A Chronostratigraphic Assessment of the Pronghorn Member of the Bakken Petroleum System

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Bridget C. Wade

Major Professor: Peter E. Isaacson, Ph.D.
Committee Members: Mercedes di Pasquo, Ph.D; Renee Breedlovestrout, Ph.D.
Department Administrator: Leslie Baker, Ph.D.

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AUTHORIZATION TO SUBMIT THESIS

This thesis of Bridget C. Wade, submitted for the degree of Master of Science with a Major in Geology and titled "**A Chronostratigraphic Assessment of the Pronghorn Member of the Bakken Petroleum System**," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

Major Professor: ____________________________ Date: _____________
Peter E. Isaacson, Ph.D.

Committee Members: ____________________________ Date: _____________
Mercedes di Pasquo, Ph.D.

____________________________ Date: _____________
Renee Breedlovestrout, Ph.D.

Department Administrator: ____________________________ Date: _____________
Leslie Baker, Ph.D.

ABSTRACT

Chronostratigraphic definition of the Pronghorn Member of the Bakken Petroleum System facilitates correlation both within the Williston Basin and to coeval formations in adjacent basins. Palynological analysis of the Pronghorn Member reveals parasequences, depositional environments, and relative age. The Pronghorn Member consists of a discrete depositional sequence, variably preserved throughout the basin although locally complete.

Three palynofacies were established within the Pronghorn Member, corresponding to an open marine Lowstand Systems Tract, an intermediate marine Transgressive Systems Tract to Highstand Systems Tract, and a restricted marine Falling Stage Systems Tract. This palynological assemblage corresponds to the palynozone VCo.

Pronghorn Member microfossil and macrofossil assemblages are similar to those of the Trident Member of the Three Forks Formation in Western Montana and suggest synchronous deposition of the two formations. Considering that the Bakken Formation occurs only in the subsurface, establishing an outcropping analog improves reservoir characterization.

ACKNOWLEDGEMENTS

It is essential I express my thanks and appreciation to Petrogulf Corporation, PRISEM Geoconsulting, and Whiting Petroleum for their insight, support, and more tangibly, core.

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1. INTRODUCTION

The Bakken Petroleum System is prominently one of the most productive resource plays in North America, producing 450 million barrels of oil between 2008 and 2013 and with estimated mean undiscovered reserves of 7.4 billion barrels of oil and 6.7 trillion cubic feet of natural gas (Gaswirth et al., 2013). The Bakken Petroleum System includes the five members within the Bakken Formation, the underlying Three Forks Formation, and the overlying Lodgepole Formation limestone seal (Nordeng, 2009; Gaswirth et al., 2013; Skinner et al., 2015).

The Bakken Petroleum System includes both a tight reservoir and conventional accumulations of hydrocarbons (Nordeng, 2009). The Bakken Formation Members, from oldest to youngest are the Pronghorn, Lower Bakken Silt, Lower Bakken Shale, Middle Bakken Silt, and Upper Bakken Shale (Figure 1.1) (Skinner et al., 2015). The Devonian-Mississippian boundary occurs within the Middle Bakken Member (Figure 1.3) (Hayes, 1985; Holland et al., 1987; Angulo and Buatois, 2011; di Pasquo et al., 2017). The Lower Bakken Shale and the Upper Bakken Shale are the petroleum source rocks and the Three Forks, the Pronghorn, the Lower Bakken Silt, and the Middle Bakken Silt members are hydrocarbon reservoirs. The Three Forks Formation is the lowermost target within the Bakken Petroleum System (Nordeng, 2009; Bottjer, 2013).

The Bakken Formation occurs exclusively within the Williston Basin subsurface, and extends from North Dakota into eastern Montana and into the southernmost portion of Saskatchewan and Manitoba (Sandberg and Hammond, 1958; Brindle, 1960; Smith and Bustin, 1998; Doughty et al., 2014). The Three Forks Formation, however, extends west of the Williston Basin, into western Montana and central-southeastern Idaho where it outcrops extensively (Figure 1.2) (Sandberg, 1961; Grader et al., 2016). In Montana and Idaho, the Three Forks Formation is overlain by the Sappington Formation, which is known to be time correlative to the Bakken Formation (Figure 1.3) (Sandberg and Hammond, 1958; Grader et al., 2014; Doughty et al., 2014; Sonnenberg, 2017). Despite the known correlation between the Bakken and the Sappington formations, the relationship between the Sappington-Three Forks and the Bakken-Three Forks, particularly at their respective formation contacts, is obscured by a stratigraphic and chronostratigraphic gap. The Central Montana Uplift which formed the western depositional margin of the Williston Basin during the late Devonian and is the eastern depositional margin for the Sappington Formation creates a stratigraphic gap while a period of nondeposition and erosion concluded the deposition of the Three Forks, creating a chronostratigraphic gap (Figure 1.5) (Sonnenberg, 2017). There is no modern analog for the black shales of the Late Devonian, therefore being able to observe them easily in outcrop has become important in understanding their nuances (Smith and Bustin, 1998).

The Pronghorn Member of the Bakken Formation, formerly known as the Sanish "sands", has been a source of confusion due to its discontinuous extent within the basin, inconsistent definition, and until recently, disputed nomenclature (Bottjer 2011; LeFever, 2015). The Pronghorn Member is bounded by unconformities and in many areas of the basin is absent, resulting in the Lower Bakken Shale or the Lower Bakken Silt directly overlying the Three Forks Formation (Berwick and Hendricks, 2011; LeFever, 2013). This is significant since where the Pronghorn sandstone facies is present, it acts as a hydrocarbon reservoir.

No analog to the Pronghorn has yet been established among the western Montana outcropping lithologies.

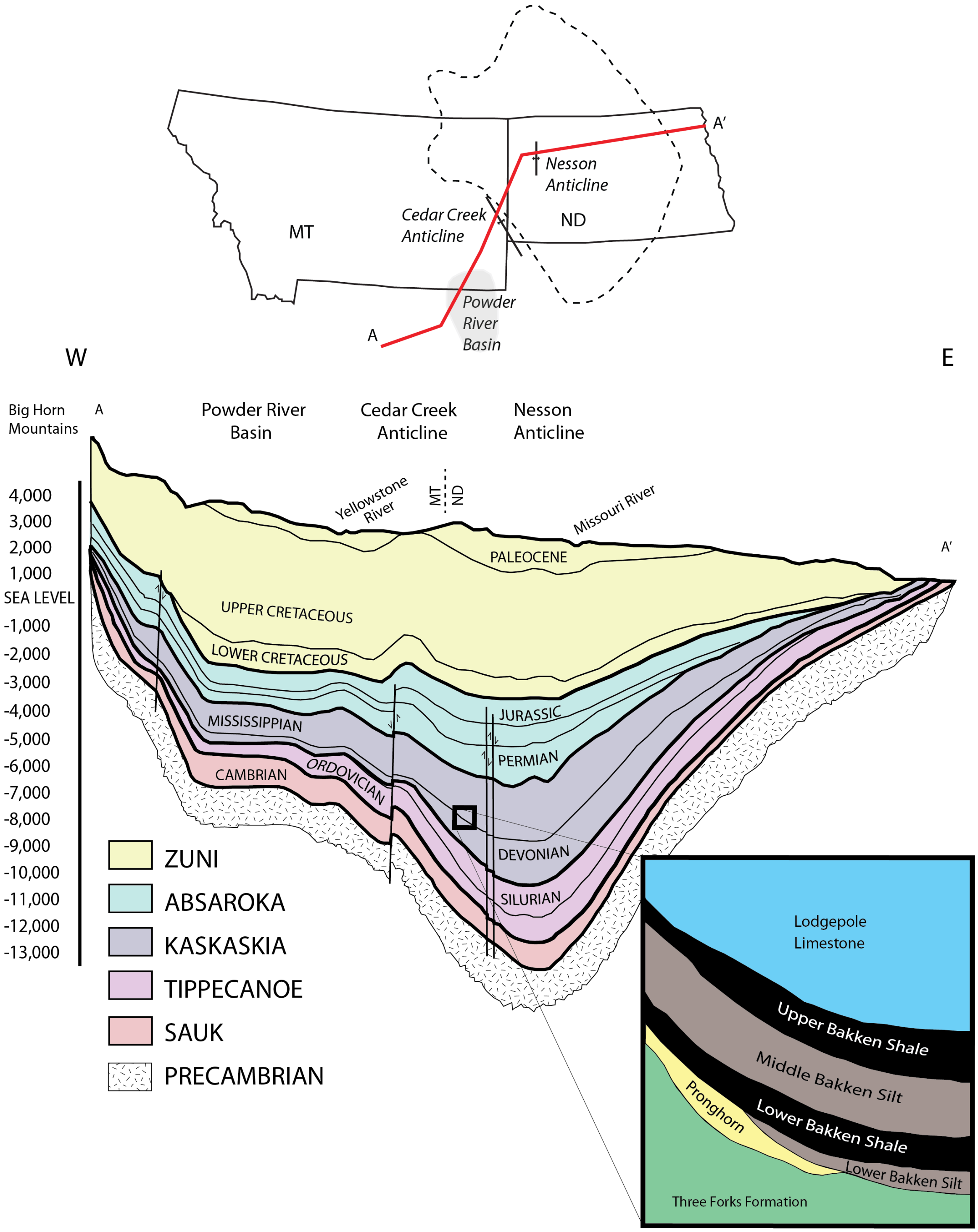

Figure 1.1. Cross section of the Williston Basin from the northeastern corner of North Dakota to the Big Horn Mountains in Wyoming. Cartoon inlay depicts relationship between Bakken Petroleum System formations. Basin profile illustrates Sloss Supersequences. Note the Bakken Petroleum System is within the Kaskaskia Supersequence. Modified from Brindle (1960) and Burgess (2008).

Figure 1.2. Geopolitical map with Williston Basin outlined in the dashed black line. Outcrops of Mississippian and Devonian formations, including the Mississippian Sappington Formation and the Devonian Three Forks Formation are shaded. Modified from Brindle (1960).

The Idaho and Montana Three Forks Formation outcrops are divided into the Logan Gulch Member and the Trident Member; the Logan Gulch Member is older than the Trident Member (Fig. 3) (Sandberg, 1965). The Three Forks Formation is bounded above and below by sequence boundaries, and its two aforementioned members are separated by a sequence boundary (Gutschick et al., 1962; Sandberg, 1963; Grader et al., 2014). The top of the Sappington Formation is also marked by the presence of a sequence boundary (Grader et al., 2014). Sequence Stratigraphy in the Williston Basin suggests a sequence boundary at the base of the Lower Bakken Silt and between the Lower Bakken Shale and Middle Bakken Silt Members, with the top of the Upper Bakken Shale Member marked by a maximum flooding surface (Smith et al., 2000; Egenhoff et al., 2011).

In western Montana, the Three Forks Formation contains fossils that indicate a Late Devonian age (Sandberg and Hammond 1958; Gutschick et al., 1962). Recent palynological work done by Warren (2016) asserts that the Devonian-Mississippian boundary is at the base of the upper member of the Sappington Formation. Within the Williston Basin, the Devonian-Mississippian Boundary is found within the Middle Bakken Silt (Holland et al., 1987). Floral and faunal assemblages from the Pronghorn Member of the Bakken Formation have yet to be detailed.

The ambiguity of the Pronghorn Member within the Williston Basin and its recent name standardization leave room for its definition, particularly regarding the location of its associated sequence boundaries. This study seeks to chronostratigraphically define the Pronghorn Member in order to place it within the context of the regional sequence stratigraphic framework and establish its relationship to the Trident Member of the Three Forks Formation and the Lower Bakken members. By correlating the Pronghorn Member to coeval formations in Western Montana, we can study these analogous Pronghorn facies in outcrop. Tying the Pronghorn to an outcropping formation facilitates more economic studies of its reservoir facies and could perhaps reveal some of its broader environmental context that led to the development of these facies. Considering the Bakken Petroleum System is already a stacked play, an additional economic interval would be valuable.

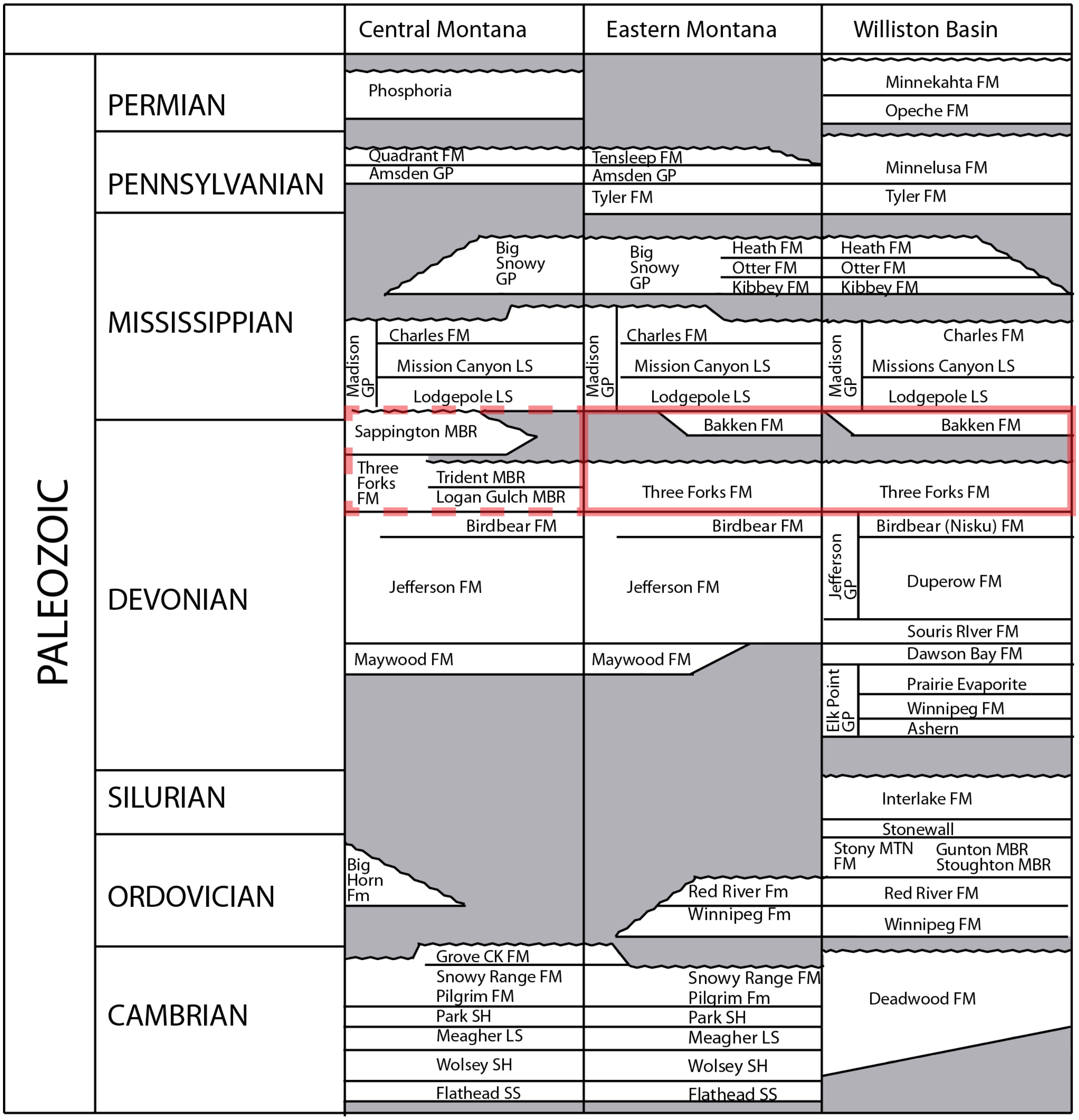

Figure 1.3. Space time correlation chart after Maughan (1988). The formations outlined in solid red are the Bakken Petroleum System source and reservoir formations. The formations outlined with the dashed red line are coeval analogous outcropping strata in Western Montana. The Sappington Formation and the Bakken Formation are separated by the Central Montana Uplift. The Lodgepole Limestone is the sealing facies.

2. OBJECTIVES

•Establish palynofacies of the Pronghorn Member.

• Define the lithofacies of the Pronghorn Member and their relationship to the palynofacies of the Pronghorn Member.

• Establish a relative age of the Pronghorn Member using palynological biostratigraphy, particularly in relation to underlying and overlying formations and members.

• Correlate the subsurface Pronghorn Member to outcropping lithologies in Montana

• Determine the relationship between the Pronghorn Member's micro/macro fossils and Montana micro/macro fossils, particularly within the Trident Member of the Three Forks Formation.

• Define the parasequences of the Pronghorn Member.

• Determine whether the Pronghorn Member can be split into a Lower and Upper Member and how these may relate to palynofacies.

3. GEOLOGIC SETTING

The Williston Basin is an intracratonic basin on the North American continent that has experienced episodic deposition throughout the Phanerozoic, along with extensive downwarping and peripheral flexure of the crust (Kent and Christopher, 1994). The earliest sediments preserved are Middle Cambrian in age, although significant subsidence did not occur until the Middle Ordovician (Crowley, 1985). The basin's intracratonic nature left deposition subject to epeiric seas, resulting in stratigraphy that coincides with Sloss's (1963) cratonic sequences (Figure 1.1). Despite significant erosional events, maximum thickness at the basin's center still reaches over 15,000 feet (Anderson, 2009). Basin sediments are thickest at the center and thin to zero at the basin margins due to both depositional onlap and erosion, with each successively younger stratum often more laterally extensive than its predecessor (Sloss 1963; Gerhard et al., 1982).

The Williston Basin is geographically situated on top of the Paleoproterozoic Trans Hudson Orogen suture, and just west of the Mesoproterozoic Belt-Supergroup, which account for many of the basin's inherited structural weaknesses (Figure 3.1) (Gerhard et al., 1982; Peterson, 1986; Kent and Christopher, 1994; Anna et al., 2010). The basin developed at the collisional junction of the Archean Wyoming, Hearne, and Superior provinces; the thickened collisional crust being a likely instigator of initial basin sag (Corrigan et al., 2010; Kent and Christopher, 1994). Many of these Proterozoic fault networks were periodically reactivated throughout the Phanerozoic and are associated with periods of accelerated subsidence and increased accommodation (Sandberg and Hammond, 1958; Gerhard et al., 1982; Dorobek et al., 1991). Unstable peripheral structures to the west of the basin were also intermittently activated throughout the Phanerozoic, affecting deposition within the basin as well as the western depositional limit of Williston Basin strata (Sandberg and Hammond, 1958; Peterson and Smith, 1986; Dorobek et al., 1991).

The Trans Hudson Orogeny was a north-south trending orogenic belt that sutured Archean provinces together to form the supercontinent Columbia during the Paleoproterozoic (Corrigan et al., 2010). Although the early Mesoproterozoic saw the break-up of Columbia, it was the birth of the paleo-North American continent, Laurentia

(Figure 3.1). By the end of the Mesoproterozoic the continents, including Laurentia, had reunited in the form of the supercontinent Rodinia (Scotese, 2009). While Laurentia was a part of Rodinia, it hosted an inter-cratonic basin, depositing the Belt-Supergroup on the western perimeter of Laurentia. After the break-up of Rodinia, and in the twilight of the Neoproterozoic, Laurentia drifted into the southern hemisphere to join the continents in the creation of the supercontinent Pannotia (Scotese, 2009). The reunion was short, Pannotia rifted apart soon after. This rift opened the paleo-Atlantic Ocean, Iapetus, and the Laurentian continent was once again autonomous. Despite these continent unions and rifts, the Laurentian core, composed of the Trans Hudson Orogen-sutured provinces and bearing the complex fault networks of numerous collisions, remained intact.

