is made up of three formations: The Mount Simon, Eau Claire, and Wonewoc. Formation contacts are most easily identified in the west and become more undivided east toward Dodge County.

Mount Simon Formation

Lithofacies Description: Two lithofacies make up the Mount Simon in the Triemstra core: conglomerate and cross stratified sandstone. The Mount Simon Formation only appears in one Columbia County core, Triemstra, as a 323-foot-thick sandstone with a four-foot-thick basal conglomerate above the Precambrian granite basement. Immediately above the Precambrian red granite basement lies a four-foot-thick conglomerate with one-to-two- inch diameter granite and quartz clasts in a sand and mud matrix. Within the conglomerate facies, there are two distinct conglomerate layers each are one foot thick with an intermediate layer of bedded sand and mud. Immediately above the conglomerate lies a tan medium-to-coarse-grained, quartz sandstone with planar and trough cross beds, significant iron staining, and mm- to cm-scale black sulfide mineralization. Iron staining steadily decreases up the formation until it is nearly absent 100 feet above the basement. At this point, there is about 10 feet of coarse quartz sand with planar and trough cross beds with one four-inch unconsolidated horizon. Above the coarse layer, medium sands

with planar and trough cross beds and minimal iron staining resume throughout to the top of the Mount Simon.

Figure 5. Triemstra core, Box 58 and 59. Transition from Precambrian granite (bottom left) to Mount Simon sandstone (top right). Precambrian is outlined in red, conglomerate is outlined in purple, and Mount Simon sandstone is outlined in yellow.

Depositional Interpretation: The weathered Precambrian clasts of the basal Mount Simon conglomerate followed by medium to coarse sands with trough and cross beds suggest the Precambrian red granite was exposed prior to a rapid sea level rise. Medium and coarse sands can be stratified via shallow marine dune formation in the upper shoreface. The lithological consistence of sandstone throughout the 300+ foot thickness of the Mount Simon suggests a constant depositional environment, one that can only be maintained with this level of sediment accumulation by the constant fill of accommodation space likely by simultaneous sedimentation, subsidence, and sea level rise resulting in aggradational deposition and accommodation being filled as quickly as it forms. Locally, this would maintain relative sea level, depositional environment, and unchanging lithofacies.

Contact Description: The Mount Simon-Eau Claire contact is a sharp, erosional disconformity (Figure 6).

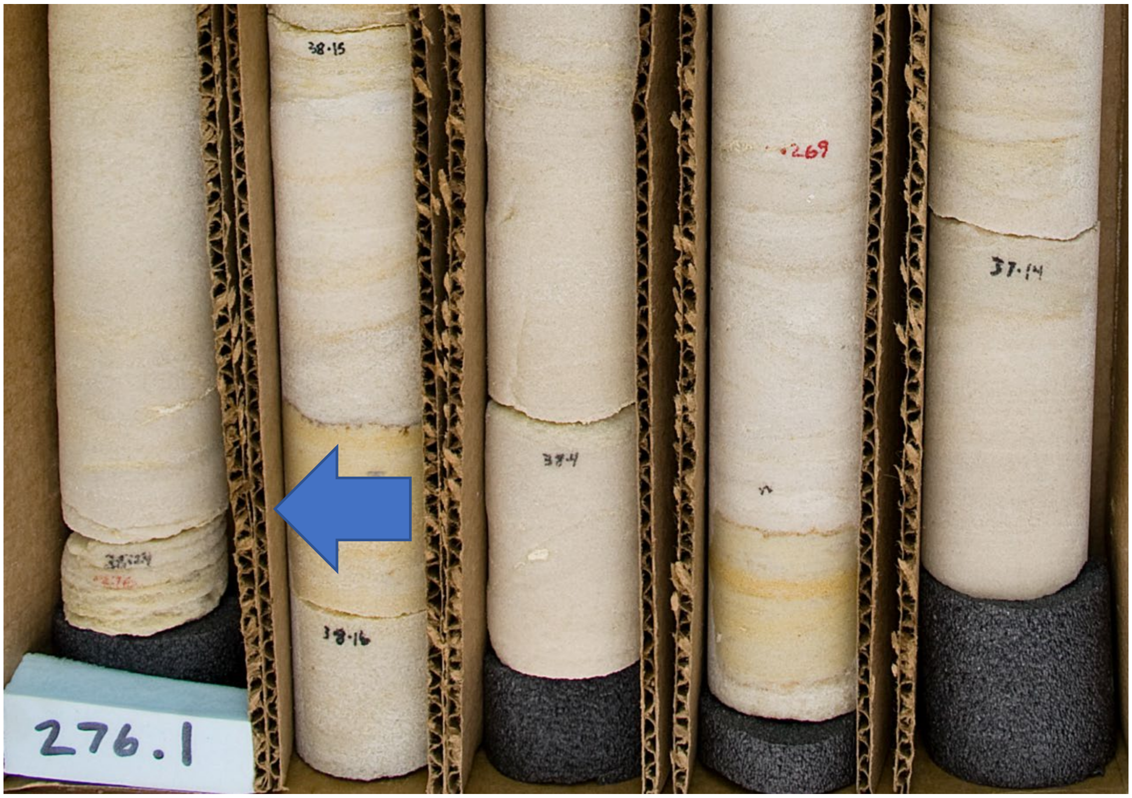


Figure 6. Triemstra Quarry, Box 26. Mount Simon-Eau Claire contact at 276 feet (bottom left). One-to-two-inch yellow silty bands in fine cross-bedded sandstone repeat throughout the Eau Claire.

Eau Claire Formation

Lithofacies Description: Four facies make up the Eau Claire Formation in Columbia County: fine bedded sandstone, hummocky cross-stratified sandstone, sandy dolomite, and bioturbated sandstone. The Eau Claire Formation is present in three Columbia County cores: Arlington Quarry, Stevenson 2, and Triemstra Quarry; as a 30 to 59-feet-thick, medium- to fine-grained, cross-bedded sandstone to sandy dolomite. The Eau Claire is slightly muddier than the Mount Simon, with bioturbation, burrows, and parasequences that include inch to foot-thick cross-bedded, fine to medium sands and

millimeter scale shale partings. In northern Columbia County, the Eau Claire is a tan to gray, medium- to fine-grained, cross-bedded sandstone with multiple one-two-inch bands of yellow siltstone (Figure 6). In the south, the Eau Claire is made up of alternating inch to foot-thick intervals of bioturbated sandy dolomite (Figure 7) and medium-grained, cross-bedded sandstone.

Figure 7. Stevenson 2, Box 18. Eau Claire sandy dolomite facies.

Depositional Interpretation: Cross-bedded sand and shale with hummocky cross-stratification is evidence for retrogradation from the lower shoreface to offshore transitional zone. Common layers of finer-grained material, bioturbation, and burrows are all additional evidence that the Eau Claire was deposited in a slightly deeper environment than the Mount Simon, suggesting a relative sea level rise.

Contact Description: The Eau Claire-Wonewoc contact is a planar, truncated, disconformable surface.

<u>Wonewoc Formation</u>

Lithofacies Description: Two facies make up the Wonewoc Formation: cross-bedded sandstone and fractured sandstone. The Wonewoc is present in six Columbia County cores: Arlington Quarry, Columbus 2, Hartmann Quarry, Salna, Stevenson 2, and Triemstra Quarry; and ranges in thickness from 42-231 feet and thickening to the northwest as it becomes less distinguishable from the lower Elk Mound units. The Wonewoc Formation is a white, tan, and pinkish, medium-to coarse-grained sandstone with planar and trough cross beds, few sandstone clasts, local inch-to foot-thick bands of weakly cemented sands, common mineralization of white material in pore spaces and along bedding planes (Figure 8), common minor fracturing/brittle offset, sulfide mineralization and iron staining.

Figure 8. Salna, Box 11. Wonewoc Formation with white, possible silcrete rip-up clasts.

Depositional Interpretation: The medium-to coarse-grained planar and trough cross beds present in the Wonewoc are attributed to the shallow marine environment of foreshore to upper shoreface. This interpretation suggests a slight sea-level fall relative to the deposition of the Eau Claire. The fractured sandstone facies can be attributed to syndepositional slumping and sliding of unconsolidated sediments along the sloped margin.

Contact Description: The Wonewoc-Tunnel City contact is a truncated to sharp erosional contact with local Wonewoc sandstone rip-up clasts in the glauconitic, lower Birkmose Member of the Tunnel City Group.

Tunnel City Group

The Tunnel City Group is present in all seven Columbia County cores: Arlington Quarry, Columbus 2, Hartmann Quarry, Rio 2, Salna, Stevenson 2, Triemstra Quarry, and Westphal 2; and ranges in thickness from 30 to 116 feet. The Tunnel City Group is made of two formations, Lone Rock and Mazomanie that are laterally discontinuous. The Mazomanie Formation is only present in northwest Columbia County, while the remainder of the Tunnel City is made up of the three Lone Rock members: Birkmose, Tomah, and Reno (Figure 9).

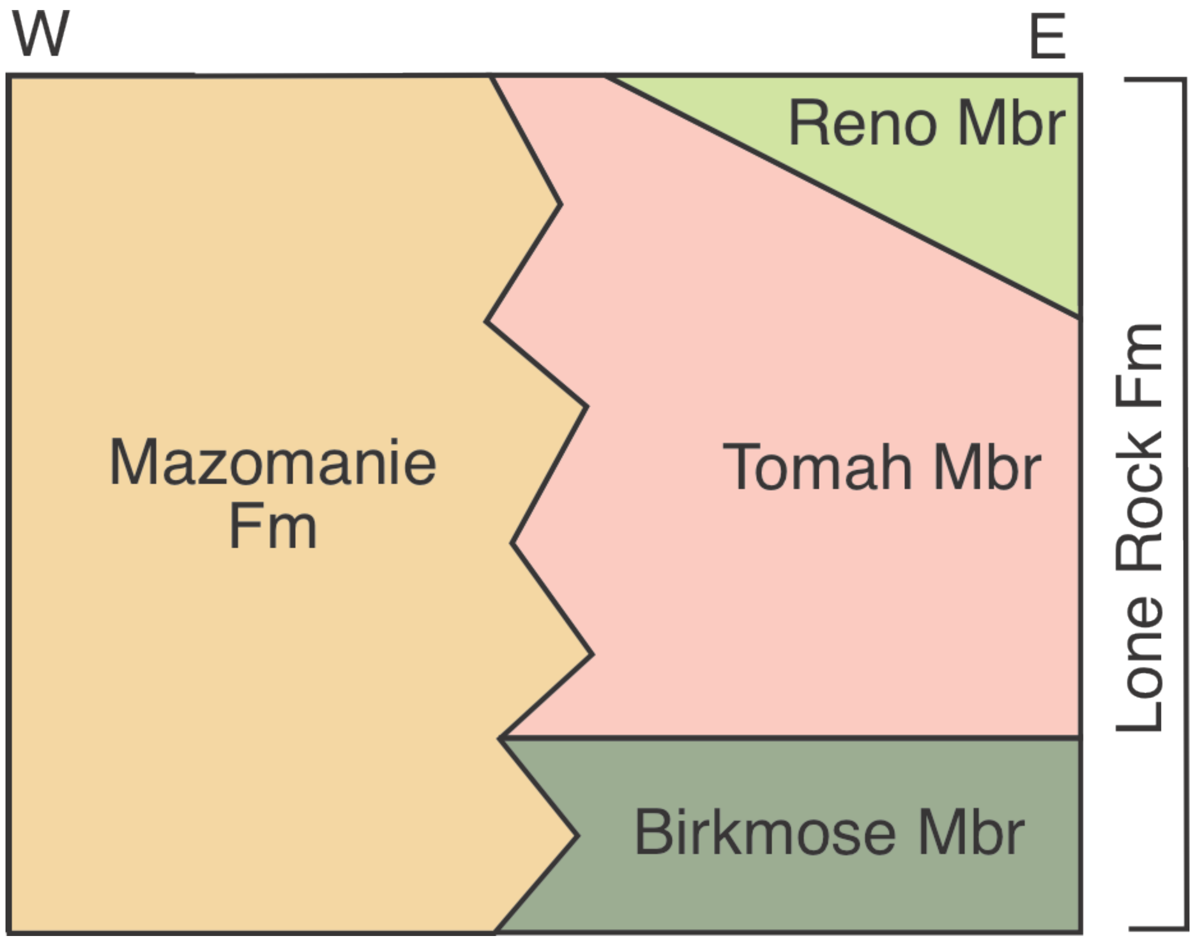


Figure 9. Tunnel City stratigraphic break down into respective formations members showing lateral and vertical distribution within the study area.

Lone Rock Formation

Seven facies make up the Lone Rock Formation: fine-grained, shaley, bioturbated sandstone (red wormstone); fine-grained, glauconitic, cross-stratified sandstone; fine-grained, glauconitic, bioturbated sandstone (green wormstone); hummocky cross-stratified sandstone, flat pebble conglomerate; glauconitic, flat-pebble conglomerate; and laminated mudstone. The Lone Rock Formation is 30-110 feet thick thickening to the east

and consists of three members: the lower Birkmose Member, the Tomah Member, and the upper Reno Member.

Lithofacies Description:

Birkmose Member

The Birkmose Member is four to 17 feet thick, thickening to the east. The Birkmose Member unconformably overlies the Wonewoc Formation and is identified by its heavily glauconitic green, fine-to medium-grained sandstone with planar and trough cross-beds, hummocky cross-stratification, and common bioturbation with silt-filled burrows (Figure 10 A). There are common two- to five-inch bands of flat pebble conglomerate or breccia with half inch sandstone clasts and glauconite matrix (Figure 10 B).

Figure 10. **(A)** Hartmann Quarry, Box 10. Birkmose Member medium-grained glauconite sands with bioturbation and siltstone filled burrows. **(B)** Stevenson 2, Box 9. Birkmose Member flat pebble conglomerate and rip-up clasts and vertical and horizontal burrows.

Tomah Member

The Tomah Member is 11 to 100 feet thick, thickening to the east. The primary lithology of the Tomah is a tan and maroon, fine- to medium-grained, quartz and glauconite, bioturbated sandstone with vertical and horizontal silt-filled burrows that convolute shaping of bedding planes referred to as wormstone (Figure 11 A).

In areas of lesser bioturbation, planar cross beds and hummocky cross-stratification can be identified. There are common three- to six-inch horizons of flat-pebble conglomerate (Figure 11 B). The upper Tomah Member includes a three-inch to two-foot-thick marker bed that is maroon, green, and tan interlaminated fine-grained sandstone and mudstone with some small-scale faulting caused by brittle offset, rip-up clasts, possible burrows, and low-angle ripples. This horizon occurs within the upper five to eight feet of the Tunnel City-Trempealeau contact and serves as a marker bed seen across Columbia and Dodge Counties (Figure 11 C).

Figure 11. (**A)** Arlington Quarry, Box 11. Tomah Member "wormstone".

(B) Rio 2, Box 9. Tunnel City Tomah Member flat pebble conglomerate and burrows.

(C) Rio 2, Box 7. Upper Tomah laminated mudstone marker bed observed in Columbia County.

Reno Member

The Reno Member is about 28 feet thick. The unit is a green, white, and tan, fine- to medium-grained quartz and glauconite sandstone with bioturbated wormstone beds (Figure 12) and some visible planar and hummocky cross-stratification. The Reno is only present in the Triemstra Quarry core and seems to be replaced laterally by the Tomah Member in cores to the south. No erosional surfaces have been identified suggesting the Reno is only deposited in the further offshore setting.

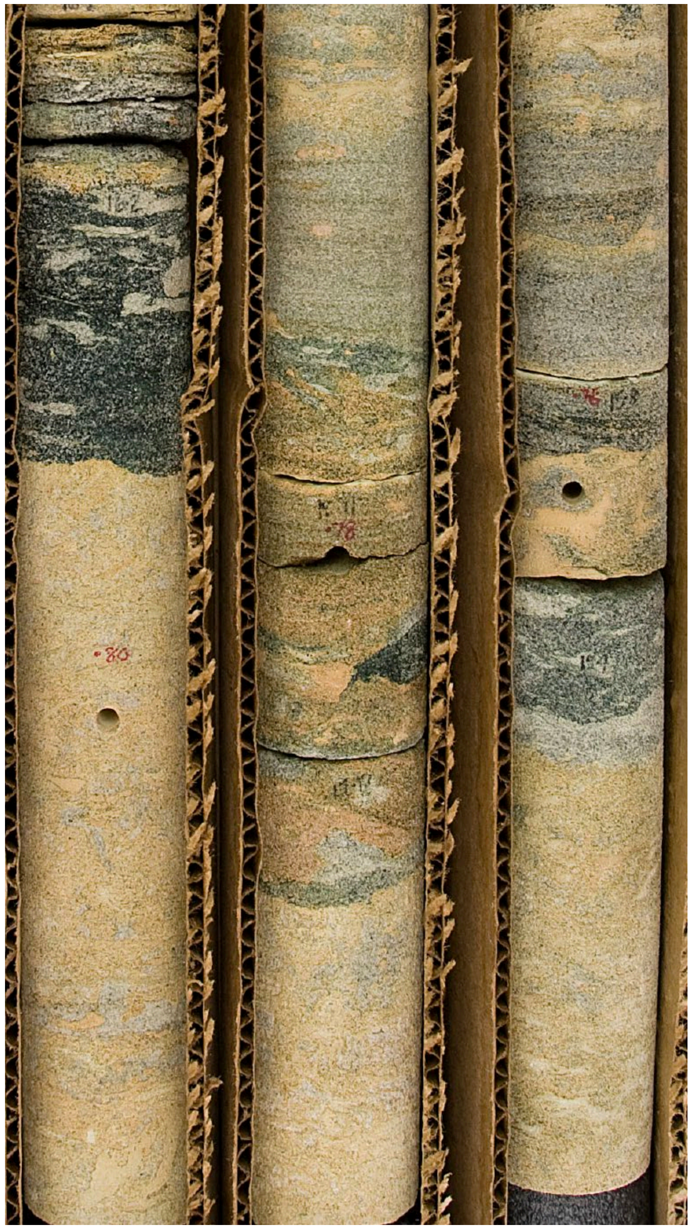


Figure 12. Triemstra Quarry, Box 8. Reno green and tan “wormstone”.

Depositional Interpretation: Bioturbation in the fine-grained sands and mud of the wormstone facies suggests deposition in a shallow marine setting in the lower shoreface to offshore transitional zone near storm wave base in which there was a constant influx of sediment and relatively low energy favorable for marine faunal dwelling. Glauconite

typically forms in submarine, low-energy, sediment-starved settings and will occur in condensed intervals with an upward decrease in concentrations during the height of marine flooding events (Middleton, 2003). The high concentrations of glauconite in the Birkmose and Reno Members suggest marine flooding events making these Lone Rock members the deepest deposits described in this study. Glauconite forms as primary mineralization in further offshore, suboxic conditions where coarse clastic sedimentation is trapped further. Flat pebble conglomerate layers are interpreted to be sandstone rip-up clasts that are introduced during storm events. The laminated mudstone marker bed is a low energy deposit interpreted to be a transition between the fine sand red wormstone facies of the Tomah Member (more proximal), and the sediment-starved glauconitic facies (more distal) of the Reno Member, in which only silt and mud are deposited (Figure 13).

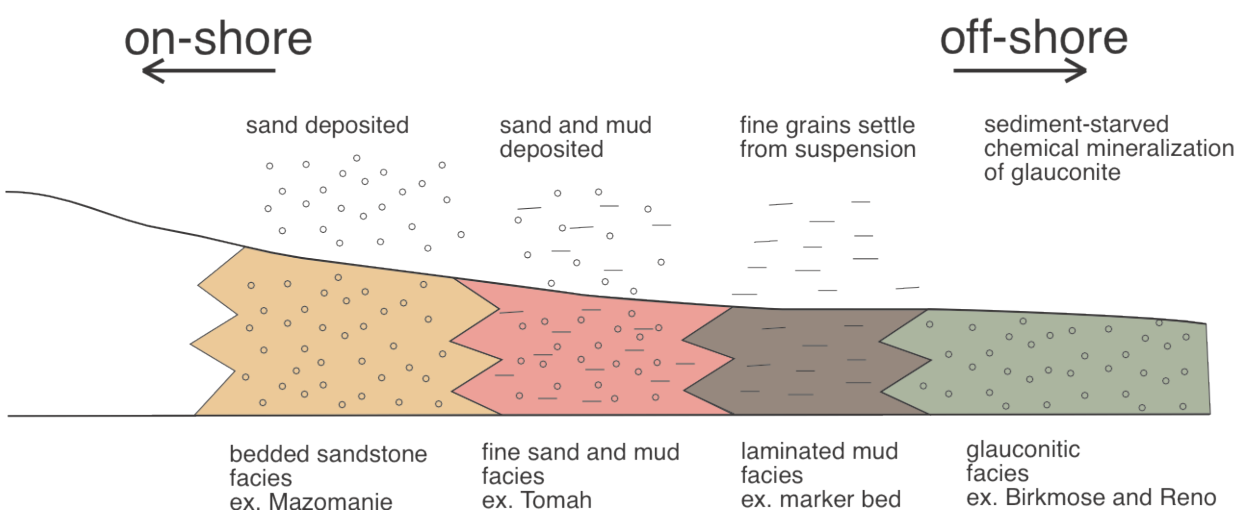


Figure 13. Facies Model: Lateral distribution of Tunnel City Formation

Contact Description: The contact between the Lone Rock Formation of the Tunnel City Group and the overlying Saint Lawrence Formation of the Trempealeau Group is a gradual transition characterized by deposits of the Reno Member fining upward into fine-grained, limier deposits of the Saint Lawrence Formation. In areas where the Saint Lawrence directly overlies the Tomah or Mazomanie Formations, there is a sharp disconformable surface.

Mazomanie Formation

Lithofacies Description: Two facies make up the Mazomanie Formation: cross stratified sandstone, and fractured sandstone. The Mazomanie is only present in one Columbia County core, Salna, and is at least 66 feet thick. The Mazomanie is a red to tan coarse to medium-grained quartz sandstone with planar and trough cross beds, brittle fractures, and uncommon bioturbation with common sulfide mineralization and iron staining (Figure 14).

Figure 14. Salna. Box 4. Mazomanie Formation cross-bedded sandstone.

Depositional Interpretation: Planar and trough cross beds in coarse sand are evidence of marine transport and formation of ripples and dunes indicating an upper shoreface environment at or above fair-weather wave base. Lithofacies in conjunction with geographic occurrence further west, on top of the arch, suggests the Mazomanie is a nearshore equivalent to the Lone Rock Formation. Fractured sandstone suggests syndepositonal deformation of sands such as slumping and sliding of unconsolidated sediments along a sloped margin that resulted in small scale normal faults.

Trempealeau Group

The Trempealeau Group is present in six Columbia County cores: Arlington Quarry, Columbus 2, Hartmann Quarry, Rio 2, Stevenson 2, Triemstra Quarry, and Westphal 2. Two formations make up the Trempealeau Group: the lower Saint Lawrence and upper Jordan Formation; and has a total thickness of about 10 to 50 feet.

<u>Saint Lawrence Formation</u>

Lithofacies Description: Four facies make up the Saint Lawrence Formation: sandy dolomite, shaly sandstone, hummocky cross-stratified sandstone, and cross-stratified sandstone. The Saint Lawrence Formation is present in five Columbia County cores: Arlington Quarry, Hartmann Quarry, Rio 2, Stevenson 2, Triemstra Quarry, and Westphal 2; and ranges in thickness from 8 to 33 ft, pinching out to the east. The Saint Lawrence ranges in composition from a tan to gray, bioturbated, sandy dolomite with millimeter- to- centimeter-scale, light green to tan, shale partings (Figure 15) to a tan, fine- to medium-grained sandstone with planar cross-beds, hummocky cross-stratification, and some weakly cemented intervals.

Figure 15. Rio 2, Box 3. Saint Lawrence sandy dolomite facies.

Depositional Interpretation: Fine grained dolomite with interbedded sands indicate low background clastic sedimentation rates, which must have occurred to allow for carbonate to form. Storm events transported pulses of sand further offshore into the carbonate-dominant region creating sandy dolomite. The low-angle planar cross-bedded sandstones and shaly sandstone facies with hummocky cross-stratification indicates a frequent transition from higher to lower energy in which larger grains were deposited during times

of high energy and finer silt and clay particles deposited during lower energy or suspension settling. These finer lithologies could be related to storms that transported and deposited sands, followed by settling of finer grains when storms subsided. The Saint Lawrence is interpreted as deposited in a shallow marine lower shoreface to offshore transitional zone environment below fair-weather wave base and above storm wave base. This depositional environment is shallower than that of the Tunnel City Group indicating a relative fall in sea level.

Contact Description: The Saint Lawrence Formation underlies the Jordan Formation across a gradational, conformable contact.

<u>Jordan Formation</u>

Lithofacies Description: Two facies make up the Jordan Formation: cross stratified sandstone and shaley sandstone. The Jordan Formation is present in six Columbia County cores: Arlington Quarry, Columbus 2, Hartmann Quarry, Rio 2, Stevenson 2, Triemstra Quarry, and Westphal 2; and ranges in thickness from 14 to 39 feet. The Jordan Formation is a tan to white, medium-grained, moderately sorted, quartz sandstone with planar cross-beds with 0.5-5-inch beds, millimeter-scale light green shale partings, and carbonate cement (Figure 16).

Figure 16. Arlington Quarry, Box 5. Jordan Formation shaly sandstone facies (left) and cross-bedded sandstone facies (right).

Depositional Interpretation: The low angle planar cross-bedded sandstones and shaly sandstone facies indicate a frequent transition from higher to lower energy in which larger grains are deposited during times of high energy and finer silt and clay particles are deposited during lower energy or settling. These lithofacies are related to foreshore to shoreface environment in which background sedimentation was coarse clastics, and finer grained silt and mud are indicative of slight marine flooding that is observed at the base of parasequence sets. The lack of carbonate and bioturbation in this facies indicates either higher sedimentation rates consistent with a shallower depositional setting, which could indicate a fall in relative sea level.

Contact Description: The Jordan Formation unconformably underlies a sharp erosional contact with the Prairie du Chien Group and commonly is characterized by silcrete accumulations within the uppermost five feet. The base of the Prairie du Chien commonly includes a very coarse one- to- three-inch horizon of white, very coarse peloid-rich sand with calcite cement, casually referred to by WGNHS as the "bubble rock" marker bed (Figure 17).

Figure 17. Hartmann Quarry, Box 3. Jordan (bottom)- Prairie du Chien "bubble rock" (top) contact.

Prairie du Chien Group

Lithofacies Description: Nine facies make up the Prairie du Chien Group in Columbia County: dolomite wackestones, sandy dolomite, silcritic dolomite, karst mottled dolomite, hummocky cross-stratified dolomite, thrombolytic dolomite, massive sandstone, paleosol, and soft sediment deformed strata. The Prairie du Chien Group is present in five Columbia County cores: Arlington Quarry, Columbus 2, Hartmann Quarry, Stevenson 2, and Triemstra Quarry; is 0-34.5 feet thick and is undivided into its respective members due to common brecciation, karst mottling, and deformational

horizons. The Prairie du Chien is most commonly a yellowish gray sandy dolomite wackstone with 1-5-inch yellow medium to coarse sand lenses, common hummocky cross-stratification, up to 1.5-inch diameter calcite filled vugs, 2-inch white silcrete nodules, brachiopods, stromatolites (Figure 18), and dendritic thrombolytic texture. These facies repeat in coarsening upward parasequences (Figure 19) from fossil-poor dolomite wackestones to thrombolytic texture, to sandy, silcritic and karst mottled texture, repeating every 6 inches to 3 feet.

Figure 18. Columbus 2, Box 4. Stromatolite in Prairie du Chien sandy dolomite facies

Figure 19. Arlington Quarry, Box 2. Prairie du Chien coarsening upwards parasequences. Lower strata in bottom left, upper strata in top right. Each parasequence outlined in a different color.

Depositional Interpretation: The Prairie du Chien is primarily carbonate with an abundance of fossils fragments, stromatolites, and thrombolites which suggests relatively low influx of clastic sedimentation and moderate wave agitation. The Prairie du Chein was most likely deposited in the lower shoreface to transitional zone. The presence of these facies suggests either a pause in clastic sedimentation, a slight sea level rise, or both in relation to the deposition of the Jordan. Silcritic dolomite and karst mottled dolomite are secondary facies that result from post-depositional, post-exhumation Ordovician exposure. Silcrete formation occurred during prolonged periods of subaerial exposure, while karst-mottled textures are related to a process that occurs in horizons at or near the ground surface where rainwater and groundwater mixing produces an aggressive solution capable of dissolving carbonate. Karsting may be extensive enough to produce failure and karst collapse at small or large scale which could result in karst-fill of finer grained sediments from paleosols or other unconsolidated material resting atop the carbonate. These facies suggest a rapid sea level fall, and a period of at or near-surface exposure of the Prairie du Chien after its deposition.

Contact Description: The Prairie du Chien- Saint Peter Contact is erosional and includes a gradual 10-foot-thick deformed contact with an upper one- to-two-foot horizon of poorly cemented, dark brown mud with soft sediment deformation (Figure 20).

Figure 20. Prairie du Chien- Saint Peter deformed contact. **(A)** Columbus 2, Box 3. Upper Prairie Du Chien bedded silty dolomite with siltstone breccia or mud cracks, dewatering structures, angular silcrete and siltstone rip-up clasts, secondary silcritic porosity, and possible burrows. **(B)** Columbus 2, Box 2. Soft-sediment deformation, angular millimeter-scale silcrete and lime mud rip-up clasts.

Ancell Group

One Columbia County core, Columbus 2, preserves the Ancell Group which only includes the Saint Peter Formation; the upper, Glenwood Formation has not been identified.

Saint Peter Formation

The Saint Peter Formation is broken up into two members the lower, Readstown Member which makes up the entirety of the 17.5-foot-thick Saint Peter Formation in the Columbus 2 core, and the upper, Tonti Member which is not preserved in any Columbia County cores.

Readstown Member

Lithofacies Description: Two facies make up the Readstown Member: a lower brecciated silcritic sandstone, and an upper massive sandstone. The Readstown Member is a white and tan medium quartz sand with abundant silcrete, brecciation, and rip-up clasts (Figure 21). This member commonly exhibits poor cementation and minor sulfide mineralization.

(right).

Figure 21. Columbus 2, Box 1. Saint Peter Formation Readstown Member lower brecciated silcritic sandstone facies (left) and upper massive sandstone facies (right).

Depositional Interpretation: These brecciated, heavily silcritic facies are interpreted to be terrestrial mass wasting events along a sloped or karsted topography. Brecciation in the silcritic sands suggests prolonged exposure and weathering from a proximal source, followed by short-distance transport from karst collapse. Additionally, lack of bedding in the massive sands indicates disturbance that erased original structures. The Readstown sandstone breccia was deposited in a nonmarine, terrestrial environment following a sea level fall and subsequent erosional event after the deposition of the Prairie du Chien.

Contact Description: Typically, the Tonti Member conformably overlies the Readstown Member in southeast Wisconsin but the Tonti Member is absent in the one Columbia County core containing the Saint Peter Formation. Here, the Sinnipee Group overlies the Readstown across an abrupt truncated surface.

Sinnipee Group

The Sinnipee Group contains three formations: the Platteville, Decorah, and Galena, but only the Platteville is preserved in the available cores of Columbia County due to erosion of overlying units.

Platteville Formation

Lithofacies Description: One facies makes up the Platteville Formation in available Columbia County cores, sandy dolomite wackestone. Due to bedrock surface, only 1.5 feet of the Sinnipee Group is preserved in one Columbia County core: Columbus 2, and is inferred to be the lowermost formation of the group: the Platteville Formation. The

Platteville Formation is a tan to gray very sandy dolomite with medium sandstone rip-up clasts at its base.

Depositional Interpretation: The abundance of fossils fragments and lack of clastic material suggests deposition in a heavily carbonate-dominant environment with moderate wave energy in the transitional zone between fair-weather wave base and storm wave base. These facies suggest a relative rise in sea level after the deposition of the Saint Peter.

Dodge County

Precambrian

The Precambrian basement is intercepted in one Dodge County core: Slinger; at an elevation of 402.5 feet msl. The Precambrian basement is the Baraboo-interval late Paleoproterozoic Iron Formation (Lamb and Stewart, 2016), a dark red and black, iron-rich, sedimentary layer with one- to two- millimeter pink, black, and white bands (Figure 22).

Figure 22. Slinger, Box 49. Dark red and brown iron-rich Precambrian basement from the Baraboo-interval late Paleoproterozoic Iron Formation.

Elk Mound Group

The Elk Mound Group appears in six Dodge County Cores: Alsum 4, Buchda Quarry, Keel, Miller Quarry, Slinger, and Westphal 2; and is at least 560 feet thick in some places. The Elk Mound is broken into three formations: the lower Mount Simon, the Eau Claire, and the upper Wonewoc; all of which are present in Dodge County.

Mount Simon Formation

Lithofacies Description: Four lithofacies make up the Mount Simon Formation: conglomerate, fractured sandstone, hummocky cross-stratified sandstone, and shaly sandstone. The Mount Simon Formation is present in three Dodge County cores: Keel, Miller Quarry, and Westphal 2; and reaches a thickness between 194 and 251 feet before core retrieval ends. The Mount Simon is estimated to be at least 200 feet thick based on one core that intersects a conglomerate at 194 feet below the top of the Mount Simon. A basal conglomerate (Figure 23) is observed in one Columbia County core just before intersecting the Precambrian basement. The Elk Mound Group at its base includes red and white medium arkosic sand with fractured planar cross beds, followed by pebbly layers and two five-foot intervals of sandy conglomerate with 1-4 cm in diameter granite, gneiss, quartz, and chert clasts. This pebbly fractured sandstone and sandy conglomerate make up the lowermost 38 feet of the Mount Simon preserved in core. A sharp surface separates the Mount Simon conglomerate from the Mount Simon sandstone; a white, medium- and fine-grained, quartz sand with planar cross beds, hummocky cross-stratification, iron staining and sulfide mineralization, and gray shale partings.

Figure 23. Keel, Box 78. Mount Simon basal conglomerate. Lower strata in bottom left, upper strata in top right.

Depositional Interpretation: Weathered, angular, crystalline clasts in the basal conglomerate suggest the Precambrian arch was subaerially exposed prior to the deposition of the Mount Simon. The dominant lithofacies of the Mount Simon, medium-to- coarse-grained cross-stratified sandstone, suggests water as a mechanism of sediment reworking. The extent of the Mount Simon would suggest it was part of a nearshore marine setting in the foreshore to upper shoreface at or above fair-weather wave base. The Mount Simon in Dodge County includes more shale partings than its time equivalent deposits in Columbia County, suggesting a slightly deeper setting that allowed for finer grains to settle from suspension. This transition from terrestrial to nearshore marine, along with the Mount Simon's thickening and greater inclusion of shale across Dodge County to the east would indicate a sea level rise that onlapped the Precambrian Wisconsin arch.

Contact Description: The Mount Simon-Eau Claire contact is a gradual transition from predominately medium-grained sands to fine-gained sands with increased levels of bioturbation and or shale partings.

Eau Claire Formation

Lithofacies Description: There are four facies in the Eau Claire: shaly sandstone, cross-stratified sandstone, hummocky cross-stratified sandstone, and fine-grained, shaly, bioturbated sandstone (Figure 24). The Eau Claire Formation is present in four Dodge County cores: Keel, Miller Quarry, Slinger, and Westphal 2; and ranges in thickness from 96-143 feet. The Eau Claire is a white, gray, to pink, fine-grained, planar-bedded, quartz

sandstone with gray and light-green shale partings, uncommon bioturbation, uncommon sulfide mineralization, and carbonate cement.

Figure 24. Keel, Box 51. Eau Claire fine sandstone with shale partings and bioturbation.

Depositional Interpretation: The finer grains and greater concentration of shale partings in the Eau Claire indicates slightly a lower energy environment relative to the Mount Simon. Cross-bedded fine-grained sand and shale suggest a shallow marine lower shoreface environment at fair-weather wave base. The presence of burrows in the finer grained material also suggests a deepening with low-energy waters ideal for marine organism dwelling. These depositional interpretations suggest a sea level rise following the deposition of the Mount Simon.

Contact Description: The Eau Claire-Wonewoc contact is a sharp contact between fine grained sands with shale partings below to a coarse grained fine to medium sand above.

<u>Wonewoc Formation</u>

Lithofacies Description: There are four lithofacies in the Wonewoc: cross-stratified sandstone; hummocky cross-stratified sandstone, fractured sandstone; and shaly sandstone. The Wonewoc is present in six Dodge County cores: Alsum 4, Buchda Quarry, Keel, Miller Quarry, Slinger, and Westphal 2; and is 132-244 feet thick. The Wonewoc sandstone is dominantly a white to tan medium- to coarse-grained quartz sandstone with planar and trough cross beds, uncommon hummocks, carbonate cement, uncommon sulfide mineralization, and few millimeter-scale wispy shale partings (Figure 25). There are two, less common, local lithofacies observed: very shaly sandstone with white, medium, quartz sand interbedded with 0.5-inch light green shale partings and small-scale iron staining (Figure 26); and high-angle, fractured, white, medium, quartz sandstone with abundant sulfide mineralization that is devoid of bedding and sedimentary structures (Figure 27).

Figure 25. Miller Quarry, Box 36. Wonewoc Formation cross-stratified, medium-grained sandstone facies.

Figure 26. Slinger, Box 30. Wonewoc Formation fractured sandstone facies with abundant sulfide mineralization.

Figure 27. Keel, Box 41. Wonewoc Formation shaly sandstone facies.

Depositional Interpretation: The dominant cross-stratified sandstone facies is attributed to a shallow marine in the foreshore to upper shoreface setting due to its sheet-like geometry and the presence of medium-to coarse-grained, bedded sands which are only observed in places where water is the mechanism of flow. A shallow marine upper shoreface environment would allow for this level of widespread stratification of coarse sands, suggesting a slight sea level fall relative to the deposition of the Eau Claire. The shaly sandstone facies is interpreted to be a lower shoreface environment implying a rise in sea level and a decrease in energy allowing for finer sediment to settle from suspension as background deposition while pulses of sand are introduced during storm deposits. The lack of bedding in the fractured sandstone facies suggests secondary fluid flow related to sulfide mineralization obscured sedimentary structures, or that syndepositional disturbance of sands, possibly by slumping and sliding, resulted in faults and erasure of any would-be sedimentary structures. The proximity of the Precambrian arch and fluctuating sea levels suggest mineralization may have originated from dissolved sulfides that were secondarily deposited in the porous fractures at this horizon in the Wonewoc.

Contact Description: The Tunnel City overlies the Wonewoc across an abrupt, sharp surface (Figure 28 A,B) in which the Wonewoc is overlain by heavily glauconitic sand beds with common millimeter-to centimeter-scale Wonewoc sandstone rip-up clasts (Figure 28 C).

Figure 28. Wonewoc-Tunnel City contact. **(A, B)** Alsum 4, Box 29. Sharp contact between Wonewoc clean sandstone (bottom), and Tunnel City glauconitic sandstone (top). Lower strata in bottom left, upper strata in top right. **(C)** Slinger, Box 22. Erosional contact with millimeter-to centimeter-scale Wonewoc rip-up clasts.

Tunnel City Group

The Tunnel City Group is present in seven Dodge County cores: Alsum 4, Bleeker, Buchda Quarry, Keel, Miller Quarry, Slinger, and Westphal 2; and ranges in thickness from 70 to 110 feet divided into two formations: the Lone Rock Formation and the Mazomanie Formation.

Lone Rock Formation

Lithofacies Description: Six facies make up the Lone Rock Formation in Dodge County: fine-grained, shaly bioturbated sandstone (red wormstone); fine-grained, glauconitic, cross-stratified sandstone; fine-grained, glauconitic, bioturbated sandstone (green wormstone); glauconitic, flat-pebble conglomerate; hummocky cross-stratified sandstone, and laminated mudstone. All three Lone Rock members are present in Dodge County.

Birkmose Member

The Birkmose Member is 6 to 11 feet thick and unconformably overlies the Wonewoc Formation. The Birkmose is the most glauconitic member of the Tunnel City (Figure 29) but is identified by its fine-to medium-grained heavily bioturbated arkosic sands and inch- to foot-scale heavily glauconitic beds (Figure 29 B and C) with planar and trough cross beds, carbonate cement, bioturbation, vertical and horizontal burrows (Figure 29 D and E), sulfide mineralization, and sandstone rip-up clasts. Flat pebble conglomerate rip-up layers are 2-4 inches thick with up to one inch sandstone clasts.

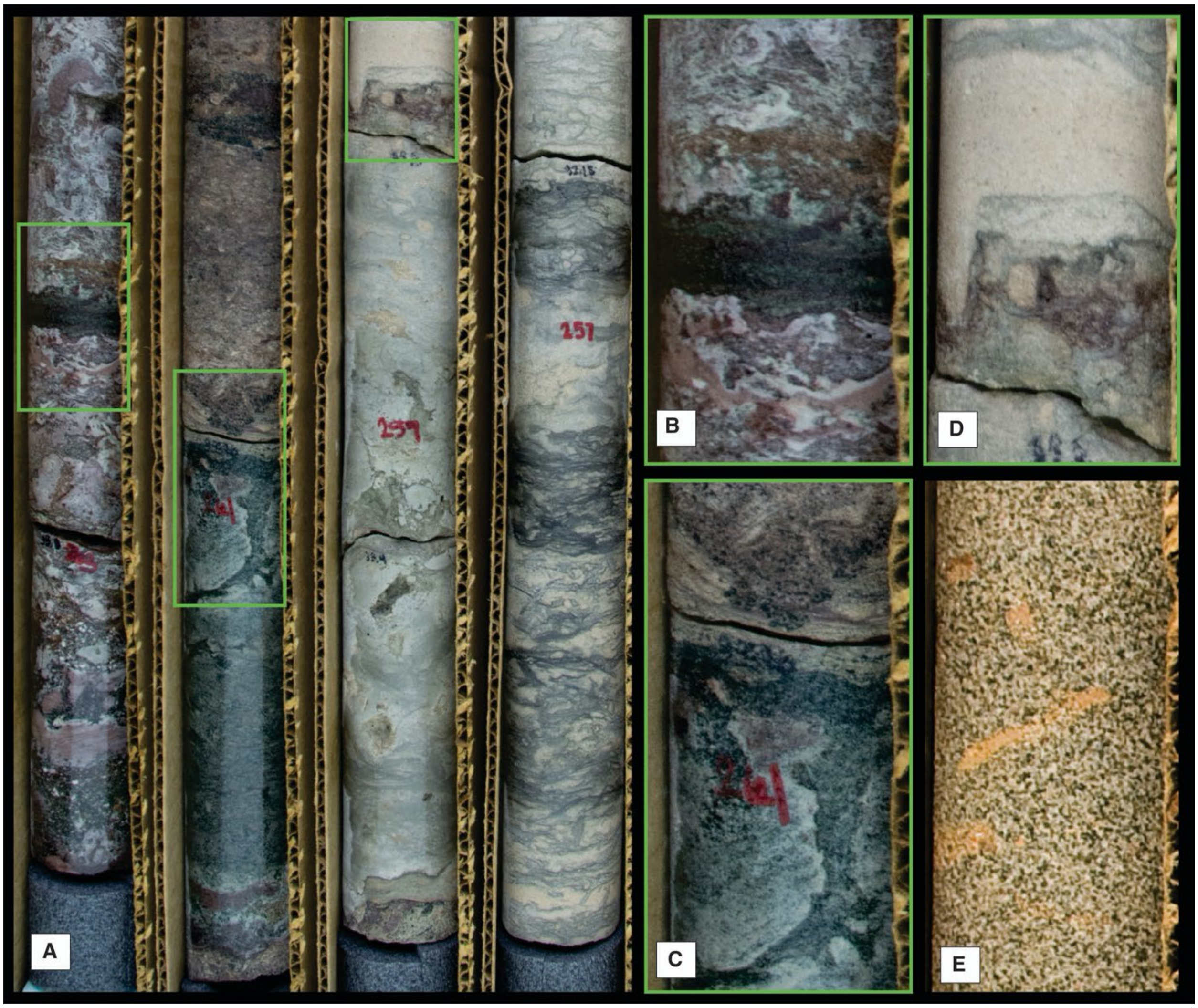


Figure 29. Birkmose Member. **(A)** Westphal 2, Box 28. **(B, C)** heavily glauconitic and bioturbated sandstone beds. **(D)** Vertical sandstone burrows. **(E)** Alsum 4, Box 29. Horizontal, fine sand to silt-filled burrows.

Tomah Member

The Tomah Member a 21- to 54-foot-thick tan and maroon “wormstone” with fine- to medium-grained quartz, and little glauconite, bioturbated sandstone with bioturbated planar beds, horizontal and vertical burrows, hummocky cross-stratification, carbonate cement, and uncommon sulfide mineralization. The

Tomah is muddier than its equivalent in Columbia County and includes many well-preserved small-scale sandstone load structures and associated finer-grained diapiric flame structures (Figure 30).

Figure 30. Buchda Quarry, Box 40. Tunnel City Tomah Member millimeter-to centimeter- scale flame structures.

The laminated marker bed seen across Columbia County near the Tunnel City-Trempealeau contact also appears in Dodge County in the upper five to ten feet of the Tomah Member. This marker bed is a three- to 14-inch-thick interlaminated fine-grained sandstone and mudstone unit with some minor faulting, rip-up clasts, possible burrows, and low-angle ripples (Figure 31).

Figure 31. Slinger, Box 14. Tunnel City Tomah Member laminated mudstone marker bed with interlaminated fine-grained sandstone and mudstone unit with some minor faulting, rip-up clasts, possible burrows, and low-angle ripples.

Reno Member

The Reno Member is thicker, better pronounced, and more glauconite-rich in Dodge County. The Reno is a 21 to 36 foot-thick, fine-to medium-grained quartz and glauconite, green “wormstone” with multiple glauconite-rich horizons, hummocky cross-stratification, and rip up clasts of underlying Tomah and Reno “wormstone” that can be 1-8 inches thick (Figure 32). In areas where bioturbation is absent, planar and trough cross beds can be observed.

Figure 32. Miller Quarry, Box 28. Tunnel City Reno Member (above and to the right of marker "266") with centimeter-scale rip-up clasts of underlying Tomah "wormstone" (below and to the left of marker "266") in glauconite sand.

Depositional Interpretation: The fine sands interbedded with mud of the "wormstone facies" and hummocky cross-stratification suggest deposition in a shallow marine offshore transitional zone near storm wave base in which there was a constant influx of sediment and relative low energy favorable for marine faunal dwelling. Glauconitic horizons are indicative of sediment starvation brought on my marine flooding (cf. Middleton, 2003) suggesting a slight deepening in which sedimentation is trapped further up-shore during intervals of relative sea level rise. Hummocks and flat pebble conglomerates are formed at storm wave base during high-energy storm events that rip-up and rework surrounding sands and mud and depositing them atop truncated surfaces followed by settling out into finer grained sediments grading up into background sedimentation. This environment would suggest a relative sea level rise after the deposition of the Wonewoc possibly due to either retrogradation of the shoreface or due to a rise in eustatic sea level. The laminated mud facies is indicative of a transition between the fine-grained sandstone red wormstone facies (further up-shore) and the sediment-starved glauconitic facies (further down-shore) in which only silt and mud are deposited.

Contact Description: The contact between the Lone Rock Formation and the overlying Saint Lawrence Formation is a gradual transition into fine-grained, lower energy sediments.

<u>Mazomanie Formation</u>

Lithofacies Description: Two facies make up the Mazomanie Formation: cross-stratified

sandstone and bioturbated sandstone. The Mazomanie Formation is only present in one northwestern Dodge County core, Alsum 4, suggesting it is laterally discontinuous to the southeast. The Mazomanie is a 56-foot thick, yellow and white, coarse-grained, quartz arenite sandstone that includes two lithofacies: cross-bedded sandstone, and bioturbated sandstone. The Mazomanie sandstone commonly includes planar and trough cross beds, bioturbation, vertical and horizontal burrows, carbonate cement, and one two-inch horizon of rip-up clasts surrounded by medium glauconite grains (Figure 33). The Mazomanie lies between the Tomah and Reno Members and is in sharp contact with these units.

Figure 33. Alsum 4, Box 25. Mazomanie Formation cross-stratified sandstone facies and bioturbated sandstone facies overlain (top right corner) by a glauconitic sandstone bed with centimeter-scale Mazomanie sandstone rip-up clasts.

Depositional Interpretation: Bioturbation, medium-to coarse planar and trough cross beds and formation of ripples and dunes indicate a shallow marine upper shoreface

environment. This environment is shallower than the time-equivalent, further offshore, Lone Rock Formation to the east.

Trempealeau Group

The Trempealeau Group is intercepted by seven cores in Dodge County: Alsum 4, Bleeker, Buchda Quarry, Keel, Miller Quarry, Slinger, and Westphal 2; and is 15 to 66 feet thick and subdivided into two formations: The lower St. Lawrence; and the upper Jordan Formation. The two become interbedded and contacts are less easily distinguishable in Dodge County.

Saint Lawrence Formation

Lithofacies Description: Seven facies make up the Saint Lawrence Formation: dolomite wackestones; silty dolomite; sandy dolomite; shaly sandstone; hummocky cross-stratified dolomite, bioturbated sandstone, and cross-stratified sandstone. The Saint Lawrence is a 4 to 22 feet thick tan to gray carbonate with varying levels of silt and sand with pink or green shale partings, hummocks, brachiopod fossils and vugs; to a tan to gray fine- to-medium-grained, poorly sorted, silty, quartz sandstone with planar cross beds, bioturbation, and vertical and horizontal burrows (Figure 34).

Figure 34. Bleeker, Box 21. Saint Lawrence Formation sandy dolomite facies with bioturbation and burrows.

Depositional Interpretation: These carbonate and clastic facies of the Saint Lawrence Formation interfinger throughout Dodge County suggesting a consistent change in energy, sedimentation, and carbonate production. Hummocks and bioturbation indicate the Saint Lawrence was deposited in a lower shoreface to transitional zone environment. The dolomite wackestones facies is related to a low-energy carbonate factory environment, silty dolomites are related to a slightly shallowing to an environment in which silt particles could settle out of suspension, sandy dolomites are related to the pulsation of sands into a carbonate-dominant setting during storm events. The shaly sandstone facies suggests shallower environments in which sand are more common, facies coarsen upward into the Jordan sandstones where the cross-stratified sandstone facies is dominant.

Contact Description: The Saint Lawrence-Jordan contact varies from gradual to sharp based on formation thicknesses. In locations where the Saint Lawrence is thinner and the Jordan is thicker, the contact is sharp suggesting a local inconformity in which the Saint Lawrence was down-cut prior to deposition of the Jordan. In places where a gradual contact is preserved, there are multiple beds of alternating dolomite and sand that coarsen upward suggesting an overall shallowing.

Jordan Formation

Lithofacies Description: Two facies make up the Jordan Formation: cross stratified sandstone and shaly sandstone. The Jordan sandstone is seven to 44 feet thick, thinning to the northeast. The dominant lithofacies is a white, yellow, and tan, medium- to- coarse-

grained, well-sorted quartz sandstone with common light green shale partings, planar and trough cross beds (Figure 35), and local weak cementation.

Figure 35. Alsum 4, Box 19. Jordan Formation medium to coarse-grained cross-bedded sandstone with shale partings.

Depositional Interpretation: The planar and trough cross-bedded sandstones and shaly sandstone facies indicate a frequent transition from higher to lower energy in which larger grains are deposited during times of high energy and finer silt and clay particles are deposited during lower energy or settling. These lithologies are related to an upper to lower shoreface environment in which alternating high and low energy conditions result in deposition of coarse- and fine-grained sediments, respectively. This facies lacks dolomite suggesting either a greater background rate of sedimentation, or that this facies is further onshore from the St. Lawrence, indicating a slight fall in sea level.

Contact Description: The upper Jordan Formation is unconformable with the overlying Prairie du Chien Group. Locally, the Jordan can be very fractured with silcrete and clay accumulations related to prolonged exposure (Figure 36).

Figure 36. Westphal Quarry, Box 20. Fractured and silcritic upper Jordan Formation near contact with Prairie du Chien.

Prairie du Chien Group

The Prairie du Chien Group is present in five Dodge County cores: Alsum 4, Bleeker, Buchda Quarry, Miller Quarry, and Slinger; and is absent in two cores: Westphal Quarry, and

Keel. The Prairie du Chien Group varies in thickness from zero to 102 feet and is subdivided into two formations: the lower Oneota; and upper Shakopee; both of which are present in Dodge County cores. In one Dodge County core, the Prairie du Chien is not easily divided into members because it is made up entirely of deformed sediments and is described separately as "deformed horizon".

Oneota Formation

Lithofacies Description: Three facies make up the Oneota Formation: sandy dolomite, hummocky cross-stratified dolomite, and flat pebble conglomerate. The Oneota Formation is 26 to 51 fee thick where present and characterizes the sandier of the two carbonate formations in the Prairie du Chien. The Oneota is a sandy dolomite wackestones with hummocks, millimeter to centimeter scale vugs commonly in the shape of brachiopods, silcrete, brachiopods and peloid grains, and one inch to one-foot layers of tan medium and coarse sand. The base of the Oneota locally includes a flat pebble conglomerate of inch-scale sandstone and dolomite rip up clasts (Figure X) and or a very coarse one- to- three-inch horizon of white, very coarse peloid-rich sand "bubble rock" with calcite cement (Figure 37).

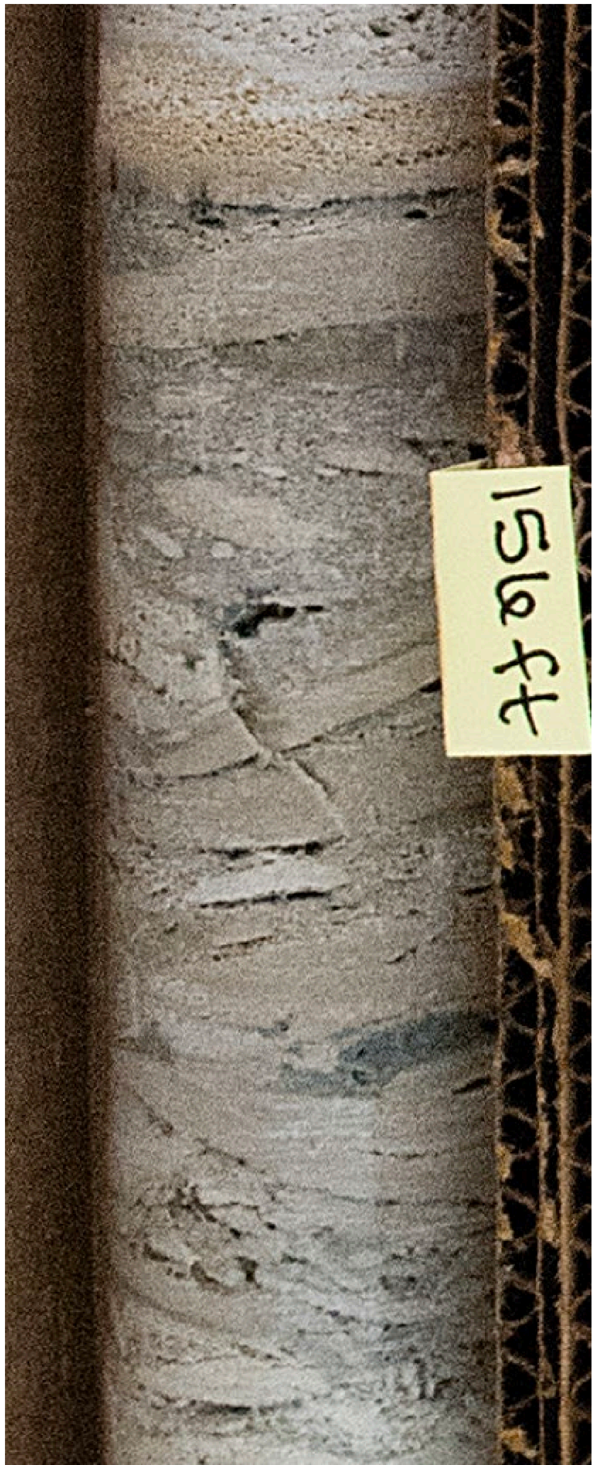


Figure 37. Bleeker, Box 16. Lower Oneota Formation flat pebble conglomerate with Jordan rip-up clasts.

Figure 38. Bleeker, Box 16. Lower Prairie du Chien Oneota coarse, silcritic sandstone "bubble rock".

Depositional Interpretation: The flat pebble conglomerate is interpreted to be rip-up clasts of the Jordan sandstone and any carbonates that may have formed during the erosional event prior to the deposition of the Prairie du Chien Group. The sandy dolomite facies suggests deposition in a shallow marine setting in the lower shoreface to upper transitional zone with moderate influx of sedimentation from storm deposits. This carbonate-rich facies suggests a slight sea-level rise in relation to the deposition of the Jordan Formation.

Contact Description: The contact between the Oneota and Shakopee Member is a truncated surface marked by a five-to-ten-foot horizon of silty dolomite with laminated shale partings (Figure 39 A and B) grading up into a silty dolomite wackestone.

Figure 39. **(A)** Buchda Quarry, Box 30. Porous, vuggy Oneota Formation (bottom left) and laminated, silty Shakopee Formation (top right). **(B)** Enlarged sharp contact horizon.

Shakopee Formation

Lithofacies Description: Five facies make up the zero-to-70-foot-thick Shakopee Formation: silty dolomite, dolomite mudstone/micrite, dolomite wackestone, silcritic dolomite, and karst-mottled dolomite. The dominant lithofacies of the Shakopee Formation is a silty dolomite micrite to wackestone with one- to- four millimeter laminated or silty shale partings, silcrete accumulation in pore space and in nodules, and millimeter- to- centimeter- scale vugs with common sulfide mineralization in cavities (Figure 40). The Shakopee Formation grades upward into more silcritic, vuggy, and karst mottled textures (Figure 41).

Figure 40. Buchda Quarry, Box 28. Millimeter-scale sulfide mineralization in vug of Shakopee Formation.

Figure 41. Buchda Quarry, Box 26. Silcritic, vuggy, very karsted upper Shakopee Formation.

Depositional Interpretation: The higher concentration of micrite, fewer coarse carbonate grains, and shale partings in the Shakopee carbonates suggests deposition in a lower energy offshore transitional zone caused by a slight sea level rise after the deposition of the Oneota. Silcrete occurs during prolonged exposure associated with major unconformities (Nichols, 2009). The silcritic and karst-mottled textures occurring in the upper Shakopee are indicative of secondary processes due to sustained exposure and karsting that only could have happened with a substantial drop in sea level, subaerial exposure, and subsurface mixing of groundwater and rainwater that dissolves carbonate.
Contact Description: The Shakopee-Saint Peter contact is a significant erosional unconformity that locally includes rip-up clasts, karst collapse structures, deformed sediments, and poor consolidation.

Deformed Horizon

Lithofacies Description: In one Dodge County core, Slinger, the Prairie du Chien Group is 31 feet of limey, soft sediment deformed strata (Figure 42) that includes laminated mudstone, deformed mudstone, fractured dolomite, massive silcrete, brecciated silcrete.

Figure 42. Slinger, Box 6. Deformed horizon in the upper Prairie du Chien with angular reworked dolomite clasts, soft-sediment deformation, silcrete accumulation, and poor consolidation.

Depositional Interpretation: The presence of silcrete is evidence of prolonged subaerial exposure associated with a major unconformity (cf. Nichols, 2009). The brecciation, minor faulting, and rip-up clasts between the Prairie du Chien and Readstown Member evidence of a mass wasting event. The inconsistent thickness of the Prairie du Chien along with the common occurrence of deformation along this horizon lead to the interpretation that the Prairie du Chien was exposed at the surface for a prolonged period of time allowing for rain and groundwater mixing at the water table within the Shakopee, subsequent dissolution of carbonate, ultimate collapse of the carbonate, and infill of any overlying silcritic duracrusts. This collapse would create a local basin in topography which could ultimately lead to the variability in thickness of the later deposition of the Saint Peter sandstone.

Ancell Group

The Ancell Group is made up of two formations: Glenwood and Saint Peter. Only the Saint Peter Formation is present in the available Dodge County cores, the Glenwood is assumed to be absent in southeast Wisconsin.

<u>Saint Peter Formation</u>

The Saint Peter Formation is present in eight Dodge County cores: Alsum 4, Bleeker, Buchda Quarry, Keel, Miller Quarry, Slinger, Swan Road, and Westphal 2 and ranges in thickness from 12 to 141 feet. The thickest packages of Saint Peter occur in cores with the thinnest underlying Prairie du Chien. Two members make up the Saint Peter Formation: the lower Readstown Member, and the upper Tonti Member, both of which are present in Dodge County cores.

Readstown Member

Lithofacies Description: Seven facies make up the Readstown Member in Dodge County: fractured sandstone, silcritic sandstone, brecciated sandstone, massive sandstone, shaly sandstone, bedded sandstone, and soft-sediment deformed strata. The Readstown is six to 34 feet thick and is thickest in cores where the underlying Tonti Member is also thickest. The dominant lithology of the Readstown Member in Dodge County is a massive white to gray medium-grained quartz sand with silcrete breccia clasts and nodules, minor fractures, and dark brown mud in fracture spaces (Figure 43).

Figure 43. Miller Quarry, Box 12. Deformed lower Readstown Member with brecciated clasts, silcrete accumulation, brittle offset and minor fracturing, and soft sediment deformation.

Depositional Interpretation: The abundance of silcrete clasts is evidence of prolonged subaerial exposure, suggesting a very slow sedimentation rate in a terrestrial environment. The abundance of massive sands, fracturing, and brecciation is evidence of syndepoitional deformation. This is combination with the underlying Prairie du Chien showing evidence of karsting supports the interpretation that the Readstown is a terrestrial, karst-collapse deposit.

Contact Description: The Readstown-Saint Peter contact (Figure 44) is a soft contact with wavy shale partings, injected mud into inch-scale sandstone blocks, and silcrete nodules.

Figure 44. Miller Quarry, Box 11. Readstown (left four columns)- Saint Peter (right column) soft, gradual contact with fluid escape textures, one inch-diameter silcrete nodule.

<u>Tonti Member</u>

Lithofacies Description: Four facies make up the Tonti Member in Dodge County: fractured sandstone, massive sandstone, planar and trough cross-bedded sandstone, and bioturbated sandstone. The Tonti is variable in thickness ranging from 17- to 131-feet thick. The dominant lithology of the Tonti Member is a pink and tan medium-grained, moderately sorted, massive to bedded sandstone with common minor brittle offset faults, and millimeter to centimeter-scale sulfide mineralization, areas of damp weakly cemented sand (Figure 45). This facies is most common in the lower and middle Tonti. The Tonti commonly displays a gradual lithology change toward its top into a gray and white medium-grained, well-sorted, massive to planar-bedded quartz sandstone with increased concentration of sulfide mineralization. This sulfide cement horizon likely occurs due to a contrast in permeability between the underlying sandstone and overlying dolomite.

Figure 45. Westphal 2, Box 12. Tonti Member pink fractured sandstone facies.

Depositional Interpretation: Syndepositional slumping and sliding of medium-grained sands is common in aeolian dune deposits suggesting part of the Tonti is aeolian, at least the lower pink fractured sands. The white and gray, upper Tonti shows less oxidation, well-sorted medium quartz sands with planar beds and burrows suggesting the upper Tonti was deposited in a shallow marine foreshore to upper shoreface environment. This interpretation documents a sea level low at the base of the Readstown, followed by sea level rise throughout the deposition of the Saint Peter Formation.

Contact Description: The Saint Peter-Shakopee contact is sharp with an abrupt transition from sandstone to dolomite. One instance of Saint Peter rip-up clasts is observed in the upper Platteville of the Keel core.

Sinnipee Group

The Sinnipee Group is present in eight Dodge County cores: Alsum 4, Bleeker, Buchda Quarry, Keel, Miller Quarry, Neda, Swan Road, and Westphal 2 as the bedrock surface in the western half of the county. The Sinnipee Group comprises three formations: the lower Platteville, Decorah, and upper Galena that have a combined maximum thickness of at least 237 feet and appears to thicken to the east. None of the Dodge County cores capture the full succession of the Sinnipee, but each of the formations is identified at least once.

<u>Platteville Formation</u>

The Platteville Formation most commonly composes the bedrock surface of the Dodge

County cores, occurring as the uppermost unit in six of the seven cores: Alsum 4, Bleeker, Buchda Quarry, Keel, Miller Quarry, Swan Road, and Westphal 2; that encounter the Platteville.

Lithofacies Description: Seven facies make up the Platteville Formation: dolomite wackestone, sandy dolomite, hummocky cross-stratified dolomite, mudstone/micrite, silty dolomite (Figure 46), and silcritic dolomite. The dominant lithology of the Platteville Formation is a gray to tan silty dolomite wackestone (Figure 47) lacking internal structure with millimeter- to centimeter-scale vugs, brachiopods, crinoids, bivalves, stromatolites, peloids, and other fossil fragments, dark gray millimeter-scale wispy shale partings, diapiric flame structures, vertical and horizontal mud-lined burrows (Figure 48), uncommon hummocks, millimeter- to centimeter-scale fine to medium sand lenses, and uncommon silcrete nodules and sulfide mineralization. The lower Platteville increases in sulfide concentration with millimeter to centimeter scale sulfide mineralization filling vugs.

Figure 46. Buchda Quarry, Box 12. Platteville Formation silty dolomite mudstone facies

Figure 47. Bleeker, Box 2. Platteville Formation dolomite wackestone with shale partings.

Figure 48. Swan Road, Box 20. Platteville Formation muddy dolomite facies with mud-lined burrows.

Depositional Interpretation: The silt and mud-rich dolomite facies suggests a shallow marine setting in which carbonate production is dominant with background settling of fine-grained clastic material. Common shale partings and burrows are attributed to low energy waters while wackestones with higher concentration of fossil fragments and hummocks suggest influence of high energy waters. These observations lead to the interpretation that the Platteville was deposited during frequent transitions from high to low energy in the offshore transitional zone between fair-weather and storm wave base. This setting suggests a relative sea level rise after the deposition of the Saint Peter.

Contact Description: The Platteville-Decorah contact is present in one Dodge County core: Swan Road; as a gradual transition from wackestone to mudstone.

<u>Decorah Formation</u>

A distinctly shale-rich unit, interpreted here as the Decorah Formation, is present in one Dodge County core: Swan Road; and is 36 feet thick. Some publications interpret the Decorah Formation to be thin to absent in eastern Wisconsin and include this interval in the lower Galena Formation (Choi et al., 1999).

Lithofacies Description: One facies makes up the Decorah Formation: dolomite mudstone/micrite. The Decorah is a chocolate brown fine-grained dolomite with few to no fossil fragments, common 1-2 mm black shale partings (Figure 49), and uncommon millimeter-scale vugs and millimeter-to centimeter-scale black sulfide mineralization.

Figure 49. Swan Road, Box 6. Decorah Formation dolomite mudstone facies with wispy shale partings.

Depositional Interpretation: The dolomite mudstone has few to no fossils or sand-sized grains which is evidence of a very low energy depositional environment. The Decorah is interpreted to be deposited in the lower offshore transitional zone to offshore, which is deeper than the Platteville and suggests a relative sea level rise.

Contact Description: The Decorah-Galena contact is only present in the Swan Road core and shows a gradual transition from dolomite mudstone to dolomite wackestone.

Galena Formation

The Galena Formation is present in two Dodge County cores: Neda, and Swan Road and is at least 49 feet thick.

Lithofacies Description: Four facies make up the Galena Formation: dolomite wackestone, hummocky cross-stratified dolomite, vuggy dolomite mudstone, and mottled dolomite. The Galena is a dark brown to dark gray dolomite wackestone with one- to two-millimeter dark gray wispy shale partings (Figure 50), abundant brachiopods, crinoids, bivalves, peloids, and other fossil fragments, and millimeter- to centimeter-scale vugs. Parasequences including hummocky beds of fossiliferous wackestones and interbedded shale fine up into a mottled texture then into fine grained mudstone with common vugs (Figure 51).

Figure 50. Swan Road, Box 2. Galena Formation dolomite wackestones facies with shale partings

Figure 51. Neda, Box 37. Galena Formation fossiliferous to fine-grained dolomite parasequence.

Depositional Interpretation: The abundance of fossil fragments in the Galena suggests a shallow marine environment in which carbonate production thrives with moderate wave energy. Shale partings are evidence of frequent transitions into low energy environments in which fine grains can settle from suspension. Parasequences that preserve high to low energy deposits provide further evidence of fluctuating wave energy. These are interpreted to be repeated storm events in the offshore transitional zone. This depositional environment is slightly shallower than that of the Decorah suggesting a slight sea level fall.

Contact Description: The Galena- Maquoketa contact is a sharp erosional contact with silcrete mineralization in the upper Galena (Figure 52).

Figure 52. Neda, Box 34. Galena Formation- Maquoketa Formation Scales Member contact.

Fond du Lac County

Precambrian

The Precambrian arch is intercepted by one Fond du Lac County core: Highway T; at an elevation of 552.5 feet msl. The Precambrian is a red, fine- to medium-grained quartzite (Figure 53).

Figure 53. Highway T, Box 35. Fine grained red granite Precambrian basement.

Tunnel City Group

Tunnel City sandstones make up the oldest Paleozoic rocks preserved in available cores from Fond du Lac County. Only one core, Ripon, obtains 12 feet of the upper Reno Member of the Lone Rock Formation. Remaining members of the Tunnel City have not been identified or described in core of Fond du Lac County.

Lone Rock Formation

Reno Member

Lithofacies Description: Four lithofacies makes up the available core containing the Reno Member: glauconitic cross-stratified sandstone, glauconitic massive sandstone, bioturbated sandstone, and shaly sandstone. The Reno Member (Figure 54) is a green and white, medium-grained, glauconite and quartz sandstone with massive to planar cross beds and vertical and horizontal burrows filled with white quartz sand. The glauconitic sands of the Reno fine upwards, include millimeter scale gray to green shale partings, and become less glauconitic in the uppermost half foot nearing the contact with the Trempealeau Group.

Figure 54. Rosendale, Box 32. Tunnel City Group Reno Member glauconitic cross-stratified sandstone facies with burrows.

Depositional Interpretation: Fine to medium grained sands along with common burrows provides evidence of deposition in a shallow marine lower shoreface environment. Abundant glauconite is evidence of a sediment-starved environment in which sedimentation is trapped further up-shore (cf. Middleton 2003).

Contact Description: The Tunnel City- Trempealeau contact is a sharp transition from a sandstone to a silty dolomite. The inclusion of shale partings above and below this contact suggest there is not a large gap in time between unit depositions.

Trempealeau Group

The Trempealeau Group is found in two Fond du Lac County cores: Highway T, and Rosendale; is about 28 feet thick, and consists of two formations: the lower Saint Lawrence, and the upper Jordan.

<u>Saint Lawrence Formation</u>

Lithofacies Description: One facies makes up the Saint Lawrence Formation in the available cores of Fond du Lac County: silty dolomite mudstone. The Saint Lawrence (Figure 55) is 8 feet of tan silty dolomite mudstone with 1-2 mm wispy gray shale partings, bioturbation, and two half- to one-inch lenses of medium-grained, white, quartz sand near the upper contact with the Jordan.

Figure 55. Rosendale, Box 31. Trempealeau Group Saint Lawrence Formation silty dolomite with shale partings.

Depositional Interpretation: The fine-grained dolomite with common shale partings suggests a shallow marine environment with low wave energy. Carbonate precipitation was the dominant form of sedimentation in this environment but clastic sedimentation via suspension fall out of silt and clay has strong influence. The Saint Lawrence is interpreted to be deposited in the offshore transitional zone. This suggests relative sea level fall following the deposition of the Tunnel City Group.

Contact Description: The Saint Lawrence-Jordan contact is a gradual, coarsening upwards for about one foot from a carbonate-dominant mudstone to a clastic-dominant sandstone.

<u>Jordan Formation</u>

Lithofacies Description: Five facies make up the 20-foot-thick Jordan sandstone in Fond du Lac County: cross-stratified sandstone, shaly sandstone, laminated mudstone, conglomerate, and paleosol. The Jordan directly overlies Precambrian quartzite in the Highway T core as a two-inch sandy conglomerate with quarter-to one-inch quartzite clasts (Figure 56), followed by three feet of tan, fine-grained, quartz sandstone with planar cross beds, light green shale partings along bedding planes, and silcrete accumulation along bedding planes. Following this shaly sandstone is one foot of dark brown, slightly deformed, oxidized sand and laminated mud before a truncated surface and more shaly sandstone (Figure 57). The dominant lithofacies of the Jordan sandstone in Fond du Lac County is a tan, medium-grained, well-sorted, quartz sandstone with planar cross beds (Figure 58), one- to two-millimeter wispy shale partings, and millimeter-scale sulfide mineralization.

Figure 56. Highway T, Box 34. Base Jordan Formation conglomerate.

Figure 57. Highway T, Box 34. Oxidized sand and mud of Jordan Formation, possible paleosol.

Figure 58. Rosendale, Box 30. Jordan Formation massive and cross-stratified sandstone facies.

Depositional Interpretation: The lower conglomerate overlying Precambrian basement includes local, angular clasts suggesting weathered clasts from a preceding erosional event were incorporated into a thin conglomerate layer at the beginning of the deposition of the Jordan. The oxidized sand and mud horizon lies on top of sands with abundant silcrete mineralization which is indicative of prolonged subaerial exposure (cf. Nichols, 2009) and has a truncated upper surface leading to the interpretation that this horizon is a paleosol that formed prior to the Jordan. The shale partings in the lower Jordan suggests deposition of fine grains that settled from suspension which occurred in the upper to lower shoreface. The dominant lithofacies of planar cross-bedded medium sand is evidence of a shallow marine foreshore environment. The Jordan's depositional environments are shallower than that of the Saint Lawrence including a basal nonmarine paleosol, suggesting a substantial sea level fall post-Saint Lawrence. The Jordan coarsens upward from a shaly sandstone to a cross-bedded medium sandstone indicating a shallowing upward progradation.

Contact Description: There is a sharp contact between the Jordan sandstone and overlying Prairie du Chien dolomite.

Prairie du Chien Group

The Prairie du Chien occurs in two Fond du Lac County cores: Highway T, and Rosendale; ranges from 63.5 to 140 feet, and is undivided into formations.

Lithofacies Description: Eleven facies make up the Prairie du Chien in Fond du Lac County: dolomite wackestone, sandy dolomite, silty dolomite, dolomite mudstone/micrite, hummocky cross -stratified dolomite, karst-mottled dolomite, silcritic

dolomite, laminated mudstone, shaly sandstone, soft sediment deformation, and paleosol. The Prairie du Chien is primarily a gray dolomite wackestone to micrite with varying levels of sand and shale but is dominantly sandy and fossiliferous at its base but interfingers with a silt, mud and silcrete facies (Figure 59) that becomes dominant toward the top. Brachiopods, crinoids, bivalves, and other fossil fragments are most common along hummocks and shale bedding planes. Millimeter- to centimeter-scale vugs are common throughout and brachiopod-shaped, and are filled with dark brown sulfide mineralization. Stromatolites are also abundant throughout the Prairie du Chien (Figure 60). Secondary lithofacies also occur in the Prairie du Chien of Fond du Lac County including karst-mottled dolomite with angular dolomite breccia (Figure 61) which occur in the most silcritic, vuggy dolomite; dark brown, soft-sediment deformed strata with heavily oxidized sand and mud and light brown cherty weathered breccia at the top (Figure 62); and a dark brown, interlaminated, fine-grained sand and mud facies with diapiric flame structures and vertical and horizontal burrows (Figure 63).

Figure 59. Rosendale, Box 26. Dominant Prairie du Chien dolomite wackestone facies.

Figure 60. Highway T, Box 31. Prairie du Chien stromatolites.

Figure 61. Highway T, Box 22. Prairie du Chien karst-mottled dolomite with dolomite breccia.

Figure 62. Rosendale, Box 24. Prairie du Chien deformed mud with weathered breccia at top.

Figure 63. Rosendale, Box 25. Prairie du Chien laminated mud facies.

Depositional Interpretation: The Prairie du Chien has several changing lithofacies that indicate a common fluctuation of wave energy and sediment supply. The silty dolomite micrite includes little to no fossils and characterizes low, fine-grained, background sedimentation in a carbonate factory setting. The interfingering sandy facies is a higher energy deposit suggesting either a drop in sea level or increase in storm events that push pulses of sand further offshore. The interlaminated mud and sand facies is evidence of repeated changes in energy attributed to the lower shoreface. The primary facies association of the Prairie du Chien is interpreted to be shallow marine lower shoreface to upper transitional zone. The silcritic dolomite, karst-mottled dolomite, and soft sediment deformed strata facies show evidence of secondary, nonmarine processes including the localized dissolution and collapse of carbonate, and the development of paleosol. Both of these processes occur under prolonged subaerial exposure, suggesting a significant sea level fall in which the Prairie du Chien was exposed at the surface prior to the deposition of the Saint Peter Formation.

Contact Description: The Prairie du Chien- Saint Peter contact is an extensive erosional unconformity with silcrete nodules and bands in the upper Prairie du Chien, and one-inch, brown, cherty possible remnant paleosol clasts in the lower Readstown Member (Figure 64).

Figure 64. Rosendale, Box 22. Prairie du Chien-Readstown contact with dolomite rip-up clasts, light brown cherty possible paleosol rip-up clasts, silcrete accumulation, and brittle offset.

Ancell Group

Saint Peter Formation

The Saint Peter Formation is present in all three Fond du Lac County cores: Highway T, Ripon, and Rosendale; and is ten to 110 feet thick. The thickness of the Saint Peter tends to be inversely proportional to the thickness of the underlying Prairie du Chien.

Readstown Member

Lithofacies Description: The Readstown Member includes two facies in Fond du Lac County: soft sediment deformed strata and shaly sandstone; and is six to 11 feet thick. The soft sediment deformed strata facies (Figure 65) makes up the lower Readstown and is a dark reddish brown and light green mud with no internal structure and poor consolidation. The shaly sandstone facies occurs in the upper Readstown and is a white, medium-grained sandstone with one- to two-millimeter light green shale partings.

Figure 65. Ripon, Box 23. Lower Readstown Member soft sediment deformed strata facies.

Tonti Member

Lithofacies Description: The Tonti includes five lithofacies: massive sandstone, cross-stratified sandstone, fractured sandstone, bioturbated sandstone, and shaly sandstone; and is ten to 102 feet thick. The lower Tonti (Figure 66) is a white and pinkish orange, medium-grained, quartz sandstone with planar and trough cross beds, high angle fractures, inch- to foot-scale bands of weak cementation, millimeter-scale sulfide mineralization, and uncommon one- to two-millimeter wispy shale partings. The upper Tonti (Figure 67) is a tan to gray, medium-grained quartz sandstone with planar and trough cross beds, vertical burrows, and millimeter- to centimeter-scale black sulfide mineralization.

Figure 66. Rosendale, Box 19. Lower Tonti Member cross-stratified sandstone facies and massive sandstone facies with brittle offset and poor consolidation.

Figure 67. Ripon, Box 12. Upper Tonti Member cross-stratified sandstone facies with brittle offset, sulfide mineralization, and burrows.

Depositional Interpretation: The combination of silcrete, weathered clasts, paleosols, and soft sediment deformed strata in the Readstown all provide evidence of nonmarine, terrestrial depositional processes following the exposure of the Prairie du Chien. The lower Tonti includes small, high-angle fractures within planar and trough cross-bedded medium sands which is possible during slumping and sliding of aeolian dune formation. The orangish-pink coloration of the Tonti is evidence of oxidation which commonly occurs in nonmarine settings. These observations support the interpretation that the lower Tonti is composed of nonmarine beach sands and aeolian dunes. The upper Tonti, however, includes unoxidized white and gray medium-grained sands with vertical burrows which provides evidence for marine deposition along the foreshore to upper shoreface. This interpretation suggests the Saint Peter was deposited during a sea level rise.

Contact Description: The Saint Peter-Sinnipee contact is gradational in the Ripon and Rosendale cores, and an abrupt truncated surface in the Highway T core.

Sinnipee Group

The Sinnipee Group is the bedrock surface in all three Fond du Lac County cores, is 96 to 161 feet thick, and is undivided into formations.

Lithofacies Description: Five facies make up the Sinnipee Group in Fond du Lac County: dolomite wackestone, dolomite packstone, silcritic dolomite, hummocky cross-stratified dolomite, and dolomite mudstone/micrite. The Sinnipee is a dark gray dolomite with one- to four-millimeter dark gray shale partings, brachiopod, crinoid, peloid, bivalve and fossil fragments that occur diffusely throughout but commonly occur in one- to six-inch

packstone bands (Figure 68) and hummocky intervals. Millimeter- to centimeter-scale silcrete nodules, blue bioturbation with vertical and horizontal burrows (Figure 69), and millimeter- to centimeter-scale vugs are also observed.

Figure 68. Highway T, Box 12. Sinnipee Group dolomite packstone facies.

Figure 69. Ripon, Box 10. Sinnipee Group dolomite with shale partings and burrows.

