Palynology of the Devonian-Carboniferous Boundary Sappington Formation, Montana

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ABSTRACT

The Sappington Formation, divided into six units by Sandberg et al (1972), contains the Devonian-Carboniferous boundary but has conflicting biostratigraphic ages. Previous studies place the D-C boundary at the base of unit 2, above the base of unit 5, and between units 4 and 6. The Sappington Formation contains three dark shale units, making it ideal for palynostratigraphy. Five sections were systematically sampled, processed according to standard organic microfossil extraction techniques modified by di Pasquo, and examined, yielding palynomorphs in both the Logan Gulch and Moose Creek localities. Based on palynology and conodont biostratigraphy, the D-C boundary is at the base of unit 6. Age diagnostic taxa found in unit 4 are *Retispora lepidophyta, Verrucosisporites nitidus, Vallatisporites hystricosus,* and *Grandispora saurota,* indicating a Strunian LN zone for unit 4. Units 1 and 4 were probably deposited in lagoons or bays, and unit 6 was probably deposited offshore.

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1. INTRODUCTION

1.1 The Sappington Formation

The Sappington Formation was deposited in the Central Montana Trough close to the equator (figure 1) (Sloss, 1950; Andrichuk, 1951; Witzke and Heckel, 1988; Sonnenberg and Pramudito, 2009).

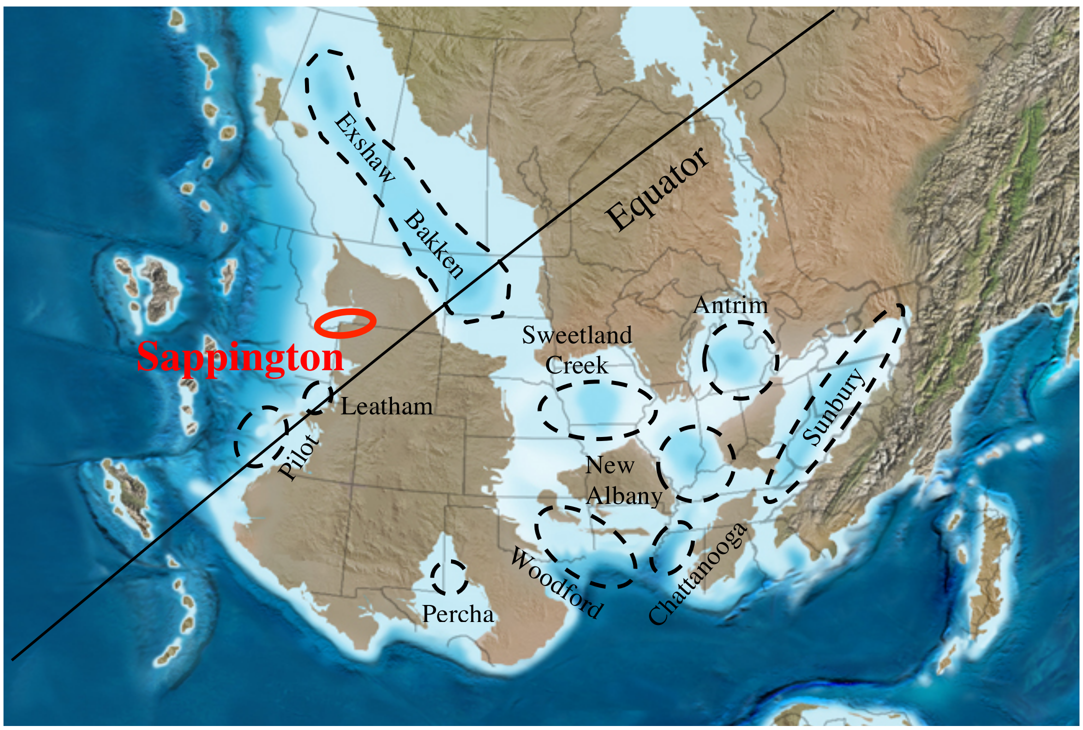

Figure 1: Late Devonian paleogeography. The Central Montana Trough, where the Sappington Formation was deposited, is outlined in red. Other basins are outlined in black. Note the Central Montana Trough's proximity to the equator (From Rodriguez, 2014).

Biostratigraphic studies have indicated that the Sappington Formation has the Devonian-Carboniferous (D-C) boundary (Archauer, 1959; Gutschick et al., 1962; Sandberg et al., 1972). However, biostratigraphic dating of the Sappington Formation has produced conflicting results (figure 3), preventing precise placement of the D-C boundary.

The D-C boundary is marked in many places worldwide by multiple organic-rich black shales. These shales are thought to be caused by global oceanic anoxia or dysoxia and tend to coincide with extinction events: the upper *trachytera* (conodont) zone *annulata* Event, the lower *expansa* (conodont) zone Dasberg Event, the LN (miospore) zone Hangenberg Event, and the lower *crenulata* (conodont) zone *crenulata* Event (Caplan and Bustin, 1999; Streel et al., 2000; Bond and Wignall, 2008; Marynowski et al., 2012). In most locations, the Sappington Formation exhibits two black shale units (units 1 and 6; Sandberg et al., 1972) and a slightly carbonaceous, dark green shale (unit 4) (Archauer, 1959; Sandberg et al., 1972; Gutschick et al., 1962). Conflicting biostratigraphic ages of units 1, 4, and 6 obscure the correlation between global events and sedimentation in the Sappington Formation.

The only two palynostratigraphic studies that have dated the Sappington Formation placed the D-C boundary above unit 4 (Sandberg et al., 1972; di Pasquo et al., 2012). Sandberg et al., however, only mentioned one taxon (*Retispora lepidophyta)* and was imprecise as to where that sample was collected. di Pasquo et al. (2012) further refined the boundary by assigning unit 6 to the Tournaisian, possibly the HD zone, placing the D-C boundary between units 4 and 6.

One conodont biostratigraphy study on the Sappington Formation indicated a Devonian age for unit 4 (Sandberg et al., 1972). Recently, another study was reported, giving a latest Devonian *praesulcata* zone age for unit 5 (Isaacson, 2014).

Combining the latest Devonian *praesulcata* zone age of unit 5 (Isaacson et al., 2014), a phosphatic lag at the base of unit 6 (Isaacson et al., 2014; Rodriguez, 2014), and palynological dates of Tournaisian in unit 6 (di Pasquo et al., 2012), it seems likely that the D-C boundary lies in unit 5 or at the base of unit 6 in the Sappington Formation.

1.1.1 Lithostratigraphy

The general stratigraphy of most Sappington Formation outcrops is as follows, from base to top (figure 2) (Gutschick and Perry, 1957; Archauer, 1959; Gutschick et al., 1962; Sandberg et al., 1972; Grader, 2011; Rodriguez, 2014).

Unit 1: Generally a dark brown or black, soft, easily weathered shale. Gutschick et al. (1962) divides this unit into three subunits, which are described further by Gutschick et al. (1962), Sandberg et al. (1972), Grader (2011), and Rodriguez (2014):

Subunit "A": Laminated, dull, "unquestionably" marine black shale (Sandberg et al., 1972). Contains few fossils (Gutschick et al., 1962).

Subunit "B": Dark grey or brown, glossy, contorted shale without any horizontal lamination. Contains only terrestrially-derived organic material (Grader, 2011; I sampled this subunit at Antelope Hill and found no palynomorphs) and tends to be more oxidized than the other subfacies of unit 1.

Subunit "C": Thin unit of dark brown, fissile, often fossiliferous shale. This unit occurs at most localities and contains both marine and terrestrial fauna, including conchostrachans, starfish, inarticulate brachiopods, conodonts, and fish parts (Gutschick et al., 1962; Sandberg et al., 1972).

Subunit "D": Very thin, greenish-gray, non-calcareous shale with brachiopods, bivalves, crinoid stems, and gastropods (Gutschick et al., 1962). This unit is rare, and is only noted to occur at Nixon Gulch, Antelope Hill, and Hardscrabble Peak (Gutschick et al., 1962; Rodriguez, 2014).

Unit 2: Silty oncolitic limestone with calcareous sponge nodules and oncolites with fossil nuclei (Gutschick et al., 1962). This unit also contains bryozoans and crinoids (Grader, 2011). Its contact with unit 3 is often gradational (Gutschick et al., 1962).

Unit 3: Generally calcareous, yellow-orange siltstone, with lenses of coarser material and sometimes crinoids (Gutschick et al., 1962). Contains occasional brachiopod fossils (Gutschick et al., 1962).

Unit 4: Green to dark grey shale and siltstone. It is usually argillaceous, calcareous, and relatively low in organic content compared to units 1 and 6 (Archauer, 1959; Gutschick et al., 1962). Unit 4 is usually heavily burrowed. Gutschick et al. (1962) noted silty channel-fill containing marine fossils.

Unit 5: Tan, resistant, calcite cemented siltstone. It exhibits ripple marks, cross bedding, channel-fill, and burrows (Gutschick and Perry, 1957; Archauer, 1959; Gutschick et al., 1962).

Unit 6: Dark grey, laterally discontinuous shale to sandstone (Gutschick et al., 1962; Rodriguez, 2014). This "shale" unit tends to be much more resistant than units 1 and 4. A basal phosphatic lag containing conodonts and fish parts appears in some localities (Rodriguez, 2014). Archauer (1959), Gutschick et al. (1962) and di Pasquo et al. (2012) record the presence of plant spores in this unit, and one sample in this study yielded both miospores and acritarchs.