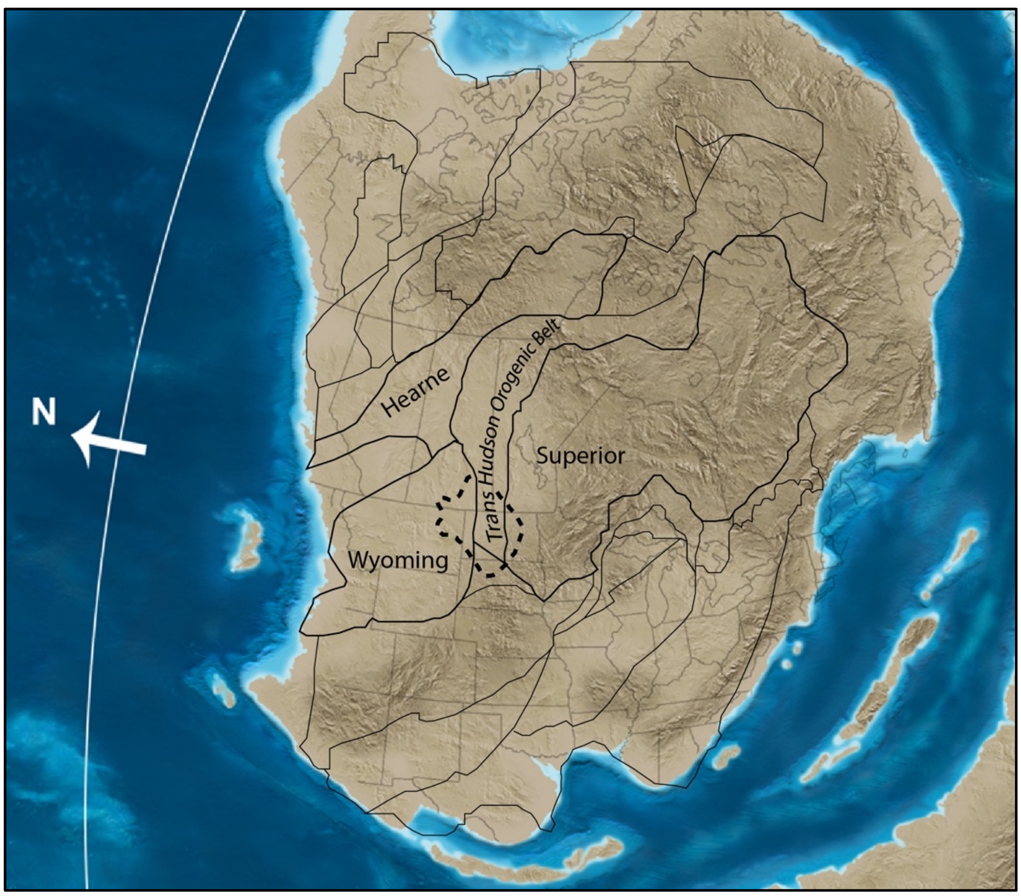

Figure 3.1. Laurentia and its provinces during the Neoproterozoic. Williston Basin is marked by the dashed line; provinces are marked by a solid line. Modified from Hoffman (1988) and Blakey (2008).

Pannotia's rift left Laurentia with a passive western margin (Dorobek et al., 1991). During the early Paleozoic Laurentia was situated equatorially and the basin, not yet structurally defined, was merely a shallow embayment along the Central Montana Trough on the western margin of the craton (Gerhard et al., 1982; Dorobek et al., 1991). The Williston Basin's mid-Cambrian through Ordovician strata belong to the Sauk sequence and are derived from an eastward transgression of the Panthalassic Ocean onto the Laurentian craton (Sloss, 1961; Gerhard et al., 1982). Resulting lithologies reflect shallow marine to terrestrial deposition that unconformably onlapped the rough, irregular crystalline basement (Gerhard et al., 1982; Neisham, 2012).

A eustatic drop during the mid-Ordovician initiated a period of erosion and nondeposition, however the existing accumulation had already begun the positive feedback loop of tectonic subsidence (LeFever et al., 1987). Despite this increasing accommodation, significant erosion of existing strata, especially along the margins, once again exposed some of the Precambrian basement resulting in younger strata overstepping older strata once sea leave rose toward the end of the Ordovician (Sloss 1963). These late Ordovician – Early Devonian strata of the Williston Basin align with the Tippecanoe sequence (Sloss 1963; Gerhard et al., 1982).

During the Devonian, the Antler allochthon was being thrust eastward onto Laurentia, loading the craton's western margin, creating the Antler foredeep and its associated back bulge basins (Figure 3.2) (Nekhorosheva and Sarg, 2011). Antler Orogenic compressive stresses are affiliated with several distal structural domes and uplifts on the western flank of the Williston Basin, which influenced erosion and deposition around and within the basin (Sandberg, 1964; Dorobek et al., 1991). These Western Montana topographic features exist along Proterozoic-defined structures and the reactivation of the Laurentian margin instigated frequent inversions of these features; topographic highs became lows, topographic lows became highs (Dorobek et al., 1991).This tectonically active western basin margin, paired with a stable eastern margin resulted in basin geometry that fluctuated frequently throughout the end of the Devonian and was periodically open to the western seas (Sandberg, 1964; Anna et al., 2013).

Towards the end of the early Devonian the Kaskaskian seas transgressed across the craton immersing the previously subaerially exposed Williston Basin in a shallow sea (Sloss, 1963; Sandberg, 1964). Subsidence within the basin center, concurrent with gentle tectonic uplift along the periphery, restricted the middle Devonian epeiric sea and concentrated both deposition and salinity within the basin center (Sandberg, 1964). The earliest Frasnian shallow waters of the Williston Basin were normal salinity and produced the extensive carbonates of the Nisku (Gerhard et al., 1982). During the second half of the Frasnian and continuing into the Famennian, minor, regional, asynchronous subsidence created a reiterative cycle of normal marine and restricted marine conditions which is reflected in the heterolithic beds of the Three Forks (Sandberg, 1964, Gerhard et al., 1982). The deposition of the Three Forks marked a pause in the middle of the Kaskaskia sequence (Gerhard et al., 1982). At the conclusion of the deposition of the Three Forks, localized regions on the periphery of the Williston Basin were activated and became positive (Sandberg and Klapper, 1967). During the second half of the Famennian minor regressions produced regional packages of coarser-grained material, although a transgressive push just before the Mississippian resulted in the organic-rich, fine-grained sediments that dominated the global seascape at the time (Sloss, 1963).

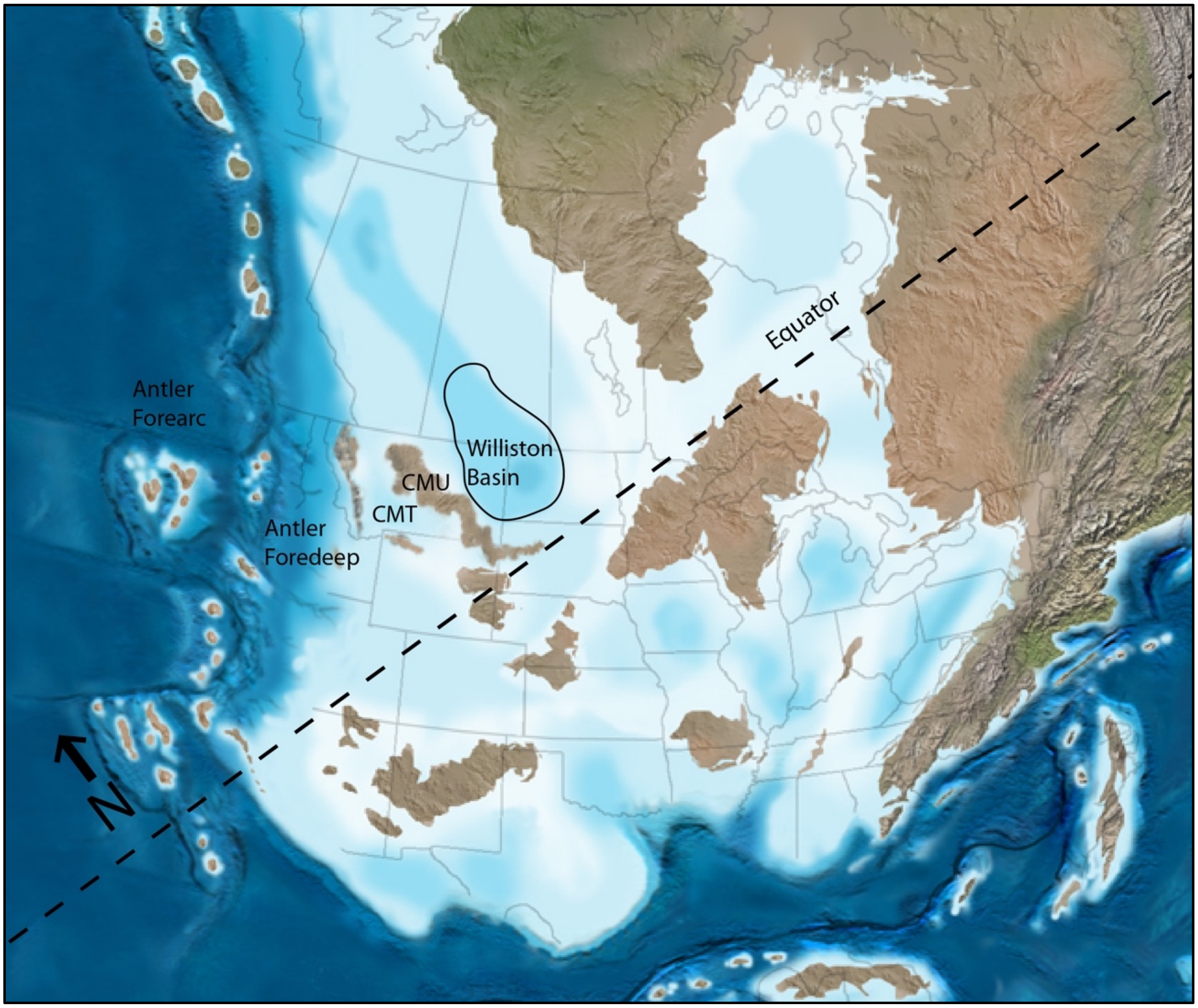

Figure 3.2. Late Devonian Paleogeographic map modified from Blakey (2008). Williston Basin demarcated by the solid black line. CMU = Central Montana Uplift; CMT = Central Montana Trough. The paleoequator is approximately 5˚ south of the Williston Basin after Smith and Bustin (1998).

4. PREVIOUS WORK

Nomenclature and Stratigraphic Placement

Both "Sanish" and "Pronghorn" are names that have been applied to the unconformible sands encountered above the Three Forks Formation, and these sands have been formally acknowledged as members of both the Bakken and the Three Forks by various authors. This inconsistent nomenclature and disputed membership has made definition of the Pronghorn an ongoing process. Lefever and Nordeng (2011) proposed abandoning the term Sanish and exclusively using the name Pronghorn to refer to the sands between the Bakken and Three Forks. In compliance with this recent attempt for standardization, all original assertions and discussion in this assessment will refer to this stratum as the Pronghorn or Pronghorn Member.

The North Dakota Geological Survey introduced the Sanish sands as a member of the Bakken in 1954. In 1958, Sandberg and Hammond described the Sanish as a member of the Three Forks, which Sandberg and others continued to support (Sandberg, 1961; Sandberg, 1964, Heck et al., 1999; Berwick, 2008). More recent studies and publications (Dykes, 2007; Bottjer et al., 2011; Johnson, 2013) including those from the North Dakota Geological Survey have asserted that the Pronghorn is a member of the Bakken Formation, citing evidence of its similarity to the Middle Bakken Silt, conodont zonation, sequence stratigraphy, and the regionally persistent unconformity between the Three Forks and the Pronghorn (Bottjer et al., 2011; LeFever et al., 2011).

Berwick (2008) identified the Pronghorn-Lower Bakken contact as a sequence boundary, suggesting that the Pronghorn Member and the Three Forks Formation must therefore be genetically related. Berwick and Henderson (2011) modified this, identifying the Three Forks-Pronghorn contact as the sequence boundary and the Pronghorn-Bakken contact as a marine flooding surface. The presence of these bounding unconformities and/or surfaces make their definition essential to the definition of the Pronghorn.

The northern portion of the Williston Basin in Canada introduces additional problems with nomenclature since the formations have not been internationally standardized. In Canada, the Bakken Petroleum System consists of the Bakken Formation and the underlying Torquay Formation and Big Valley Formation (Christopher, 1961). The Canadian Big Valley Formation and Torquay Formation are part of the Three Forks Group and they are analogous to the United States Three Forks Formation (LeFever et al., 1991). The Big Valley Formation has been correlated lithologically to the Pronghorn Member of the Bakken Formation however, relative ages seem to suggest that the Big Valley is younger (Playford and McGregor, 1993; Bottjer et al., 2011).

Palynozones & Biozones

The latest Devonian stage, the Famennian, from 372.2 – 360.7 Ma, has been divided into three substages in North America and four substages in Europe which are defined by the appearance of particular microfossils, usually conodonts (Streel et al., 1998; Sandberg et al., 2002; Trapp et al., 2004). These substages, from oldest to youngest, are the lower Famennian, middle Famennian, the upper Famennian, and the uppermost Famennian in Europe and lower Famennian, middle Famennian, and upper Famennian in North America (Streel et al., 1998; Sandberg et al. 2002). The European uppermost Famennian and North American upper Famennian are also referred to as the Strunian, which is what this stage will be referred to throughout the extent of this study. The Strunian occurs from 363.0-360.7 Ma and is defined by the beginning of the late *expansa* conodont zone and continues to the end of late *praesulcata* zone (Figure 4.1.) (Streel et al., 1998; Streel et al., 2006). The beginning of the late *expansa* zone corresponds to the beginning of the LL palynozone, and the end of the late *praesulcata* zone corresponds to the end of palynozone LN. The end of palynozone LN is marked by the last occurrence biohorizon, or LOB, of *Retispora lepidophyta*. The palynozones, in ascending order, LL, LE, and LN are thus wholly contained within the Strunian (Figure 4.1.). The palynozone VH precedes the palynozone LL and is within the Middle Famennian, not the Strunian.

Conodont biostratigraphy has refined the placement of the Devonian-Carboniferous Boundary in the Bakken Formation with the identification of the first occurrence biohorizon, or FOB, of the Tournaisian conodont *Siphonodella sulcata* within the Middle Bakken Silt (Christopher, 1961; Macqueen and Sandberg, 1970; Thorez et al., 2006; Egenhoff, 2016). This places the Lower Bakken members and the Three Forks Formation firmly in the Late Devonian. To date, there has been little work done on defining the Strunian-middle Famennian boundary in the Williston Basin (Sandberg et al*.,* 1988; Egenhoff, 2016).

The Sappington Formation in Western Montana has been established as an analogous depositional system to the Bakken Petroleum System and has been studied as a proxy (Doughty et al. 2014). The similarity in the lithologies of the Sappington Formation and Bakken Formation, their proximity to one another, as well as the presence of the Devonian-Carboniferous Boundary datum, have facilitated correlation.

The Trident Member of the Three Forks Formation of Western Montana has been dated and given a Middle Famennian age based on microfossil data, corresponding to the conodont zones *postera, trachytera,* and *marginifera,* and the palynozone VCo (Sandberg and Poole, 1977; di Pasquo et al*.,* 2017). The Lower and Middle Sappington Formation is given a Strunian age, corresponding to the upper *expansa* and the *praesulcata* conodont zones, and the LL, LE, and LN palynozones (di Pasquo et al*.,* 2017). The Devonian-Mississippian Boundary, announced by the FOB, of *sulcata,* is within the top of the Middle Sappington (di Pasquo et al*.,* 2017)

Based on Playford and McGregor's 1993 palynological assessment of the Canadian Bakken Petroleum System, the Big Valley Formation and the Torquay Formation would be Strunian due to the reported presence of *Retispora lepidophyta;* however, precise sampling locations were not given.

Retispora lepidophyta is one of the most diagnostic miospores of the Strunian due to its global distribution and high abundance, sometimes composing as much as 50% of sample miospore assemblages (Streel, 2008). The *Retispora lepidophyta* FOB is the beginning of the VH palynozone, just before the Strunian, and its last occurrence biohorizon, or LOB, is the end of the LN palynozone, marking the end of the Devonian.

Based on Playford and McGregor's (1993) reported findings of *Retispora lepidophyta,* the Big Valley Formation, which is considered coeval to the Trident member of the Three Forks Formation, would be younger than the Trident Member.

Certain megafaunas have also served as diagnostic age markers. Ammonoid zones have been established for the Paleozoic and have been particularly useful in the Devonian. The *Wocklumeria* ammonoid zone corresponds to the *praesulcata* conodont zone and the *Gattendorfia* ammonoid zone corresponds to the Tournasian (Sandberg and Klapper, 1967; Korn, 2000; di Pasquo et al., 2017). The *Clymenia* zone precedes the *Wocklumeria* zone (Sandberg and Klapper, 1967; Korn, 2000).

Consideration of megafaunas is significant since the VCo palynozone has a low abundance of miospores and is predominantly composed of long-ranging acritarchs.

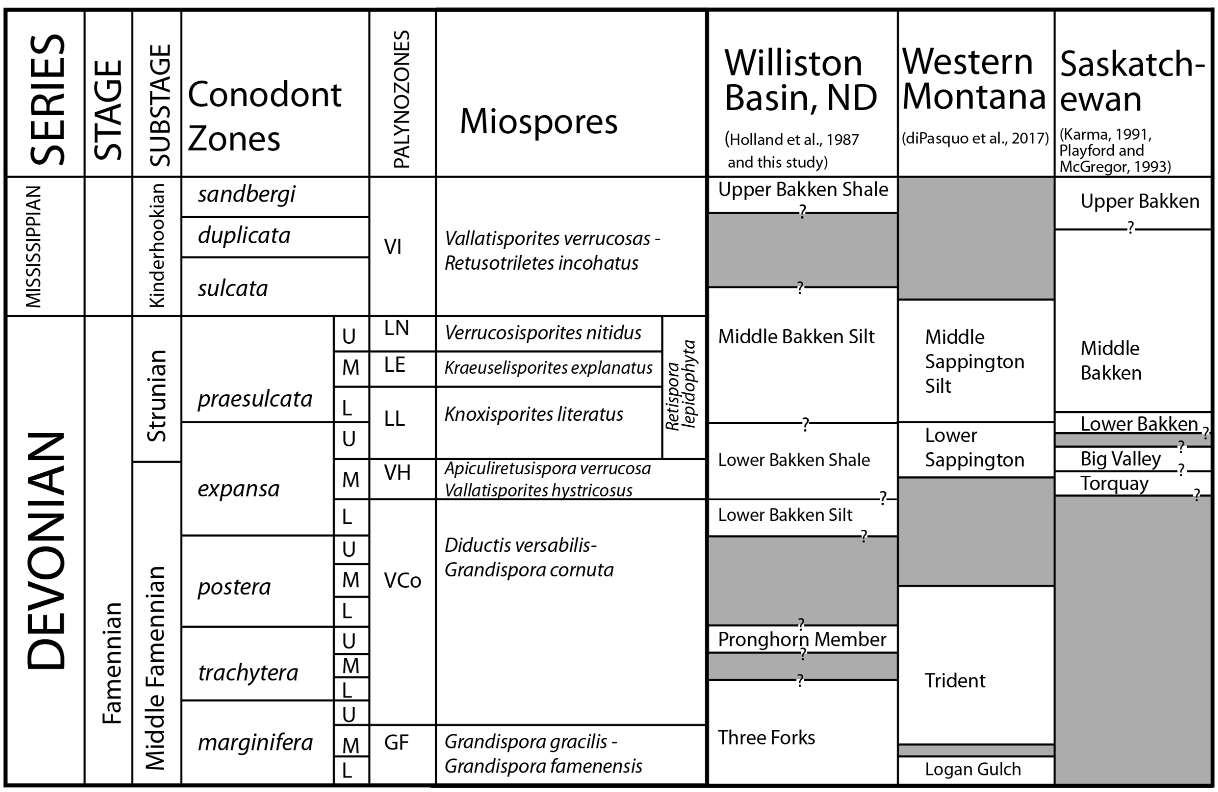

Figure 4.1. Biozonation correlation chart. After di Pasquo et al., (2017).