Depositional Interpretation: Shale partings and burrows throughout the Sinnipee Group provide evidence of low energy shallow marine carbonate factory setting. Common horizons of fossil clast packstones and hummocky cross stratification indicate deposition within storm wave base. The depositional environment of the Sinnipee is interpreted to be a shallow marine carbonate platform in the lower offshore transitional zone in which fine-grained carbonate and shale make up background sedimentation while storm events deposit larger fossil fragments in concentrated bands. This environmental interpretation suggests a relative sea level rise after the deposition of the Saint Peter Formation.

Jefferson County

Elk Mound Group

The Elk Mound Group occurs in one Jefferson County core: HBFA; is at least 241 feet thick; and contains three formations: the lower Mount Simon, the Eau Claire, and the upper Wonewoc.

<u>Mount Simon Formation</u>

Lithofacies Description: Three facies make up the Mount Simon: massive sandstone, cross-stratified sandstone, and shaly sandstone. The HBFA core ends after the Mount Simon reaches 62.5 feet in thickness. The Mount Simon (Figure 70) is a white to tan medium-grained, moderately sorted quartz sandstone with common one- to two-millimeter gray wispy shale partings, carbonate cement, uncommon millimeter- to centimeter-scale vugs, bioturbation, brown sand or light green mud-filled vertical and horizontal burrows, uncommon sulfide mineralization, and one to six-inch horizons of

weak cementation. The shaly sandstone intervals include one- to four-inch intervals shale coarsening upward into half-to one-inch planar cross-beds.

Figure 70. HBFA box 61, Mount Simon Formation shaly sandstone facies.

Depositional Interpretation: Cross bedding, carbonate cement, bioturbation, and burrows of the Mount Simon sandstone provide evidence for deposition in a shallow marine upper shoreface to lower shoreface environment. Shale and cross-bedded sandstone are interpreted to be stacked shallow marine bars of the upper shoreface.

Contact Description: The Mount Simon-Eau Claire contact is a three-foot, gradual, fining upward horizon.

Eau Claire Formation

Lithofacies Description: Three facies make up the Eau Claire in Jefferson County: bioturbated fine-grained sand, hummocky cross-stratified sandstone, and laminated mud. The Eau Claire (Figure 71) is a dark gray to green interlaminated fine-grained sandstone and mudstone with millimeter-to centimeter- scale laminations, abundant bioturbation, vertical and horizontal burrows, glauconite-rich fine-grained sand laminations, and diapiric flame structures. Two, three- and 20-foot, horizons of the same lithology are observed with abundant red oxidization.

Figure 71. HBFA, Box 56. Eau Claire Formation bioturbated sandstone facies with interlaminated glauconitic fine-grained sand and gray mud with bioturbation, burrows, flame structures, and rip-up clasts.

Depositional Interpretation: Fine-grained clastic material, bioturbation, burrows, and hummocky cross-stratification are evidence of a low energy, shallow marine environment within storm wave base. The glauconite-rich sand beds provide evidence of a sediment starved marine environment related to flooding surfaces (cf. Middleton, 2003) suggesting this deposit is far enough offshore for sedimentation to be trapped further up-shore. The depositional environment of Eau Claire in Jefferson County is interpreted to be the deepest shallow marine setting observed in the study area in the lower offshore transitional zone to offshore, at or below storm wave base where sedimentation is limited, wave energy is low, and marine organisms dwell. This interpretation suggests a relative sea level rise after the deposition of the Mount Simon.

Contact Description: The Eau Claire-Wonewoc contact is a gradational, overall coarsening upward four-foot horizon of interbedded burrowed mud and bedded sand.

Wonewoc Formation

Lithofacies Description: The Wonewoc Formation contains four facies: cross-stratified sandstone, shaly sandstone, massive sandstone, and bioturbated sandstone; and is 120 feet thick. The Wonewoc (Figure 72) is a tan, medium-grained, well-sorted, quartz sandstone with planar and trough cross-beds, carbonate cement, uncommon one- to two- millimeter light green shale partings, vertical and horizontal burrows, millimeter-to centimeter-scale vugs, millimeter-to centimeter-scale sulfide mineralization, uncommon iron staining, and one- to six-inch horizons of weak cementation.

Figure 72. HBFA, Box 42. Wonewoc Formation shaly sandstone facies with burrows.

Depositional Interpretation: Cross bedding, carbonate cement, bioturbation, and burrows provide evidence for deposition in a shallow marine in the upper shoreface. This interpretation suggests a relative sea level fall after the deposition of the Eau Claire. The sustained lithofacies of the Wonewoc observed across a 120-foot thickness suggests the constant filling of accommodation space which is possible via simultaneous subsidence and deposition which would maintain local sea level, depositional environment, and resulting lithofacies.

Contact Description: The Wonewoc-Tunnel City contact (Figure 73) is sharp and identified by an abrupt decrease in grain size and sudden presence of glauconite.

Figure 73. HBFA, Box 39. Wonewoc-Tunnel City sharp contact in the upper third column.

Tunnel City Group

Lone Rock Formation

The Lone Rock Formation is one of two laterally discontinuous formations in the Tunnel City Group and is 54 to 72 feet thick in Jefferson County. The second formation, the Mazomanie, is locally absent in the available Jefferson County cores. Two cores intercept the Tunnel City: HBFA and Mankowski, both of which include all three conformable members of the Lone Rock Formation: the lower Birkmose, and upper Reno.

Birkmose Member

Lithofacies Description: Three lithofacies make up the four to five- foot thickness of the Birkmose Member: bioturbated glauconitic fine sandstone, hummocky cross-stratified sandstone, and flat pebble conglomerate. The Birkmose is a green and maroon, fine-grained sandstone with brown silt- and mud-filled vertical and horizontal burrows, hummocks, one- to three-inch bands of heavily glauconitic sands and rip-up clasts (Figure 74), and flat pebble conglomerates.

Figure 74. Mankowski, Box 25. Tunnel City Birkmose Member arkosic wormstone beds with heavy bioturbation and dense glauconite beds with rip-up clasts.

Tomah Member

Lithofacies Description: Five facies make up the Tomah Member: bioturbated fine sand "red wormstone", glauconitic fine-grained sandstone, planar cross-bedded sandstone, hummocky cross-stratified sandstone, and flat pebble conglomerate. The Tomah Member (Figure 75) is 22.5 to 40 feet-thick and is most commonly observed as a maroon fine-grained quartz and lesser glauconite sand interbedded with light brown to green silt and mud, heavy bioturbation,

vertical and horizontal burrows, diapiric flame structures, hummocks, one to three inch flat-pebble conglomerate layers, and uncommon millimeter-scale sulfide mineralization.

Figure 75. Mankowski, Box 23. Tunnel City Tomah Member “red wormstone” facies with abundant bioturbation, vertical and horizontal burrows, flat pebble conglomerate, and fine sand and silt laminations.

Reno Member

Lithofacies Description: The Reno Member contains three facies: bioturbated glauconitic fine sandstone, hummocky cross-stratified sandstone, and cross-stratified sandstone; and is 26 feet thick. The Reno (Figure 76) is a fine-grained glauconite and quartz sandstone interbedded with millimeter-to centimeter brown silt and mud laminations with bioturbation, vertical and horizontal burrows, diapiric flame structures, hummocks, and common planar and trough cross beds.

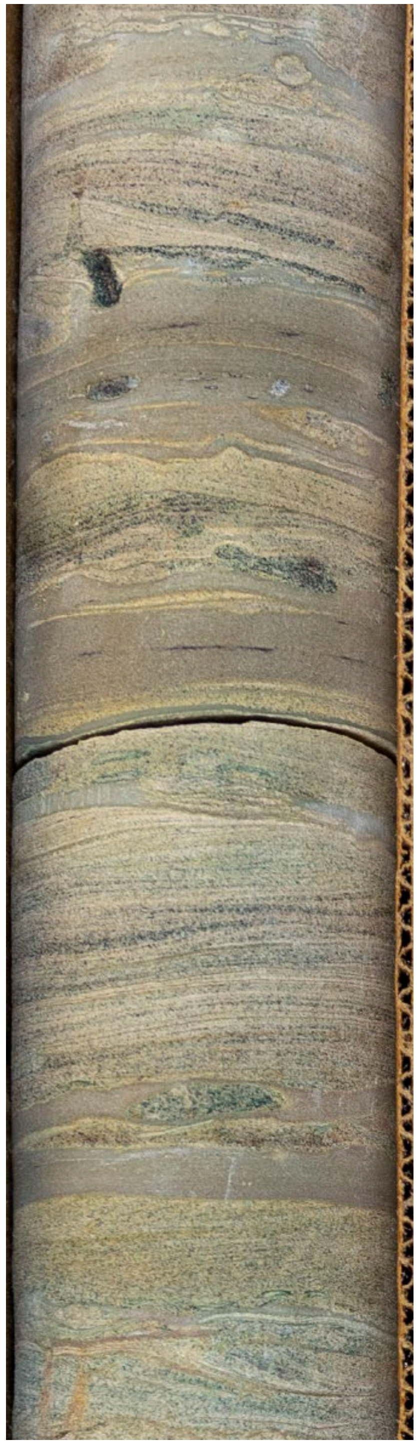


Figure 76. Mankowski, Box 21. Tunnel City Reno Member with planar fine-grained glauconitic cross beds, hummocky cross-stratification, bioturbation, and diapiric flame structures.

Depositional Interpretation: Interbedded fine-grained sand and mud with hummocks, and common burrows provides evidence of deposition in a low energy, shallow marine environment in which marine organisms dwell. Abundant glauconite is further evidence of a shallow marine, sediment-starved environment in which sedimentation is trapped further up-shore (cf. Middleton 2003). The truncated surfaces below many of the heavily glauconite-rich bands with rip-up clasts are a result of storms and subsequent marine flooding events. The Tunnel City is interpreted to be the furthest off-shore deposit seen in Jefferson County cores, deposited in the offshore transitional zone. This depositional environment is deeper than the Wonewoc suggesting a relative sea level rise.

Contact Description: The upper Reno gradually becomes less glauconitic until its uppermost one inch in which glauconite is abundant and sharply overlain by the silty dolomite of the lower Saint Lawrence Formation.

Trempealeau Group

The Trempealeau Group is 31 to 33 feet-thick and consists of two members: the lower Saint Lawrence Formation, and upper Jordan Formation. Both formations are distinguished in the Mankowski core but are undivided in the HBFA core.

<u>Saint Lawrence Formation</u>

Lithofacies Description: The Saint Lawrence is about 23 feet thick and includes two facies: silty dolomite mudstone, and silty dolomite wackestone. The Saint Lawrence is a light gray to tan silty dolomite mudstone to fossil-poor wackestone with one- to two-millimeter wispy light green shale partings, half- to two-inch light brown silt bands

common with abundant horizontal burrows (Figure 77), uncommon glauconite and millimeter-scale vugs.

Figure 77. HBFA, Box 31. Saint Lawrence dolomite with horizontal sand-filled burrows in silty dolomite beds.

Depositional Interpretation: A carbonate-dominant facies, burrows, and fossils all provide evidence of a shallow marine carbonate platform environment. The abundance of silt indicates background sedimentation of fine particles that are likely settling from suspension slightly further offshore. The Saint Lawrence is interpreted to be deposited in the offshore transitional zone. This environment is shallower than that of the Tunnel City, suggesting a relative fall in sea level.

Contact Description: The Saint Lawrence-Jordan contact is sharp and observed as a glauconite and silcrete-rich in the Mankowski core.

<u>Jordan Formation</u>

Lithofacies Description: The Jordan is about 10 feet thick and includes one primary lithofacies: cross-stratified sandstone. The Jordan (Figure 78) is a tan, fine- to medium-grained planar cross-bedded sandstone with carbonate cement, millimeter-scale vugs sometimes in the shape of brachiopods, millimeter-scale sulfide mineralization, and iron staining.

Figure 78. Mankowski, Box 17. Trempealeau Group Jordan Formation cross-stratified sandstone with iron staining and brachiopod shaped vugs.

Depositional Interpretation: Planar cross bedding and the presence of fossils suggest the Jordan was deposited in the foreshore to upper shoreface. This environment is shallower than the Saint Lawrence, suggesting a relative sea level fall.

Contact Description: The Jordan- Prairie du Chien contact (Figure 79) is abundant in brecciated silcrete clasts that fine upwards into bioturbated shale of the lower Prairie du Chien.

Figure 79. Mankowski, Box 16. Jordan-Prairie du Chien contact with silcrete accumulation, reworked bedding, and brecciated reworked clasts.

Prairie du Chien Group

The Prairie du Chien is present in two Jefferson County cores: HBFA and Mankowski, is 11 to 56 feet thick, and is undivided into formations.

Lithofacies Description: Six facies make up the Prairie du Chien in Jefferson County: bioturbated shale, dolomite mudstone/micrite, sandy dolomite wackestone, hummocky cross-stratified dolomite, thrombolytic dolomite, and silcritic dolomite. The dominant lithology of the Prairie du Chien is a silty dolomite mudstone with one- to two-millimeter light green and gray shale partings, bioturbation (Figure 80 A), millimeter- to centimeter-scale silcrete, millimeter- to centimeter-scale vugs filled with sulfide mineralization (Figure 80 B), recurring thrombolytic texture (Figure 80 C), dendritic marcasite mineralization (Figure 80 D), and one- to six-inch beds of yellow medium sand and hummocks.

Figure 80. Prairie du Chien silty dolomite facies with the following common characteristics. **(A)** Mankowski, Box, 15. Bioturbated dolomite mudstone. **(B)** HBFA, Box 24. Sulfide-filled vug. **(C)** HBFA, Box 28. Thrombolytic dolomite. **(D)** HBFA, Box 21. Marcasite mineralization.

Depositional Interpretation: A carbonate-dominant facies, burrows, thrombolites, and fossils all provide evidence of a shallow marine carbonate platform environment. The abundance of silt indicates background sedimentation of fine particles that are likely settling from suspension. The Prairie du Chien is interpreted to be deposited in the offshore transitional zone. This environment is deeper than that of the Jordan suggesting a relative rise in sea level. Silcrete is known for being a product of prolonged subaerial exposure, this in combination with inconsistent thickness of the unit, suggests the Prairie du Chien may have been exposed post-deposition and subsequently karsted or weathered.

Contact Description: The Prairie du Chien- Saint Peter contact is a silcrete rich, slightly deformed, erosional contact (Figure 81).

Figure 81. Mankowski, Box 14. Prairie du Chien- Saint Peter deformed contact with silcrete accumulation, brecciated reworked dolomite and silcrete clasts, rip-up clasts, and brittle offset.

Ancell Group

The Saint Peter Formation accounts for the entirety of the Ancell Group in Jefferson County and is intercepted by all three available cores: HBFA, Mankowski, and Mobil. The Glenwood shale Formation is locally absent.

Saint Peter Formation

The Saint Peter is broken up into two members: the lower Readstown and upper Tonti and has a combined thickness of 59 to 109 feet which is inversely proportional to the thickness of the underlying Prairie du Chien.

Readstown Member

Lithofacies Description: The Readstown Member 12 to 15 feet thick and includes two lithofacies: silcritic brecciated sandstone, and soft-sediment deformed strata. The Readstown (Figure 82) is a white to tan medium-grained sandstone with abundant silcrete in pore space and in quarter-to one-inch nodules, local weak cementation, and common brown-mud and silcrete soft sediment deformation.

Figure 82. Mankowski, Box 13. Saint Peter Readstown Member deformed sandstone facies with abundant silcrete accumulation, angular reworked silcrete and sandstone clasts, soft-sediment deformation, and vuggy secondary porosity.

Tonti Member

Lithofacies Description: The Tonti is 47 to 94 feet thick and includes four lithofacies: cross-stratified sandstone, massive sandstone, fractured sandstone, and bioturbated sandstone. The Tonti (Figure 83) is a tan to orangish pink fine- to medium-grained sandstone with planar and trough cross beds, to massive sandstone with common small-scale faults and deformation bands (Figure 84), common millimeter- to centimeter-scale sulfide mineralization, iron staining, and local weak cementation.

Figure 83. HBFA, Box 16. Saint Peter Tonti Member cross-stratified sandstone facies with weak cementation, bioturbation, and sulfide mineralization.

Figure 84. Mankowski, Box 7. Saint Peter Tonti Member massive sandstone facies with a high angle deformation band.

Depositional Interpretation: Angular clasts and soft sediment deformation of the Readstown Member immediately overlying an exposure surface of the Prairie du Chien are compatible with a subaerial karst-fill or weathered clast accumulation hypothesis suggesting the Readstown is nonmarine. Additionally, fine- to medium-grained sand, common, slumping and sliding, and iron staining observed in the Tonti Member are evidence for aeolian dune environments. The Saint Peter is interpreted to be partly aeolian and beach and partly foreshore to upper shoreface based on these observations. This interpretation suggests a sea level rise following a prolonged exposure after the deposition of the Prairie du Chien.

Contact Description: In the Mankowski core, the Saint Peter- Sinnipee contact (Figure 85) is a heavily oxidized, poorly cemented horizon with a two-inch light green laminated shale bed, light brown cherty clasts, and silcrete mineralization. If the upper Saint Peter is nonmarine here, this is contact is a possible paleosol. The HBFA and Mobil cores have sharp, heavily oxidized contacts with abundant millimeter- to centimeter-scale sulfide mineralization, and sandstone rip-up clasts (Figure 86). All of these contacts suggest another brief sea level drop and resulting disconformity prior to the deposition of the Sinnipee in Jefferson County.

Figure 85. Mankowski, Box 2. Diffuse Saint Peter- Sinnipee contact with green shale laminations and light brown cherty silcritic reworked layer, possibly paleosol.

Figure 86. Mobil, Box 27. Abrupt Saint Peter- Sinnipee contact with abundant millimeter- to centimeter-scale sulfide mineralization.

Sinnipee Group

The Sinnipee Group is the bedrock surface in all three Jefferson County cores: HBFA, Mankowski, and Mobil and is a total of 27 to 246 feet thick. There are three members in the Sinnipee Group: the lower Platteville Formation, the Decorah, and the upper Galena Formation, but they are not divided due to lack of additional data in Jefferson County.

Lithofacies Description: The Sinnipee contains five facies: bioturbated dolomite wackestone, silcritic silty dolomite mudstone, sandy dolomite wackestone, and hummocky cross-stratified dolomite. The dolomite wackestone facies is gray to brown, fossil-poor with uncommon large crinoid stems (Figure 87), brachiopods, and other fossil fragments, blue bioturbation, vertical and horizontal burrows, and millimeter-scale vugs. The silty dolomite facies (Figure 88) is a light brown carbonate mudstone with millimeter- to centimeter-scale vugs, and millimeter- to centimeter-scale silcrete nodules. The sandy dolomite wackestone facies is light brown with one- millimeter wispy shale partings, hummocks, and common one- to six-inch yellow medium sand lenses with abundant millimeter- to centimeter-scale vugs and brachiopod-shaped vugs.

Figure 87. Mobil, Box 26. Two-inch-long crinoid stem in Sinnipee Group dolomite wackestone facies.

Figure 88. HBFA, Box 6. Sinnipee Group silcritic silty dolomite facies (left), and bioturbated dolomite facies (right).

Depositional Interpretation: The silt and mud-rich dolomite facies suggests a shallow marine setting in which carbonate production is dominant with frequent background settling of fine-grained clastic material. Common shale partings and burrows are attributed to low energy waters while wackestones with higher sand and fossil concentrations suggest moderate wave energy. These observations lead to the interpretation that the Sinnipee was deposited in the offshore transitional zone at or near storm wave base. This interpretation suggests a relative sea level rise after the deposition of the Saint Peter.

Sequence Stratigraphy, Depositional Environments, and Erosional Events

This study has produced detailed descriptions of 22 cores across a four-county study area totaling nearly 9,000 feet of strata. These descriptions pay particular attention to lithology, grain size, sedimentary structures, bioturbation, contacts, and unconformities within each unit. These observations were used to interpret likely depositional environments of each lithofacies. These environments were divided into facies associations in a regional schematic facies model that constrains lithologies to their locality of origin along a terrestrial to offshore basinal slope margin. These facies are observed to be stacked vertically both within and between major rock formations, indicating frequent changes in sea level that would shift any one locality laterally from one facies to another. Continuous deposition, lithification, and preservation of sediments left behind a sequence of environmental signatures that were interpreted to reconstruct the regional relative sea level changes throughout time. A site-specific stratigraphic column (Figure 89) shows the most common lithofacies observed in each stratigraphic unit, their relative thickness, and corresponding implication for relative sea level.

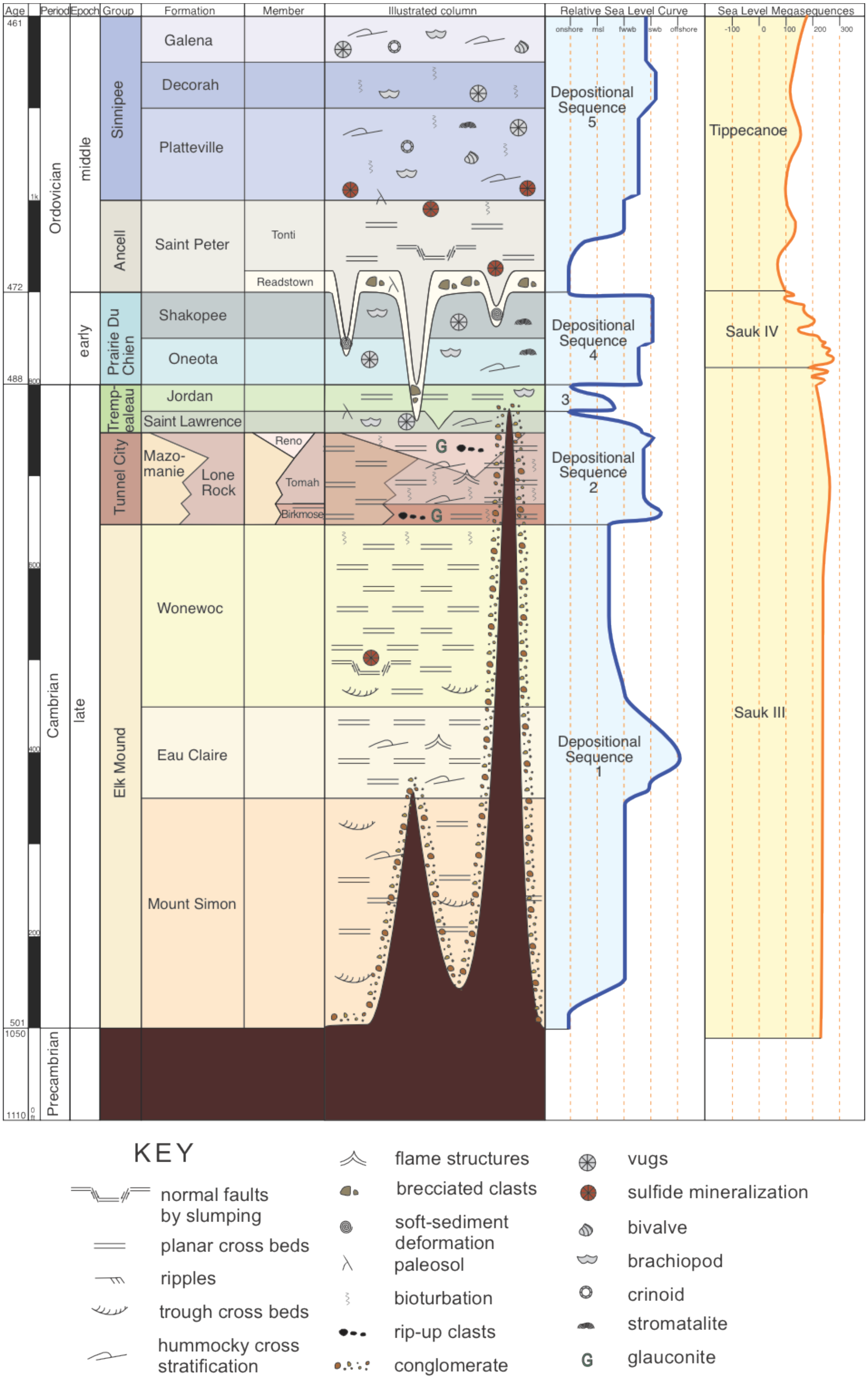

Age
Period
Epoch
Group
Formation
Member
Illustrated column
Relative Sea Level Curve
Sea Level Megasequences
onshore
msl
fwwb
swb
offshore
461
472
488
501
1050
1110
Ordovician
Cambrian
Precambrian
middle
early
late
Sinnipee
Ancell
Prairie Du Chien
Tremp-ealeau
Tunnel City
Elk Mound
Galena
Decorah
Platteville
Saint Peter
Shakopee
Oneota
Jordan
Saint Lawrence
Mazo-manie
Lone Rock
Wonewoc
Eau Claire
Mount Simon
Tonti
Readstown
Reno
Tomah
Birkmose
Depositional Sequence 5
Depositional Sequence 4
3
Depositional Sequence 2
Depositional Sequence 1
Tippecanoe
Sauk IV
Sauk III
KEY
normal faults by slumping
planar cross beds
ripples
trough cross beds
hummocky cross stratification
flame structures
brecciated clasts
soft-sediment deformation
paleosol
bioturbation
rip-up clasts
conglomerate
vugs
sulfide mineralization
bivalve
brachiopod
crinoid
stromatalite
glauconite

Figure 89. Illustrated stratigraphic column with regional units, facies, and relative sea level curve for late Cambrian to middle Ordovician strata along the southeast Wisconsin arch (modified from WGNHS, 2006). Far right column includes sea level megasequences for comparison to global sea level trends (from Golonka and Kiessling, 2002).

Major North American cratonic sequences outline global sea level trends that are observed to have driven depositional sequences throughout the Phanerozoic. Strata ages in this study are related to the Sauk III, Sauk IV, and early Tippecanoe megasequences (Sloss, 1963; Golonka and Kiessling 2002; Haq and Schutter, 2008; and others) with a major Sloss sequence boundary between the early (Prairie du Chien) and middle (Saint Peter) Ordovician. The relative sea level curve created in this study based on facies interpretation is a similar curve to that of the megasequences with the most major trends being observed locally. Differences are attributed to intrabasinal mechanisms such as subsidence and sediment supply and the position of the study area being up-slope where it experienced greater exposure and lesser deposition than localities further offshore used in more complete sea level reconstructions.

This study area is located mid-continent on a topographic high which restricted accommodation and deposition, therefore only the furthest up-dip deposits are preserved. Sequences observed in this study are in fact composites of multiple large-scale sequences that are preserved in greater thickness and resolution further offshore in Iowa, Illinois, and Michigan (Witzke et al., 1996). An up-dip location limits the record of accommodation changes but major background sea level variations can be detected in facies changes. Unconformities between the composite sequences correspond to major sequence boundaries, and these can be used to interpret facies changes within the succession. The composite sequences in this study, though not representative of complete cratonic trends in sea level, are bounded by unconformities, define

large scale patterns, and give framework for facies changes observed around the arch. The terminology of "sequence" will be adopted in for these composite packages as they pertain to changing facies environments driven by major sea level trends.

Parasequences are defined in this study as meter-scale, shallowing upward successions that make up parsequence sets, and sequences. The identification of stacked parasequences within groups and formations were used to document relative sea level fluctuations. Parasequences that display an overall fining, or deepening upwards sequence are indicative of retrogradation caused by a transgressing shoreline which indicate sea level rise (cf. Coe and Church, 2003). Parasequences that display a repeated set of facies without overall fining or coarsening indicate aggradation caused by a sustained depositional environment in which sea level rise is equal to the accommodation space being created (cf. Coe and Church, 2003). Parasequences with overall coarsening and shallowing upwards sequences were not observed in this study as preservation of these sequences are rare due to the erosional consequences of regressions related to sea level fall (cf. Coe and Church, 2003). Based on the observation of these local sea level trends, five depositional sequences were identified.

Depositional Sequence 1

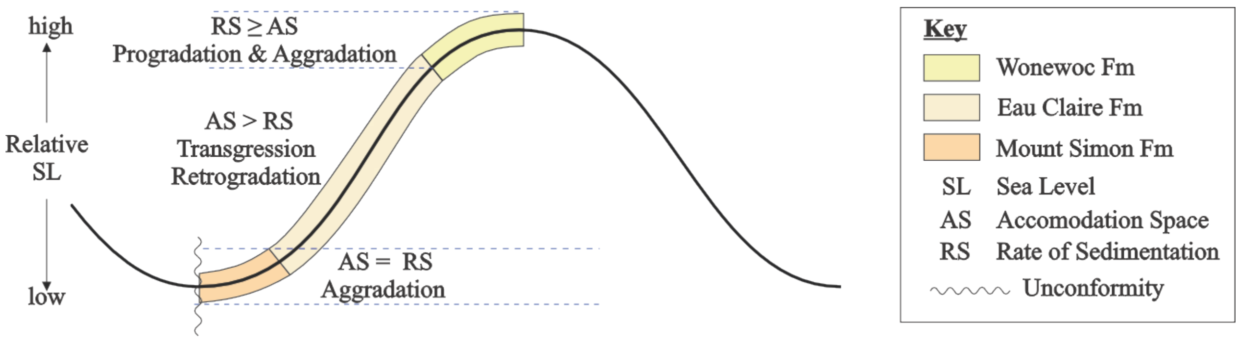


Figure 90. Model of the sea level driven accommodation space and sedimentation rate relationship that influenced gradation along slope margin during deposition of the Elk Mound Group sandstones.

A significant erosional event predates all Paleozoic strata observed in southeast Wisconsin. This erosion left behind the Precambrian arch highlands that acted as both the primary clastic sedimentary source and the topography upon which the shallow marine shoreface would transgress and regress. Changes in relative sea level or the creation of accommodation space is a function of basin subsidence, eustatic sea level change, and sedimentation rates. A relative sea-level rise in the late Cambrian initiated the deposition of Elk Mound sandstones. Weathered, angular clasts from the Precambrian arch were incorporated into the lowermost Cambrian formation, the Mount Simon Formation, producing a 5-to 10-foot conglomerate bed at its base. This conglomerate is likely equivalent to the Parfreys Glen Formation described in Columbia County, about 100 miles to the east (Clayton and Attig, 1990). The Mount Simon sandstone displays uniform medium-to coarse-grained, cross-stratified, quartz sandstone deposited in a shoreface environment throughout its hundreds of feet in thickness. This sustained lithofacies suggests the aggradation of shoreface deposits during this time, and that accommodation space was simultaneously being filled as it was created. This can occur when

relative sea level is first beginning to rise and the level of sedimentation does not over or under step accommodation, resulting in a maintained, aggrading facies (Coe and Church, 2003).

The base Eau Claire Formation is marked by a flooding surface overlain by coarsening-upward parasequences that stack into an upward-fining, retrogradational parasequence set. Each succeeding parasequence displays finer and finer lithologies upward until the Eau Claire is predominately a fine-grained sandstone with increased thicknesses of laminated mud horizons and bioturbation indicative of an offshore transitional zone facies association. This retrogradational parasequences set suggests accommodation created by sea level rise was outstepping sedimentation rates causing the shoreface to transgress resulting in progressively deeper environments at a given site through time (cf. Coe and Church, 2003).

The overall coarser grainsize of the Wonewoc Formation indicates progradation of the shoreline. The Wonewoc is characterized by an aggradational parasequence set composed of 100- to 200 feet of uniformly stacked, medium to coarse-grained, cross-stratified sandstone. These strata were likely deposited within a shoreface environment. The shoreface kept pace with relative sea level rise and resulted in consecutive stacks of aggrading shoreface sands.

Depositional sequence 1 of the Elk Mound Group sandstone includes three major formations that sequentially display aggradational, retrogradational, and aggradationally stacked parasequence sets that resulted from an overall rise in relative sea level.

Depositional Sequence 2

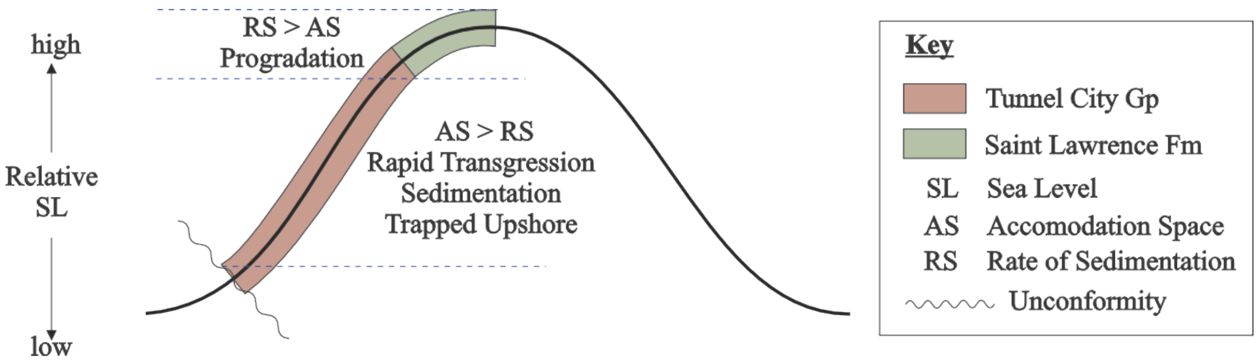


Figure 91. Model of the sea level driven accommodation space and sedimentation rate relationship that influenced sediment starvation and progradation along slope margin during depositional sequence 2.

The Elk Mound-Tunnel City contact is a sharp unconformable surface. In the west, the base of the Tunnel City is marked by the Mazomanie Formation, a cross-bedded coarse-grained clastic shoreface unit that fines upward and eastward into its fine-grained, bioturbated, lateral-equivalent, the Lone Rock Formation. The Lone Rock Formation composes the base of the Tunnel City Group in the east and is a glauconite-rich, fine-grained clastic sandstone with substantial bioturbation and hummocky cross-stratification indicative of deposition in a sediment-starved (cf. Middleton, 2003) offshore transitional zone facies association. The deepening upward retrogradational sequence of both units provide evidence for a rapid transgression (cf. Coe and Church, 2003). The Mazomanie fines upwards indicating retrogradation of the shoreface onto the Wisconsin Arch. The Lone Rock already being further offshore, exhibits significant sediment starvation as a rapid rise in sea level likely cut off the coarse clastic sediment supply to that area, restricting such facies farther shoreward.

The Saint Lawrence marks the beginnings of carbonate production with pulses of medium-grained sand beds. This shallow carbonate deposit shows evidence of increasing clastic

sediment supply up section, indicating the gap between rate of creation of accommodation space and sedimentation rates was closing (cf. Coe and Church, 2003). The inclusion of medium-grained sandstones suggests the Saint Lawrence was deposited closer to the shoreline in the upper transitional zone to lower shoreface environment, marking the start of clastic progradation.

Depositional sequence 2 of the Tunnel City sandstones and Saint Lawrence dolomite includes a major flooding event that trapped sediment onshore to the west indicating a rapid rise in relative sea level followed by decreased rate of relative sea level rise as indicated by a coarsening upward succession signaling progradation (cf. Coe and Church, 2003).

<u>Depositional Sequence 3</u>

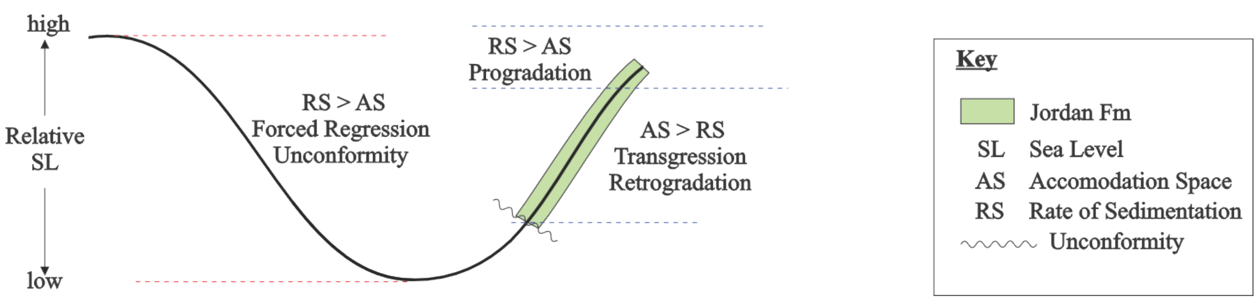


Figure 92. Model of the sea level driven accommodation space and sedimentation rate relationship that drove a forced regression during deposition of the Jordan Formation.

The Jordan is observed to down cut the underlying Saint Lawrence likely as a result of drainage following sea level fall. The Jordan is a medium-to coarse-grained cross-bedded quartz sandstone that could be attributed to fluvial or foreshore facies associations. The absence of a shoreface environment is evidence of a forced regression caused by rapid sea level fall (cf. Coe and Church, 2003). This would suggest the shoreline prograded and stepped down over the

intermediate facies that would normally occur between the Saint Lawrence and Jordan, making the base of the Jordan unconformable. The unconformity caused by this forced regression is present in the central to eastern study area, while the Saint Lawrence and Jordan remain conformable to the west. The upper Jordan marks another unconformable horizon with a sharp contact to overlying strata.

Deposition of sequence 3 is interpreted to have been controlled by a rapid drop in sea level that caused a forced regression and resulting unconformity. Once the rate of sea level fall slowed, sedimentation rate outpaced the creation of accommodation space, and the Jordan sandstone was deposited.

Depositional Sequence 4

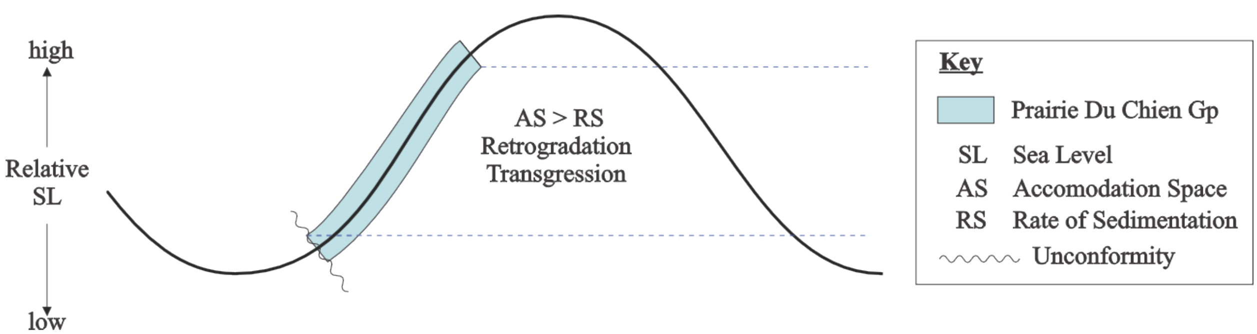


Figure 93. Model of the sea level driven accommodation space and sedimentation rate relationship that drove retrogradation during deposition of the Prairie du Chien.

The base of the Prairie du Chien is commonly marked by a bed of coarse quartz sand. In places the Prairie du Chien can be divided into two formations, the lower Oneota sandy dolomite and upper Shakopee mudstone dolomite, which show an overall fining upwards trend. The Oneota Formation contains inch thick medium-grained quartz sand lenses and fossils characteristic of the lower shoreface facies association. The Oneota-Shakopee contact is marked

by a laminated mud interval suggesting a marine flooding event. The Shakopee Formation contains little to no coarse-grained clastics and is indicative of the deeper, offshore transitional zone facies. These retrograding facies suggest a rise in relative sea level that created accommodation space quicker than sediment could be deposited, resulting in deepening during the Prairie du Chien (cf. Coe and Church, 2003). The upper Prairie du Chien is heavily eroded, karsted, and downcut by overlying strata marking the most substantial unconformity described in this study.

Depositional sequence 4 includes a gradual retrogradation of carbonate facies throughout the deposition of the Prairie du Chien indicating a relative sea level rise.

<u>Depositional Sequence 5</u>

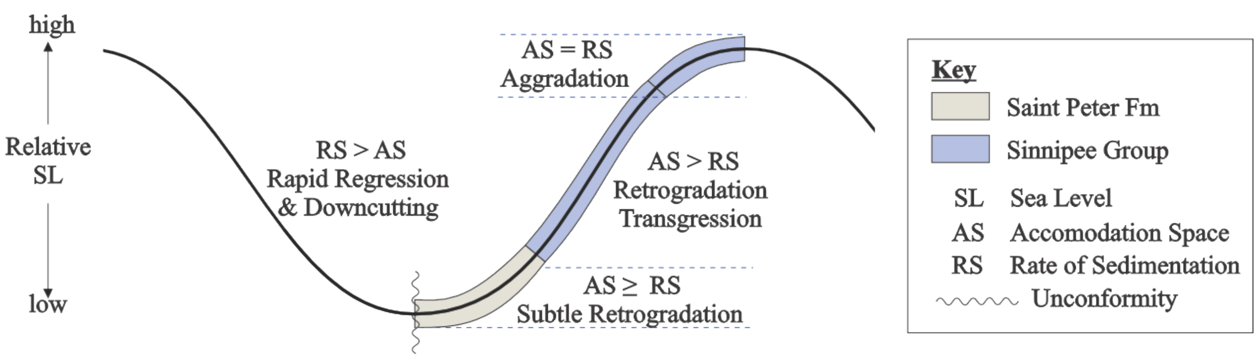


Figure 94. Model of the sea level driven accommodation space and sedimentation rate relationship that drove the retrogradation that deposited the Saint Peter and Sinnipee over an extensive erosional unconformity surface.

A widespread erosional contact marks the base of the Saint Peter Formation indicating a significant drop in sea level that resulted in prolonged subaerial exposure and downcutting of underlying strata. This study observed the Saint Peter to unconformably overlie units as old as

the Saint Lawrence but it has also been observed cutting well into the Late Cambrian Elk Mound Groups in areas across Wisconsin (WGNHS, 2006). Low sea level exposed the Prairie du Chien platform and subjected it to two erosional processes: downcutting by incised drainage patterns and karst dissolution of carbonate by meteoric waters. The resulting topography was filled by the earliest Saint Peter sands.

The lower Saint Peter Formation includes a 5-15-foot silcritic, brecciated, coarse-grained quartz sandstone known as the Readstown Member. The Readstown likely began filling the jagged topography with slumping and sliding of weathering material along incised valleys and karst rims. This is thought to have occurred in a terrestrial setting due to its angularity and inclusion of silcrete, a mineral indicative of subaerial exposure (cf. Nichols, 2009). The overlying Tonti Member is a clean, medium-grained cross-bedded quartz sandstone that is variably thick (up to 140 feet) suggesting it continued to fill depressions in the eroded topography. The reworking of older quartz arenite Cambrian sands during the development of incised valleys could have provided a sediment source for the Saint Peter explaining its spectacular uniformity in grain size and lithology. The lower Tonti shows common disturbed horizons of small normal faulting that could be attributed to syndepositional disturbance due to slumping and sliding along incised valleys and karst rims, or the slopes of aeolian dunes. The upper Tonti includes bioturbation and vertical burrow providing strong evidence for shallow marine shoreface deposition for at least a portion of this member. The lower Readstown and upper Tonti are thought to be of terrestrial facies association. The lower to upper Tonti is within the grain size range and displays sedimentary structures that could be attributed to fluvial, aeolian, or coastal processes making its facies association difficult to pinpoint. The uppermost Tonti however, includes bioturbation indicating it was deposited in the upper shoreface. The

evidence of both terrestrial and marine facies suggest the Saint Peter contains a sequence of retrogradational facies. The contact between nonmarine and marine has not been identified but it is thought that filling of topography and possible retrogradation of facies occurred in the early Saint Peter and the middle to upper Tonti represents aggradation based on its overall consistency in lithology throughout a substantial thickness (cf. Coe and Church, 2003).

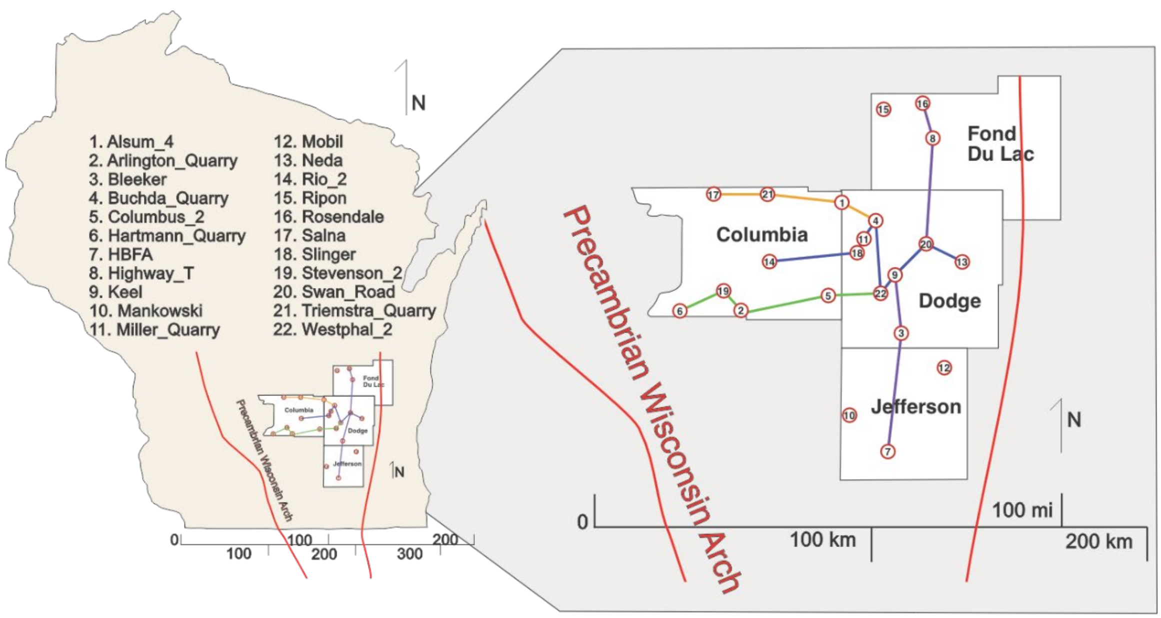
The Saint Peter-Sinnipee contact is sharp marked by a facies change into muddy dolomite wackestone thought to be a marine flooding event caused by a rapid rise in relative sea level that trapped coarse clastic sedimentation further shoreward. A carbonate ramp setting was quickly established which maintained sedimentation during the rapid transgression. The Sinnipee Group is divided into three formations where possible. The lower Platteville is a dolomite wackestone with abundant shale partings from fine clastics settling out of suspension, and common hummocky cross stratification indicating an offshore transitional zone to offshore facies association. The Decorah is a silty dolomite mudstone that displays little to no fossils and abundant bioturbation suggesting it was deposited in a slightly deeper offshore transitional zone environment. The upper Galena is a dolomite wackestone with thin shale partings and common bioturbation indicating it was deposited slightly shallower but still in the offshore transitional zone to offshore facies. Fining upwards parasequence observed in the Platteville and Decorah suggest relative sea level was rising quicker than sedimentation could occur, resulting in the retrogradation of facies (cf. Coe and Church, 2003). The slight shallowing observed in the Galena could be the onset of another retrogradational parasequence, or it could indicate the slowing of the sea level transgression (cf. Coe and Church, 2003).

Depositional sequence 5 began after a rapid regression resulting in fluvially incised and karstified topography for which the early Saint Peter unconformably filled. Lower Saint Peter

breccia first deposited as valley walls and karst rims collapsed. Once sea level stopped dropping and accommodation space was created offshore, facies began to retrograde, covering the previously exposed shelf with fluvially and coastally reworked Cambrian sands with a fresh sheet of Saint Peter sandstone.

Regional trends in stratigraphy across the study area

Four cross sections are presented to display regional trends in unit thickness and deformational horizons across the study area. Subsurface contacts were drawn based on core description and interpreted at depth by maintaining unit thickness. Topography of the Precambrian arch was interpreted based on dip of overlying strata.



Cross Section B-1 (yellow line): Salna, Triemstra_Quarry, Alsum_4, Buchda_Quarry

Cross Section B-2 (blue line): Rio_2, Slinger, Miller_Quarry, Buchda_Quarry, Keel, Swan_Road, Neda

Cross Section B-3 (green line): Hartmann_Quarry, Stevenson_2, Arlington_Quarry, Columbus_2, Westphal_2, Keel

Cross Section B-4 (purple line): HBFA, Bleeker, Swan_Road, Highway_T, Rosendale

Figure 95. Approximate location of cores from Columbia, Dodge, Fond du Lac and Jefferson Counties recovering Cambrian and Ordovician sediments near the Wisconsin Arch.

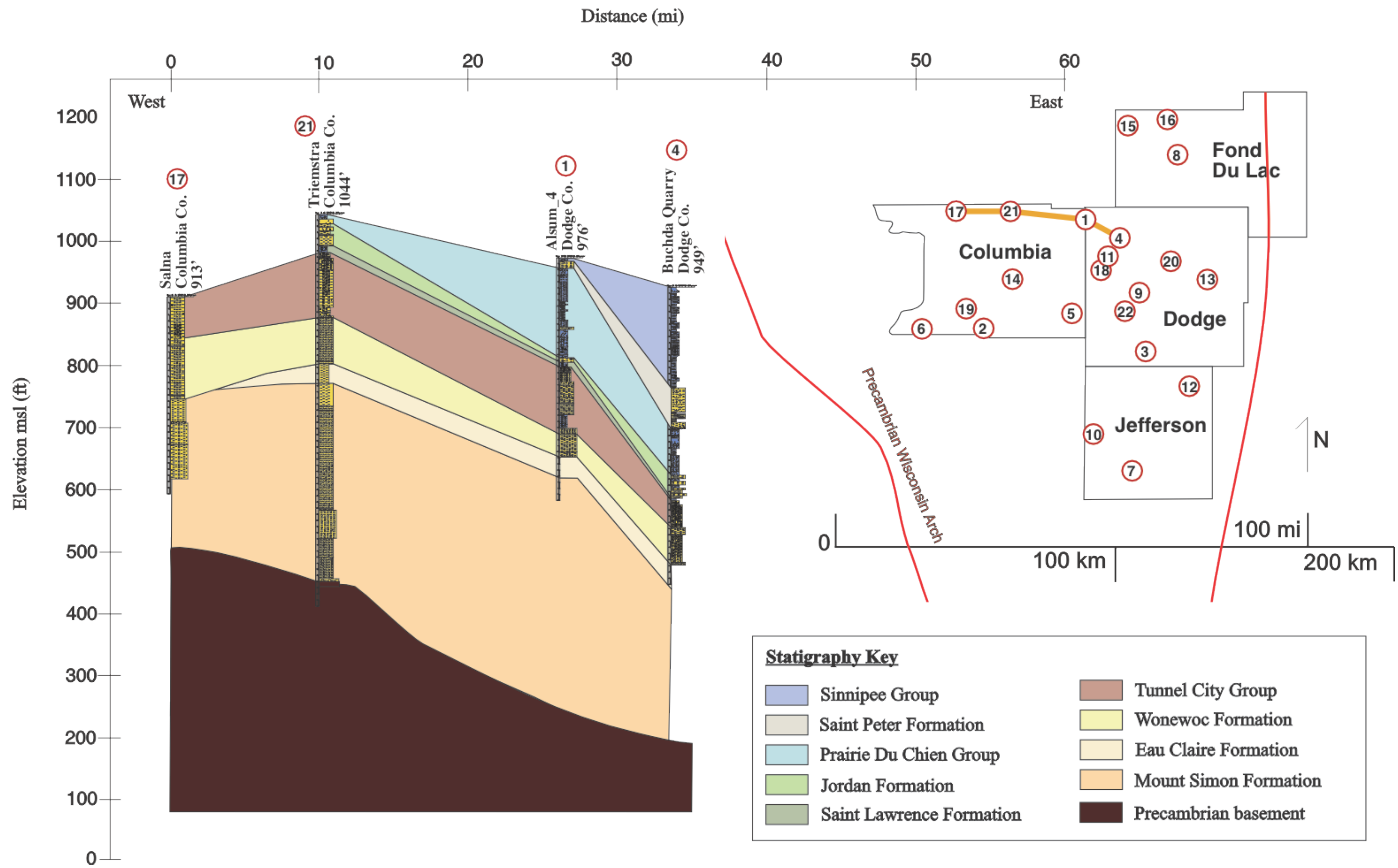


Figure 96. Cross section across northern Columbia and Dodge Counties with 220X vertical exaggeration hung on 0 SL

A cross section across northern Columbia and Dodge Counties (Figure 96) shows one intersection of the Precambrian arch at 444 feet above sea level in the Triemstra core under central Columbia County. The Elk Mound Group sands vary in thickness as they fill topography. The Eau Claire Formation appears to pinch out to the west as shallower facies are observed atop the arch. Tunnel City Group sandstones appear to maintain thickness as they are deposited atop the arch, but thin to the east. The Precambrian arch was drawn continuing to slope up west of the Triemstra intersection because the Salna core does not contain the Eau Claire Formation, indicating it may have been pinching out along a sloped margin.

The Saint Lawrence and Jordan Formations appear to thicken and thin in an inversely proportional relationship to one another. This is likely due to the downcutting into the Saint Lawrence at the end of depositional sequence 2, and subsequent filling of topography by the Jordan during depositional sequence 3. The Prairie du Chien Group and Saint Peter Formation show a similar inversely thick relationship to one another, again due to an erosional event of the underlying formation during a major unconformity. The Prairie du Chien platform was eroded by incised valleys and karst following the regression in depositional sequence 4 and filled by the Saint Peter in depositional sequence 5.

Lithologically, the Elk Mound Group sandstones appear to fine toward the east with higher concentrations of bioturbation occurring in that direction suggesting the location of deeper waters and increased distances from the shoreline. The Tunnel City Group transitions from the shallow water coarse-grained, quartzose, cross-stratified Mazomanie Formation, to its laterally adjacent deeper water, fine-grained, glauconitic, bioturbated, and hummocky cross-stratified Lone Rock Formation to the east between the Salna and Slinger cores.

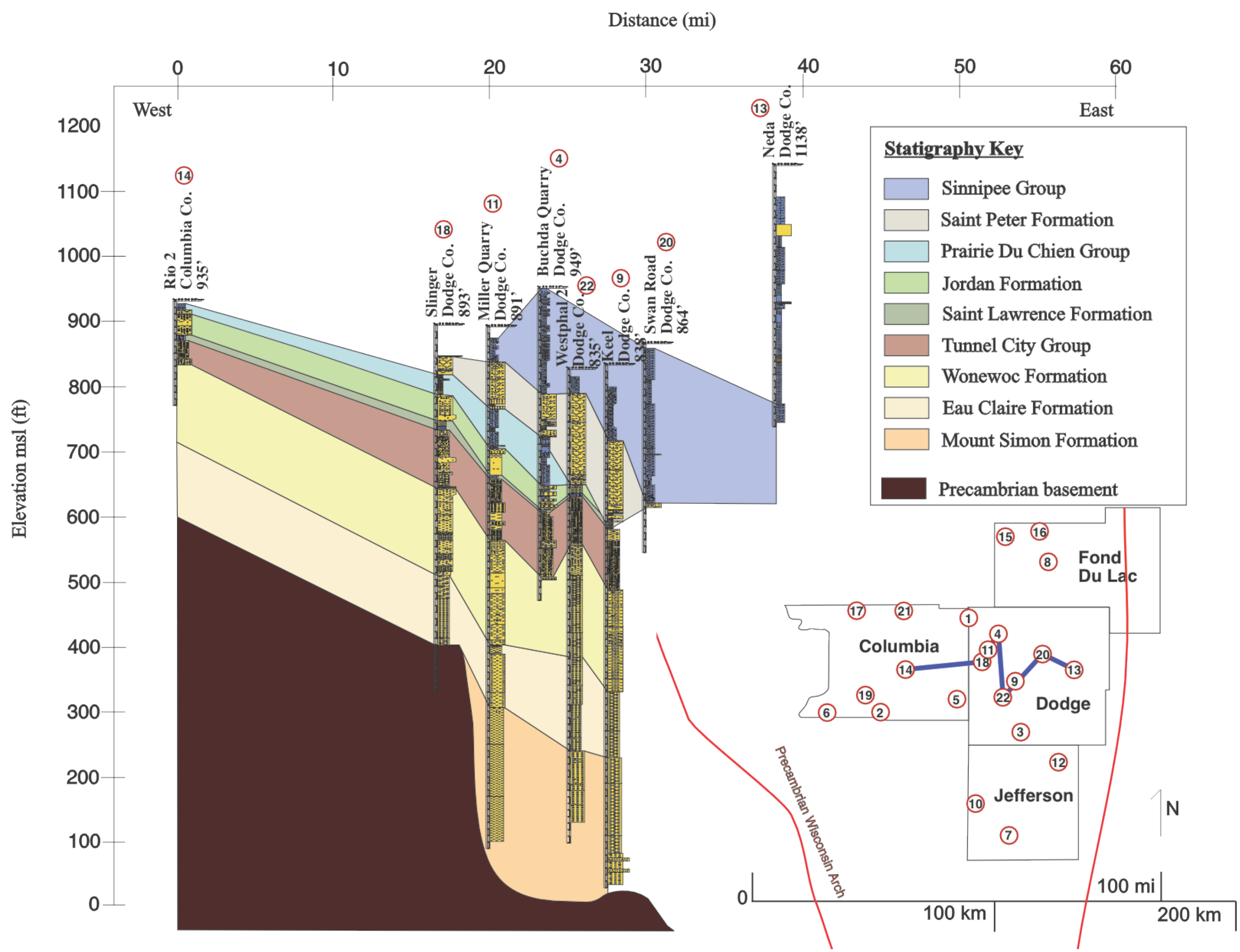


Figure 97. Cross section across central Columbia and Dodge Counties with 220X vertical exaggeration hung on 0 SL

A cross section across central Columbia and Dodge County (Figure 97) shows one intersection of the Precambrian basement at 403 feet above sea level (18. Slinger Core). The Elk Mound Group sandstones are observed to reach depths of 102 feet above sea level without reaching basement indicating a steep downward slope of in Precambrian topography to the east the Slinger core. The Keel core reaches the lower Mount Simon conglomerate around 70 feet above sea level suggesting the Precambrian basement occurs just below the base of the core. This core indicates that steep relief occurs along the eastern flank of the arch and that in this area, the Mount Simon was deposited in low areas adjacent on the eastern flank of the arch.

The Elk Mound Group sands vary in thickness as they fill topography of the arch. The Tunnel City Group strata are observed to maintain thickness as they overlie interpreted Precambrian basement. The Trempealeau and Prairie du Chien Groups appear to thin eastward. Unconformities are observed at the top of the Saint Lawrence and Prairie du Chien. This thinning of the Saint Lawrence is attributed to downcutting related to a forced regression at the end of depositional sequence 2. The Jordan likely filled this eroded topography as observed in other cross sections. However, this cross section shows thinning and absence of the Jordan in eastern cores. This is interpreted to result from the erosional event of depositional sequence 4 beneath the St. Peter Sandstone, in which incised valleys cut down through the Prairie du Chien platform and into the Jordan. Jaggy topography of the Prairie du Chien is attributed to both incised valleys and karstification that was later filled by Saint Peter sandstones in depositional sequence 5.

Lithologically, most units display uniformity across the study area, with the exception of a 20-foot interval of the shallow marine Mazomanie Formation pinching out into the upper Tunnel City of the western Rio 2 core. The Tunnel City consists entirely of the deeper marine Lone Rock Formation further offshore to the east.

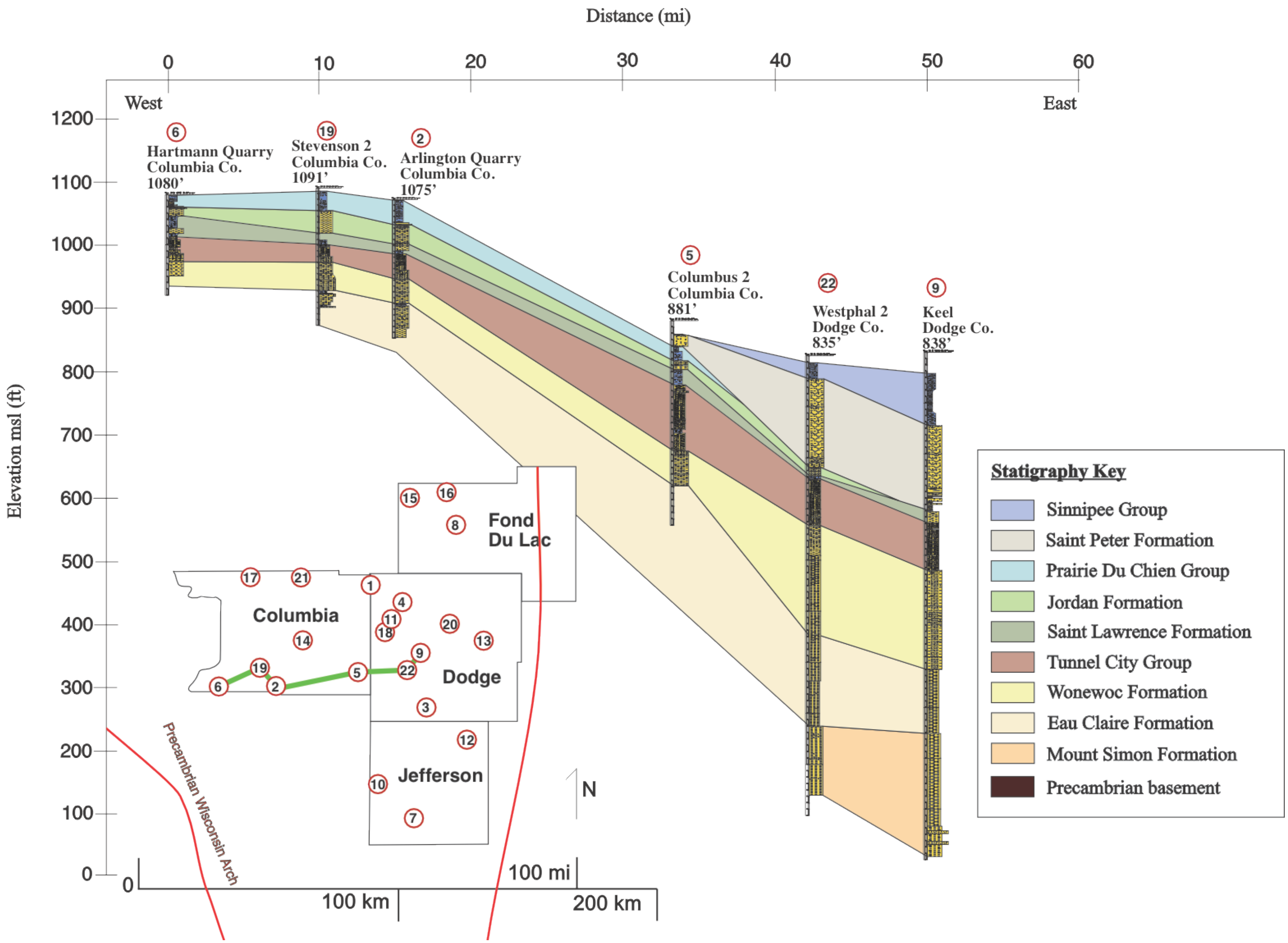


Figure 98. Cross section across southern Columbia and Dodge Counties with 220X vertical exaggeration hung on 0 SL

A cross section across southern Columbia and Dodge County (Figure 98) shows the thickening of facies to the east. No cores in this section intersect Precambrian basement rocks, but the dip of the strata and thickness trends of the stratigraphy can infer the arch is underlying southern Columbia County at a higher elevation to the west under Hartmann Quarry, Stevenson 2, and Arlington Quarry, and sloping down into the basin off to the east. The Keel core interests the lower Mount Simon conglomerate around 75 feet above sea level, indicating that the Precambrian is likely just beneath this elevation.

Thickness variation is observed between the Saint Lawrence and the Jordan Formations, partly due to the downcutting and filling of depressions cut on the Saint Lawrence following depositional sequence 2. The Jordan sandstone becomes thinner, and lithologically finer to the east suggesting increased deposition of this facies up the sloped shoreface during progradation, while increased deposition of finer facies occurred to the east. Another major change in thickness is observed where the Prairie du Chien pinches out the east. This is interpreted to be a result of the erosional event of depositional sequence 4 in which incised valleys cut down through the entirety of the Prairie du Chien platform. These valleys were subsequently filled by Saint Peter sandstones in depositional sequence 5.

Lithologically, these facies remain relatively uniform from west to east across the section with the exception of the Eau Claire and the Jordan Formations. Both of these facies become finer grained to the east indicating a transition into lower energy environments offshore. Though the Hartmann Quarry and Stevenson 2 cores are southwest and south of the Salna and Rio cores that contain the Mazomanie Formation, they do not include this shallow-marine deposit, instead, the finer-grained, glauconitic Lone Rock makes up the entirety of the Tunnel City. This suggests southwestern Columbia County was a deeper environment than northwestern Columbia County.

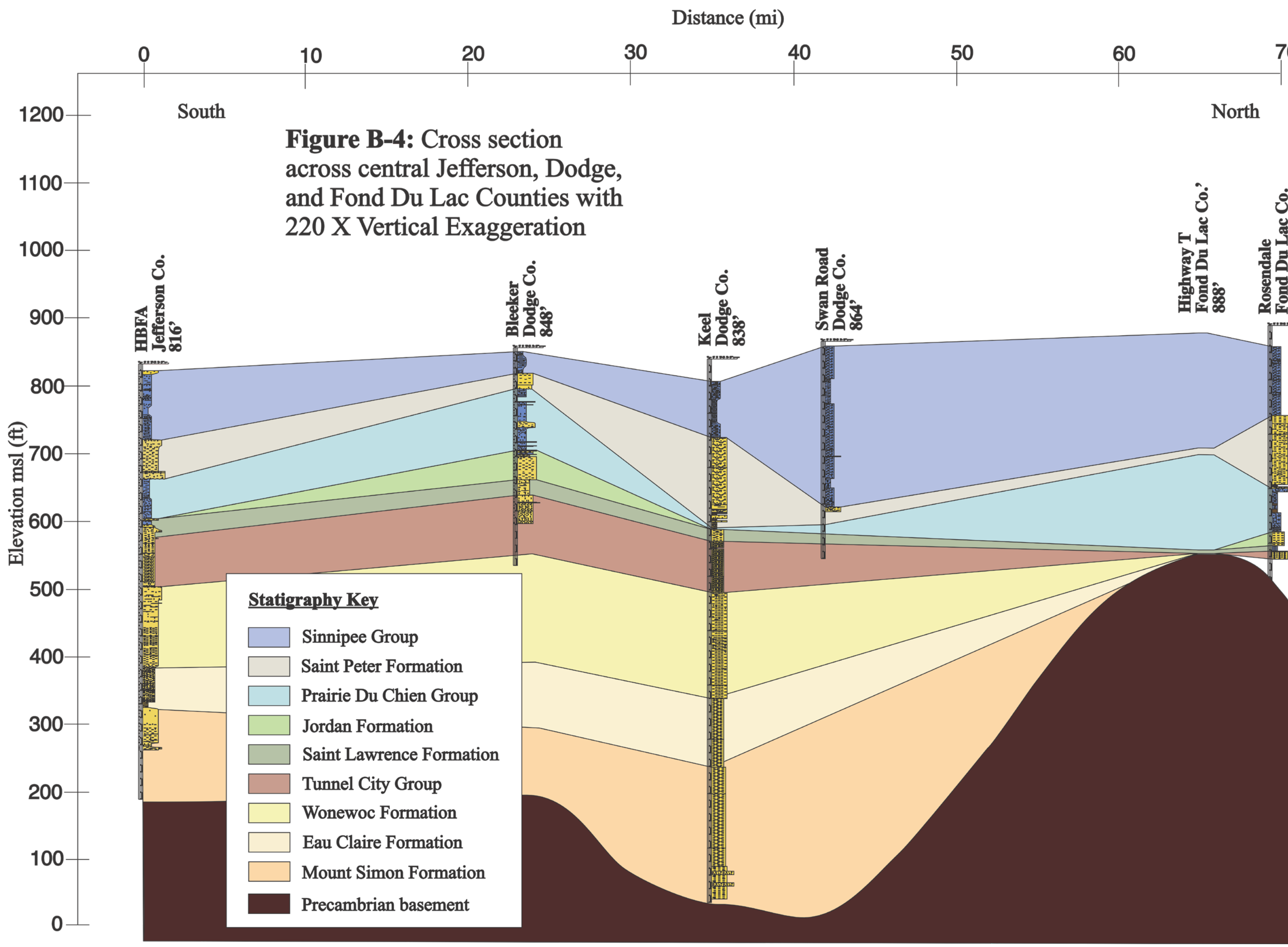


Figure 99. Cross section across central Jefferson, Dodge, and Fond du Lac Counties with 220 X

A cross section across central Jefferson, Dodge, and Fond du Lac Counties (Figure 99) shows strata maintaining thickness as it fills in topography created by the Precambrian arch. One core, Highway T, intersects the Precambrian at 553 feet above sea level. Elk Mound Group and Tunnel City sandstones are interpreted to lap onto the arch moving north because the first unit on top of the arch under Highway T is the Saint Lawrence.

The Trempealeau Group shows a thinning to the north with variable inclusion of the Jordan sandstone. The variability of thickness in the Saint Lawrence is thought to be a result of erosion related to a regression at the end of depositional sequence 2. The absence of the Jordan is attributed to its observed thinning eastward in previous cross sections. The two cores that contains Jordan sandstone are interpreted to be lobate features of an undulating shore face deposit beyond which to the east, the Jordan pinches out.

An interesting relationship between the upper Saint Peter and the base of the Sinnipee Group is observed between the Keel and Rosendale cores in which the Saint Peter is anomalously thin in Swan Road and Highway T cores. More data is needed to fully understand this relationship. Ongoing work by the WGNHS is studying a trend between the elevation of the base of the Sinnipee and topography of the Precambrian surface (see Discussion of Ongoing and Future Work).

Lithologically, the facies in each of these strata remain relatively uniform from south to north likely because they would be of the same facies association as the coastline was parallel to the south-striking Precambrian arch.

Discussion of Sequence Stratigraphy

Five composite depositional sequences separated by unconformities were identified in the late Cambrian to middle Ordovician strata of southeast Wisconsin. Depositional sequence 1 includes the Elk Mound Group sandstones and consist of aggradational and retrogradational parasequences indicative of a sea level rise. Depositional 2 includes the Tunnel City Group and Saint Lawrence Formation and consists of retrogradation followed by a slight progradation and represents a rapid rise in sea level. Depositional sequence 3 includes the Jordan Formation and consists of a progradation after a major forced regression indicating rapid sea level fall followed by a brief rise. Depositional sequence 4 includes the Prairie du Chien Group and consists of retrogradation caused by rapid transgression indicating a relative sea level rise. Depositional sequence 5 includes the Saint Peter Formation and Sinnipee Group and consists of retrogradation caused by a transgression resulting from sea level rise after a prolonged period of sea level low.

Discussion of Regional Trends in Stratigraphy

Four cross sections were used to highlight regional trends that occur west to east, and south to north across the study area. Changes in thickness, elevation, and lithology were all observed to be related to the topography of the south-striking Precambrian arch, and eastward basin. Cross sections interpret strata to be onlapping Precambrian arch highs, filling topographic lows, and maintaining thickness above the underlying Precambrian highs. Coarser-grained, shallow marine facies were observed at their thickest in the western regions of the study area while finer-grained, deeper marine facies were observed in the eastern regions of the study area.

Discussion of Depositional Influence of the Wisconsin Arch

The Precambrian basement rock of southeast Wisconsin is poorly understood due to a historical lack of data. However, the brief insights this study provides, the Wisconsin Arch is much more anomalous in topography and composition than previously assumed. This study describes three different Precambrian lithologies in three different cores from Columbia, Dodge, and Fond du Lac County Counties, each of which intersect the basement at elevations that vary by a magnitude of 500 feet. For the sake of this study, the Precambrian arch has been described based on its influence on overlying stratal thickness and elevation-related facies association as it pertains to proximity to the marine shoreline.

Few cores intersect the Precambrian basement limiting quantitative data on surface elevation of the arch, however, enough cores transect entire formations of the late Cambrian to observe that unit thickness is roughly maintained throughout the upper Elk Mound and Tunnel City, with the exception of strata that direct overlie and onlap the arch. Unit elevation seems to be contingent upon the elevation of the Precambrian arch in lower strata and becomes less appreciable in strata higher in the lower Paleozoic succession as lower sediments have begun to fill primary topography.

The Precambrian high acted as the shelf margin for which Cambrian and Ordovician sediments were deposited. This topographic high is understood to be the major driving force for lateral facies changes that are observed to exhibit fining or pinch out eastward across the study area. Relief on the arch allowed for the deposition of strictly shallower facies atop areas of higher elevation, and deeper facies in areas with lower basement elevation. Northwest Columbia County exhibits overall coarser-grained, shallow mariner facies while the easternmost cores of Dodge, Fond du Lac, and Jefferson counties exhibit finer-grained, deeper marine facies. This

suggests the Precambrian basement, though not intersected by core in this area, reaches a topographic high in northwestern Columbia County relative to the rest of the study area.

Discussion of Deformed Horizons

Major deformation horizons are observed along the Prairie du Chien- Saint Peter contact in Columbia, Dodge, Fond du Lac, and Jefferson County. The horizon is a one-to-20 feet thick brecciated, reworked dolomite, dark brown mud, and white sand. Common deformation characteristics include angular dolomite rip-up clasts, soft-sediment deformed (faulted and folded) mud, poor cementation of sands, and highly silcritic dolomite and sand beds (Figure 100).

The Prairie du Chien dolomite underlying the deformation horizon is often fractured with high amounts of vugs and secondary porosity. The lower Saint Peter Readstown Formation overlying the deformation horizon is a white, brecciated, silcritic sandstone rare dolomite rip-up clasts. The Prairie du Chien Group and Saint Peter Formation thicknesses show an inversely proportional relationship across the study area suggesting a downcutting or local depression of the Prairie du Chien surface prior to deposition of the Saint Peter sands.

High amounts of silcrete in the deformed horizons suggest evidence of a prolonged subaerial exposure (cf. Nichols, 2009) in which alteration of the Praire du Chien surface occurred. Angular rip up clasts, soft sediment deformed muds, and poor consolidation suggest sediment collapse along unstable slopes during exposure. An unstable slope was likely created during exposure by two processes: the creation of extensive incised valleys and/or by karsting caused by ground water head fluctuation.

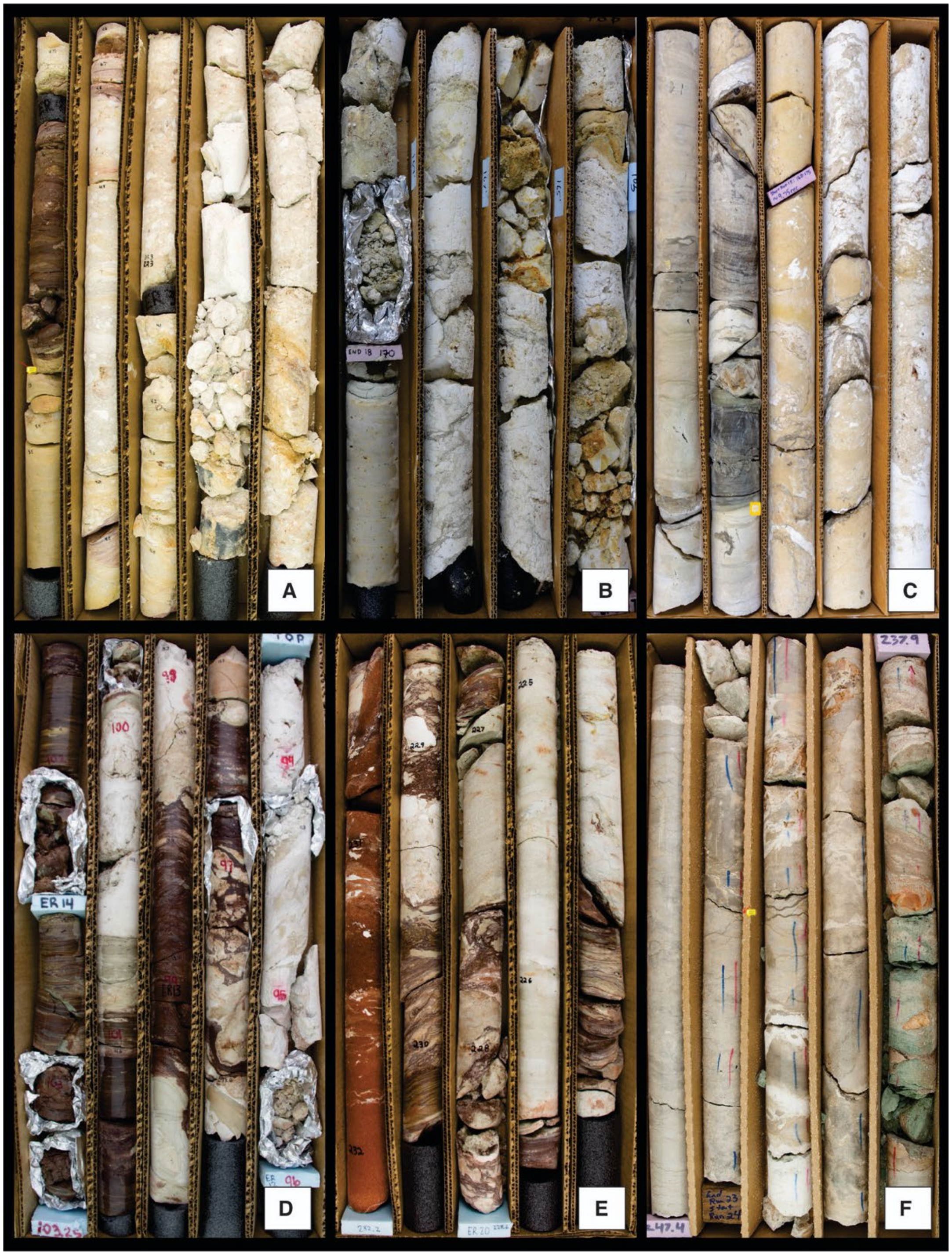


Figure 100. A deformed horizon along the Prairie du Chien-Saint Peter contact is observed in cores throughout the study area. **(A)** Columbus 2 Box 2, Columbia County. **(B)** HBFA Box 20, Jefferson County. **(C)** Mankowski Box 14, Jefferson County. **(D)** Slinger Box 6, Dodge County. **(E)** Keel Box 21, Dodge County. **(F)** Rosendale Box 21, Fond du Lac County.

Discussion of Ongoing and Future Work

The WGNHS is interested in using the findings of this study to create comprehensive groundwater models that will determine the effect of major contacts, changing lithology, and sulfide concentrations on water quality and flow dynamics. Additionally, the continued study of the Precambrian Wisconsin arch and related tectonism throughout the early Paleozoic remains at the forefront of WGNHS's mapping and research interests. Recent work by the WGNHS has compared the elevation of the base Sinnipee Group to an aeromagnetic anomaly map (Figure 101 and 102). Structure contour lines and mapped folds of the base Sinnipee overlie Precambrian anomalies nearly perfectly (Stewart, 2021). This observation could provide new insights into how the Precambrian arch affected sedimentation throughout the early Paleozoic.

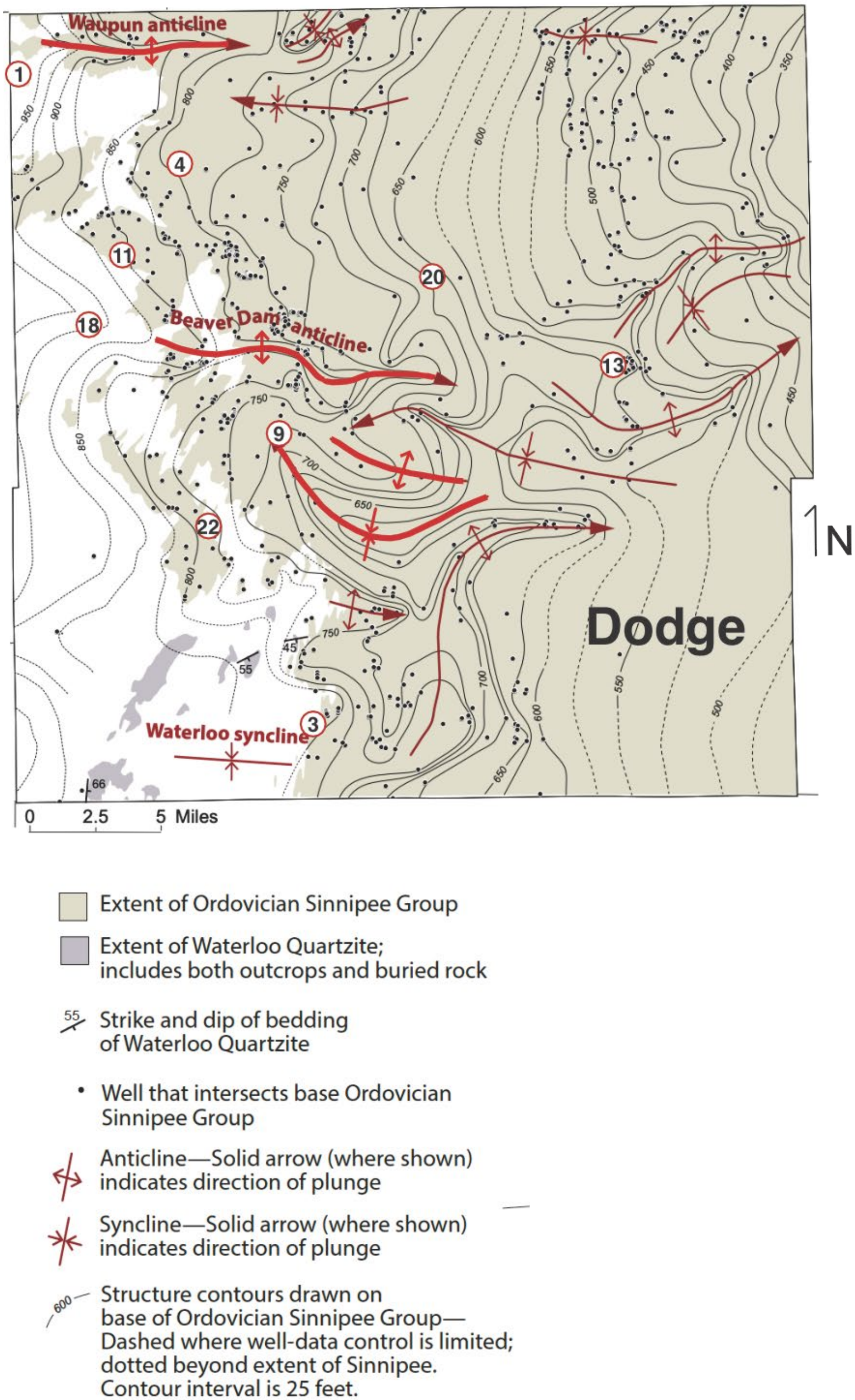


Figure 101. Dodge County core locations in relation to base Sinnipee Group elevation contours with anticline and syncline structures (modified from Stewart, 2021).