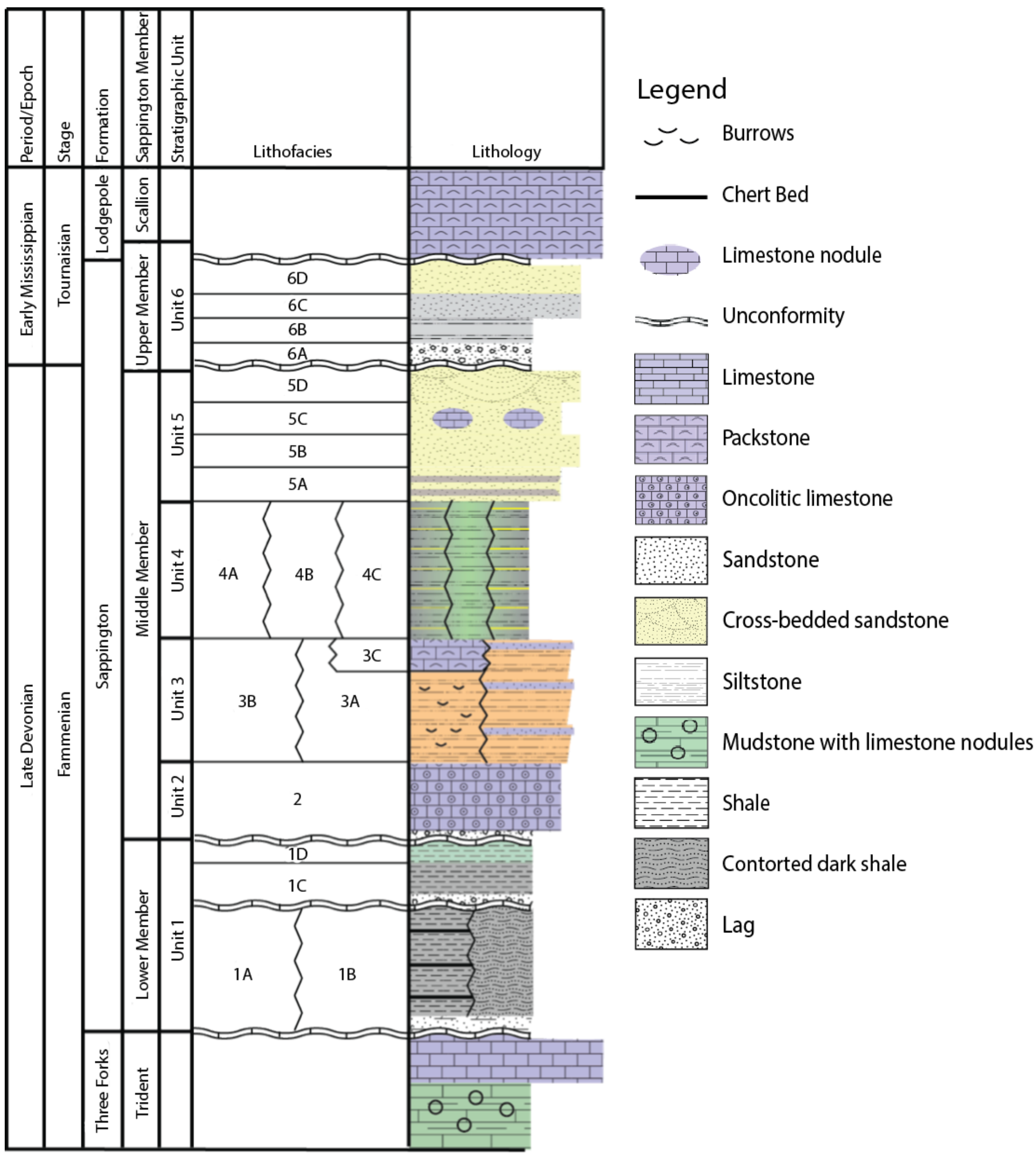

Figure 2: General stratigraphy of the Sappington Formation (from Rodriguez, 2014).

1.1.2 Biostratigraphy

The biostratigraphic data on the Sappington Formation have been interpreted differently by many authors (figure 3). Most of the disparities in dating occur in the age of unit 4. Different biota indicate different ages: brachiopods tend to give a Mississippian age for unit 4 (Gutschick and Rodriguez, 1967), while palynology and conodonts yield a Devonian age (Sandberg et al., 1972). Since these studies were published there have been many changes in fossil ranges, names, and biostratigraphic zonations, necessitating reevaluation of the Sappington Formation's biostratigraphy.

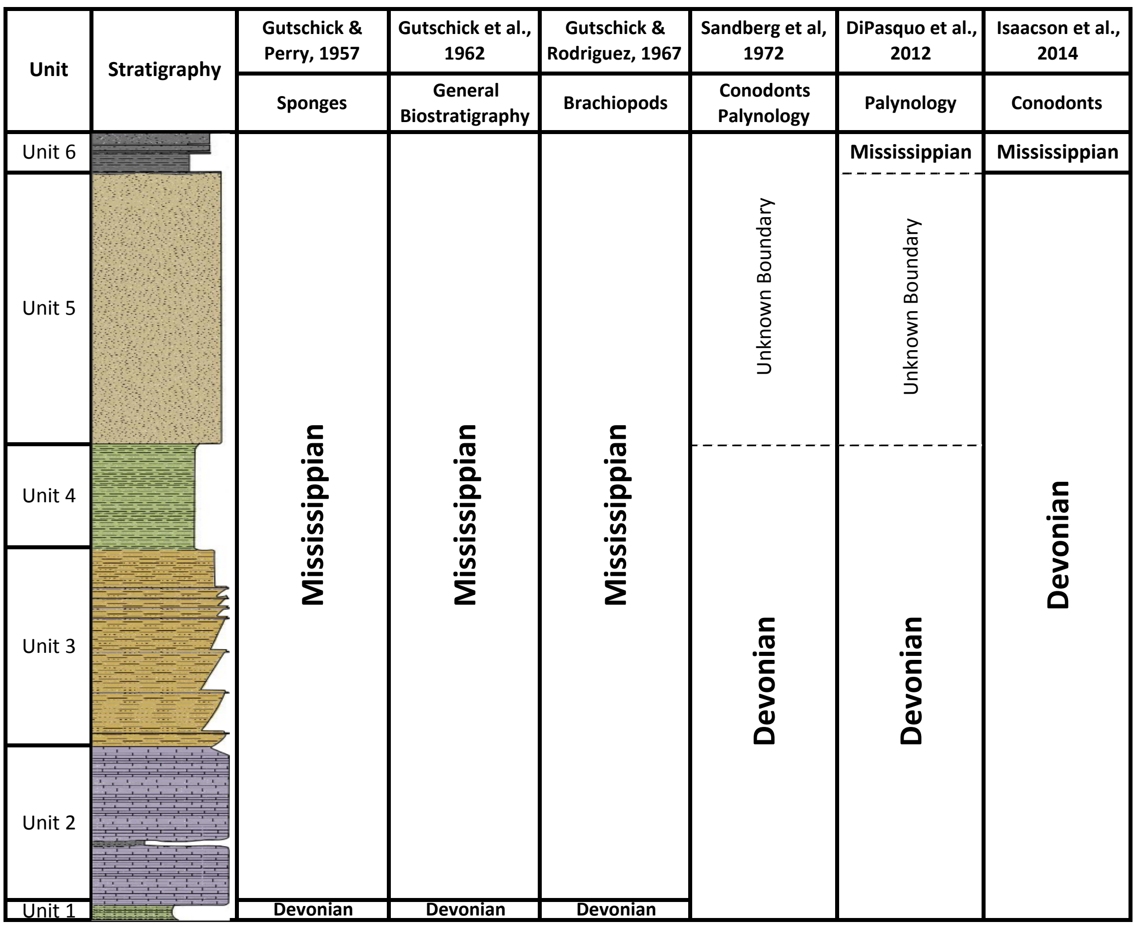

Figure 3: Stratigraphic placement of the Devonian-Mississippian boundary according to each biostratigraphy study. The biota used in each study are listed underneath their respective citations.

Conodonts

Conodonts have been the focus of biostratigraphic studies in the Sappington Formation, but provide limited, often outdated data. Published conodont studies of the Sappington Formation are as follows:

Archauer (1959): A conodont assemblage was found in unit 4 that included species of *Siphonognathus* and *Polygnathus*. The study suggested that these are representative of an assemblage separate from that of unit 6. Unit 6 had an assemblage of *Bryanthodus*, *Ligonodina*, and *Siphonognathus*, but the study did not call this a representative assemblage because of the elements' uneven stratigraphic distribution. No date was given for the Sappington Formation.

Sandberg and Klapper (1967): An assemblage was recovered from a lag at the base of the Sappington Formation. The assemblage included *Palmatolepis rugosa rugosa, P. rugosa postera, P. perlobata perlobata, P. gracilis gracilis, Spathognathodus jugosus, S. praelongus, S. stabilis, Polygnathus perplexa, P. triangularis, P. semicostata, P. granulosa, and Pseudopolygnathus marburgensis,* indicating an upper *Polygnathus styriaca* zone for unit 1 (now lower *Palmatolepis expansa* zone).

Sandberg et al. (1972): *Siphonodella sulcata* was separated it from its successor *Siphonodella praesulcata.* A new North American conodont zone was named based on the occurrence of *S. praesulcata*, representing the final conodont zone of the Devonian. Based on this zone, units 2, 3, 4, and 5 are reported to be in the latest Devonian *praesulcata* zone, while unit 1 is in the Upper *Polygnathus styriacus* zone (now Lower *expansa*) and unit 6 is in the *crenulata* zone. Unit 6 also may be Devonian in some localities.

Isaacson et al. (2014): The samples studied indicated a latest Devonian *praesulcata* zone for unit 5 (present species: *Apatognathus varians, Bispathodus stabilis,* and *Polygnathus communis*) and a middle Tournaisian *isosticha* zone at 6 inches above the base of the Scallion Member of the overlying Lodgepole Formation (present species: *Siphonodella isosticha*). This indicates an unconformity spanning four conodont zones: *sulcata, duplicata, sandbergi,* and lower *crenulata.* Combining this new conodont data, the presence of a lag at the base of unit 6, and the palynological dates of Strunian for unit 4 and Tournaisian for unit 6, the D-C boundary is suggested to be at the top of unit 5.

Palynology

Palynological data on the Sappington Formation are also very limited. The studies that have reported on Sappington palynology are as follows:

Archauer (1959): *Tasmanites* was found in both the upper (unit 6) and lower (unit 1) black shale units. *Tasmanites* species were more abundant and diverse in unit 1 than in unit 6. *Punctatisporites* species and other unidentified miospores were also found.

Gutschick et al. (1962): Unidentified miospores were found in units 1 and 6 (Gutschick units A, B, C, and I). Using ostracodes and microcrinoids, the D-C boundary was placed at the base of unit 3.

Sandberg et al. (1972): An assemblage collected from unit 4 on Peak 9559 in the Bridger Mountains, MT included *Baculatisporites fusticulus, Cristatisporites echinatus, Grandispora echinata, Lophozonotriletes rarituberculatus, Dictyotriletes trivialis, Hymenozonotriletes lepidophytus (Retispora lepidophyta),* and an *Archaeoperisaccus* species. Consequently, unit 4 was concluded to be latest Devonian.

di Pasquo et al. (2012): Samples collected from the Logan Gulch yielded no biostratigraphically useful palynomorphs. A "monosaccoid" leiosphaerid assemblage was recovered from unit 1. A Strunian age was suggested for unit 4, but the index fossil *Retispora lepidophyta* was absent from preparations. A Tournaisian assemblage was found in unit 6, indicating that the D-C boundary is between units 4 and 6.