Microfossils

The palynology of the Late Devonian and Early Mississippian has been studied extensively on a global level, however its resolution within the North American continent is still relatively low (Braman and Hills, 1992). The palynology of the Williston Basin has been limited to borehole samples from Southern Saskatchewan and the outcropping Sappington Formation and Three Forks Formation of Western Montana. This has left the U.S. Williston Basin Bakken Petroleum System palynology poorly defined.

Previous work done in Western Montana on the outcropping Sappington Formation and Three Forks Formation members delineated palynological assemblages, linked them to existing palynozones and conodont biozones, and increased the chronostratigraphic resolution around the Devonian-Mississippian boundary. The Devonian-Mississippian boundary occurs above Unit 4 of the Sappington (Figure 4.2), which, correlates to the Middle Member of the Bakken Formation. Below the Devonian-Mississippian boundary, di Pasquo et al., (2017) established the biozones LAs3 in the Middle Sappington and LAs2 and LAs1 in the Upper and Lower Trident, respectively, based on the palynological assemblages found.

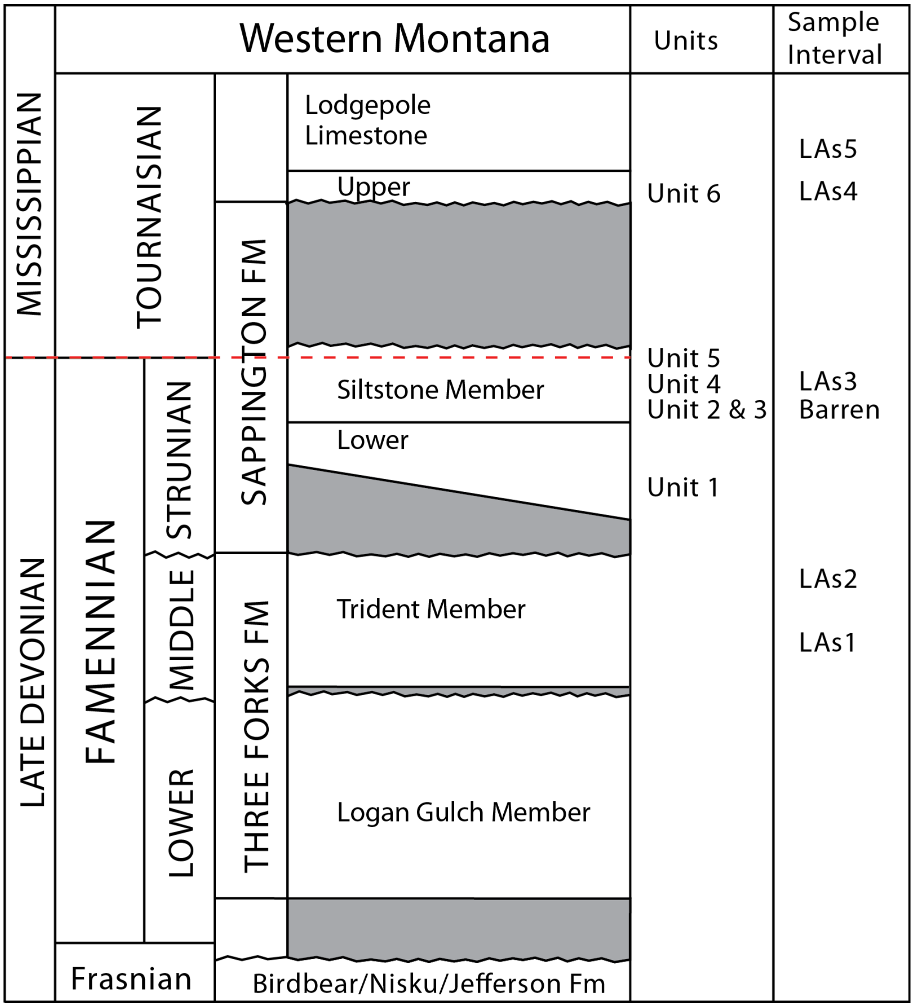

Figure 4.2. Samples and sampling locations as well as biocorrelations from the Western Montana Sappington and Three Forks Formations from di Pasquo et al., 2017. Modified from di Pasquo et al., 2017.

The LAs1 assemblage of the Lower Trident Member of the Three Forks Formation has a low species richness and high abundance of long-ranging acritarchs. The phytoplankton identified with this assemblage include: *Ammonidium loriferum, Cymatiosphaera perimembrana, Gorgonisphaeridium absitum, Gorgonisphaeridium evexispinosum, Gorgonisphaeridium ohioense, Gorgonisphaeridium plerispinosum,* a variety of *Leiosphaeridia* morphotypes, *Michrystridium coronatum, Solisphaeridium astrum,* *Stellinium micropolygonale, Unellium lunatum, Unellium piriforme, Veryhachium downeii, Veryhachium polyaster* and *Veryhachium trispinosum*. The miospores identified with this assemblage include: *Auroraspora macra, Grandispora echinata,* and *Retusotriletes incohatus*. The LAs1 assemblage also includes some scolecodonts. Di Pasquo et al., (2017) found this assemblage consistent with the VCo biozone.

The LAs2 assemblage from the Upper Trident Member of the Three Forks was low in species richness and included *Gorgonisphaeridium ohioense, Ammonidium loriferum, Unellium* spp., *Michrystridium* spp., *Veryhachium* spp., *Auroraspora macra, Grandispora echinata,* as well as abundant, poorly-preserved Leiosphaerids. Di Pasquo et al., (2017) did not assign this interval an age based on the LAs2 assemblage.

Di Pasquo et al., (2017) noted a distinct shift from the LAs1 and LAs2 assemblages of the Trident and the LAs3 assemblage of the Middle Sappington. They identified 55 spore species and 11 phytoplankton species in the LAs3 assemblage. The phytoplankton species include: *Cymatiosphaera chelina, Cymatiosphaera* sp., *Cymatiocphaera* spp., *Duvernaysphaera tenuicingulata, Navifusa/Deusilites* sp., *Dictyotidium fairfieldensis, Gorgonisphaeridium absitum, Gorgonisphaeridium evexispinosum, Gorgonisphaeridium ohioense, Gorgonisphaeridium plerispinosum, Gorgonisphaeridium winslowiae,* Leosphaerids-tasmanitids, *Maranhites stockmansii, Maranhites mosesii, Pterospermella* sp., *Stellinium micropolygonale,* and *Veryhachium downeii.* The spores identified include: *Anapiculatisporites* sp. cf. *A. semicuspidatus, Apiculatasporites* sp., *Apiculiretusispora* sp. cf. *A. verrucosa, Auroraspora macra, Bascaudaspora submarginata, Claytonsporites rarisetosa (Dibolisporites abstruses), Convolutispora oppressa, Convolutispora vermiformis, Convolutispora major, Cordylosporites* spp., *Cristatisporites* sp. cf. *C. mattheusii/ C. menendezii, Cyclogranisporiites* sp., *Diaphanospora perplexa, Diaphanospora rugosa, Diaphanospora submirabilis, Dictyotriletes flavus, Dictyotriletes trivialis, Emphanisporites orbicularis, Emphanisporites rotatus, Endoculeospora setaceae, Endosporites micromanifestus, Grandispora echinata, Grandispora praecipua, Grandispora saurota, Grandispora* spp., *Knoxisporites concentricus, Knoxisporites literatus, Knoxisporites* sp. cf. *K. heredatus (K. pristinus), Kraeuselisporites explanatus, Leiotriletes cf. struniensis, Leiozonotriletes* sp. cf. *Spelaeotriletes crustatus, Lophotriletes* sp., *Lophozonotriletes* sp. cf. *triangulates,* *Lophozonotriletes* sp. cf. *L. curvatus, Punctatisporites hannibalensis, Punctatisporites* spp., *Pustulatisporites dolbii, Pustulatisporites* sp., *Retispora lepidophyta, Retusotriletes crassus, Retusotriletes incohatus, Retusotriletes* sp. cf. *R. leptocentrum, Rugospora flexuosa (Hymenozonotriletes famenensis), Rugospora radiata, Spelaeotriletes crustatus, Spelaeotriletes* sp.cf. *S. pretiosus, Tumulispora rarituberculata, Vallatisporites drybrookensis, Vallatisporites splendens, Vallatisporites vallatus, Velamisporites perinatus, Velamisporites/Rugospora* spp., *Verrucosisporites mesogrumosus, Verrucosisporites nitidus,* and *Verrucosisporites papulosus.* The presence of *Retispora lepidophyta* and *Verrucosisporites nitidus* suggest that the LAs3 assemblage is of the Strunian LN palynozone.

Palynology of southern Saskatchewan's Bakken Formation serves as another valuable comparison. Playford and McGregor (1993) sampled the Upper, Middle, and Lower members of the Bakken Formation as well as the underlying Big Valley Formation and Torquay Formation, although precise sampling locations were not provided. The Big Valley Formation is stratigraphically and lithologically similar to the Pronghorn Member of the Bakken Formation (Bottjer et al., 2011). *Gorgonisphaeridium winslowiae* was found to be the most useful acritarch in establishing an age within the Williston assemblages since it seems to be entirely restricted to the Strunian, a necessary distinction considering miospores were rare in the Torquay Formation and the Big Valley Formation (Playford and McGregor, 1993).

In the Lower Shale Member of the Bakken Formation Playford and McGregor (1993) identified the following: *Gorgonisphaeridium ohioense, Gorgonisphaeridium plerispinsoum, Gorgonisphaeridium winslowiae,* and *Michrystridium stellatum.* Miospore species identified include: *Retispora lepidophyta, Vallatisporites galearis, Vallatisporites splendens, Verrucosisporites nitidus.* They suggest a Strunian age for the Lower Bakken member based on the prasinophytes identified, which they could no further define with the limited miospores present.

In the Big Valley Formation Playford and McGregor (1993) identified the following phytoplankton species: *Centrasphaeridium lecythium, Daillyidium pentaster, Gorgonisphaeridium ohioense, Gorgonisphaeridium plerispinosum, Gorgonisphaeridium winslowaie, Michrystridium stellatum, Multiplicasphaeridium ramispinosum, Solisphaeridium* *ramispinosum, Solisphaeridium spinoglobosum, Stellinium micropolygonale, Unellium piriforme, Unellium winslowiae(lunatum), Veryhachium downeii,* and *Veryhachium lairdii.* Miospore species reported included only *Retispora lepidophyta.*

In the Torquay Formation the phytoplankton species include: *Michrystridium stellatum, Michrystridium* sp. *B., Unellium piriforme, Unellium winslowiae (lunatum), Veryhachium downeii,* and *Veryhachium lairdii.* Miospore species identified included *Retispora lepidophyta.*

The Late Devonian Antrim Shale of the Michigan Basin has been studied extensively paleontologically, including through a palynological lens. Wicander and Loeblich (1977) did a comprehensive study of the Antrim Shale's microphytoplankton assemblage contributing our understanding of North American palynology. The Antrim Shale was deposited from the Frasnian until the Strunian and contains a diverse, well-preserved microphytoplankton assemblage.

The uppermost assemblage of the Antrim Shale of the Wicander and Loeblich (1977) study contained a diverse assemblage of microphytoplankton, with an overall species richness of 48. Species include: *Barathrisphaeridium paxillum, Cymatiosphaera adaiochorata, Cymatiosphaera ambotrocha, Cymatiosphaera antera, Cymatiosphaera buonolopha, Cymatiosphaera cavea, Cymatiosphaera cecryphala Cymatiosphaera chelina, Cymatiosphaera craticula, Cymatiosphaera fistulosa, Cymatiosphaera fritilla, Cymatiosphaera limbatisphaera, Cymatiosphaera maculosiverticulla, Cymatiosphaera melikera, Cymatiosphaera parvicarina Cymatiosphaera platoloma, Cymatiosphaera turbinata, Cymatiosphaera rhodana, Dasypilula storea, Elektoriskos dolos, Gorgonosphaerdium absitum, Gorgonisphaeridium elongatum, Gorgonisphaeridium ohioense, Gorgonisphaeridium plerispinosum, Gorgonisphaeridium separatum, Lophosphaeridium impensum, Michrystridium adductum, Michrystridium coronatum, Multiplicisphaerdium amitum, Multiplicisphaerdium trunculum, Solatisphaera sapra, Solisphaeridium apodasmion Solisphaeridium spinoglobosum, Spurimoyeria falcilaculata, Stellinium comptom Stellinium octoaster, Stellinium protuberum, Unellium ampullium, Unellium cornutum, Veryhachium arcarium, Veryhachium centrabrachium, Veryhachium cymosum, Veryhachium patulum,* and *Veryhachium roscidum.*

A study of the middle Famennian Annulata Shale in Poland, a formation coeval to the Trident Member of the Three Forks Formation in Western Montana, catalogs palynomorphs from a similar suite of strata below the Devonian-Mississippian boundary. Racka et al. (2010) described some select miospores and microphytoplankton. The miospores identified include: *Auroraspora macra, Auroraspora solisorta, Diducties mucronatus, Diducites poljessicus, Diducites versabilis, Endoculeospora gradzinski, Endoculeospora setacea, Grandispora cornuta, Grandispora distincta, Grandispora echinata, Grandispora facilis, Grandispora famenensis, Grandispora graciliis, Grandispora lupata, Hymenospora intertextus, Lophozonotriletes proscurrus, Retispora macroreticulata, Rugospora radiata, Spelaeotriletes papulosus.* Some of the microphytoplankton identified include: *Ammonidium loriferum, Dictyotidium* sp., *Gorgonisphaeridium ohioense, Leiosphaerids, Polyedryxium embudum, Unellium piriforme,* and *Veryhachium trispinosum.*

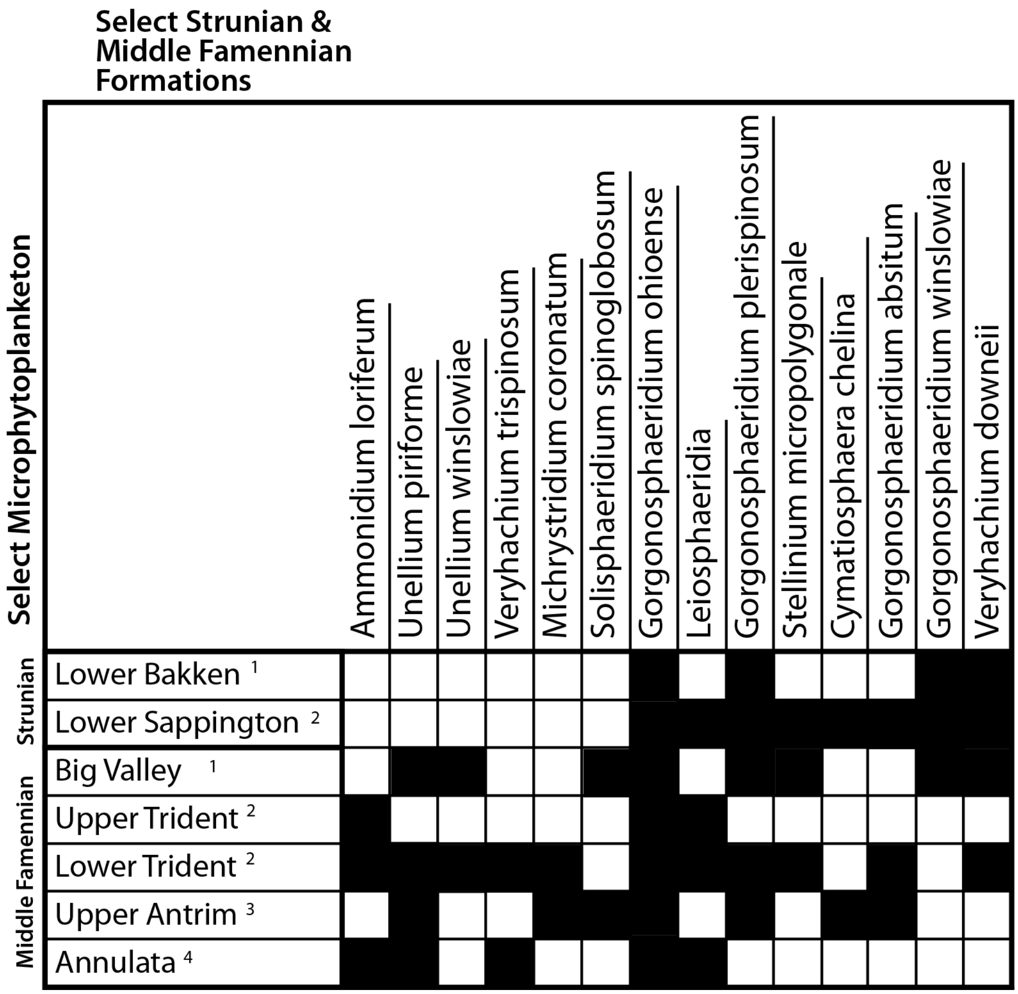

Figure 4.3. Chart illustrating selected microphytoplankton and their occurrences in Strunian and Middle Famennian formations. A black box indicates the presence of a microphytoplankton, a white box indicates the absence of a microphytoplankton. 1. Playford and McGregor, 1993; 2. Di Pasquo et al., 2017; 3. Wicander and Loeblich, 1977; 4. Racka et al., 2010. From di Pasquo et al., 2017 Lower Sappington refers to LAs3, Upper Trident refers to LAs2, and Lower Trident refers to LAs1.

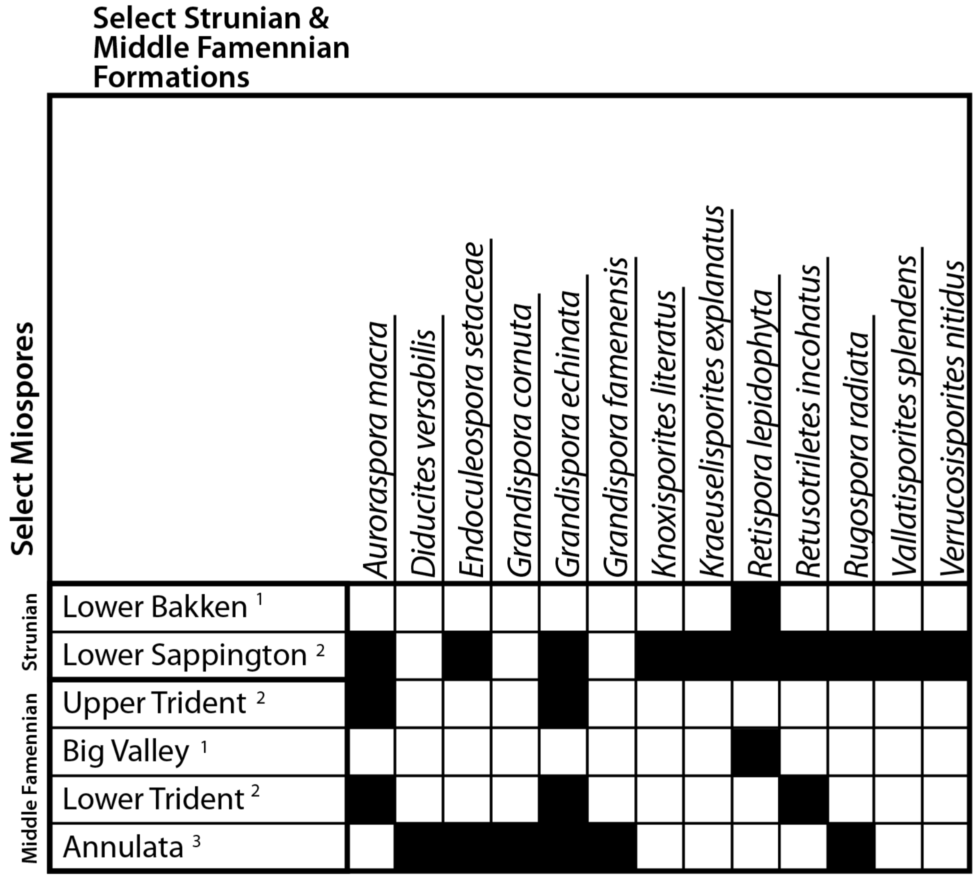

Figure 4.4. Chart illustrating selected miospores and their occurrence in Middle Famenian and Strunian formations. A black box indicates the presence of a miospore, a white box indicates the absence of a miospore. 1. Playford and McGregor, 1993; 2. Di Pasquo et al., 2017; 3. Racka et al., 2010. From di Pasquo et al., 2017 Lower Sappington (Unit 4 Sappington) refers to LAs3, Upper Trident refers to LAs2, and Lower Trident refers to LAs1.