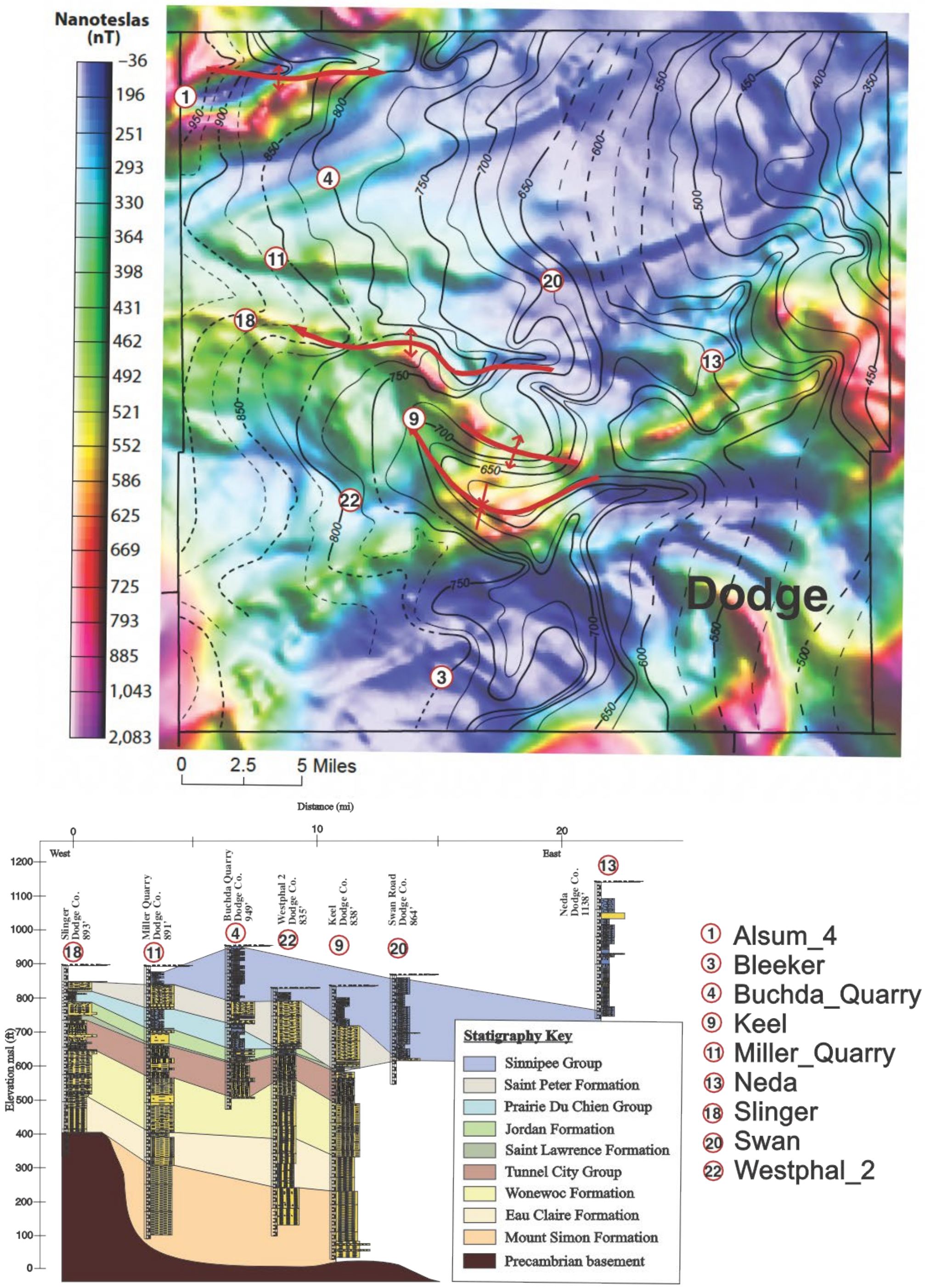


Figure 102. Sinnipee Group elevation contours and folds superimposed on aeromagnetic anomalies showing strong correlation (modified from Stewart, 2021). Vertically exaggerated cross section of Dodge County cores show Cambrian and Ordovician strata's relationship to Precambrian surface (dark red).

This study of early Paleozoic strata will be continued in summer work through the WGNHS. 3-D models of this study area will be constructed using ArcGIS Pro's Voxel Geo software to view stratigraphic contacts through any planar cross section. In addition to continued work related to this study area, a similar study of Cambrian and Ordovician strata will begin with particular interest in Lafayette and Dodge Counties of southwestern Wisconsin. Stratigraphic section will be remeasured, described, and interpreted in further detail to understand sedimentology, stratigraphy, and deformation as it pertains to deposition along the western Wisconsin arch into the Hollendale embayment.

Conclusions

Early Paleozoic strata of Columbia, Dodge, Fond du Lac, and Jefferson County, Wisconsin display a combination of clastic and carbonate sedimentary packages that were deposited along an intercontinental, shallow marine margin along the Precambrian Wisconsin arch from the late Cambrian to middle Ordovician. Detailed logs of 22 cores were used to carefully identify lithologic and stratigraphic contacts that were interpreted to tell a story of changing environments driven by fluctuating sea level over a 40-million-year period. A model of eight facies associations was created to show the changing environments along the shelf from nonmarine terrestrial to offshore marine. The study of parasequences in the stratigraphy identified five depositional sequences driven by fluctuations in sea level. Regional trends in thickness, elevation, and lithology of the stratigraphy were identified in cross section and explained using the facies model and depositional sequences of this study.

Particular attention was given to the nature of deformed and altered horizons. The mechanisms of soft sediment slumping and sliding, karst collapse, tectonic disturbance, and glacial overriding were considered as cause of deformation in this study. This study found that deformation occurred most commonly along major sequence boundaries. Horizons that repeatedly displayed deformation and alteration include: the Saint Lawrence-Jordan contact and the Prairie du Chien-Saint Peter contact. Both of these contacts correspond to depositional sequence boundaries that are related to fall in sea level. Deformation in the Saint Lawrence-Jordan contact is related to slumping and sliding along incised valleys carved into the Saint Lawrence that were formed during a forced regression and resulting sea level low. The Jordan sandstone later filled these incisions when sea level began to rise. Similarly, deformation along the Prairie du Chien-Saint Peter contact is attributed to a prolonged sea-level low that resulted in substantial erosion of the exposed Prairie du Chien platform. Prolonged subaerial exposure during the sea level low allowed for the development of complex drainage networks that cut down into the Prairie du Chien and underlying strata. Karstification of Prairie du Chien carbonates also occurred from the mixing of meteoric waters and groundwater. Deformation along this horizon is a result of slumping and sliding and alluvial accumulation along the incised valley walls and karst margins.

Deformation caused by glacial overriding was ruled out because disturbance and alteration were observed to be along significant stratigraphic contacts suggesting they were related to unconformities between depositional sequences in deep time. Additionally, there is no evidence of disturbance in strata overlying deformed horizons to suggest stress from glacial overriding would have affected these stable rocks at depth. This study did not find enough evidence to confirm or deny the level influence tectonics had on deformational horizons.

However, this study does provide strong explanation for the nature of deformation by slumping and sliding of incised valley margins and karst collapse supported by constructed sea level curves, lateral facies trends, and identification of prolonged subaerial exposure between stratigraphic units.

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APPENDIX :
CORE LOGS

CORE LOG SYMBOL LEGEND

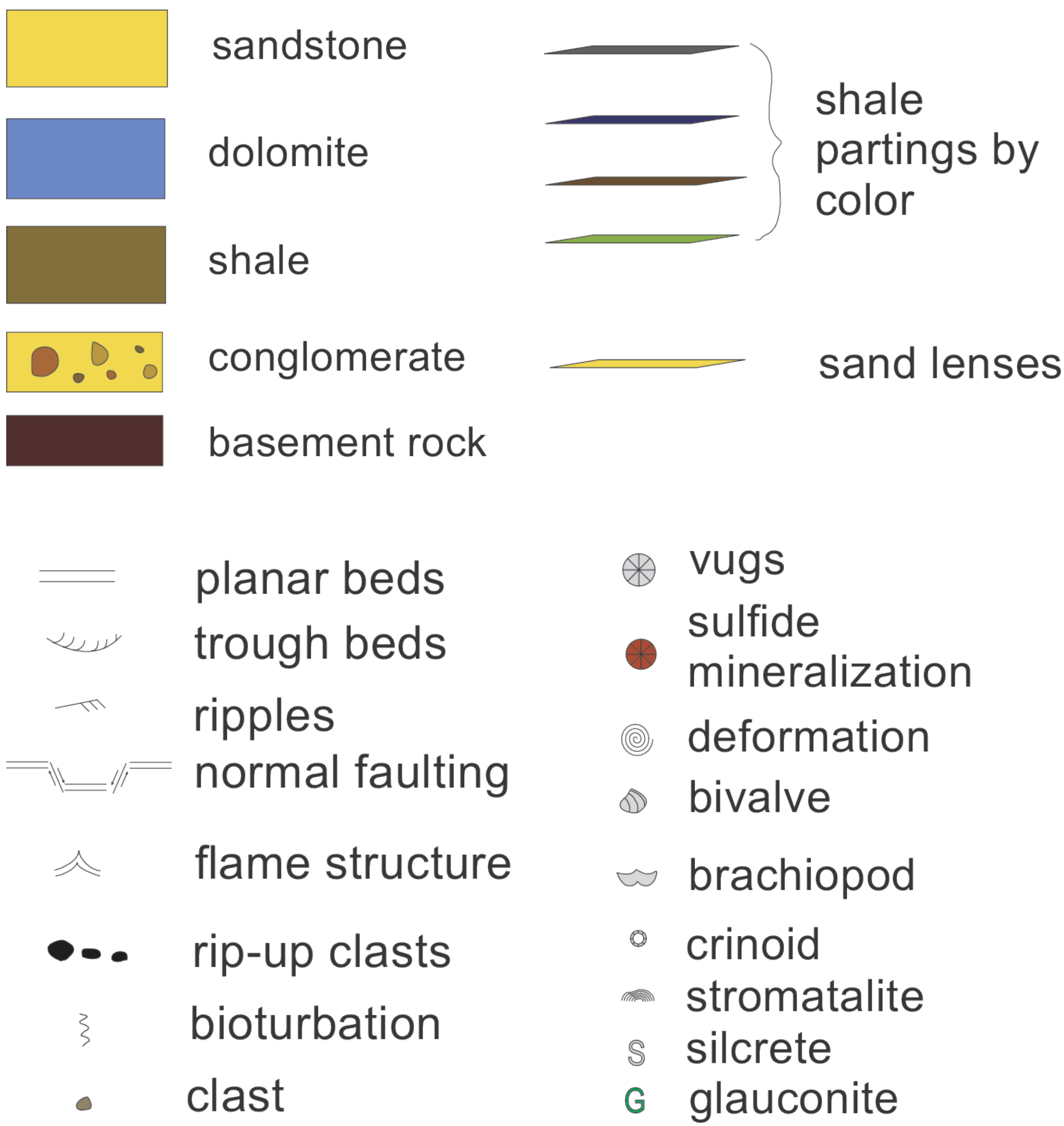
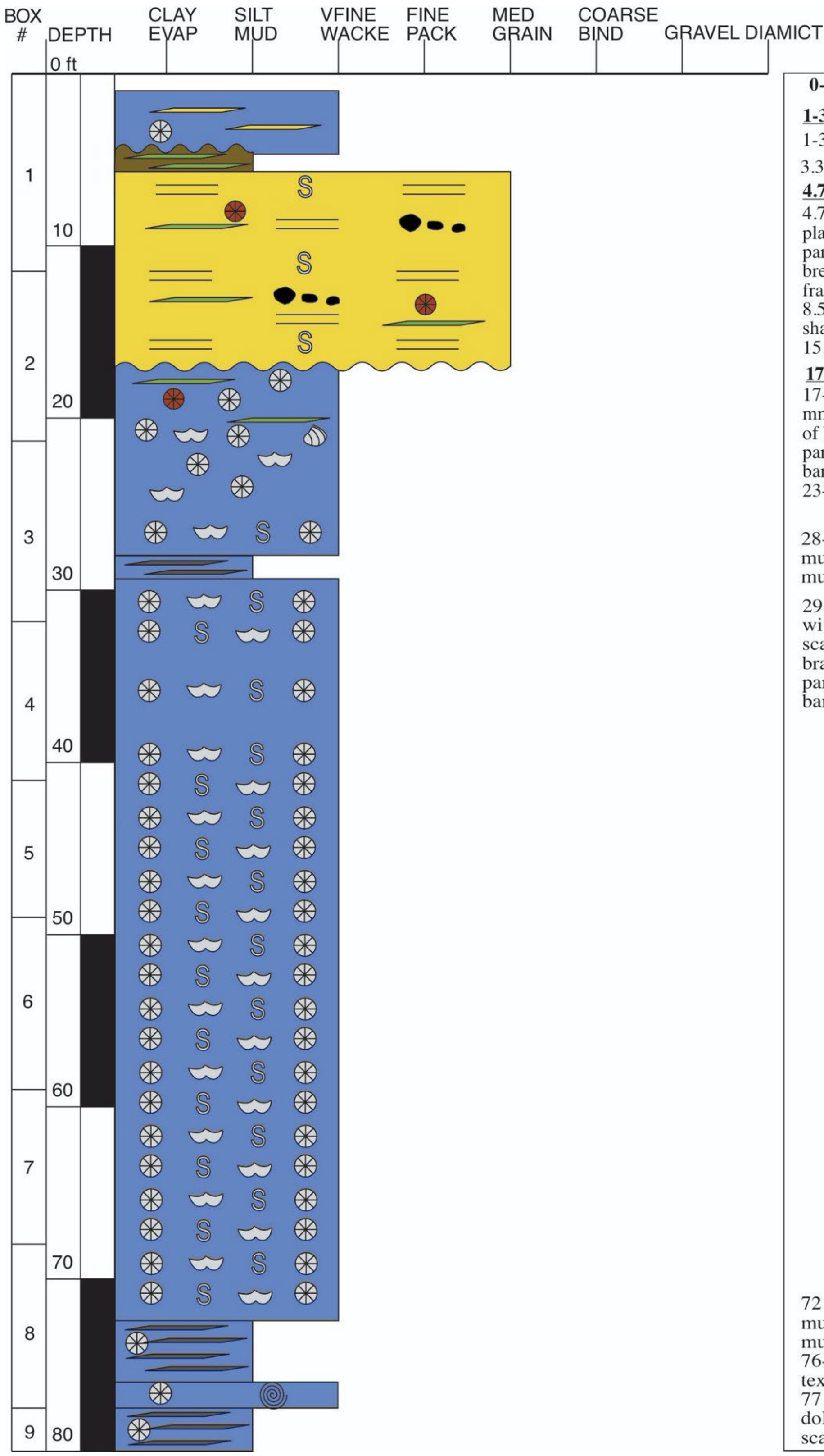


Figure A-i. Core Log Symbol Legend

Figure A-1. Alsum 4, Dodge County

Elevation: 976’ Total Depth: 328.4’



0-1 ft core loss

1-3.3 ft Sinnipee Gp Platteville Fm

1-3.3’ gray sandy dolomite wackestone

3.3-4.7’ tan and light green laminated mud

4.7-17 ft St Peter Fm

4.7-17’ white medium quartz sand with planar cross beds, light green shale partings, sulfide mineralization, brecciation and quartz and silcrete in fractured pore space

8.5-8.7’ 1-2 cm light green brecciated shale in shandstone

15.9-16’ layer of .5 cm mud cracked shale

17-114 ft Prairie Du Chien Gp Shakopee

17-28’ gray dolomite wackestone with mm to cm scale vugs often in the shape of brachiopods, 1mm light green shale partings, cm scale silcrete nodules and bands, oolitic texture

23-23.1’ flat pebble conglomerate?

28-29.5’light gray to white dolomite mudstone with dark gray mm scale mud partings. Tidal flat.

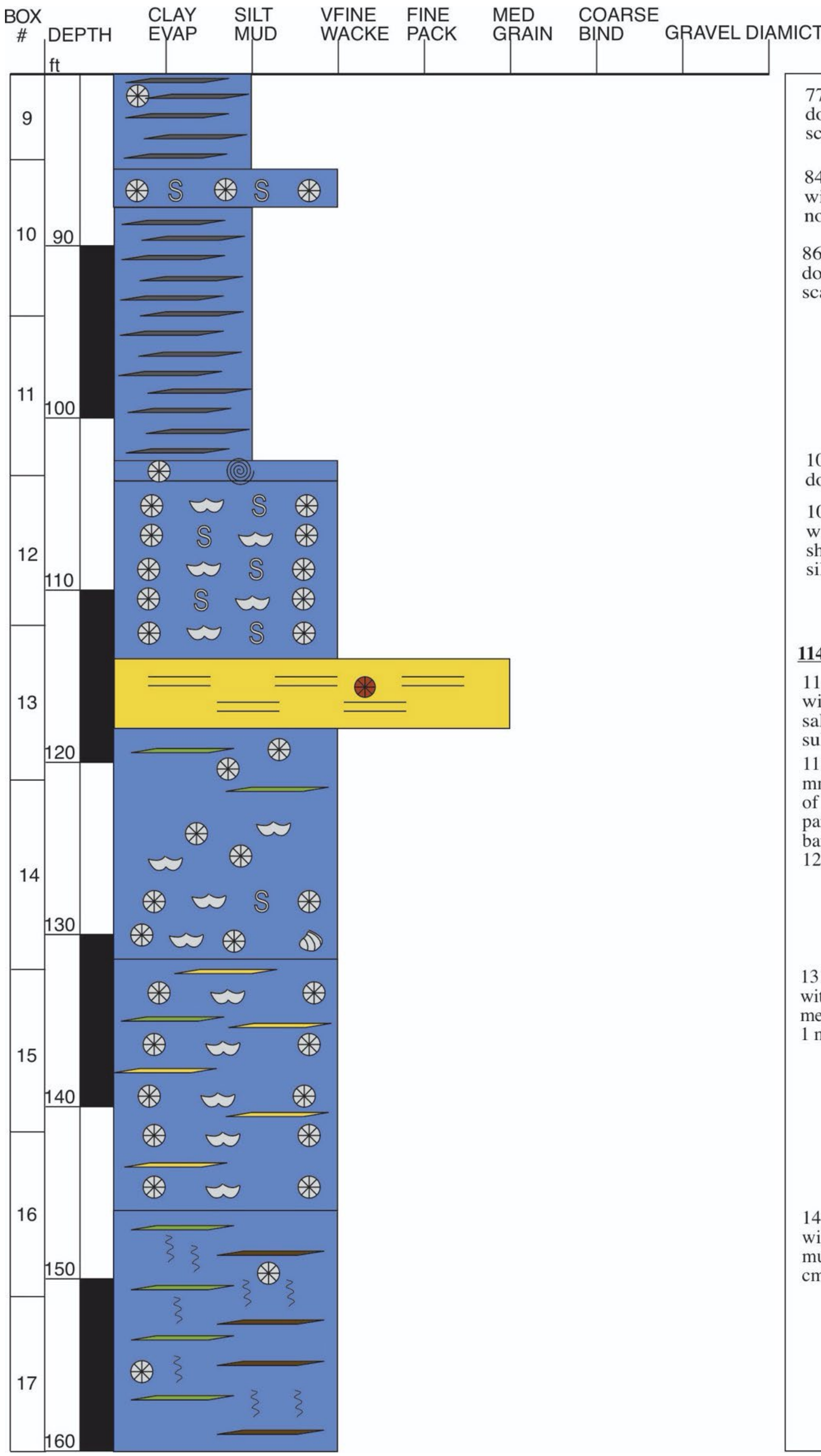
29.5-72.5’gray dolomite wackestone with thrombolitic texture, mm to cm scale vugs often in the shape of brachiopods, 1mm dark gray shale partings, cm scale silcrete nodules and bands

72.5-76’ light gray to white dolomite mudstone with dark gray mm scale mud partings. Tidal flat.

76-77.5’ dark gray mottled dolomite texture, possible karst fill

77.5-84.4’ light gray to tan laminated dolomite mudstone with dark gray mm scale mud partings. Tidal flat.

Figure A-1. Alsum 4 continued



77.5-84.4' light gray to tan laminated dolomite mudstone with dark gray mm scale mud partings. Tidal flat.

84.4-86.4' gray dolomite wackestone with cm scale vugs and silcrete nodules

86.4-102.5' light gray to tan laminated dolomite mudstone with dark gray mm scale mud partings. Tidal flat

102.5-103.5 dark gray mottled dolomite texture, possible karst fill

103.5-114' gray dolomite wackestone with mm to cm scale vugs often in the shape of brachiopods, mm to cm silcrete nodules and bands

<u>114-165 ft Prairie Du Chien Gp Oneota</u>

114-118' white medium quartz sand with planar cross beds and 1 inch of salt and pepper texture with black sulfide grains

118-131.5' gray dolomite wackestone with mm to cm scale vugs often in the shape of brachiopods, 1mm light green shale partings, cm scale silcrete nodules and bands

127.4-128.3' thrombolotic texture

131.5-146' light gray to tan sandy dolomite with mm to cm scale vugs, 0.5-3 cm medium quartz sand lenses, and light green 1 mm shale partings

146-165' tan silty laminated dolomite with yellow, light green and maroon mud/silt bioturbated layers, few mm to cm scale vugs

Figure A-1. Alsum 4 continued

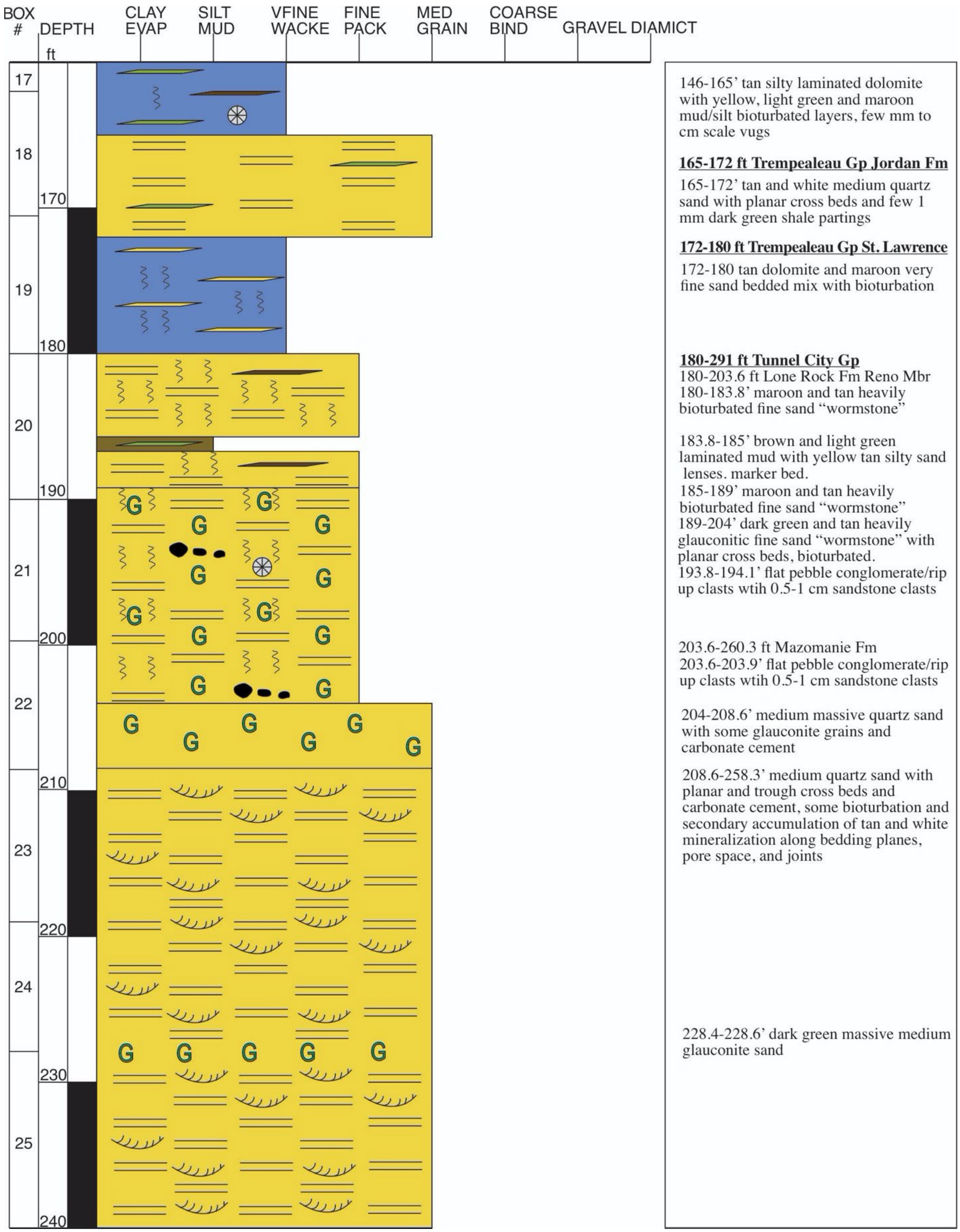


Figure A-1. Alsum 4 continued

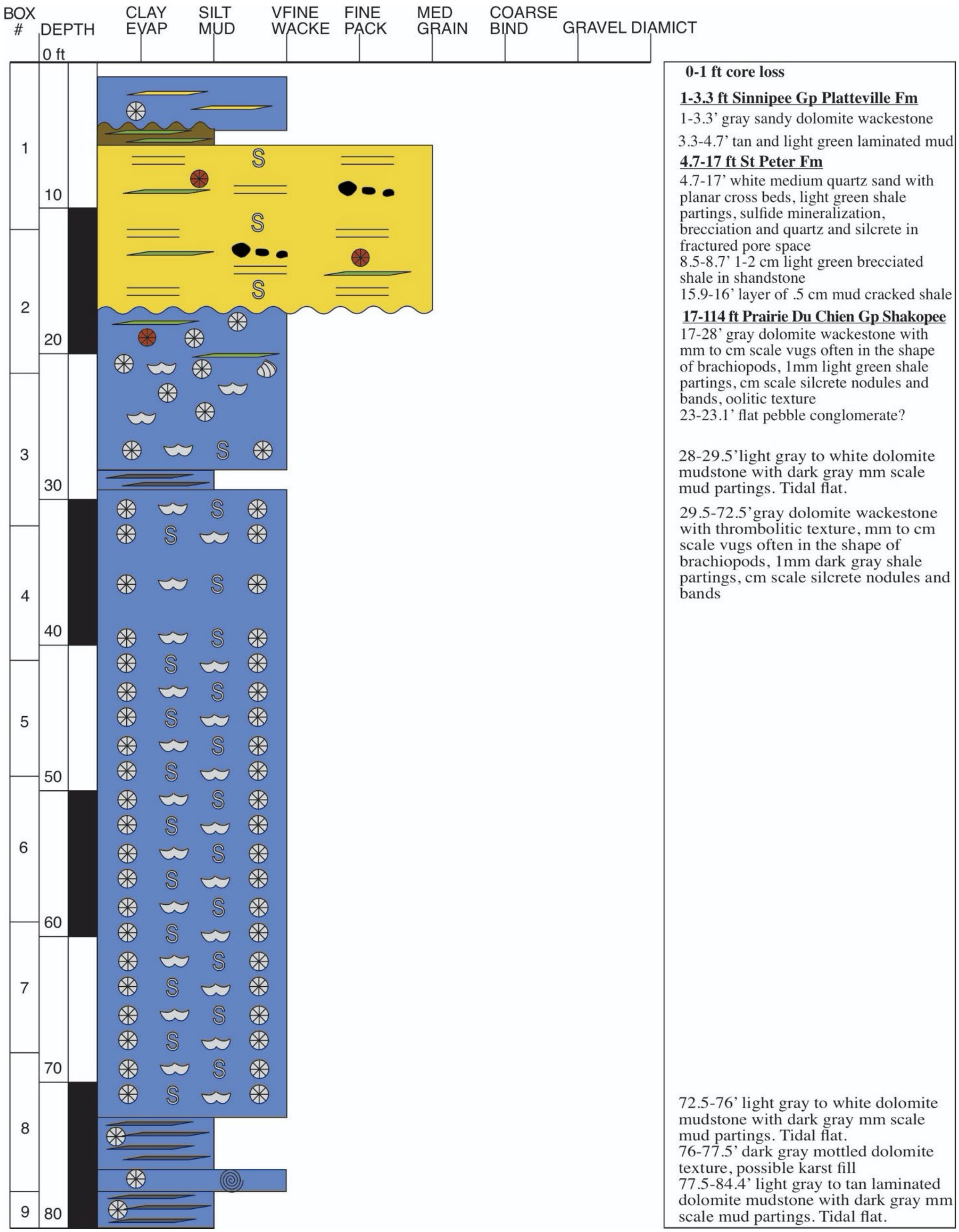
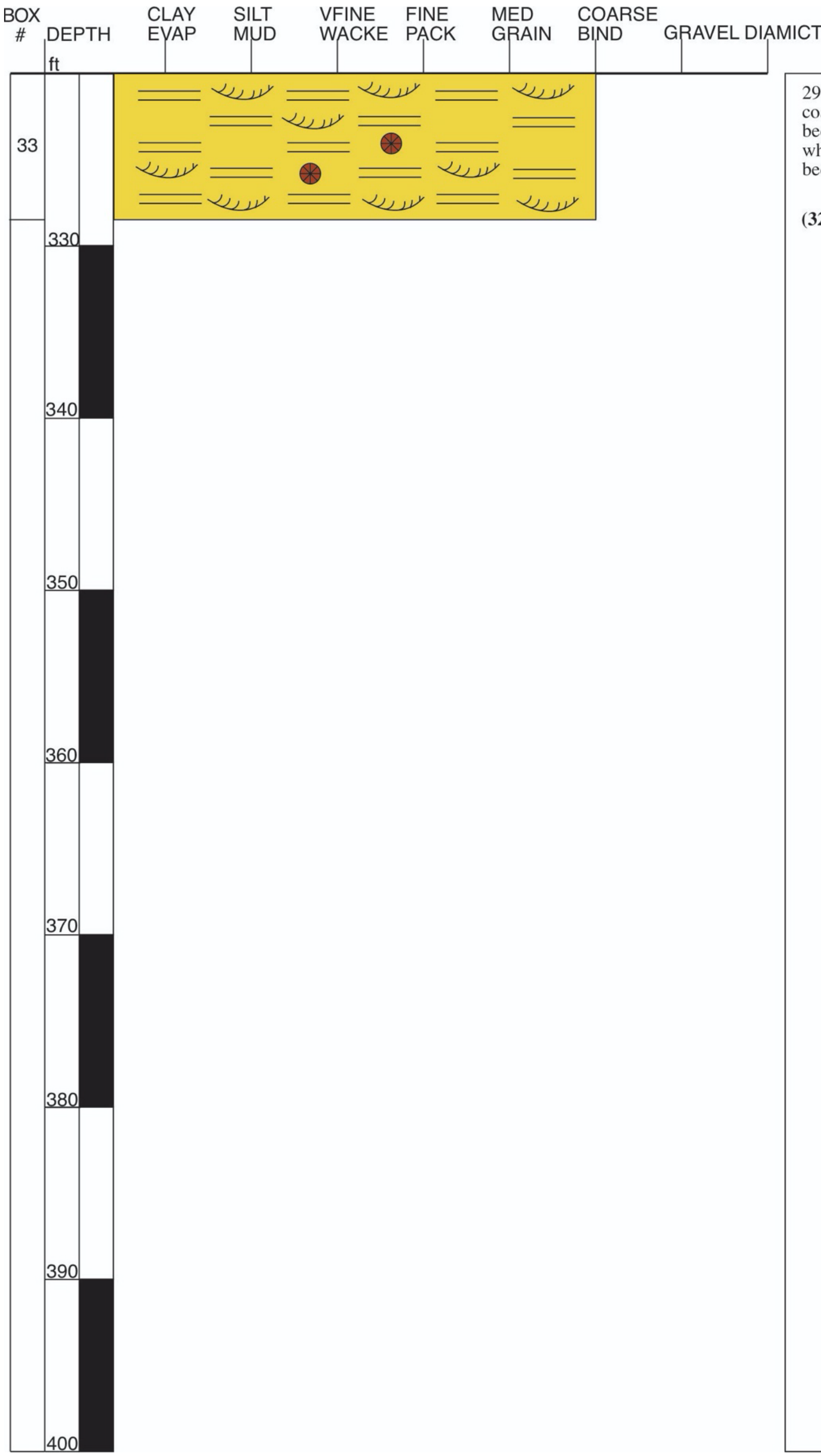


Figure A-1. Alsum 4 continued



291-328.4' white, tan, and light pink coarse sand with planar and trough cross beds, some secondary accumulation of white and tan mineralization in pore space, bedding planes and joints

(328.4 ft end core)

Figure A-2. Arlington Quarry, Columbia County

Elevation: 1075’ Total Depth: 238.6’

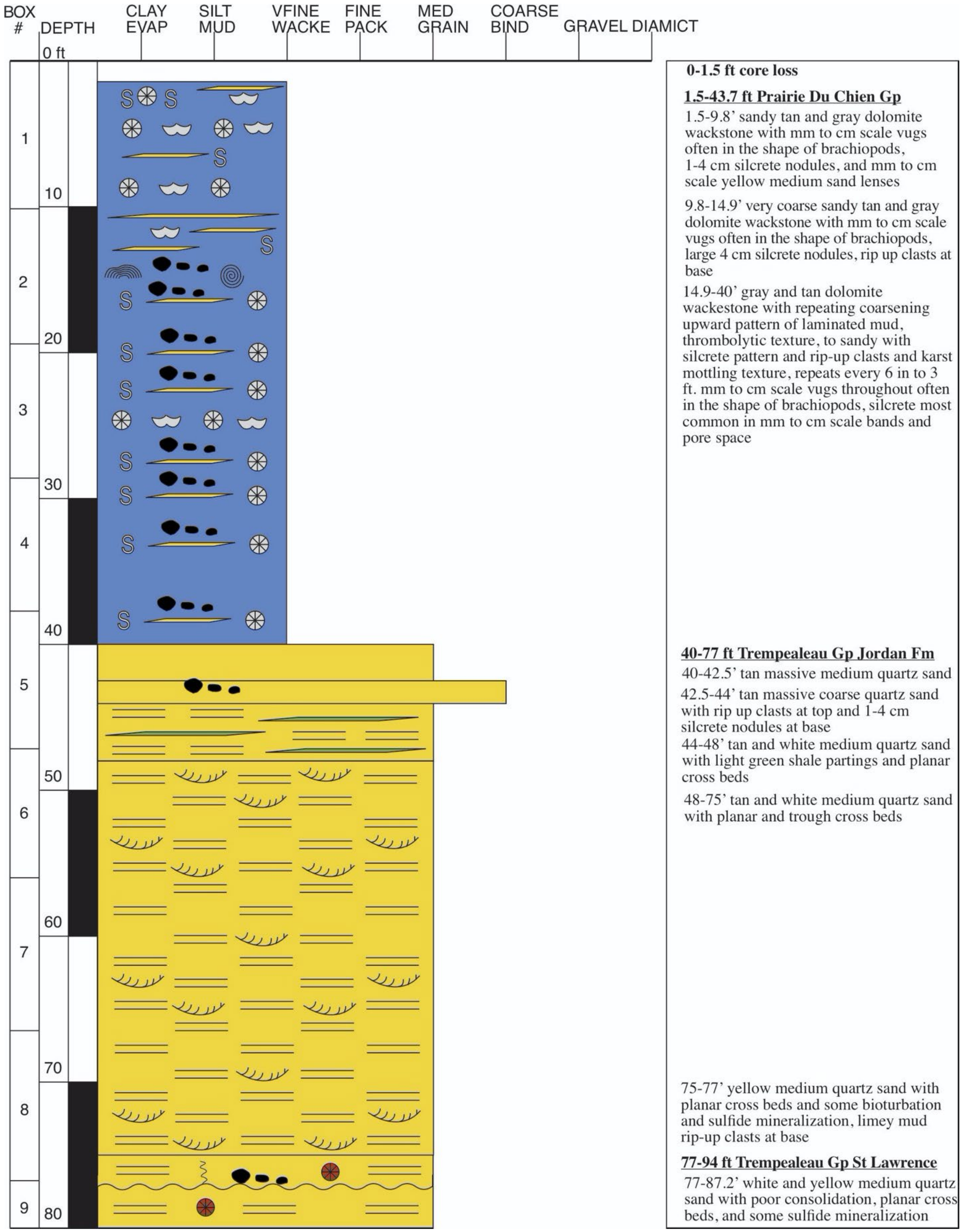


Figure A-2. Arlington Quarry continued

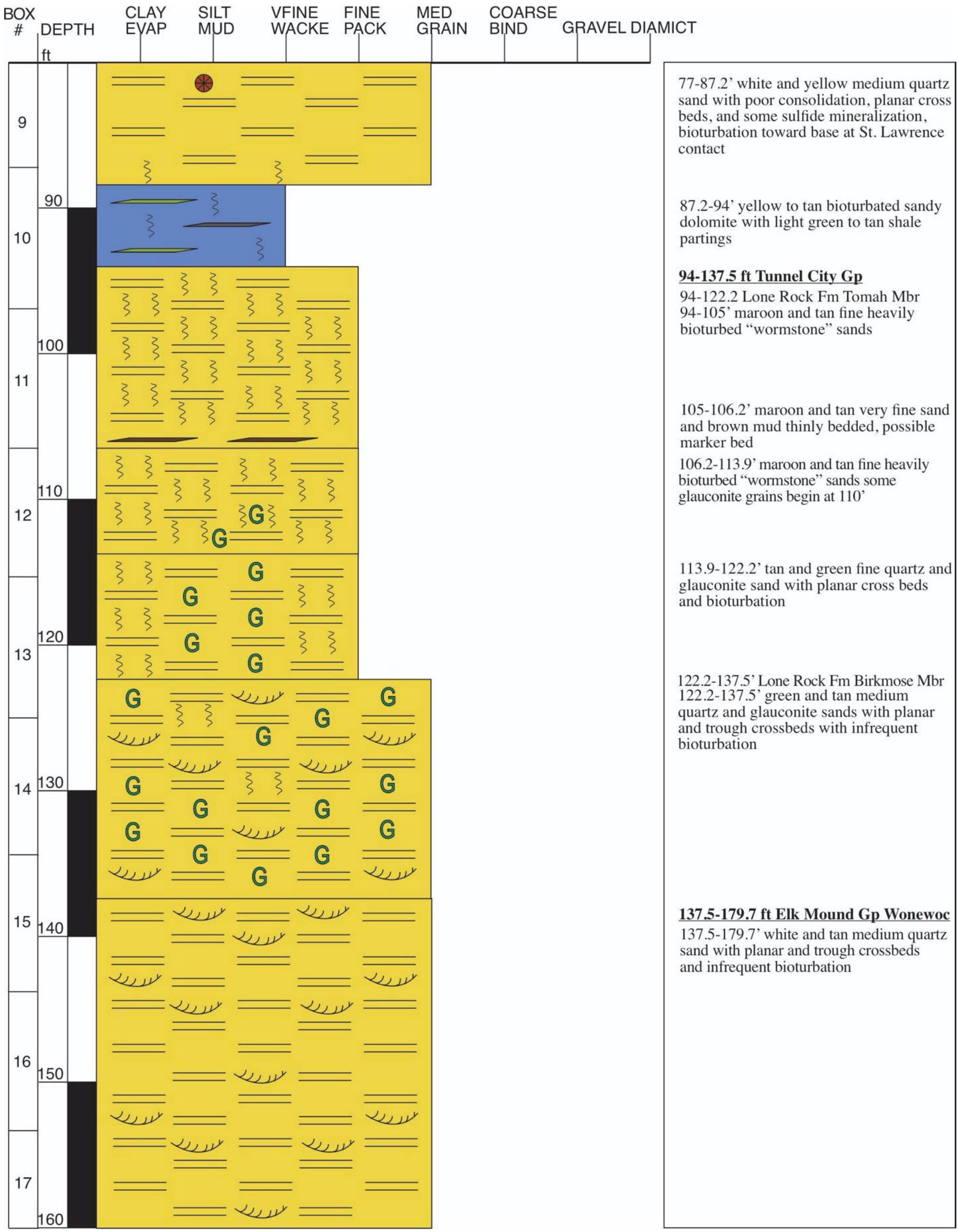


Figure A-2. Arlington Quarry continued

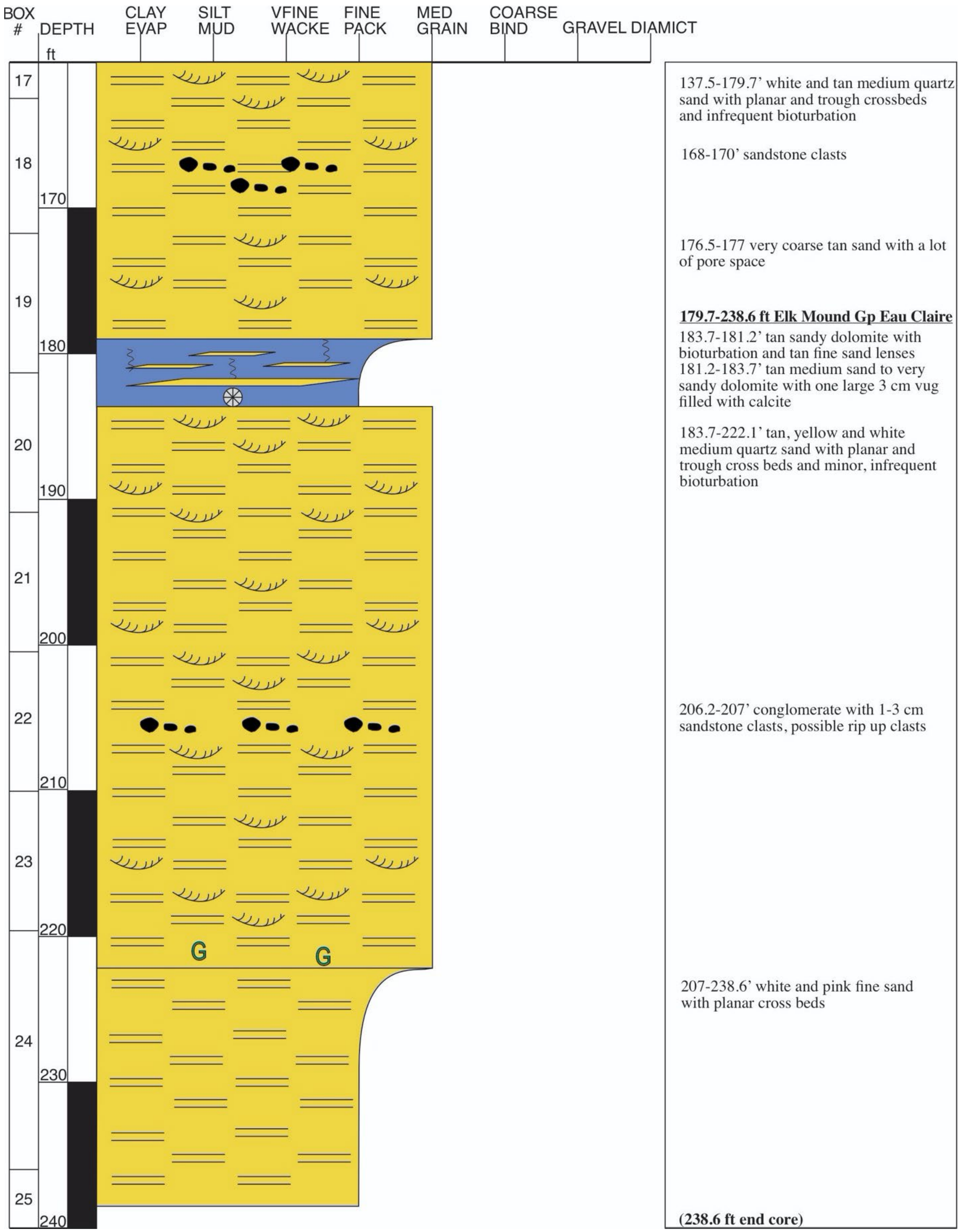
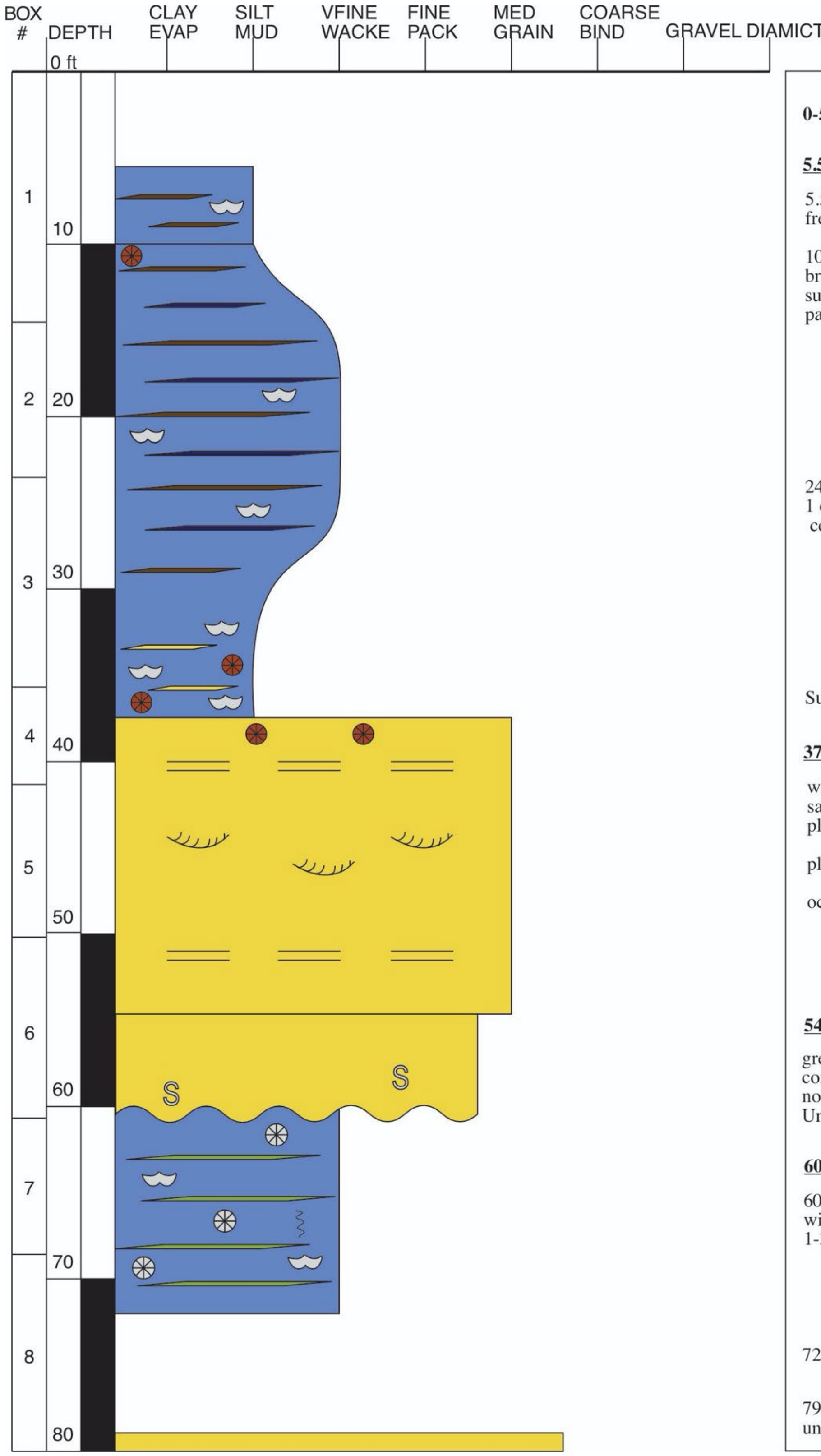


Figure A-3. Bleeker, Dodge County

Elevation: 848’ Total Depth: 258.3’



0-5.5 ft core loss

5.5-37.5 ft Sinnipee Gp. Platteville Fm.

5.5-10’ light brown silty dolomite with frequent 1-2 mm brown shale partings

10-24’ alternating gray/blue and light brown sandy dolomite with Fe staining, sulfide mineralization, and dark gray shale partings

24-37.5’ light brown sandy dolomite with 1 cm sand lenses of m-c sand $CaCO_3$ cement

Sulfide cement horizon

37.5-54.75 ft St Peter Fm. Tonti

white to yellow medium bedded quartz sandstone with Fe stains along bedding planes

planar and trough cross beds common

occasional fining upwards sequences

54.75- 60.75 ft St Peter Fm. Reedstown

green to gray fine to medium poorly consolidated sand with frequent silcrete nodules

Unconformity- unconsolidated rubble

60.75- 118 ft Prairie Du Chien Shakopee

60.75- 72’ light gray dolomite wackestone with 1 mm light green shale partings and 1-3 cm vugs

72-79.5’ no core recovery

79.5- 80’ light brown medium to coarse unconsolidated sand

Figure A-3. Bleeker continued

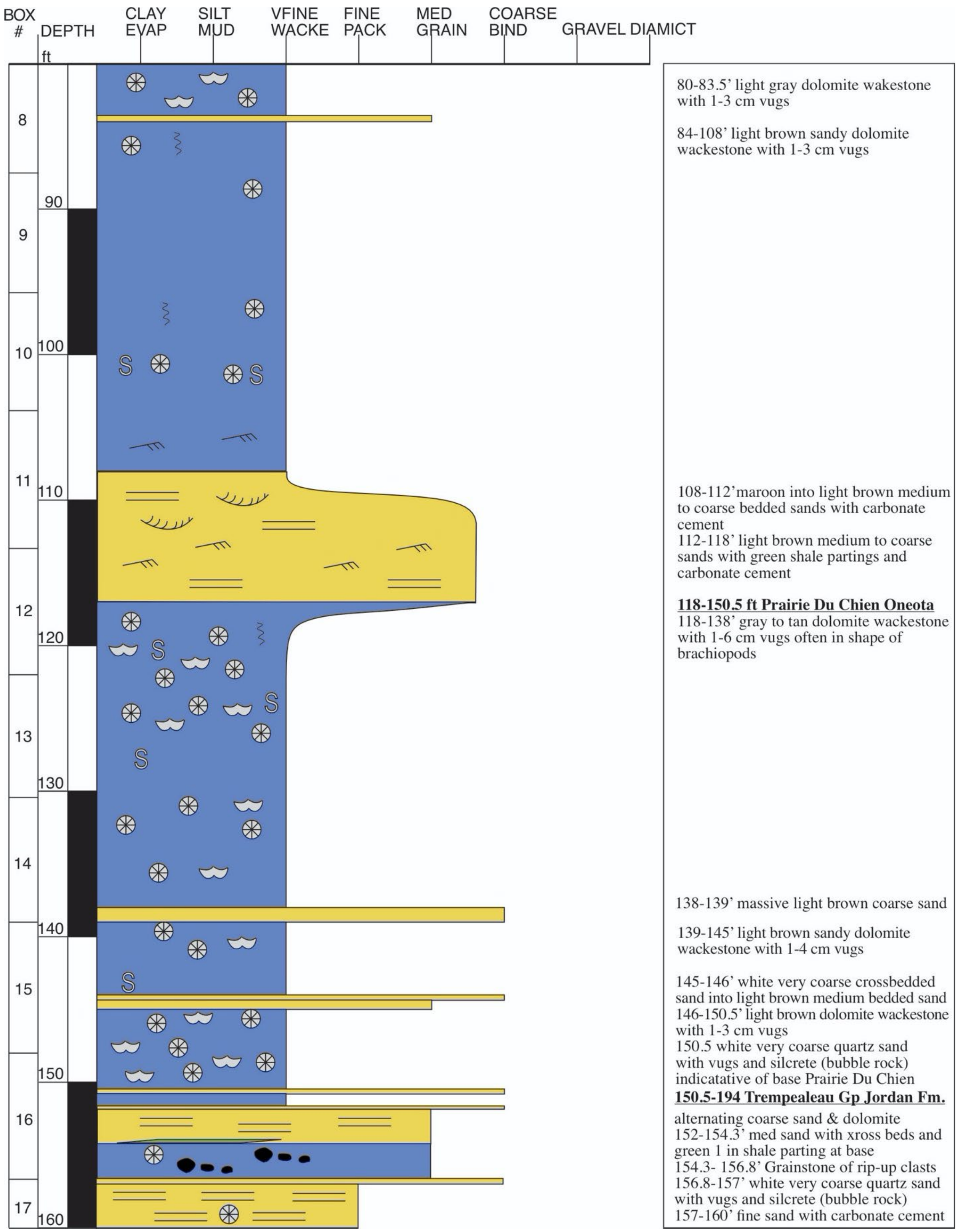


Figure A-3. Bleeker continued

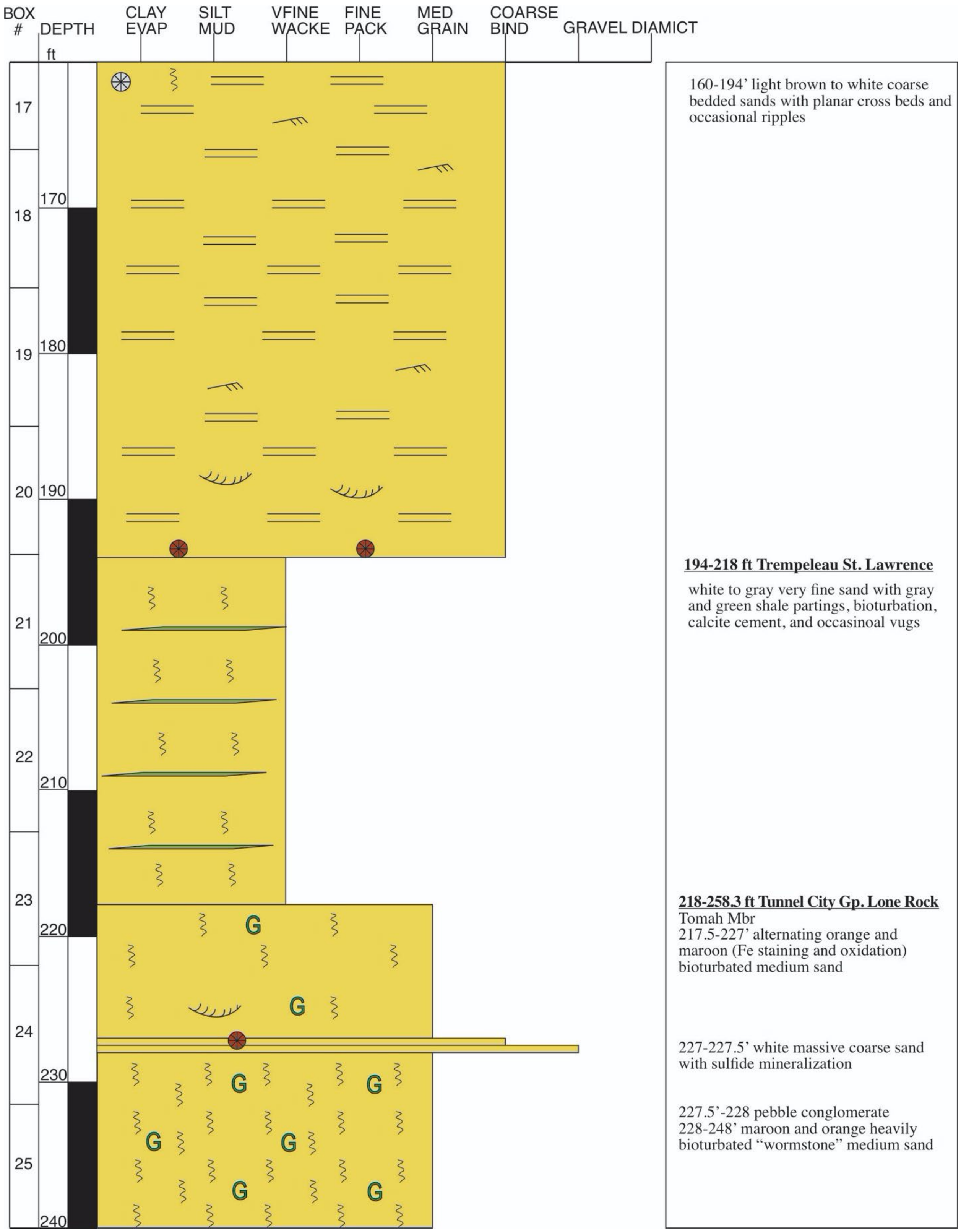
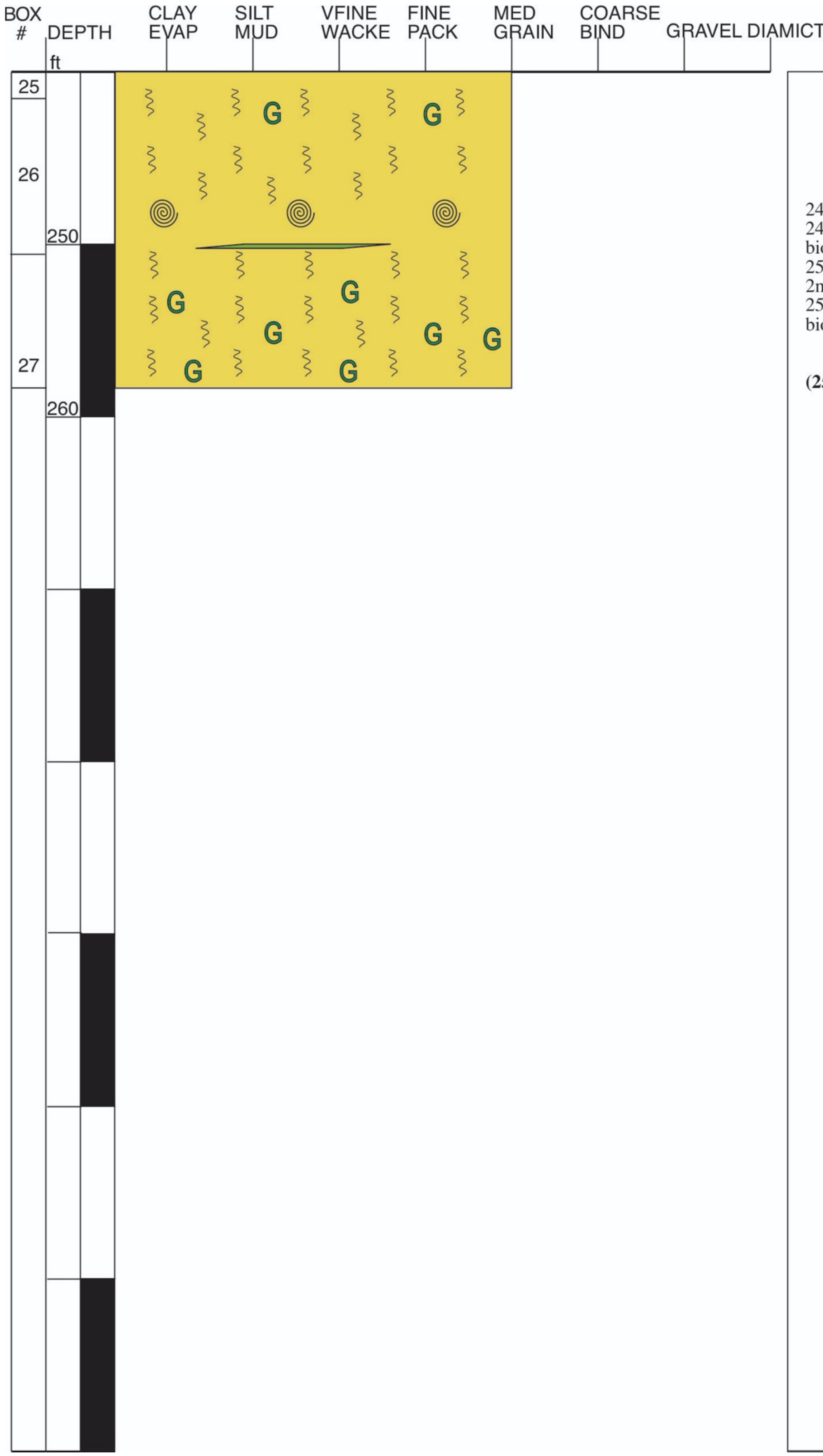


Figure A-3. Bleeker continued



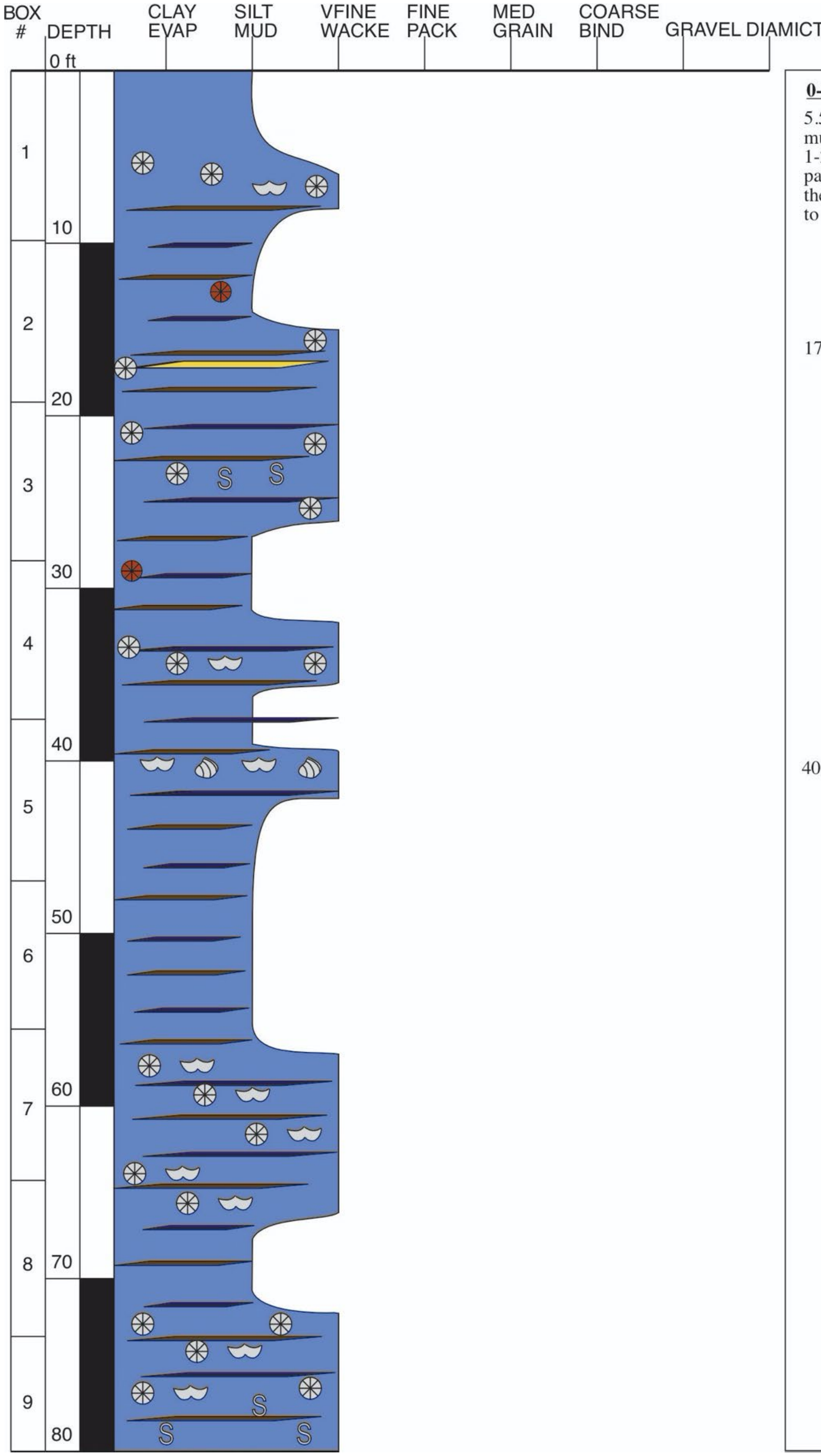
248-248.75' deformed
248.75- 250' maroon and orange heavily bioturbated "wormstone" medium sand
250-250.5 light brown medium sand with 2mm green shale partings
250.5-258.3 maroon and orange heavily bioturbated "wormstone" medium sand

(258.3' end core)

Figure A-4. Buchda Quarry, Dodge County

Elevation: 949'

Total Depth: 448.5'



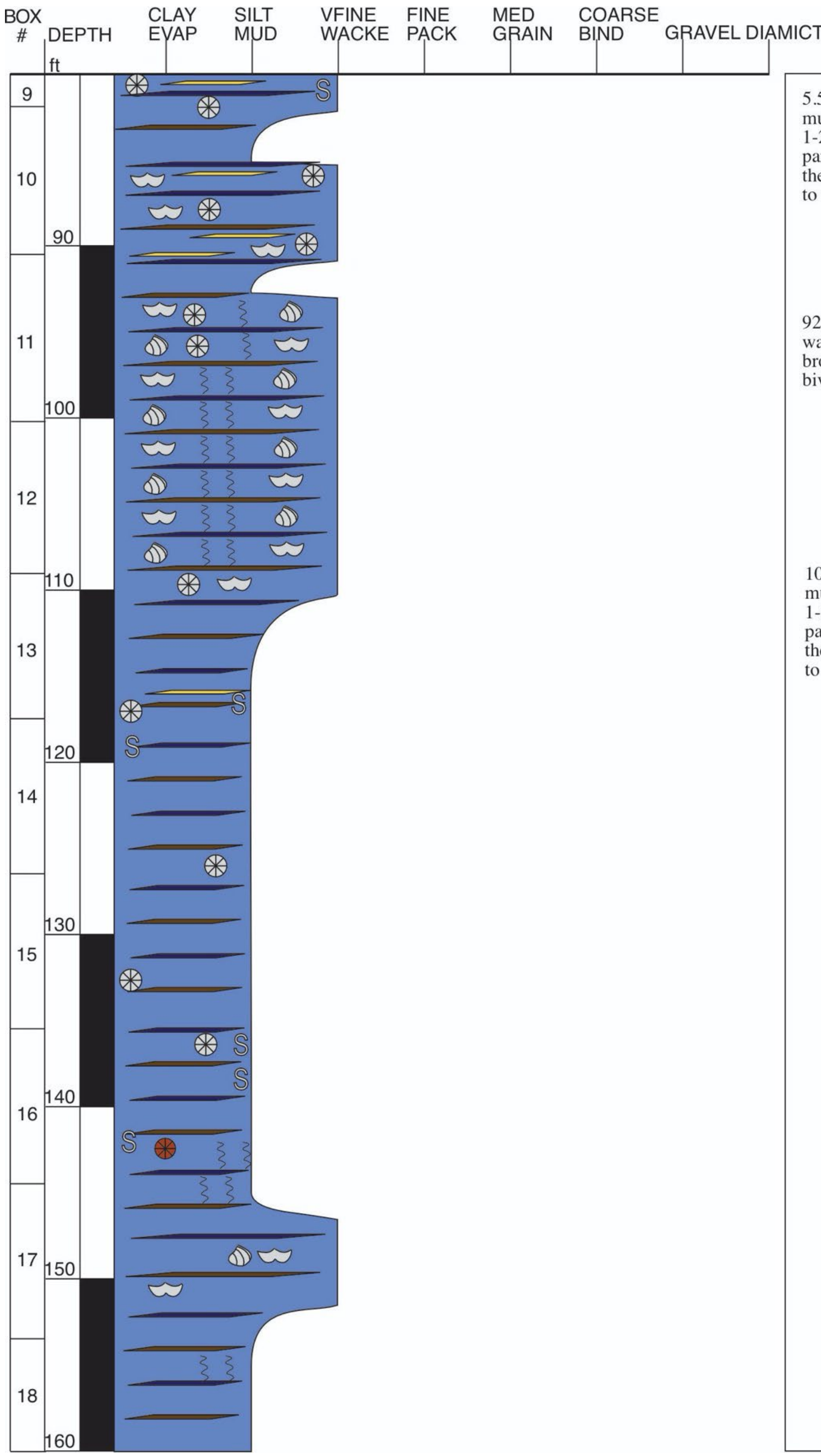
0-162.4 Sinnipee Group Platteville Fm

5.5-92' gray and tan silty dolomite mudstone to wackestone with frequent 1-2 mm brown and dark blue shale partings, mm to cm scale vugs often in the shape of brachiopods, occasional mm to cm scale silcrete nodules and bands

17.4' white vuggy coarse sand

40.2'-40.3 bed of fossils in dark blue shale

Figure A-4. Buchda Quarry continued



5.5-92' gray and tan silty dolomite mudstone to wackestone with frequent 1-2 mm brown and dark blue shale partings, mm to cm scale vugs often in the shape of brachiopods, occasional mm to cm scale silcrete nodules and bands

92-109' dark gray silty dolomite wackestone with frequent dark blue and brown shale partings, brachipod and bivalve fossils, and bioturbation

109-162.4' gray and tan silty dolomite mudstone to wackestone with frequent 1-2 mm brown and dark blue shale partings, mm to cm scale vugs often in the shape of brachiopods, occasional mm to cm scale silcrete nodules and bands

Figure A-4. Buchda Quarry continued

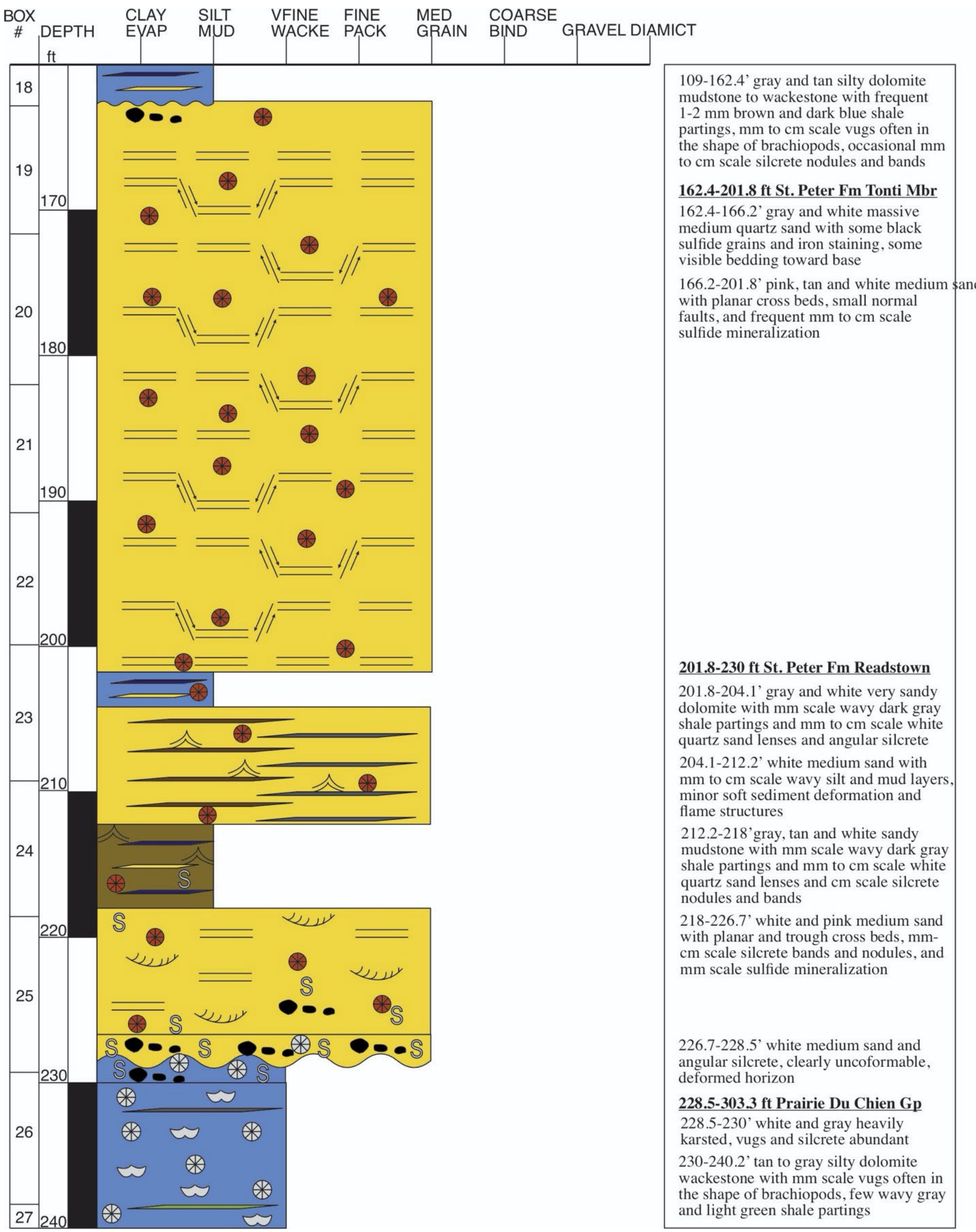
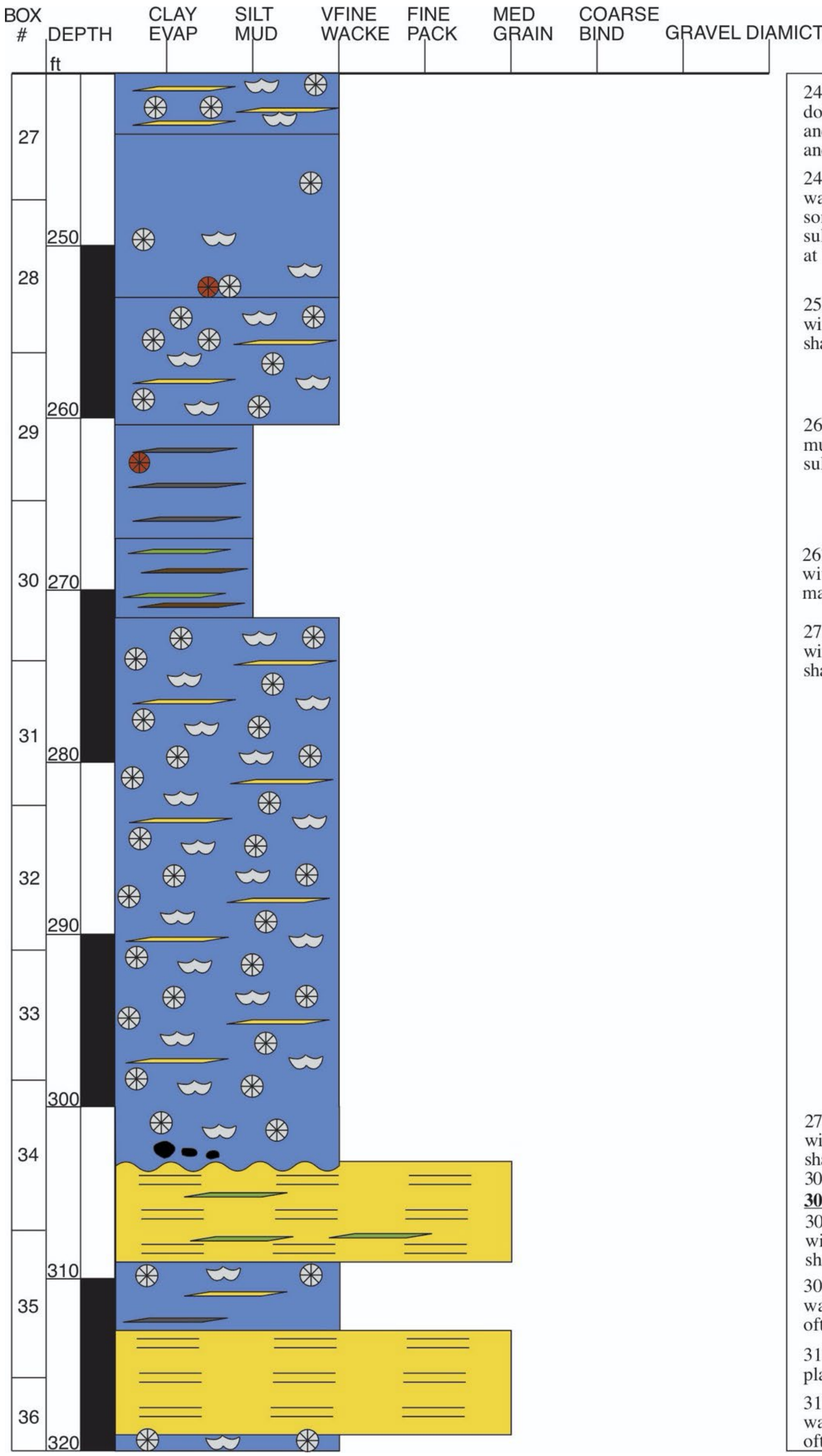


Figure A-4. Buchda Quarry continued



240.2-243.5' tan to light gray sandy dolomite wackestone with mm scale vugs and white to yellow medium sand lenses and in matrix

243.5-253' tan to light gray silty dolomite wackestone with mm scale vugs sometimes shaped like brachiopods, sulfide mineralization within 1.5 cm vug at base

253-260.3' gray sandy dolomite wackestone with mm to cm scale vugs often in the shape of brachiopods

260.3-267' gray layered silty dolomite mudstone with 2-8 mm beds, one 3 cm sulfide nodule at 262.8'

267-272' tan silty laminated dolomite with 2-8 mm yellow, light green and maroon mud/silt layers

272-303' gray sandy dolomite wackestone with mm to cm scale vugs often in the shape of brachiopods

272-303' gray sandy dolomite wackestone with mm to cm scale vugs often in the shape of brachiopods
303-303.3' 3 cm sandstone rip ups

303.3-340.6 ft Trempealeau Gp Jordan

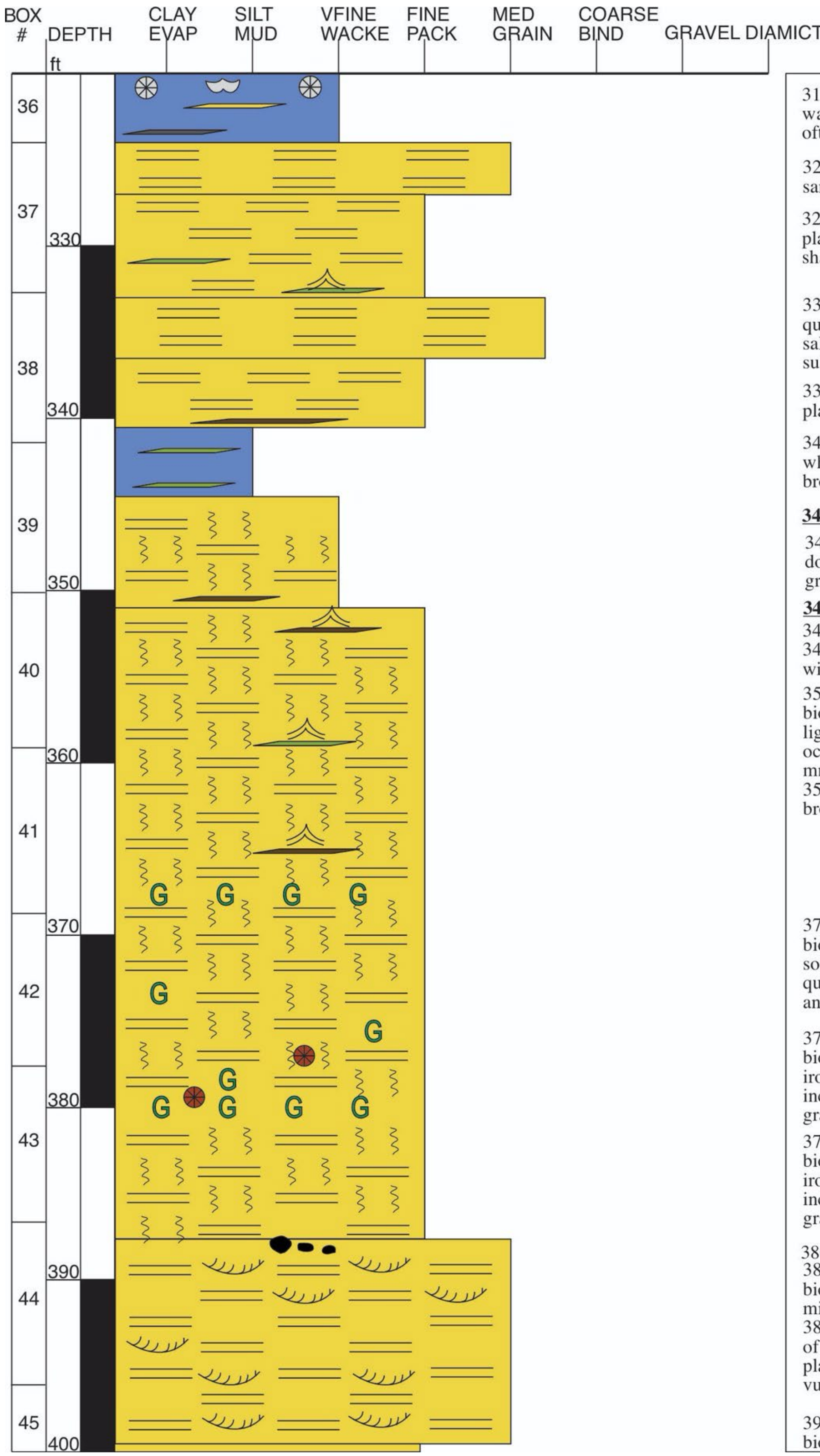
303.3-309' white medium quartz sand with planar beds and 1-2 mm light green shale partings