1.2 Bakken Formation Biostratigraphy

Devonian-Carboniferous boundary palynological studies in the neighboring Bakken Formation of the Saskatchewan subsurface may elucidate species and biostratigraphic zonations likely to be found in the Sappington Formation (see figure 4 for stratigraphy and nomenclature). The only comprehensive, non-proprietary study on the subject is by Playford and McGregor (1993). This study found a latest Devonian LV zone in the Lower Bakken shale and an assemblage in the Upper Bakken shale including *Retispora lepidophyta.* The occurrence *R. lepidophyta* in the Upper Bakken was attributed to reworking based on lack of evidence for *in situ* deposition. Based on conodont evidence for a *crenulata* zone in the Upper Bakken, the Upper Bakken was tentatively assigned an early Tournaisian age. The authors did not rule out the possibility of in situ deposition, however, and called for further examination to confirm reworking. The dates for the Bakken sandstone member were more difficult to ascertain based on little variability in assemblage composition, but it was stated to likely be no older than the LE zone.

Another, smaller study of USGS Bakken cores (Big Sky 1 in the Lower Bakken at 9926 and 9920 ft.) found long-ranging acritarchs and abundant leiosphaerids (50-400μm in diameter) (di Pasquo et al., 2012). Because of the absence of biostratigraphically useful species, the study did not assign an age to the unit. However, palynological preparations gave some insight into possible depositional environments of the Lower Bakken, which were determined to be associated with a lagoon setting.

Conodont studies in the Bakken Formation may also assist in dating the Sappington Formation. Hayes (1985) assigned the Lower Bakken to the Famennian, tentatively to the upper *Polygnathus styriacus* zone (now lower *expansa*). The Upper Bakken was assigned to the Tournaisian *Siphonodella crenulata* zone. Hayes suggested that the D-C boundary might be at the base of the Upper Bakken. Holland et al. (1987) placed the D-C boundary at the base of unit 2 in the Bakken Sandstone based on the appearance of a Mississippian brachiopod fauna in the third member. Thrasher (1987) also placed the D-C boundary at the base of Bakken Sandstone unit 2 based on a Devonian brachiopod fauna in unit 1, plant fossils in unit 2, and a Mississippian brachiopod fauna in unit 3. Karma (1991) suggested that the D-C boundary was at the base of unit 3 in the Bakken Sandstone based on conodont and paleobotanical evidence. Drees and Johnston (1996) confirmed previous reports of early Tournaisian conodonts in the Upper Bakken, including the *sulcata* and lower *crenulata* zones, and suggested a probable *expansa* zone for the Lower Bakken. Drees and Johnston gave no approximate location of the D-C boundary due to lack of evidence. Despite biostratigraphic dating conflicts in the Bakken Sandstone, virtually all conodont studies agree that the upper shale is Tournaisian and the lower shale is Famennian.

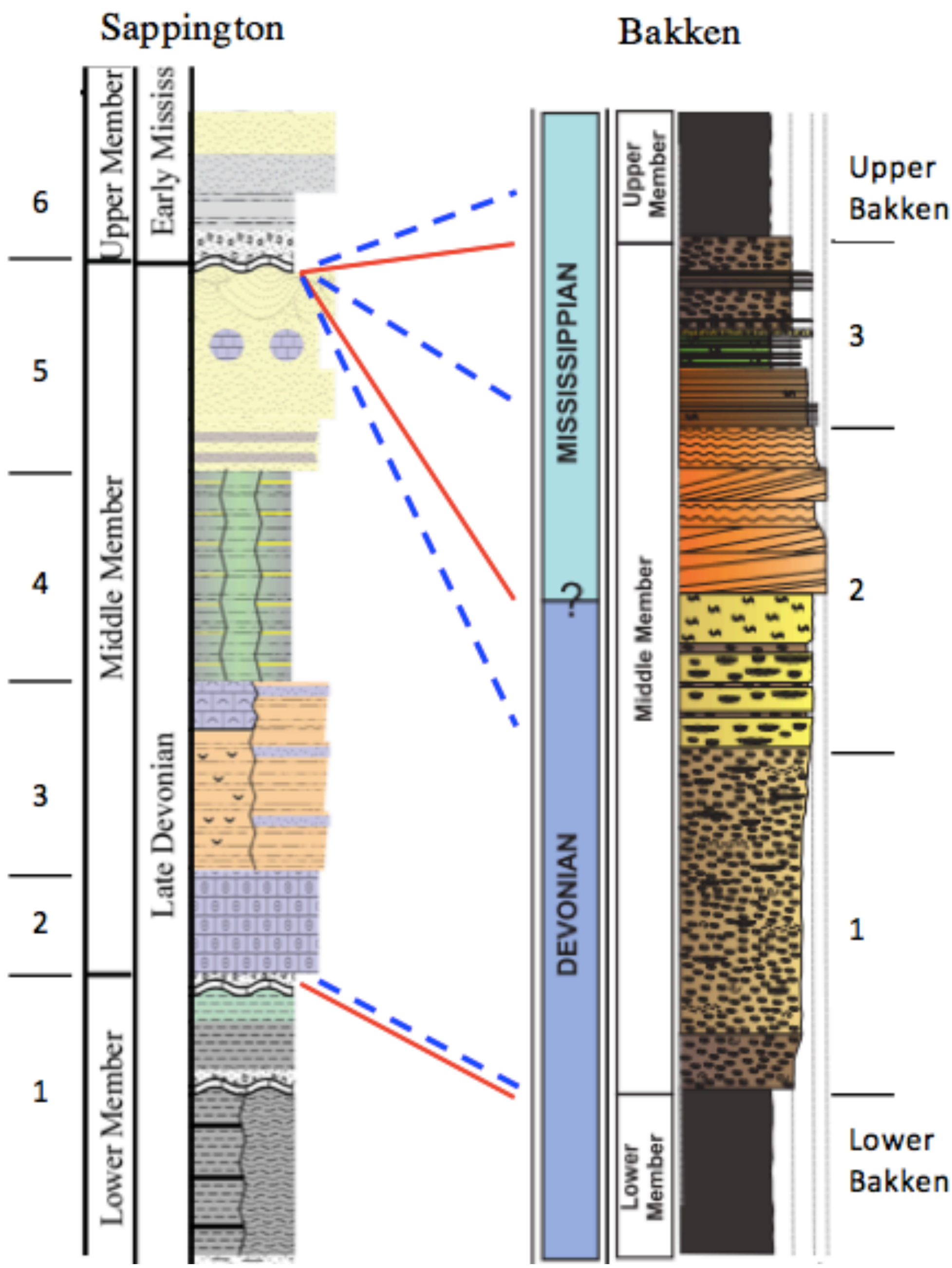

Figure 4: Previous lithologic (solid red) and biostratigraphic (dashed blue) correlations based on previous studies of the Bakken and Sappington formations (modified from Rodriguez, 2014). Sappington unit divisions are from Sandberg et al. (1972). Bakken unit divisions are from Thrasher (1985).

1.3 Significance of Study

The Sappington Formation is exposed, unlike its petroliferous correlative neighbor, the Bakken Formation, which is almost entirely in the subsurface (Playford and McGregor, 1993). Outcrop examination can be helpful in understanding lithological characteristics, such as weathering profiles, which are not visible in cores. To accurately relate the Sappington Formation to the Bakken Formation, precise stratigraphic correlation is necessary.

The Sappington and Bakken formations' stratigraphy were largely caused by eustatic fluctuations, so they are lithostratigraphically correlative (Rodriguez, 2014). Exact correlation is difficult, especially in the upper three units (figure 4); however, the base of unit 2 in the Sappington Formation is correlated with the base of the Bakken Sandstone based on lithology (Rodriguez, 2014) and palynology (di Pasquo et al., 2012). Biostratigraphy can be a powerful tool, and since both the Bakken and Sappington formations have black shales ideal for preservation of palynomorphs, palynostratigraphy is a promising option for correlation. Understanding how these two formations correlate will allow for more precise correlation with other D-C boundary units worldwide and increase understanding of how extinction events and Gondwanan glaciation affected western North America.

This study provides up-to-date, comprehensive palynological data on the Sappington Formation, expanding on a preliminary study reported in di Pasquo et al. (2012) by taking systematic samples over all three shale units at multiple localities. This study also includes an analysis of organic matter in black shale, providing new depositional environment information for all three units. Possible correlations with glaciations, anoxic periods, extinction events, and other D-C boundary units worldwide are also presented.

2. METHODS

2.1 Sample Collection

General lithology samples were collected from multiple localities for palynological productivity assessment (figure 5). Specific, systematic samples were collected from three localities: Nixon Gulch, Antelope Hill, and Logan Gulch. Using a measuring tape, samples were collected at 10cm-20cm intervals from each location's black or green shale and silty shale units. 24 samples were collected from Logan Gulch (Trident Shale: 1, unit 1: 1, unit 4: 15, unit 6: 7), 15 samples were collected from Nixon Gulch (Trident Shale: 1, unit 1: 1, unit 4: 4, unit 6: 9), and 8 samples were collected from unit 1 at Antelope Hill. Samples from the lower contact, upper contact, and stratigraphic middle of each shale unit over 20cm thick were taken at two localities: Moose Creek and Trident. 5 samples were collected at Moose Creek (unit 1: 1, unit 4: 1, unit 6: 3) and 7 samples were collected at Trident (unit 1: 3, unit 4: 3, unit 6: 1).

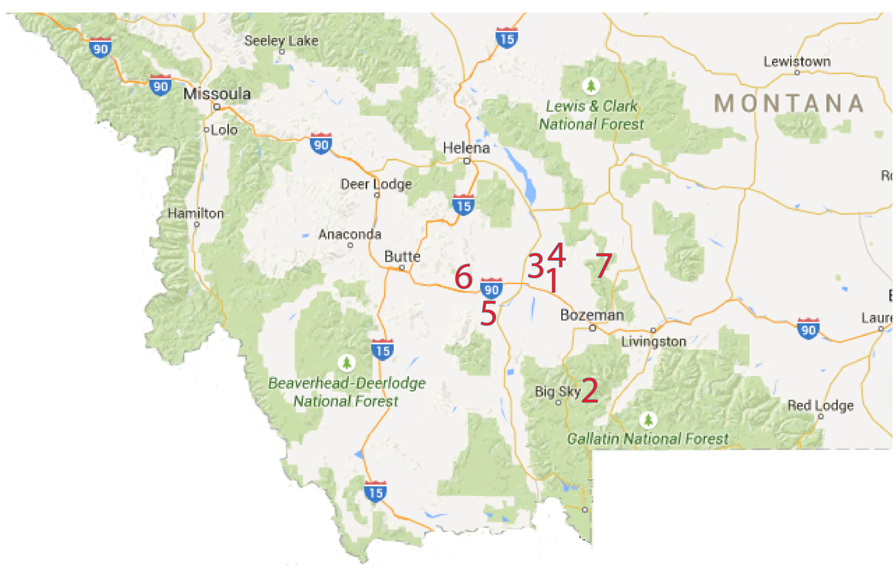

Figure 5: Localities sampled for this study. All sections are located in southwestern Montana. Map modified from Google Maps (2015). 1) Logan Gulch, 2) Moose Creek, 3) Trident, 4) Nixon Gulch, 5) Antelope Creek, 6) Red Hill

2.2 Sample Processing

Samples were processed for palynomorph extraction and palynofacies assessment using standard methodology (Traverse, 2007) as described below:

1. Crushed roughly 10g of sample using a mortar and pestle.

2. *Pretreat with HCl to remove carbonate:* Crushed samples were placed in test tubes with 15-20ml of 18% HCl and agitated until effervescence ceased. Samples were then washed two times with distilled water. Note: HCl was mixed with tap water for samples from Moose Creek and Trident.