Macrofossils

Macrofauna of the Bakken Formation (Figure 4.5) have been described by various authors, however, the Bakken's lack of outcrop necessitates use of core. Thrasher (1985) delineated the macrofauna from the Bakken Formation from a suite of cores dispersed throughout the center of the basin. He does not distinguish the Lower Bakken Silt and the Pronghorn Member from the Lower Bakken shale so all megafaunas from the lowermost portions of the Lower Bakken Shale have been considered from his study. At the base of the Lower Bakken Shale he identified *Barroisella*, a bellerophontid (*Phragmosphaera* sp), a coiled cephalopod, conodonts, *Cyzicus (Lioestheria*) sp., *Foerstia,* hylothyrid, *Lingula* sp 2, orthoceroid nautiloid, fragments of a small, costate rhynchonellid, a rhynchonellid (*Rugaltarostrum montanensis*), ostracods, low–spired gastropod (*S Straparollus* sp.), bivalves, fish fragments, fish scales, and minute spinules of an unknown organism. He observed "ostracod-like organisms," *Tasmanites,* and *Spirophyton*-like trace fossils just above the base of the Lower Bakken Member. He noted that the faunal assemblages observed in his study are comparable to those of Devonian black shales of the eastern United States. Hayes (1985) reported finding *Tasmanites, Lingula* sp*., Orbiculoidea* sp*.,* fish teeth, fish bones, conchostracans, rare ostracods, woody plant material, and sponge spicules in the Lower Bakken Shale. Similarly, he did not distinguish the Lower Bakken Silt and the Pronghorn member from the Lower Bakken Shale.

Three Forks Formation macrofaunal descriptions from the Williston Basin are notably more limited and less detailed. However, core description of the Three Forks Formation includes the presence of brachiopods, bryozoans, and algal tubes or cyanobacteria (Berwick and Hendricks, 2011).

In the Canadian portion of the Williston Basin, description of the Bakken Formation's "lower bioturbated silt" in Saskatchewan recorded the presence of *Helminthopsis (Nerites* ichnofacies) and *Chondrites* (*Cruziana* ichnofacies), crinoid columnals and ossicles, brachiopods, and ostracods (Pemberton et al*.,* 1992).

In the outcropping Sappington Formation of western Montana, macrofauna have been cataloged by numerous authors. Gutschick et al. (1962) reported that Lower Sappington, units A-E, macro fossils were scarce to rare in the lowest units increasing to very abundant in unit E. They identified the brachiopods *Orbiculoidea* sp*., Lingula* sp*.,* and *Furcaster* n. sp*.,* asterozoans, bryozoans, foraminifera, sponges, hydrozoans, the conchostracan *Lioestheria* n. sp*., Tasmanities* sp*.,* conodonts, an unidentified spiny brachiopod, and fish fragments likely from Paleoniscids.

Further, a clymenid ammonoid was identified from the Upper Trident member, corresponding to the *Clymenia* ammonoid zone (di Pasquo et al*.,* 2017). Other studies of the Montana Three Forks have identified brachiopods, including *Cyrtiopsis, Cyrtospirifer, Leiorhynchus,* and *Microspirifer, Strophopleura* as well as goniatites (Gutschick et al., 1962; Gutschick et al., 1964; Sando et al., 1985).

Comparing other middle Famennian and Strunian formations' macrofauna to those of the Pronghorn improves the quality of the dataset and the likelihood of assigning an accurate age. A comprehensive study of the Late Devonian Annulata Shale in Poland, a formation coeval to the Trident Member of the Three Forks Formation, by Racka et al. (2010) identified a distinctive assemblage of megafaunas. They identified the bivalve *Guerichia,* the clymenid *Platyclymenia,* the goniatite *Erfoudites* sp., pyritised trochospiral gastropods, the trilobite *Cyrtosymbole* sp., lingulids, including *Orbiculoidea* and *Barriosella,* and imprints of the ostracod *Richterina zimmermanni.* Another Polish study of Late Devonian brachiopods yielded *Barriosella sp., Orbiculoidea sp., Aulacella interlineata, Leptoterorhynchus magnus, Pugnaria plana, ?Pugnaria* sp., *Planovatirostrum* spp., *?Eoparaphorhyncus* sp., *?Centrorhyncus* sp., and *Cranaena Igaviensis* in the uppermost *marginifera, trachytera, postera* and Lower *expansa* conodont zones, which corresponds to the VCo palynozone (Halamski and Balinski, 2007). Another study in Poland found the uppermost *marginifera* zone, or the lower VCo palynozone, to contain the goniatitid genera *Cheiloceras, Felisporadoceras, Gundolficeras, Polonoceras, Protonoceras, Pseudoclymenia, Sporadoceras, and Tornoceras* and the clymeniid genera *Platyclymenia* and *Praeflexiclymenia* (Marynowski et al., 2007).

In the Strunian Upper *expansa* and *praesulcata* zones, Halamski and Balinski (2007) identified: *Schellwienella pauli, Mesoplica* sp., *Aulacella interlineate, Rozmanaria equitans, Pugnaria plana, Novaplatirostrum sauerlandense, Hadyrhyncha* sp., *Cleiothyridina struniensis*, *Cyrtospiriferidae* indet., *Sphenospira juli, ?Eomartiniopsis* sp., and *Reticulariidae*.

Some authors have suggested that the Bakken Formation grades laterally into the Three Forks Formation. Thrasher (1985) refutes this idea based on his assessment that the two do not share fauna, stating that this indicates diachronous ages for the Three Forks and Bakken Formations (Figure 4.5). It should be noted that Thrasher does not identify and isolate the Pronghorn Member in his study and does not make a distinction between subsurface Three Forks Formation and Western Montana Trident and Logan Gulch members of the Three Forks Formation.

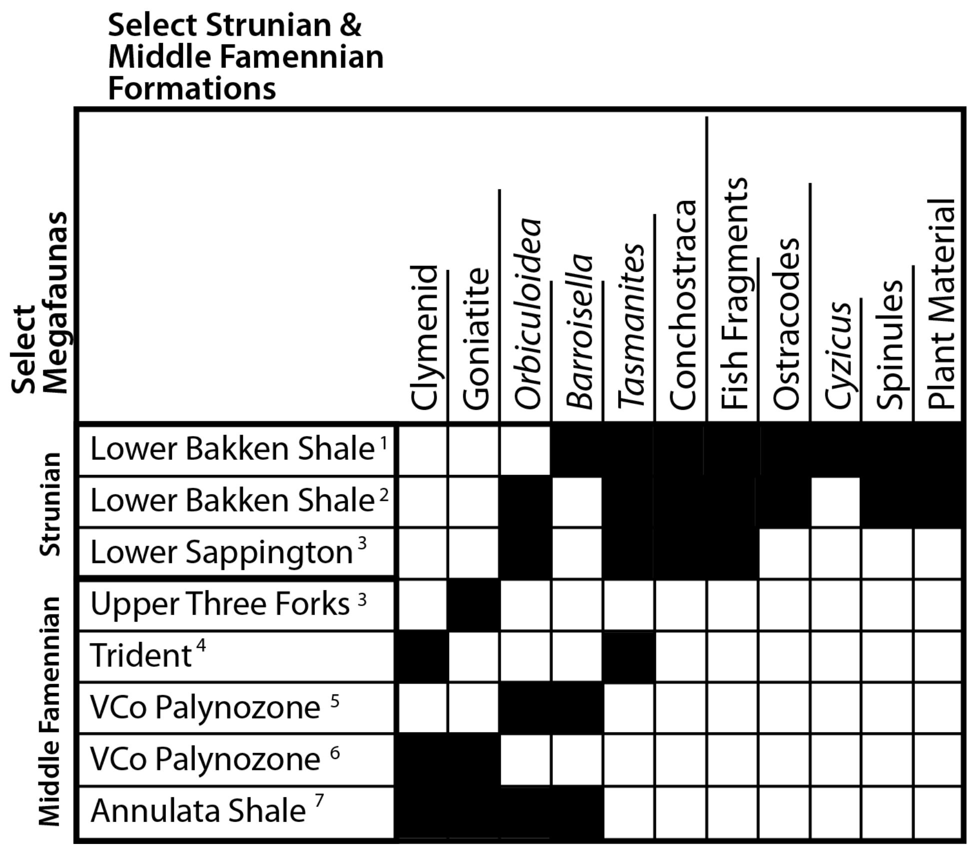

Figure 4.5. Chart illustrating the occurrence of selected Famennian megafaunas in Strunian and middle Famennian formations. A black box indicates the presence of a fossil organism; the white box indicates the absence of a fossil organism. 1. Thrasher, 1985; 2. Hayes, 1985; 3. Gutschick et al., 1962; Gutschick et al., 1964; 4. Di Pasquo et al., 2017; 5. Halamski and Balinski, 2007; 6. Marynowski et al., 2007; 7. Racka et al., 2010.

Core Description

Petrophysical and lithostratigraphic studies of the Bakken Petroleum System have documented the lithologies and attributes of the Pronghorn Member (Berwick and Hendricks, 2011; Bottjer et al., 2011; Johnson, 2013; Skinner et al., 2015). Recent attention has been given to the Pronghorn Member's sequence stratigraphic placement in order to better understand its petrophysical traits and determine whether the Pronghorn member can be split into an Upper Pronghorn and a Lower Pronghorn and whether the Pronghorn limestone correlates to the "Crystal Limestone" of Saskatchewan or the upper Trident Limestone of Western Montana (Skinner et al., 2015).

The Pronghorn Member of the Bakken Formation is consistently bounded above and below by unconformities and ranges in thickness from 0-114 feet due to regional structure and significant erosion (Skinner et al., 2015). Three to five lithofacies have been utilized to describe the Pronghorn, although these lithofacies are inconsistently represented throughout the basin; in some areas certain facies have been eroded completely (LeFever and Nordeng, 2011; Bottjer et al., 2011; Skinner et al., 2015). The main lithofacies identified include a basal, bioturbated sandstone, a limestone, a petroliferous fissile mudstone with siltstone interlaminae, a dolomitic burrowed siltstone with claystone interlaminae, and storm beds (Berwick and Hendricks, 2011; Bottjer et al., 2011; Johnson, 2013; Skinner et al., 2015).

A transgressive lag has been recognized with the limestone facies and has been identified as the contact between the Lower Bakken Silt and the Pronghorn Member, although it has also been identified as an internal lag (Johnson, 2013; Skinner et al., 2015). A lag deposit represents a rise in relative sea level after exposure and can signify the presence of a new depositional sequence. When it begins a depositional sequence, it is referred to as a sequence boundary.

The Big Valley Formation is sometimes considered an equivalent to the Pronghorn Member, and contains a "Crystal Limestone" which has been correlated to the Pronghorn Limestone (Kasper, 1992; Bottjer et al., 2011, Skinner et al., 2015). The Trident Formation's relationship to the Big Valley Formation is unclear, some authors consider the two coeval and others have argued that the Trident Formation is younger than the Big Valley Formation (Playford and McGregor, 1993; Halbertsma, 1994; Doughty et al. 2014; Hartel et al., 2014). These three formations, the Pronghorn, the Trident, and the Big Valley, are lithologically and stratigraphically similar, however their relationships to each other are undefined. In western Montana, no equivalent to the Pronghorn Member has been explicitly established.

Significant Surfaces and Parasequences

Especially in mudrock dominated systems, teasing out parasequence boundaries from lithology is difficult since clast size is relatively homogenous and boundary expression can be subtle. Only recently has the sequence stratigraphy of the Pronghorn Member been considered and the variations between models proposed attests to its elusiveness.

Sonnenberg (2015) argues that the Bakken Formation consists of five systems tracts. He identifies the sequence boundary at the base of the Pronghorn and a sequence boundary in the Middle Bakken Silt to bracket a sequence. With this model, the Pronghorn consists of a Lowstand Systems Tract distally and a Transgressive Systems Tract proximally. Sonnenberg (2015) considers the lag at the top of the Pronghorn Member to be a Transgressive Surface.

Skinner et al., (2015) also identify the Pronghorn Member as a Lowstand Systems Tract, however they suggest that the Lower, Middle, and Upper Bakken are part of a Transgressive Systems Tract and that the Maximum Flooding Surface is what separates the Bakken Formation from the overlying Lodgepole Formation. This model, like that of Sonnenberg (2015), includes the Pronghorn as a single parasequence within the Bakken Formation sequence.

Hohman (2012) separates the Pronghorn Member into its own distinct sequence. He identifies the basal Pronghorn-Three Forks contact as a sequence boundary. He interprets the basal bioturbated Pronghorn sandstone as part of a Transgressive Systems Tract and a Hightstand Systems Tract in the Pronghorn limestone. He considers the lag separating the Pronghorn and the Lower Bakken Shale as a sequence boundary, completing the depositional sequence.

5. METHODS

Core from the Three Tribes 151-94-3H in Mountrail County, ND was described and analyzed for palynomorphs. In total, 18 samples were taken and processed from the Pronghorn Member (Figure 6.2). The sampling interval was approximately every five inches with adjustments made to target lithologies that are appropriate for palynology. Higher density sampling was also done around visible depositional lags. Samples were taken with a one-inch diameter diamond bit drill, producing approximately one inch by one-inch core plugs. Before processing, all core plugs were split and examined for macrofossils.

Samples were processed using standard palynology processing procedures as delineated by Traverse (1988) and Playford (1971). Per core plug, 5-10 grams of sample were weighed, crushed, and allowed to sit in dilute hydrochloric acid for up to 12 hours. Samples were then rinsed with distilled water, then allowed to sit in 48% hydrofluoric acid for 48 hours, then rinsed 12-15 times with distilled water before being sieved with 25μm stainless steel mesh. Due to the high organic content of the black shales, some samples were sieved as many as three times. All residues were retained.

Both >25μm and <25μm residues of each sample were mounted in glycerin jelly and examined for palynomorphs under a binocular microscope. Particularly productive residues were mounted on multiple slides. Recovered palynomorphs were documented with still images through the entire depth of field, and the slide coordinates were recorded. Slides were examined using a Nikon Eclipse E200. Pictures were taken with an AmScope MU800 microscope attachment.

Identification of palynomorphs was done in conjunction with Dra. Mercedes di Pasquo, of the Centro de Investigaciones Científicas y Transferencia Tecnológica a la Producción in Diamante, Argentina.

Emphasis was placed on species absence or presence, although relative abundance was considered. Beta diversity, or community similarity, was determined using the Sørenson coefficient of community, which is

$$CC_S = \frac{2c}{s_1 + s_2}$$

where c is the number of species common to both communities, and s_1 and s_2 are the number of species in communities 1 and 2, respectively. This relative determination of community similarity ranges from 0, in which no species are shared between communities, and 1, in which all species are shared between communities. Therefore, the higher the coefficient, the more similar the communities and the lower the coefficient, the less similar the communities. The Sørenson coefficient of community, in addition to seriated plotting, aided in determination of assemblages within the Pronghorn Member as well as assemblage similarity between the Pronghorn and various Late Devonian formations.

Macrofossils were observed under a stereoscope and identified from the literature. Frequently, macrofossil locations were then processed for palynology.

Two additional cores, the Curl 23-14 and the Cherry State 21-16-TFH, were examined and analyzed lithostratigraphically. Ideal microfossil sampling locations were identified.

6. RESULTS

Three cores of the Pronghorn Member are described in this study (Figure 6.1) and stratigraphic columns are annotated for palynological sampling in the Three Tribes 151-93-3H. Particular attention is given towards lag deposits and favorable lithologies. All macrofossils are photographed and described. Ideal sampling locations are identified on the Cherry State 21-16-TFH and Curl 23-14 for future work. Palynomorph microfossils are also photographed and identified.

Figure 6.1. Location map showing wells where cores were taken. C = Curl 23-14; CS = Cherry State 21-16TF; TT = Three Tribes 151-93-3H.

Palynology

One of the biggest advantages of palynological analysis from core is the relatively high yield rates compared to samples taken from outcrop. Oxidation and diagenesis quickly destroy the otherwise resilient palynomorphs making productive sampling from outcrop difficult. From the author's outcrop sampling and communication with other Paleozoic palynologists, the author has recognized a 10-20% yield rate from outcrop. 95% of the samples taken from core for this study yielded although preservation was variable.

18 samples from the Three Tribes 151-93-3H were processed and analyzed for palynomorphs and palynofacies (Figure 6.2). Three palynofacies were established, Palynofacies 1, Palynofacies 2, and Palynofacies 3. Lithology strongly influences yields in palynology, with siltier, "fudge-like" textures historically having the highest success rates (Traverse, 1988). Despite the bioturbation, the highest yields were from the basal, sandier Pronghorn lithologies. Palynomorphs of the Pronghorn Member were predominantly long-ranging, cosmopolitan prasinophytes. The most abundant palynomorphs throughout the Pronghorn Member samples were Leiosphaerids and of the genus *Gorgonisphaeridium*.

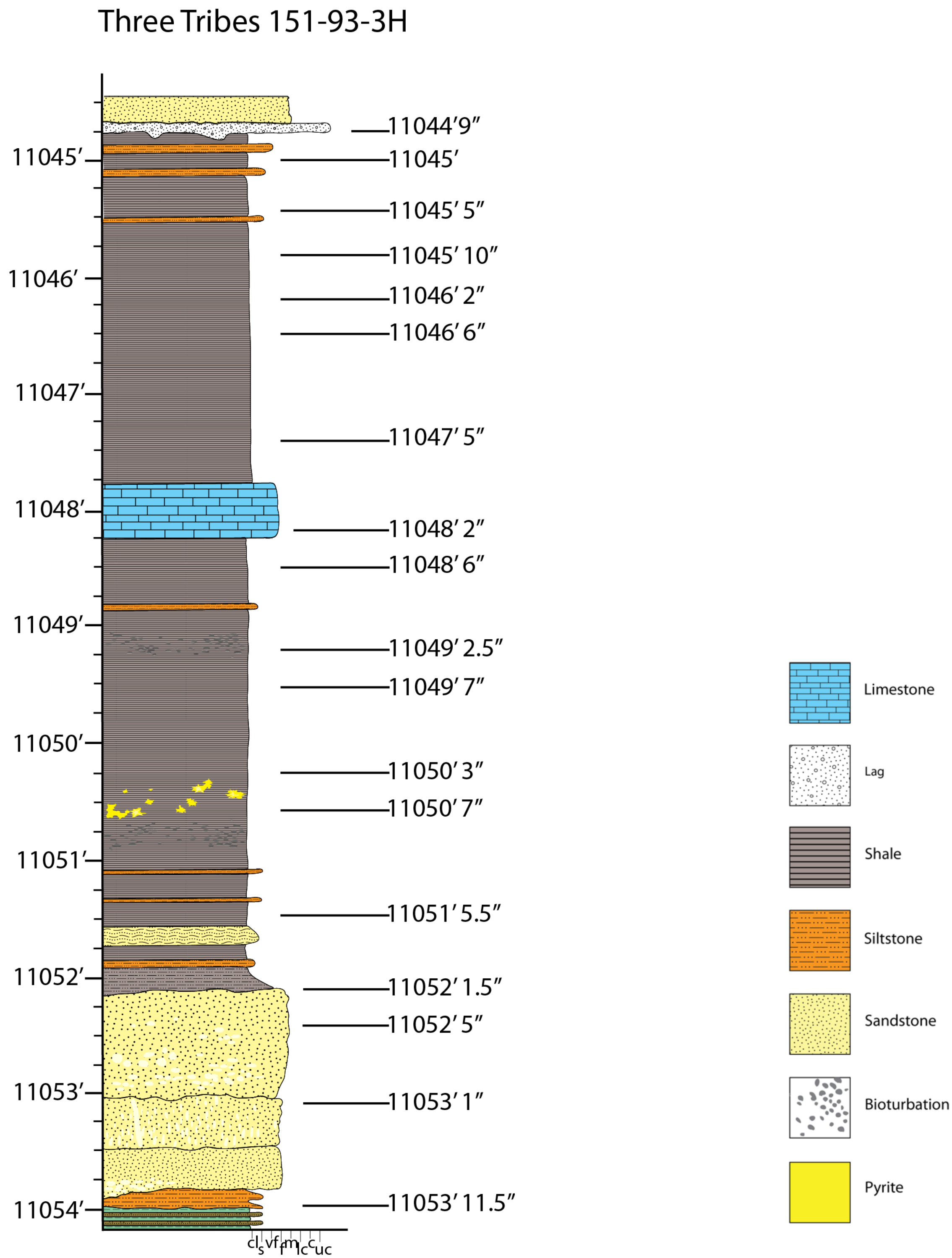

Figure 6.2. Palynology sampling locations from the Three Tribes 151-93-3H.