309-312' light gray sandy dolomite wackestone with mm to cm scale vugs often in the shape of brachiopods

312-319' white medium quartz sand with planar cross beds

319-324' light gray very sandy dolomite wackestone with mm to cm scale vugs often in the shape of brachiopods

Figure A-4. Buchda Quarry continued



319-324' light gray very sandy dolomite wackestone with mm to cm scale vugs often in the shape of brachiopods

324-327' tan to white medium quartz sand with planar cross beds

327-333' tan to light pink fine sand with planar cross beds and light green 1-8 mm shale layers with flame structure at 332.9'

333-336.5' white to tan medium to coarse quartz sand with planar cross beds, and salt and pepper texture with some black sulfide grains

336.5-340.3' tan to light pink fine sand with planar cross beds

340.3-340.6' 2 mm alternating layers of white and black coarse sand with light brown mud, possible lag deposits

340.6-344.8 ft Trempealeau St Lawrence

340.6-344.8' light gray to tan silty dolomite mudstone with 1-2 mm light green shale partings

344.8-444 ft Tunnel City Gp Lone Rock

344.8-380.9 ft Reno Mbr

344.8-351' tan and maroon very fine sand with planar cross beds and bioturbation

351-370' maroon and tan heavily bioturbated fine sand "wormstone" with light brown mud lenses, flame structures, occasional 2-8 mm glauconite layers, and mm scale sulfide mineralization

359.2-359.4' laminated green, yellow and brown mud marker bed

370-377' white and tan and tan heavily bioturbated fine sand "wormstone" with some salt and pepper texture of white quartz sand with dark green glauconite and sulfide grains

377-380.9' maroon and tan heavily bioturbated fine sand "wormstone" with iron stained white quartz sand with increasing layers of dark green glauconite grains, mm scale sulfide mineralization

377-380.9' maroon and tan heavily bioturbated fine sand "wormstone" with iron stained white quartz sand with increasing layers of dark green glauconite grains, mm scale sulfide mineralization

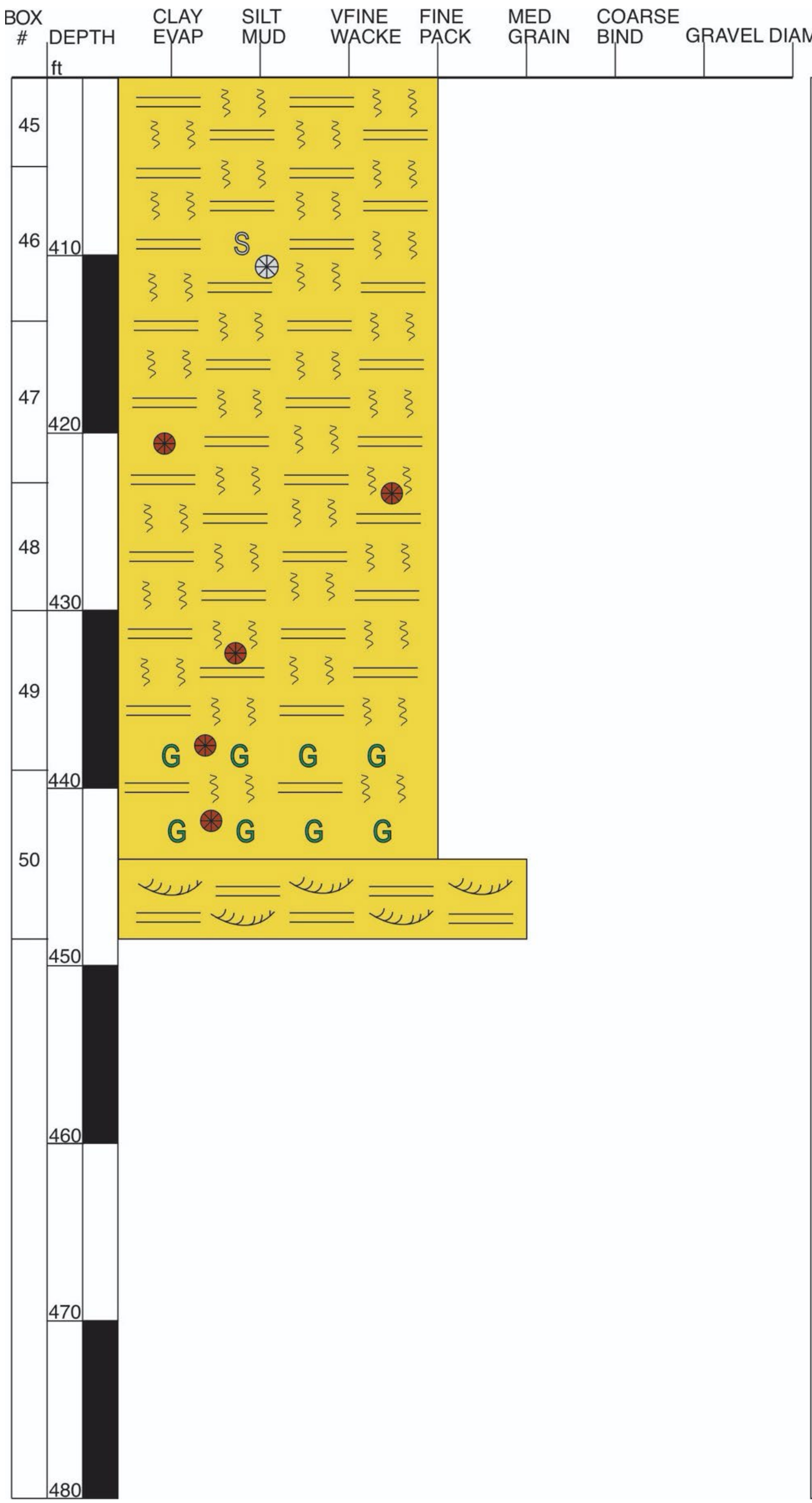
380.9-433 ft Tomah Mb

380.9-387.8' white and tan and tan bioturbated fine sand with white secondary mineralization in pre space and joints

387.8-399.5' rip up clasts at upper contact of facies, tan medium quartz sand with planar and trough cross beds, mm scale vugs, possible carbonate cement

399.5-444' maroon and tan heavily bioturbated fine sand "wormstone"

Figure A-4. Buchda Quarry continued



399.5-444' maroon and tan heavily bioturbated fine sand "wormstone" abundant iron staining, some mm-cm scale vugs filled with sulfide mineralization

433-444 ft Birkmose Mbr

438.5-444' heavily glauconitic

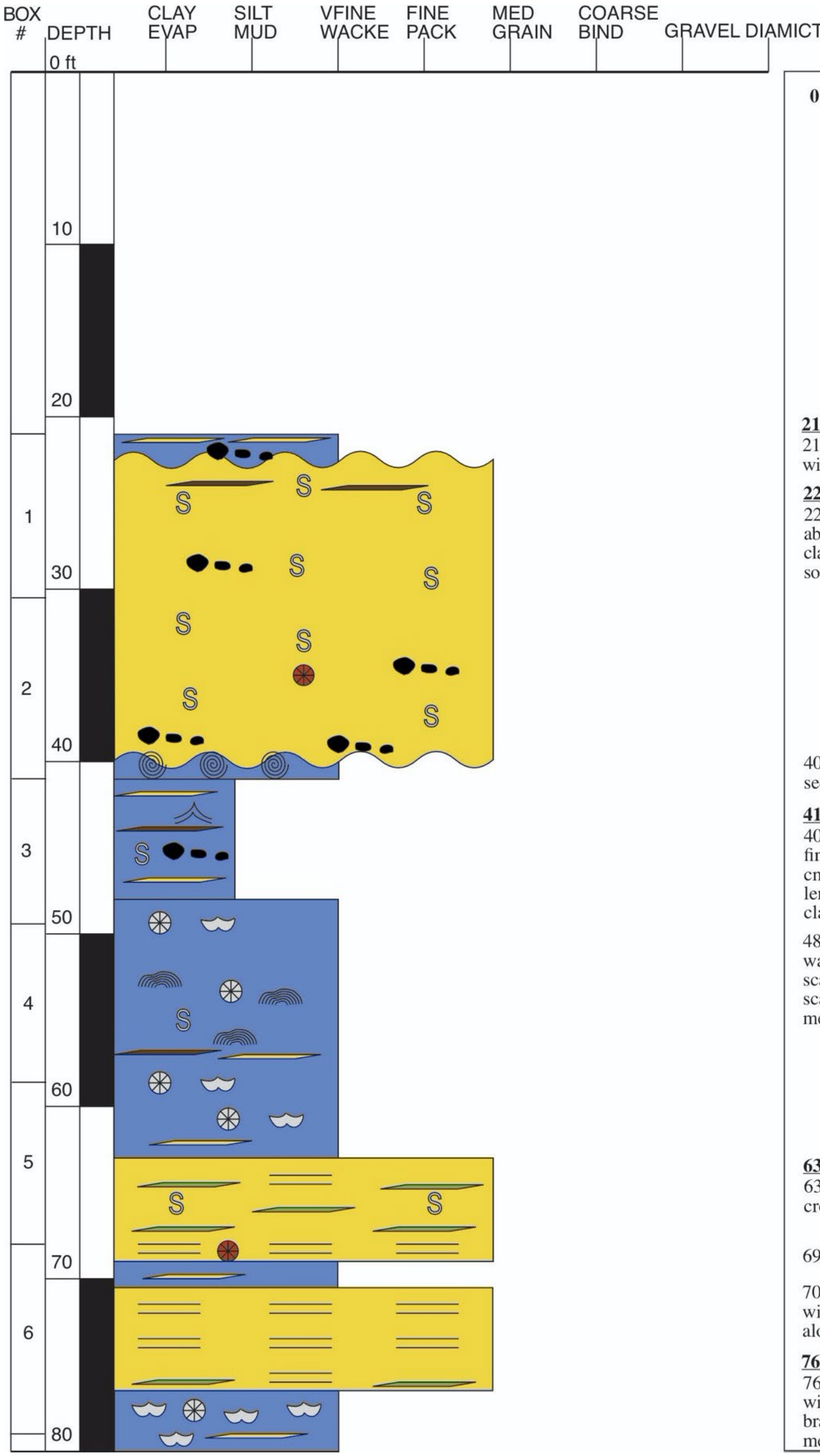
444-448.5 ft Elk Mound Gp Wonewoc

444-448.5' white to tan medium quartz sand with planar and trough cross beds

(448.5 end core)

Figure A-5. Columbus 2, Columbia County

Elevation: 881’ Total Depth: 258.2’



0-21 ft core loss

21-22.5 ft Sinnippee Gp Platteville Fm

21-22.5’ tan to gray very sandy dolomite with medium sandstone rip up clasts at base

22.5-40 ft St Peter Fm Readstown Mbr

22.5-40’ white and tan medium sand with abundant silcrete, brecciation, and rip-up clasts, areas of very poor consolidation and some sulfide mineralization

40-41’ dark brown mud with soft sediment deformation

41-63 ft Prairie Du Chien Group

40-48’ tan, maroon, and yellow muddy fine grained dolomite with some mm to cm scale silcrete nodules, fine sand lenses, flame structures, and brecciated clast bands

48-63’ tan to gray sandy dolomite wackestone with stromatolites, mm to cm scale vugs, brachiopods, few mm to cm scale silcrete nodules, and mud and medium sand lenses

63-76.5 ft Trempealeau Gp Jordan Fm

63-69’ white medium sand with planar cross beds and light green shale partings

69-70.5’ tan sandy dolomite

70.5-76.5’ white and yellow medium sand with planar cross beds, and green staining along bedding planes at base

76.5-100.5 ft Trempealeau St Lawrence

76.5-88’ yellow to pink sandy dolomite with mm scale vugs often in the shape of brachiopods, muddy brachiopod casts, and medium sand lenses with planar cross beds

Figure A-5. Columbus 2 continued

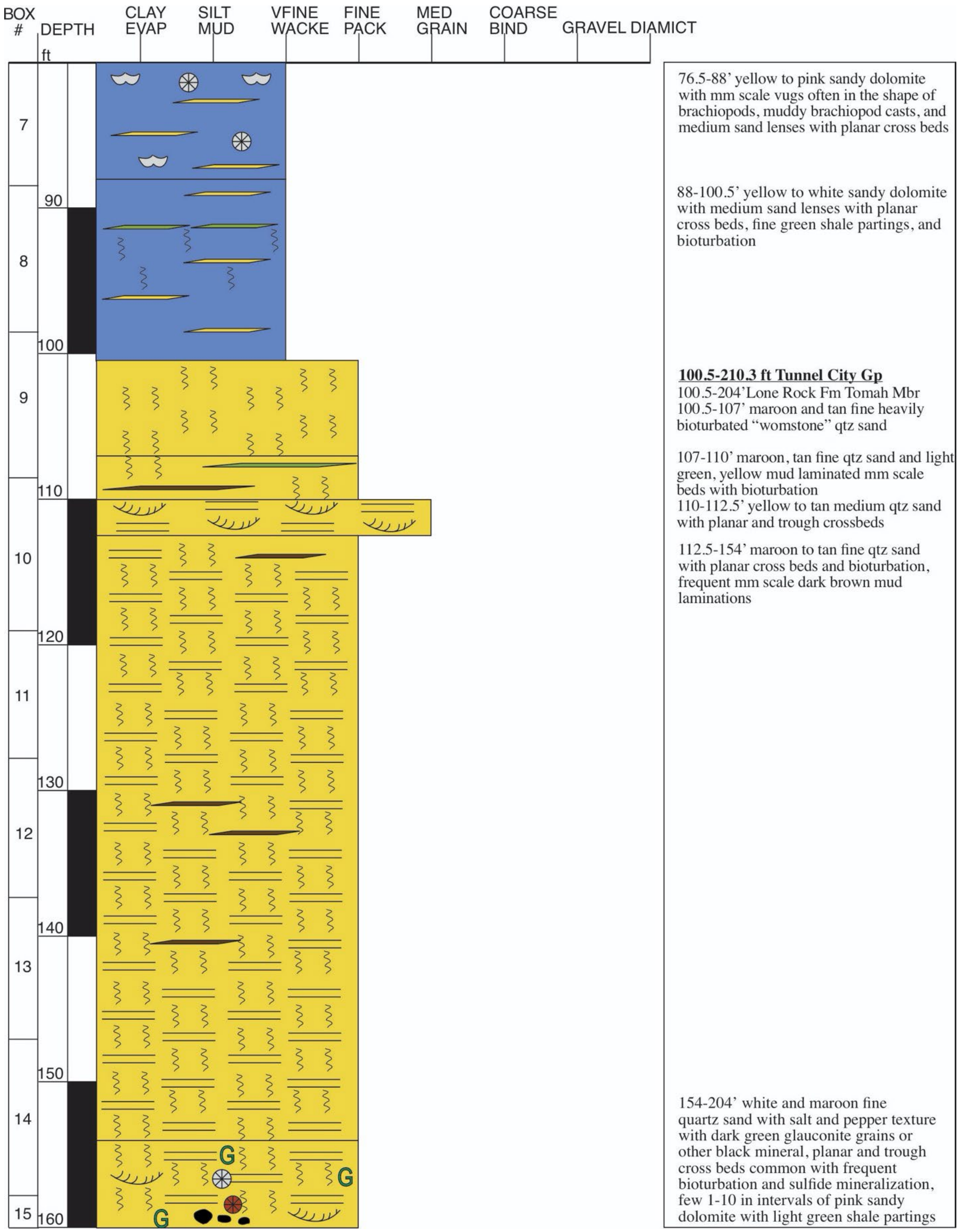
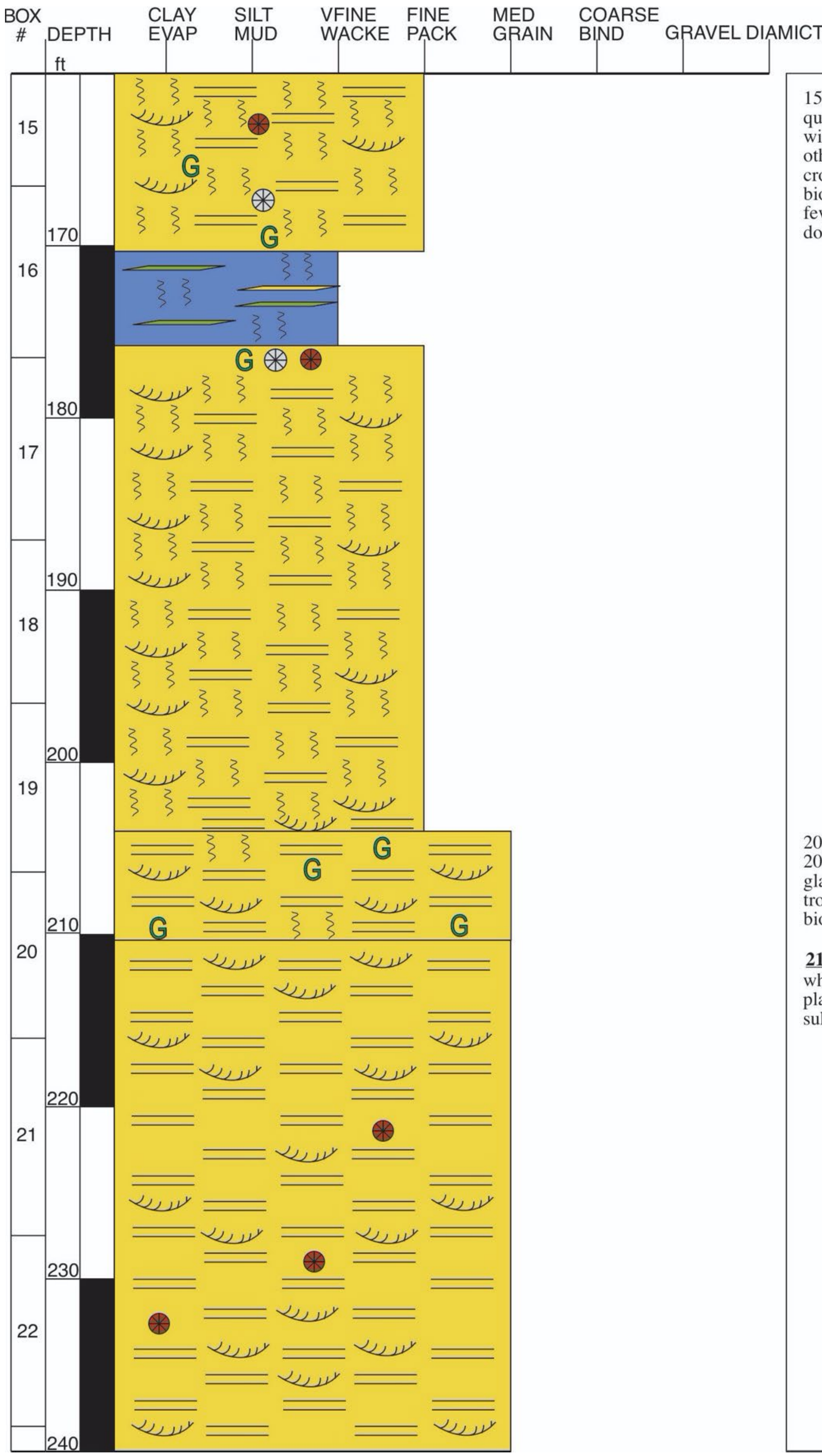


Figure A-5. Columbus 2 continued



154-204' white and maroon fine quartz sand with salt and pepper texture with dark green glauconite grains or other black mineral, planar and trough cross beds common with frequent bioturbation and sulfide mineralization, few 1-10 in intervals of pink sandy dolomite with light green shale partings

204-210.3' Lone Rock Birkmose Mbr
204-210.3' maroon quartz and green glauconite medium sand with planar and trough cross beds and frequent bioturbation and sulfide mineralization,

210.3-258.2 ft Elk Mound Gp Wonewoc
white medium quartz sand with massive, planar and trough cross beds, occasional sulfide mineralization along bedding planes

Figure A-5. Columbus 2 continued

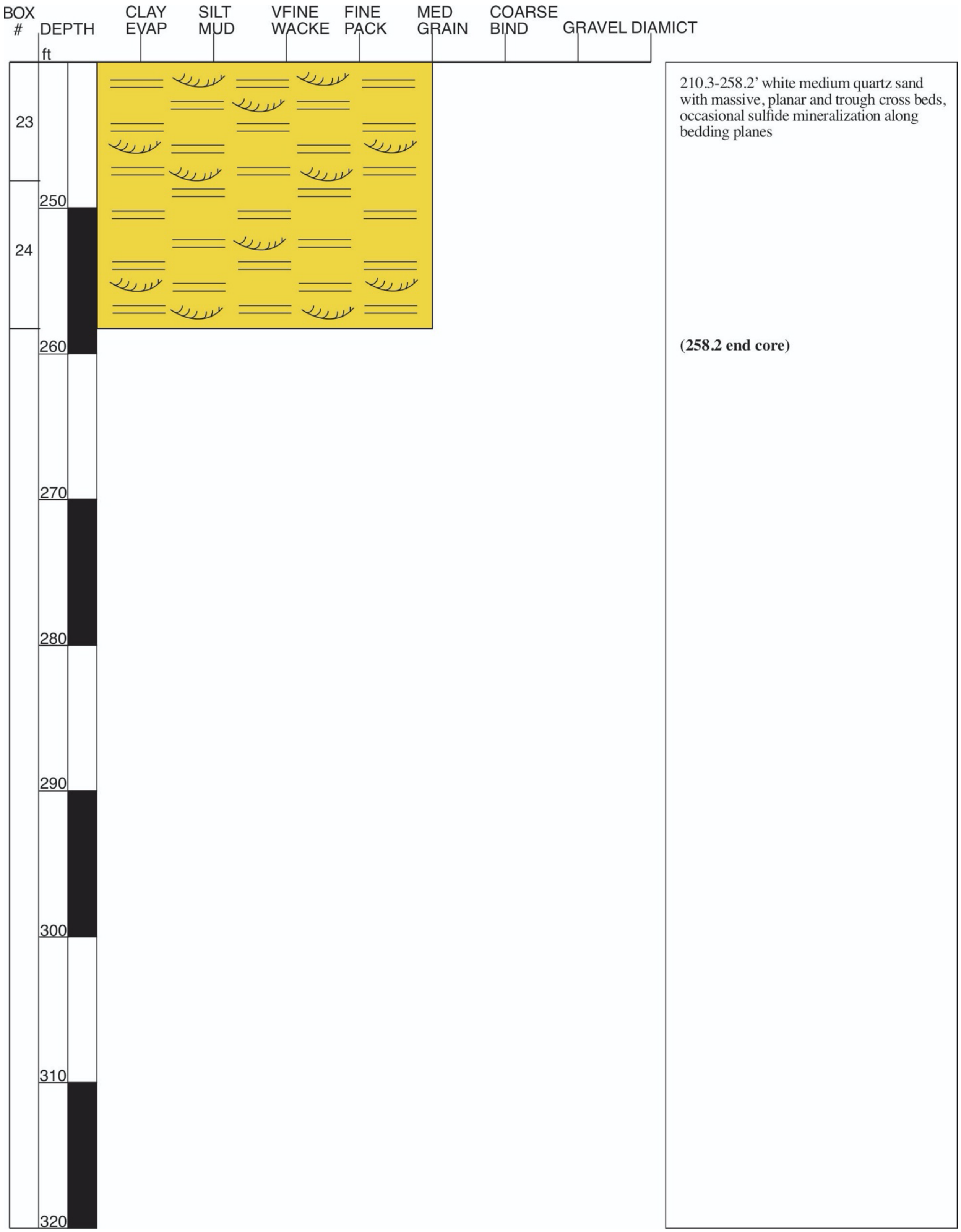
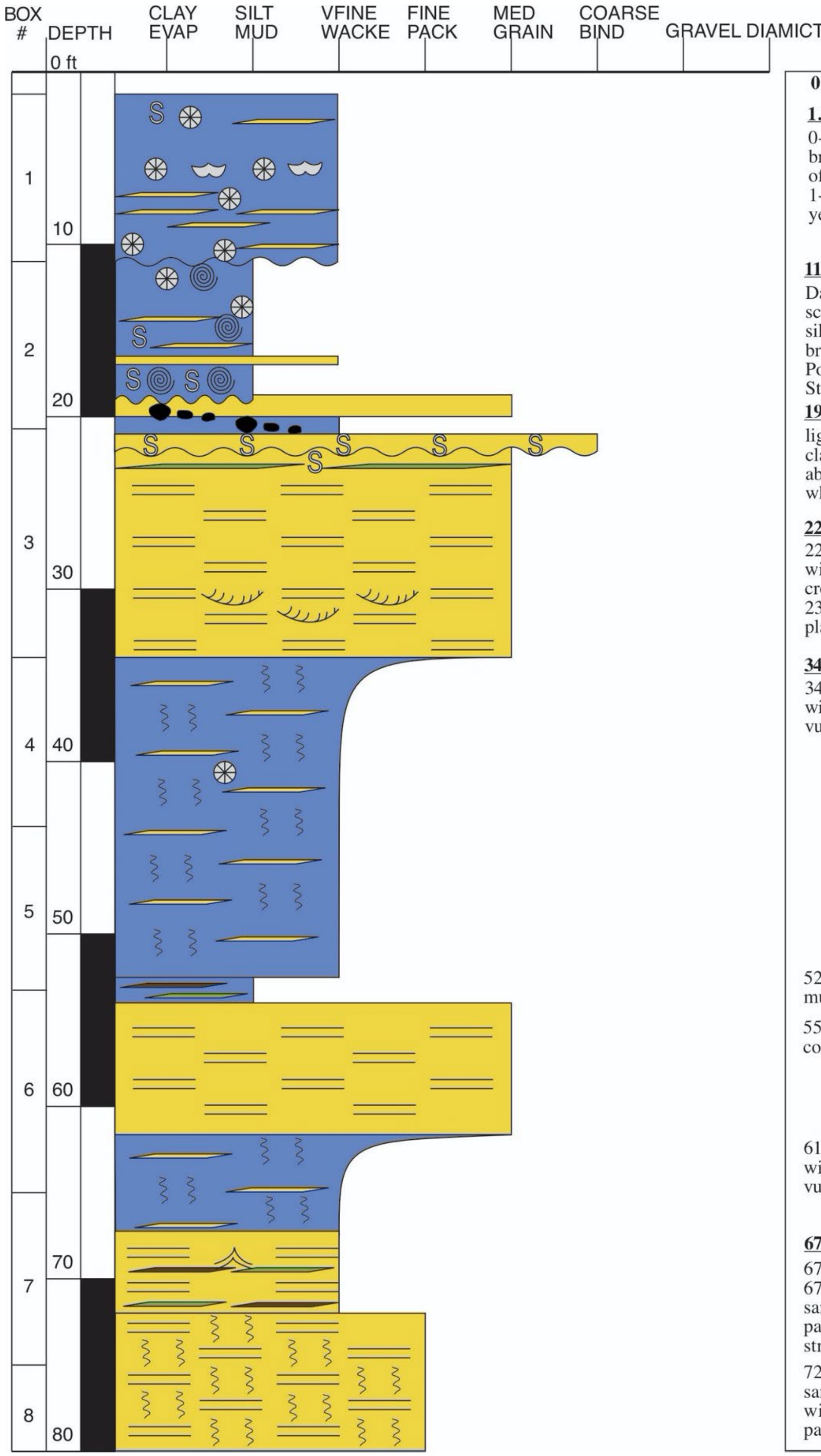


Figure A-6, Hartmann Quarry Columbia County

Elevation: 1080’ Total Depth: 129.4’



0-1.2 ft core loss

1.2-22 ft Prairie Du Chien Shakopee

0-11’ gray polished dolomite wackestone broken up with mm to cm scale vugs often in the shape of brachiopods, 1-4 cm silcrete nodules, and 1-4 cm yellow medium sand lenses

11-19 ft deformed lime mud and sand

Dark brown lime mud with mm to cm scale vugs, frequent sand lenses and silcrete nodules, soft sediment and brecciated deformation structures Potential karst fill of Prairie Du Chien-St. Peter contact

19-22 ft Prairie Du Chien Oneota

light brown sandy dolomite with rip up clasts, three fining upwards cycles, abundant silcrete in pore space, and white coarse “bubble rock” at base

22-34.5 ft Trempealeau Gp Jordan Fm

22-23’ white to medium sand with light green shale partings and planar cross beds

23-34.5’ yellow medium sand with planar and tough cross beds

34.5-67.4 ft Trempealeau Gp St Lawrence

34.5-52.42 tan sandy dolomite wackestone with occasional bioturbation, mm scale vugs, and cm scale sand lenses

52.2-55’ green and tan laminated dolomite mudstone/shale

55-61.5’ tan medium sand with poor consolidation and planar cross beds

61.5-67.4’ tan sandy dolomite wackestone with occasional bioturbation, mm scale vugs, and cm scale sand lenses

67.4-106.7 ft Tunnel City Gp

67.4-90’ Lone Rock Fm Tomah Mbr

67.4-72.2’ maroon and yellow very fine sand with light green and gray shale partings, planar cross beds, and flame structures. marker bed.

72.2-83.7’ maroon and yellow fine sand heavily bioturbated “wormstone” with planar cross beds, and gray shale partings

Figure A-6, Hartmann Quarry continued

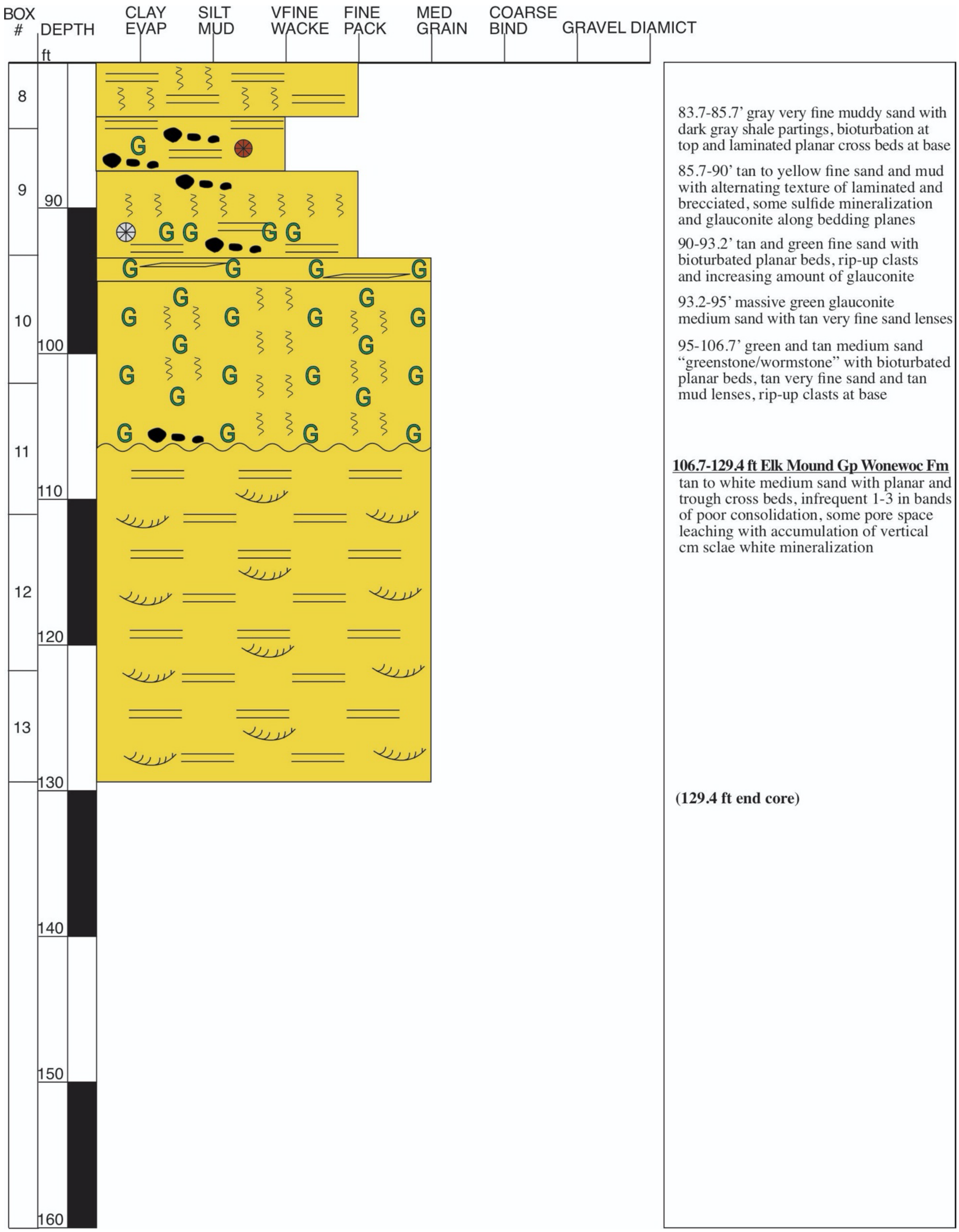
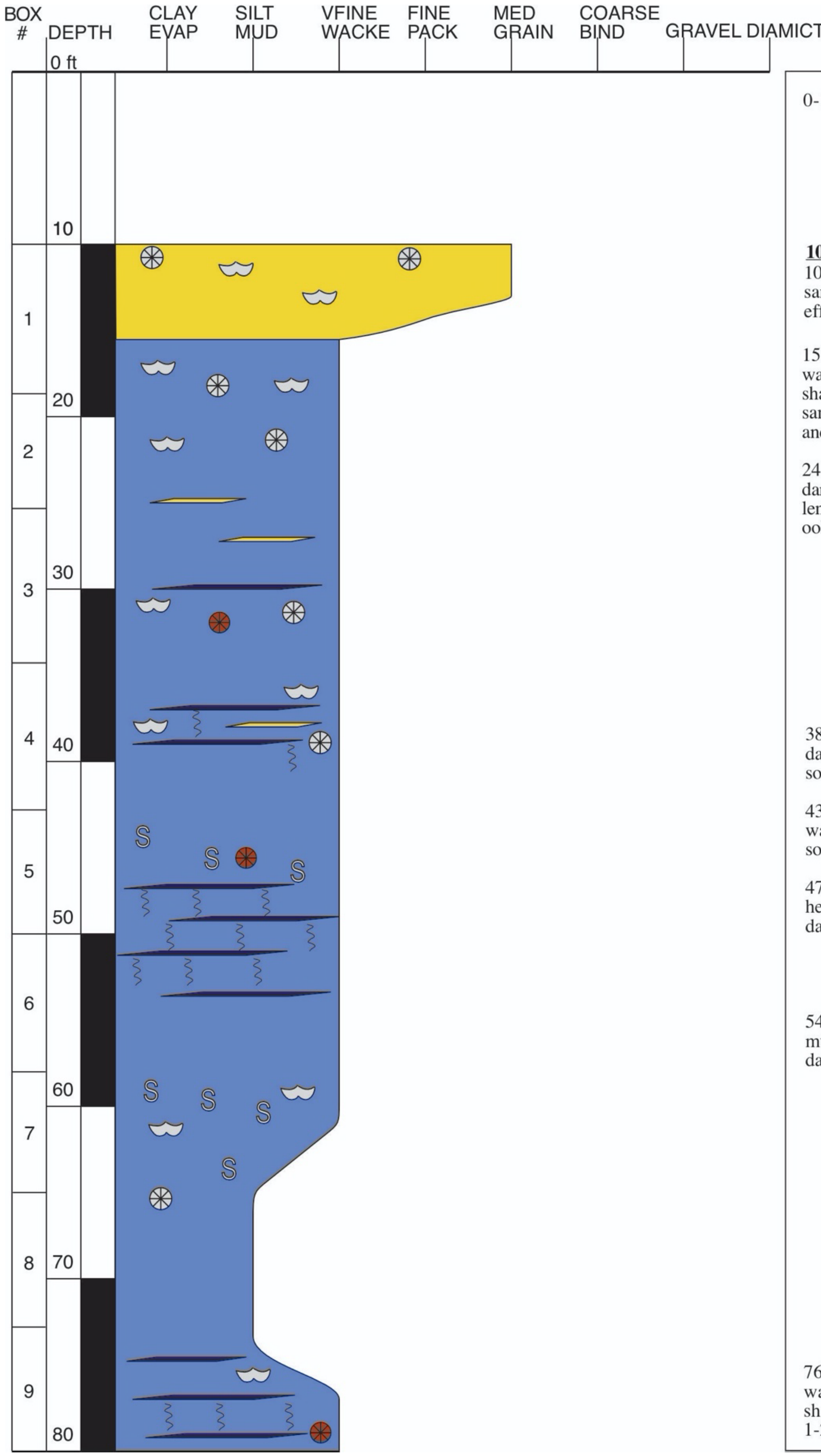


Figure A-7, HBFA, Jefferson County

Elevation: 816’ Total Depth: 567.6’



0-10 ft core loss

<u>10-111’ Sinnipee Gp.</u>
10-15.5’ light brown massive medium sand, with 1-3 cm vugs and very effervescent carbonate cement

15.5-24.5 gray to light brown dolomite wackestone with 0.5-1 cm vugs often in the shape of brachiopods. Occasional 1mm sand lenses filled with medium quartz sand and glauconite

24.5-38 gray dolomite wackestone with dark gray shale partings and very few sand lenses with coarse quartz sand and oolites/pellets

38-43’ light gray dolomite wackestone with dark gray bioturbated shale partings and some Fe staining

43-47.5’ light gray to light brown dolomite wackestone with few shale partings and some Fe staining. 1-3 cm silcrete bands

47.5-54’ gray dolomite wackestone with heavy (60%) bioturbation and frequent dark gray shale partings

54-76.8’ light gray dolomite wackestone to mudstone with 1-3 cm silcrete nodules and dark gray shale partings

76.5-80’ light brown sandy dolomite wackestone with bioturbation, brown shale partings, mm- 2 cm sand lenses, and 1-2 cm sulfide mineralization

Figure A-7, HBFA continued

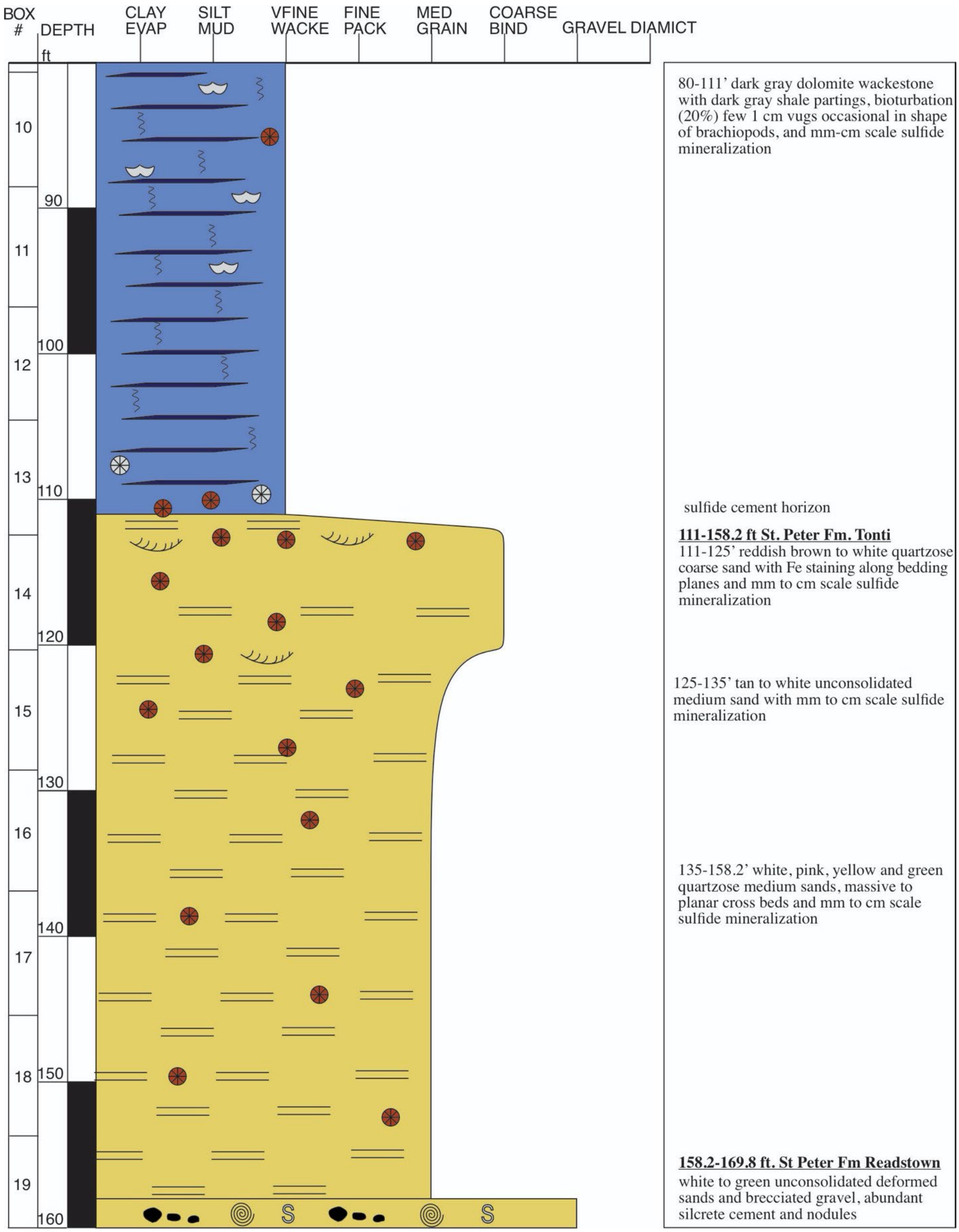


Figure A-7, HBFA continued

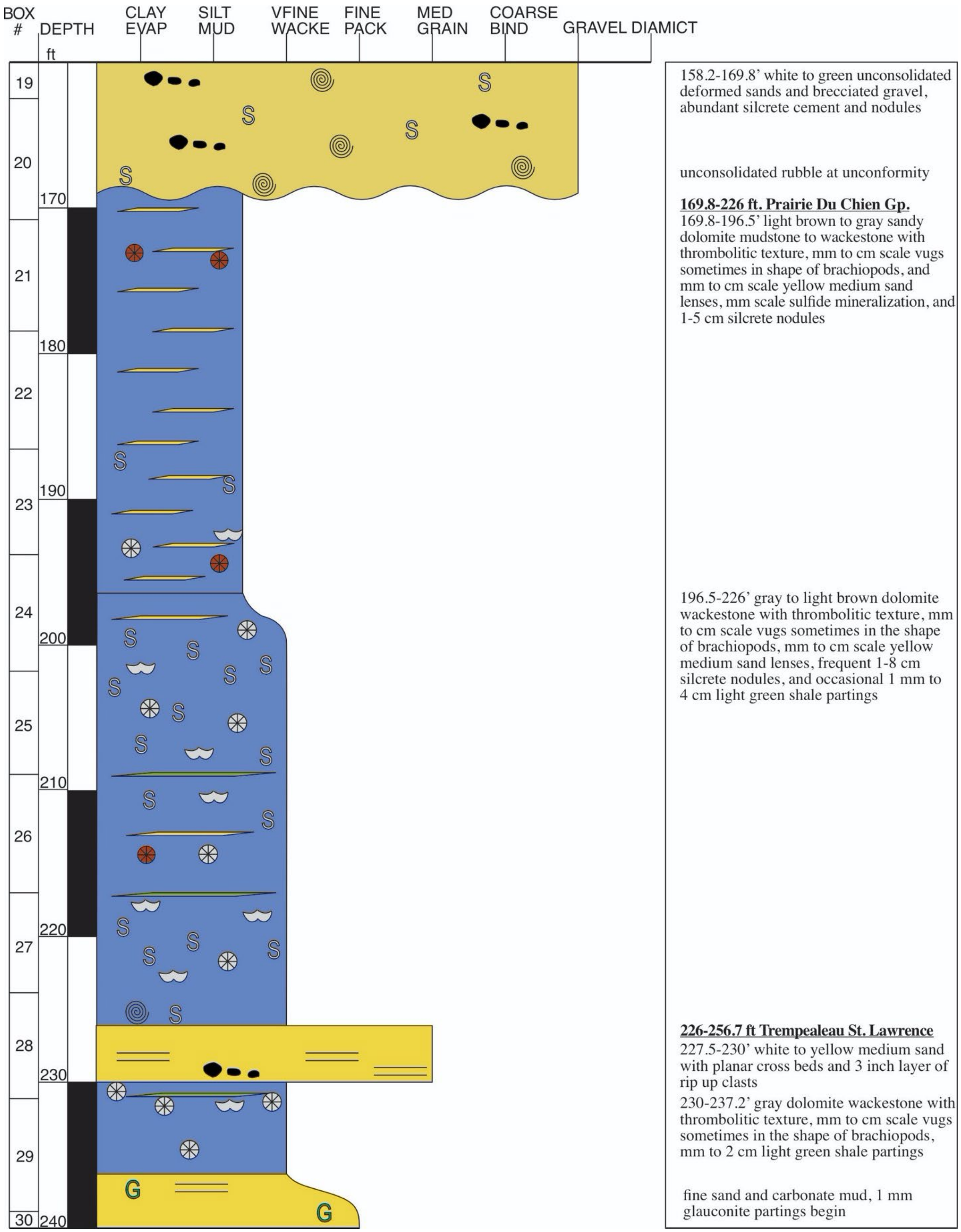


Figure A-7, HBFA continued

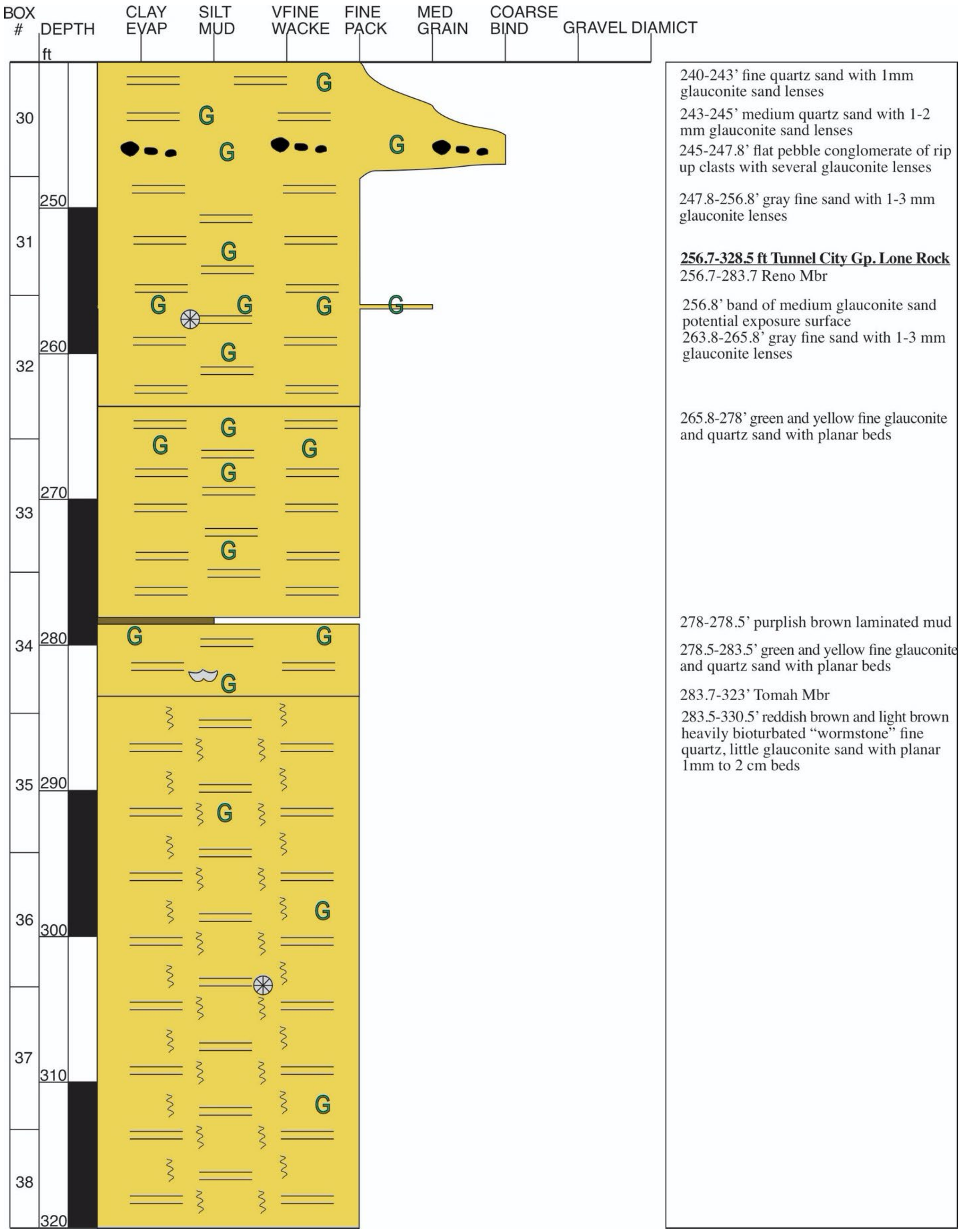
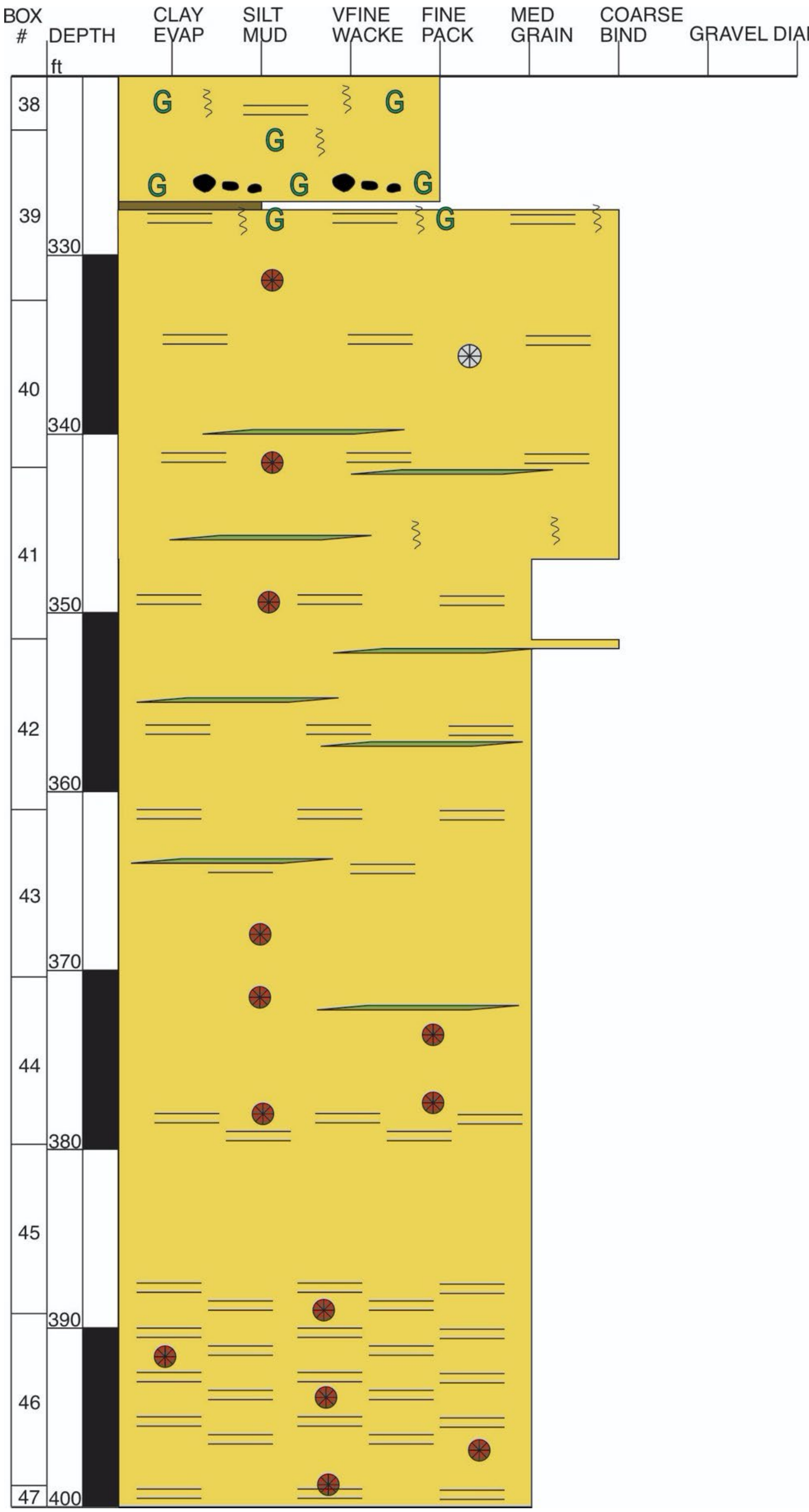


Figure A-7, HBFA continued



283.7-323' Tomah Mbr

323-327.3' Brikmose Mbr

326.5-327.3' fine glauconite with 1-3 cm coarse Wonewoc sandstone rip up clasts

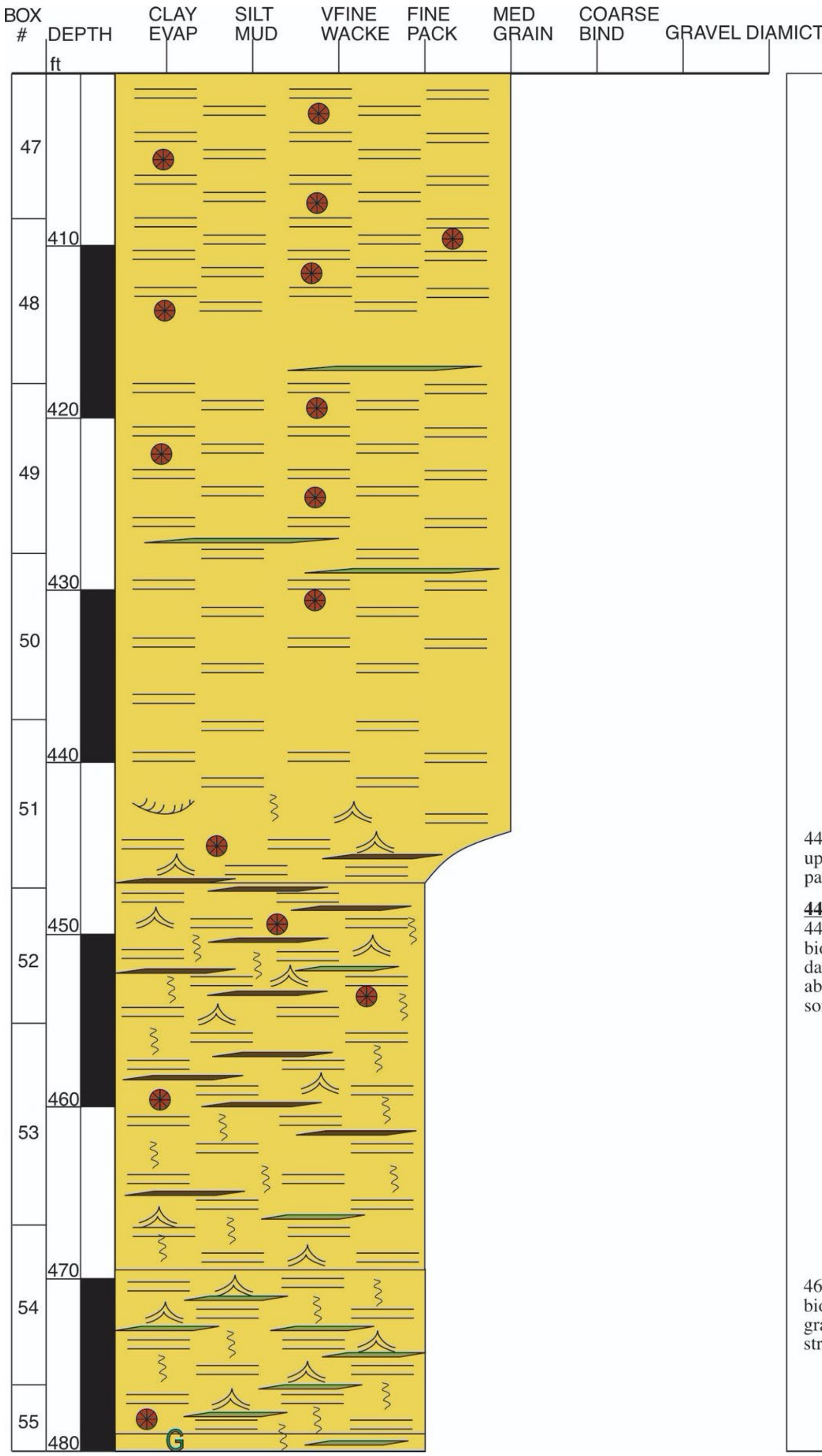
327.3-447 ft Wonewoc Fm

327.3-328.5' yellow brown bioturbated coarse quartz and glacuconite planar bedded sands

328.5-347' white to orange massive coarse sand with Fe staining along infrequent planar beds, occasional 1-6 cm unconsolidated layers and mm to cm scale light green shale partings. Carbonate cement very effervescent

347-445' white to orange massive medium sand with Fe staining along infrequent planar beds, occasional 1-6 cm unconsolidated layers and mm to cm scale light green shale partings . Carbonate cement very effervescent

Figure A-7, HBFA continued



445-447’ gradational contact, coarsening upwards trend with 1mm-1cm clay partings and flame structures

447-505 ft Eau Claire Fm.
447-469.5’ dark red to gray heavily bioturbated fine sands with mm to cm dark brown and green shale partings, abundant Fe staining, flame structures some layers of sand poorly consolidated

469.5-479’ green and yellow heavily bioturbated fine sands with mm to cm gray and green shale partings, and flame structures

Figure A-7, HBFA continued

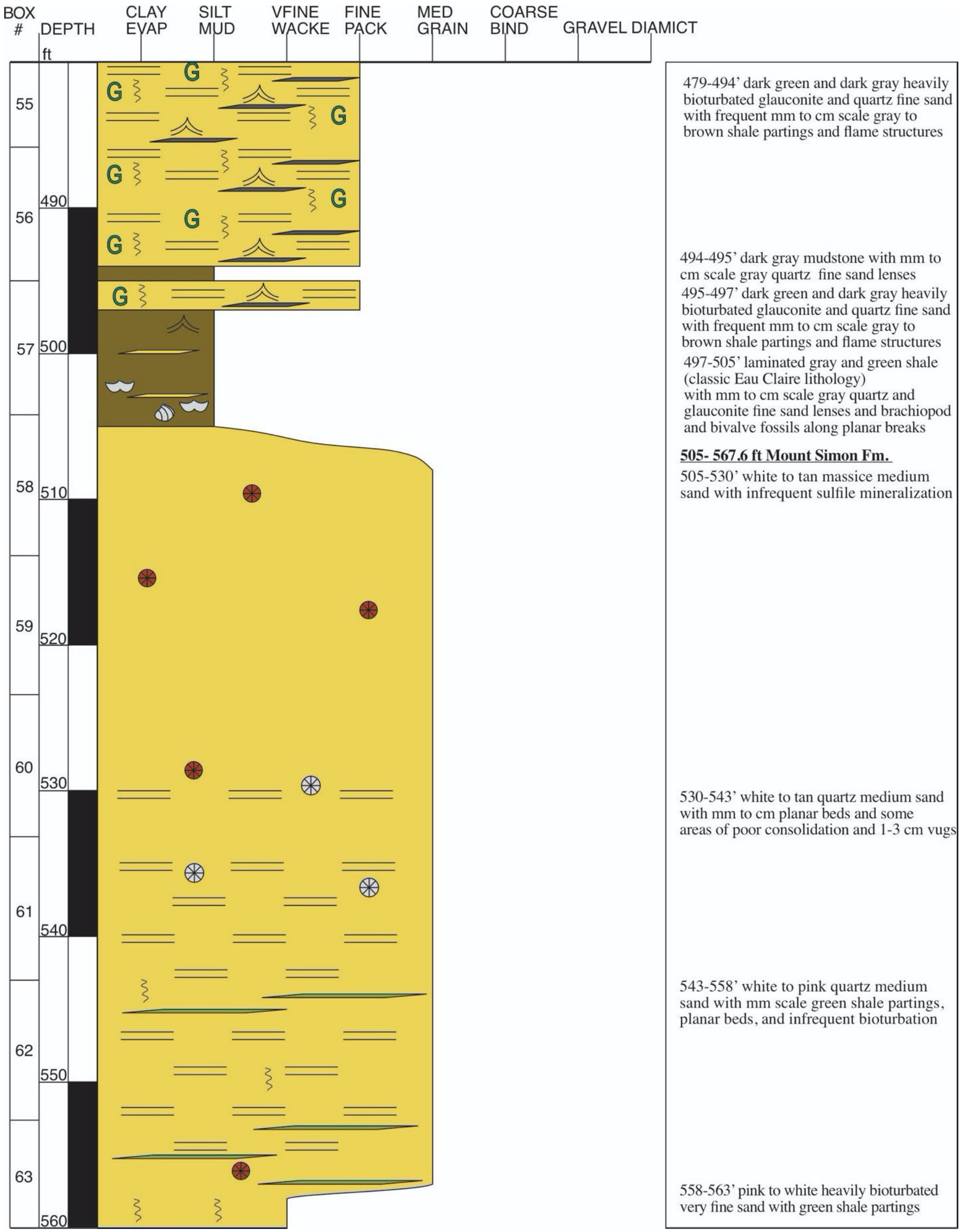
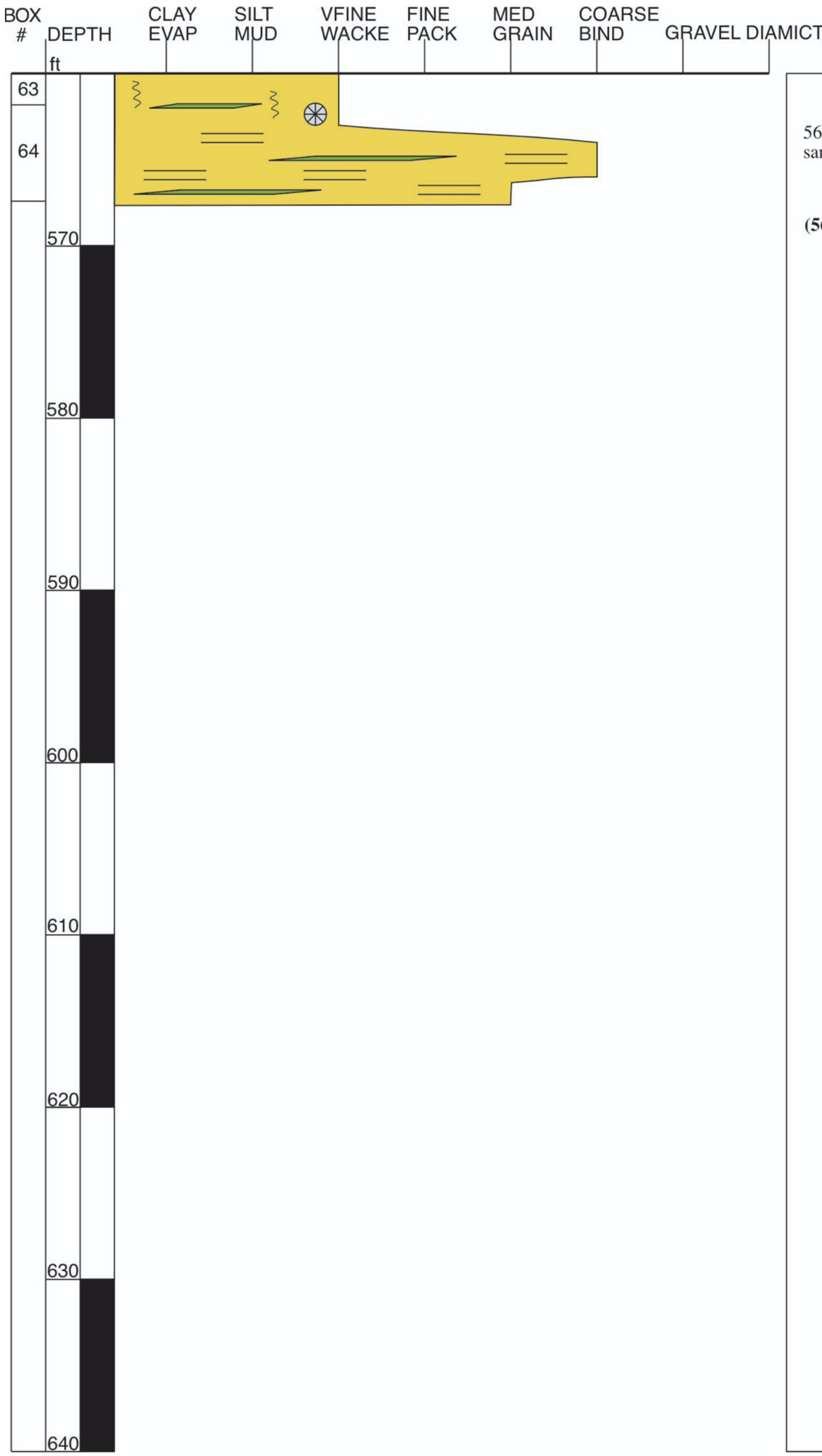


Figure A-7, HBFA continued

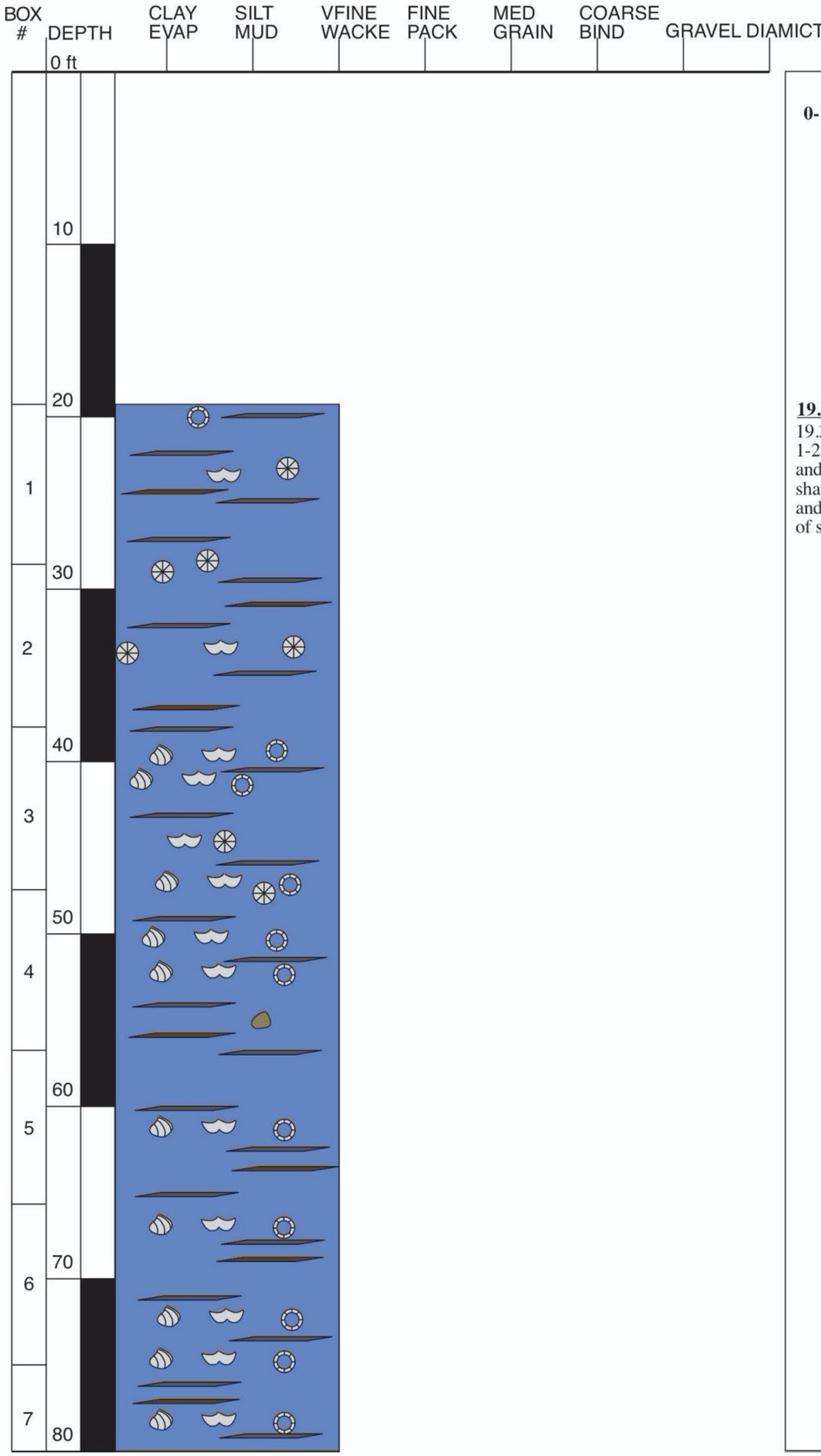


563-567.6' white to pink coarse to medium sand with mm scale green shale partings

(567.6' end core)

Figure A-8, Highway T2, Fond du Lac County

Elevation: 888’ Total Depth: 339’



0-19.3 ft core loss

<u>19.3-180.5 ft Sinnipee Gp</u>

19.3-106’ brown dolomite wackestone with 1-2 mm gray and brown shale partings, and mm to cm scale vugs often in the shape of brachiopods, brachiopod, crinoid and bivalve fossils occur in 1-3 cm bands of shale

Figure A-8, Highway T2 continued

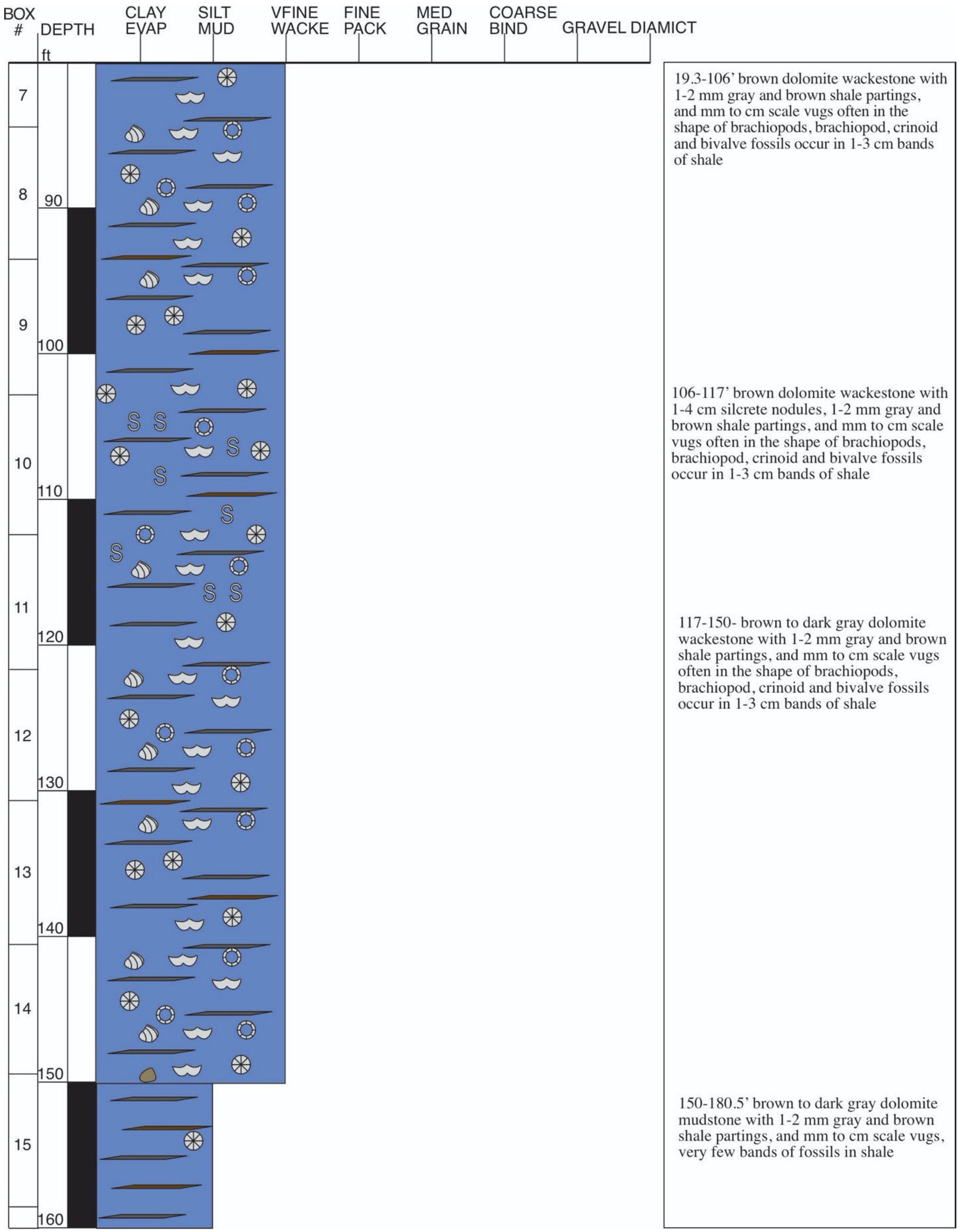


Figure A-8, Highway T2 continued

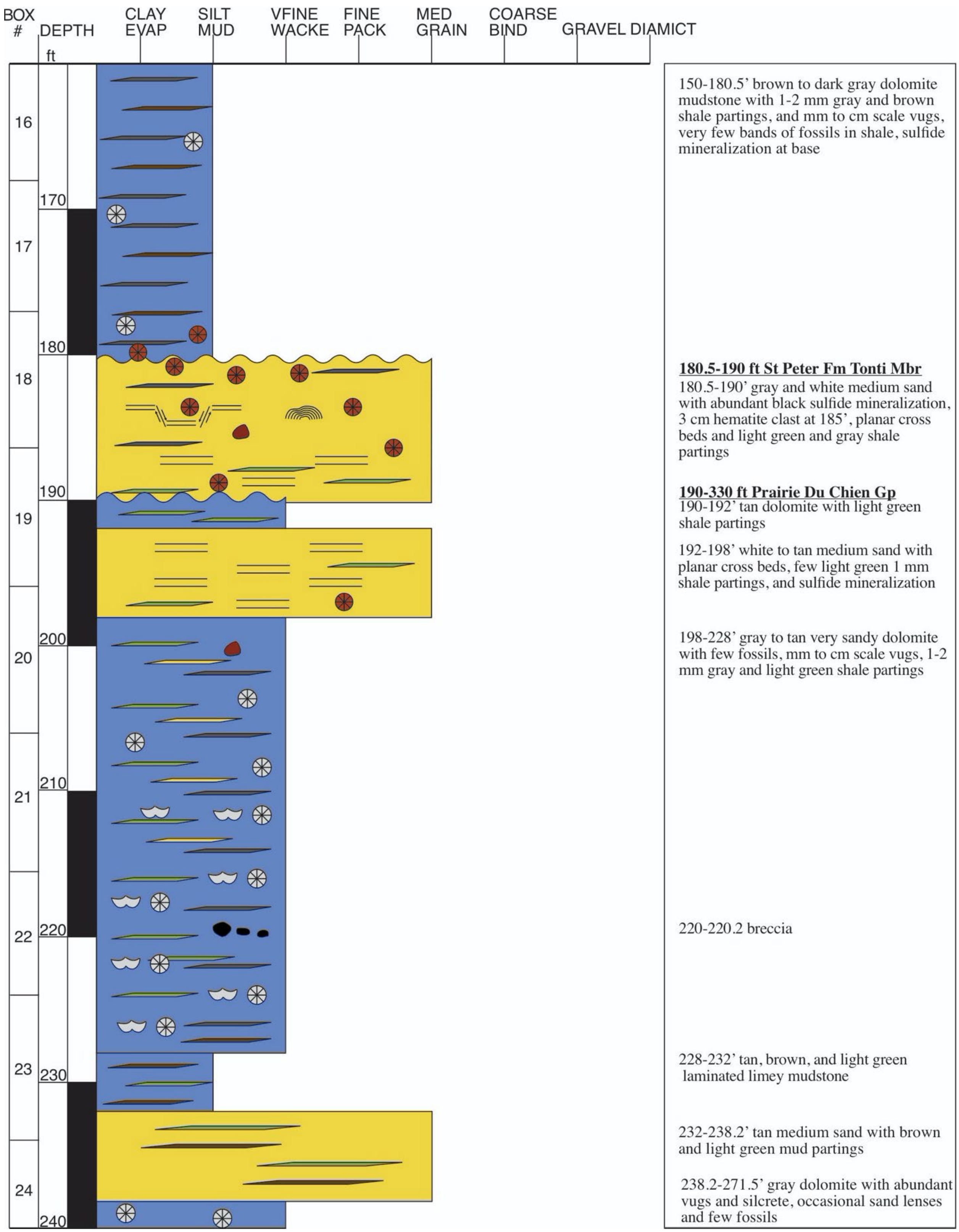


Figure A-8, Highway T2 continued

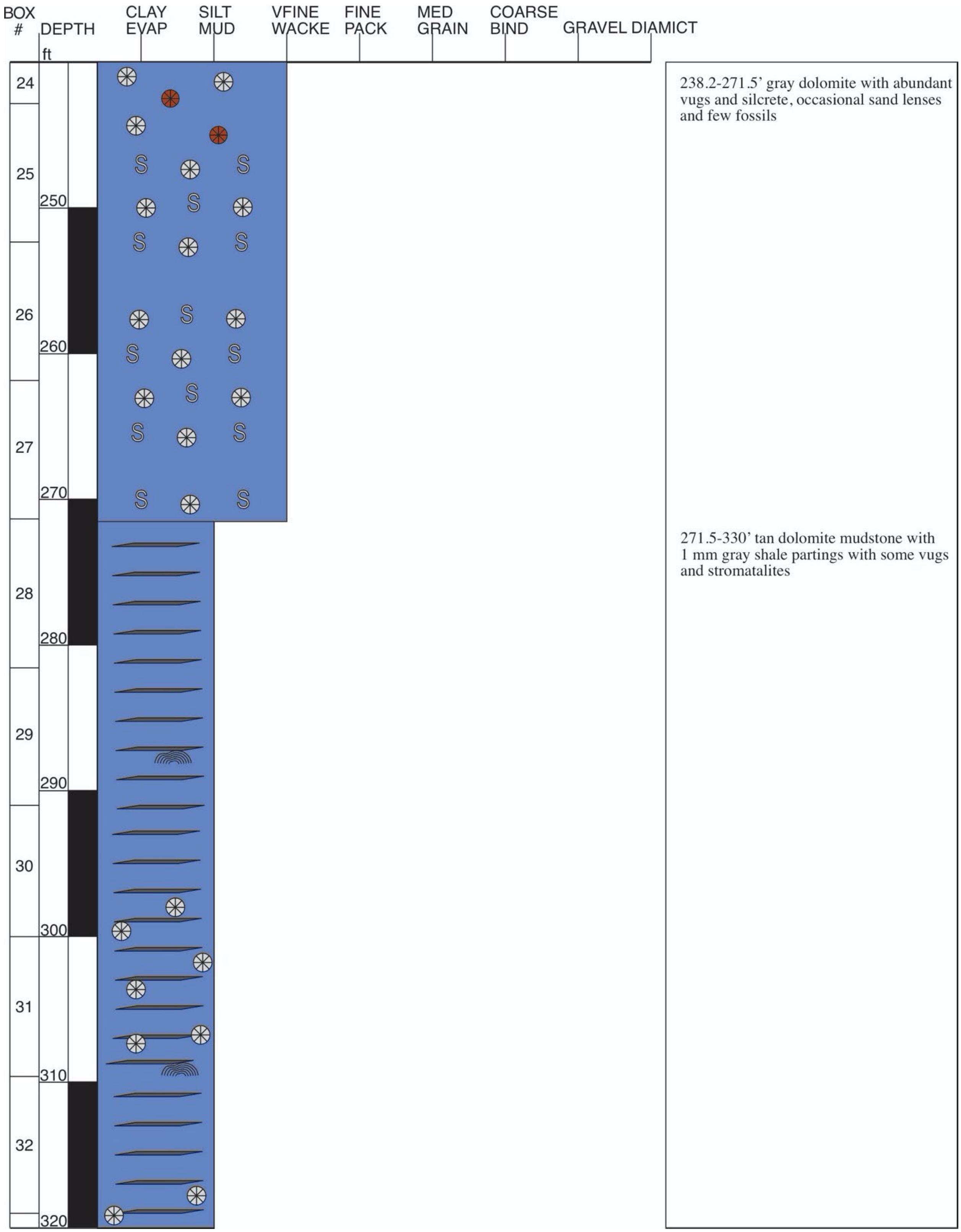


Figure A-8, Highway T2 continued

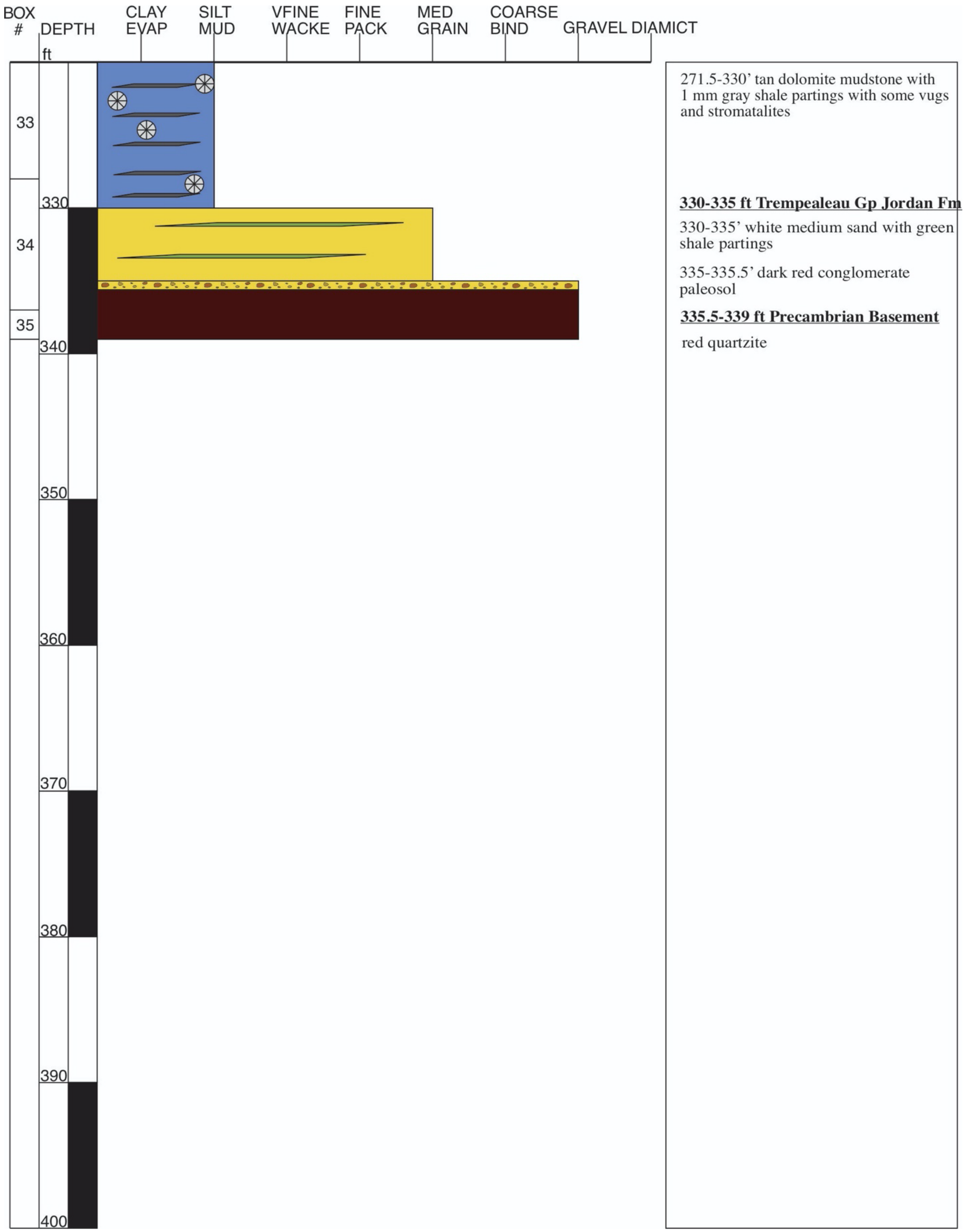
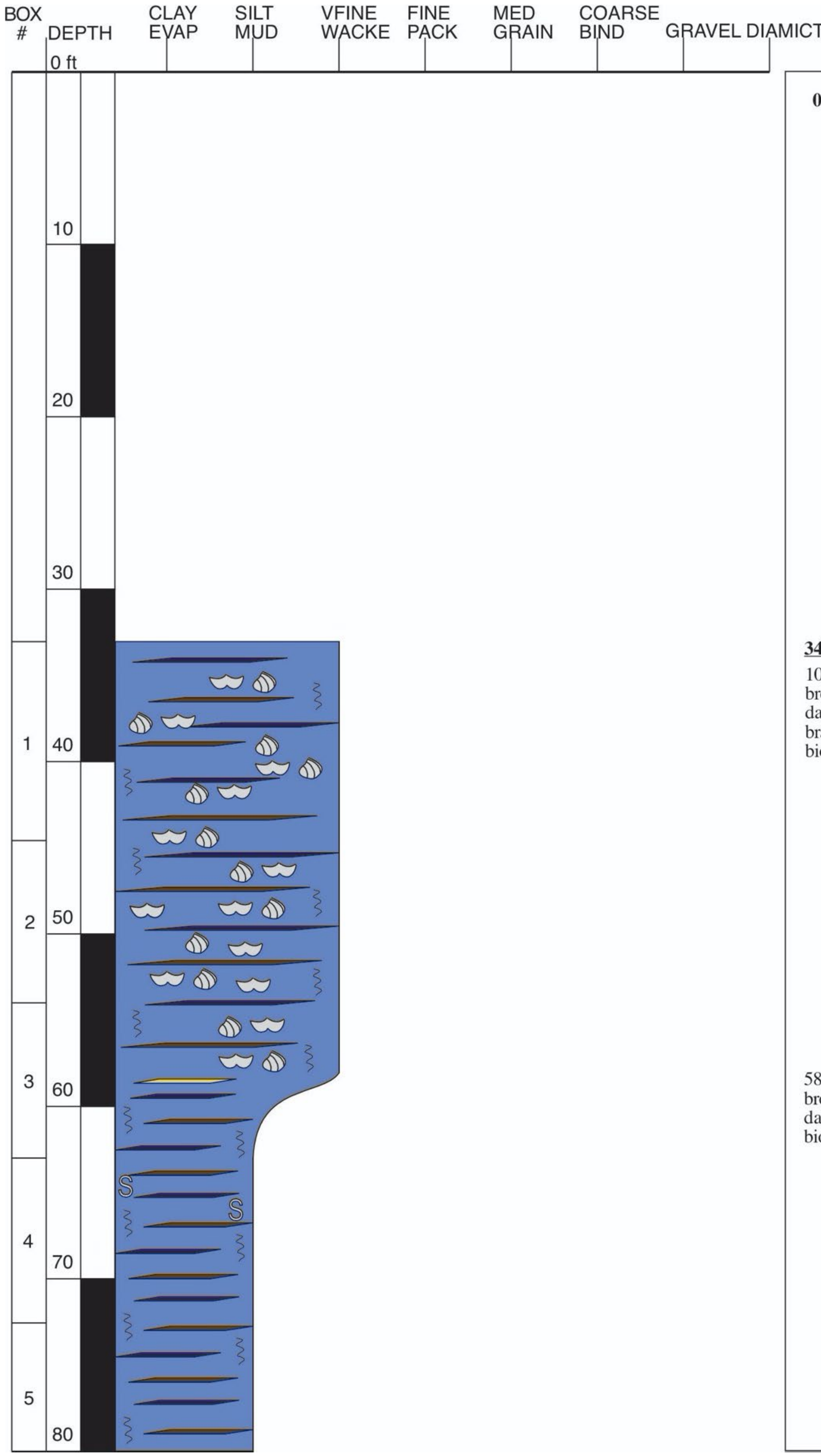