3. *Digest in HF for removal of silicates:* Sample residues were left in HF until generally digested, between 48 hours and two weeks. If samples were not digested within this time period, samples were washed and treated with HF again until digested. Samples were then washed 3 times and mounted.

Additional steps for palynomorph extraction

4. *Boil in HCl to disaggregate organic matter:* Samples that were still obscured by organic matter were boiled in HCl. Sample residues were placed in a test tube with HCl and boiled directly in flame. Samples were then washed three times and mounted.

5. *Sieve to concentrate palynomorphs:* Samples that were still obscured by fine organic matter were sieved with a 25µm mesh.

6. *Final mounting of slides and storage:* Most intermediate and final preparations of organic residues were mounted on slides using glycerine jelly with a drop of formaldehyde for preservation. Samples from Logan Gulch, Nixon Gulch, and

Antelope Hill are catalogued under the acronym CICYTTP-Pl and stored at the Palynological Collection of the Laboratory of Palynostratigraphy and Paleobotany in the *Centro de Investigaciones Científicas y Tecnológicas de Transferencia a la Producción (CICYTTP-CONICET),* Diamante, Entre Rios, Argentina. Samples from Moose Creek, Trident, and all other localities are housed in the Paleontology lab at University of Idaho. Palynomorphs were studied and illustrated in a trinocular transmitted light microscope bearing a video camera (Leica DM500 and Leica EC3, 3.0 Mp; Nikon Eclipse E200).

2.3 Biostratigraphy

Palynomorphs in each slide were identified using previous descriptions and photographs from existing literature (Hacquebard, 1957; Higgs, 1975; Playford, 1976; Playford and McGregor, 1993; Wicander and Playford, 2013). The stratigraphic intervals represented by each slide were then assigned to Euramerican palynozones (Clayton et al., 1977; Richardson and McGregor, 1986). Units were then assigned current geologic ages (Cohen et al, 2014).

2.4 Palynofacies

The types of organic matter contained in a rock depend on the environment at the time of deposition. Terrestrial organic matter, such as miospores and phytoclasts, indicate terrestrial influence in the system. Marine organic matter, such as acritarchs and prasinophytes indicate a marine depocenter (Tyson, 1995; Batten, 1996).

Samples were recorded with representative abundances of organic matter as a general survey of the types of organic matter present. Abundances are based on one to three drops of residue drawn from the middle of the test tube's water column immediately after agitation.

Immediate, uniform withdrawal of agitated residues helps to ensure as best as possible that organic matter types with various densities have representative concentrations on slides. Human selection between one, two, or three drops of residue per slide ensures that residues on slides will be visible and not too dense or too sparse.

Samples were assessed using qualitative analysis according to a simplified scheme adapted from Tyson (1995). Abundance percentage categories were selected at levels that were as easy to recognize as possible to avoid error and bias in categorization. Abundances presented in this study are intended to provide only basic information on relative abundances. An in-depth study would be necessary to determine specific, quantitative proportions for use in precision-oriented depositional environment studies. The system this study used is as follows:

Unstructured Organic Matter

l = low: less than 10% of the total organic matter

m = moderate: 10% - 50% of the total organic matter

a = abundant: greater than 50% of the total organic matter

Specified unstructured organic matter categories are as follows:

1. Amorphous organic matter (AOM): organic matter with no cellular structure

2. Brown phytoclasts: pieces of plant debris that are relatively well preserved

3. Black phytoclasts: opaque black plant debris with clearly structured shapes. These are usually heat-altered brown phytoclasts from sources such as wildfires, burial and recycling, and contact metamorphism (Traverse, 2007).

Structured Organic Matter

To characterize palynomorph abundance per slide of a sample level, the absolute count of palynomorphs recorded is based on one to three drops of residue on a slide according to this system:

r = rare: less than 5 palynomorphs of the specified affinity on the slide

m = moderate: 5 to 10 palynomorphs of the specified affinity on the slide

a = abundant: greater than 10 palynomorphs of the specified affinity on the slide

Specified structured organic matter categories examined are as follows:

1. Acritarchs: marine plankton of unknown taxonomic affinity

2. Algal cysts: circular palynomorphs with various algal or invertebrate affinities

3. Miospores: land plant reproductive spores

4. Woody Tissue: clearly structured woody tissues from land plants

5. Scolecodonts: pieces of polychaete annelid jaws

3. RESULTS

3.1 Sample Productivity

The most palynostratigraphically productive units are slightly calcareous, moderately carbonaceous shales. These are seen almost exclusively in unit 4. Logan Gulch and Moose Creek were the most productive localities, and unit 4 yielded the most well preserved palynomorphs (see figure 6 for table of locality and unit productivity). At Logan Gulch, 9 out of 24 samples yielded palynomorphs and three other samples yielded only phytoclasts. Out of 15 samples at Nixon Gulch, zero samples yielded palynomorphs, but four samples yielded phytoclasts. At Antelope Hill, zero samples yielded palynomorphs, but all seven samples yielded phytoclasts. All five samples at Moose Creek yielded phytoclasts and palynomorphs; however, the palynomorphs in unit 1 were poorly preserved. All seven samples yielded phytoclasts at the Trident locality, but zero yielded palynomorphs. Each section's results are described further in section 3.1.2.

Biostratigraphic Productivity of Sections and Units Collected and Processed

Section	Unit 1	Unit 4	Unit 6
Antelope Hill	Phytoclasts		
Beaver Creek			Very Sparse
Frazier Lake		Productive	
Horseshoe Canyon		Moderate	
Logan Gulch	Barren	Productive	Phytoclasts
Moose Creek		Productive	Moderate
Nixon Gulch	Barren	Barren	Phytoclasts
Red Hill	Barren		
Trident	Phytoclasts	Phytoclasts	Phytoclasts

Figure 6: Biostratigraphic productivity of all localities that were both collected and processed. "Barren" indicates the absence of palynomorphs, "Very Sparse" indicates the presence of less than five palynomorphs in a slide, "Moderate" indicates the presence of between five and ten palynomorphs in a slide, "Abundant" indicates the presence of over ten palynomorphs in a slide, and "Phytoclasts" indicates the absence of palynomorph but presence of phytoclasts.

3.1.1 General Productivity of Each Shale Unit

Unit 1

Most palynomorphs are made of sporopollenin or similar organic substances, which are destroyed during oxidation, diagenesis, and other forms of weathering (Traverse, 2007). Because of its weathered nature, unit 1 was unproductive in nearly all locations. Fresh samples are very difficult to access, even with significant trenching. Unit 1 samples from Moose Creek yielded few palynomorphs, and those preserved were damaged beyond recognition.

Unit 4

Unit 4 was productive in the Logan Gulch, Moose Creek, and Frazier Lake localities. It tends to be a slightly calcareous green to gray shale with a lower concentration of amorphous organic matter than either unit 1 or unit 6.

Unit 6

Unit 6 is very organic rich and tends to have high concentrations of fine unstructured organic matter and degraded phytoclasts. Acritarchs were visible and in good condition at Moose Creek, but miospores were damaged.

3.1.2 Productivity at Each Locality

Locality productivity can vary widely based on depositional environment and any weathering, oxidation, diagenesis, or metamorphism undergone. Some localities' and units' environments were too oxygenated or too high energy to preserve palynomorphs. Palynomorphs may have been preserved in other areas prior to destruction by diagenesis. For the best productivity, the most suitable lithologies are green, gray, and black shales and mudstones. These represent low energy and reducing or hypoxic conditions conducive to organic matter preservation (Traverse, 2007).

Logan Gulch (figure 10)

Sixteen samples were collected systematically from units 1, 4, and 6 at Logan Gulch. Units 1 and 6 were barren, except for intermittent phytoclasts in unit 6. Unit 4 was productive at most intervals above 60cm from its base.

Palynology. Many miospores and acritarchs were found in unit 4. These included abundant specimens of *Retispora lepidophyta,* a cosmopolitan Strunian index miospore. Species found and their abundances are listed in figures 17 and 18 and the appendix. The miospore diversity is much greater than the acritarch diversity, with eight times the number of species.

Palynofacies (figure 7). Because slides made from the original HF digestion of Logan Gulch samples are not accessible, palynofacies assessment was performed only on palynomorph abundances. Unit 4 exhibited algal cysts, wood tissue, acritarchs, high concentrations of miospores, and both black and brown phytoclasts.

Moose Creek (figure 11)

Five samples were collected and processed from Moose Creek: one sample from each of units 1 and 4, and three samples from unit 6 at the upper and lower contacts and in the stratigraphic middle.

Palynology. Moose Creek exhibited miospores in unit 4, including *Retispora lepidophyta,* and both acritarchs and miospores in unit 6, including *Micrhystridium stellatum* (see Plate 4 figures 9 and 10).

Palynofacies (figure 8). Moose Creek exhibits miospores in all three units; however, those seen in unit 1 are very poorly preserved and unidentifiable. Amorphous organic matter was high in all samples except for unit 4, which had a smaller concentration. Acritarchs were found in unit 6, and scolecodonts were found in unit 1.

Trident (figure 12)

Seven samples were collected from the Trident locality: three from unit 1 (lower contact, middle, and upper contact), three from unit 4 (lower contact, middle, and upper contact), and one from unit 6.

Palynology. Two possible miospores were found in the Trident section, one in unit 4 and one in unit 6. These were too poorly preserved to permit definitive identification as miospores.

Palynofacies (figure 9). Amorphous organic matter was abundant in all units, with more moderate concentrations in the upper part of unit 4. Phytoclasts were visible in every unit.

Nixon Gulch (figure 13)

Fifteen samples were collected systematically from units 1, 4, and 6 at Nixon Gulch. All intervals were biostratigraphically barren; however, amorphous organic matter, phytoclasts, and *Botryococcus* were present in unit 6.

Antelope Hill (figure 14)

Unit 1 was systematically sampled from Antelope Hill. It was biostratigraphically barren, but contained phytoclasts in all samples.

Red Hill

Unit 1 at Red Hill was barren. Due to its proximity to an igneous sill, the black shales at Red Hill are thermally overmature. Heating of rock over 200°C carbonizes palynomorphs. This turns them opaque black and makes any recognition of palynomorphs impossible (Traverse, 2007). Organic matter is black under microscope; any potentially biostratigraphically useful palynomorphs have been destroyed during heating.