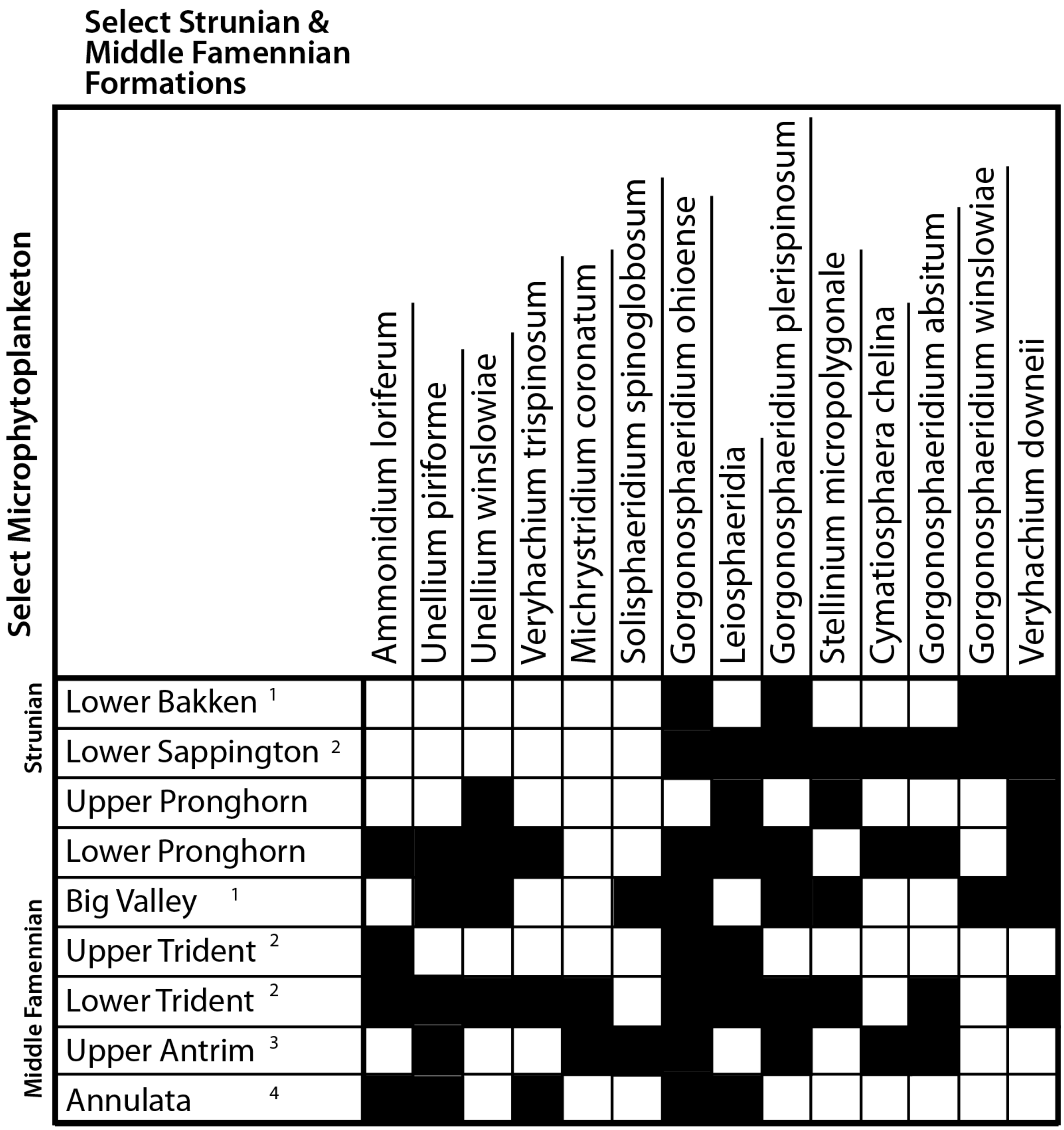

Figure 6.3. Chart illustrating selected microphytoplankton and their occurrences in Strunian and middle Famennian formations. A black box indicates the presence of a species; a white box indicates the absence of a species. 1. Playford and McGregor, 1993; 2. Di Pasquo et al., 2017; 3. Wicander and Loeblich, 1977; 4. Racka et al., 2010. From di Pasquo et al., 2017 Lower Sappington refers to LAs3, Upper Trident refers to LAs2, and Lower Trident refers to LAs1. Upper and Lower Pronghorn are from this study.

Palynofacies

Palynological analysis of the Three Tribes 151-93-3H resulted in the development of 3 palynofacies. These palynofacies are a high abundance, moderate diversity, good preservation prasinophyte assemblage, a low diversity, good preservation prasinophyte and miospore assemblage, and a low diversity and poor preservation palynofacies with high amounts of amorphous organic material, or AOM (Figure 6.5). These palynofacies can be seen as visually distinct when presented in a seriated chart and are supported by beta diversity comparisons (Figure 7.3 and Figure 6.4).

Palynofacies 1: High Abundance, Moderate Diversity, Good Preservation Prasinophyte Assemblage

Palynofacies 1 consists of 17 identified prasinophyte species and some poorly-preserved miospores and prasinophytes of indeterminate taxonomy. This facies had rare AOM, some opaques, and some phytoclasts. Charcoal was observed at 11053′ 11.5″ and significant amounts of euhedral pyrite within palynomorphs was observed at 11053′ 1″. This palynofacies encompassed all samples taken between 11052′ 1.5″ and 11053′ 11.5″, a total of four samples, all within the basal bioturbated Pronghorn sandstone. This assemblage contained the most diverse and most abundant acritarch assemblage.

Palynofacies 2: Good Preservation Prasinophyte and Miospores Assemblage

Palynofacies 2 consists of 12 prasinophyte species, 3 miospore species, some poorly preserved palynomorphs of indeterminate taxonomy, some opaques, some AOM, and some phytoclasts. A scolecodont was observed at 11050′ 7″ and charcoal was observed at 11049′ 2.5″. This facies consists of seven samples taken between 11048′ 2″ and 11051′ 5.5″. The sample taken from the Pronghorn limestone resulted in no identifiable palynomorphs. Limestones are notoriously unfavorable lithologies for palynology (Traverse, 1988). This palynofacies was moderately diverse but was dominated by *Gorgonisphaeridium* spp. and Leiosphaerids.

Palynofacies 3: Low Diversity, Poor Preservation

Palynofacies 2 consists of 9 identified prasinophyte species, 1 miospore, and numerous poorly-preserved, indeterminate prasinophyte and rare, indeterminate poorly-preserved miospores, as well as organic fragments of unknown origin. This palynofacies had high amounts of AOM, some opaques and some phytoclasts. This palynofacies included all samples taken between 11044′ 9″ and 11047′ 11″, a total of 7 samples. This assemblage consisted of almost exclusively Maranhites spp. and Leiosphaerids.

The sample taken at 11044′ 9″ was taken at the Lower Bakken Silt lag-Upper Pronghorn contact, partially including coarse sediments from the lag as well as clays from the Upper Pronghorn shale. This likely accounts for the relatively high diversity of this sample in the context of the Palynofacies 3 samples.

	P3	P2	P1
P3	1		
P2	0.6	1	
P1	0.38	0.64	1

Figure 6.4. Chart displaying Sørenson community similarity coefficients of the three assemblages of the Pronghorn Member from the Three Tribes 151-93-3H core.

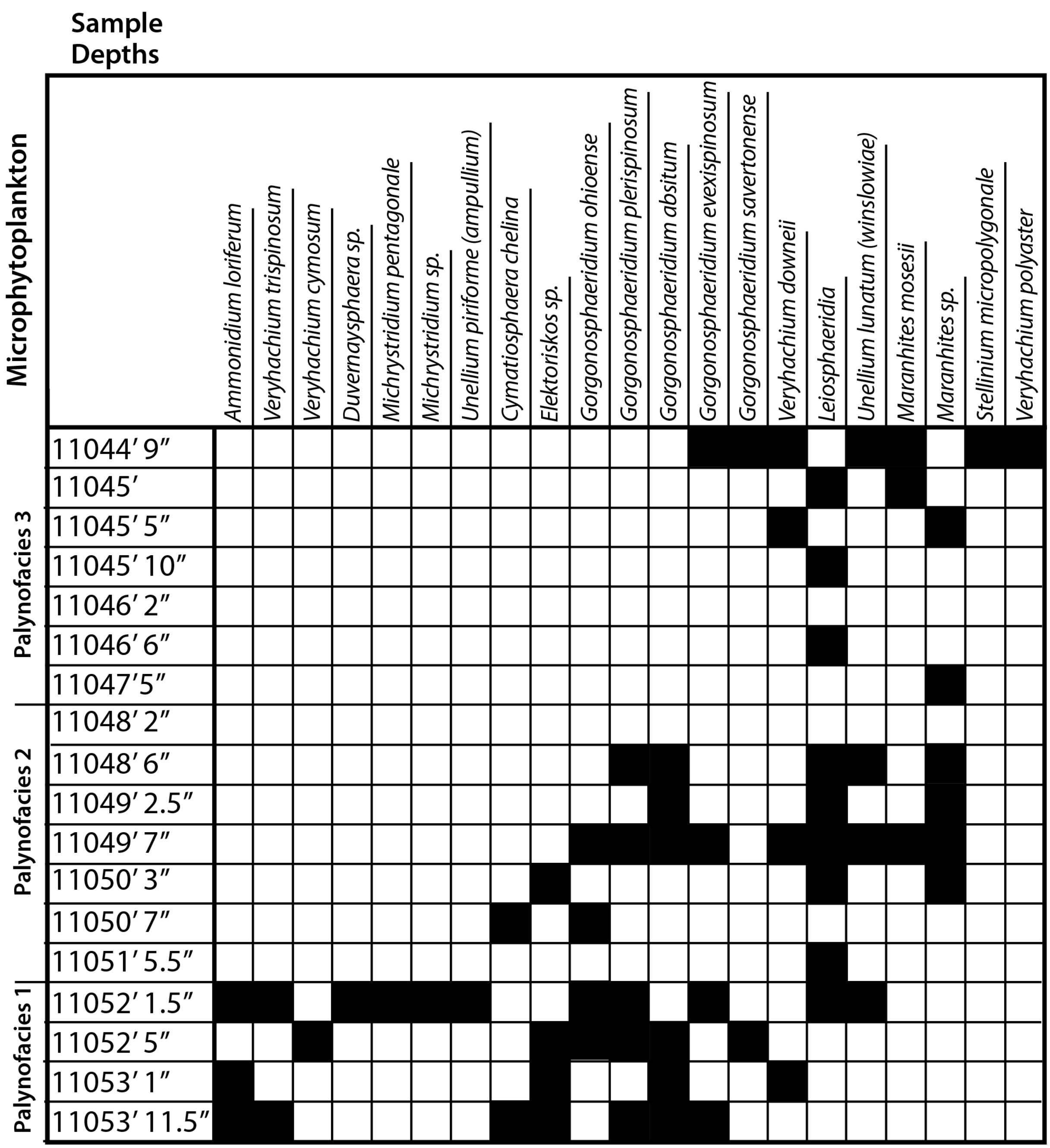

Figure 6.5. Chart depicting absence or presence of various prasinophytes in the Pronghorn Member of the Three Tribes 151-93-3H core. Black box indicates the presence of a species while a white box indicates the absence of a species. Palynofacies are listed on the left hand side of the chart.

Macrofossils

The Three Tribes 151-93-3H was examined for macrofossils (Plates 3 & 4). Various indeterminate fossil fragments were observed and some fossils were identified (Figure 6.6). Multiple clymenids were identified, which is significant since clymenids are a diagnostic middle Famennian fossil. Indeterminate coiled cephalopods and low spired gastropods, common in the Lower Bakken Shale, were also identified.

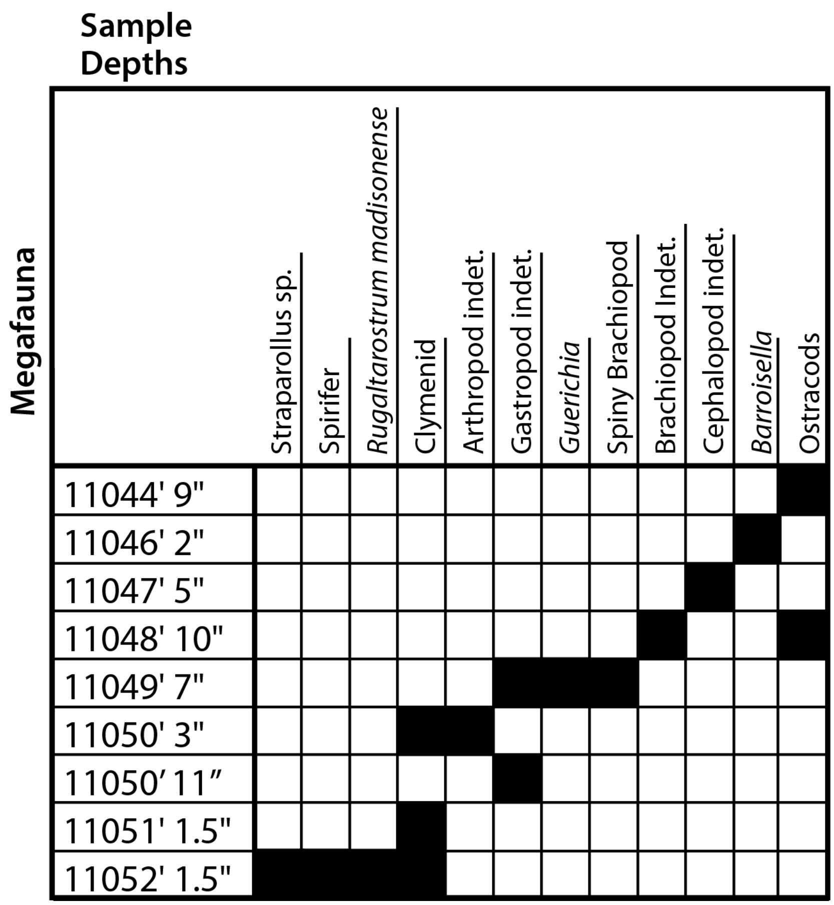

Figure 6.6. Chart depicting the presence of various faunas found in the Pronghorn Member. A black box indicates the presence of an organism; a white box indicates the absence of an organism.

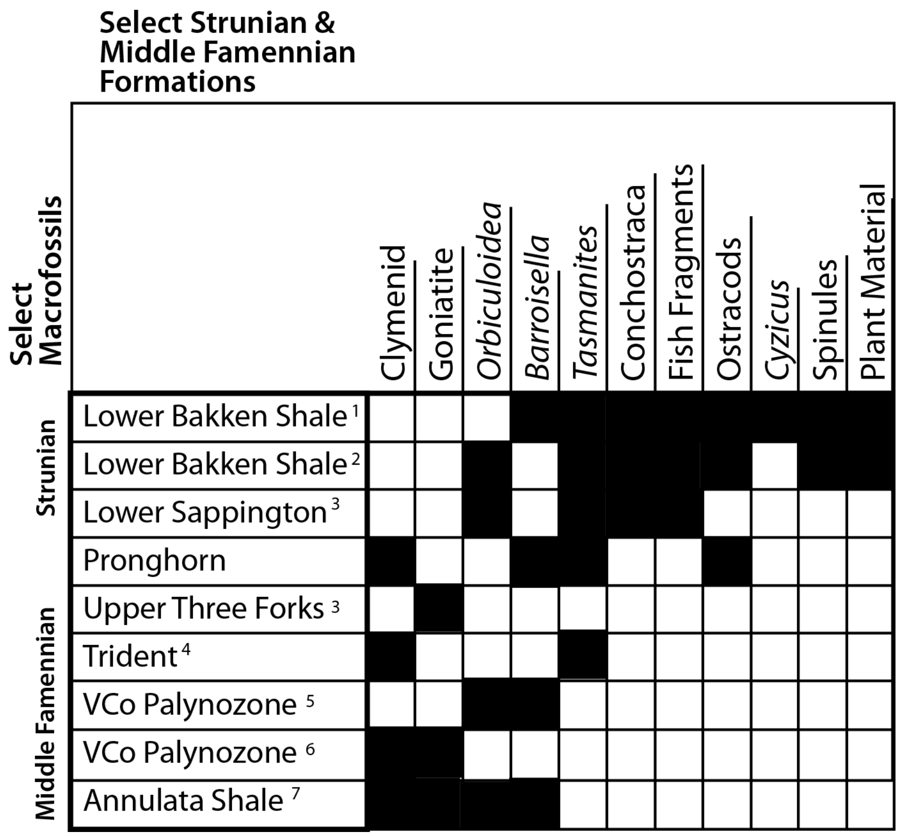

Figure 6.7. Chart depicting macrofaunas from the Pronghorn Member (this study) as well as from analogous formations. 1. Thrasher, 1985; 2. Hayes, 1985; 3. Gutschick et al., 1962; 1964; 4. Di Pasquo et al., 2017; 5. Halamski & Balinski, 2007; 6. Marynowski et al., 2007; 7. Racka et al., 2010.

Lithofacies

Four lithofacies were identified for the Pronghorn Member based on the Three Tribes 151-93-3H, the Cherry State 21-16-TFH, and the Curl 23-14 (Figures 6.10, 6.11, and 6.12). From oldest to youngest, these lithofacies are 1) a heavily bioturbated, well-sorted, fine-grained sandstone with dolomitic cement 2) a fissile mudstone and siltstone with some sandstone interlaminae and occasional bioturbation, and 3) a mudstone to wackestone with often indeterminate bioclasts, and a 4) fissile mudstone.

The Pronghorn Member overlies the tan siltstones and green mudstones of the Three Forks Formation. These distinctively colored siltstone and mudstones appear as rip-up clasts in the basal Pronghorn Member lag. Overlying the Pronghorn is either the Lower Bakken Silt or the Lower Bakken Shale. In the Three Tribes 151-93-3H the Lower Bakken Silt is not present above the Pronghorn indicating either erosion or a period of nondeposition. The Curl 23-14 and the Cherry State 21-16-TFH both contained the Lower Bakken Silt.