Figure A-9, Keel, Dodge County

Elevation: 838’ Total Depth: 795’



0-34 ft Quaternary

34-116 ft Sinnipee Gp

10-58’ alternating gray/blue and light brown dolomite wackestone with 1-4 mm dark gray and brown shale partings, brachiopods, bivalves and peloids, some bioturbation

58-96’ alternating gray/blue and light brown dolomite mudstone with 1-4 mm dark gray and brown shale partings and bioturbation with occasional silcrete nodules

Figure A-9, Keel continued

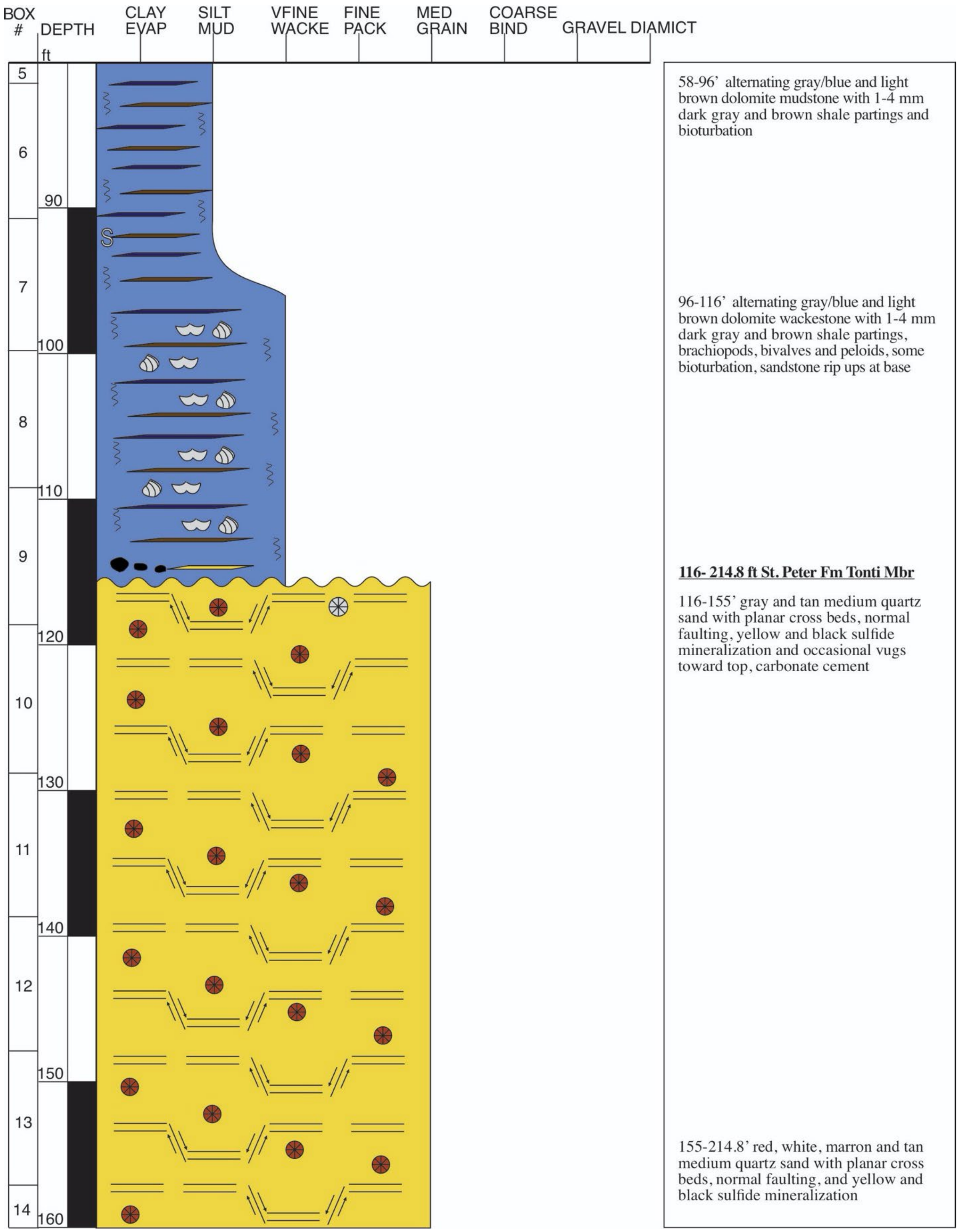
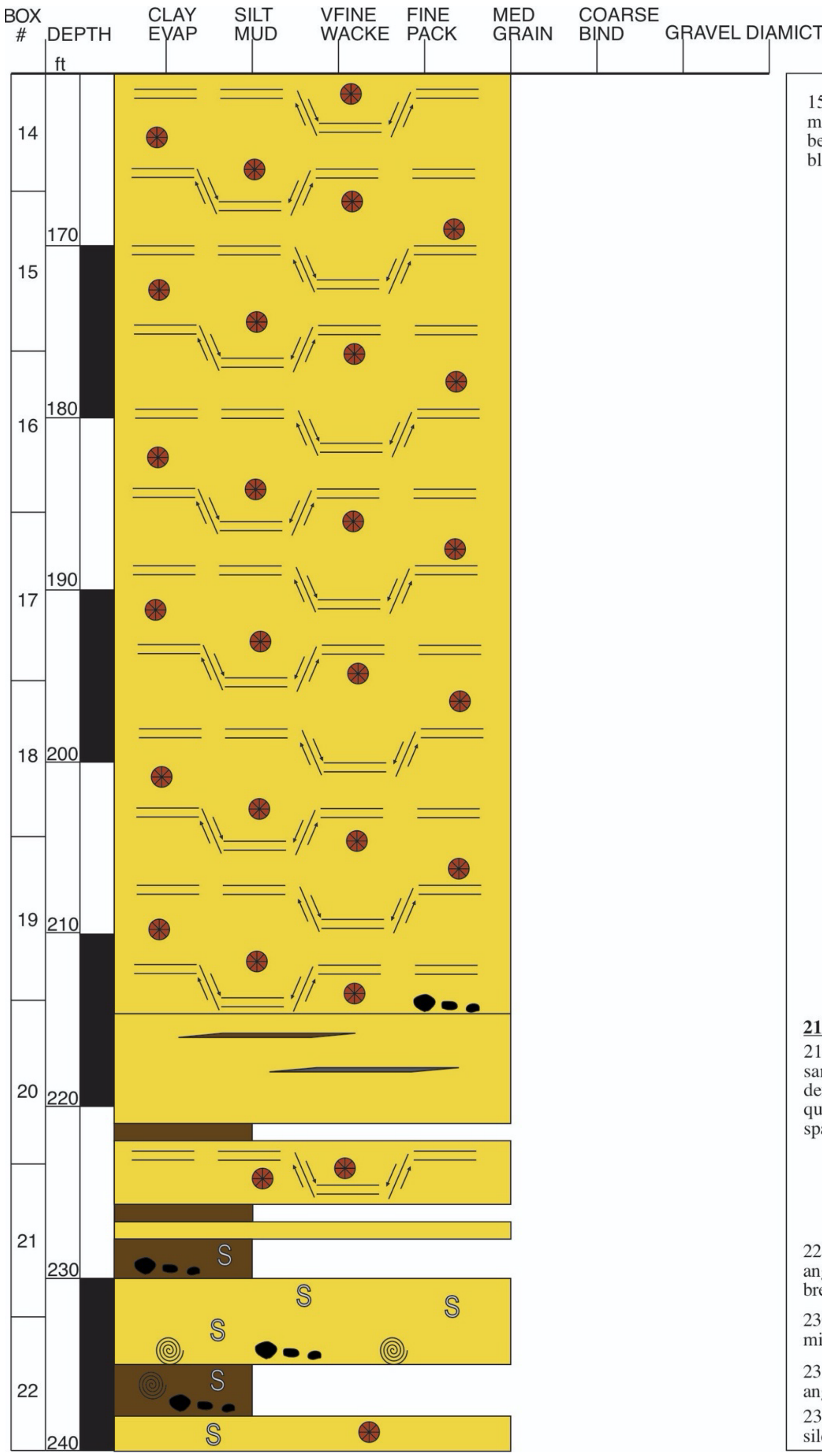


Figure A-9, Keel continued



155-214.8' red, white, marron and tan medium quartz sand with planar cross beds, normal faulting, and yellow and black sulfide mineralization

<u>214.8-248.6 ft St Peter Fm Readstown</u>

214.8-227.5' white and tan medium sandstone with 1-5 in dark brown deformed mud layers, brecciation and quartz and sulfide mineralization in pore space and along fractures

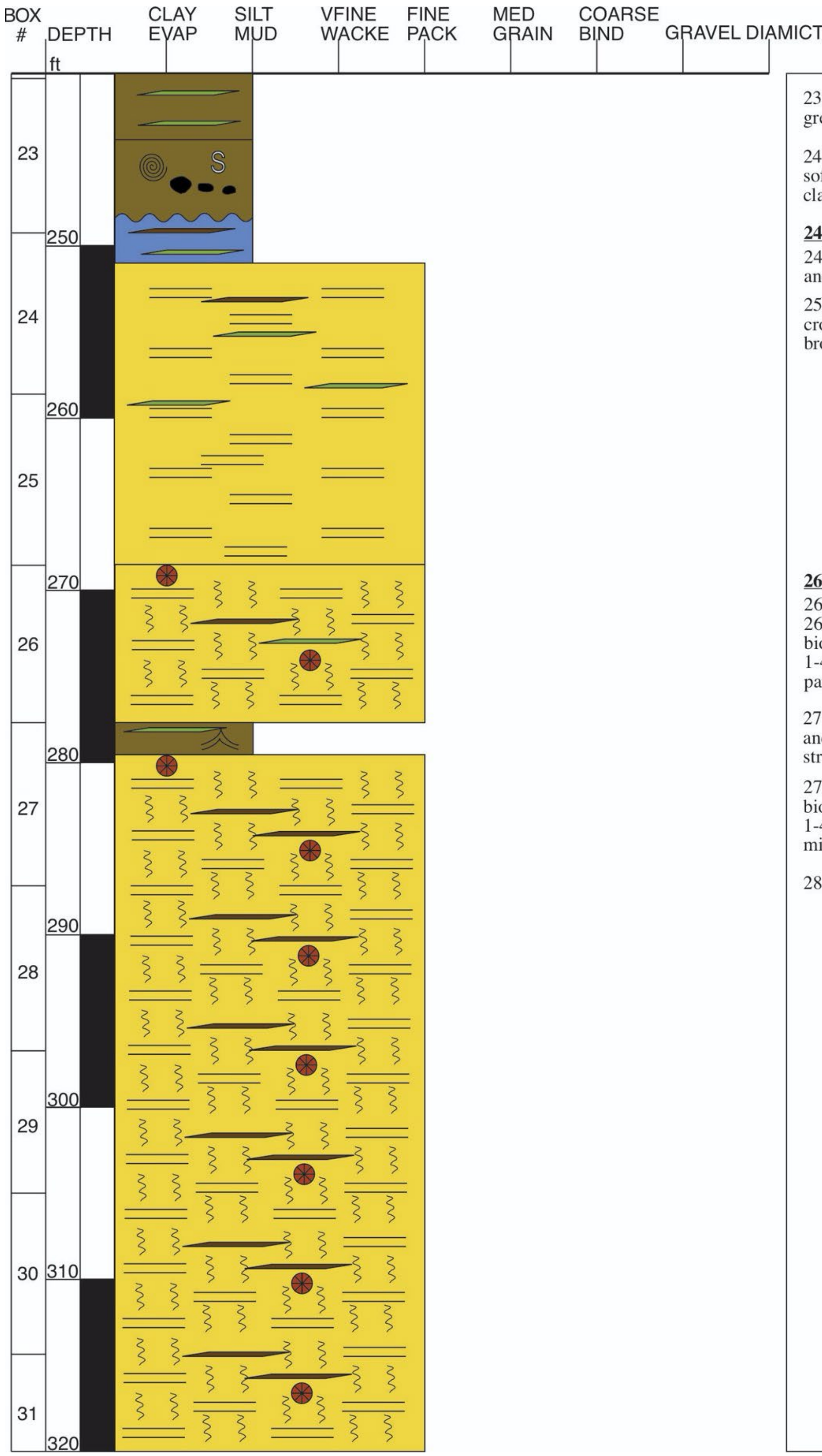
227.5-230' dark brown mud with high angle soft sediment deformation, white brecciated sand clasts and silcrete nodules

230-235' red medium sand with silcrete mineralization in pore space

235-238.1' dark brown mud with high angle soft sediment deformation

238.1-239.9' red medium sand with silcrete mineralization in pore space

Figure A-9, Keel continued



239.9-243.9' laminated dark brown, light green and tan mud

243.9-248.6' brown mud with high angle soft sediment deformation, white sand clasts and silcrete

<u>**248.6-268.6 ft Trempealeau St Lawrence**</u>

248.6-251' tan dolomite with light green and brown wavy shale partings

251-268.6' brown fine sand with planar cross beds, and occasional green and brown shale partings

<u>**268.6-343.6 ft Tunnel City Gp Lone Rock**</u>

268.6-289 ft Reno Mbr

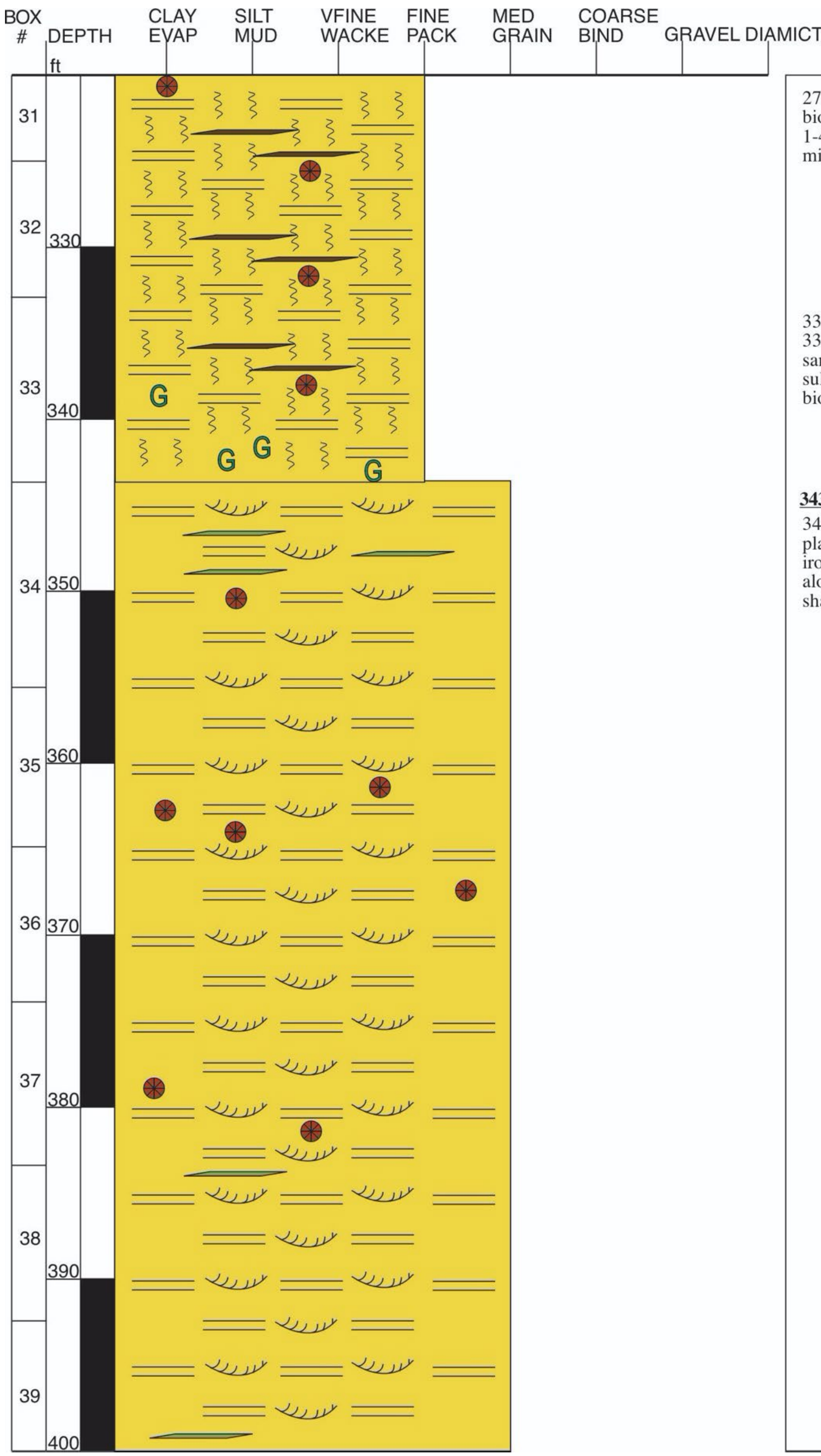
268.6-277.8 maroon and tan fine heavily bioturbated quartz sand "womstone" with 1-4 mm brown and light green shale partings, sulfide mineralization common

277.7-279.5'- laminated dark brown mud and fine yellow sand marker bed, flame structures

279.5-337' maroon and tan fine heavily bioturbated quartz sand "womstone" with 1-4 mm brown shale partings, sulfide mineralization common

289-337 ft Tomah Mbr

Figure A-9, Keel continued



279.5-337' maroon and tan fine heavily bioturbated quartz sand "womstone" with 1-4 mm brown shale partings, sulfide mineralization common

337-343.6 ft Birkmose Mbr
337-343.6' maroon and dark green fine sand with dark green glauconite and black sulfide grains, sulfide mineralization and bioturbation common. Birkmose member

<u>343-500 ft Elk Mound Gp Wonewoc Fm</u>

343.6-500' white medium sand with planar and trough cross beds, occasional iron staining and sulfide mineralization along bedding planes, and light green shale partings

Figure A-9, Keel continued

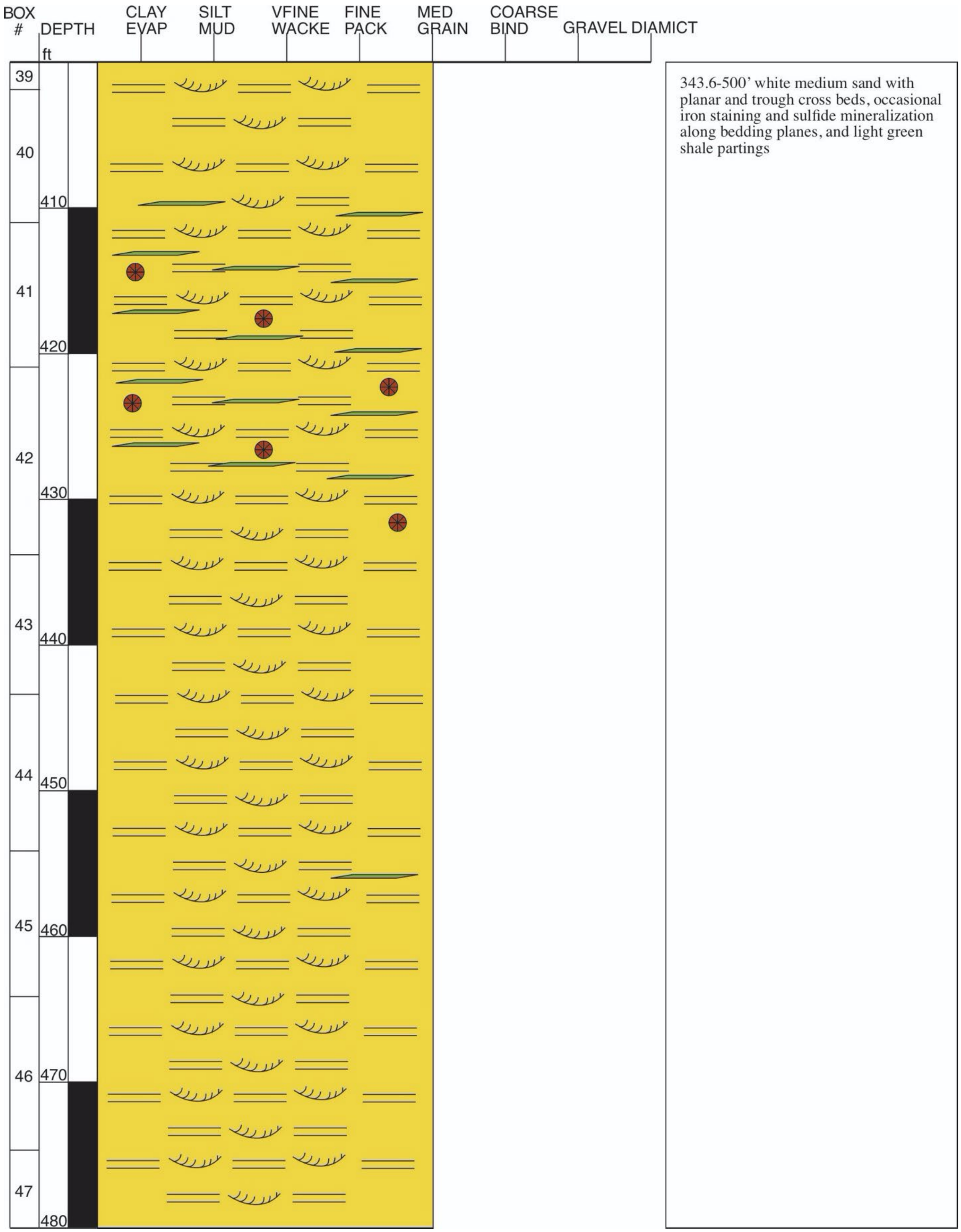


Figure A-9, Keel continued

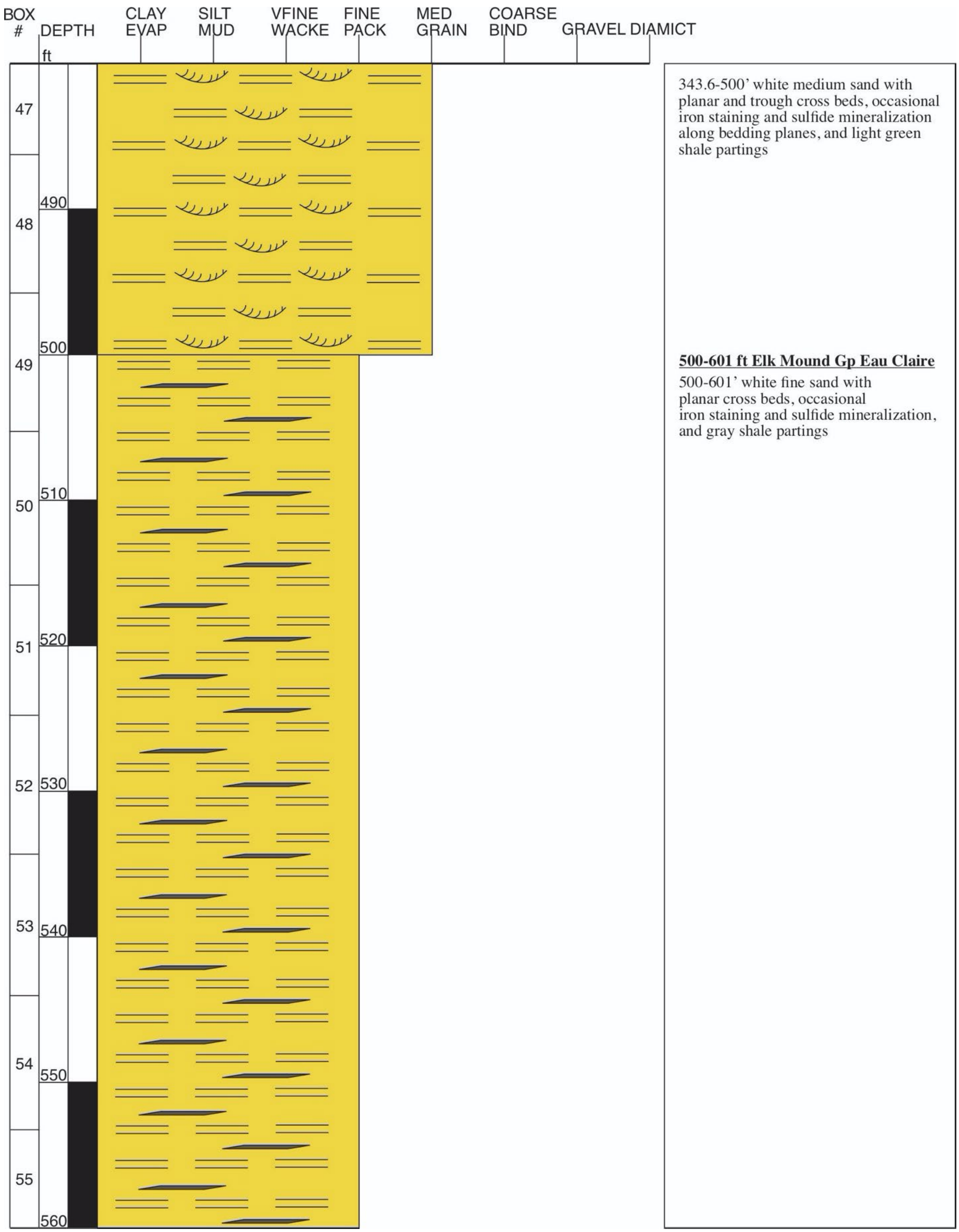


Figure A-9, Keel continued

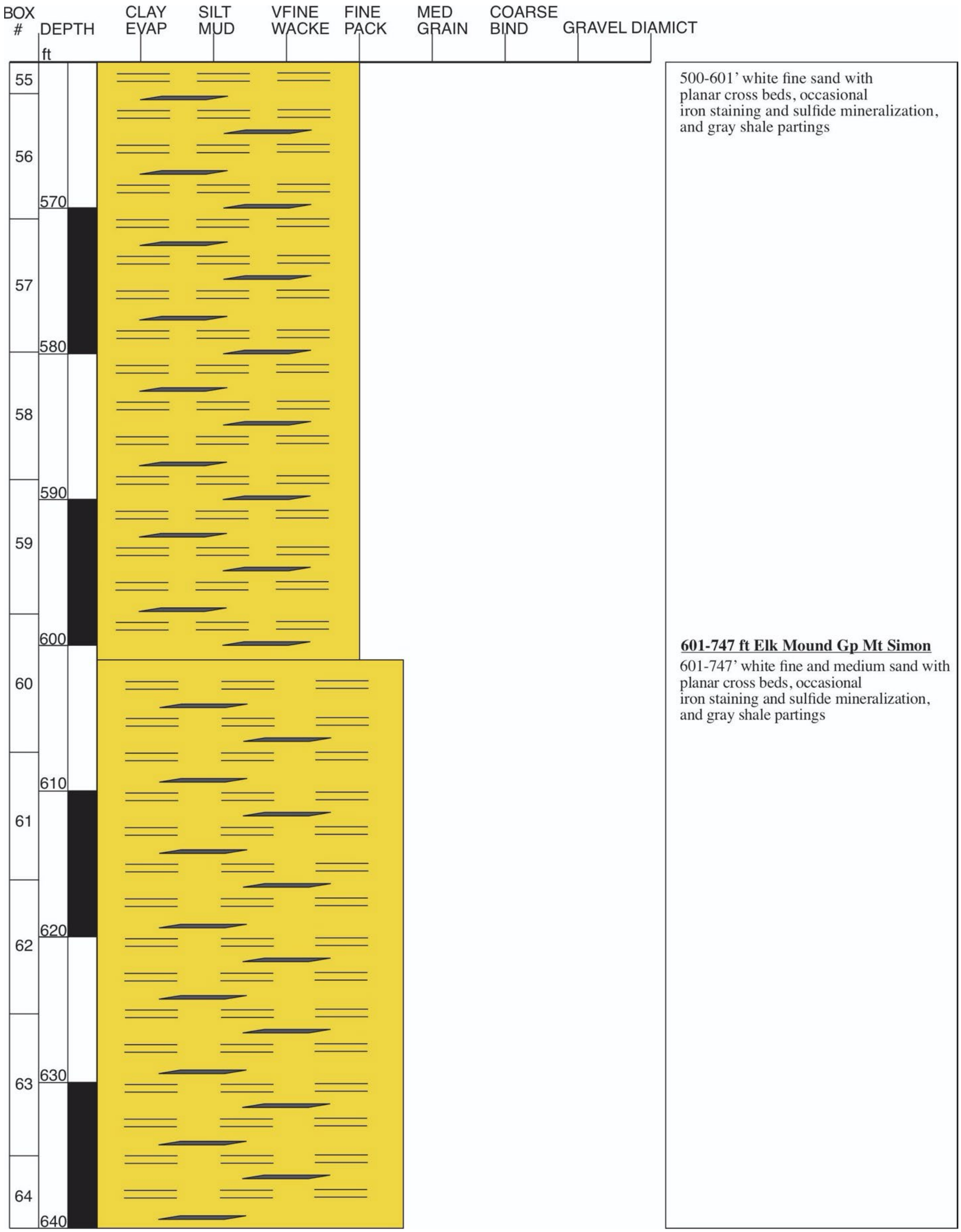
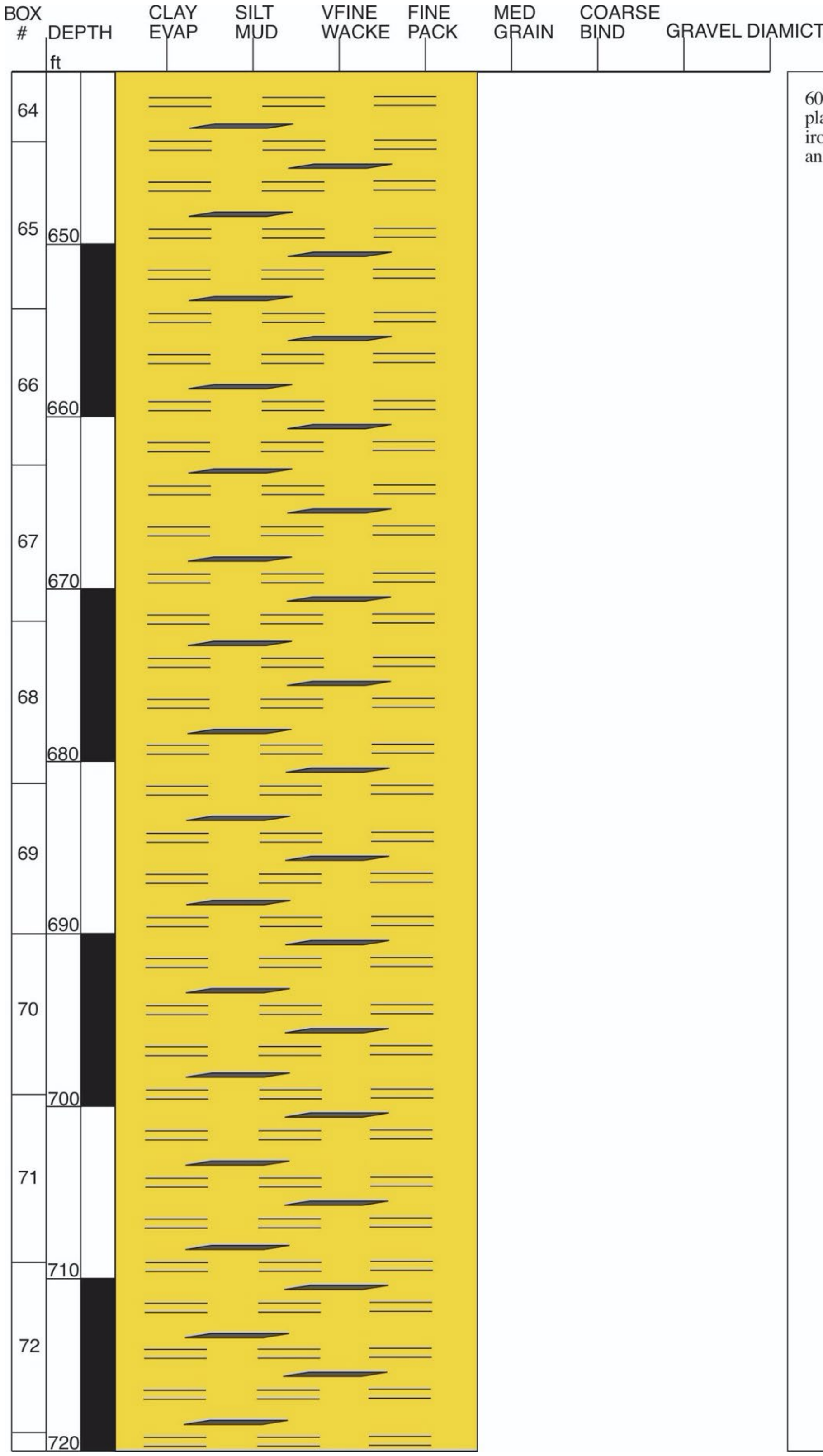


Figure A-9, Keel continued



601-747' white fine and medium sand with planar cross beds, occasional iron staining and sulfide mineralization, and gray shale partings

Figure A-9, Keel continued

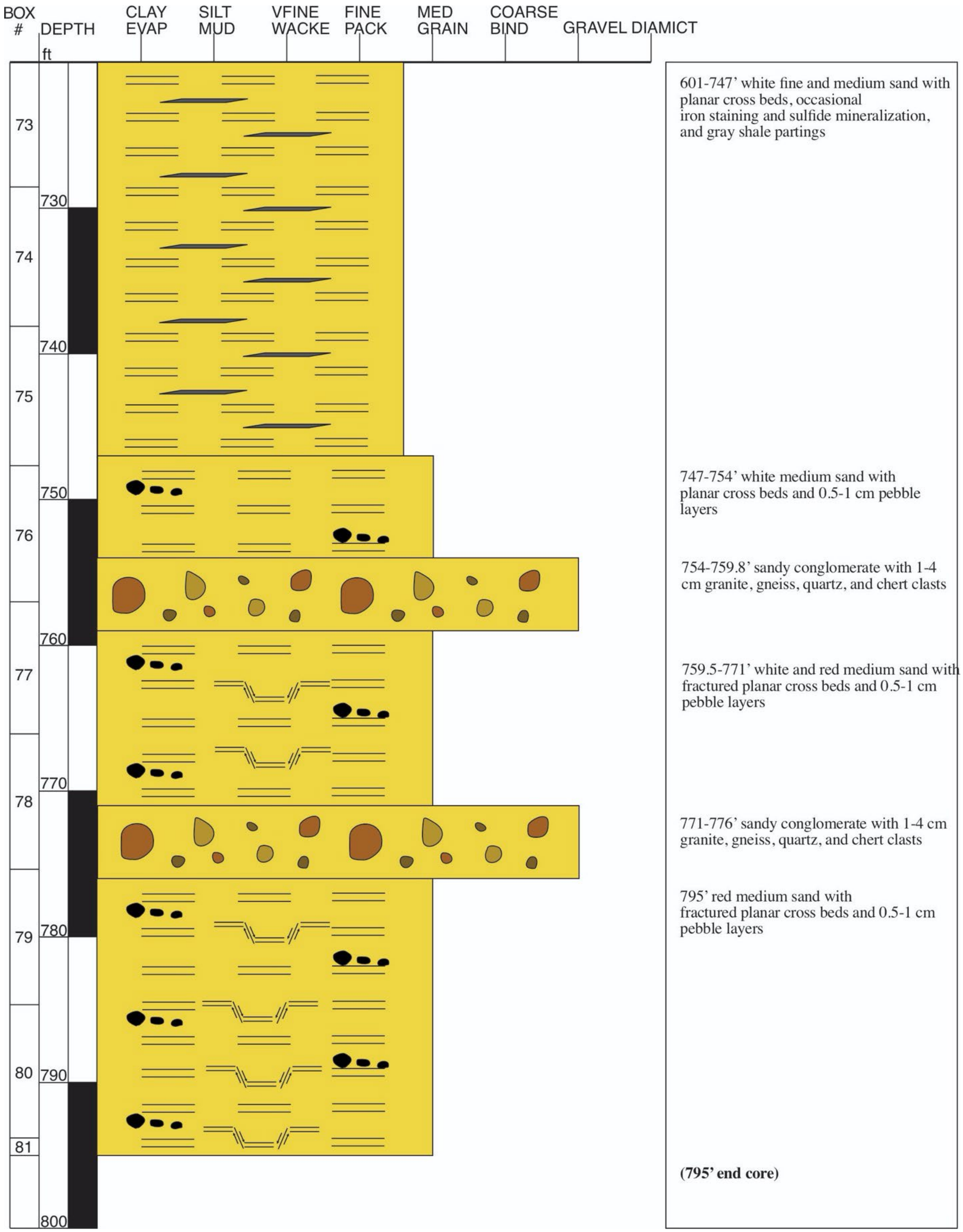
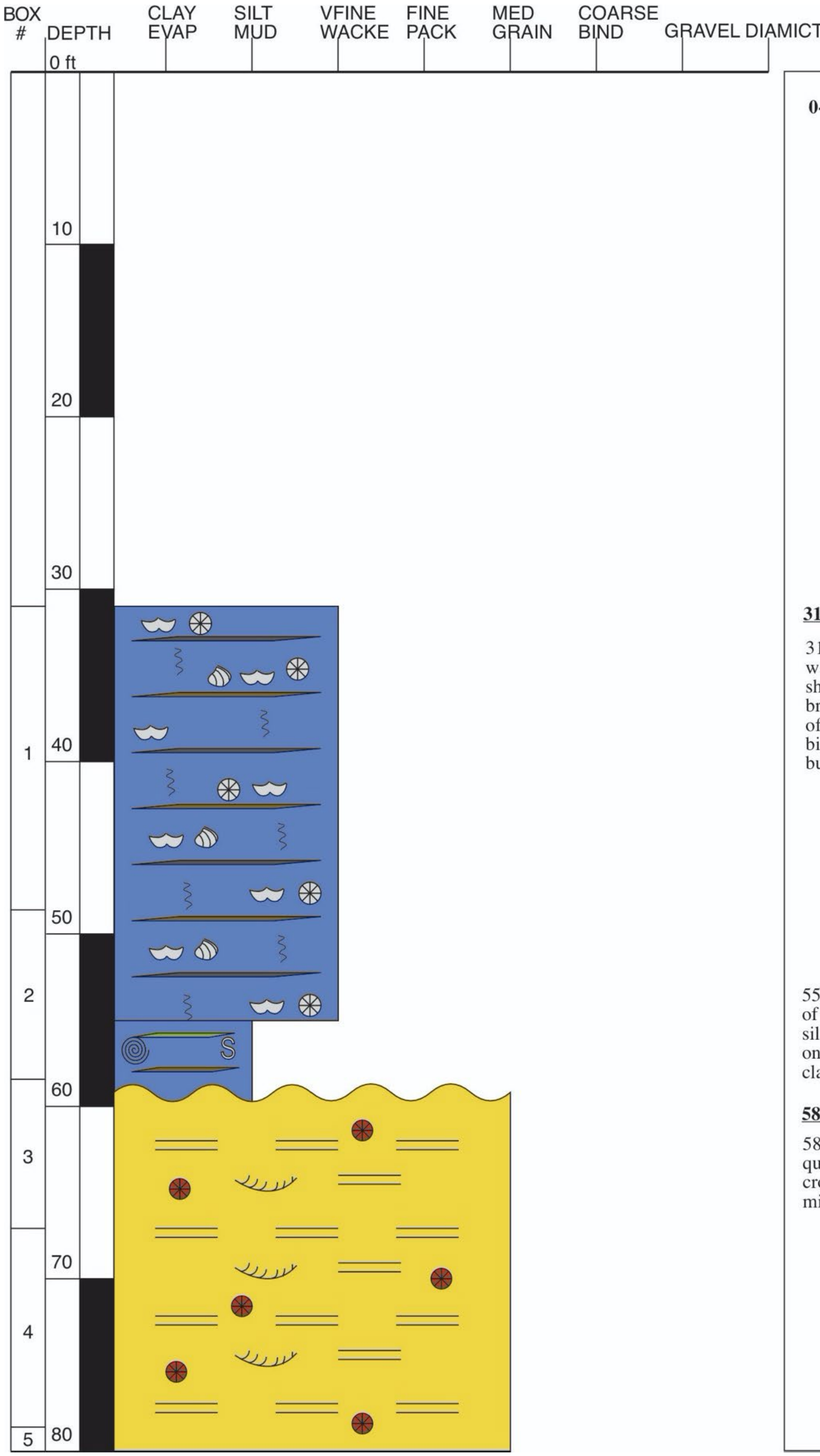


Figure A-10, Mankowski, Jefferson County

Elevation: 877’ Total Depth: 265’



0-31 ft core loss

31-58.4 ft Sinnipee Gp Platteville Fm

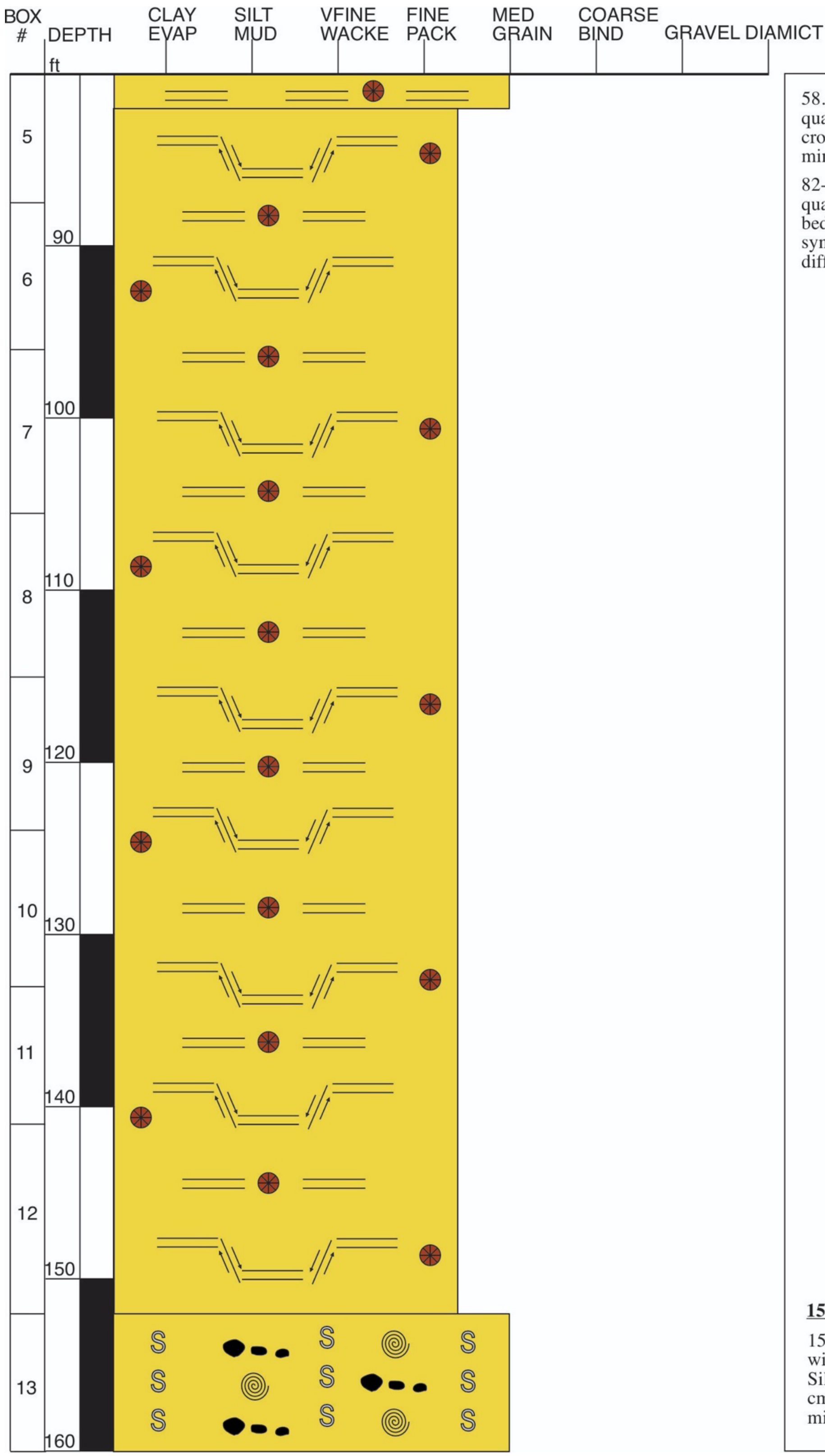
31-55’ tan to gray silty dolomite wackestone with 1-4 mm gray wispy shale partings, mm to cm scale reddish brown wispy silt layers, mm scale vugs often in the shape of brachiopods, bioturbation with horizontal and vertical burrows in muddier horizons

55-58.4’ light brown weathered interval of poorly consolidated limey mud, some silcrete accumulation, bioturbation and one 3 inch band of light green laminated clay at 55’

58.4-152 ft Saint Peter Fm Tonti Mbr

58.4-82’ orange to white medium-grained quartz sandstone with planar and trough cross beds, mm to cm scale sulfide mineralization, and carbonate cement

Figure A-10, Mankowski continued



58.4-82' orange to white medium-grained quartz sandstone with planar and trough cross beds, mm to cm scale sulfide mineralization, and carbonate cement

82-152' white to pink fine to medium quartz sand with planar and trough cross beds, high angle fractures likely due to syndepositonal slumping and sliding, and diffuse mm scale sulfide mineralization

<u>**152-167 ft Saint Peter Fm Readstown**</u>

152-167' white and gray medium sands with abundant silcrete and deformation. Silcrete often occurs as brecciated mm to cm scale clasts. Little to no sulfide mineralization

Figure A-10, Mankowski continued

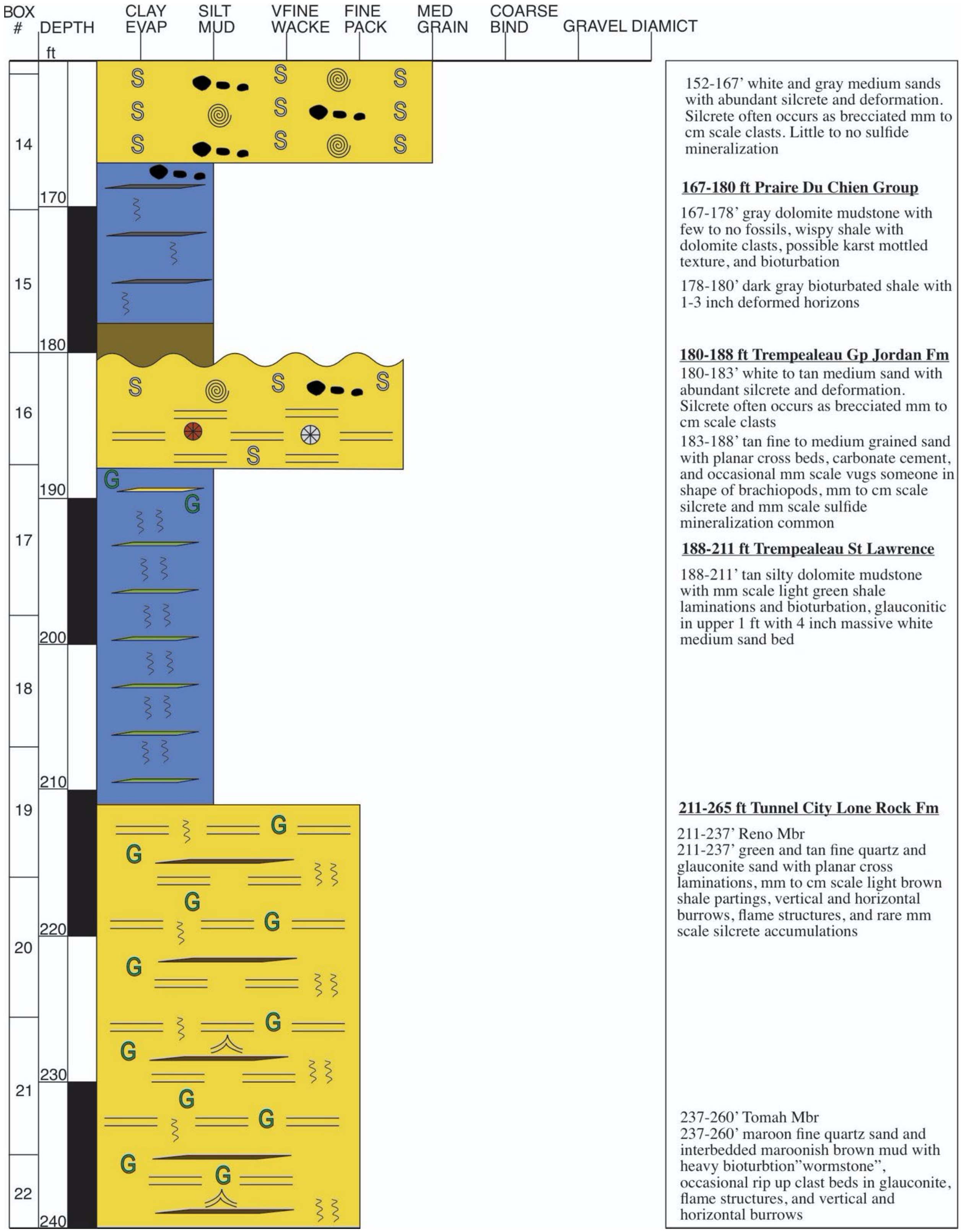
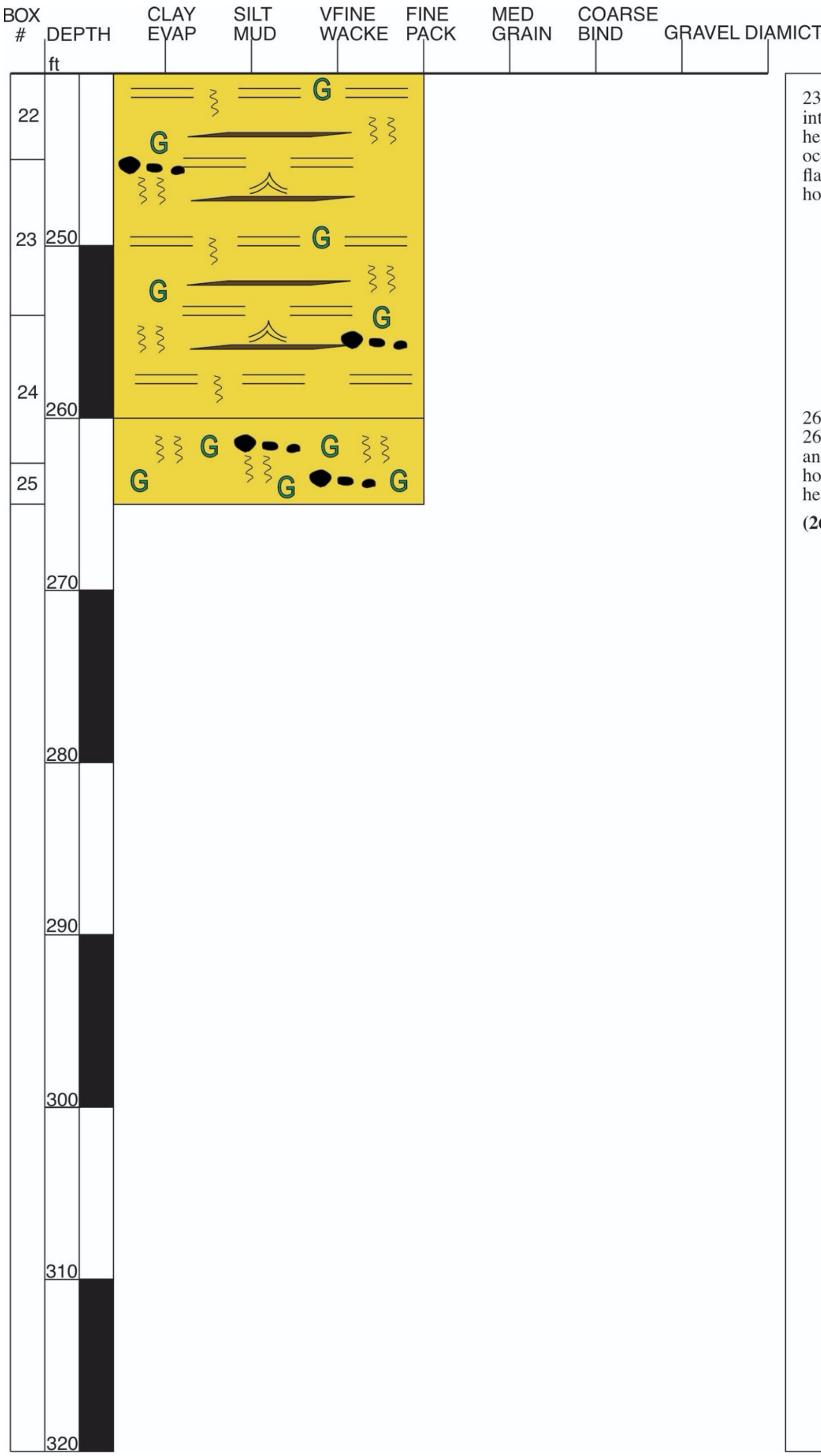


Figure A-10, Mankowski continued



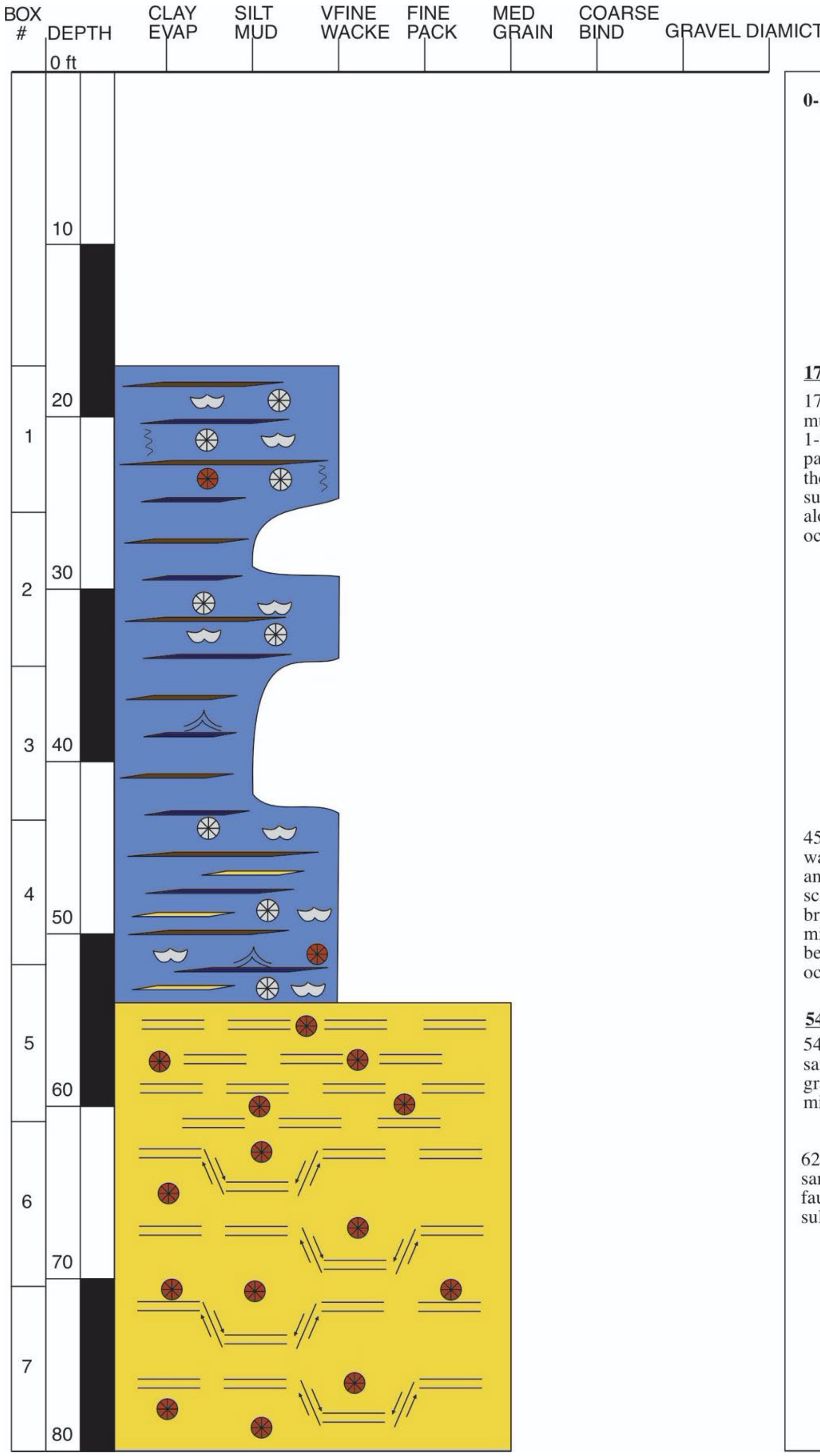
237-260' maroon fine quartz sand and interbedded maroonish brown mud with heavy bioturbtion"wormstone", occasional rip up clast beds in glauconite, flame structures, and vertical and horizontal burrows

260-265' Birkmose Mbr
260-265' maroon and green glauconite and quartz fine sand with vertical and horizontal burrows and rip up clasts in heavily glauconitic beds

(265 ft end core)

Figure A-11, Miller Quarry, Dodge County

Elevation: 891' Total Depth: 788.6'



0-17 ft core loss

<u>17-54 ft Sinnipee Gp Platteville Fm</u>

17-45' gray and tan silty dolomite mudstone to wackestone with frequent 1-2 mm brown and dark blue shale partings, mm to cm scale vugs often in the shape of brachiopods, mm to cm scale sulfide mineralization in nodules and along bedding planes, some flame structures, occasional bioturbation

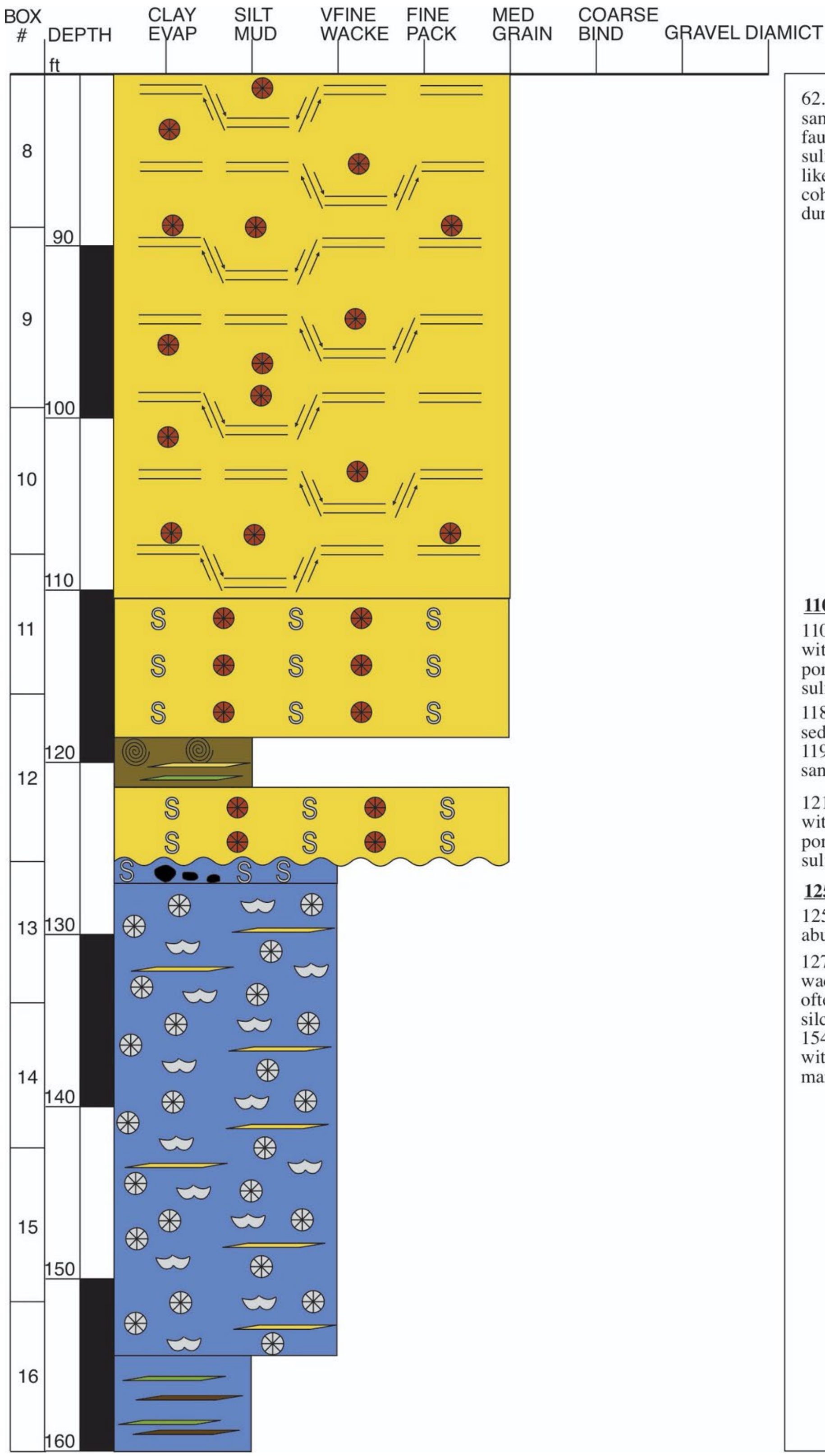
45-54' gray and tan sandy dolomite wackestone with frequent 1-2 mm brown and dark blue shale partings, mm to cm scale vugs often in the shape of brachiopods, mm to cm scale sulfide mineralization in nodules and along bedding planes, some flame structures, occasional bioturbation

<u>54-110.5 ft St. Peter Fm Tonti Mbr</u>

54-62.2' gray and white medium quartz sand with planar cross beds, black sulfide grains and mm to cm scale sulfide mineralization

62.2-110.5' pink, tan and white medium sand with planar cross beds, small normal faults, and frequent mm to cm scale sulfide mineralization

Figure A-11, Miller Quarry continued



62.2-110.5' pink, tan and white medium sand with planar cross beds, small normal faults, and frequent mm to cm scale sulfide mineralization. Minor faulting likely syn-depositional slumping of cohesive, damp grains (possible eolian dunes)

110.5-125.8 ft St. Peter Fm Readstown

110.5-118.7'white and gray medium sand with silcrete accumulation in nodules, pore space and bedding planes, mm to cm sulfide mineralization

118.7-119.4' dark brown mud with soft sediment deformation
119.4-121.3' laminated white medium sand and light green mud

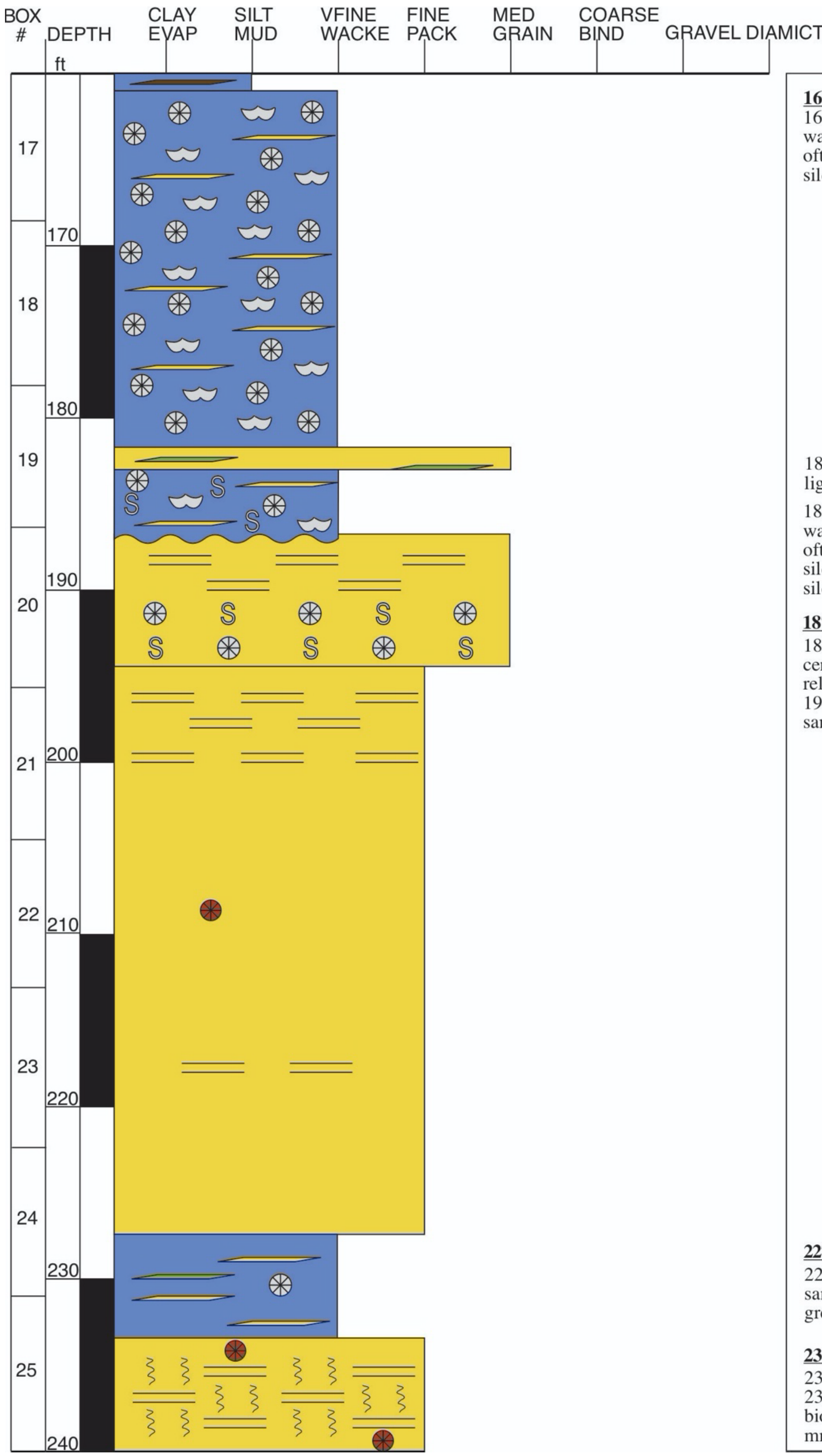
121.3-125.8'white and gray medium sand with silcrete accumulation in nodules, pore space and bedding planes, mm to cm sulfide mineralization

125.8-161 ft Prairie Du Chien Shakopee

125.8-127 mottled, karsted texture with abundant silcrete accumunlation

127-154.5' gray sandy dolomite wackestone with mm to cm scale vugs often in the shape of brachiopods, some silcrete in pore spaces
154.5-161' tan silty laminated dolomite with 2-8 mm yellow, light green and maroon mud/silt layers

Figure A-11, Miller Quarry continued



161-187' ft Prairie Du Chien Oneota
161-180.8' gray sandy dolomite wackestone with mm to cm scale vugs often in the shape of brachiopods, some silcrete in pore spaces

180.8-182' white medium sand with light green shale partings

182-187' gray sandy dolomite wackestone with mm to cm scale vugs often in the shape of brachiopods, some silcrete in pore spaces and mm to 4 cm silcrete nodules and bands

187-227.2 ft Trempealeau Gp Jordan
187-194.4' white medium sand with vugs, cemented sandstone, and minor fractures related to exposure
194.4-227.2' white to tan massive fine sand with occasional planar beds

227.2-233.2 ft Trempealeau St. Lawrence
227.2-233.3' white and maroon meduim sandy bedded dolomite with 1 mm light green shale partings and mm scale vugs

233.2-327.5 ft Tunnel City Gp
233.2-266 ft Lone Rock Fm Reno Mbr
233.2-241' maroon and tan heavily bioturbated fine sand "wormstone" with mm scale sulfide mineralization

Figure A-11, Miller Quarry continued

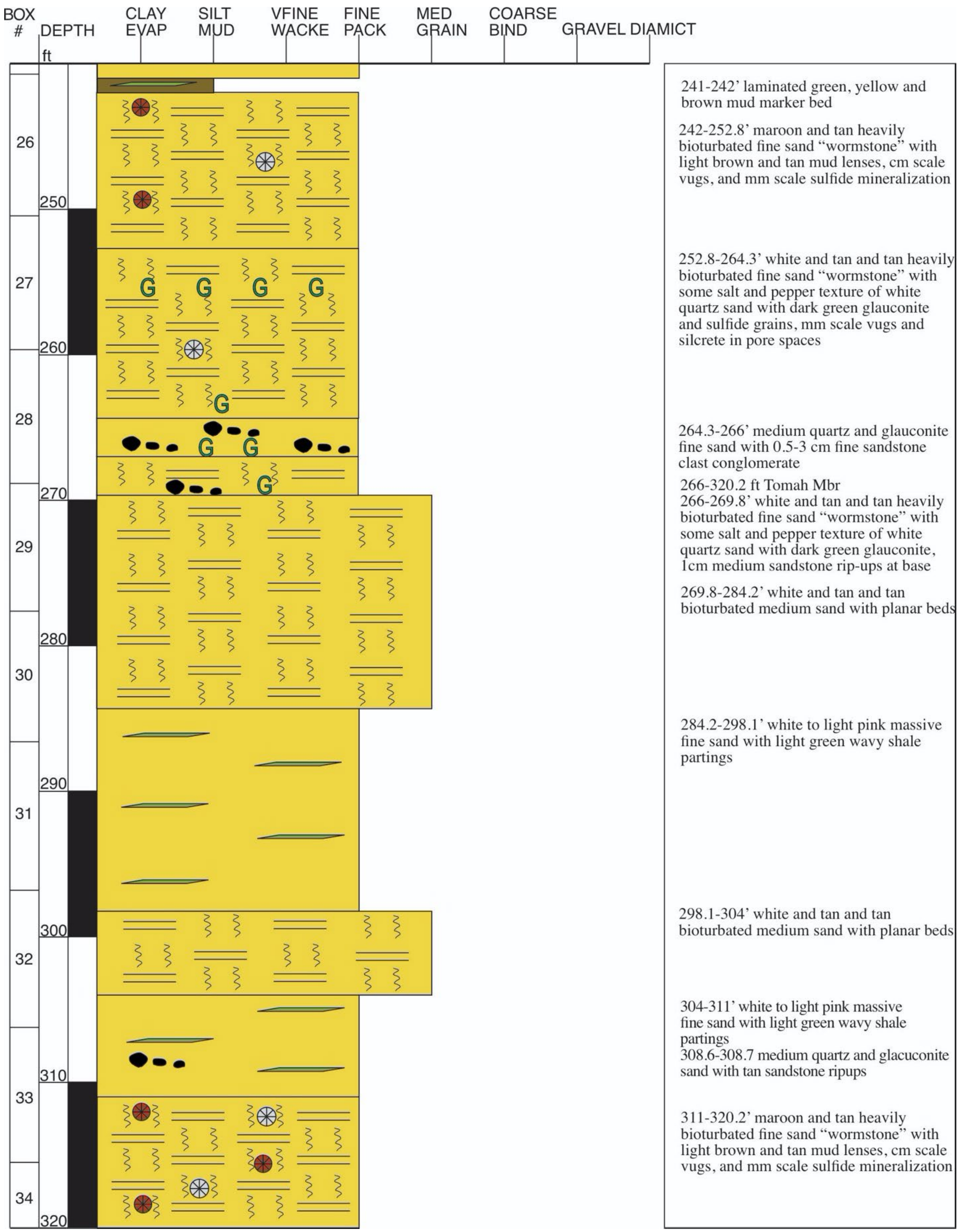
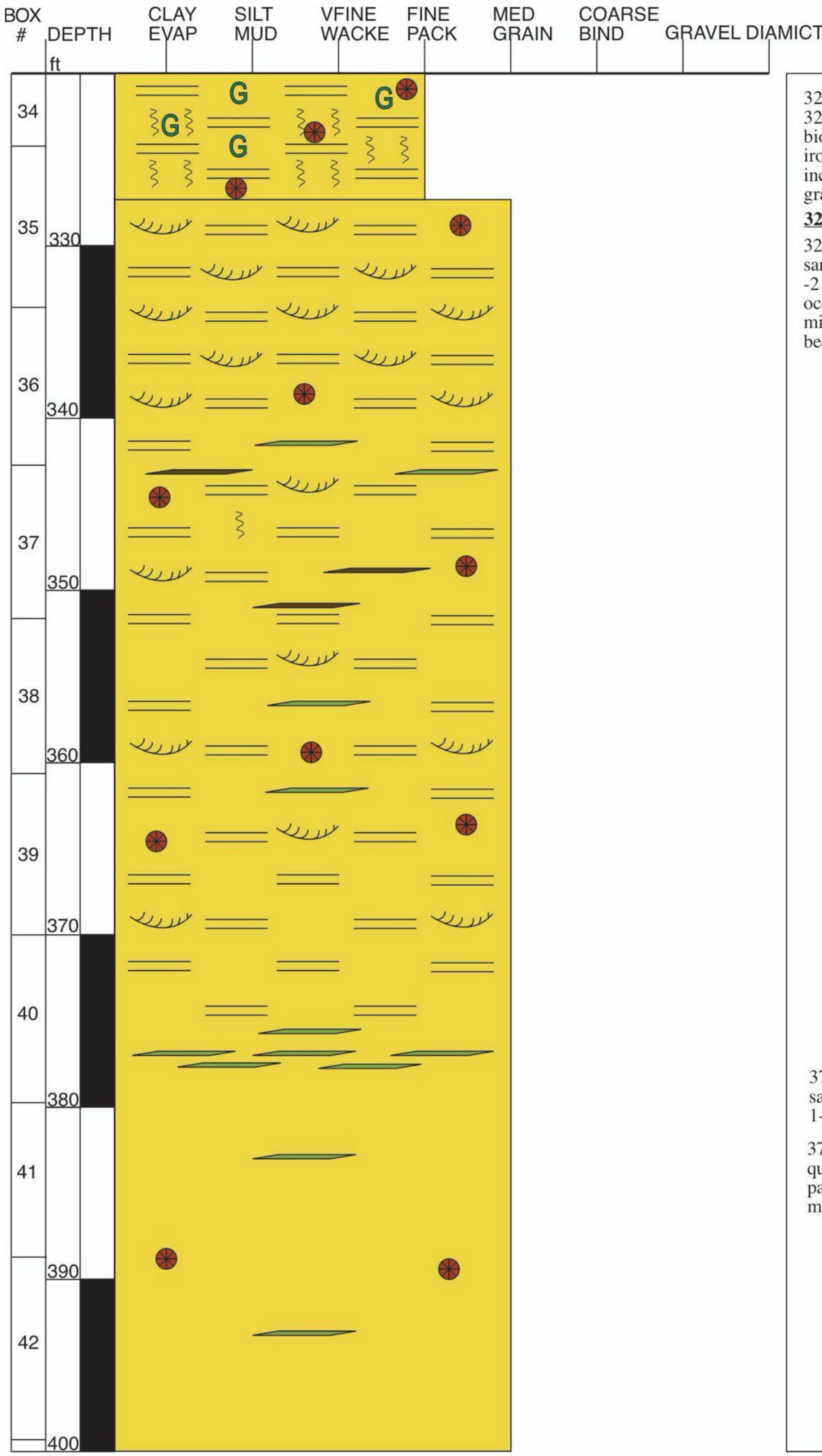