Logan Gulch Organic Matter

Unit	Sample	Acritarchs	Algal Cysts	Miospores	Brown Phyt	Black Phyt	Wood Tissue	Notes
Tri	1121							Barren
U1	1098							Barren
U4	1099							Barren
	1100							Barren
	1101							Barren
	1102	a	m	a	m	m	r	
	1103	r	r	a	m	a	r	
	1104	r	r	a	m	m	r	
	1105	r	r	a	m	m		
	1106							Barren
	1107							Barren
	1108							Barren
	1109	r	m	a	m	m		
	1110	m	r	a	m	m	?	
	1111							Barren
	1112							Barren
	1113							Barren
U6	1114					x		
	1115					x		
	1116							fine particulate organic matter
	1117							AOM
	1118							fine particulate organic matter
	1119							fine particulate organic matter
	1120				x			

Figure 7: Palynofacies at Logan Gulch. Because slides with only HF processing are not accessible, amorphous organic matter concentrations are not considered at this locality.
For phytoclasts (left three columns):
a = abundant (>50%),
m= moderate (10%-50%),
l = low (<10%);
For palynomorphs (right three columns):
a = abundant (>10 specimens),
m = moderate (5-10 specimens)
r = rare (<5 specimens);
? = questionable identification, damaged. or obscured,
p = poorly preserved,
x = presence recorded with no abundance data.

Moose Creek Organic Matter

Unit	Sample	AOM	Brown Phyt	Black Phyt	Acritarchs	Algal Cysts	Miospores	Wood Tissue	Scolecodonts
U1	MC01	a	m	m			r,p	?	r
U4	MC02	m	a	l		r	a		
U6	MC03	a	l	l	r		r		
	MC04	a	l	l	?		r,p		
	MC05	a	l	l					

Figure 8: Moose Creek Palynofacies. Palynomorphs were visible in all units at this locality; however, those visible in unit 1 were damaged and poorly preserved. Residues used for palynofacies at this locality were processed only with HF. a = abundant (>50%), m= moderate (10%-50%), l = low (<10%); for palynomorphs (right four columns): a = abundant (>10 specimens), m = moderate (5-10 specimens) r = rare (<5 specimens); ? = questionable identification, very damaged. or obscured, p = poorly preserved.

Trident Organic Matter

Unit	Sample	AOM	Brown Phyt	Black Phyt	Acritarchs	Algal Cysts	Miospores	Wood Tissue	Scolecodonts
U1	TS01	a	m	l					
	TS02	a	m	m					
	TS03	a	m						
	TS04	a	m	l			?		
U4	TS05	m	m	m					
	TS06	m	m	m					
U6	TS07	a	m	l			?		

Figure 9: Palynofacies at the Trident locality. Palynomorphs were rare, but amorphous organic matter was generally abundant. Residues used for palynofacies at this locality were processed only with HF. For amorphous organic matter (left three columns): a = abundant (>50%), m= moderate (10%-50%), l = low (<10%); for palynomorphs (right four columns): a = abundant (>10 specimens), m = moderate (5-10 specimens) r = rare (<5 specimens); ? = questionable identification, damaged. or obscured, p = poorly preserved.

Figure 10: Stratigraphy and sample locations at Logan Gulch. Sample locations are noted with a dashed line and a sample number, also referenced in figure 7. Notes on stratigraphy are to the left of the column. Samples from di Pasquo et al. (2012) are in red.

Figure 11: Stratigraphy and sample locations at Moose Creek. Sample locations are noted with a dashed line and a sample number, also referenced in figure 8. Notes on stratigraphy are to the left of the column.

Figure 12: Stratigraphy and sample locations at Trident. Sample locations are noted with a dashed line and a sample number, also referenced in figure 9. Notes on stratigraphy are to the left of the column.

Figure 13: Stratigraphy and sample locations at Nixon Gulch. Sample locations are noted with a dashed line and a sample number. Notes on stratigraphy are to the left of the column.

Figure 14: Stratigraphy and sample locations at Antelope Hill. Sample locations are noted with a dashed line and a sample number. Notes on stratigraphy are to the left of the column.

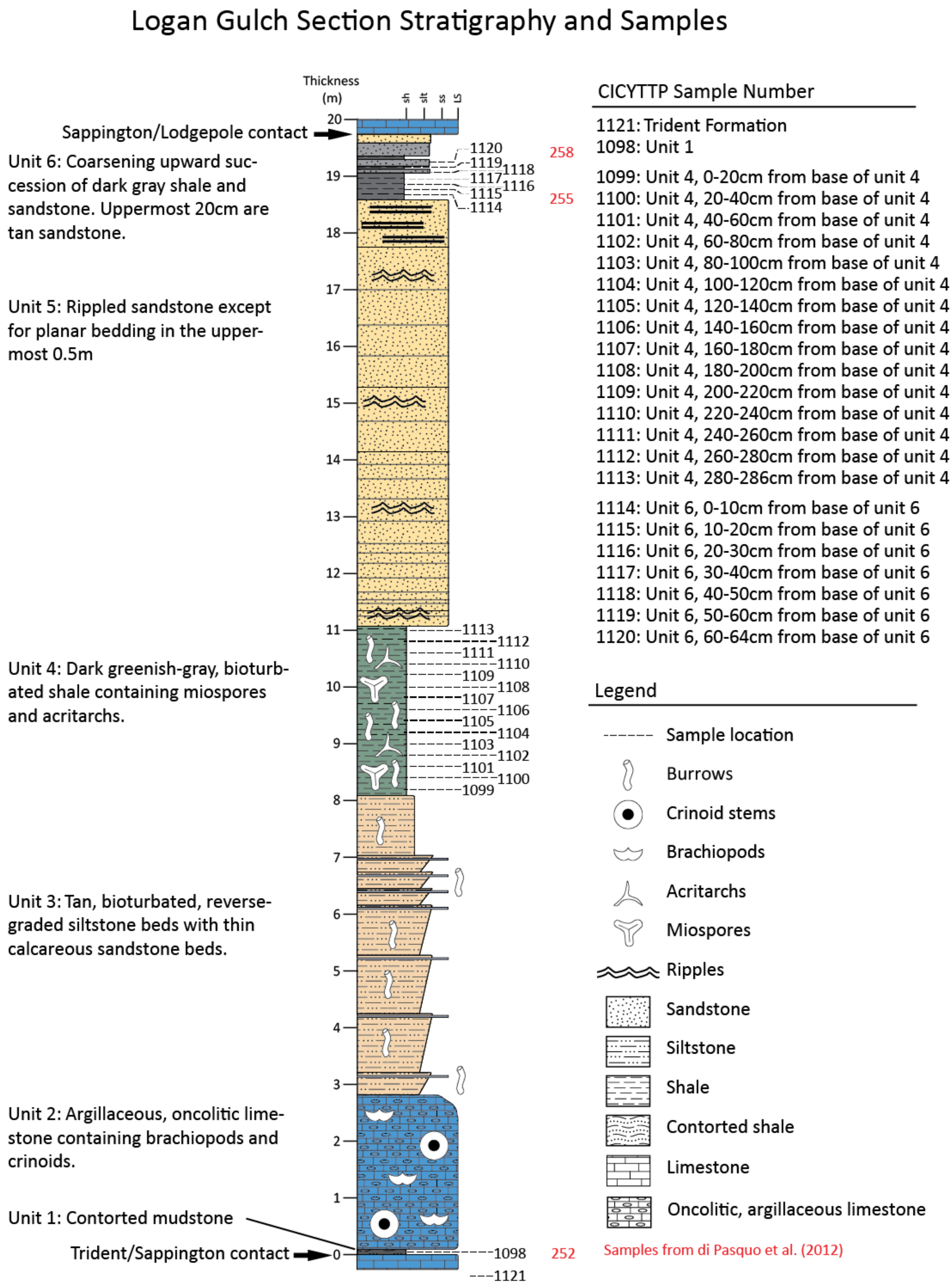
Logan Gulch Section Stratigraphy and Samples
Thickness (m)
sh
slt
ss
LS
Sappington/Lodgepole contact
Unit 6: Coarsening upward succession of dark gray shale and sandstone. Uppermost 20cm are tan sandstone.
Unit 5: Rippled sandstone except for planar bedding in the uppermost 0.5m
Unit 4: Dark greenish-gray, bioturbated shale containing miospores and acritarchs.
Unit 3: Tan, bioturbated, reverse-graded siltstone beds with thin calcareous sandstone beds.
Unit 2: Argillaceous, oncolitic limestone containing brachiopods and crinoids.
Unit 1: Contorted mudstone
Trident/Sappington contact
258
255
252
CICYTTP Sample Number
1121: Trident Formation
1098: Unit 1
1099: Unit 4, 0-20cm from base of unit 4
1100: Unit 4, 20-40cm from base of unit 4
1101: Unit 4, 40-60cm from base of unit 4
1102: Unit 4, 60-80cm from base of unit 4
1103: Unit 4, 80-100cm from base of unit 4
1104: Unit 4, 100-120cm from base of unit 4
1105: Unit 4, 120-140cm from base of unit 4
1106: Unit 4, 140-160cm from base of unit 4
1107: Unit 4, 160-180cm from base of unit 4
1108: Unit 4, 180-200cm from base of unit 4
1109: Unit 4, 200-220cm from base of unit 4
1110: Unit 4, 220-240cm from base of unit 4
1111: Unit 4, 240-260cm from base of unit 4
1112: Unit 4, 260-280cm from base of unit 4
1113: Unit 4, 280-286cm from base of unit 4
1114: Unit 6, 0-10cm from base of unit 6
1115: Unit 6, 10-20cm from base of unit 6
1116: Unit 6, 20-30cm from base of unit 6
1117: Unit 6, 30-40cm from base of unit 6
1118: Unit 6, 40-50cm from base of unit 6
1119: Unit 6, 50-60cm from base of unit 6
1120: Unit 6, 60-64cm from base of unit 6
Legend
Sample location
Burrows
Crinoid stems
Brachiopods
Acritarchs
Miospores
Ripples
Sandstone
Siltstone
Shale
Contorted shale
Limestone
Oncolitic, argillaceous limestone
Samples from di Pasquo et al. (2012)