Lithofacies 1: Bioturbated Sandstone

The base of Lithofacies 1 is consistently marked by a lag on top of the underlying Three Forks Formation. This lag is composed of Three Forks Formation clasts. This lithofacies is heavily bioturbated, well-sorted, and an often slightly coarsening upwards siltstone to fine sandstone. Bioturbation ranges from completely churned with no discernible trace fossils or remnant sedimentary structures to moderately bioturbated with visible trace fossils. This lithofacies is frequently dolomitic. Both horizontally and vertically-oriented and trace fossils were observed, including *Planolites, Cruziana,* and *Skolithos*. Some fish fragments were identified from this interval along with some conodonts, molluscs, brachiopods, and other various indeterminate bioclasts. No significant pyrite was observed throughout this lithofacies.

The bioturbated sandstone of Lithofacies 1 was present in all three cores examined and ranged from 1-2 feet in thickness. Vertical burrows were observed in the Three Tribes 151-93-3H but not in the Curl 23-14 or Cherry State 21-16-TFH.

Figure 6.8. Lithofacies 1 bioturbated sandstone from the Three Tribes 151-93-3H core.

Lithofacies 2: Laminated Mudstone and Siltstone

Lithofacies 2 consists of laminated mudstone and siltstone with occasional very fine sandstone interlaminae and rarely, unidirectional ripples. Occasional small, horizontal ichnofossils, possibly *Planolites* and *Cruziana,* were observed in localized areas. Pyrite, with occasional marcasite, frequently occurred as nodules or within laminations. Pyritized burrows and fossils are common. The brachiopods *Orbiculoidea, Barroisella, Rugaltorostrum,* and a spirifer, the bivalve *Guerichia,* some gastropods, and clymenids were observed in this lithofacies. An unidentified spiny brachiopod, morphologically similar to *Echinaurus,* was found in the Three Tribes 151-93-3H core in Lithofacies 2.

Lithofacies 2 comprises the top of the Pronghorn Member interval in the Cherry State 21-16-TFH, where it is truncated by a phosphatic bone lag. Lithofacies 2 was absent in the Curl 23-14 and a 1.5-3 feet thick in the Three Tribes 151-93-3H and Cherry State 21-16-TFH. This lithofacies succeeded Lithofacies 1 in the Three Tribes 151-93-3H core.

Lithofacies 3: Limestone

The Pronghorn limestone lithofacies ranges from a mudstone to a packstone with occasional bioturbation. The packstone consists of indeterminate valve fragments. This lithofacies was present in all three cores but was consistently less than a foot thick.

No fossils or bioclasts were observed in the limestone facies of the Three Tribes 151-93-3H. In the Curl 23-14, Lithofacies 3 was constrained both above and below by a lag. In the Cherry State 21-16-TFH limestone facies, soft sediment deformation is present at the 11044′ 10″ bedding plane midway through the limestone interval and the limestone bed above this contact is bioturbated. The limestone facies of the Three Tribes 151-93-3H consisted of mudstone.

Lithofacies 4: Laminated Mudstone

Lithofacies 4 consists of a black laminated mudstone with rare siltstone interlaminae. This lithofacies frequently contained pyritized *Tasmanites* on bedding planes as well as localized concentrations of euhedral and framboidal pyrite (Figure 6.9). This lithofacies was heterolithically skeletal, resulting in totally barren beds to beds with fossils including *Barroisella* and a clymenid. This lithofacies was only observed in the Three Tribes 151-93-3H and was three feet thick.

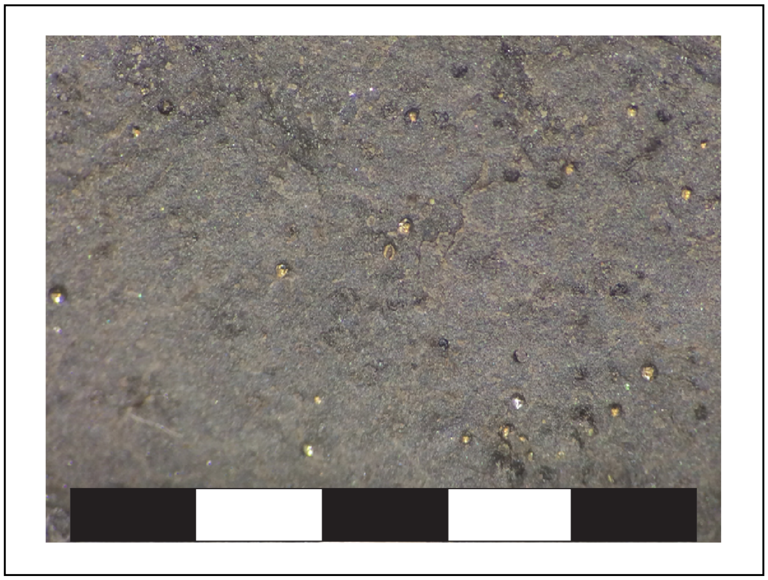

Figure 6.9. Pyritized Tasmanites on bedding plane at 11046′ 2″ of the Three Tribes 151-93-3H. Scale is 5cm.

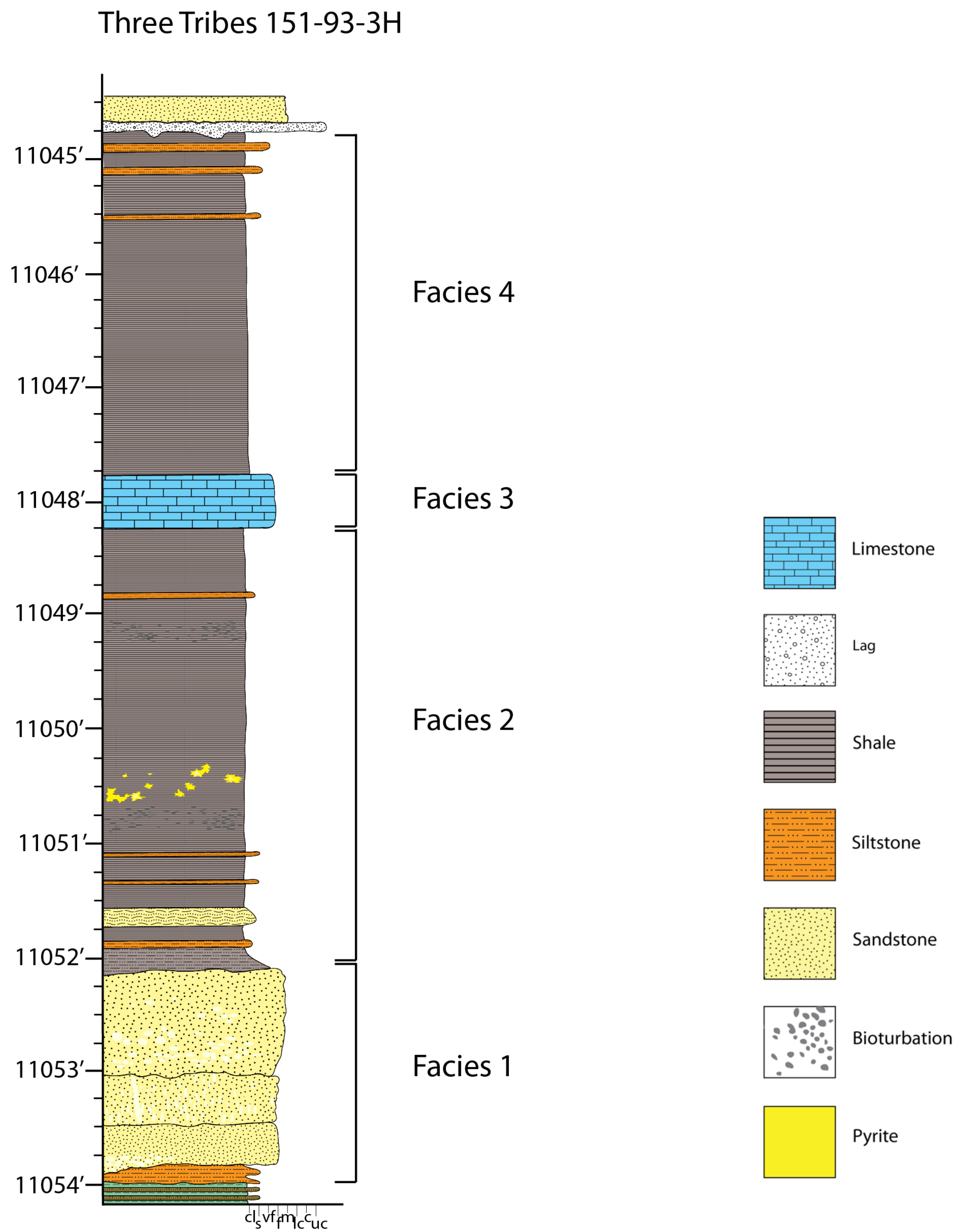

Figure 6.10. Lithofacies of the Three Tribes 151-93-3H Pronghorn Member.

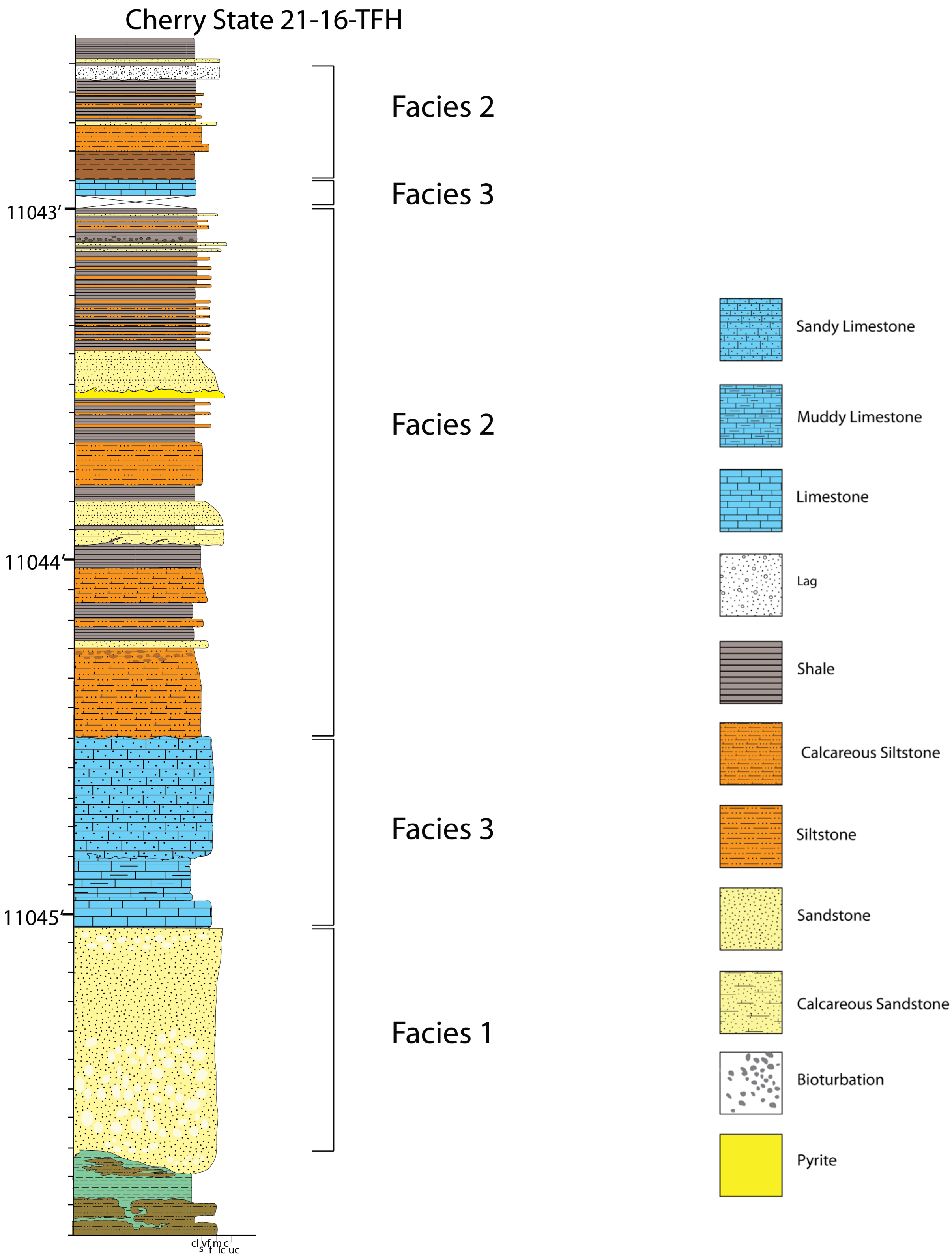

Figure 6.11. Lithofacies of the Cherry State 21-16TFH Pronghorn Member.

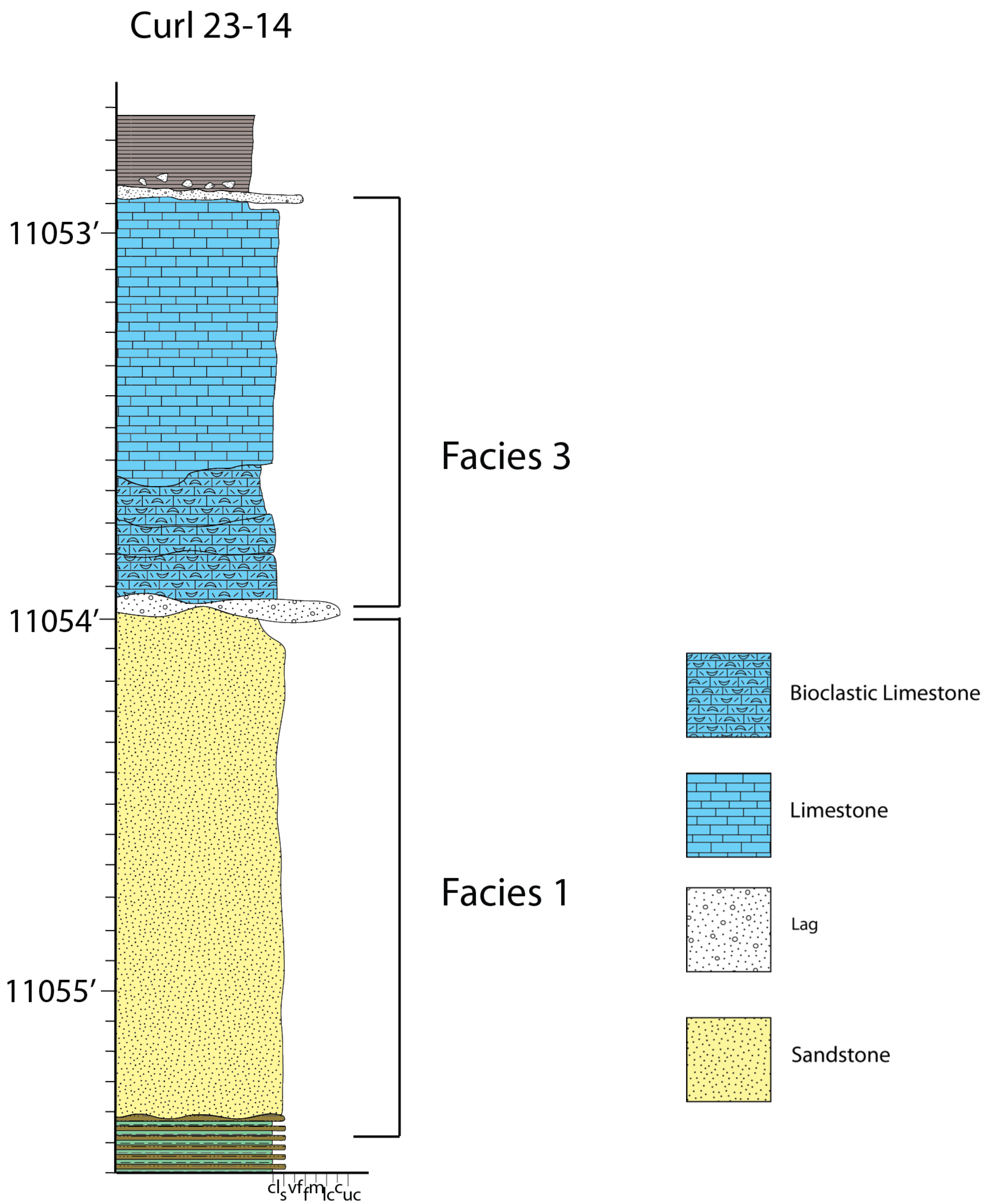

Figure 6.12. Lithofacies of the Curl 23-14 Pronghorn Member.

7. DISCUSSION

Palynofacies

The three palynofacies of the Pronghorn Member of the Bakken Petroleum System contain predominantly autochthonous palynomorphs with little terrestrial influence. Based on the work of Streel (1999), Leiosphaerid-dominated assemblages reflect a restricted marine back barrier environment, *Gorgonisphaeridium* spp. indicate intermediate marine environments, and diverse acritarch assemblages reflect offshore marine environments. Applying these depositional correlations to the three assemblages established in the Pronghorn Member suggest open marine conditions existing throughout the deposition of Palynofacies 1 shifting towards slightly restricted during the deposition of Palynofacies 2, with the Leiosphaerid-dominated assemblage of Palynofacies 3 indicating a restricted marine environment of deposition.

The assemblages found within the Pronghorn Member most closely resemble the assemblages from the Trident Formation from di Pasquo et al. (2017*)*. Based on palynology, the Pronghorn can be divided into a lower and upper member. In the Three Tribes 151-93-3H, there is an undeniable palynological shift at 11052′ 1.5″. This distinctive palynological shift is determined to be the boundary between the Upper and Lower Pronghorn. This shift is similar to the shift from LAs1 to LAs2 from the di Pasquo et al., (2017) study of the Trident Member of the Three Forks Formation (Figure 4.2). The Upper Pronghorn most closely resembles the Upper Trident and the Lower Pronghorn most closely resembles the assemblage of the Lower Trident. The similarity both in the species, species richness, and in species evenness of these two sets of assemblages, strengthens their correlation.

The sparse palynological data recovered from the Upper Trident led di Pasquo et al*.*, (2017) to withhold assigning a palynozone to the Upper Trident. The Lower Trident, however, had a distinct VCo assemblage. The Lower Pronghorn, in sharing many species with the Lower Trident, also exhibits a VCo assemblage.

The Lower Bakken Shale and the Lower Sappington have few species in common with those found in the Pronghorn Member. The acritarchs identified within the Pronghorn Member are also consistent with those found in the Torquay Formation.

The Pronghorn Upper and Lower assemblages were compared to the palynological assemblages found in other Late Devonian formations with the Sørenson community coefficient (Figure 7.1). This beta diversity index highlights the similarity between the Pronghorn and the Lower Sappington and the Pronghorn and the Lower Trident and the dissimilarity between the Pronghorn and the Lower Bakken Shale.

	UPH	LPH
Lower Bakken[1]	0.33	0.19
Lower Sappington[2]	0.58	0.41
Big Valley[1]	0.35	0.32
Upper Trident[2]	0.2	0.34
Lower Trident[2]	0.62	0.62
Upper Antrim[3]	0.13	0.19
Annulata[4]	0.19	0.41

Figure 7.1 Community similarity between the Upper and Lower Pronghorn and various Late Devonian formations using the Sørenson community coefficient. UPH = Upper Pronghorn, LPH = Lower Pronghorn (this study). 1. Playford and McGregor, 1993; 2. Di Pasquo et al., 2017; 3. Wicander and Loeblich, 1977; 4. Racka et al., 2010.