Figure A-11, Miller Quarry continued



320.2-327.5' Birkmose Mbr
320.2-327.5' maroon and tan heavily bioturbated fine sand "wormstone" with iron stained white quartz sand with increasing layers of dark green glauconite grains, mm scale sulfide mineralization

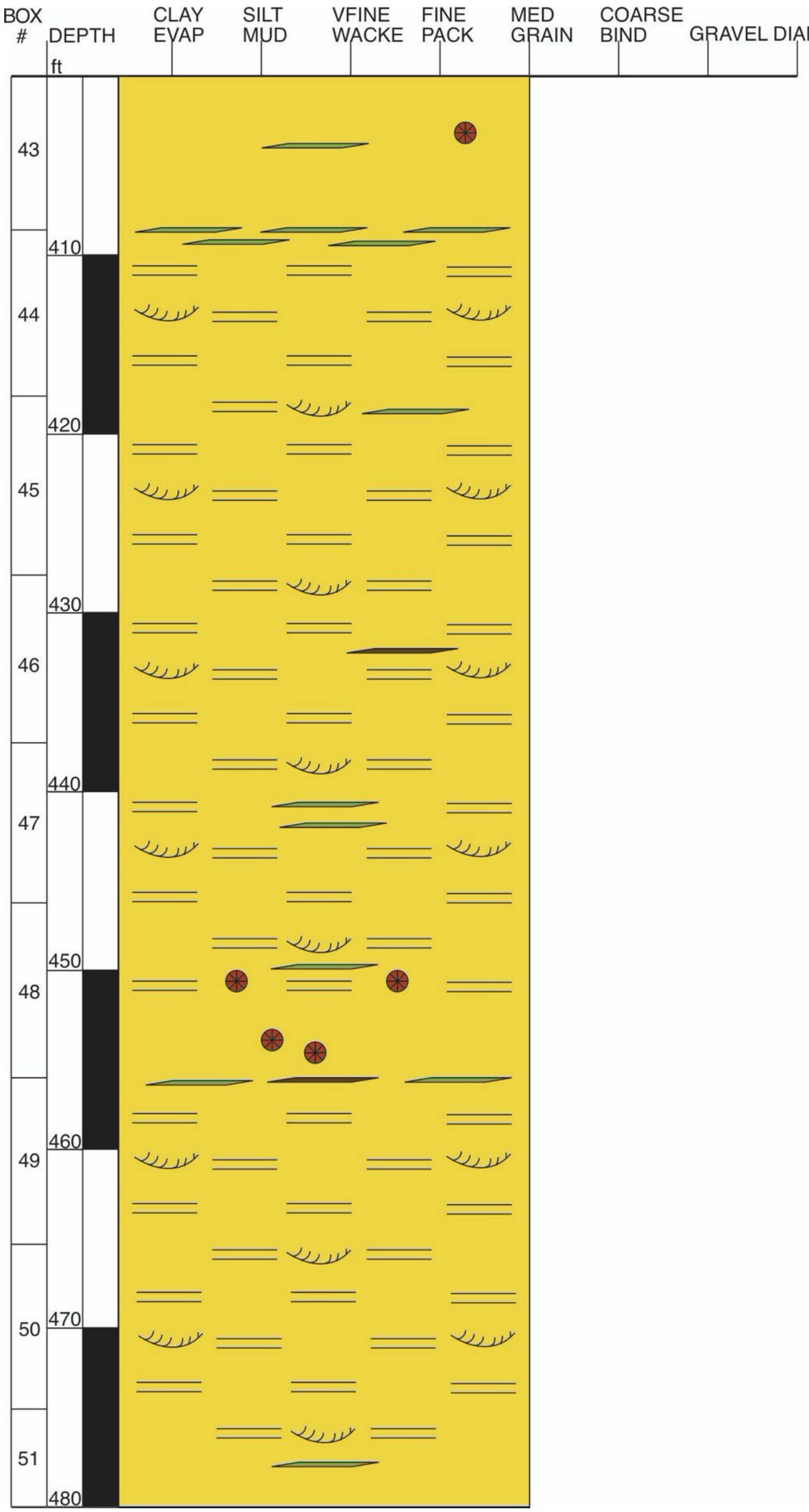
327.5-487.9 ft Elk Mound Gp Wonewoc

327.5-376.5' white to tan medium quartz sand with planar and trough cross beds, 1 -2 mm light green and brown shale partings occasional mm to cm sulfide mineralization in pore space and along bedding planes, and little bioturbation

376.5-378' white to medium quartz sand with planar cross beds and abundant 1-5 mm light green shale partings

378-408.6' white to tan massive medium quartz sand with 1-2 mm light green shale partings, occasional mm to cm sulfide mineralization

Figure A-11, Miller Quarry continued



378-408.6' white to tan massive medium quartz sand with 1-2 mm light green shale partings, occasional mm to cm sulfide mineralization

408.6-409.6' white to medium quartz sand with planar cross beds and abundant 1-5 mm light green shale partings

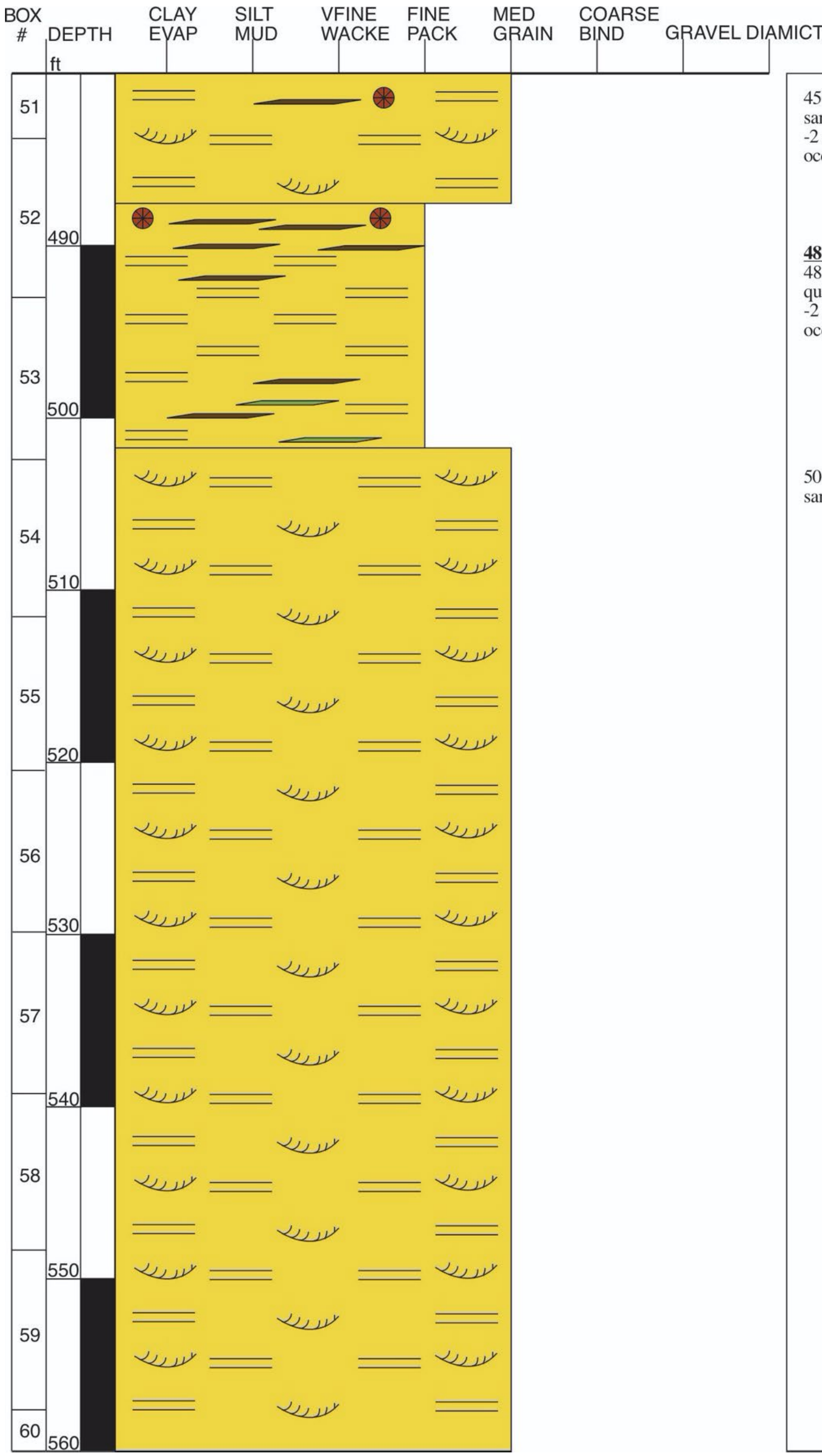
409.6-451.2' white to tan medium quartz sand with planar and trough cross beds, 1 -2 mm light green and brown shale partings occasional mm to cm sulfide mineralization

451-.2-456' white to tan massive medium quartz sand with mm scale sulfide mineralization

456-456.5' white medium sand with 2-5 mm laminated beds of light green and brown shale

456.5-487.8' white to tan medium quartz sand with planar and trough cross beds, 1 -2 mm light green and brown shale partings occasional mm to cm sulfide mineralization

Figure A-11, Miller Quarry continued

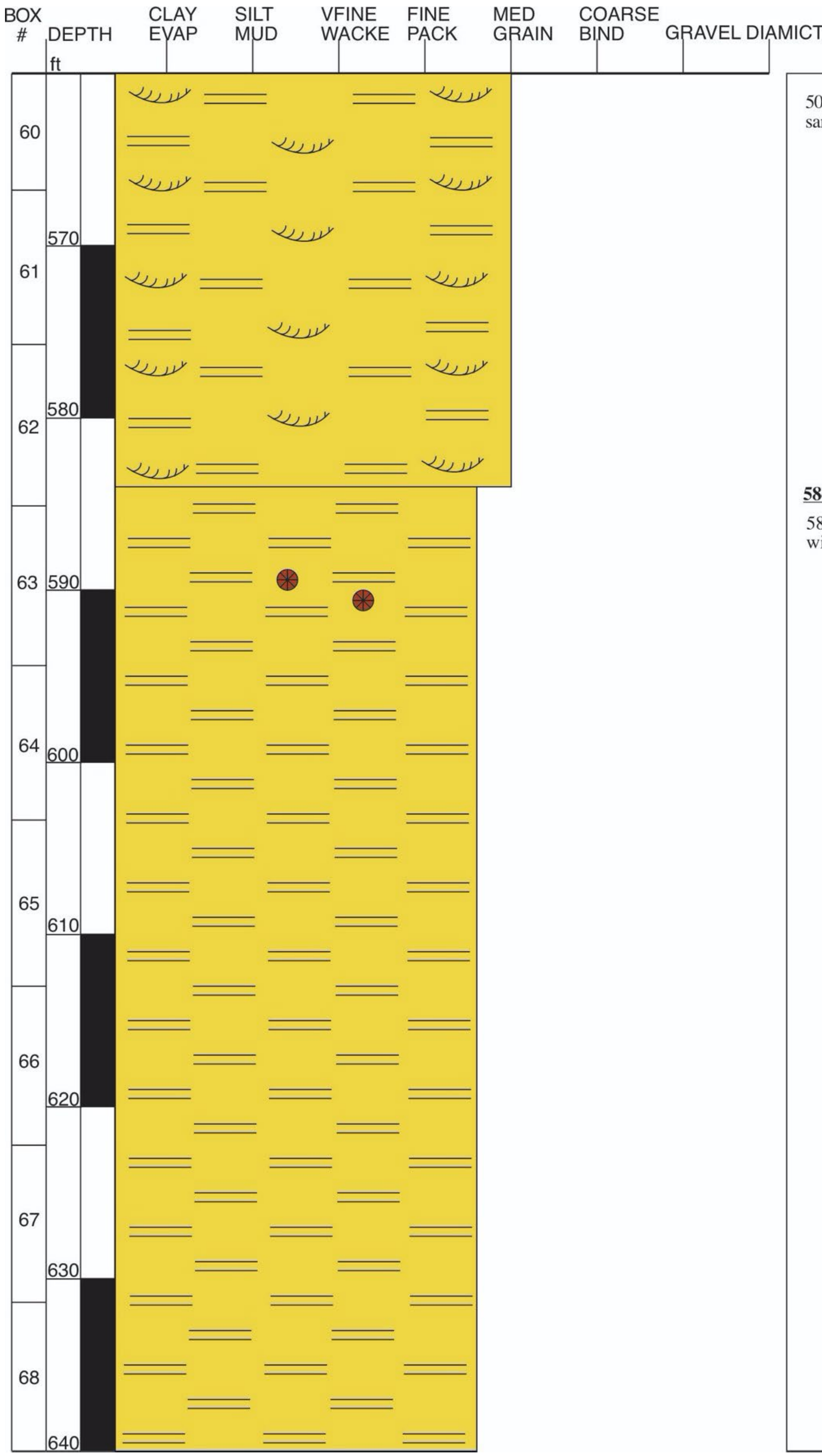


456.5-487.8' white to tan medium quartz sand with planar and trough cross beds, 1 -2 mm light green and brown shale partings occasional mm to cm sulfide mineralization

<u>487.8-584' Elk Mound Gp Eau Claire Fm</u>
487.8-501.8' fine white to tan medium quartz sand with planar and cross beds, 1 -2 mm light green and brown shale partings occasional mm scale sulfide mineralization

501.8-584' white to tan medium quartz sand with planar cross beds

Figure A-11, Miller Quarry continued

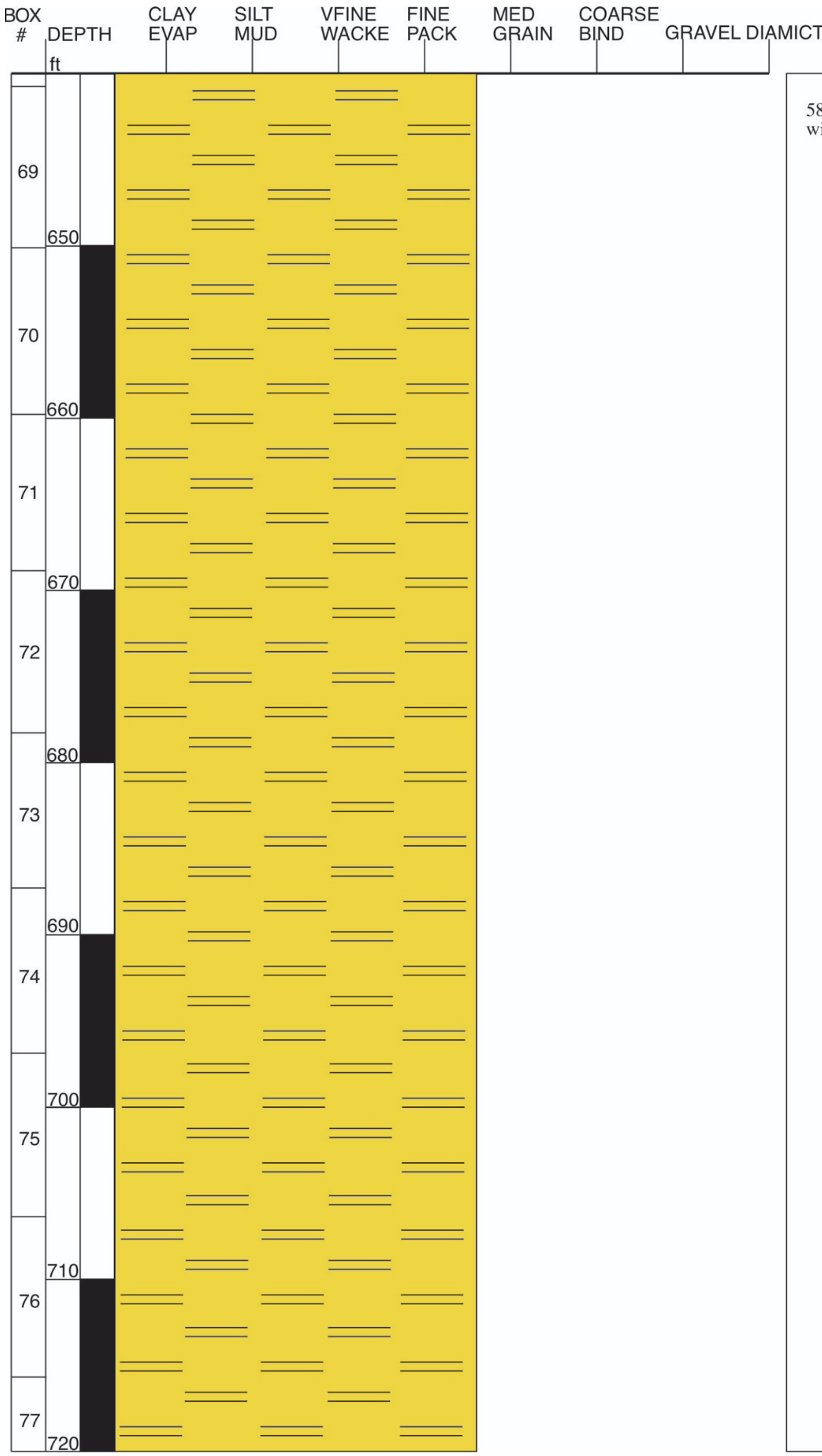


501.8-584' white to tan medium quartz sand with planar cross beds

584-788.6 ft Eau Claire Fm Mt Simon Fm

584-788.6' white fine and medium sand with planar cross beds

Figure A-11, Miller Quarry continued



584-788.6' white fine and medium sand with planar cross beds

Figure A-11, Miller Quarry continued

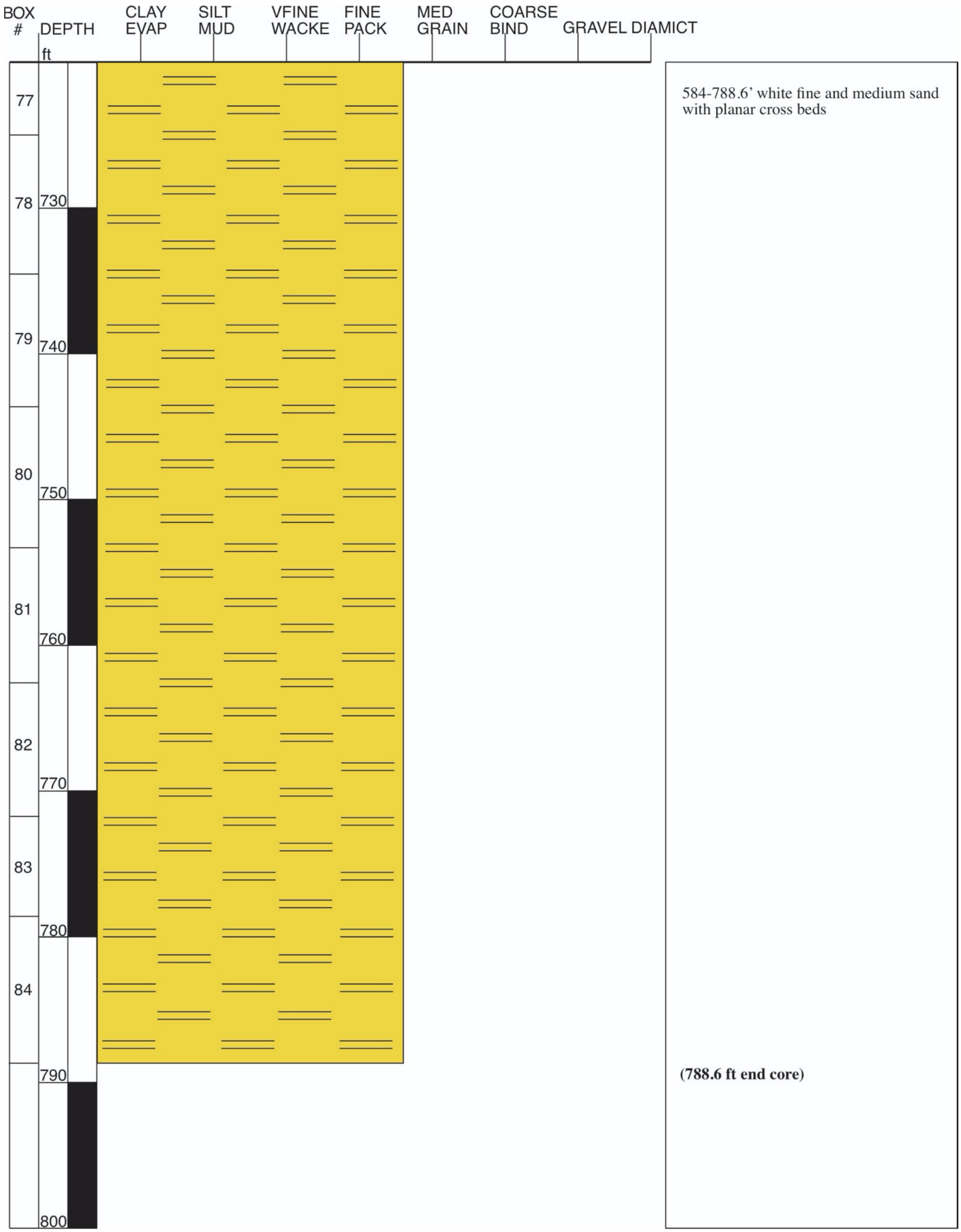
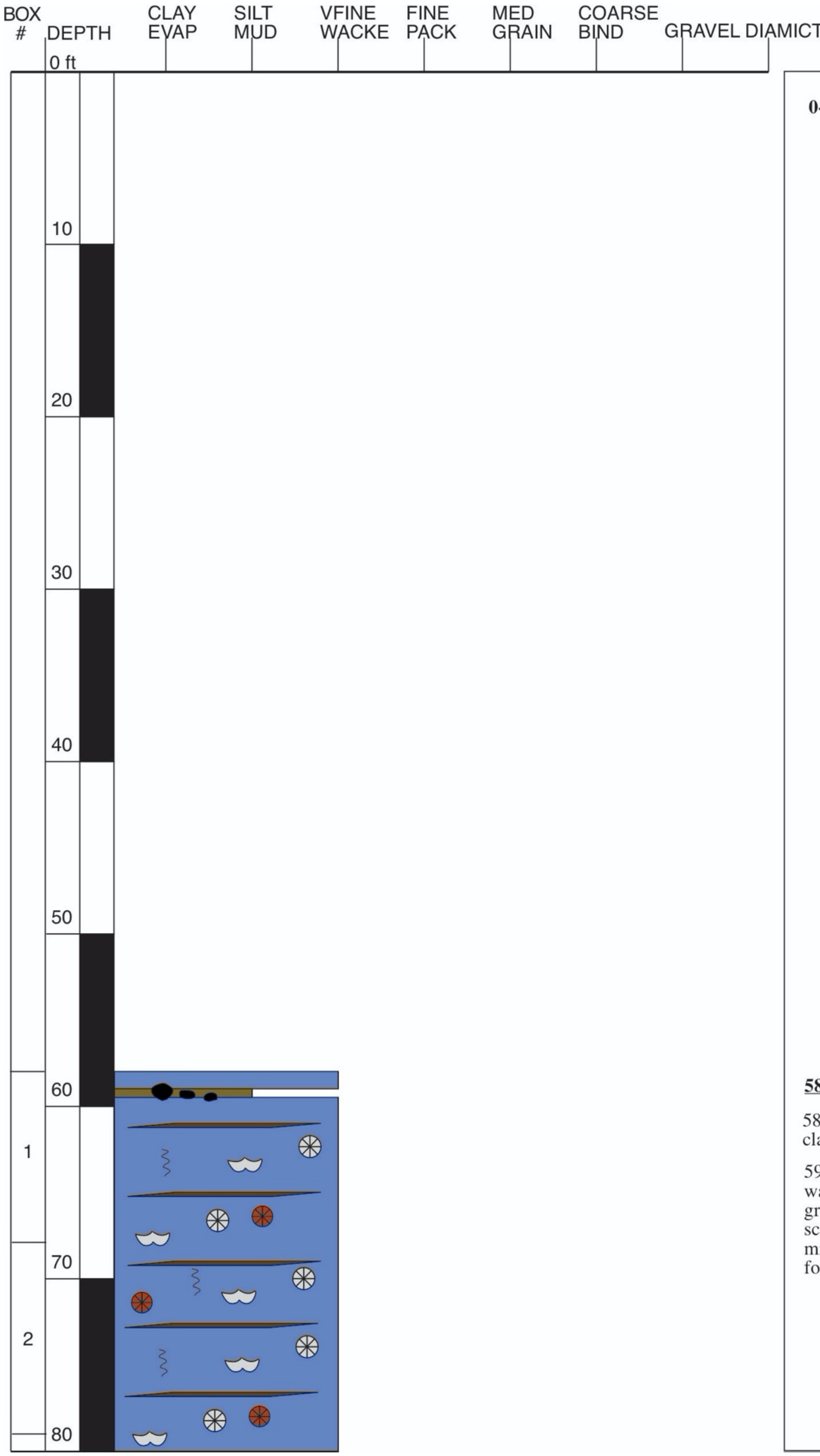


Figure A-12, Mobil, Jefferson County
Elevation: 878’ Total Depth: 317’



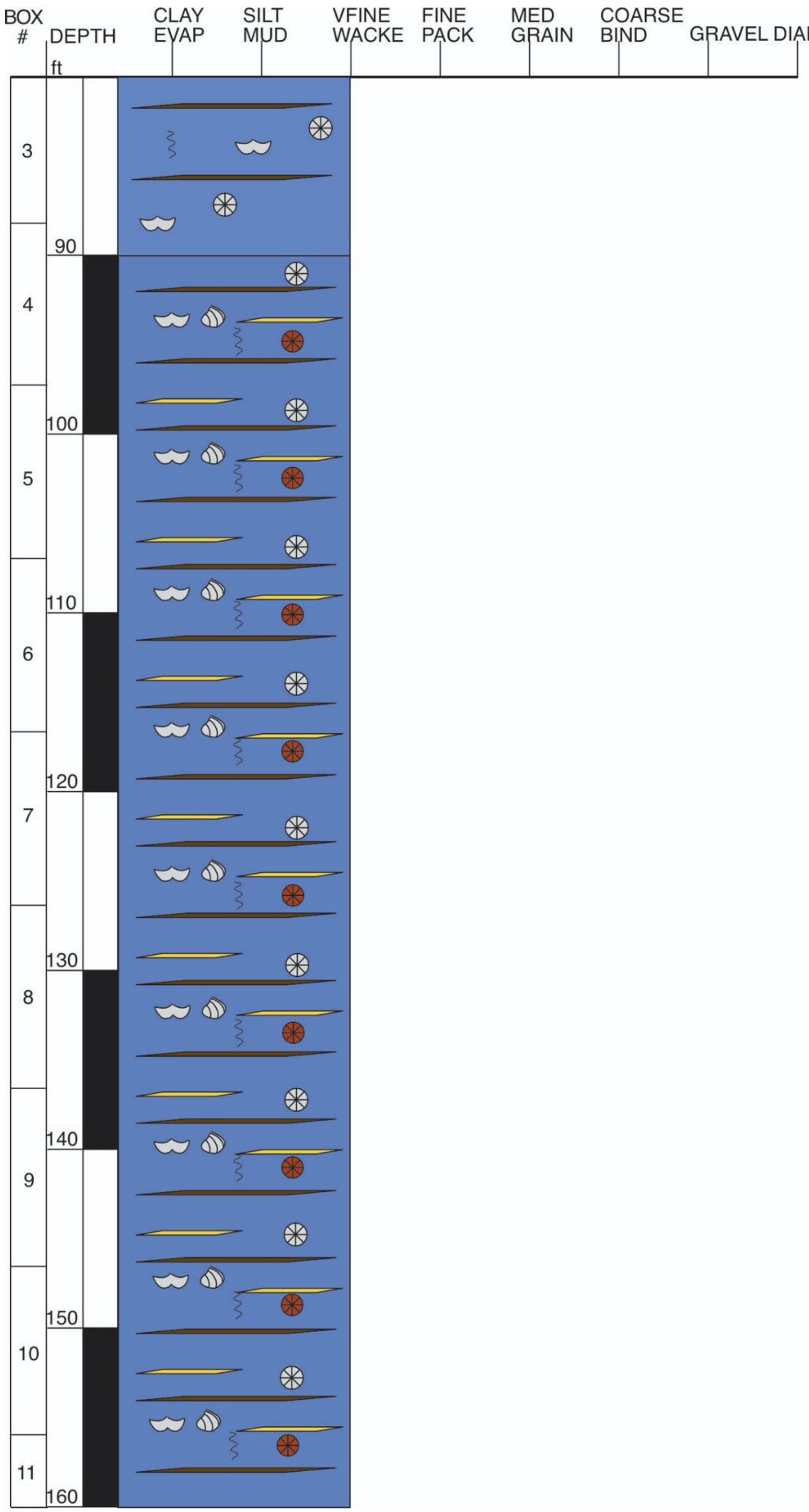
0-66 ft core loss

58- 222 ft Sinnipee Gp Galena Fm

58-59.2 brown paleosol with dolomite clasts

59.2-90 brown to gray silty dolomite wackestone with 1 mm brown and dark gray wispy shale partings, mm to cm scale vugs often with sulfide mineralization fillings, brachiopod and fossil fragments, occasional bioturbation

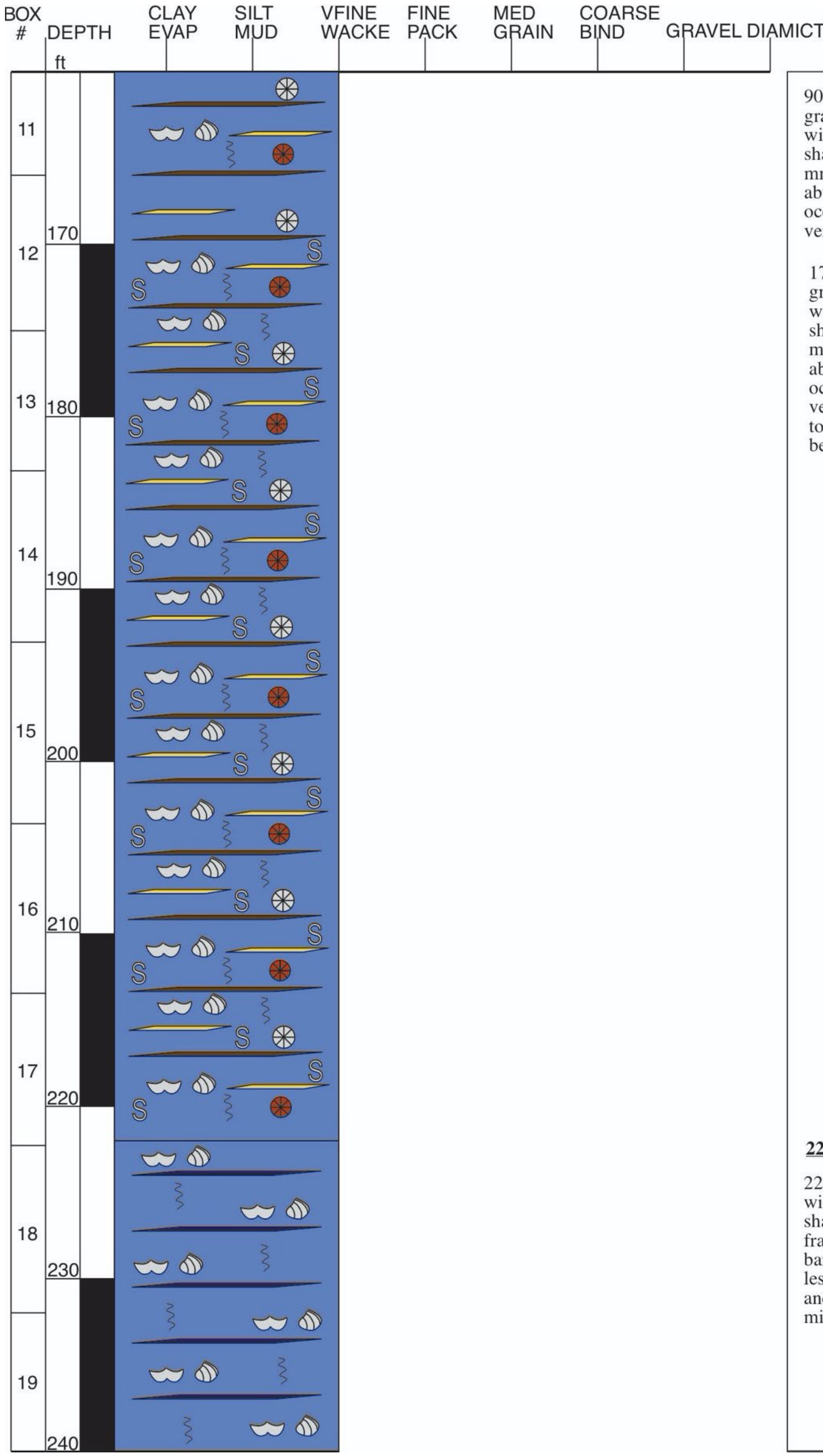
Figure A-12, Mobil continued



66-90 brown to gray silty dolomite wackestone with 1 mm brown and dark gray wispy shale partings, mm to cm scale vugs often with sulfide mineralization fillings, brachiopod and fossil fragments, occasional bioturbation

90-170 light brown fine to medium-grained sandy dolomite wackestone with 1 mm brown and dark gray wispy shale partings, mm to cm scale vugs, mm to cm scale sulfide mineralization, abundant brachiopods, fossil fragments, occasional bioturbation, and mm scale vertical burrows along shale partings

Figure A-12, Mobil continued



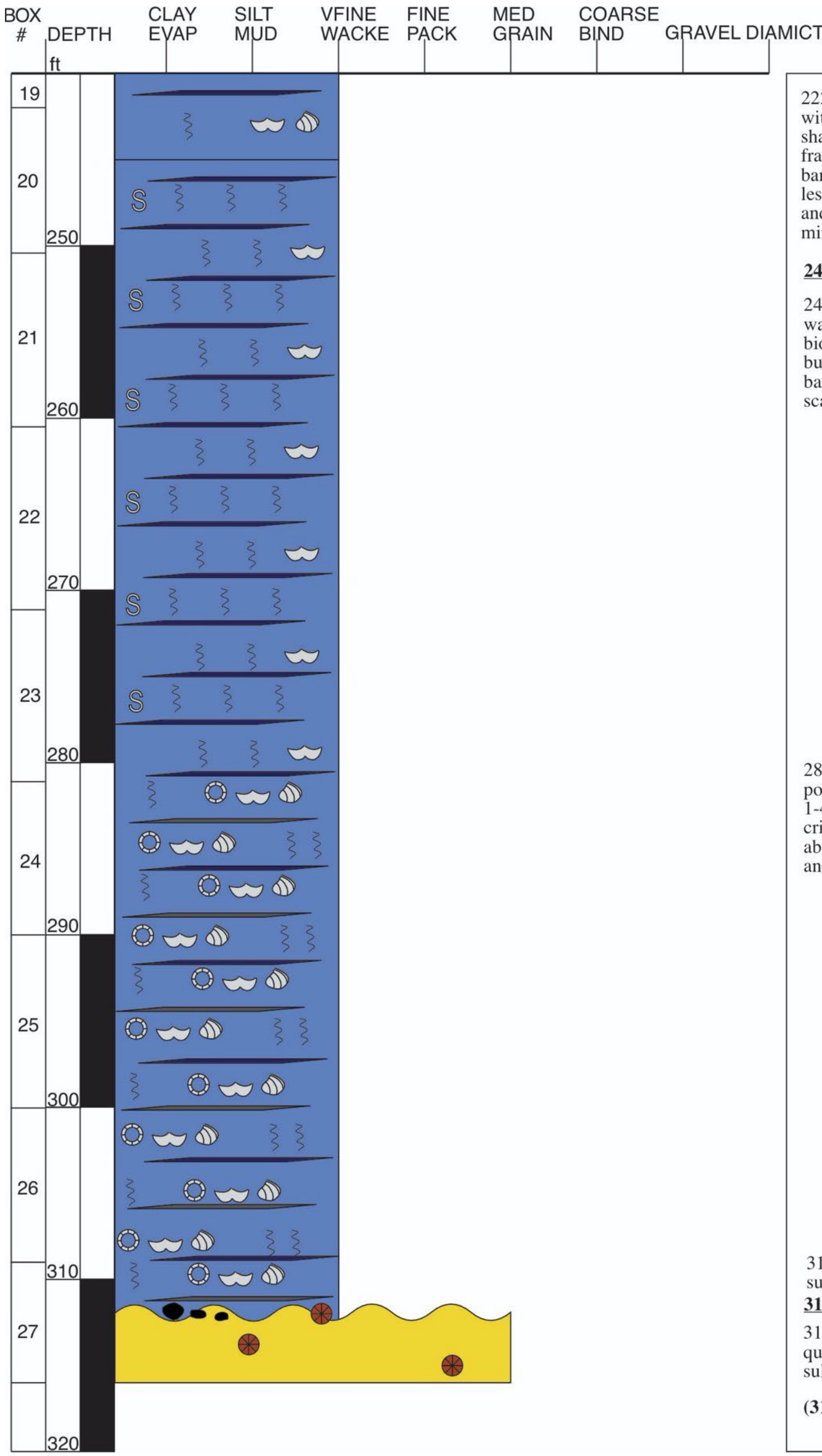
90-170 light brown fine to medium-grained sandy dolomite wackestone with 1 mm brown and dark gray wispy shale partings, mm to cm scale vugs, mm to cm scale sulfide mineralization, abundant brachiopods, fossil fragments, occasional bioturbation, and mm scale vertical burrows along shale partings

170-222 light brown fine to medium-grained sandy dolomite wackestone with 1 mm brown and dark gray wispy shale partings, mm to cm scale vugs, mm to cm scale sulfide mineralization, abundant brachiopods, fossil fragments, occasional bioturbation, and mm scale vertical burrows along shale partings, up to 1.5 inch silcrete nodules and bands become more common

222-245 ft Sinnipee Gp Decorah Fm

222-245' dark gray dolomite wackestone with 1-2 mm blue and dark gray wispy shale partings, brachiopod and fossil fragments concentrated in 0.2-2 inch bands, vertical and horizontal burrows, less common mm to cm scale burrows, and less frequent mm scale sulfide mineralization

Figure A-12, Mobil continued



222-245' dark gray dolomite wackestone with 1-2 mm blue and dark gray wispy shale partings, brachiopod and fossil fragments concentrated in 0.2-2 inch bands, vertical and horizontal burrows, less common mm to cm scale burrows, and less frequent mm scale sulfide mineralization

245-312 ft Sinnipee Gp Platteville Fm

245-280' light brown fossil-poor dolomite wackestone with abundant blue bioturbation, vertical and horizontal burrows, 1 inch silcrete nodules and bands, occasional sandy lenses with mm scale vugs and brachiopods

280-312' gray dolomite wackestone with polished outer texture, dark blue to gray 1-4 mm wispy shale partings, frequent crinoid, brachiopod, and fossil fragments, abundant blue bioturbation and vertical and horizontal burrows

312-312.2' abundant burrows, rip ups and sulfide mineralization at contact

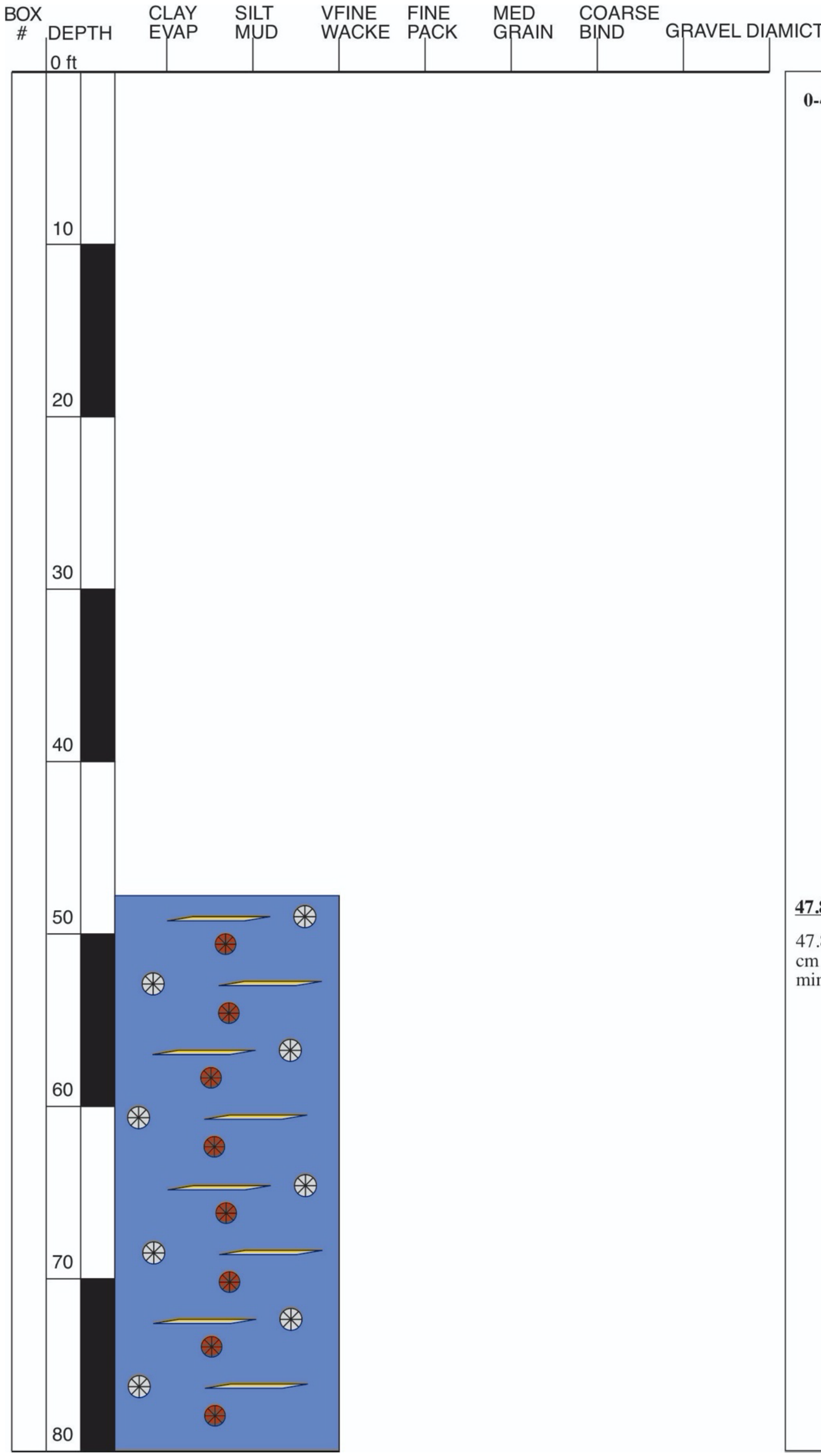
312-317 ft Saint Peter Fm Tonti Mbr

312-317' tan fine to medium massive quartz sand with dispersed mm scale sulfide mineralization

(317 ft end core)

Figure A-13, Neda, Dodge County

Elevation: 1138’ Total Depth: 393.5’

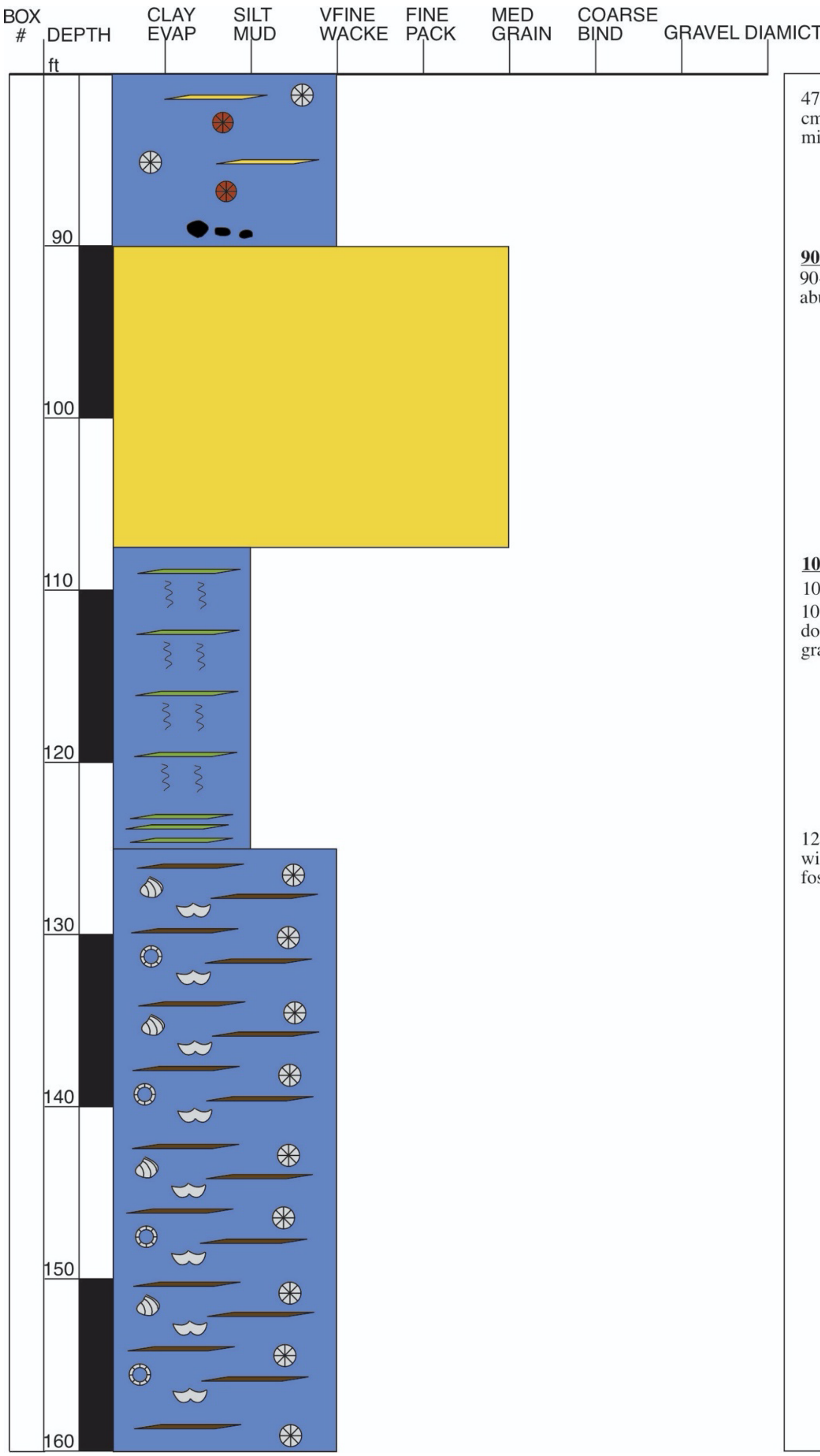


0-47.8 ft core loss

47.8-90 ft Silurian

47.8-90’ light brown sandy dolomite with cm scale vugs, iron staining and sulfide mineralization

Figure A-13, Neda continued



47.8-90' light brown sandy dolomite with cm scale vugs, iron staining and sulfide mineralization

<u>90-107.5 Neda Formation</u>
90-107.5' dark maroon medium sand with abudant iron, some burrow fills

<u>107.5-365 Maquoketa Fm</u>
107.5-198.5 Brainard Mbr
107.5-125 dark green to gray mottled dolomite with green limey mudstone gradational contact at base

125-181 dark gray dolomite wackestone with 1-2 mm black shale partings with fossils, comon 1-6 in bands of grainstone

Figure A-13, Neda continued

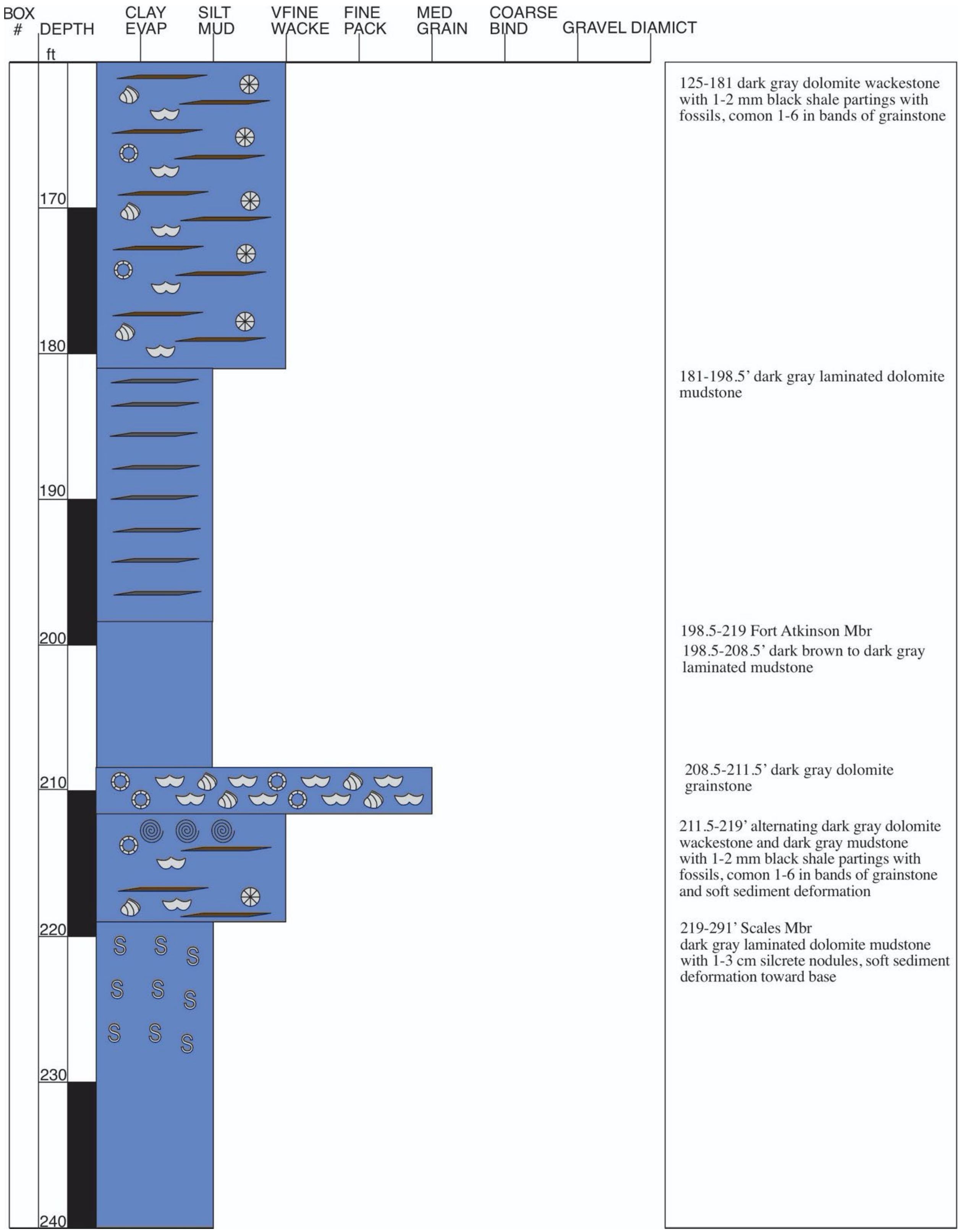


Figure A-13, Neda continued

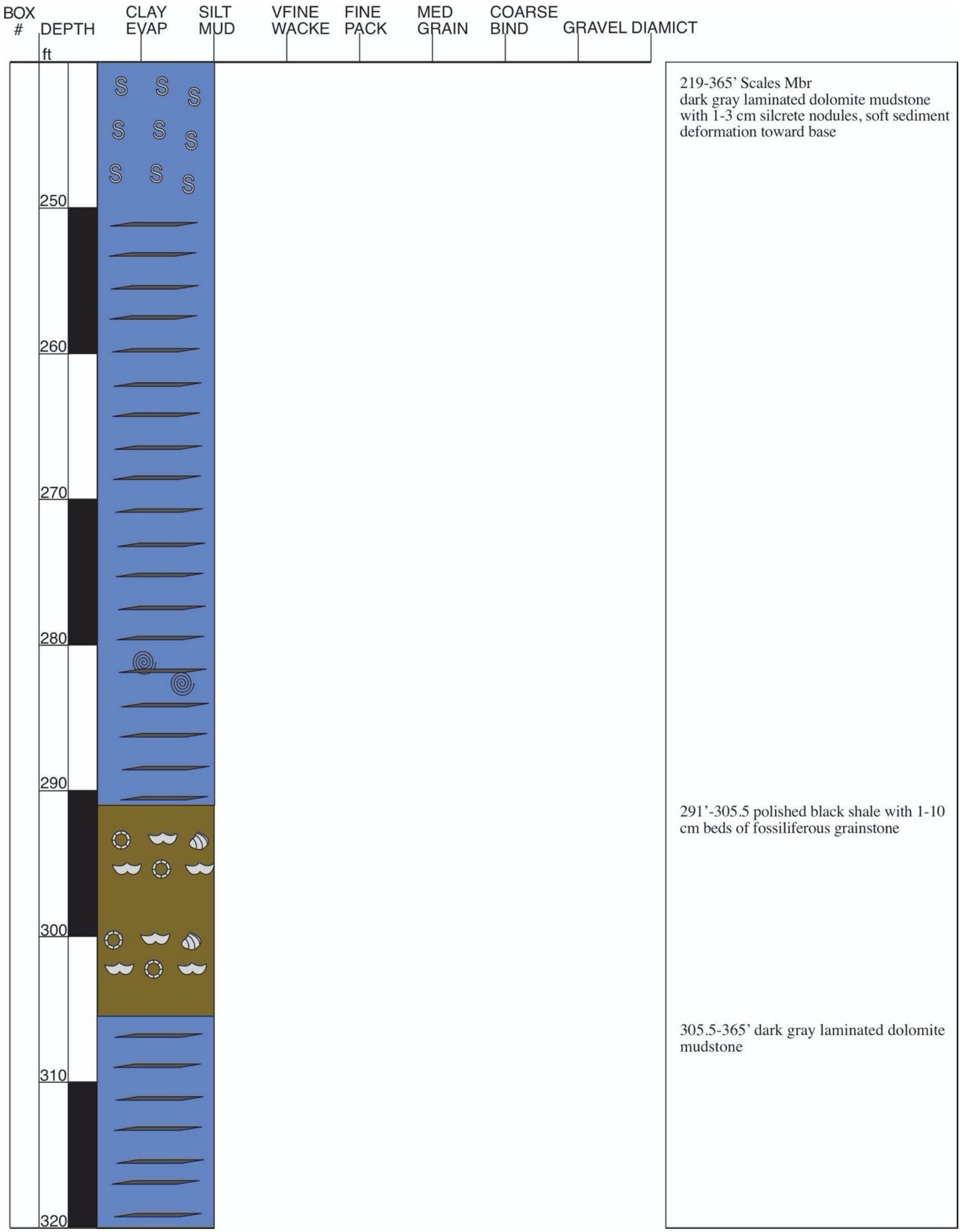
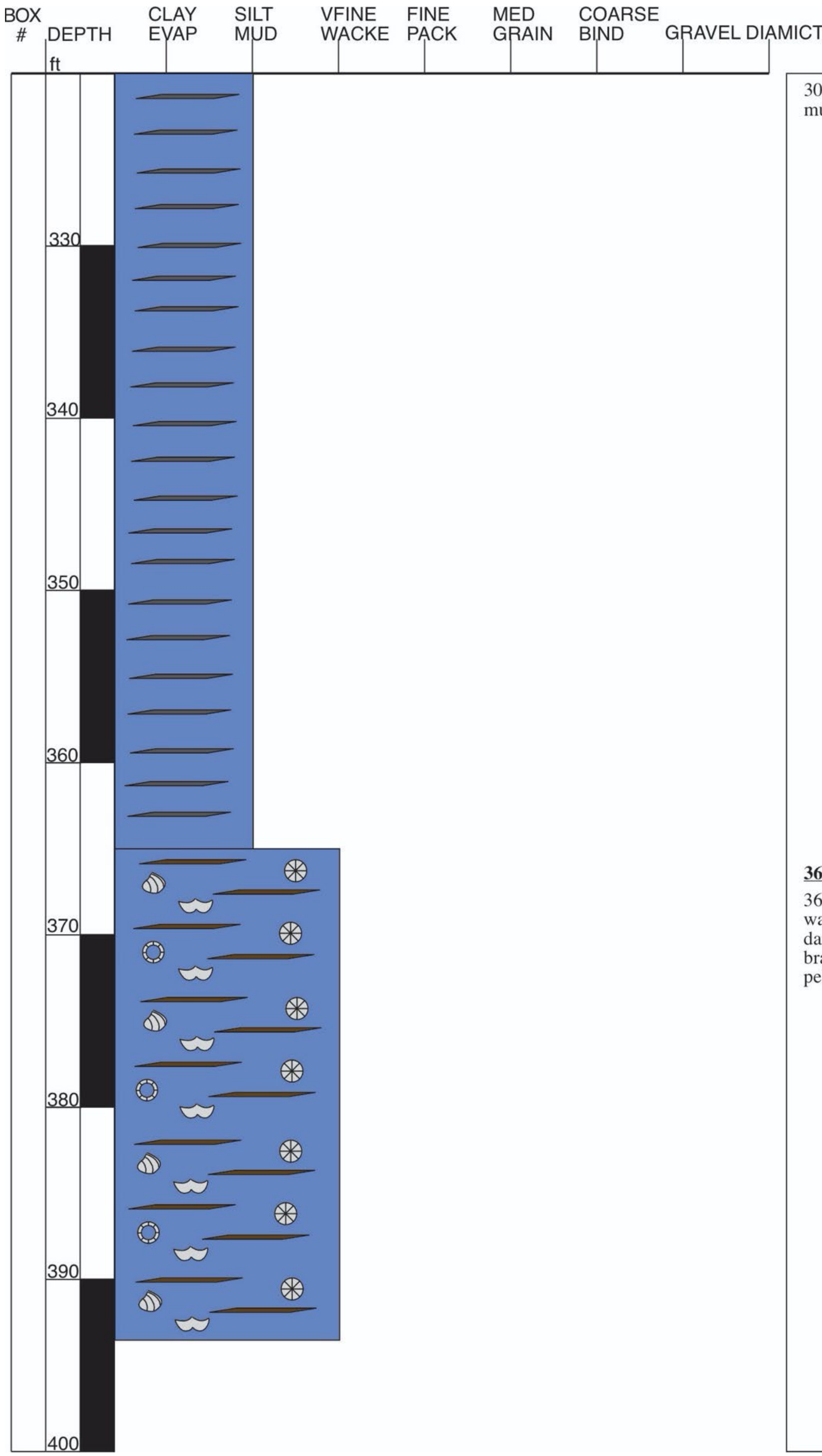


Figure A-13, Neda continued



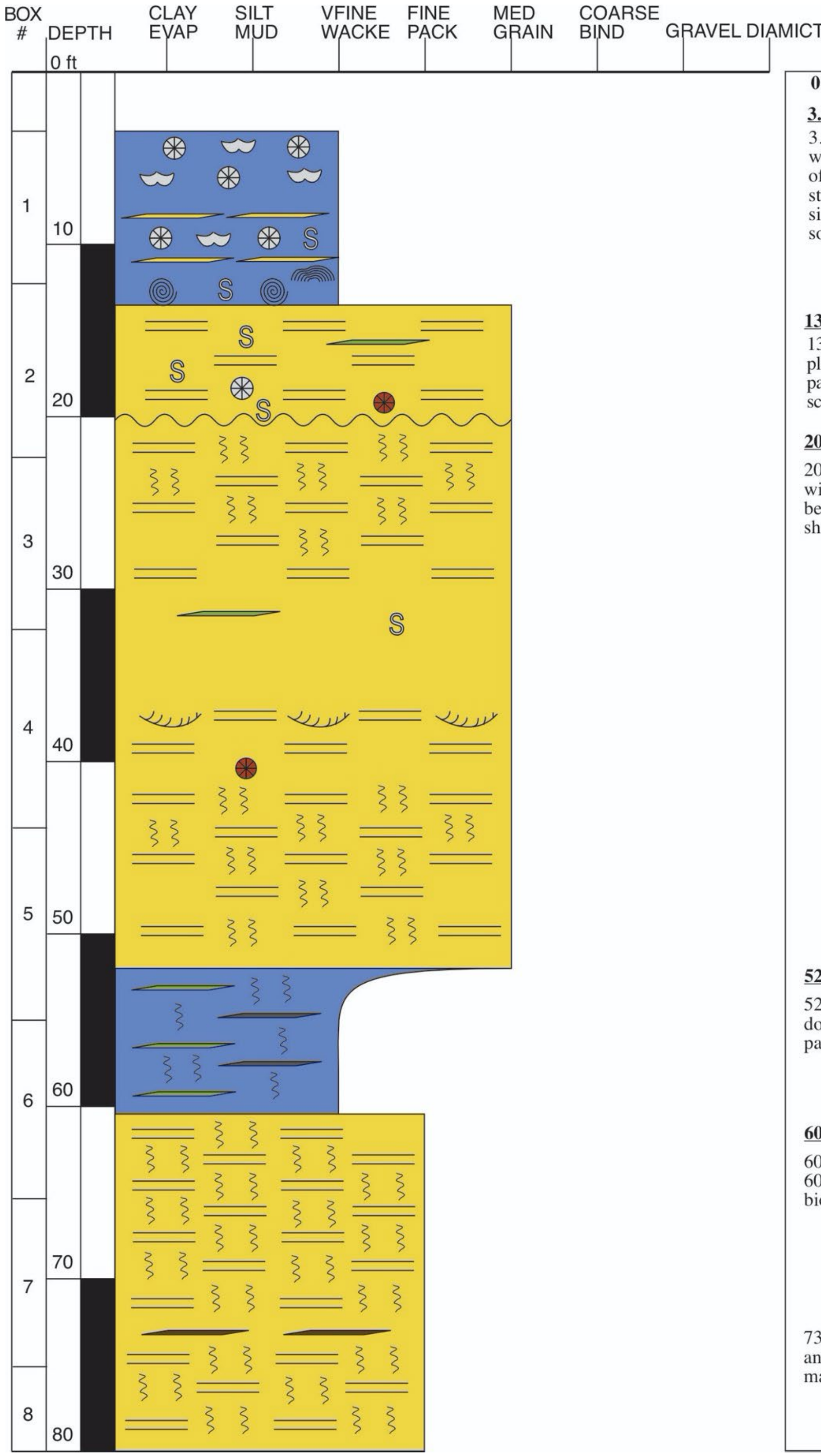
305.5-365' dark gray laminated dolomite mudstone

<u>365- 393.5 ft Sinnipee Group</u>

365-393.5' dark brown dolomite wackestone with mottled texture, 1-2 mm dark gray wispy shale partings, brachiopods, crinoids, bivalves and peloids common, mm to cm scale vugs

Figure A-14, Rio 2, Columbia County

Elevation: 935’ Total Depth: 97.8’



0-3.5 ft core loss

3.5- 13.5 ft Prairie Du Cien Gp Shakopee

3.5-13.5’ sandy tan and gray dolomite wackstone with mm to cm scale vugs often in the shape of brachiopods, stromatalites, mm to cm scale vugs and silcrete nodules and filling pore space, soft sediment deformation at base

13.5-20.1 ft Prairie Du Chien Oneota

13.5-20.1 tan and white medium sand with planar cross beds, few light green shale partings, some sulfide mineralization, mm scale vugs, and some silcrete mineralization

20.1-52 ft Tremealeau Gp Jordan Fm

20.1-52’ yellow and white medium sand with massive, planar,, and trough cross beds, bioturbation, occasional light green shale partings, and silcrete nodules

52-60.5 ft Tremealeau Gp St Lawrence

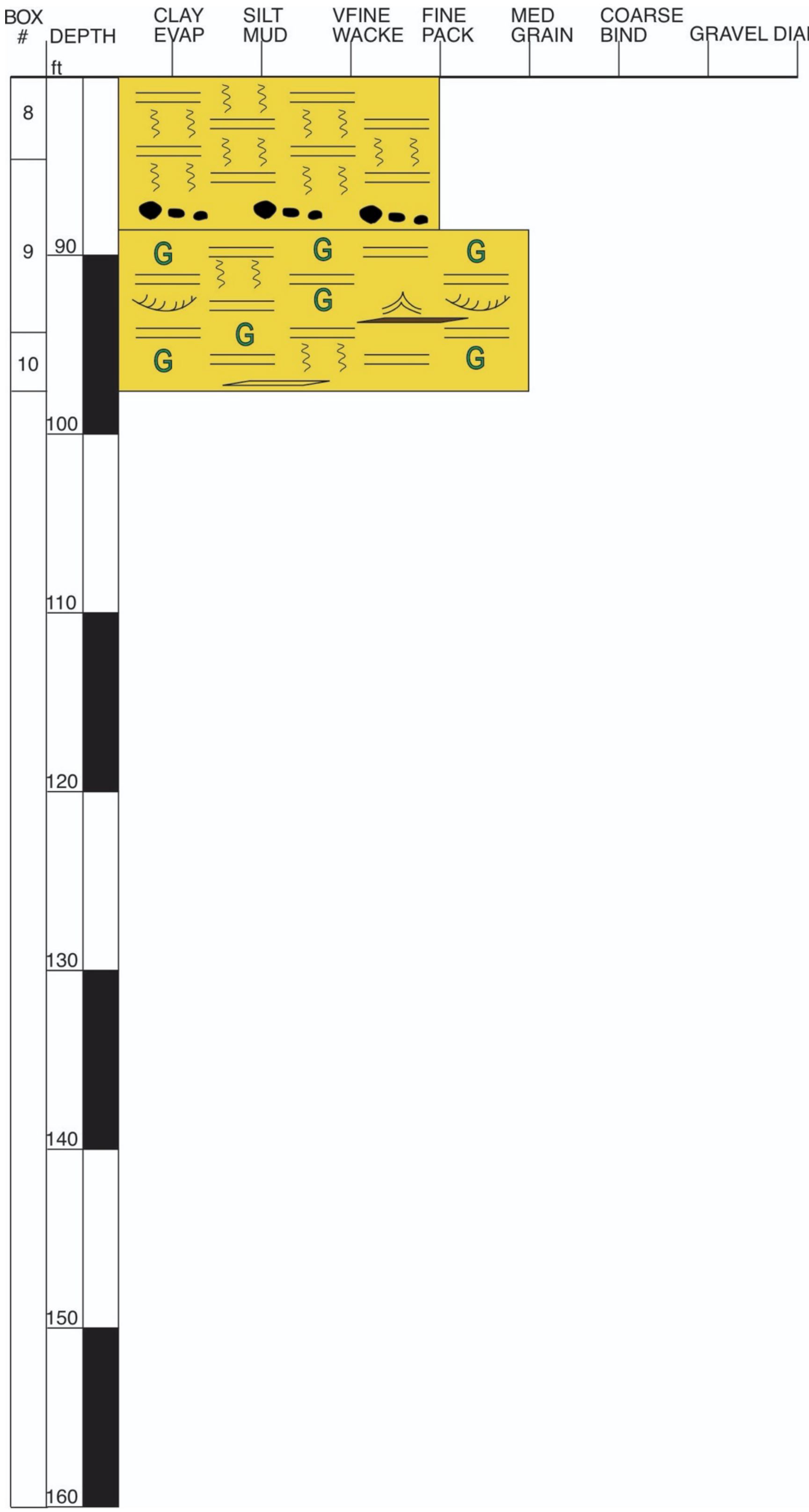
52-60.5’yellow to tan bioturbated sandy dolomite with light green to tan shale partings

60.5-97.8 Tunnel City Gp

60.5-88.5’ Lone Rock Fm Tomah Mbr
60.5-88.5’maroon and tan fine heavily bioturbed “wormstone” sands

73.1-74’ maroon and tan very fine sand and brown mud thinly bedded, possible marker bed

Figure A-14, Rio 2 continued



60.5-88.5’maroon and tan fine heavily bioturbed “wormstone” sands

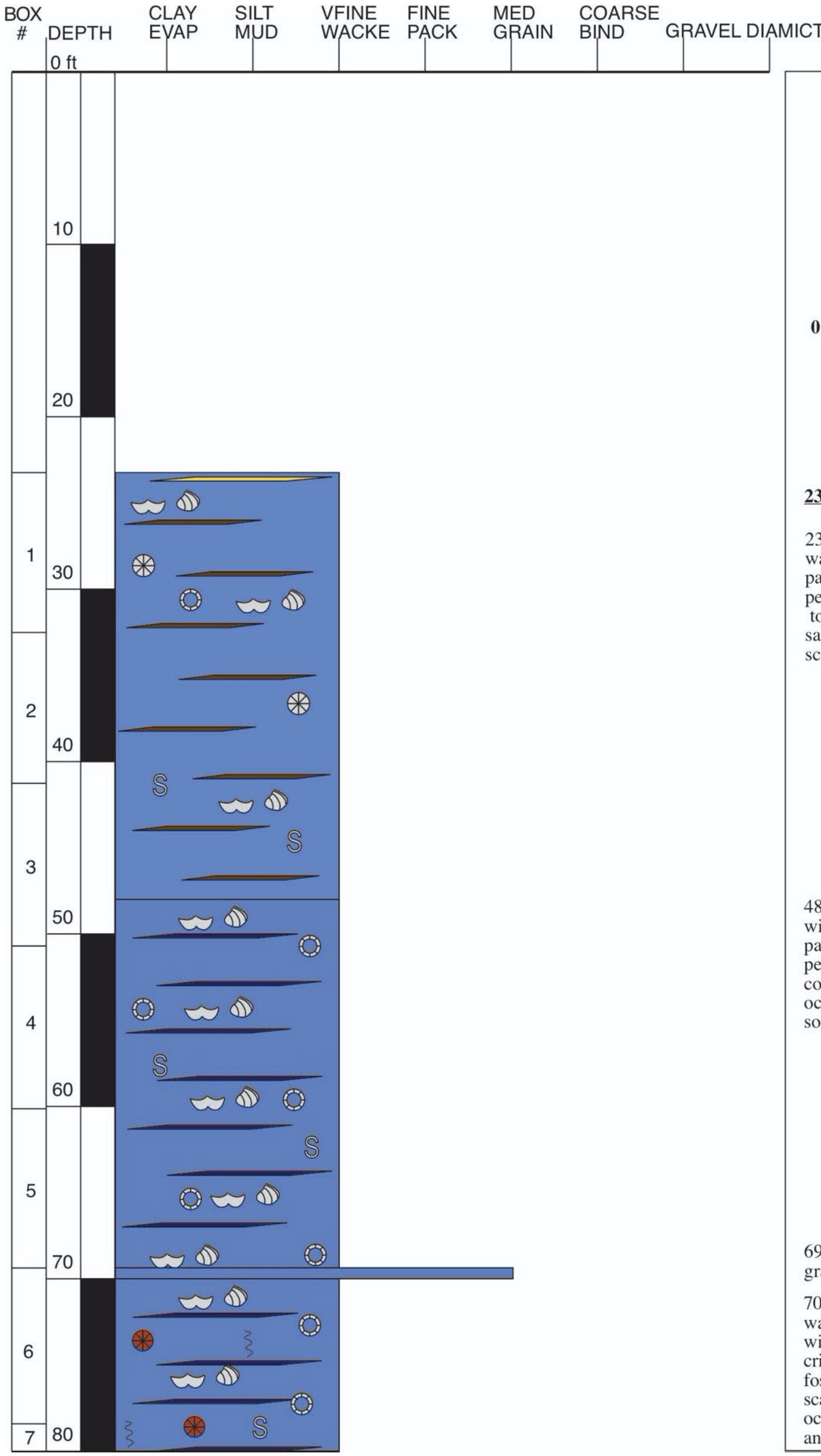
87.5-87.8’ flat pebble conglomerate with 3 mm to 2 cm sandstone clasts

88.5-97.8’ Lone Rock Fm Birkmose Mbr
88.5-97.8’ green and tan medium quartz and glauconite sands with planar and trough crossbeds with infrequent bioturbation, 1-2 mm maroon mud partings and fine tan sand partings with few flame structures

(97.8 ft end core)

Figure A-15, Ripon, Fond du Lac County

Elevation: 1029’ Total Depth: 231.1’



0-23.8 ft core loss

<u>**23.8-120 ft Sinnipee Gp Undivided**</u>

23.8-48’ light brown silty dolomite wackestone with dark gray wispy shale partings, brachiopods, crinoids, bivalves, peloids and other fossil fragments, mm to cm scale vugs, few medium grained sand lenses, and occasional mm to cm scale silcrete nodules and bands

48-69.3’ dark gray dolomite wackestone with dark gray to blue wispy shale partings, brachiopods, crinoids, bivalves, peloids and other fossil fragments most common in shale beds, few vugs and occasional mm scale silcrete nodules, some vertical and horizontal burrows

69.3-70’ligth gray fossil fragment grainstone

70-120’ chocolate brown dolomite wackestone with frequennt dark gray wispy shale partings, brachiopods, crinoids, bivalvues, peloids and other fossil fragments, few vugs, mm to cm scale sulfide mineralization, and occasional mm to cm scale silcrete nodules, and vertical and horizontal burrows

Figure A-15, Ripon continued

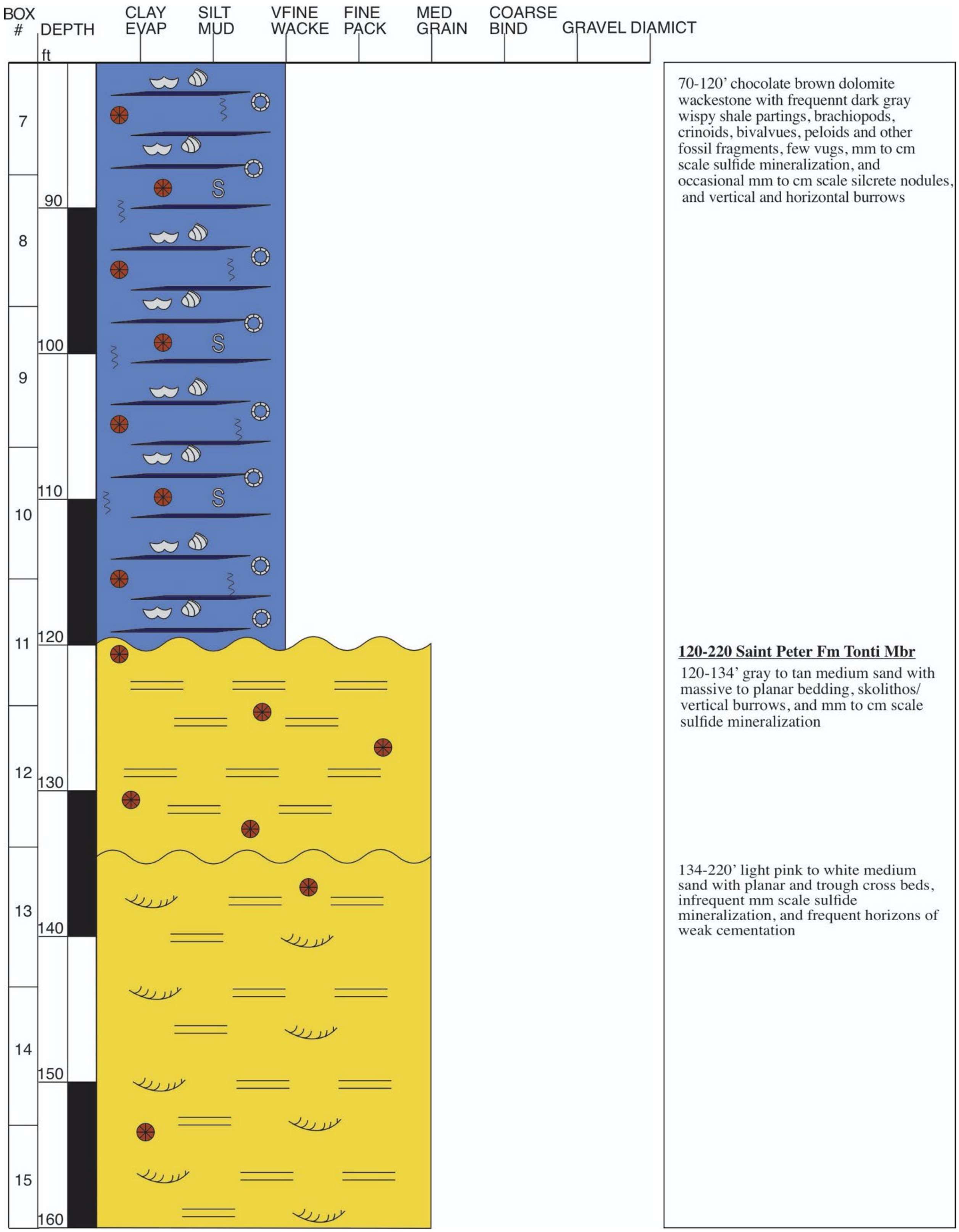
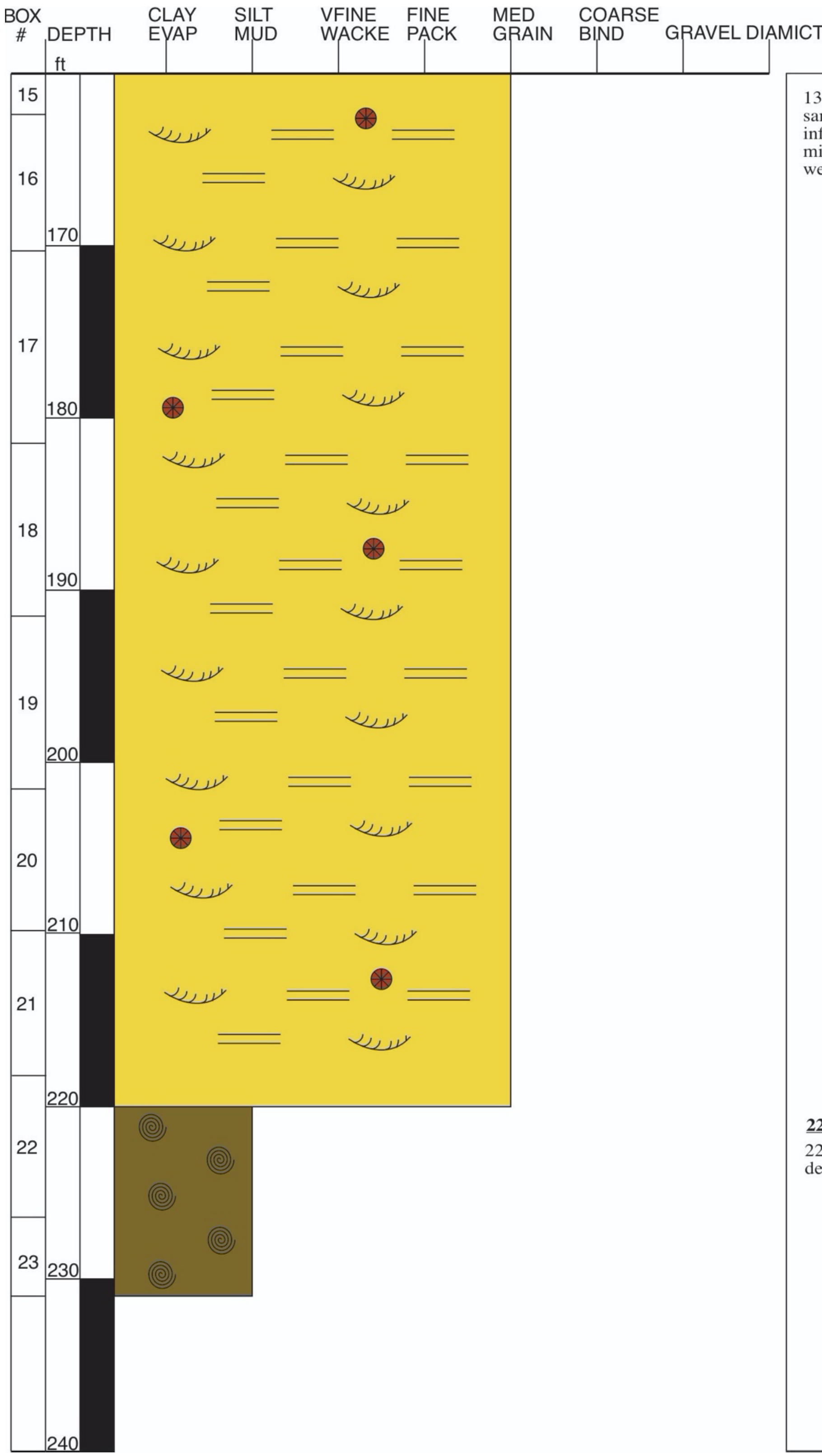