Figure 10

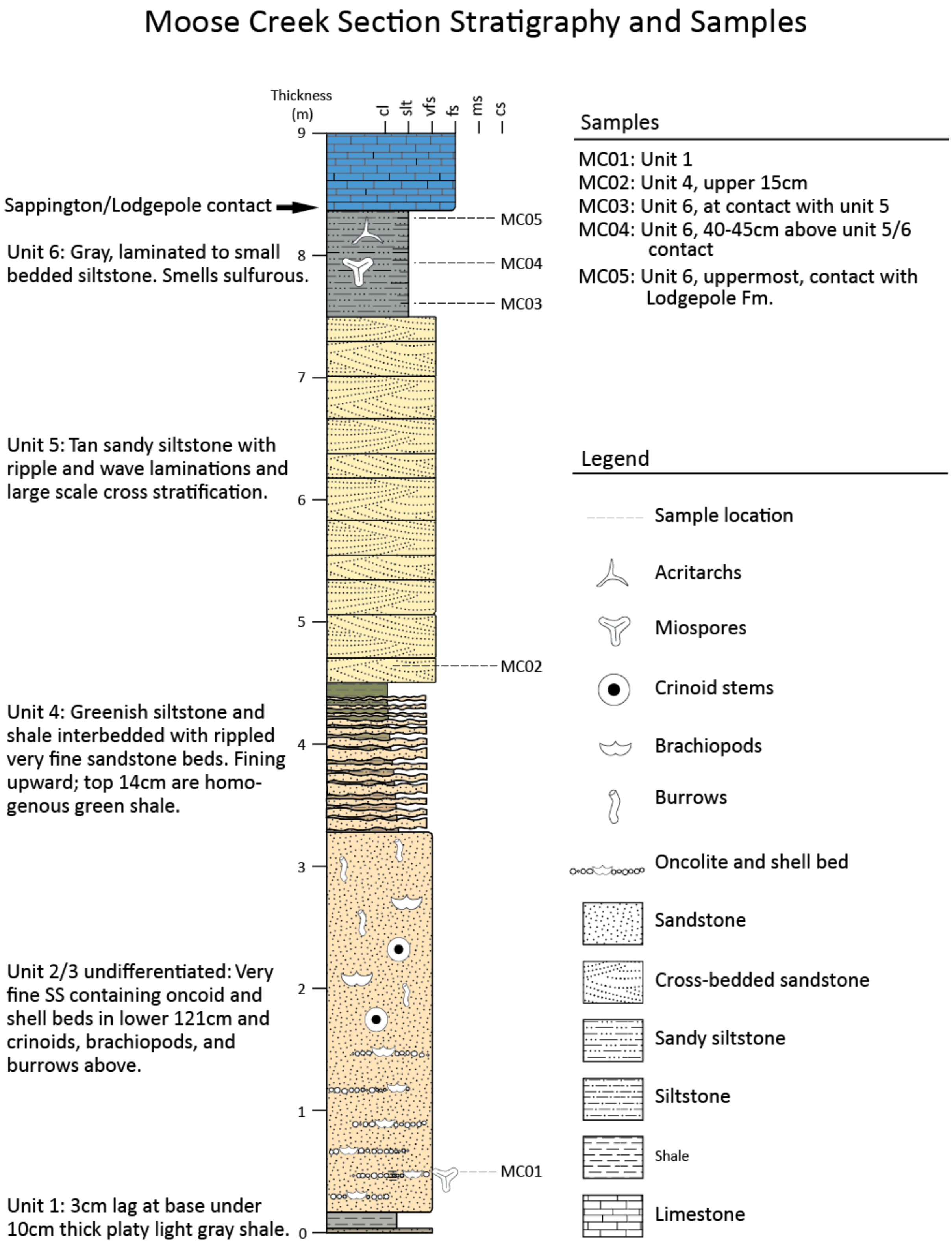
Moose Creek Section Stratigraphy and Samples
Thickness (m)
cl
slt
vfs
fs
ms
cs
9
8
7
6
5
4
3
2
1
0
Sappington/Lodgepole contact
Unit 6: Gray, laminated to small bedded siltstone. Smells sulfurous.
Unit 5: Tan sandy siltstone with ripple and wave laminations and large scale cross stratification.
Unit 4: Greenish siltstone and shale interbedded with rippled very fine sandstone beds. Fining upward; top 14cm are homo-genous green shale.
Unit 2/3 undifferentiated: Very fine SS containing oncoid and shell beds in lower 121cm and crinoids, brachiopods, and burrows above.
Unit 1: 3cm lag at base under 10cm thick platy light gray shale.
MC05
MC04
MC03
MC02
MC01
Samples
MC01: Unit 1
MC02: Unit 4, upper 15cm
MC03: Unit 6, at contact with unit 5
MC04: Unit 6, 40-45cm above unit 5/6 contact
MC05: Unit 6, uppermost, contact with Lodgepole Fm.
Legend
Sample location
Acritarchs
Miospores
Crinoid stems
Brachiopods
Burrows
Oncolite and shell bed
Sandstone
Cross-bedded sandstone
Sandy siltstone
Siltstone
Shale
Limestone

Figure 11

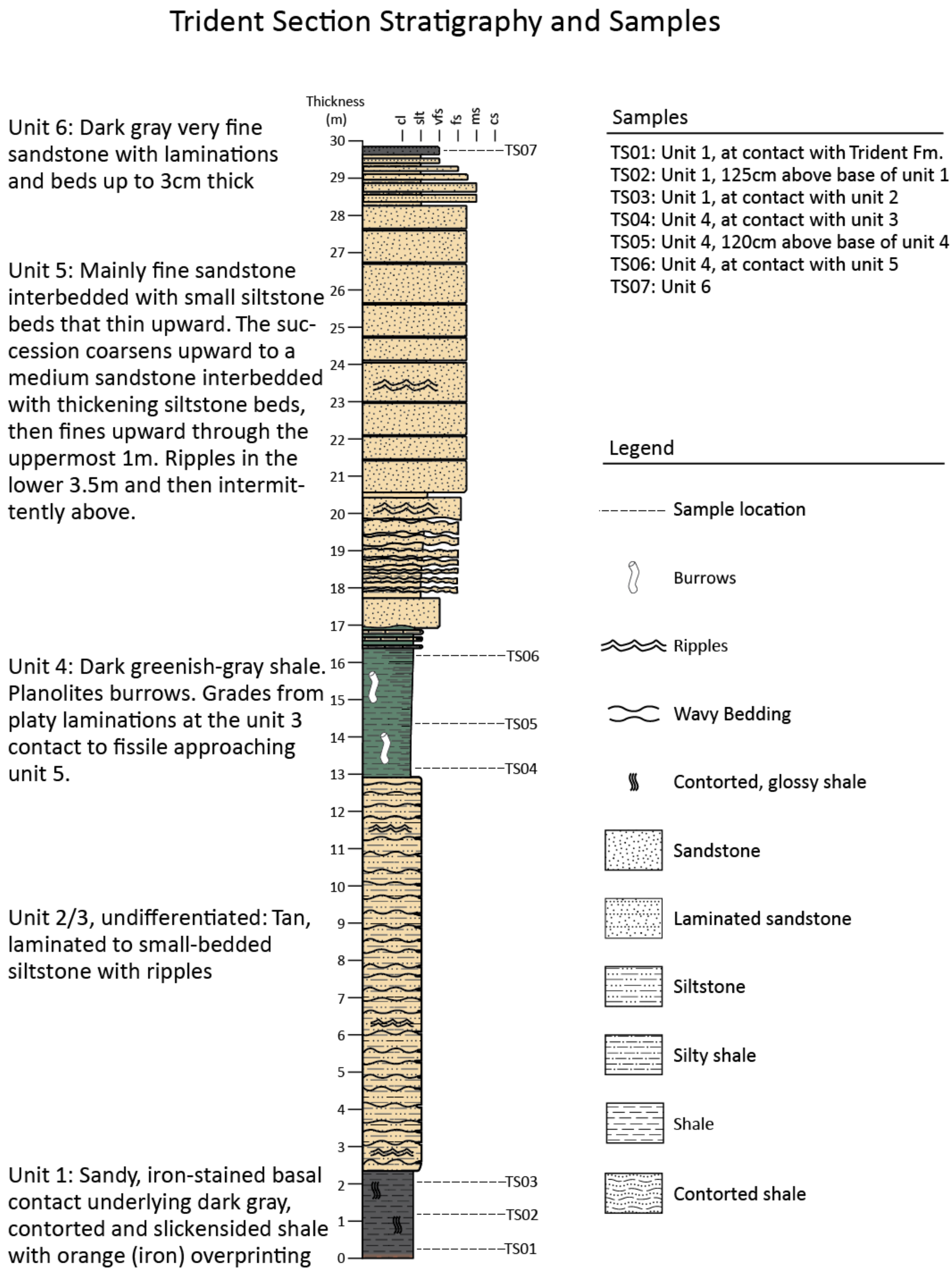
Trident Section Stratigraphy and Samples
Thickness (m)
cl
slt
vfs
fs
ms
cs
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
TS07
TS06
TS05
TS04
TS03
TS02
TS01
Unit 6: Dark gray very fine sandstone with laminations and beds up to 3cm thick
Unit 5: Mainly fine sandstone interbedded with small siltstone beds that thin upward. The succession coarsens upward to a medium sandstone interbedded with thickening siltstone beds, then fines upward through the uppermost 1m. Ripples in the lower 3.5m and then intermittently above.
Unit 4: Dark greenish-gray shale. Planolites burrows. Grades from platy laminations at the unit 3 contact to fissile approaching unit 5.
Unit 2/3, undifferentiated: Tan, laminated to small-bedded siltstone with ripples
Unit 1: Sandy, iron-stained basal contact underlying dark gray, contorted and slickensided shale with orange (iron) overprinting
Samples
TS01: Unit 1, at contact with Trident Fm.
TS02: Unit 1, 125cm above base of unit 1
TS03: Unit 1, at contact with unit 2
TS04: Unit 4, at contact with unit 3
TS05: Unit 4, 120cm above base of unit 4
TS06: Unit 4, at contact with unit 5
TS07: Unit 6
Legend
Sample location
Burrows
Ripples
Wavy Bedding
Contorted, glossy shale
Sandstone
Laminated sandstone
Siltstone
Silty shale
Shale
Contorted shale