Macrofossils

The macrofossils present in the Pronghorn include those found in the younger Sappington Formation and Lower Bakken Shale as well as those in the Trident Member of the Three Forks Formation in Montana, the middle Famennian Annulata Shale of the eastern US, and within the VCo palynozone formations of Poland (Figure 6.7). These shared faunas, such as *Barroisella* and *Tasmanites* are long ranging and present throughout the Strunian and middle Famennian. The ostracods found in the Pronghorn were also reported from the Lower Bakken Shale and the spiny brachiopod found in the Pronghorn seems to only bare semblance to the reported spined brachiopod found in the Sappington Formation. Ostracods and spiny brachiopods have not been reported from the Trident Member, the Three Forks, the Annulata, or the VCo formations. However, the majority of macrofossils reported from the Lower Bakken Shale and Sappington Formation were not present in the Pronghorn. Clymenids, on the other hand, were only seen in middle Famennian formations and are also considered representative of a middle Famennian age (Korn 2000).

Environmental interpretations can also be made based on some of the faunas found. *Guerichia,* observed at 11049′ 7″ in the Three Tribes 151-93-3H, is considered to be a deep-water bivalve (Becker et al*.,* 2016). The presence of a spiny brachiopod buried *in situ* indicate the water was oxygenated during its life.

Lithofacies

Lithofacies 1

LF1, the bioturbated sandstone lithofacies suggests deposition in a shallow, oxygenated marine environment. This could be a widespread lowstand fan throughout a relatively shallow, low-accommodation, low sediment-supply period of the basin's history.

Lithofacies 2

The laminated mudstone and siltstone of LF2 contained a ripple as well as euhedral pyrite and a brachiopod with its spines intact suggests episodically rapid sedimentation. The additional presence of euhedral pyrite suggests an aerobic to dysaerobic environment. The siltstones and occasional fine-grained sandstone interlaminae imply active involvement of a current, although this too must have been episodic considering the presence of a well preserved spiny brachiopod *in situ*. Although no specific depth has been assigned to it, the bivalve *Guerichia,* found in this lithofacies, is considered a deep water bivalve (Becker et al*.,* 2016). The lack of disseminated pyrite suggests at least marginally oxygenated water (Brett and Allison, 1998).

Lithofacies 3

The Pronghorn limestone, LF3, was present in all three cores. The often coarse bioclastic nature of this lithofacies and occasional bioturbation supports a shallow marine setting.

Lithofacies 4

The presence of disseminated euhedral and framboidal pyrite suggests dysaerobic to euxinic conditions. The pyrite spheres in this interval have been described by Schieber and Baird (2001) in the Late Devonian shales of the Appalachian and Illinois Basins. These sand-sized grains were determined to be *Tasmanites* that have fallen out of suspension and deposited far from the effects of any current capable of transporting gains of this size. They suggest that a complete sphere indicates pyritization of an uncompressed *Tasmanites* cyst and suggests a rate of pyritization that surpasses the rate of deposition. The fragile nature of the algal cyst lipoidal membrane and the complete, smooth nature of the pyrite spheres also suggests that diagenetic pyritization occurred early, before any accumulation of overburden. This lithofacies contained discrete fossiliferous beds separated by beds devoid of macrofossils. Heterolithically skeletal lithologies can indicate a fluctuating redox boundary (Brett and Allison, 1998).

Paleoenvironmental Interpretation, Significant Surfaces, & Parasequences

The Pronghorn Member of the Bakken Formation is bounded by unconformities. The transition from the tidal-flat, sabkha depositional environment of the Three Forks Formation to the bioturbated sandstone of the Pronghorn Member is abrupt, marked by the basal Pronghorn lag which consists of Three Forks Formation intraclast rip ups. This basal unconformity likely represents extensive, time-transgressive erosion. The top of the Pronghorn Member is consistently marked by the presence of a phosphatic bone lag (Figure 7.2). These unconformities signify the occurrence of a depositional sequence within the Pronghorn Member. Analysis of the palynology, macrofossils, lithology, and stacking patterns elucidates parasequences and significant surfaces and enables paleoenvironmental interpretations.

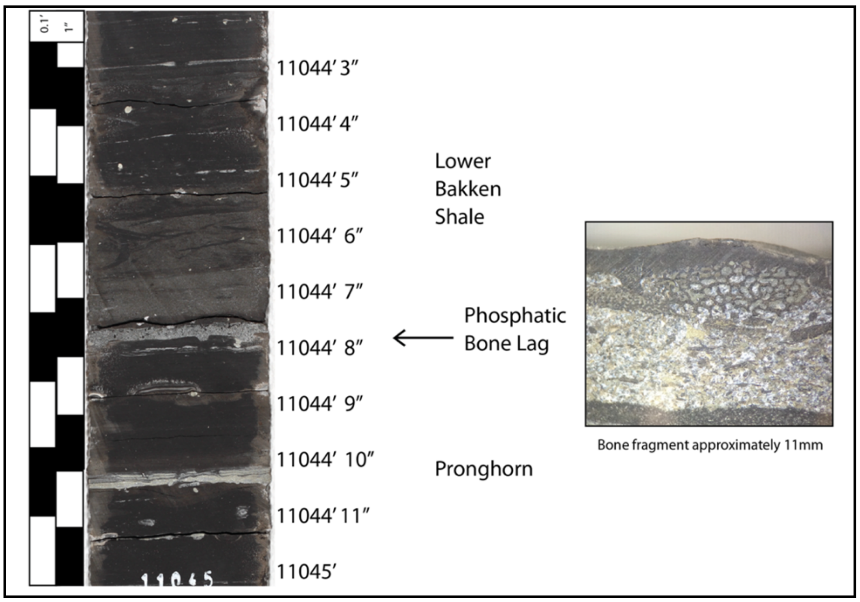

Figure 7.2. Three Tribes 151-93-3H Pronghorn Member-Lower Bakken Silt phosphatic bone lag.

The basal Pronghorn Member sandstone was deposited as part of a Lowstand Systems Tract (LST) on top of the Three Forks Formation-Pronghorn Member sequence boundary. These basal sandstone packages are likely time transgressive and palynological analysis of the Curl 23-14 and Cherry State 21-16-TFH would likely support diachronous deposition. At this point in the sequence, the depositional environment within the basin would have been open marine. These sandstones are capped by a Transgressive Surface (TS). The TS divides P1 from P2 and P3 (Figure 7.4 and Figure 7.5). The Lower Pronghorn corresponds to Palynozone 1(P1) and the Upper Pronghorn corresponds to Palynozones 2 (P2) and Palynozone 3 (P3). The LST corresponds to the Lower Pronghorn and P1.

The Transgressive Systems Tract (TST) of the Pronghorn is less lithologically homogenous than the LST. In the Three Tribes 151-93-3H the TST is composed of laminated claystone to fine-grained sandstone. The sandstone interlaminae contain a uni-directional ripple. In the Curl 23-14 and the Cherry State 21-16-TFH, the TST is a skeletal wackestone to packstone. This lithologic variance is likely the result of the distance between the Three Tribes 151-93-3H and the Curl 23-14 and the Cherry State 21-16-TFH (Figure 7.4). Relative to the lithology and palynology, the TST would have been deposited on the shelf, in a slightly more restricted, relatively shallow marine depositional environment. The top of the TST is marked by the Maximum Flooding Surface (MFS).

The Highstand Systems Tract (HST) in the Three Tribes 151-93-3H is composed of laminated clays with rare siltstone interlaminae and a mudstone carbonate. This interval is occasionally bioturbated and has occasional pyritization. In the Cherry State 21-16-TFH the base of the HST consists of a wackestone and coarsening packages of mudstone to very fine sandstone with occasional bioturbation. The HST limestone in the Curl 23-14 is truncated by a sequence boundary and overlain by the Lower Bakken Silt (Figure 7.4). In the Three Tribes 151-93-3H the HST would be deposited in a relatively deep environment as sea level rose. The Basin shallows to the west, which is reflected in the erosive sequence boundary present in the Curl 23-14. The sequence boundary capping the Cherry State 21-16TFH and the Three Tribes 151-93-3H, is overlain by the Falling Stage Systems Tract (FSST).

The FSST of the Three Tribes 151-93-3H and Cherry State 21-16-TFH is packages of laminated clays interlaminated with siltstones. The FSST is not present in the Curl 23-14. Relative to the palynology, the FSST would have been deposited in a more restricted marine environment. The FSST is topped by a sequence boundary and overlain by the Lower Bakken Silt or the Lower Bakken Shale. This upper sequence boundary is a phosphatic bone lag.

The palynofacies of the Three Tribes 151-93-3H, rather than the lithofacies, more clearly reveal genetic relatedness within the Pronghorn Member and illuminate parasequence boundaries (Figure 7.4 and Figure 7.5). The TS marks the boundary between

P1 and P2 and the sequence boundary at the base of the FSST marks the boundary between P2 and P3.

Relative to its parasequences, the Pronghorn Member can be divided into an Upper Pronghorn and Lower Pronghorn at the MFS (Figure 7.3). The Upper Pronghorn consists of the HST and the FSST and the Lower Pronghorn consists of the LST and the TST. The Lower Pronghorn includes P1 and the Upper Pronghorn includes P2 and P3 (Figure 7.3).

This sequence stratigraphic model is similar to the model described by Hohman (2012) since it separates the Pronghorn Member into its own depositional sequence, distinct from the rest of the Bakken Formation. It differs in Hohman's (2012) exclusion of a Lowstand Systems Tract and Falling Stage Systems Tract form the Pronghorn sequence. The model presented here shares the interpretation with Sonnenberg (2015) and Skinner et al., (2015) that the Pronghorn contains a Lowstand Systems Tract.

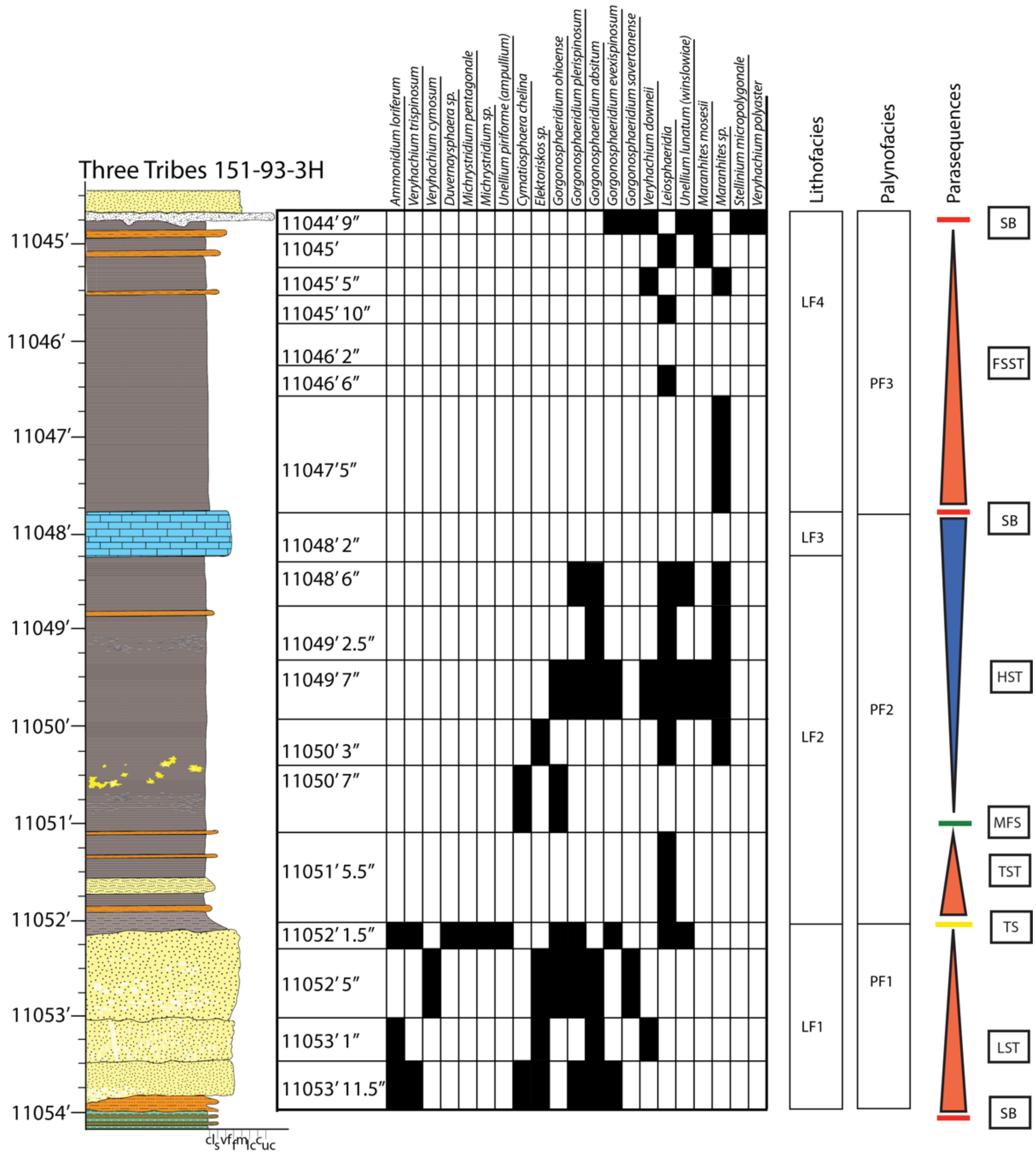

Figure 7.3. Palynology seriation chart correlated to the Three Tribes 151-93-3H stratigraphic section, palynofacies, lithofacies, and sequence stratigraphy. In the parasequences column, the red line indicates a sequence boundary, the yellow line indicates a transgressive surface, and a green line indicates a maximum flooding surface. SB = Sequence Boundary, LST = Lowstand Systems Tract, TS = Transgressive Surface, TST = Transgressive Systems Tract, MFS = Maximum Flooding Surface, HST = Highstand Systems Tract, FSST = Falling Stage Systems Tract.

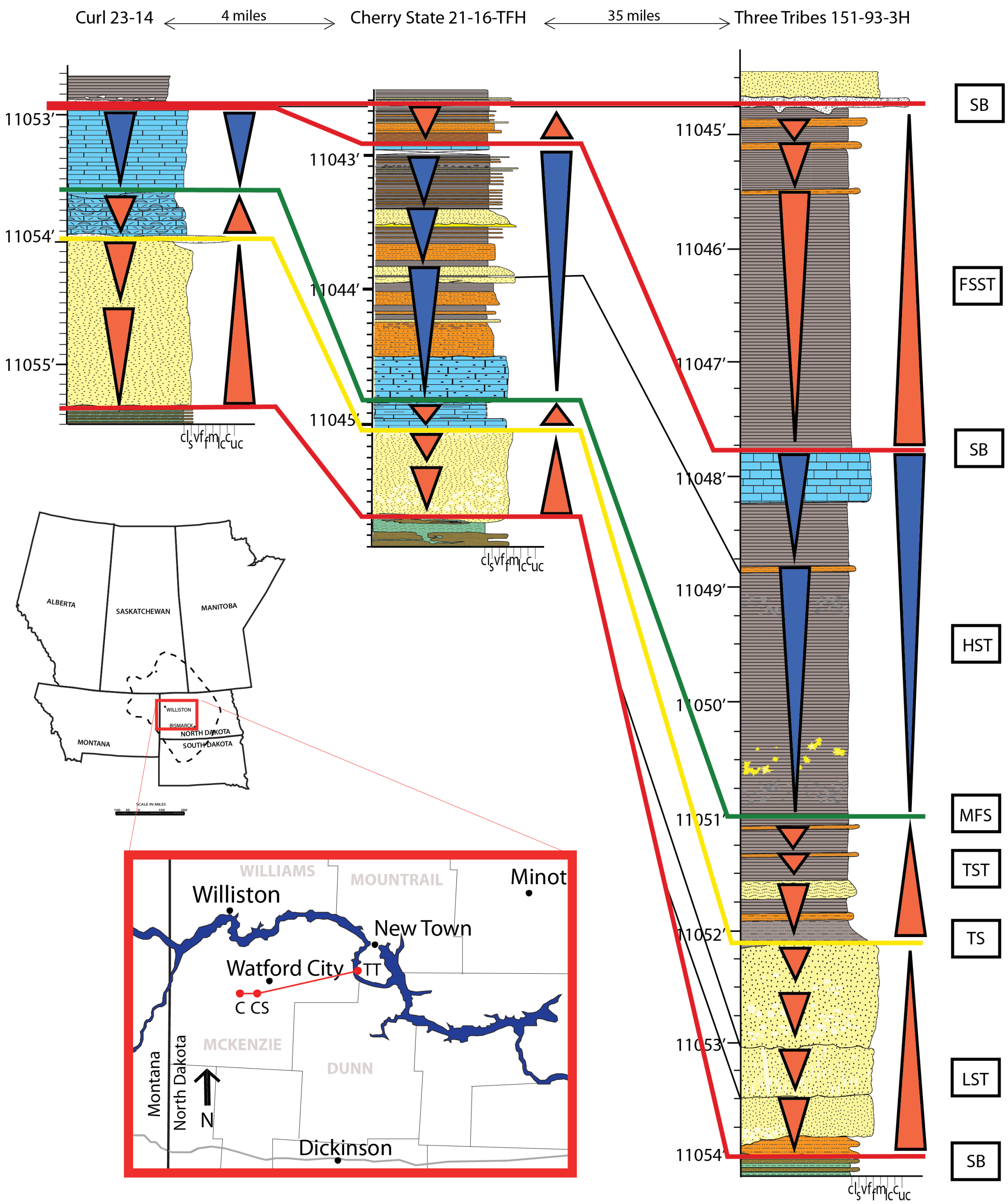

Figure 7.4. Sequence stratigraphic correlation of the Curl 23-14, Cherry State 21-16-TFH, and Three Tribes 151-93-3H. Core locations noted on geopolitical map with distances between wells listed between core names. C = Curl 23-14; CS = Cherry State 21-16-TFH; TT = Three Tribes 151-93-3H. Columns are hung on the Lower Bakken Silt lag.

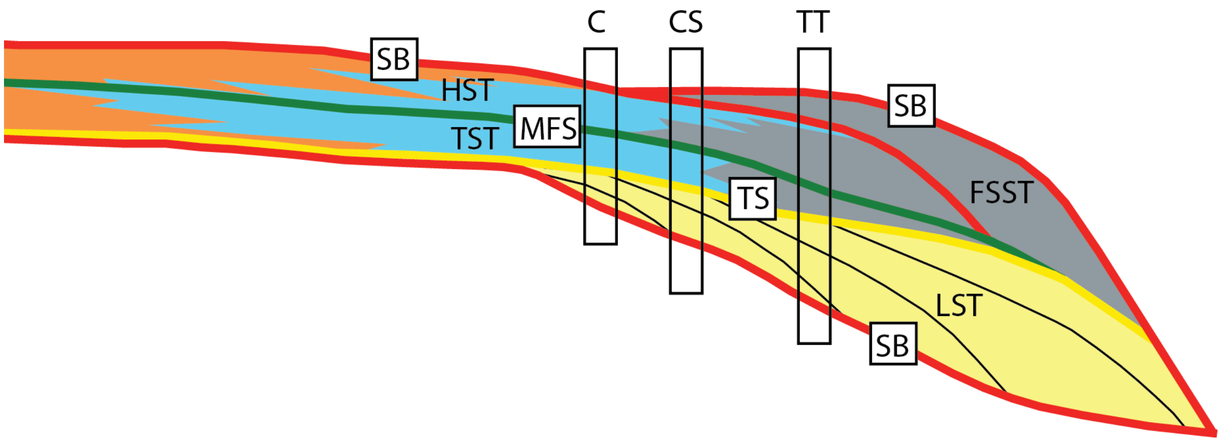

Figure 7.5. Sequence stratigraphic model of the Curl 23-14, Cherry State 21-16-TFH, and Three Tribes 151-93-3H. C = Curl 23-14; CS = Cherry State 21-16-TFH; TT = Three Tribes 151-93-3H, SB = sequence boundary, MFS = maximum flooding surface, TS = Transgressive Surface, FSST = falling stage systems tract, HST = Highstand Systems Tract, TST = transgressive systems tract, LST = lowstand systems tract.