Figure A-15, Ripon continued



134-220' light pink to white medium sand with planar and trough cross beds, infrequent mm scale sulfide mineralization, and frequent horizons of weak cementation

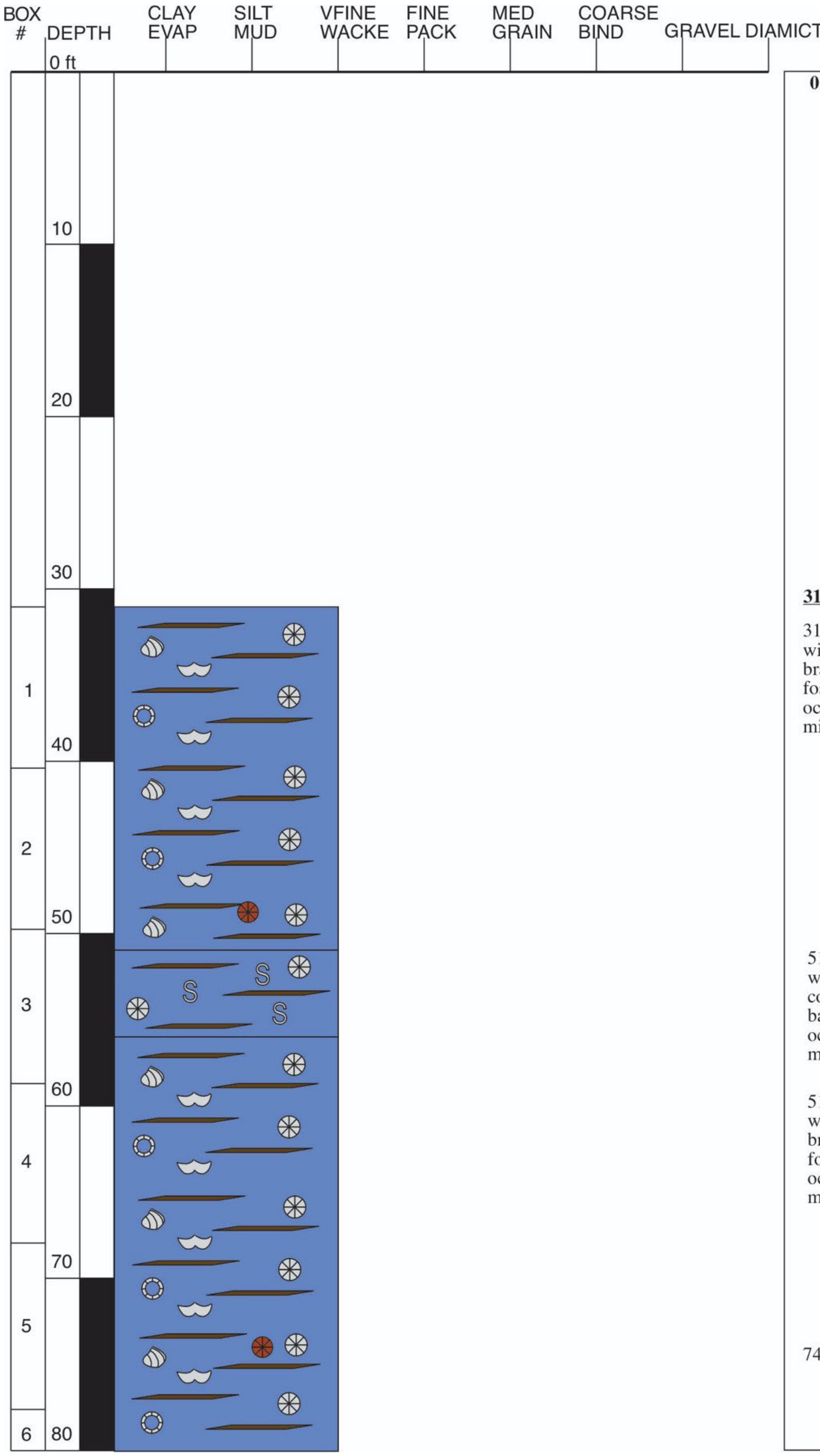
220-231 ft Saint Peter Fm Readstown

220-231 dark brown and light green deformed mud

Figure A-16, Rosendale, Fond du Lac County

Elevation: 888'

Total Depth: 343.3'



0-31.1 ft core loss

31.1-132.2 ft Sinnipee Gp Platteville Fm

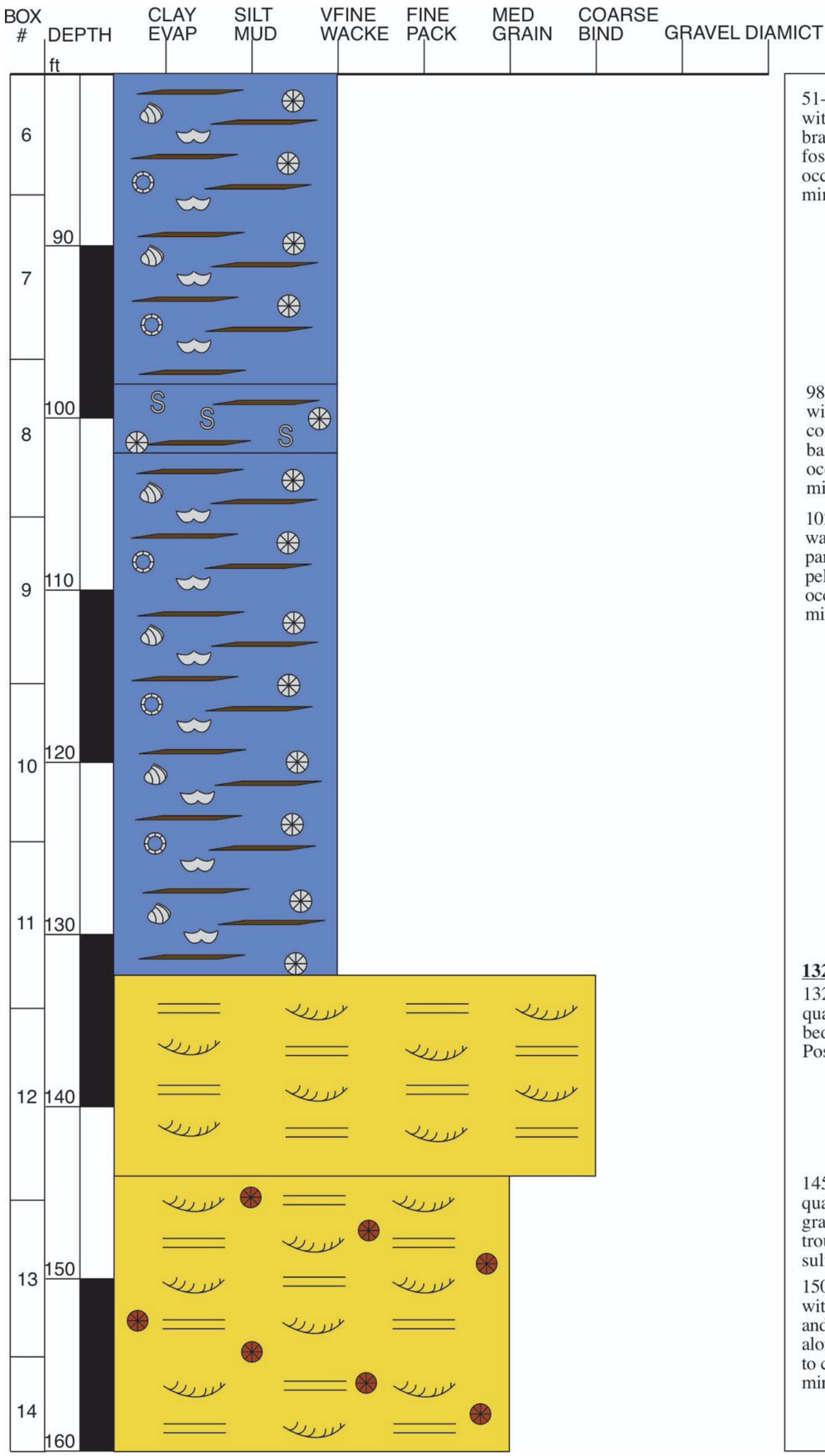
31.1-51' dark brown dolomite wackestone with 1-2 mm black shale partings, brachiopod, bivalve, crinoid and peloid fossils, mm to cm scale vugs, and occasional mm to cm scale sulfide mineralization

51-56' dark brown dolomite wackestone with 1-2 mm black shale partings, common 1-4 cm silcrete nodules and bands, mm to cm scale vugs, and occasional mm to cm scale sulfide mineralization

51-98' dark brown dolomite wackestone with 1-2 mm black shale partings, brachiopod, bivalve, crinoid and peloid fossils, mm to cm scale vugs, and occasional mm to cm scale sulfide mineralization

74.8-75' possible hardground

Figure A-16, Rosendale continued



51-98' dark brown dolomite wackestone with 1-2 mm black shale partings, brachiopod, bivalve, crinoid and peloid fossils, mm to cm scale vugs, and occasional mm to cm scale sulfide mineralization

98-102' dark brown dolomite wackestone with 1-2 mm black shale partings, common 1-4 cm silcrete nodules and bands, mm to cm scale vugs, and occasional mm to cm scale sulfide mineralization

102-132.2' dark brown dolomite wackestone with 1-2 mm black shale partings, brachiopod, bivalve, crinoid and peloid fossils, mm to cm scale vugs, and occasional mm to cm scale sulfide mineralization

132.2-234 ft Saint Peter Fm Tonti Mbr

132.2-145.3' gray, white and tan coarse quartz sand with some black iron stained beds, planar and trough cross beds. Possible aeolian transport

145.3-150' gray, white and tan medium quartz sand with some black sulfide grains, black iron stained beds, planar and trough cross beds, and mm to cm scale sulfide mineralization

150-176' orange medium quartz sand with some black sulfide grains, planar and trough cross beds, white mineralization along bedding planes and pore space, mm to cm scale sulfide nodules, and some minor normal faulting

Figure A-16, Rosendale continued

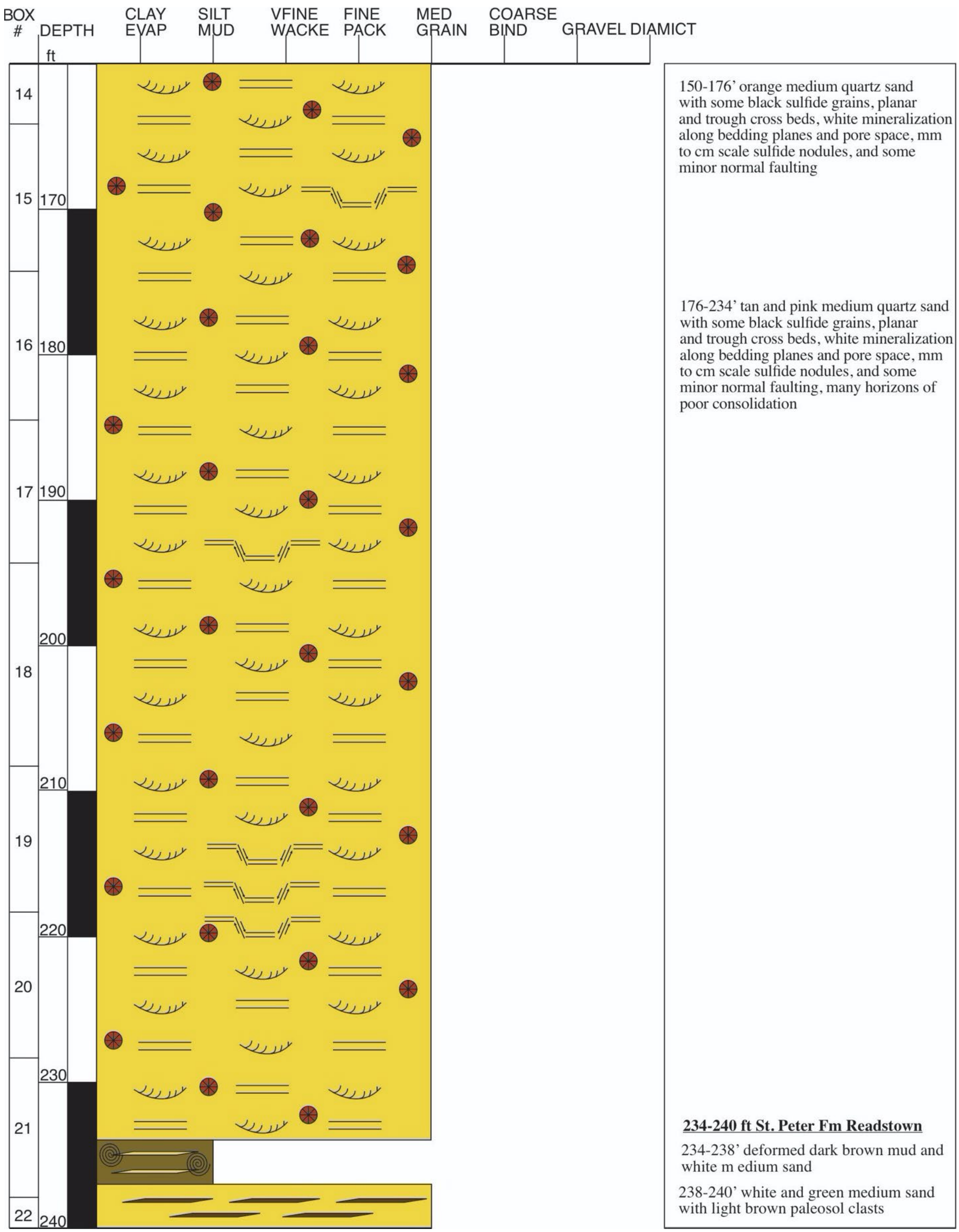
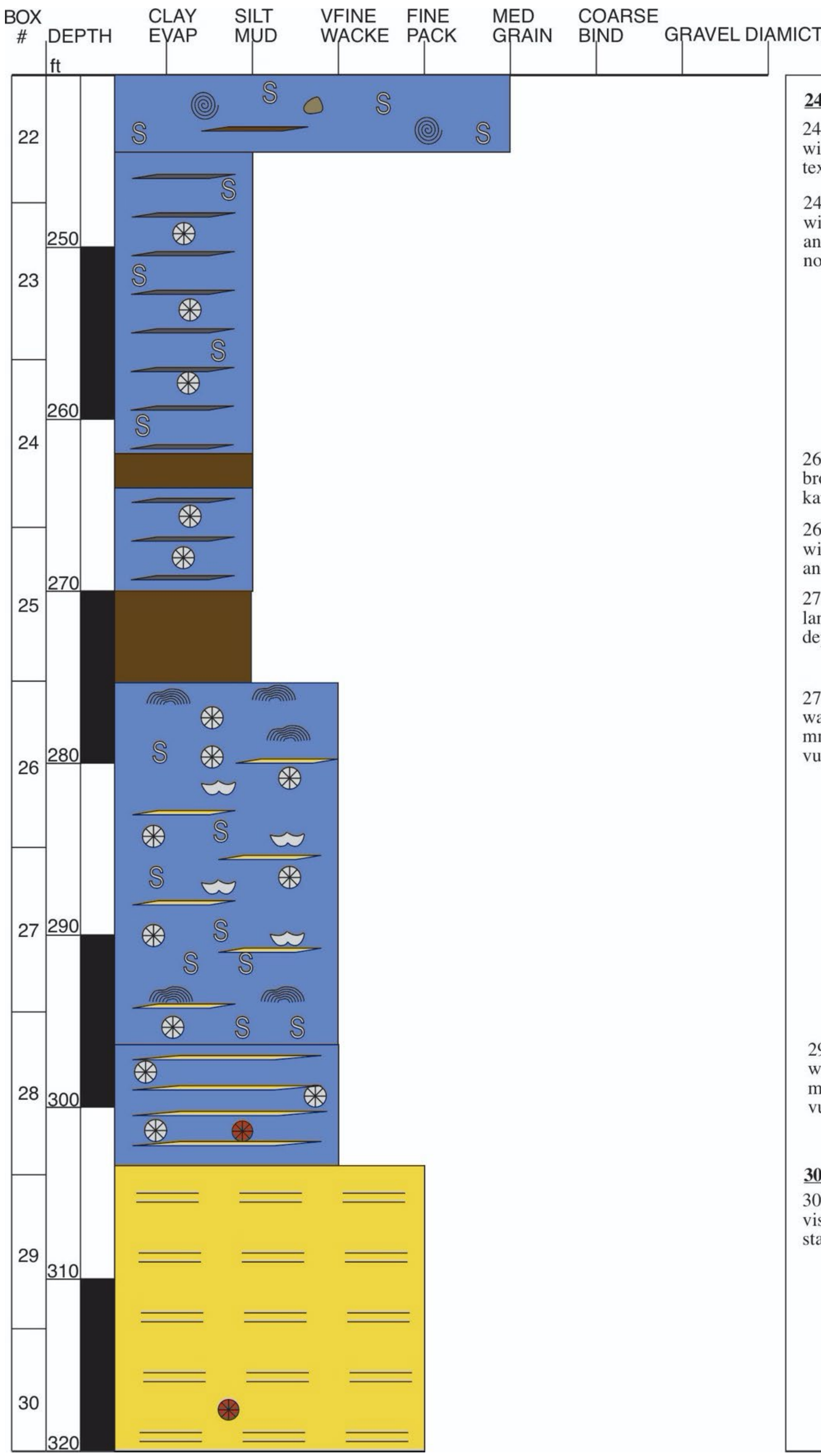


Figure A-16, Rosendale continued



240-303.5 ft Prairie Du Chien Gp

240-244.5’ gray carbonate conglomerate with mottled, deformed, karst collapse texture and cm scale silcrete nodules

244.5-262’ gray silty carbonate mudstone with 1-2 mm wispy dark shale partings, and mm to cm scale vugs and silcrete nodules

262-264’ dark brown mudstone with light brown paleosol clast at top, possible karstic paleosol

264-270’ gray silty carbonate mudstone with 1-2 mm wispy dark shale partings, and mm to cm scale silcrete nodules

270-275.2’ light and dark brown laminated mudstone, possible tidal flat deposit

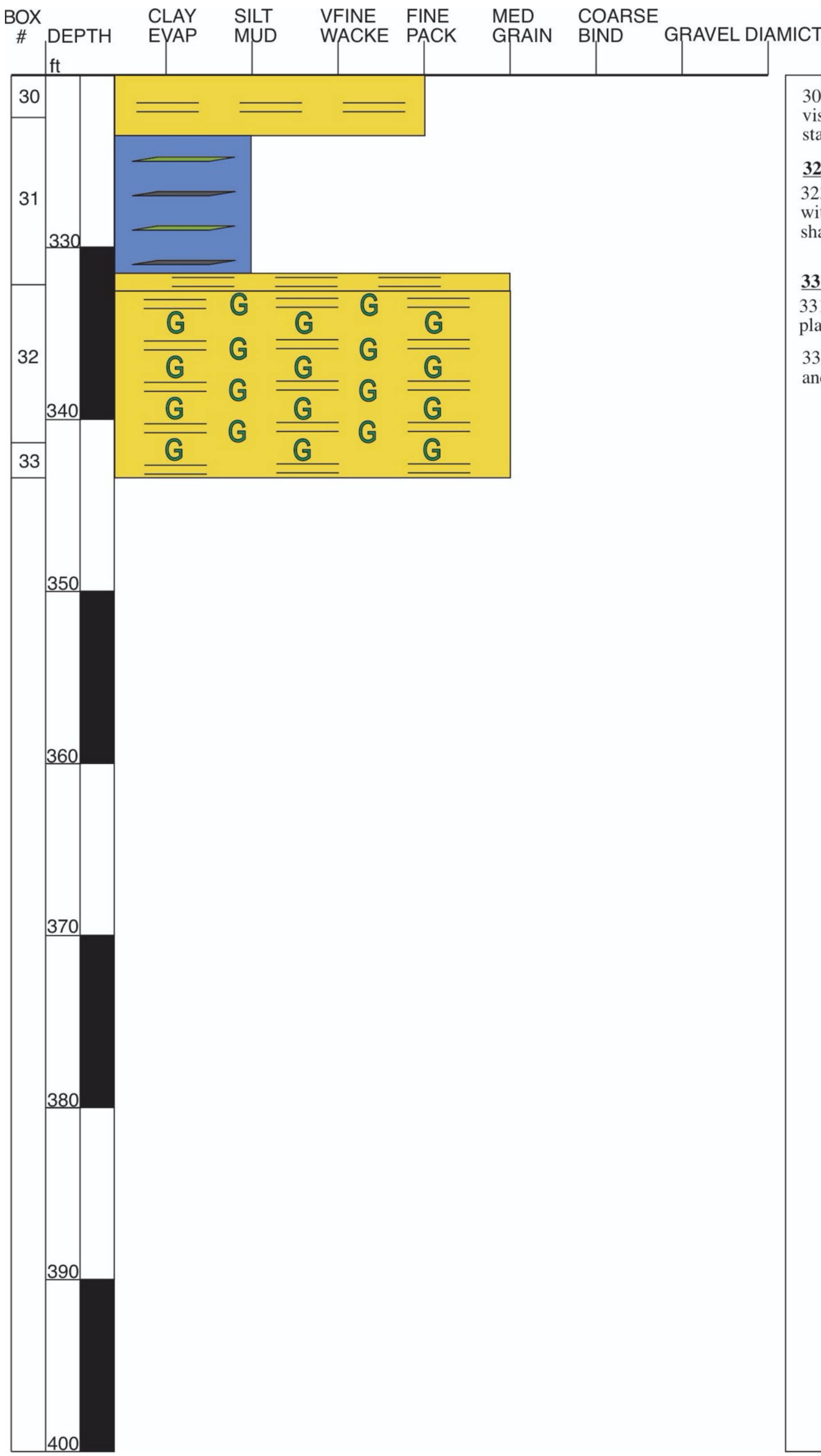
275.2-296.4’ light gray sandy dolomite wackestone with stromatalites, oolites, mm to cm vugs and silcrete nodules, some vugs in shape of brachiopods

296.4-303.5’very sandy dolomite wackestone with 1-10 cm white to tan medium sand lenses, and mm to cm scale vugs and sulfide mineralization

303.5-323.5 Trempealeau Gp Jordan Fm

303.5-323.5 tan fine sand with some visible planar cross beds, minor iron staining and little sulfide mineralization

Figure A-16, Rosendale continued



303.5-323.5 tan fine sand with some visible planar cross beds, minor iron staining and little sulfide mineralization

323.5-331.5 Trempealeau St. Lawrence

323.5-331.5 tan very sandy silty dolomite with 1 mm light green and gray wispy shale partings

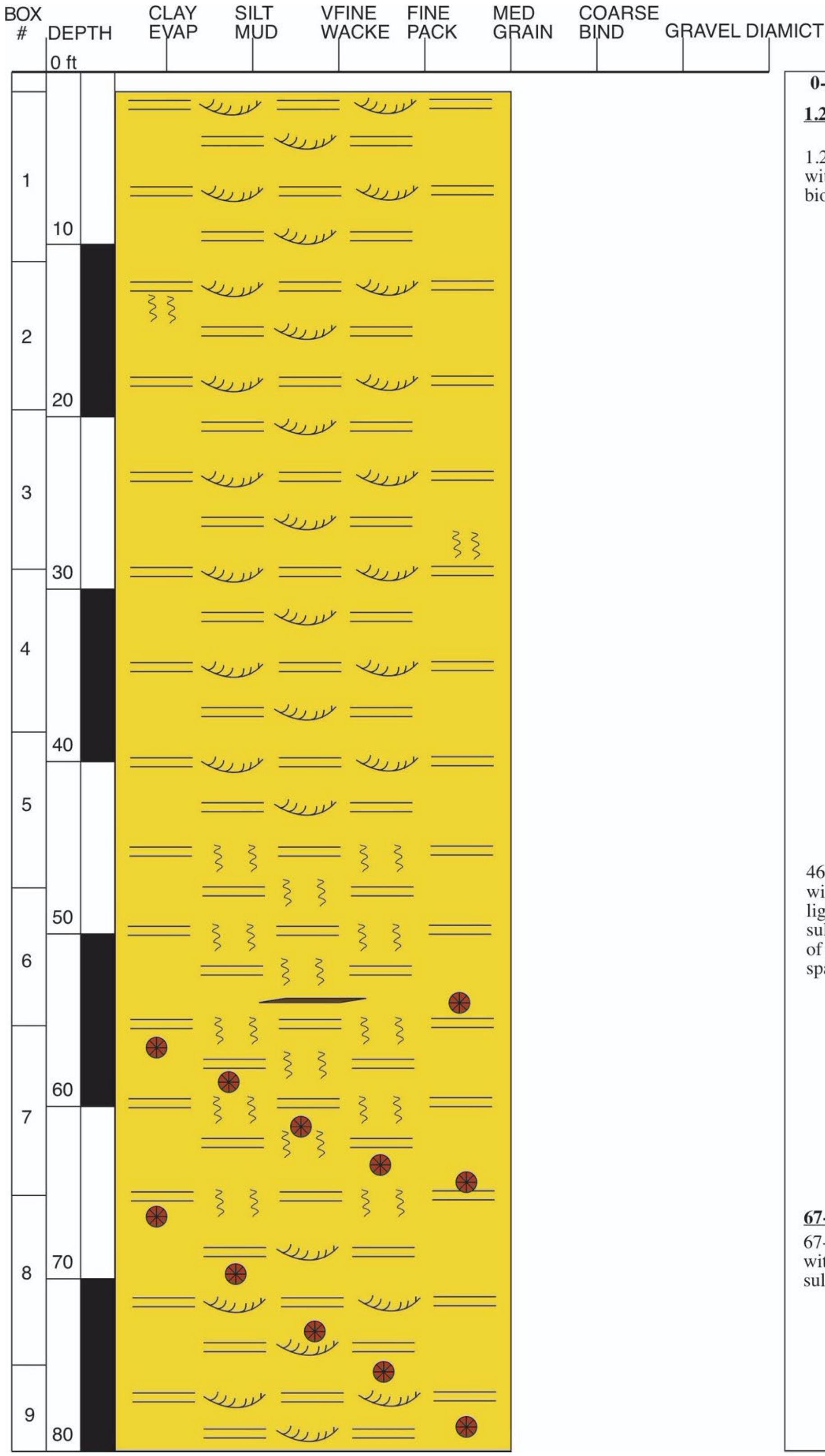
331.5-343.3 Tunnel City Gp

331.5-332.5' tan medium quartz sand with planar cross beds and some bioturbation

332.5-343.3' green medium glauconite and quartz sand with planar cross beds

Figure A-17, Salna, Columbia County

Elevation: 913’ Total Depth: 298’



0-1.2 ft core loss

<u>1.2-67 ft Tunnel City Gp Mazomanie</u>

1.2-46’ tan and maroon medium sand with planar and trough cross beds, some bioturbation

46-67’ maroon medium sand with planar cross beds, bioturbation, light brown shale partings, abundant sulfide mineralization, and accumulation of yellow/white mineralization in pore space and along bedding planes

<u>67-166 ft Elk Mound Gp Wonewoc Fm</u>

67-91.5’ maroon medium sand with planar and trough cross beds and sulfide mineralization

Figure A-17, Salna continued

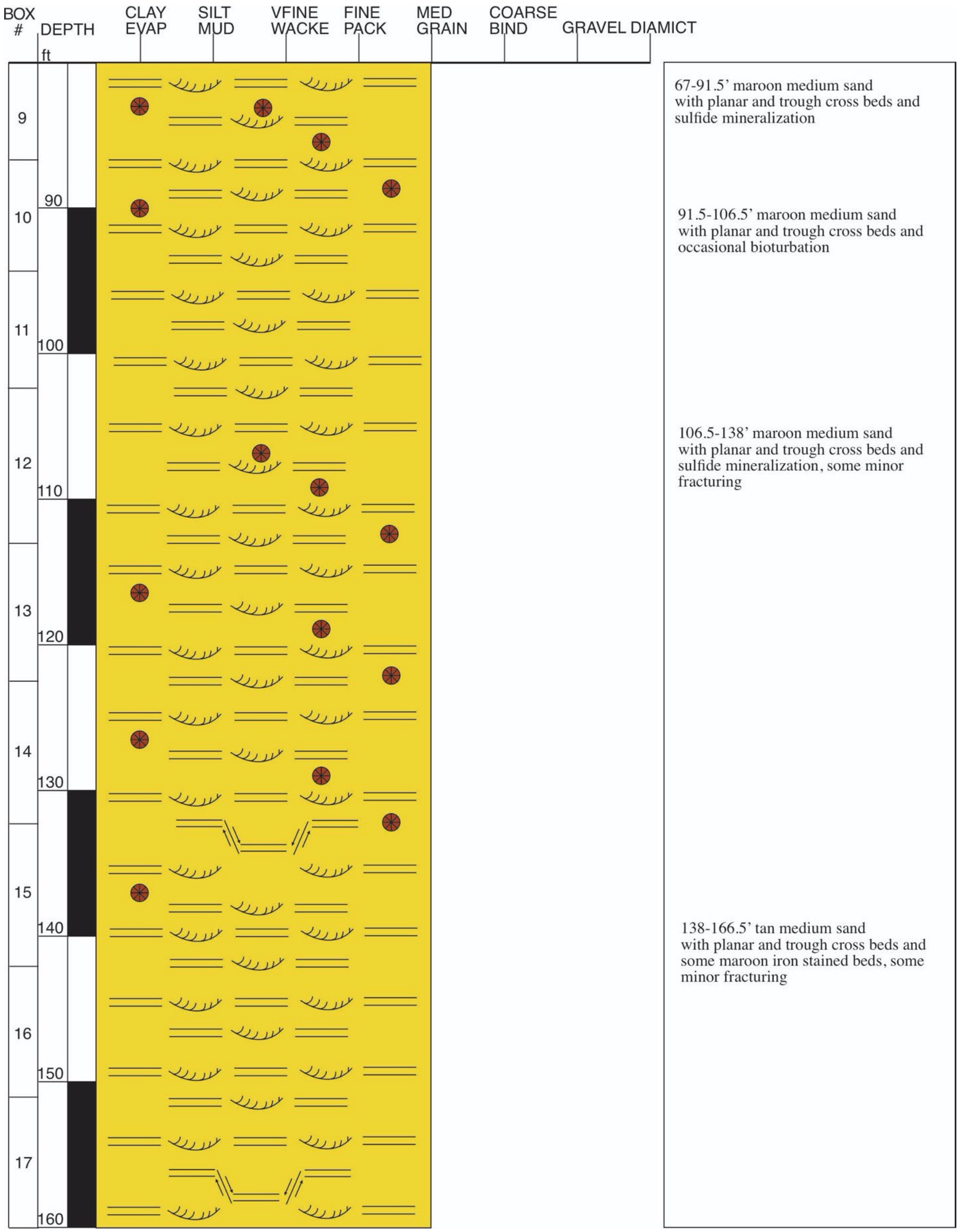
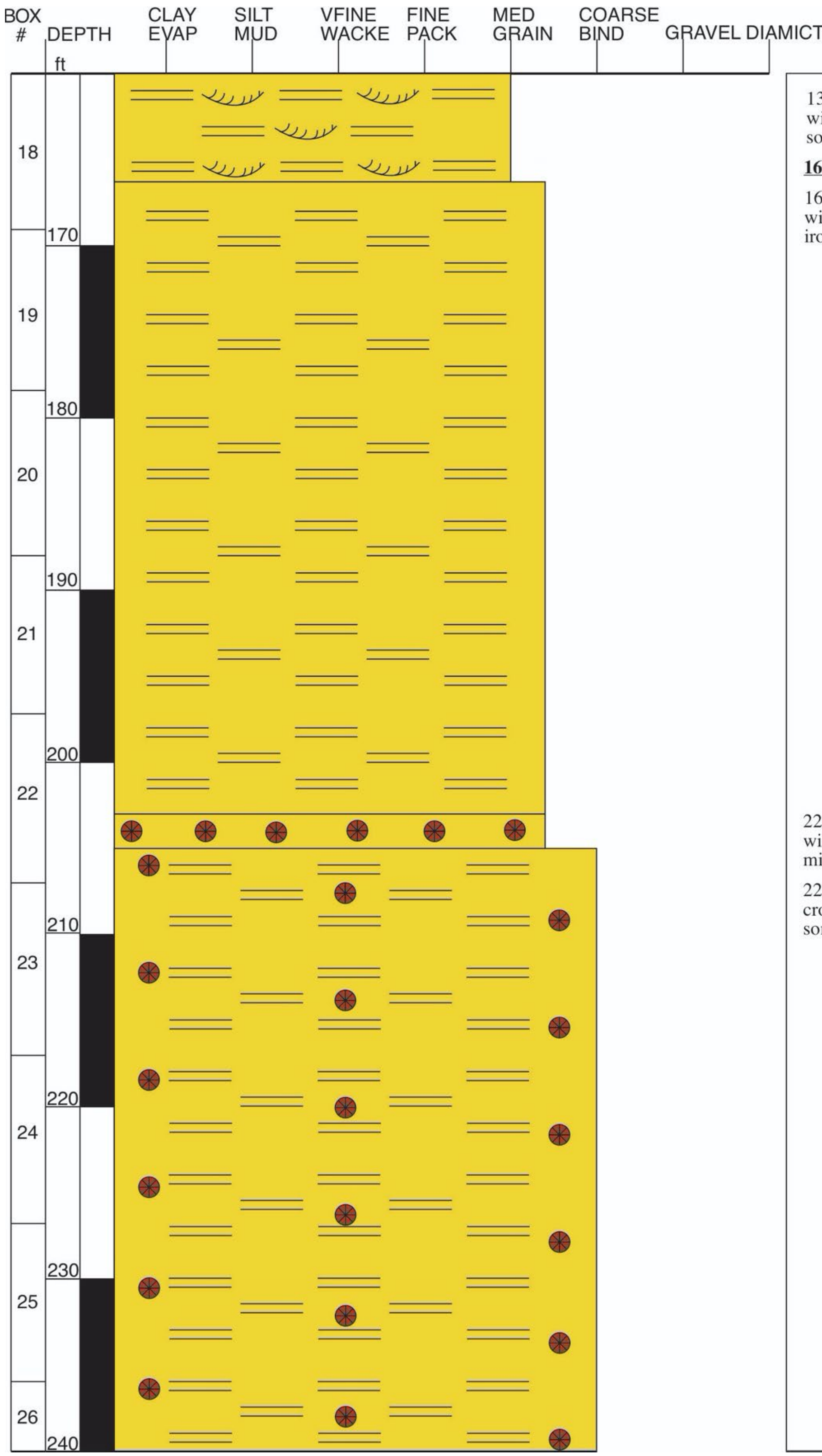


Figure A-17, Salna continued



138-166.5' tan medium sand with planar and trough cross beds and some maroon iron stained beds

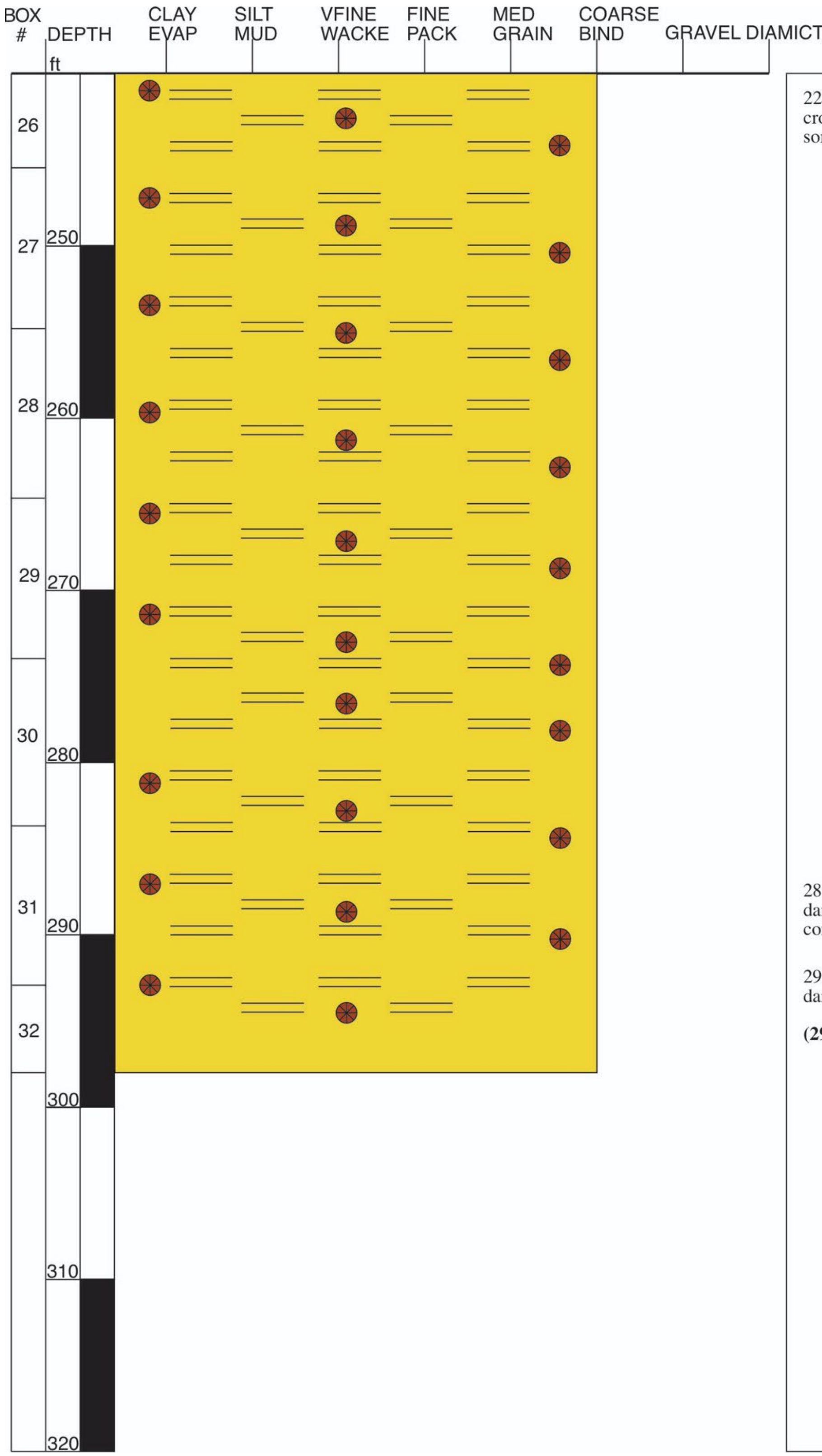
166-298 ft Elk Mound Gp Mt Simon Fm

166.5-223' tan medium and coarse sand with planar cross beds and some orange iron stained beds

223-225' tan medium and coarse sand with abundant iron staining and sulfide mineralization

225-288' tan coarse sand with planar cross beds, dark brown sulfide grains, and some orange iron stained beds

Figure A-17, Salna continued



225-288' tan coarse sand with planar cross beds, dark brown sulfide grains, and some orange iron stained beds

288-295.5' tan coarse quartz sand with dark brown sulfide grains and very poor consolidation

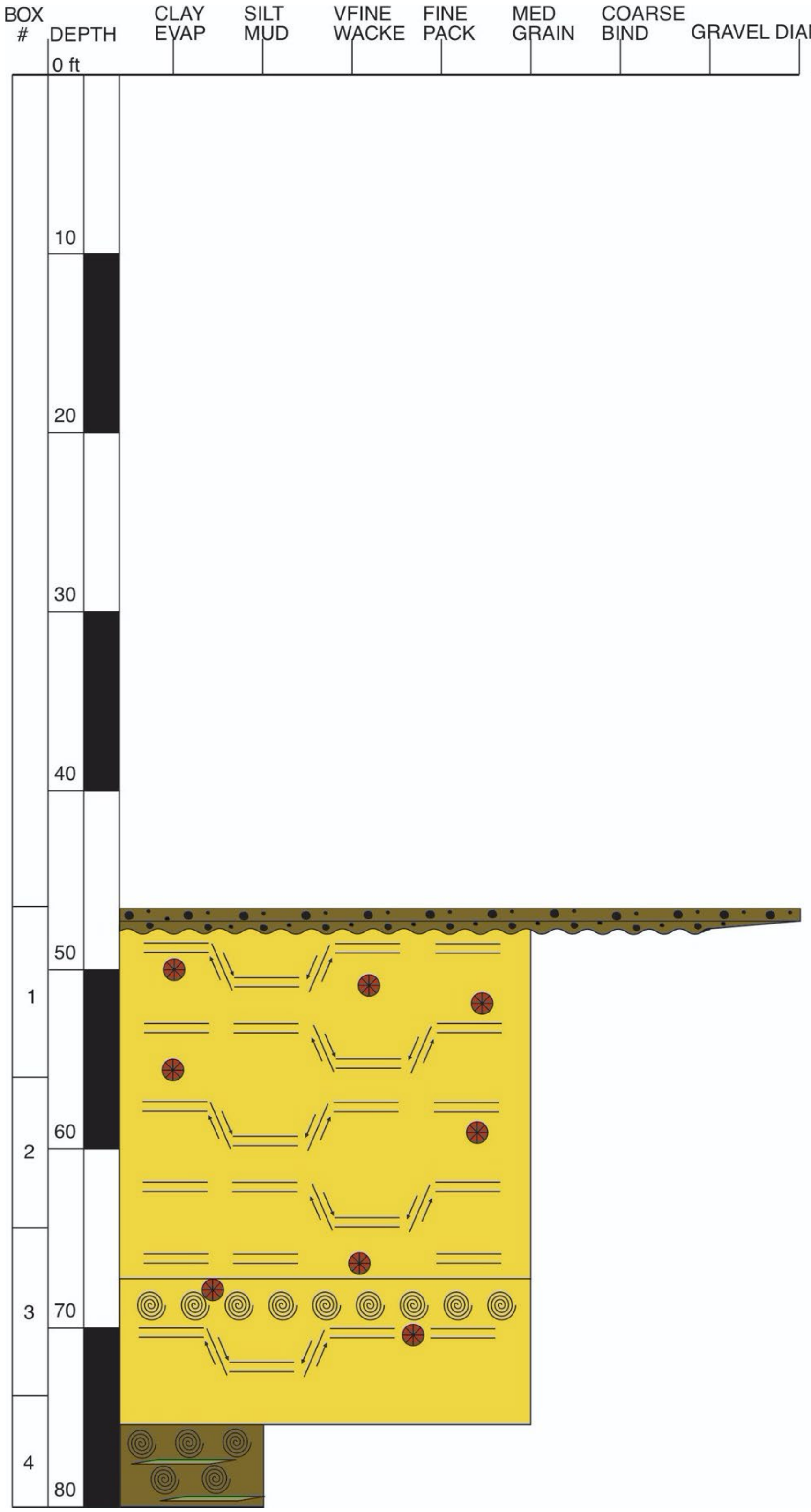
295.5-298' tan coarse quartz sand with dark brown sulfide grains

(298 ft end core)

Figure A-18, Slinger, Dodge County

Elevation: 893'

Total Depth: 498.4'



0-46.5 ft core loss

46.5-47.5 ft Quaternary
unconsolidated diamict and gravel with 1-4 cm rounded gravel clasts, likely from Sinnippee Platteville Fm.

47.5- 67.3 ft St. Peter Fm Tonti
yellow and red banded medium sand with planar crossbeds, frequent 1mm -3 cm sulfide mineralization, and occasional minor normal faulting

67.3-75.3 ft St. Peter Fm Readstown
67.3-75.3' yellow to tan massive medium sand with deformation, and sulfide mineralization often along minor faults

75.3-106.3 ft Prairie Du Chien Gp
75.3-82' dark brown and light green deformed mud with white dolomite rip ups and silcrete accumulations

Figure A-18, Slinger continued

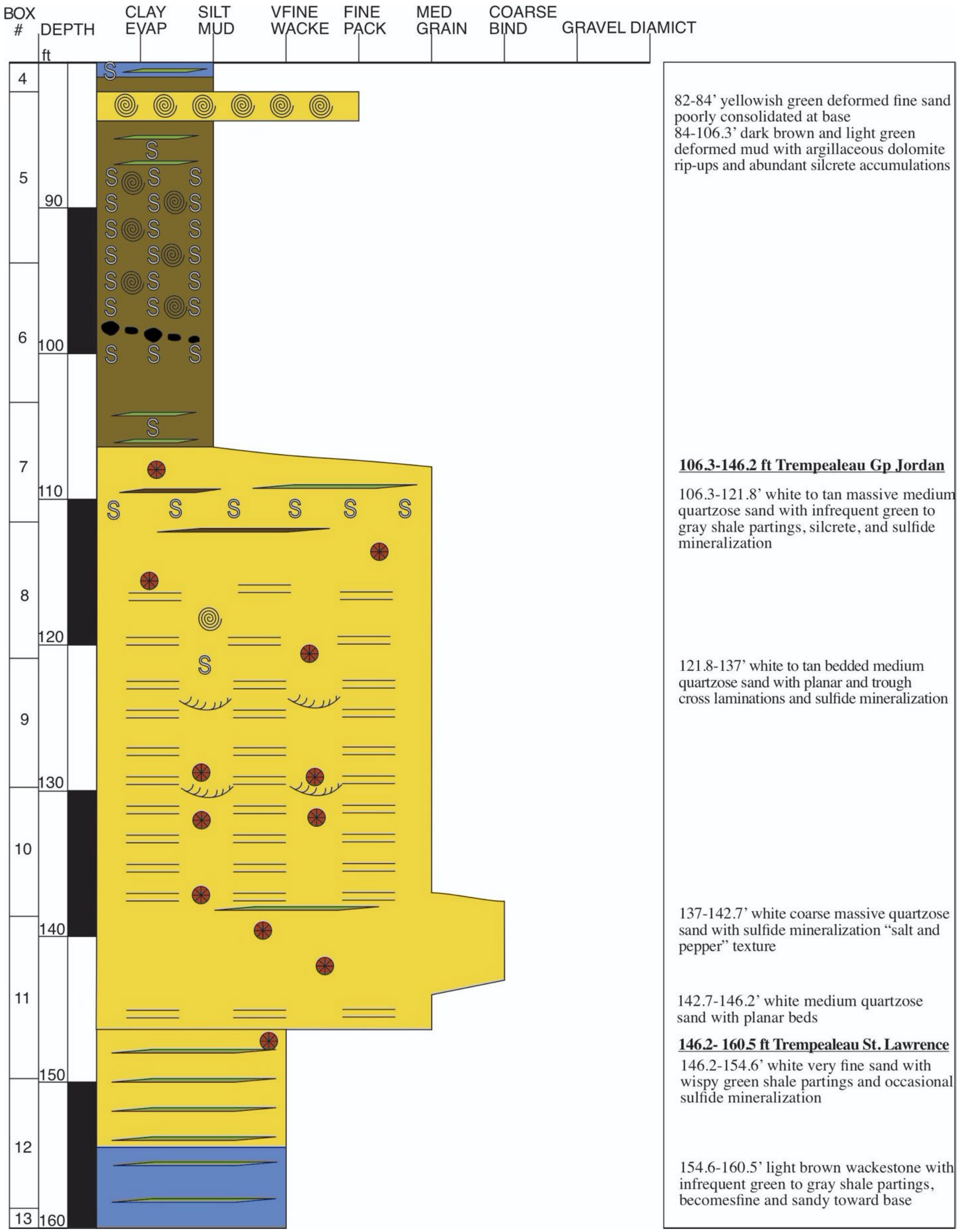


Figure A-18, Slinger continued

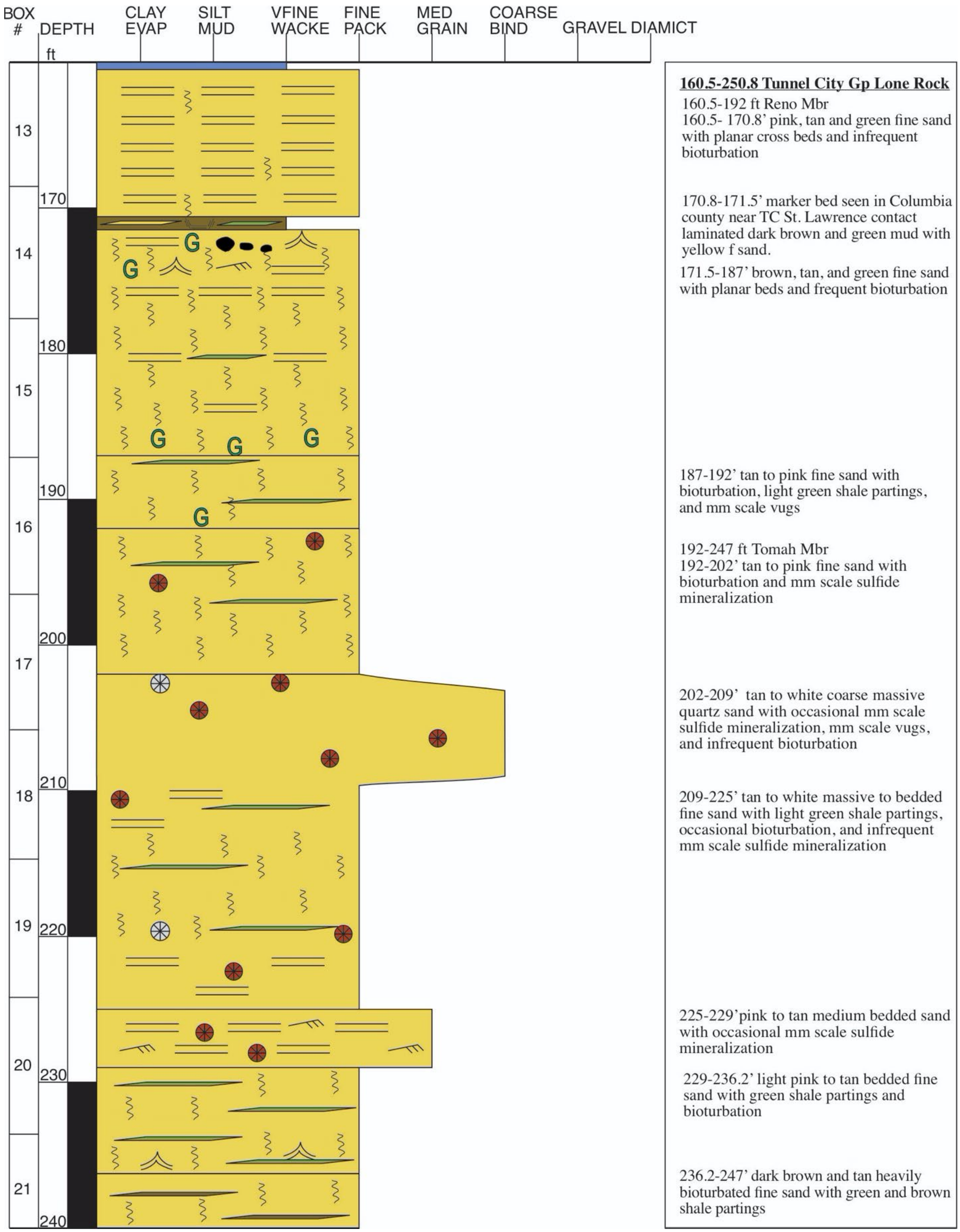
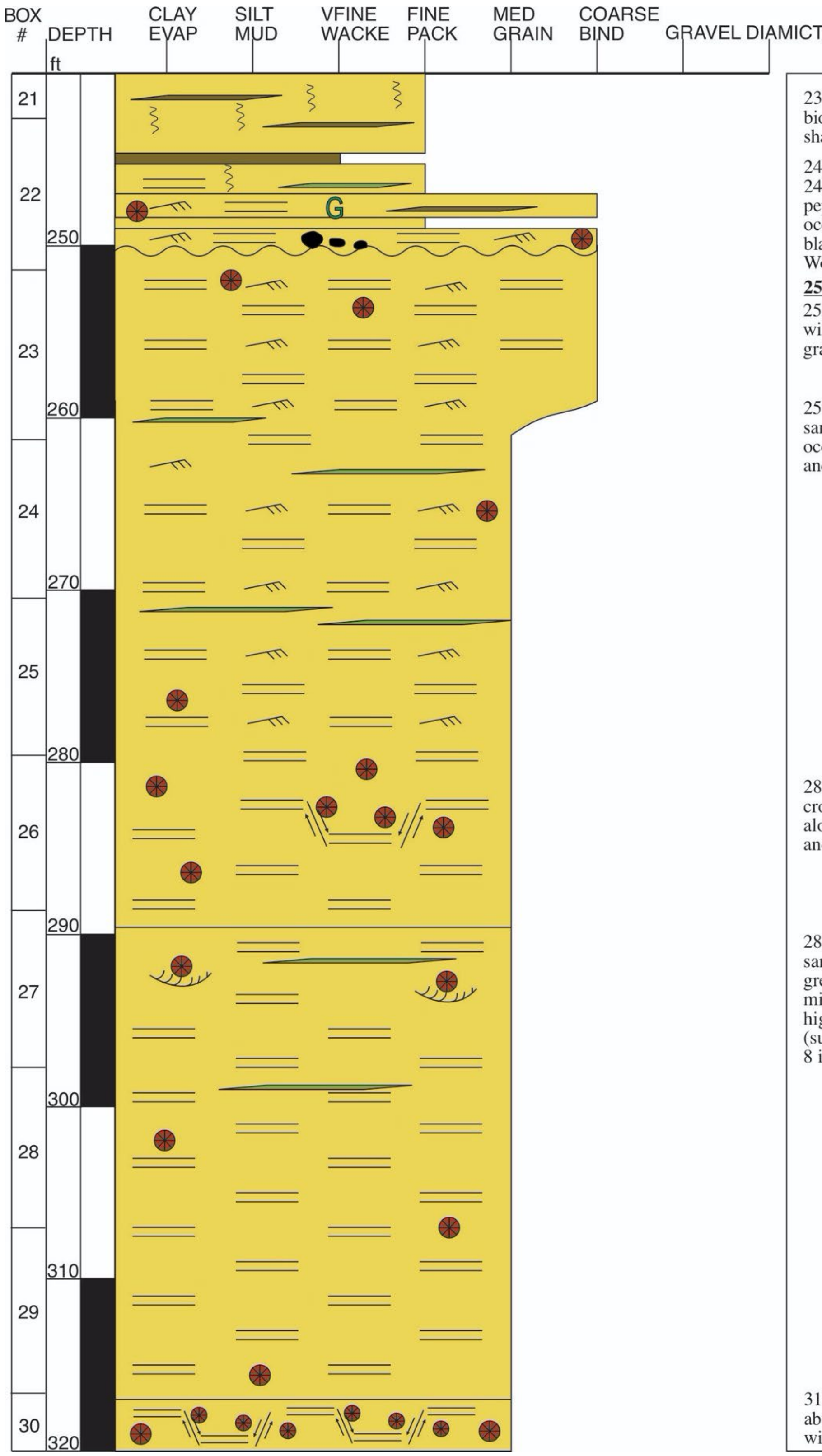


Figure A-18, Slinger continued



236.2-247' dark brown and tan heavily bioturbated fine sand with green and brown shale partings

247-250.8 ft Lone Rock Fm Birkmose Mbr
247-250.8' white coarse sand "salt and pepper" texture with planar cross beds and occasional mm to cm scale shale partings. black sand grains may be sulfide
Wonewoc sandstone rip-up clasts at base

250.8-383 ft Wonewoc Fm

250.8-259' white to tan bedded coarse sand with some black "salt and pepper" sulfide grains

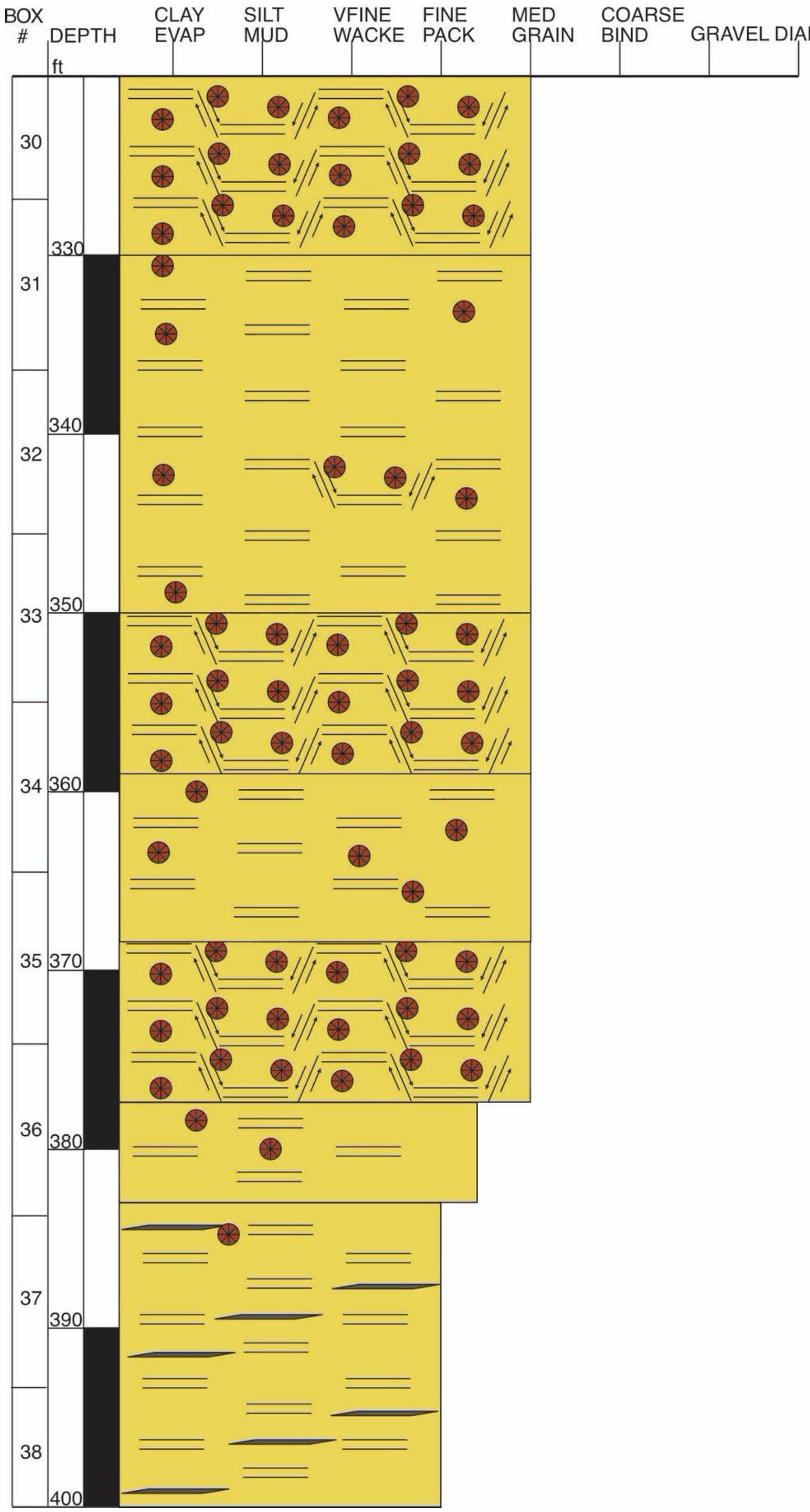
259-281' white to tan medium bedded quartz sand with light green shale partings and occasional mm scale sulfide mineralization and sulfide grains

281-289.7' white medium quartz sand with cross beds, frequent sulfide mineralization along high angle faults and bedding planes and red iron staining

289.7-317' white and pink medium quartz sand with planar and trough cross beds, green shale partings and sulfide mineralization along bedding planes, some high angle fractures with white and black (sulfide) mineralization, some areas (up to 8 inches) of poor consolidated

317-330' white medium sand with abundant high angle fractures 1-15mm wide filled with black sulfide mineralization

Figure A-18, Slinger continued



317-330' white medium sand with abundant high angle fractures 1-15mm wide filled with black sulfide mineralization

330-350' white and tan medium quartz sand with massive to planar cross beds, and sulfide mineralization along bedding planes, some high angle fractures with white and black (sulfide) mineralization

350-359' white medium sand with abundant high angle fractures 1-15 mm wide filled with black sulfide mineralization

359-368.5' white and tan medium quartz sand with massive to planar cross beds, and sulfide mineralization along bedding planes, some high angle fractures with white and black (sulfide) mineralization

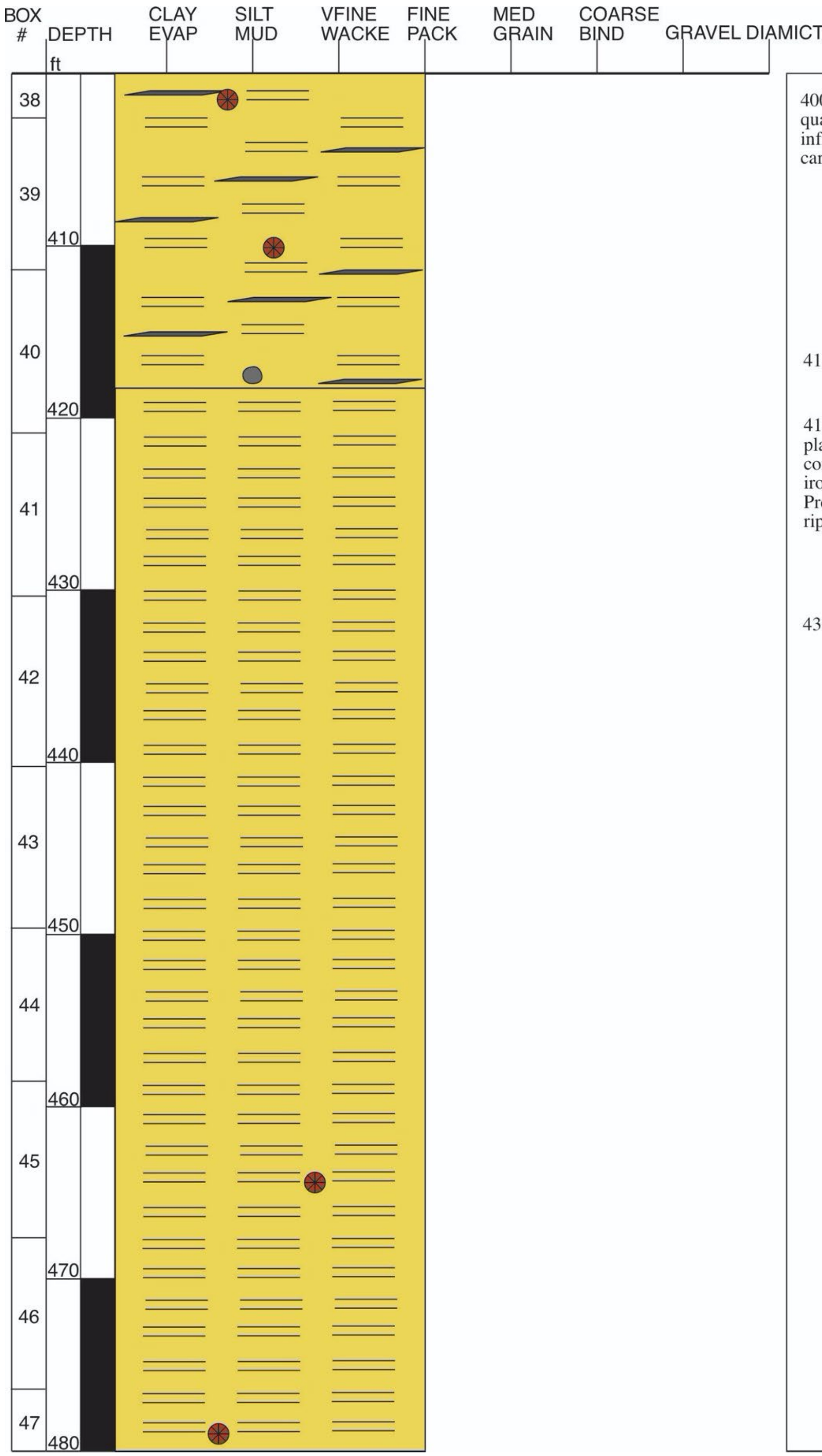
368.5-377.2' white medium sand with abundant high angle fractures 1-15 mm wide filled with black sulfide mineralization

377.2-383' white medium to fine quartz sand with mm scale gray shale partings and some sulfide mineralization

<u>**383-498.2 ft Eau Claire Fm.**</u>

383-400' white to pink fine bedded quartz sand with gray shale partings and infrequent sulfide mineralization, carbonate cement

Figure A-18, Slinger continued



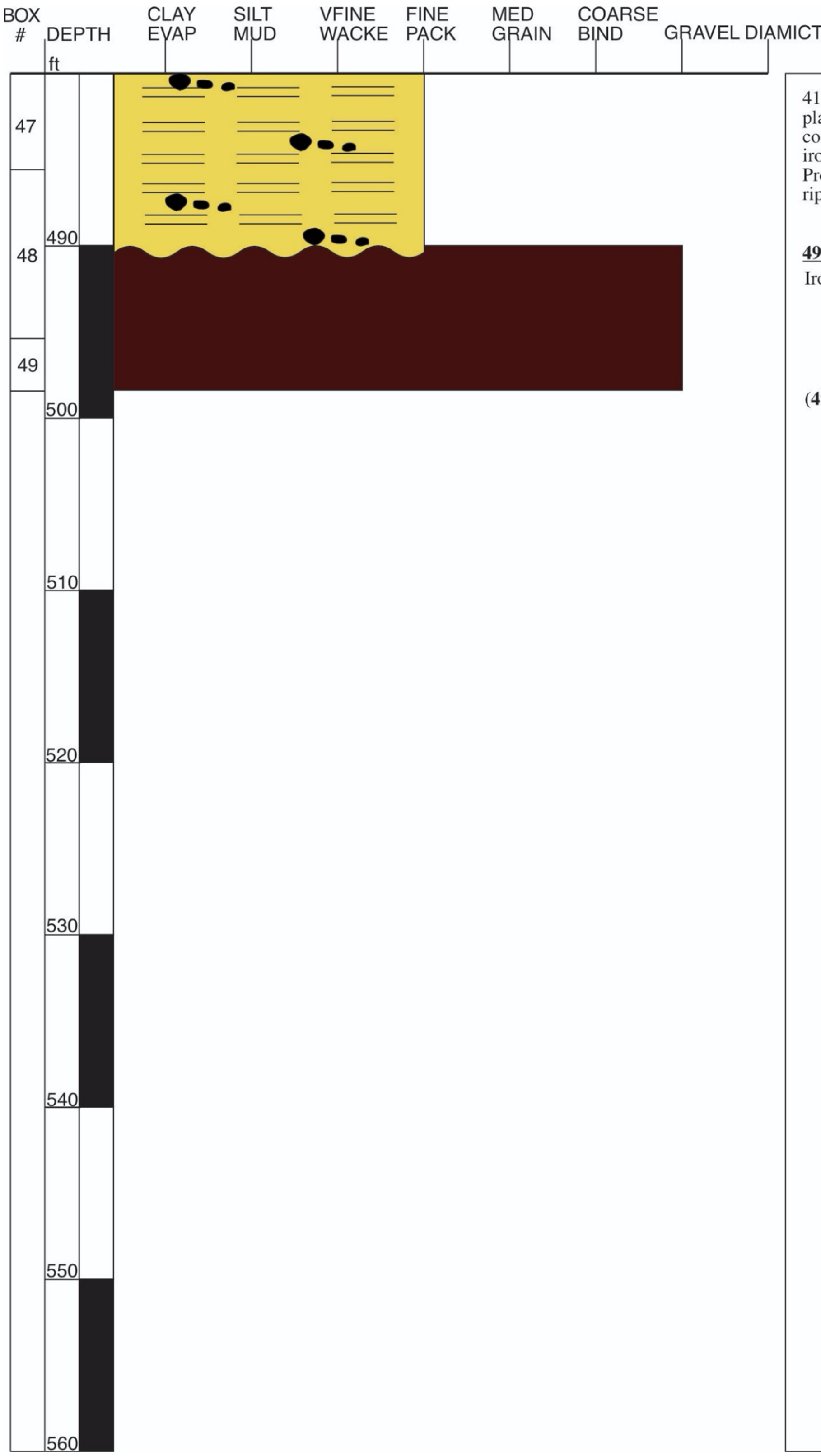
400-418.2' white to pink fine bedded quartz sand with gray shale partings and infrequent sulfide mineralization, carbonate cement

418' gray chert clast 15 mm diameter

418.2-490.5 white fine quartz sand with planar laminated beds, few areas of poor consolidation, red to dark brown iron staining toward base close to Precambrian basement, with cm scale rip-up clasts 10 ft within contact.

431.5' light gray chert band 3 cm wide

Figure A-18, Slinger continued



418.2-490.5' white fine quartz sand with planar laminated beds, few areas of poor consolidation, red to dark brown iron staining toward base close to Precambrian basement, with 1-4 cm rip-up clasts 10 ft within contact.

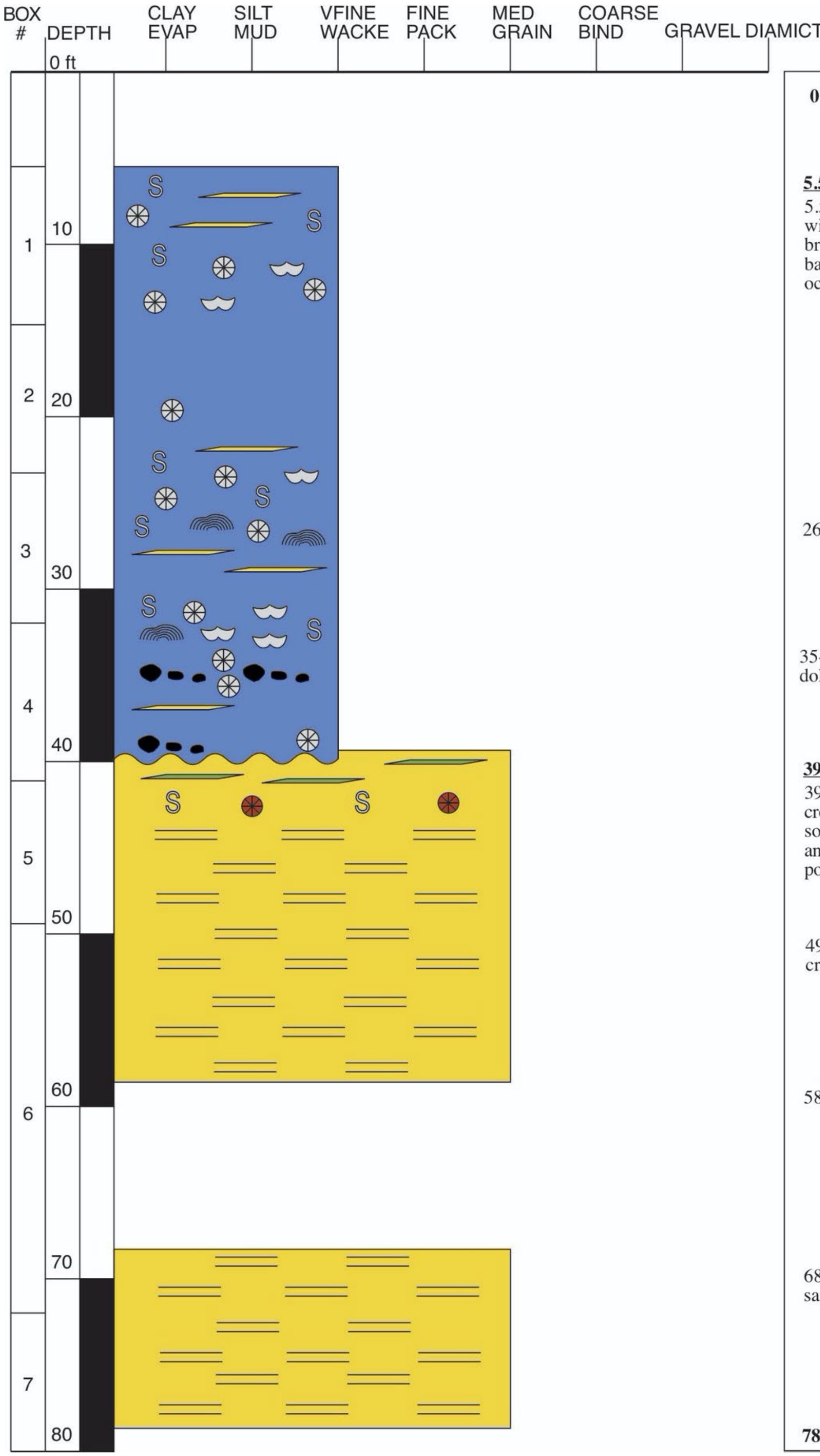
490.5-498.4 ft Precambrian basement

Iron rich, mafic

(498.4 ft end core)

Figure A-19, Stevenson 2, Columbia County

Elevation: 1091’ Total Depth: 208.4’



0-5.5 ft core loss

5.5-39.9 ft Prairie Du Chien Gp

5.5-39.9’ tan to gray dolomite wackestone with 1-3 cm vugs often in the shape of brachiopods, 1-4 cm silcrete nodules and bands, yellow fine sand lenses, and occasional stromatolites

26-28’ 2-6 cm stromatalites

35-35.5’ brecciated dolomite with 3-4 cm dolomite and fine sandstone clasts

39.9-78.8 ft Trempealeau Gp Jordan Fm

39.9-49.5’ white quartz sand wtih planar cross beds and light green shale partings, some mm scale sulfide mineralization, and silcrete along bedding planes and in pore space

49.5-58.5 white quartz sand wtih planar cross beds

58.5-68.5’ core loss/ misnumbering?