Figure 12

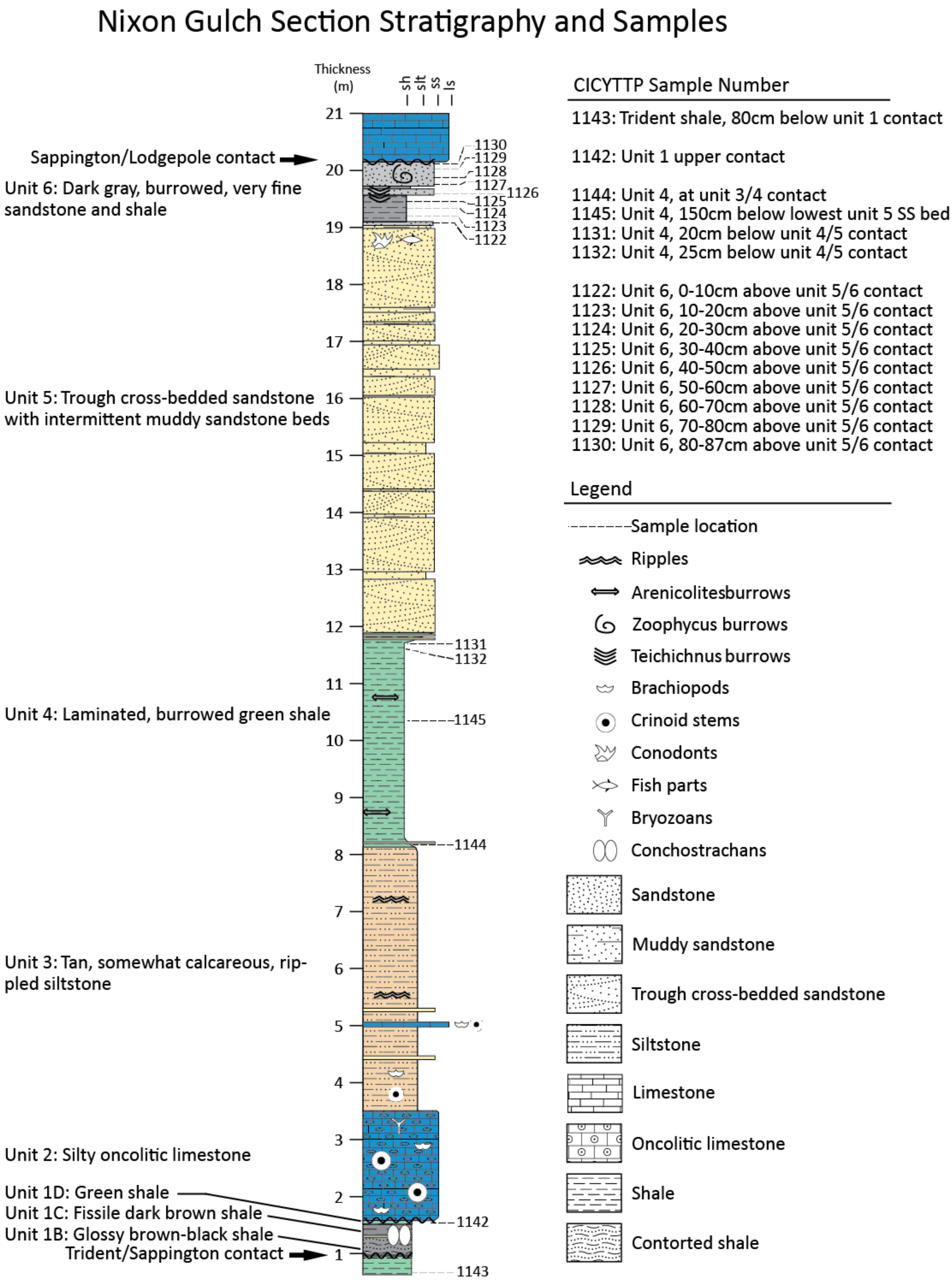
Nixon Gulch Section Stratigraphy and Samples
Thickness (m)
sh
slt
ss
ls
Sappington/Lodgepole contact
Unit 6: Dark gray, burrowed, very fine sandstone and shale
Unit 5: Trough cross-bedded sandstone with intermittent muddy sandstone beds
Unit 4: Laminated, burrowed green shale
Unit 3: Tan, somewhat calcareous, rippled siltstone
Unit 2: Silty oncolitic limestone
Unit 1D: Green shale
Unit 1C: Fissile dark brown shale
Unit 1B: Glossy brown-black shale
Trident/Sappington contact
CICYTTP Sample Number
1143: Trident shale, 80cm below unit 1 contact
1142: Unit 1 upper contact
1144: Unit 4, at unit 3/4 contact
1145: Unit 4, 150cm below lowest unit 5 SS bed
1131: Unit 4, 20cm below unit 4/5 contact
1132: Unit 4, 25cm below unit 4/5 contact
1122: Unit 6, 0-10cm above unit 5/6 contact
1123: Unit 6, 10-20cm above unit 5/6 contact
1124: Unit 6, 20-30cm above unit 5/6 contact
1125: Unit 6, 30-40cm above unit 5/6 contact
1126: Unit 6, 40-50cm above unit 5/6 contact
1127: Unit 6, 50-60cm above unit 5/6 contact
1128: Unit 6, 60-70cm above unit 5/6 contact
1129: Unit 6, 70-80cm above unit 5/6 contact
1130: Unit 6, 80-87cm above unit 5/6 contact
Legend
Sample location
Ripples
Arenicolitesburrows
Zoophycus burrows
Teichichnus burrows
Brachiopods
Crinoid stems
Conodonts
Fish parts
Bryozoans
Conchostrachans
Sandstone
Muddy sandstone
Trough cross-bedded sandstone
Siltstone
Limestone
Oncolitic limestone
Shale
Contorted shale

Figure 13

Antelope Hill Section Stratigraphy and Samples

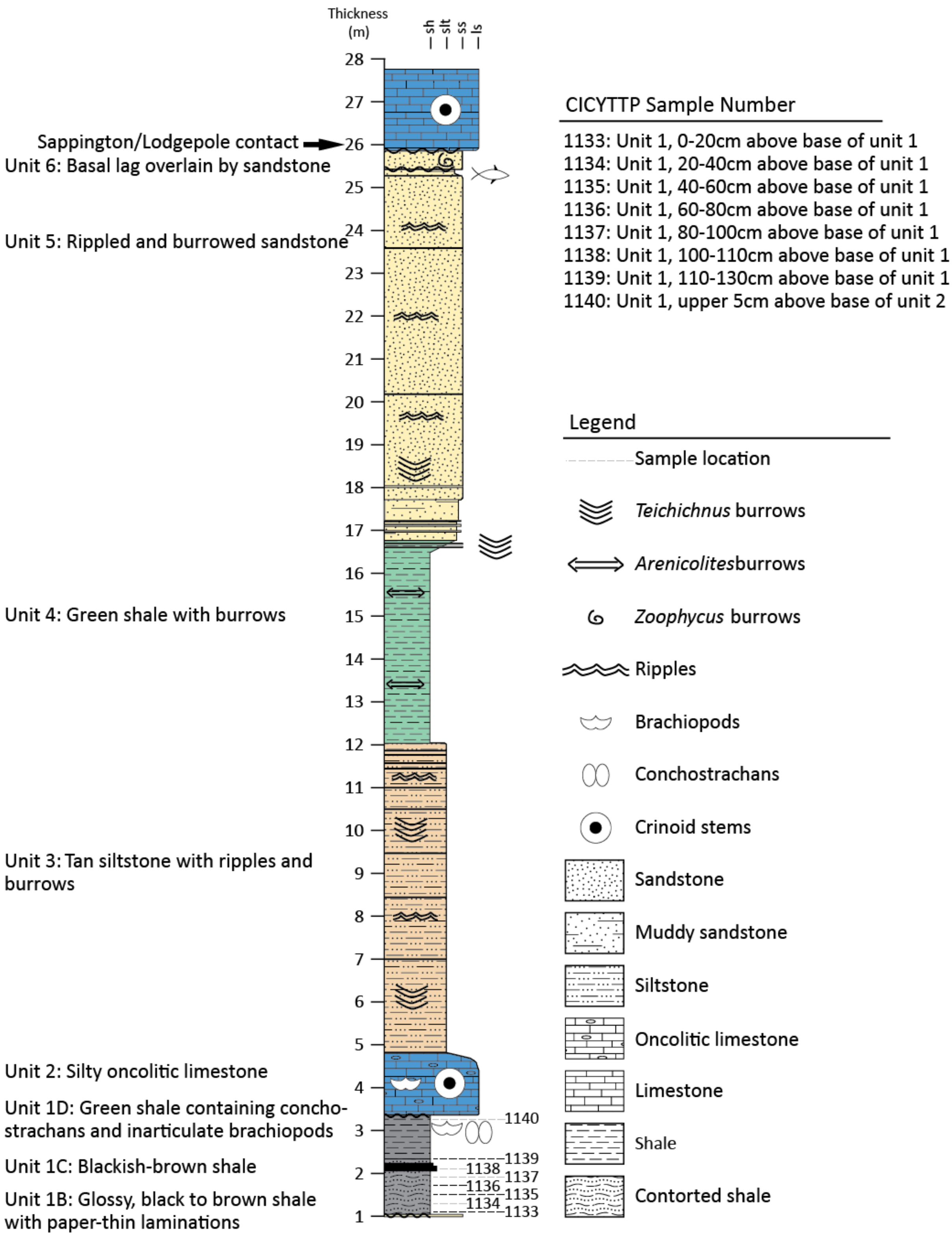

Figure 14

4. DISCUSSION

4.1 Biostratigraphy

Seven samples from the Logan Gulch middle shale (unit 4) were productive for palynostratigraphy, yielding well preserved assemblages of miospores, acritarchs, and leiosphaerids. These results confirm, in a new location, the previous report of *R. lepidophyta* in the middle shale at Peak 9559, Bridger Mountains, Montana (Sandberg et al., 1972).

The data from this study indicate that unit 4 is late Strunian (Warren et al., 2014). This refines the date found by di Pasquo et al. (2012) (sample locations shown in figure 10) by confirming the presence of the Strunian index fossil *Retispora lepidophyta*. The co-occurrence of *Retispora lepidophyta* with *Verrucosisporites nitidus* in this unit indicates placement in the late Strunian *lepidophyta-nitidus* (LN) Zone and places the D-C boundary above unit 4.

Isaacson et al. (2014) states that their conodont data, the presence of a lag at the base of unit 6, and the palynological dates of Strunian for unit 4 and Tournaisian for unit 6 by di Pasquo et al. (2012) suggest that the D-C boundary is at the base of unit 6. Based on these studies and the data gathered in this study, the D-C boundary is tentatively placed at the base of unit 6.

Selected Taxa Comments

Retispora lepidophyta **(**Kedo, 1957; Playford, 1976) (plate 1, figs. 2 and ll): *R. lepidophyta* was the most common species identified at the Logan Gulch locality, comprising 18.2% of all palynomorphs identified and 14.7% of all palynomorphs observed (some palynomorphs are unidentifiable due to damage or being obscured on the slide).

Verrucosisporites nitidus (Playford, 1964): Only one specimen of *V. nitidus* was definitively identified, but several other *Verrucosisporites* spp. had somewhat similar characteristics and could be classified as morphotypes.

Krauselisporites explanatus (Luber and Waltz, 1941; Azcuy and di Pasquo, 2005) (plate 3, figure 7): Four specimens of *K. explanatus* were identified at the base of the LN zone in unit 4. This is a long-ranged species that extends into the Tournaisian (Playford and McGregor, 1993).