8. CONCLUSIONS

• Palynological analysis of the Three Tribes 151-93-3H defined 3 palynofacies. These palynofacies are P1, a high abundance, moderate diversity, good preservation prasinophyte assemblage, P2, a low diversity, good preservation prasinophyte and miospore assemblage, and P3 a low diversity and poor preservation palynofacies with high amounts of AOM.

• The Pronghorn Member contains four lithofacies. These lithofacies are (LF1) the bioturbated sandstone, (LF2) a laminated mudstone and siltstone with rare sandstone interlaminae, (LF3) a carbonate mudstone to a packstone, and (LF4) a laminated mudstone. Palynofacies 1 was produced from LF1, Palynofacies 2 was produced from LF2, and PF3 was produced from LF4. These palynofacies correspond to the parasequences present within the Pronghorn and manifest genetic relatedness of the sediment packages.

• The Pronghorn Member belongs to the VCo palynozone based on palynological data which places it in the Middle Famennian. The presence of a clymenid in the Lower Pronghorn supports this palynozone and stage. The Trident Member of the Three Forks is also within the VCo palynozone.

• The Pronghorn Member and the Trident Member have a similar assemblage of biota. The Upper Trident, similar to the Upper Pronghorn has low species diversity. The Lower Trident, similar to the Lower Pronghorn, has higher species diversity and a higher abundance of species. Few macrofauna have been reported from the Trident, however, clymenids, present in the Pronghorn Member, are one of the reported fauna. Scolecodonts were also found in both the Pronghorn and the Trident. Additionally, both the Pronghorn and the Trident represent a complete depositional sequence.

• The Pronghorn consists of a complete sequence although it is variably preserved throughout the basin and only regionally complete. In the Three Tribes 151-93-3H and the Cherry State 21-16TFH a LST, TST, HST, and FSST are all present. The Lower Bakken Silt-sequence boundary has eroded the FSST from the Curl 23-14.

• The Pronghorn Member can be divided into an Upper Pronghorn and Lower Pronghorn at the MFS. The Upper Pronghorn consists of the HST and the FSST and the Lower pronghorn consists of the LST and the TST. The Lower Pronghorn includes P1 and the Upper Pronghorn includes P2 and P3.

9. RECOMMENDATIONS

Palynological sampling of the Cherry State 21-16-TFH and Curl 23-14 would improve chronostratigraphic resolution of the Pronghorn. This would also facilitate palynofacies correlation throughout the basin and contribute to the determination of parasequences within the Pronghorn Member. Palynological sampling of the Logan Gulch, Montana Trident Member core would also improve the accuracy of Bakken-Sappington and Three Forks-Pronghorn correlation. Conodont ages for the Pronghorn Member would also facilitate inter-basin correlation.

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APPENDIX

All fossil images are from the Three Tribes 151-93-3H. Microfossils were documented with a binocular microscope and macrofossils were documented with a stereoscope.

Plate 1

1. *Unellium cf. piriferum* Rauscher, 1969
2. *Gorgonisphaeridium ohioense* Wicander, 1974
3. *Gorgonisphaeridium plerispinosum* Wicander, 1974
4. *Michrystridium* sp.
5. *Veryhachium trispinosum* Deunff, 1954
6. *Stellinium micropolygonale* Playford, 1977
7. *Unellium lunatum* Stockmans and Williére, 1962
8. *Ammonidium loriferum* Hashemi and Playford, 1998
9. *Ammonidium loriferum* Hashemi and Playford, 1998

Plate 2

1. Multiplicisphaeridium sp.
2. *Gorgonisphaeridium absitum* Wicander, 1974
3. *Auroraspora macra* Sullivan, 1968
4. *Cymatiosphaera chelina* Wicander and Loeblich, 1977
5. *Gorgonisphaeridium savertonense* Wicander and Playford, 2013
6. Leiosphaeridia
7. scolecodont

Plate 3

1. Ostracod - 11044′ 9″
2. *Barroisella* - 11046‘ 2“
3. Pyritized gastropod - 11049′ 2.5″
4. Ostracod - 11048′ 10″
5. Indet. Cephalopod - 11047′ 5″
6. *Guerichia* - 11049′ 7″
7. Spiny brachiopod - 11049′ 7″
8. Spiny brachiopod spine - 11049′ 7″
9. Clymenid - 11051′ 1.5″
10. Brachiopod spine – 11049′ 7″

Plate 4

1. Costate brachiopod fragment - 11048′ 10″
2. *S. straparollus* sp - 11052′ 1.5″
3. Juvenile Clymenid? - 11052′ 1.5″
4. Indet. fossil - 11050‘ 3“
5. *Rugaltarostrum madisonense* - 11052′ 1.5″
6. Gastropod - 11050‘ 11“
7. Bone fragment - 11046′ 2″
8. Indet valve - 11050‘ 3“
9. Indet. arthropod fragment 11050′ 3″

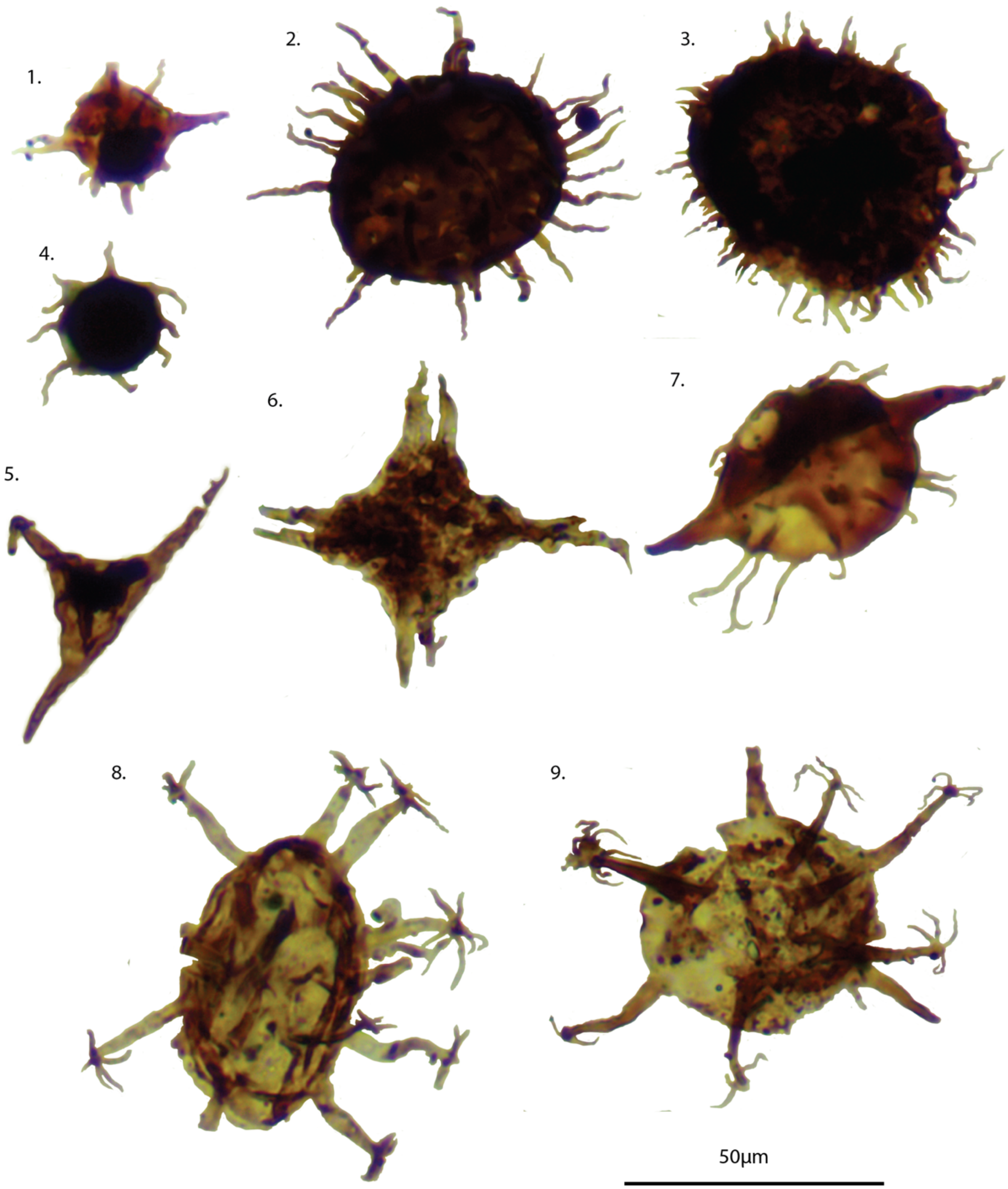

Plate 1

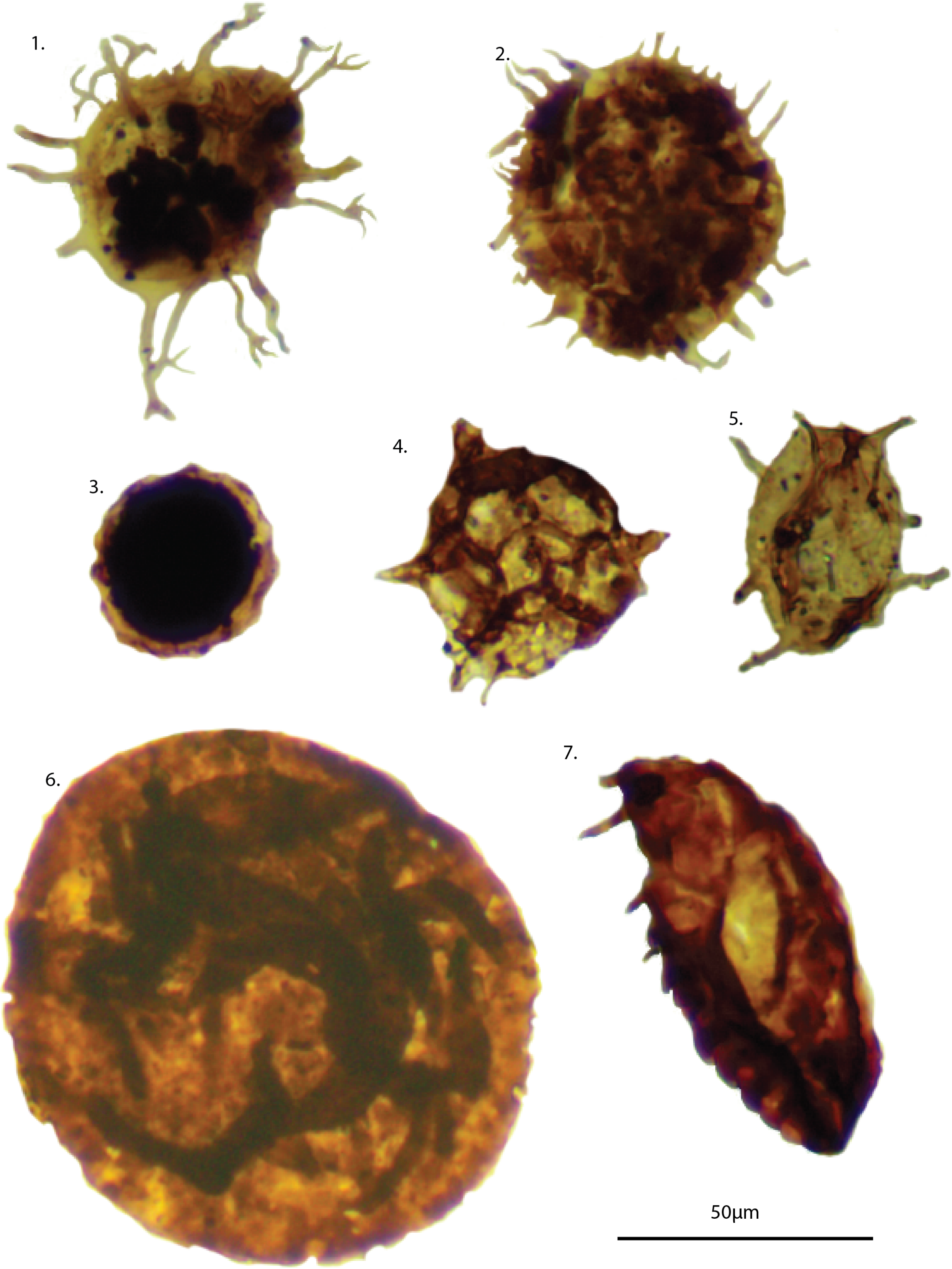

Plate 2

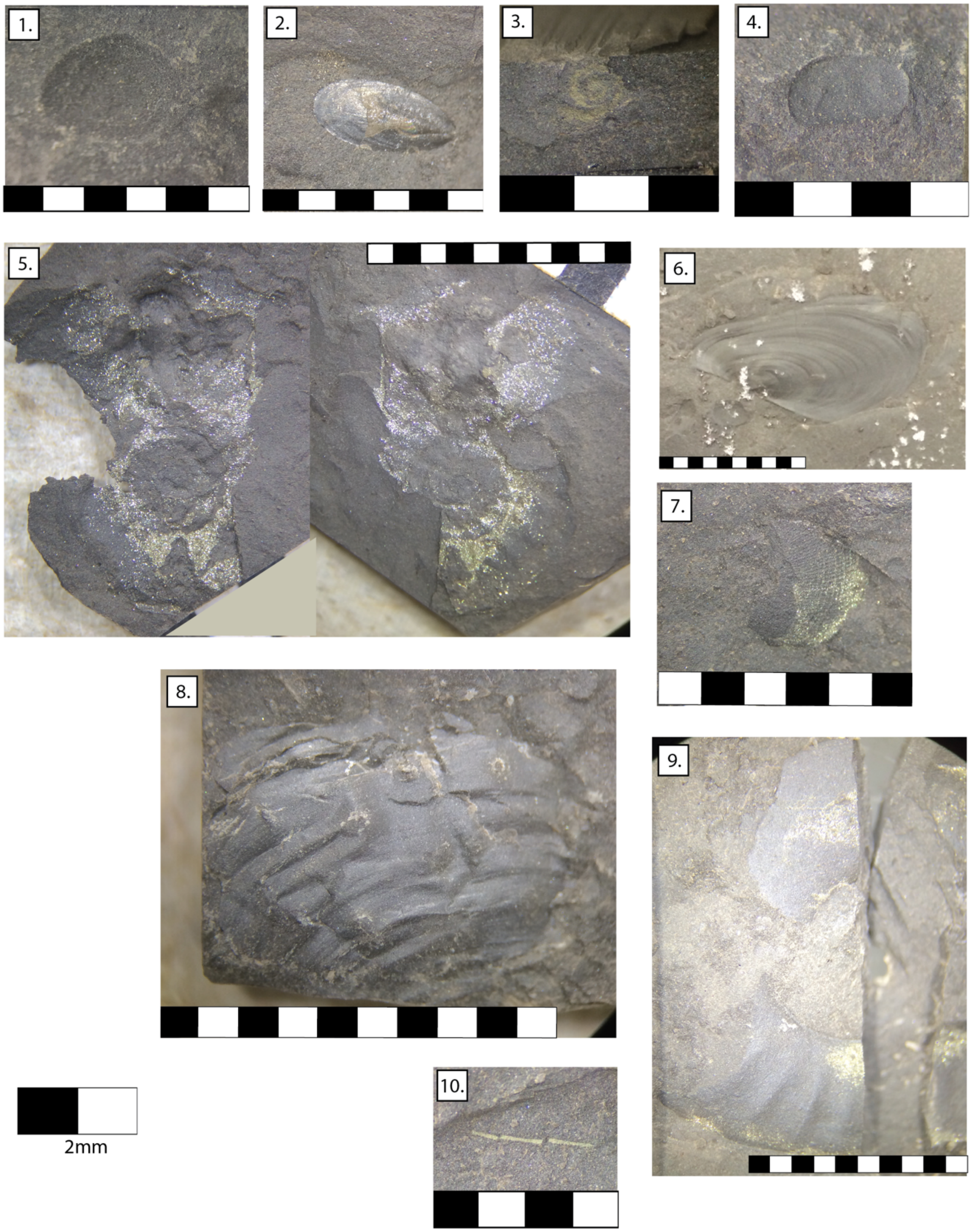

Plate 3

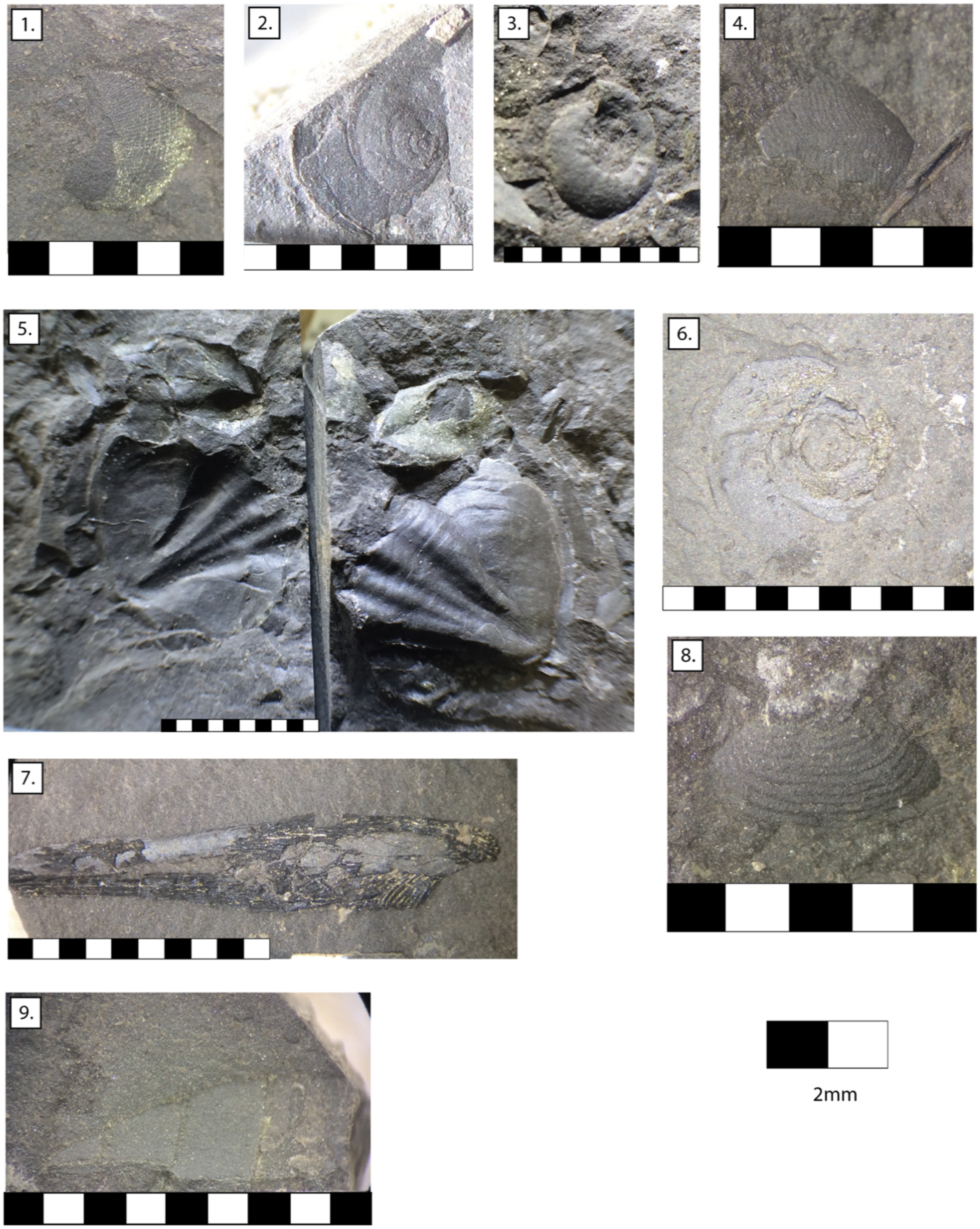

Plate 4