68.5-78.8’ white to tan medium quartz sand with planar cross beds

78.8-90.8 ft core loss

Figure A-19, Stevenson 2 continued

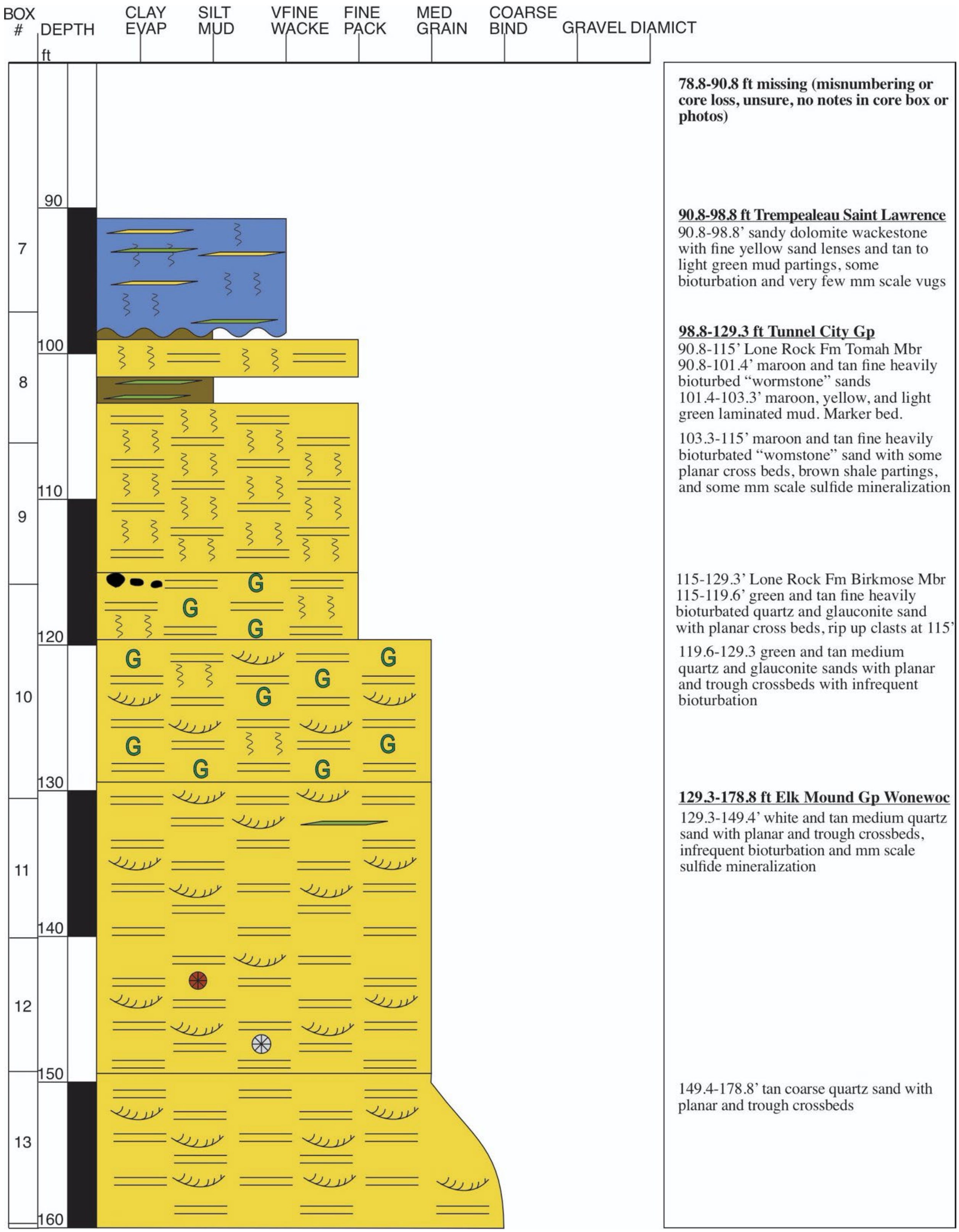
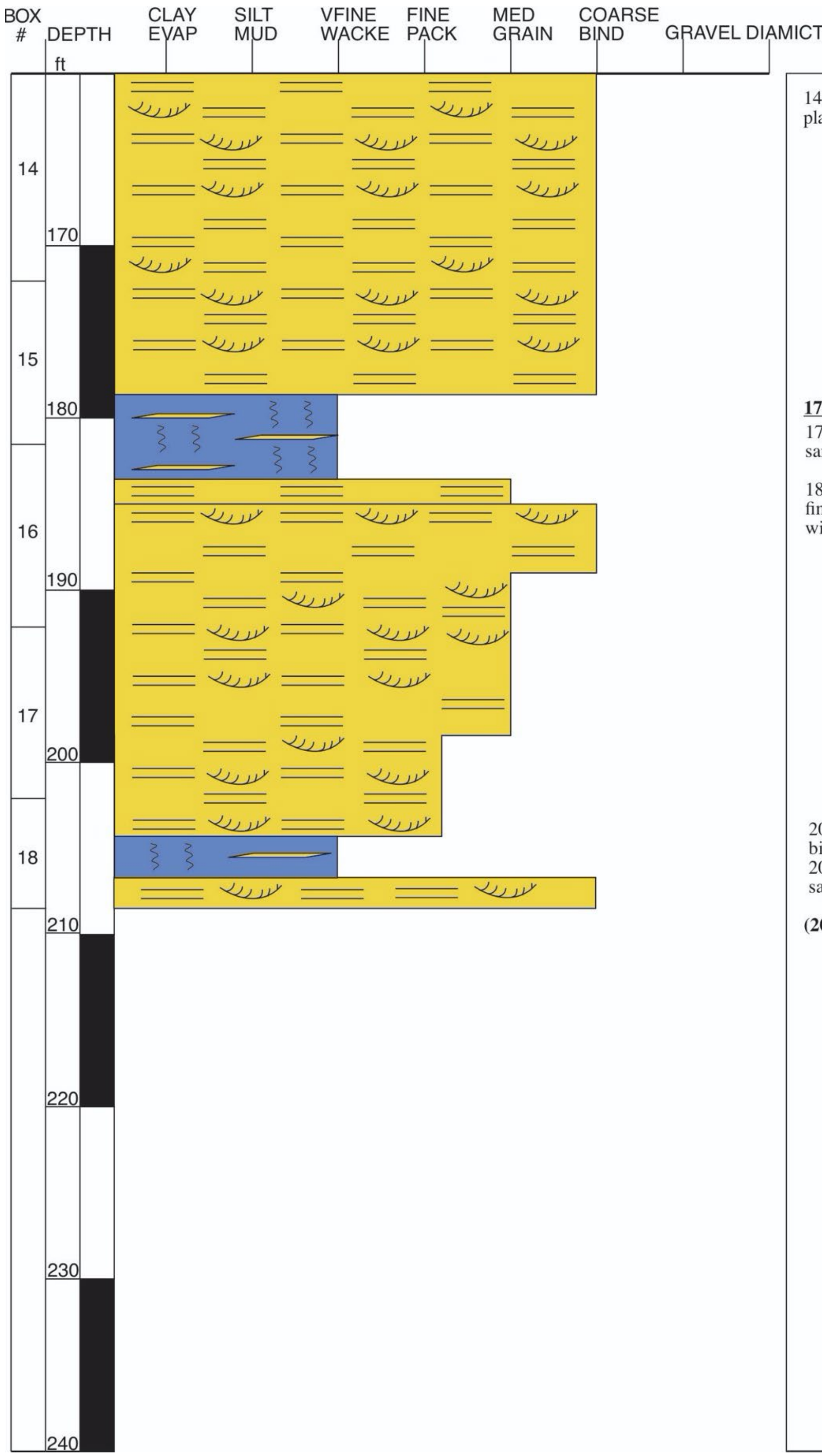


Figure A-19, Stevenson 2 continued



149.4-178.8' tan coarse quartz sand with planar and trough crossbeds

<u>178.8-208.4 ft Elk Mound Eau Claire</u>

178.8-183.5' white to tan sandy dolomite bioturbated wackestone

183.5-204.2' yellow and white coarse to fine, coarsening upwards, quartz sand with planar and trough cross beds

204.2-206.8' white to tan sandy dolomite bioturbated wackestone

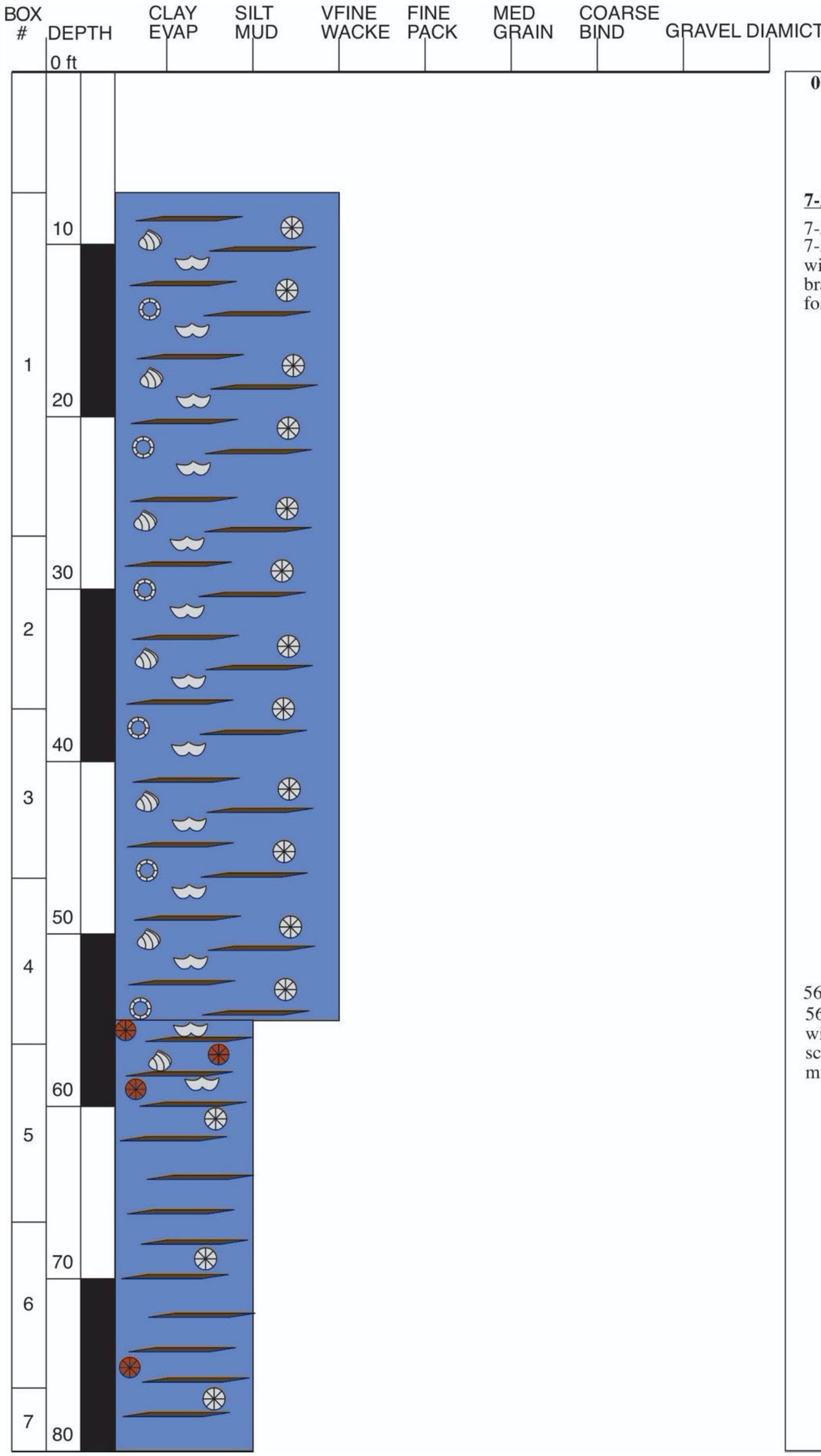
206.8-208.4' yellow and white fine quartz sand with planar and trough crossbeds

(208.4 ft end core)

Figure A-20, Swan Road, Dodge County

Elevation: 864'

Total Depth: 251'



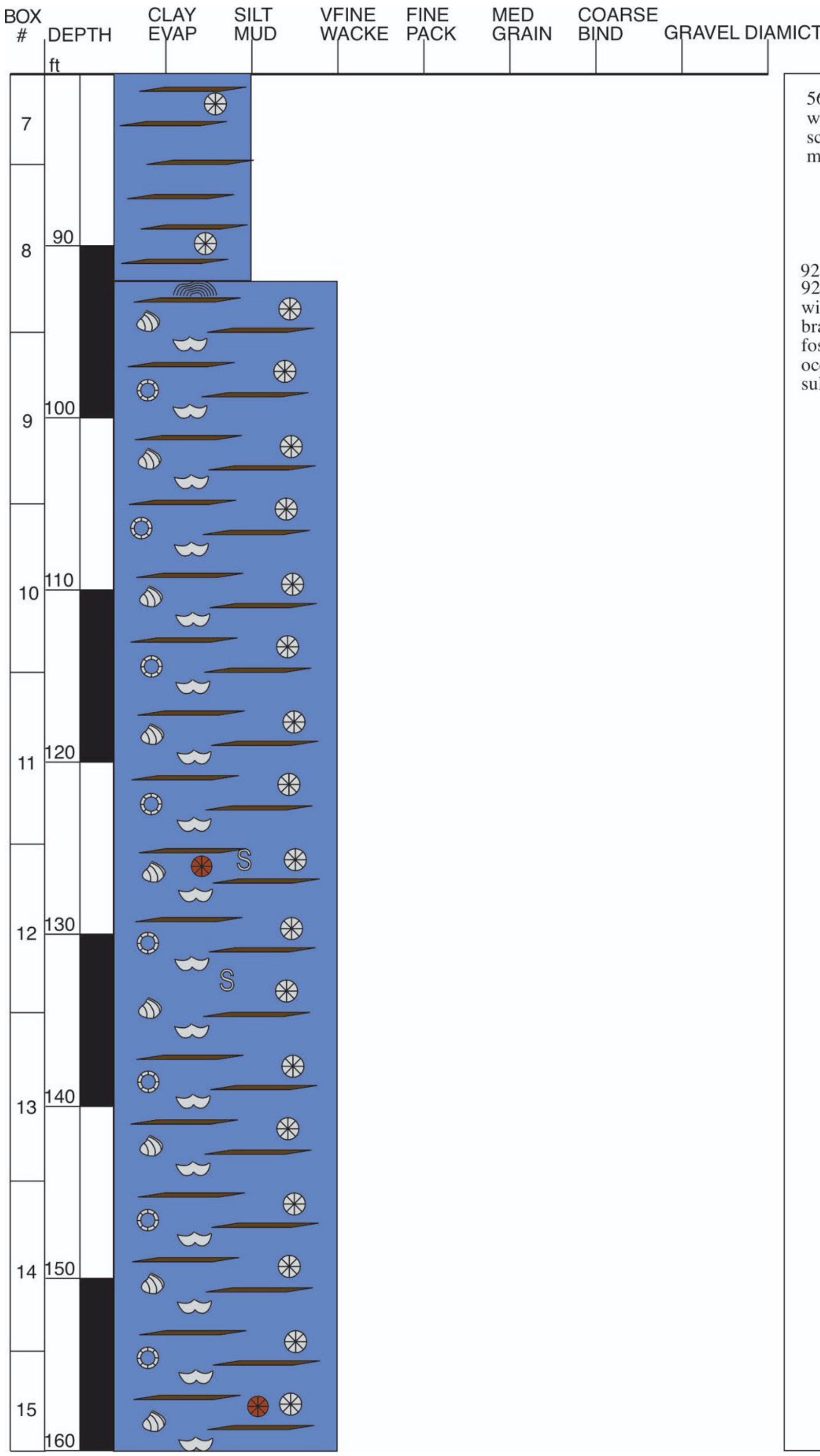
0-7 ft core loss

7-244 ft Sinnipee Group

7-56 ft Galena Fm
7-56' dark brown dolomite wackestone with 1-2 mm black shale partings, brachiopod, bivalve, crinoid and peloid fossils, and mm to cm scale vugs

56-92 ft Decorah Fm
56-92' dark brown dolomite mudstone with 1-2 mm black shale parting, mm scale vugs and cm scale black sulfide mineralization

Figure A-20, Swan Road continued



56-92' dark brown dolomite mudstone with 1-2 mm black shale parting, mm scale vugs and cm scale black sulfide mineralization

92-244 ft Platteville Fm
92-169' dark brown dolomite wackestone with 1-2 mm black shale partings, brachiopod, bivalve, crinoid and peloid fossils, and mm to cm scale vugs, occasional cm scale sulfide nodules and sulfide mineralization

Figure A-20, Swan Road continued

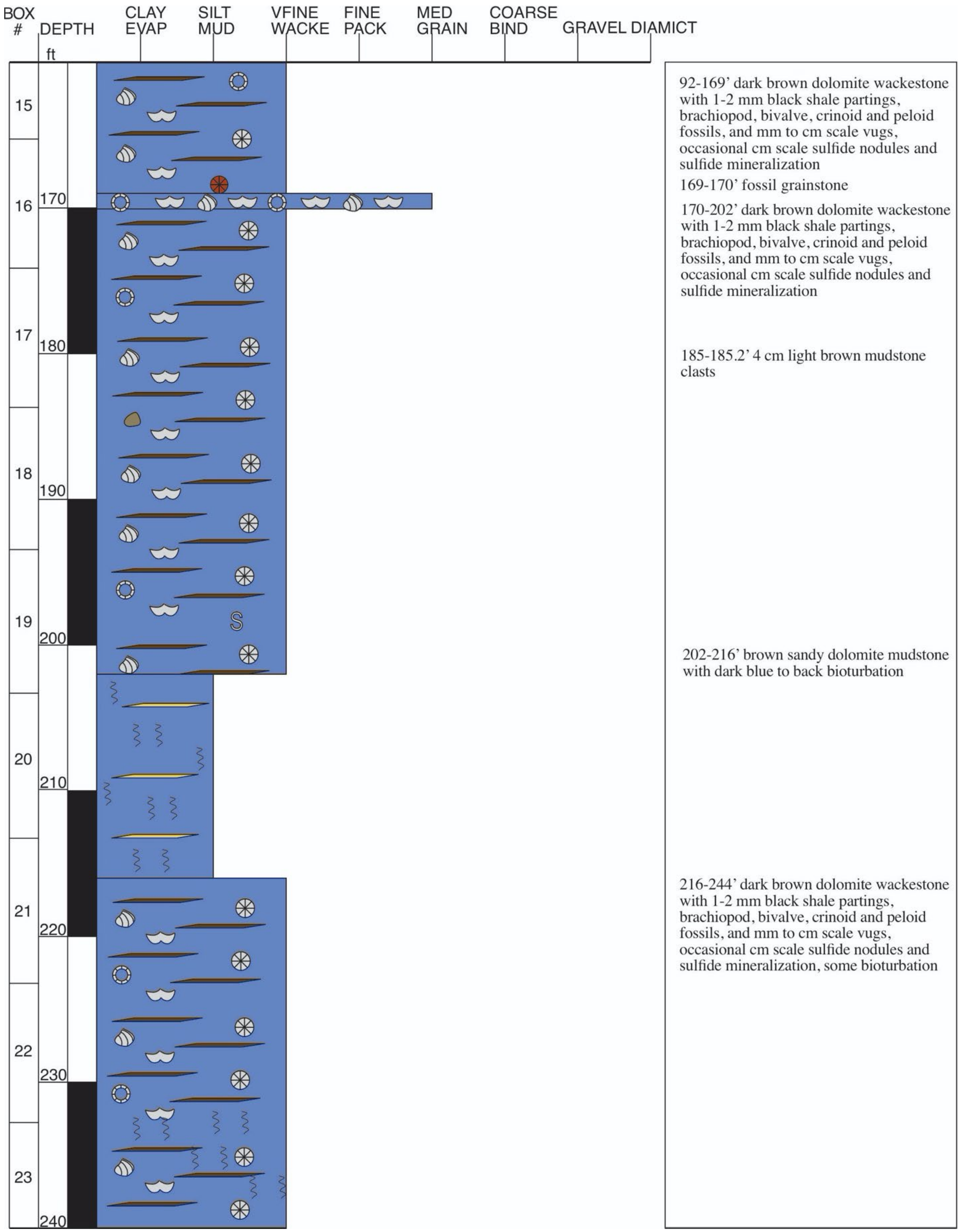
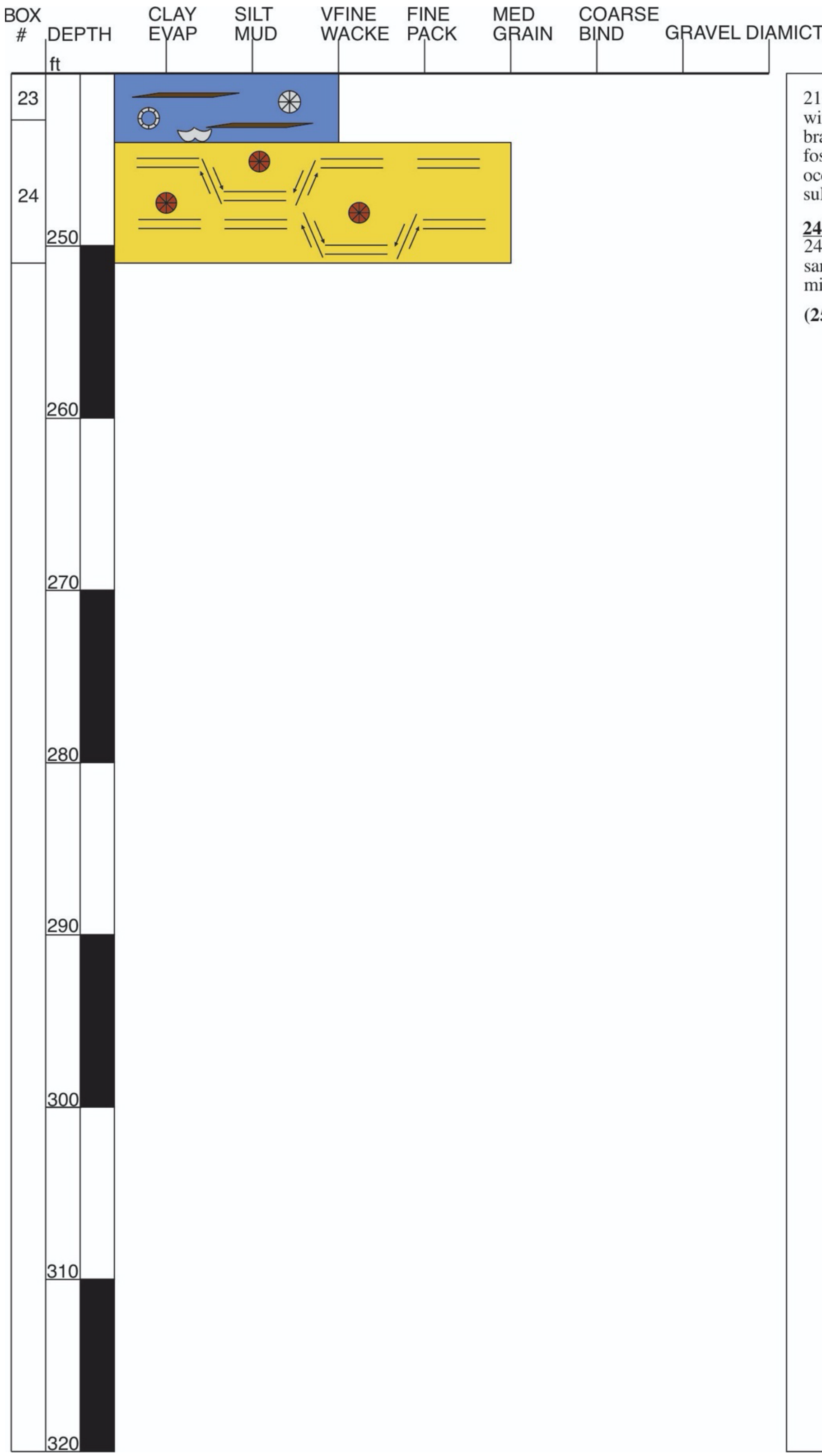


Figure A-20, Swan Road continued



216-244' dark brown dolomite wackestone with 1-2 mm black shale partings, brachiopod, bivalve, crinoid and peloid fossils, and mm to cm scale vugs, occasional cm scale sulfide nodules and sulfide mineralization, some bioturbation

<u>244-251 ft St. Peter Fm Tonti Mbr</u>
244-251' gray and white medium quartz sand with faulting and black sulfide mineralization

(251 ft end core)

Figure A-21, Triemstra Quarry, Columbia County

Elevation: 1044’ Total Depth: 606’

0-15.1 ft Prairie Du Chien Gp

0-7.5’ yellowish gray sandy dolomite wacksestone with mm- 3cm calcite filled vugs, brachiopods, and thrombolitic texture, 1-5 in yellow medium sand lenses

7.5-15.1’ yellow medium massive sand with 2-8 mm vugs, and carbonate cement

15.1-51.2 ft Trempealeau Gp Jordan Fm

15.1-21.3’ white fine sand with planar cross beds and mm scale sulfide mineralization

21.3-27’ yellow to dark tan medium sand with vugs often in the shape of brachiopods, some planar cross beds, bioturbation and 1-2 mm white mineralization in pore space and along bedding planes

27-31.4’ tan fine sand with planar cross beds and one 3 mm light brown mud lense

31.4-33.6’ yellow to dark tan medium sand with vugs often in the shape of brachiopods, some planar cross beds, bioturbation and 1-2 mm white mineralization in pore space and along bedding planes

33.6-51.2’ white medium sand with planar cross beds and light green shale partings

51.2-62.5 ft Trempealeau Gp Lone Rock

51.2-62.5’ tan dolomite and maroon and light green very fine sand bedded mix with bioturbation

62.5-178.8 ft Tunnel City Gp

62.5-90.5’ Lone Rock Fm Reno Mr

62.5-69’ tan and maroon heavily bioturbated fine sand “wormstone” with light green shale partings

69-70’ brown and light green laminated mud with yellow tan silty sand lenses. marker bed.

70-71.5’ tan and maroon heavily bioturbated fine sand “wormstone” with light green shale partings with some glauconite grains

71.5-90.5’tan and dark green quartz and glauconite medium sand “wormstone” with planar cross beds, bioturbated, some rip-up clasts

Figure A-21, Triemstra Quarry continued

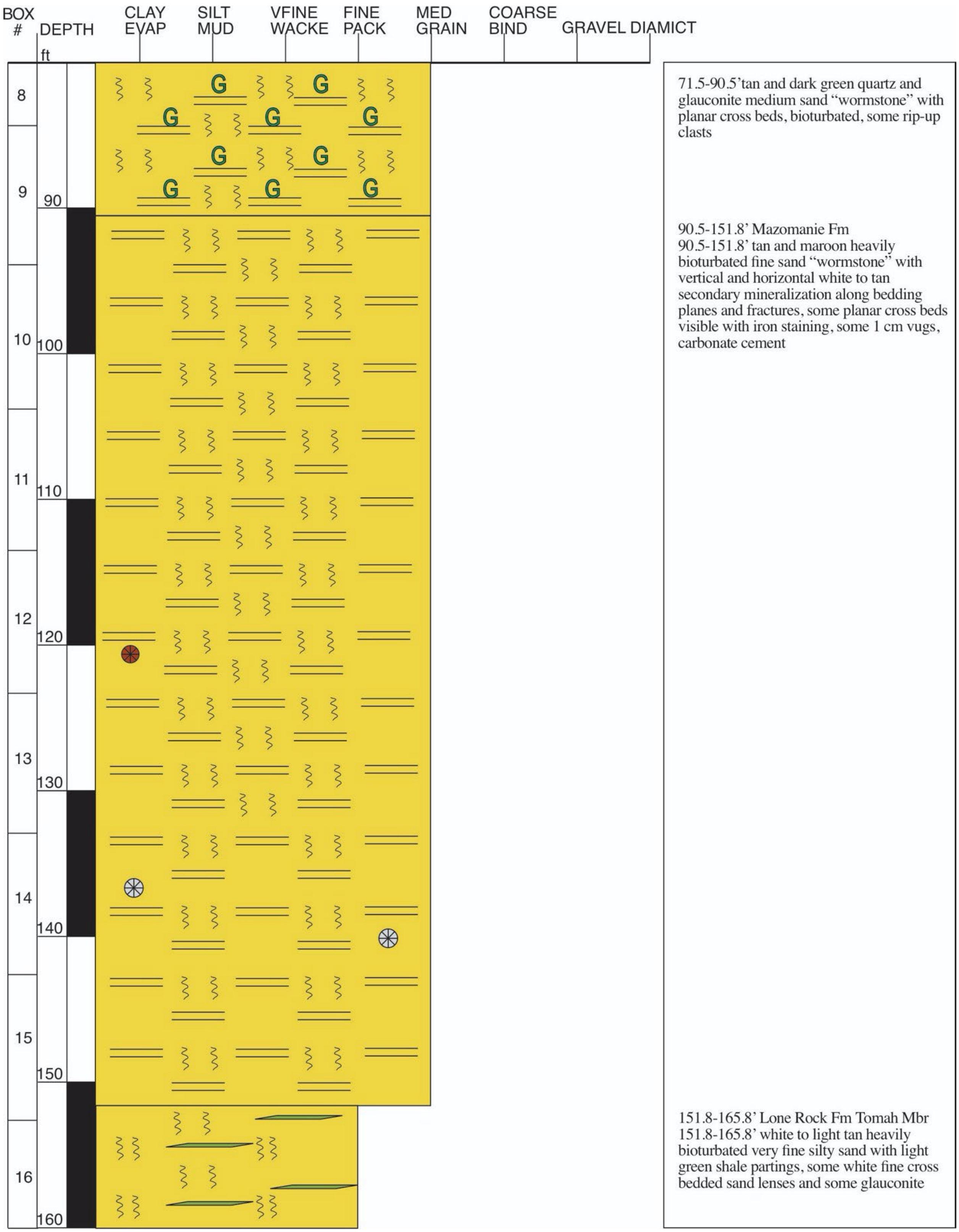
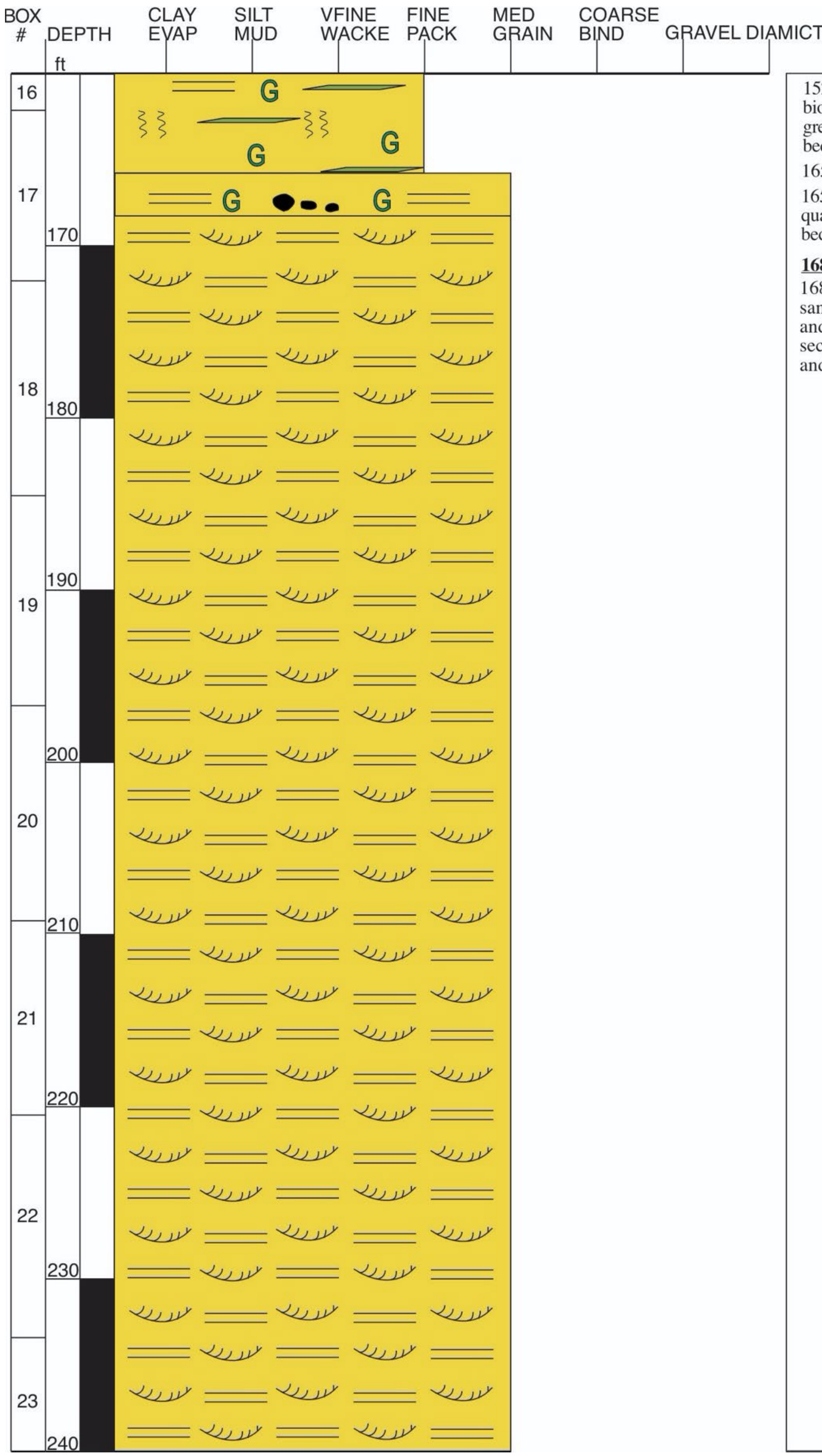


Figure A-21, Triemstra Quarry continued



152.8-165.8' white to light tan heavily bioturbated very fine silty sand with light green shale partings, some white fine cross bedded sand lenses and some glauconite

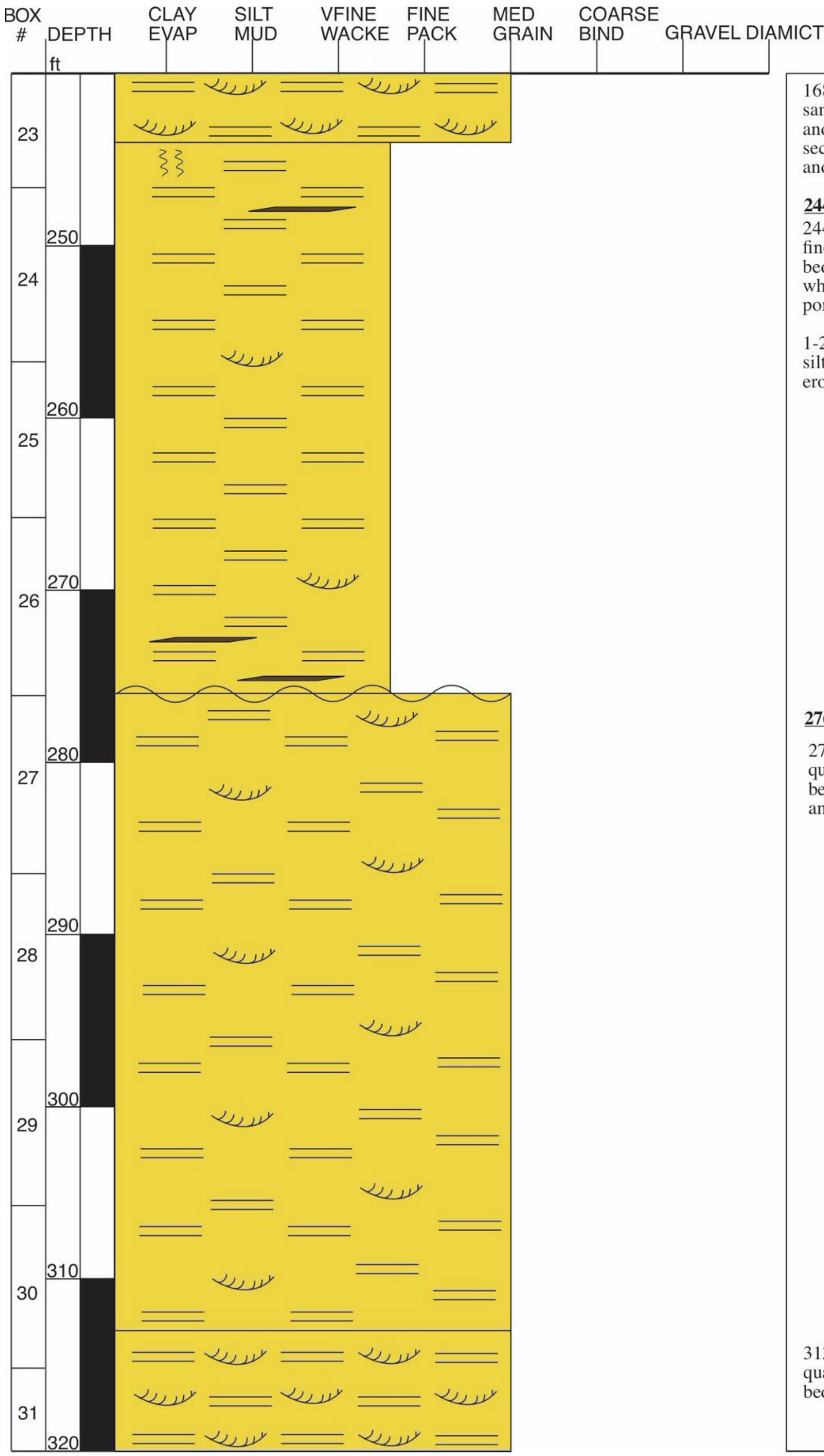
165.8-168.2' Lone Rock Fm Birkmose Mbr

165.8-168.2' dark brown and green medium quartz and glauconite sand with planar cross beds with rip up clasts at base

168.2-244 ft Elk Mound Gp Wonewoc Fm

168.2-244' white to tan medium quartz sand with planar and trough cross beds and vertical and horizontal white to tan secondary mineralization in pore space and along bedding planes

Figure A-21, Triemstra Quarry continued



168.2-244' white to tan medium quartz sand with planar and trough cross beds and vertical and horizontal white to tan secondary mineralization in pore space and along bedding planes

244-276 ft Elk Mound Gp Eau Claire Fm

244-276' white to light gray very fine to fine sand with planar and trough cross beds and occasional vertical and horizontal white to tan secondary mineralization in pore space and along bedding planes

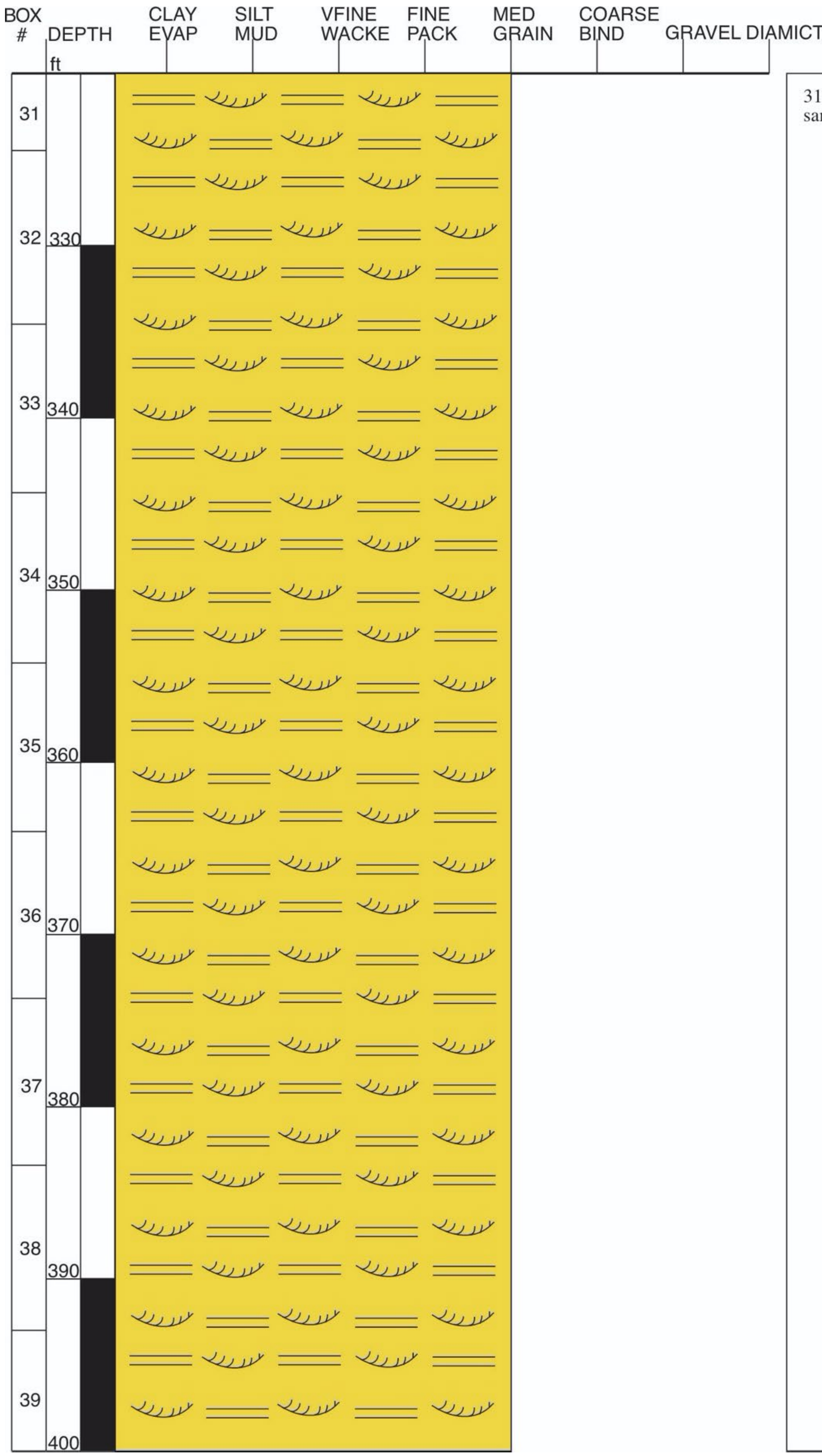
1-2 in layers of yellow very fine to silt/mud topped with light brown, wavy erosional surfaces

276-599.5 ft Elk Mound Gp Mt Simon Fm

276-313.8' white to light tan medium quartz sand with planar and trough cross beds, white mineralization in pore space and along bedding planes

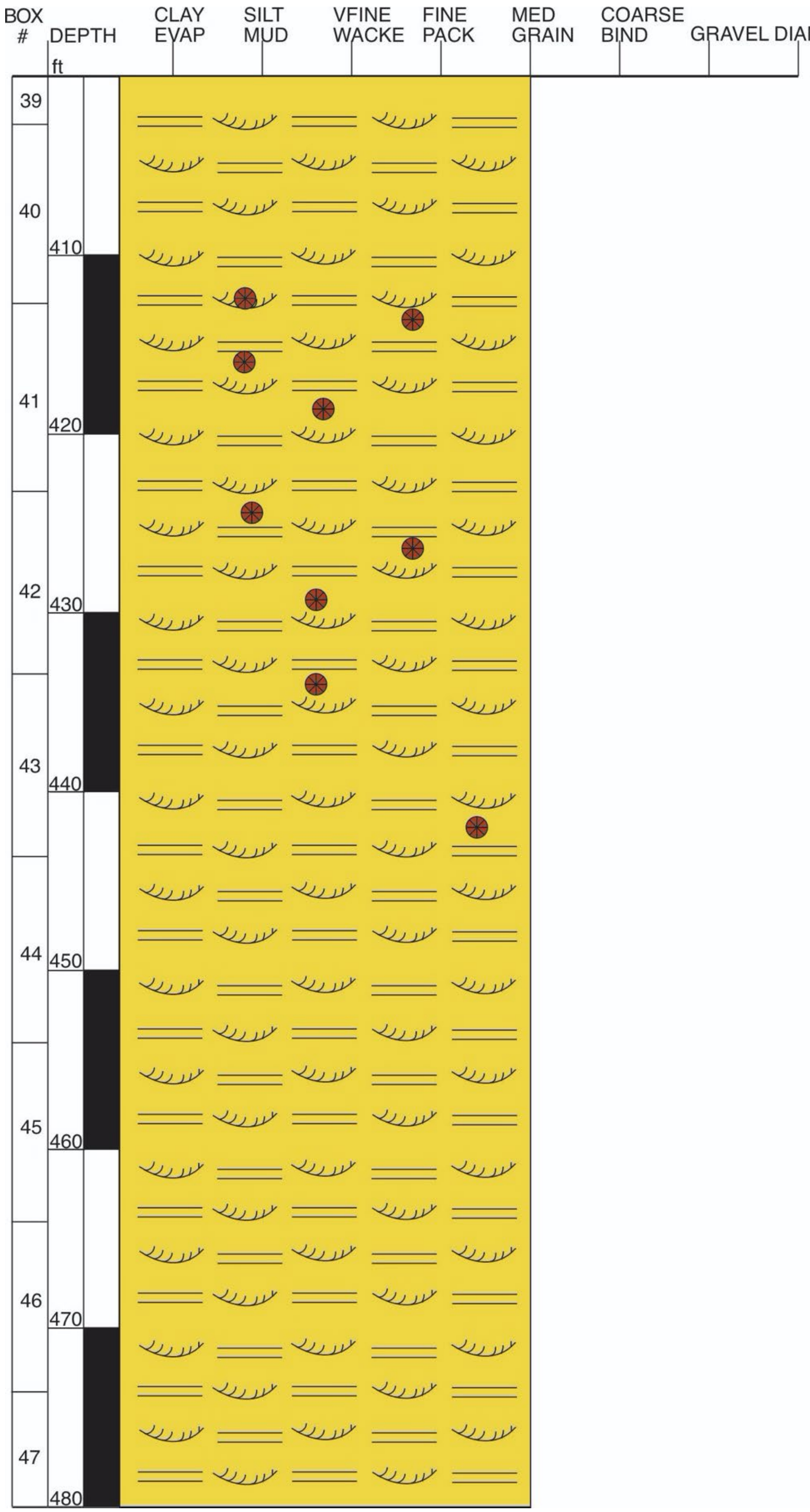
313.8-413' white to light tan medium quartz sand with planar and trough cross beds

Figure A-21, Triemstra Quarry continued



313.8-413' white to light tan medium sand with planar and trough cross beds

Figure A-21, Triemstra Quarry continued



313.8-413' white to light tan medium sand with planar and trough cross beds

413-442.8' white to light tan medium sand with planar and trough cross beds and mm to 3 cm sulfide mineralization

442.8-483' white to light tan medium sand with planar and trough cross beds

Figure A-21, Triemstra Quarry continued

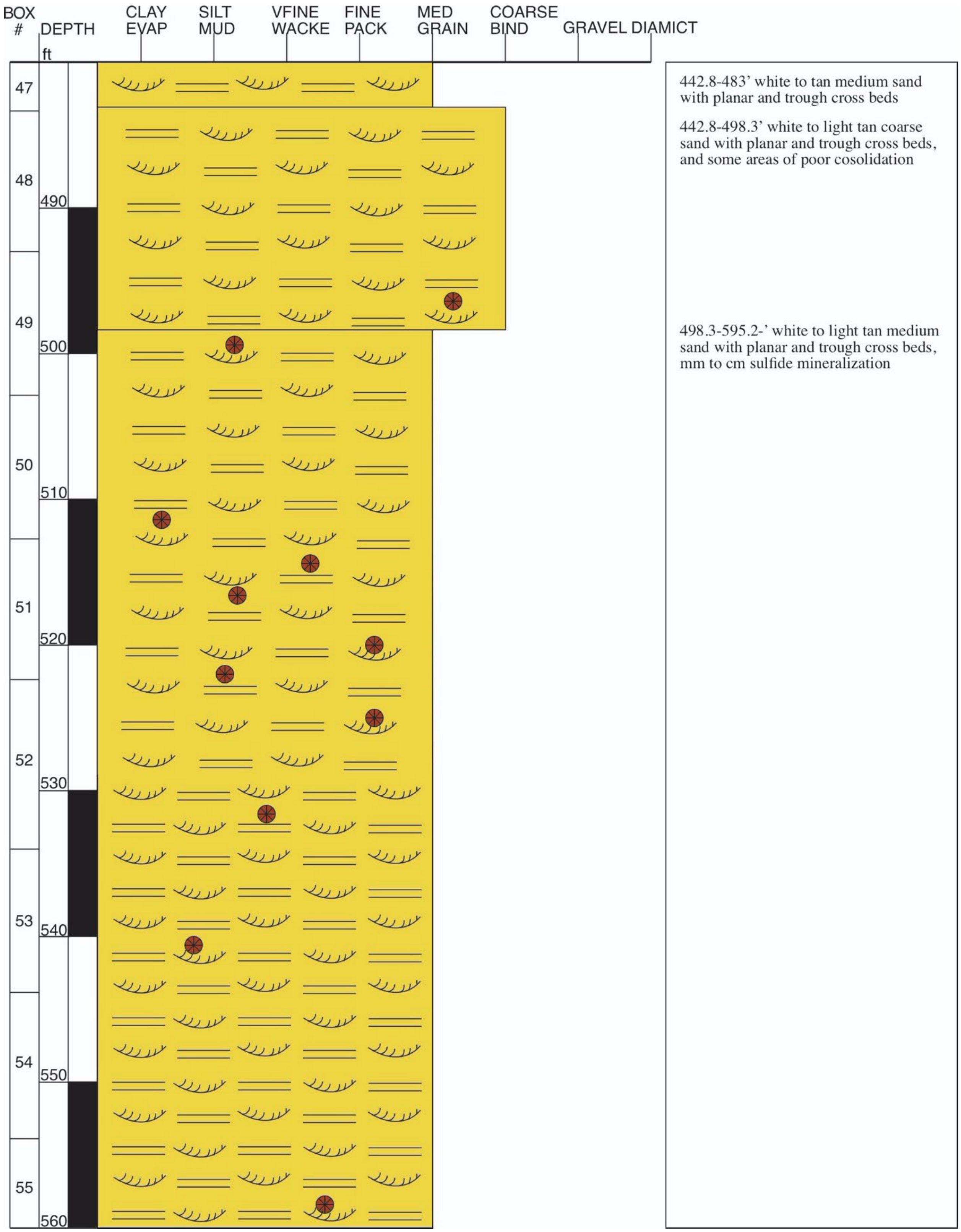
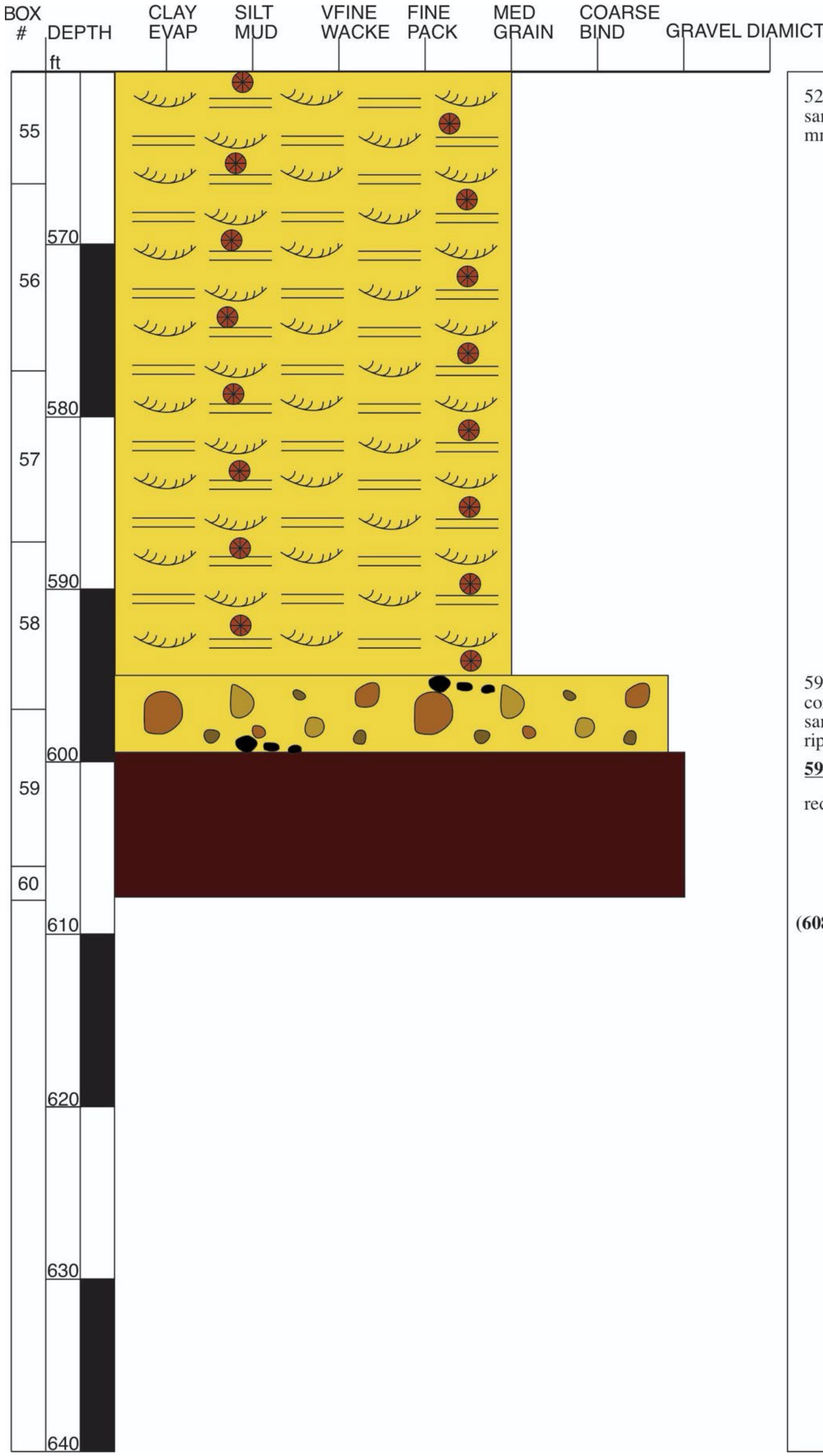


Figure A-21, Triemstra Quarry continued



529-595.2-' white to light tan medium sand with planar and trough cross beds, mm to cm sulfide mineralization

595.2-599.5' matrix supported sandy conglomerate with tan and red medium sand matrix and abundant precambrian rip up clasts

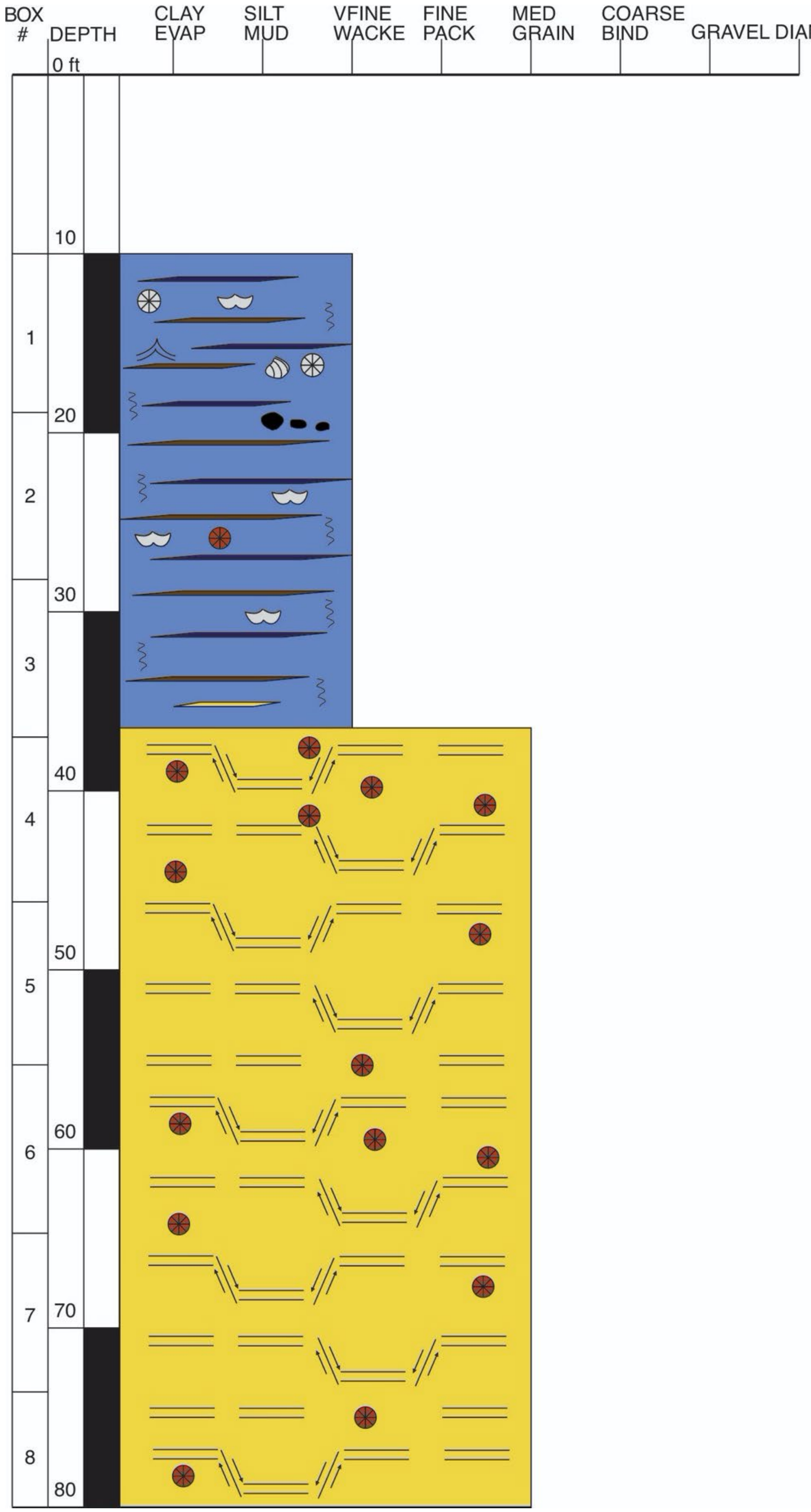
599.5-608.6 ft Precambrian basement

red grainte

(608.6 ft end core)

Figure A-22, Westphal 2, Dodge County

Elevation: 835’ Total Depth: 688.1’



0-10 ft core loss

<u>10-36.5 ft Sinnipee Gp Platteville Fm</u>

10-36.5’ alternating gray/blue and light brown dolomite wackestone with mm scale vugs often in the shape of brachiopods, and 1-2 mm dark gray and brown shale partings, some flame structures, rip-up clasts, consistent change in energy

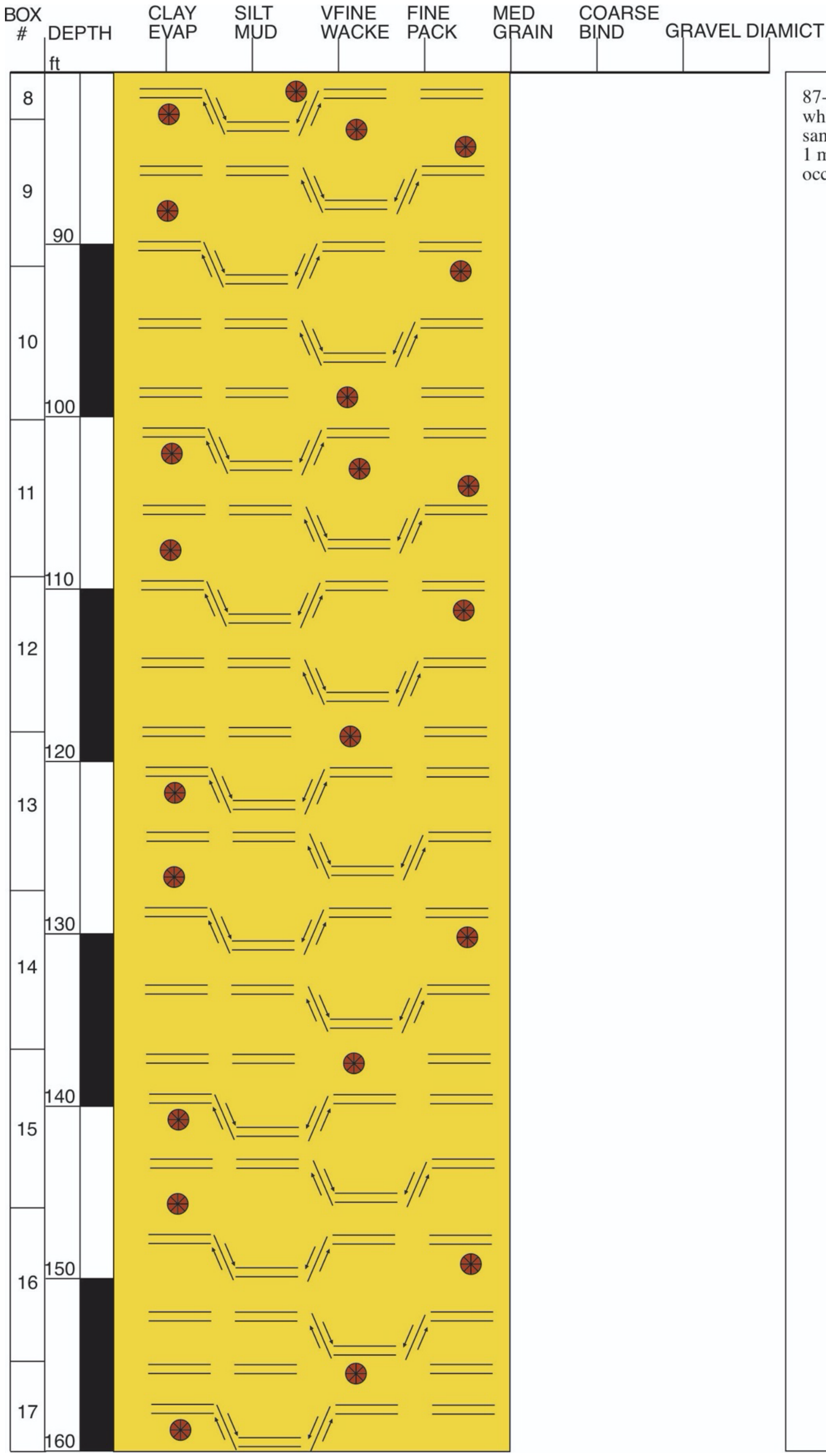
<u>36.5-167.5 ft St Peter Fm Tonti Mbr</u>

36.5-66’ white and gray medium quartz sand with planar cross beds, frequent 1 mm -3 cm sulfide mineralization, and occasional minor normal faulting

36.5-72.4’ alternating pink and yellow and white and gray banded medium quartz sand with planar cross beds, frequent 1 mm -3 cm sulfide mineralization, and occasional minor normal faulting

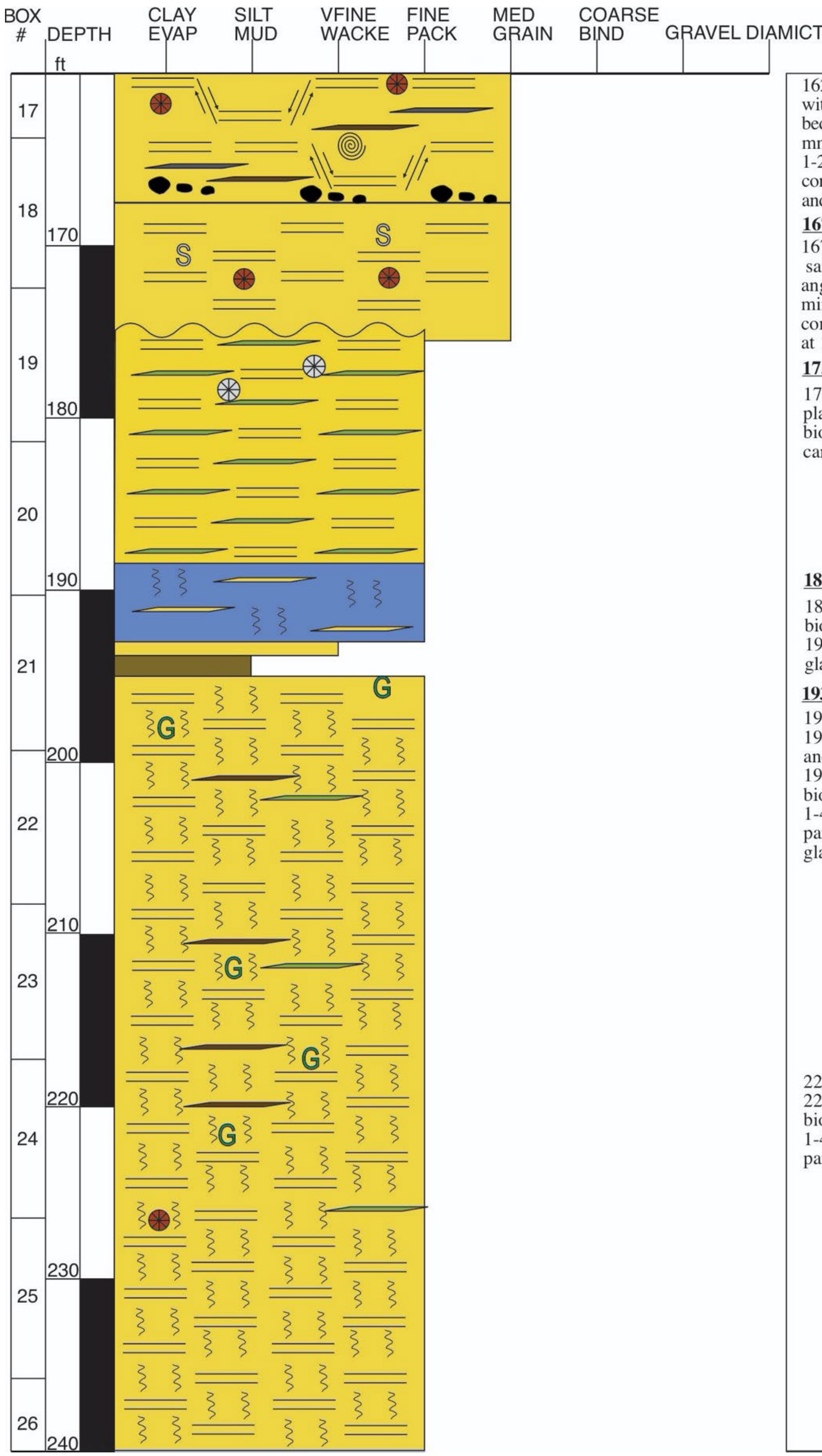
72.4-87’white and gray medium quartz sand with planar cross beds, frequent 1 mm -3 cm sulfide mineralization, and occasional minor normal faulting

Figure A-22, Westphal 2 continued



87-162' alternating pink and tan and white and gray banded medium quartz sand with planar cross beds, frequent 1 mm -3 cm sulfide mineralization, and occasional minor normal faulting

Figure A-22, Westphal 2 continued



162-167.5' pink and gray medium sand with planar, trough, and normal faulted beds, mm to cm scale sulfide mineralization, mm to cm scale dark gray shale bands, 1-2 cm silcrete bands, layers of poor consolidation, deformation, rip up-clasts and rubble at base

167.5-175.7 ft St Peter Fm Readstown

167.5-175.8' white and tan medium quartz sand with massive to planar cross beds, angular silcrete nodules, mm scale sulfide mineralization, few layers of poor consolidation, vuggy coarse bubble rock at 169.7-169.9'

175.7-188.5 ft Trempealeau Gp Jordan

175.7-188.5' white fine quartz sand with planar cross beds 1-2 mm wavy to bioturbated light green shale partings, carbonate cement

188.5-193.8 ft Trempealeau St Lawrence

188.5-193' tan and maroon sandy bioturbated dolomite wackestone
193-193.8' white quartz and green glauconite fine sand with planar cross beds

193.8-264.6 ft Tunnel City Gp Lone Rock

193.8- 220 ft Reno Mbr
193.8-195'- laminated dark brown mud and fine yellow sand marker bed
195-220' maroon and tan fine heavily bioturbated qtz sand "womstone" with 1-4 mm brown and light green shale partings, occasional beds with abundant glauconite grains

220-257 ft Tomah Mbr
220-257' maroon and tan fine heavily bioturbated qtz sand "womstone" with 1-4 mm brown and light green shale partings

Figure A-22, Westphal 2 continued

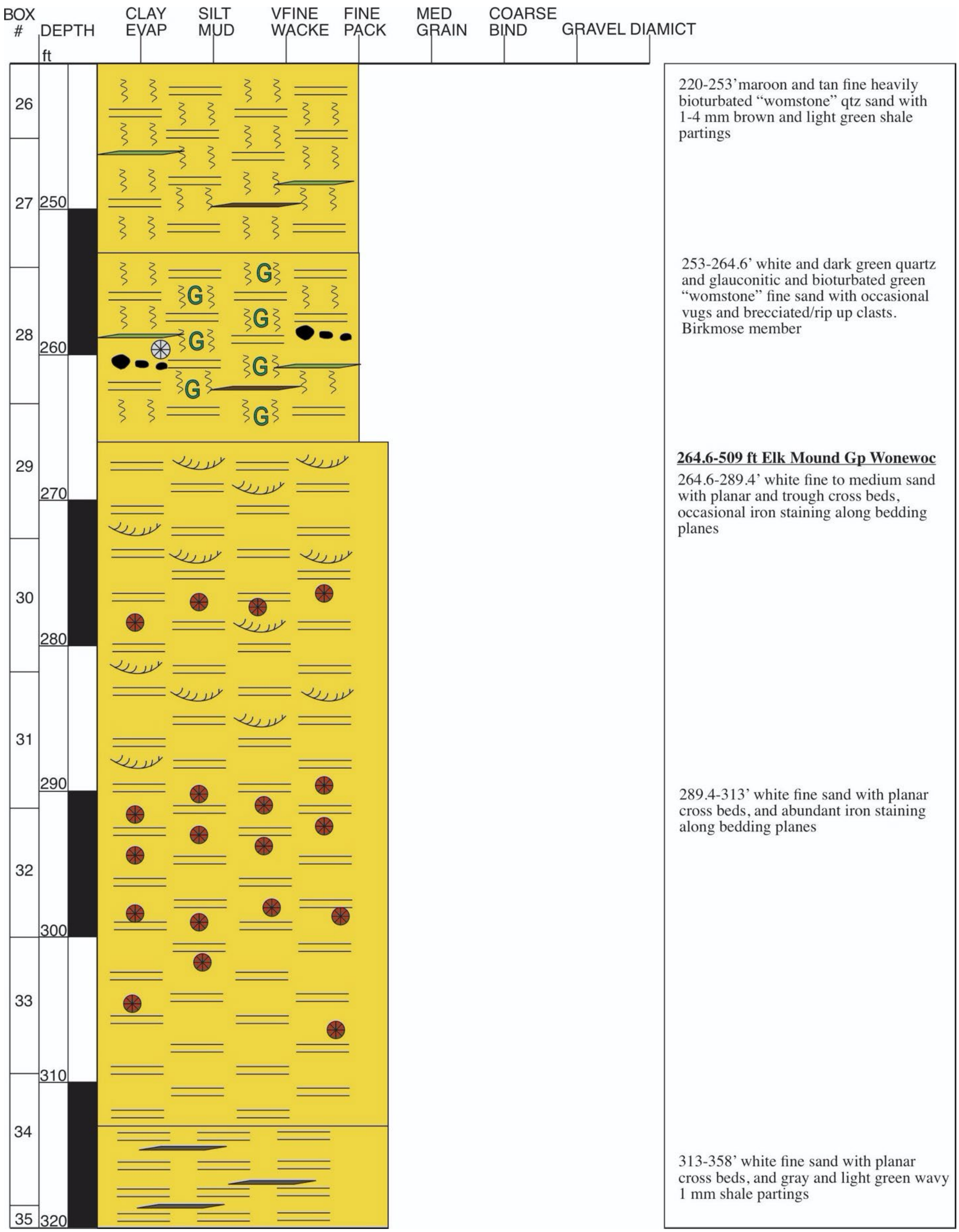


Figure A-22, Westphal 2 continued

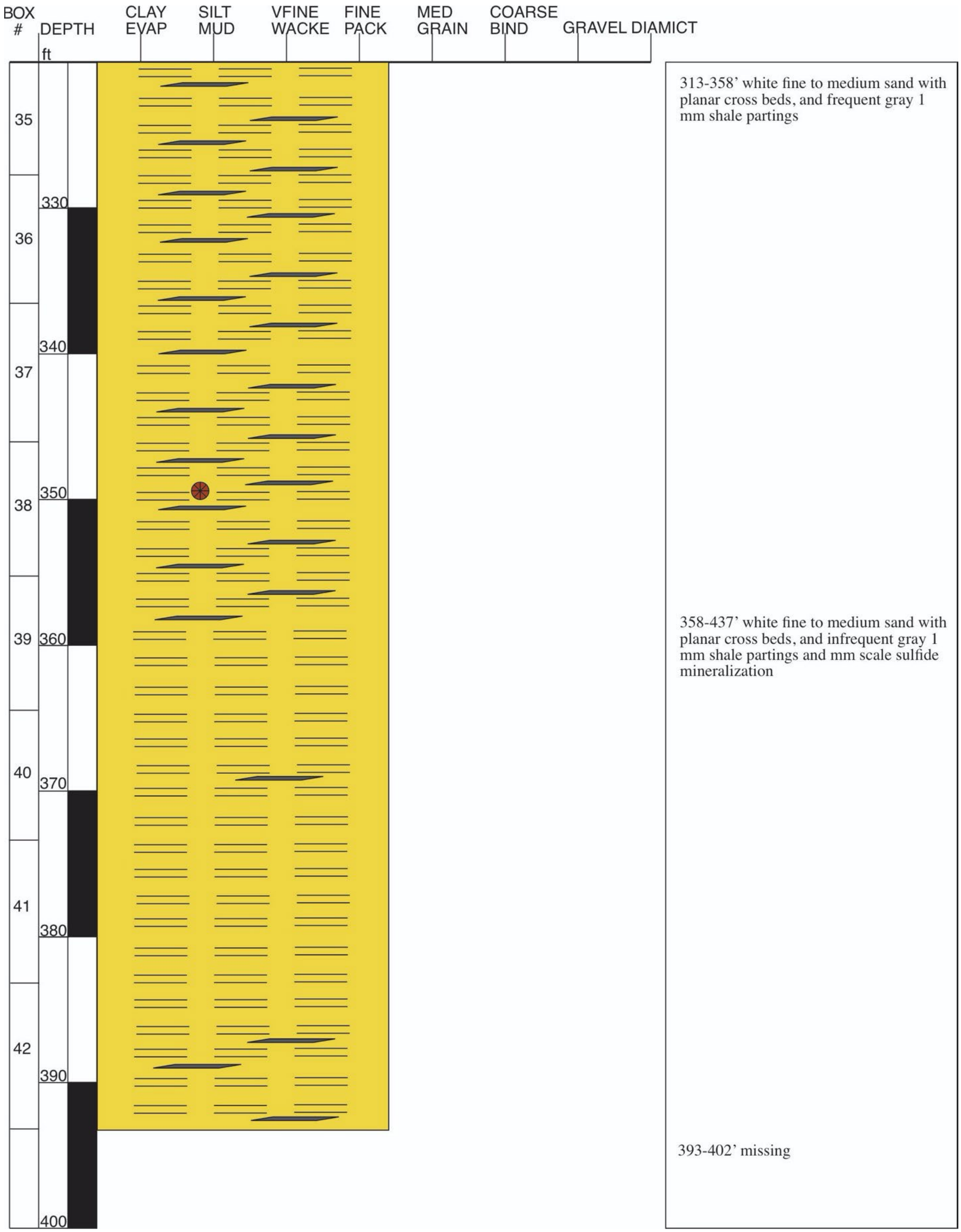
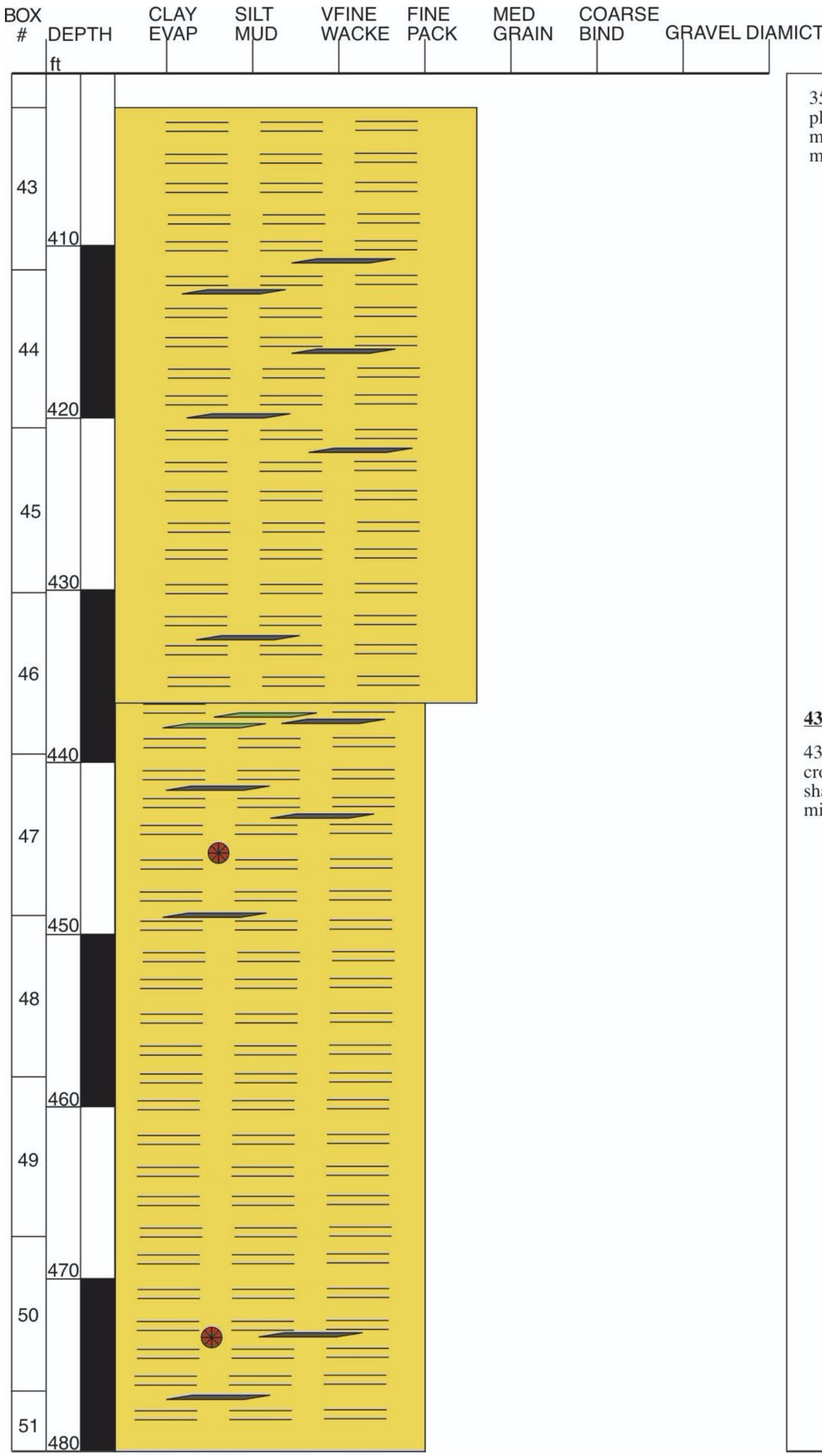


Figure A-22, Westphal 2 continued



358-509' white fine to medium sand with planar cross beds, and infrequent gray 1 mm shale partings and mm scale sulfide mineralization

<u>**437-580 ft Elk Mound Gp Eau Claire**</u>

437-509' white fine sand with planar cross beds, and infrequent gray 1 mm shale partings and mm scale sulfide mineralization

Figure A-22, Westphal 2 continued

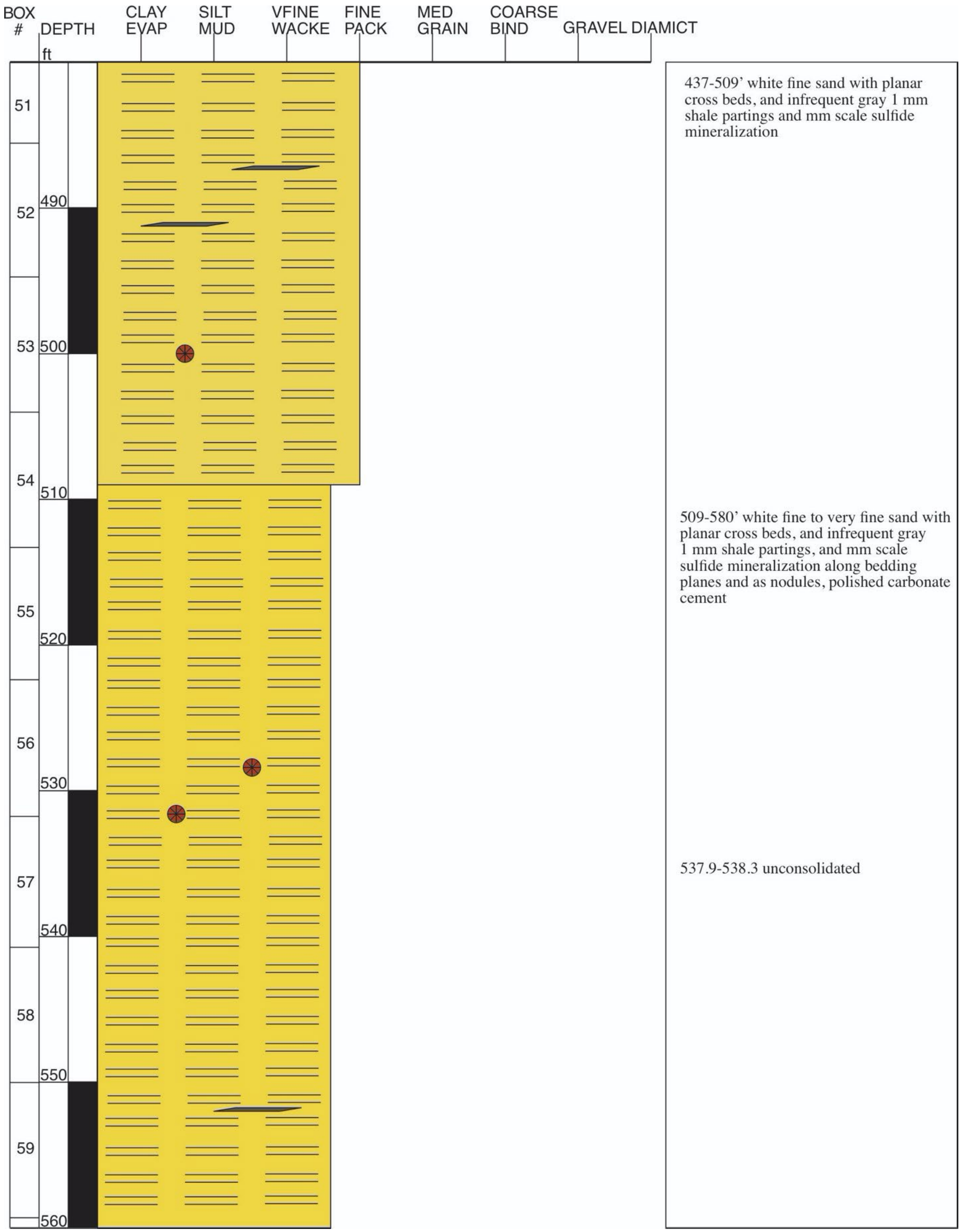
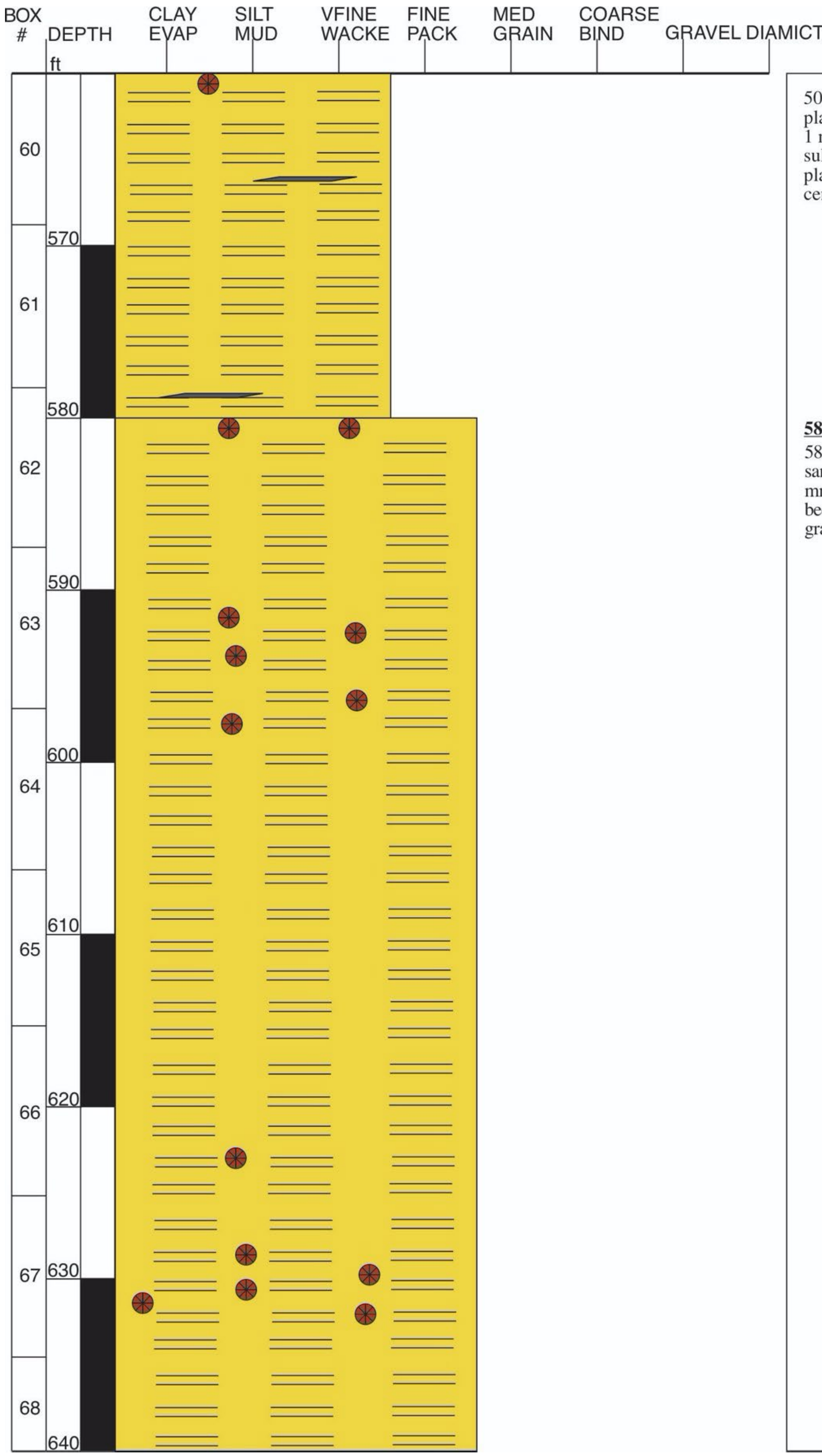


Figure A-22, Westphal 2 continued



509-580' white fine to very fine sand with planar cross beds, and infrequent gray 1 mm shale partings, and mm scale sulfide mineralization along bedding planes and as nodules, polished carbonate cement

580-688.15 ft Elk Mound Gp Mt Simon

580-688.15' white fine to medium quartz sand with planar cross beds, more abundant mm to cm scale sulfide mineralization along bedding planes and as nodules, infrequent gray 1 mm shale partings

Figure A-22, Westphal 2 continued