Micrystridium stellatum (Deflandre, 1945) (plate 4, figure 6): The specimen of *M. stellatum* found in Moose Creek unit 6 is 30μm in total diameter. It is dark and somewhat damaged, unlike the other two acritarchs found at Moose Creek in unit 6. This may suggest possible reworking, but since this taxon is long-ranging and has been reported from the Paleozoic and the Mesozoic (Playford and McGregor, 1993), it is impossible to tell if this is the case.

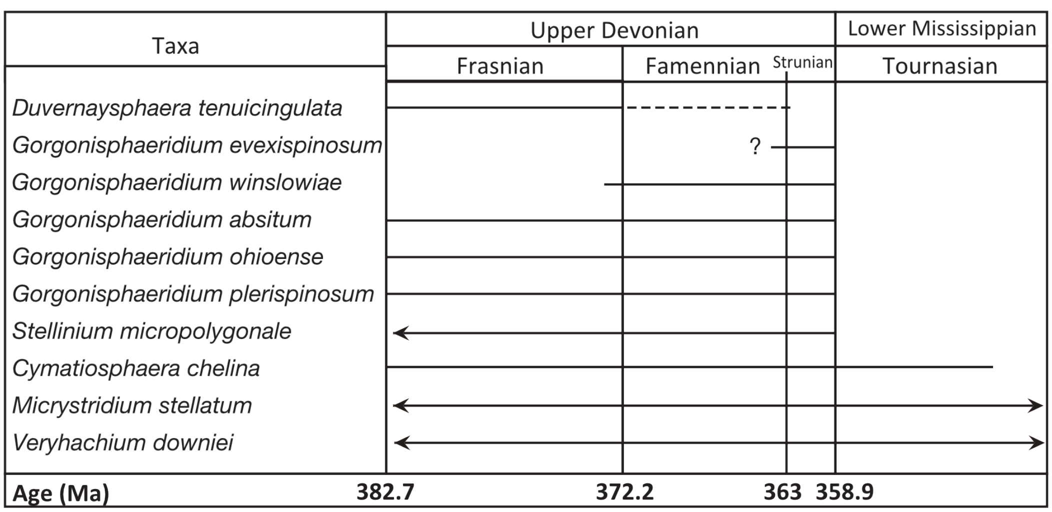

Figure 15: Ranges of marine taxa seen in unit 4 of the Sappington Formation at Logan Gulch based on Hacquebard (1957), Wicander (1974), Higgs (1975), McGregor (1979), Playford and McGregor (1993), Higgs, Finucane, and Tunbridge (2002) Melo and Loboziak (2003), Heal and Clayton (2008), Wicander and Playford (2013). Ages from Cohen et al. (2014) and Streel et al. (2006).

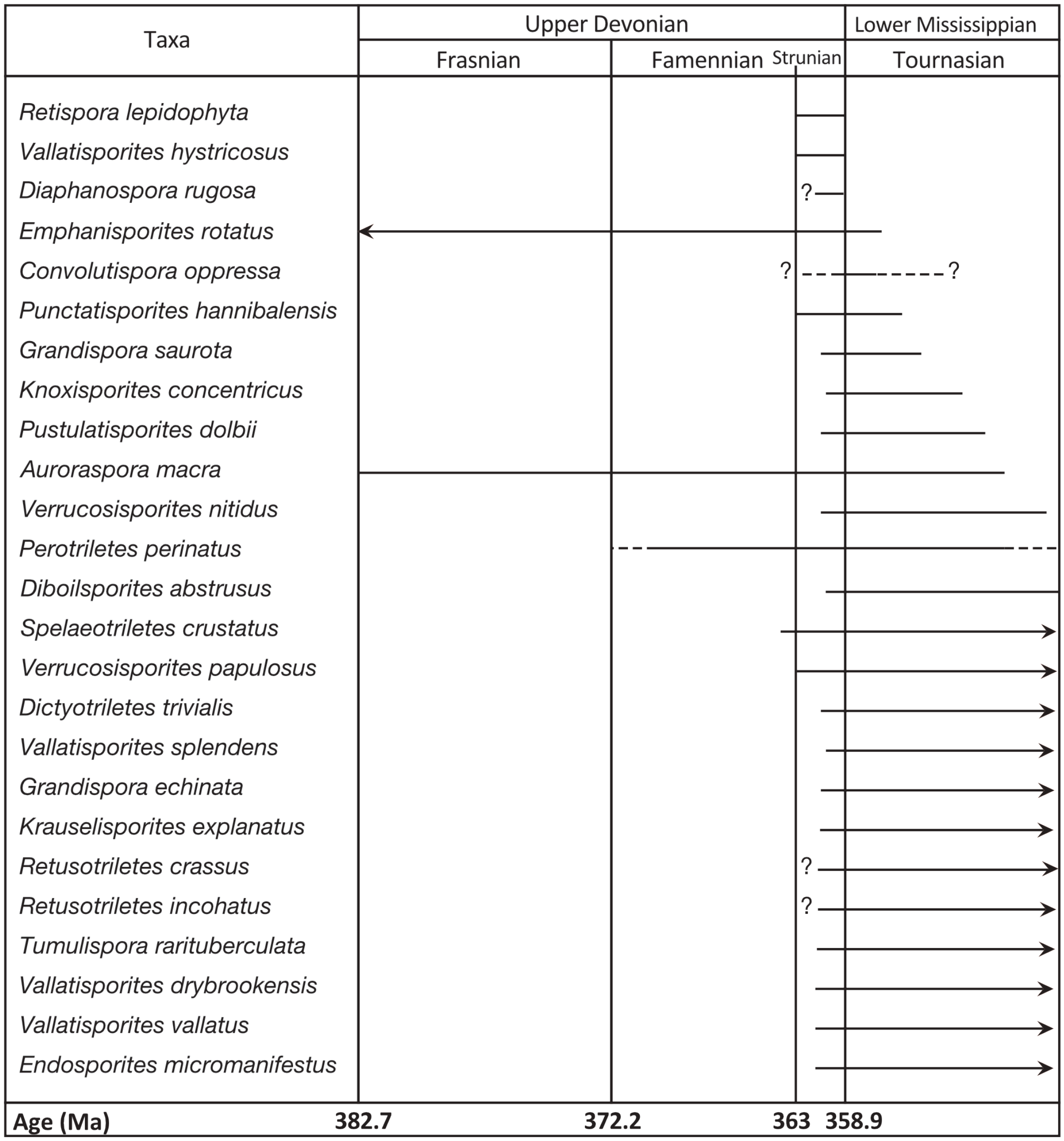

Figure 16: Ranges of miospore taxa seen in unit 4 of the Sappington Formation at Logan Gulch based on information from Hacquebard (1957), Wicander (1974), Higgs (1975), McGregor (1979), Playford and McGregor (1993), Higgs, Finucane, and Tunbridge (2002) Melo and Loboziak (2003), Heal and Clayton (2008), Wicander and Playford (2013). Ages from Cohen et al. (2014) and Streel et al. (2006).

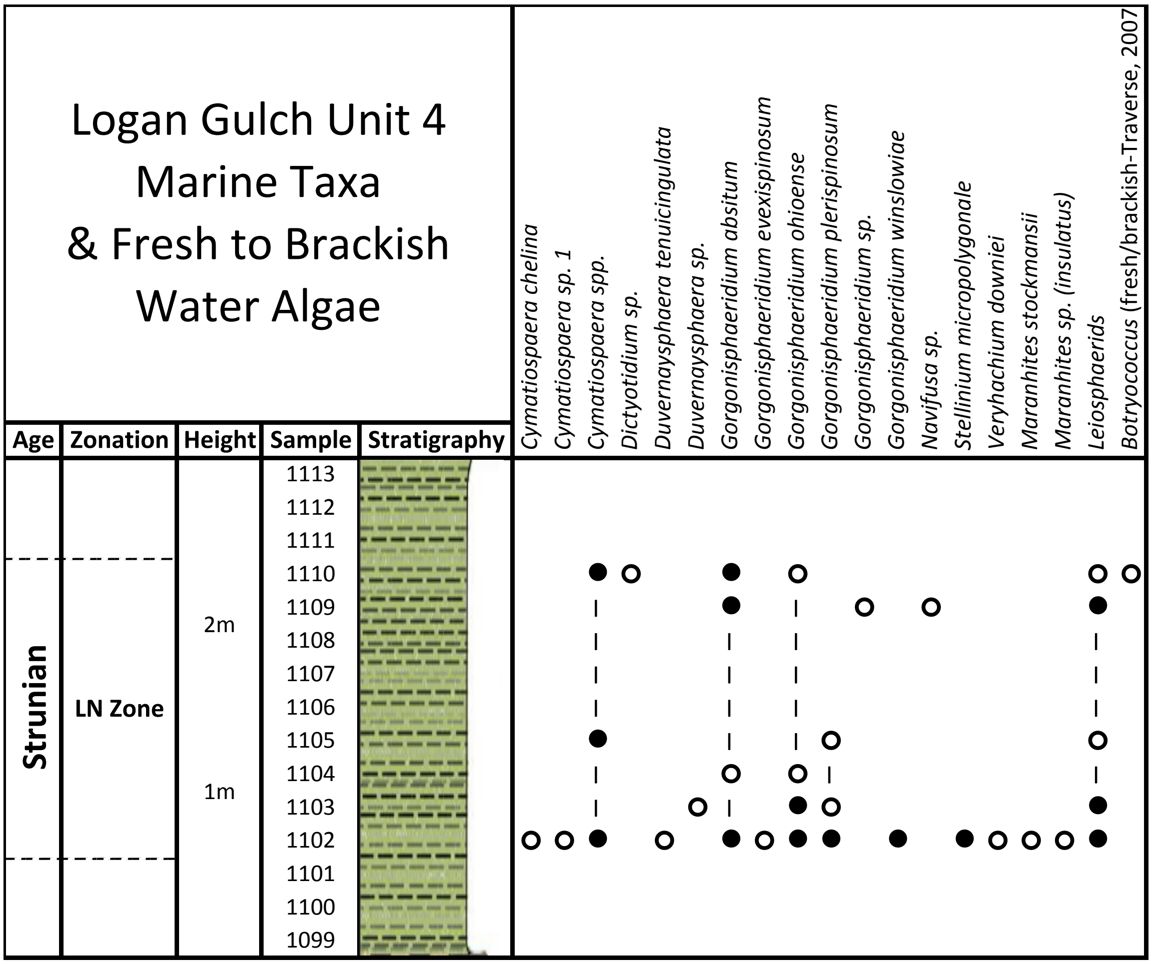

Figure 17: Stratigraphic ranges of marine taxa and fresh/brackish water algae in unit 4 of the Sappington Formation at the Logan Gulch locality. Open circles indicate the presence of one specimen; closed circles indicate the presence of two or more specimens.

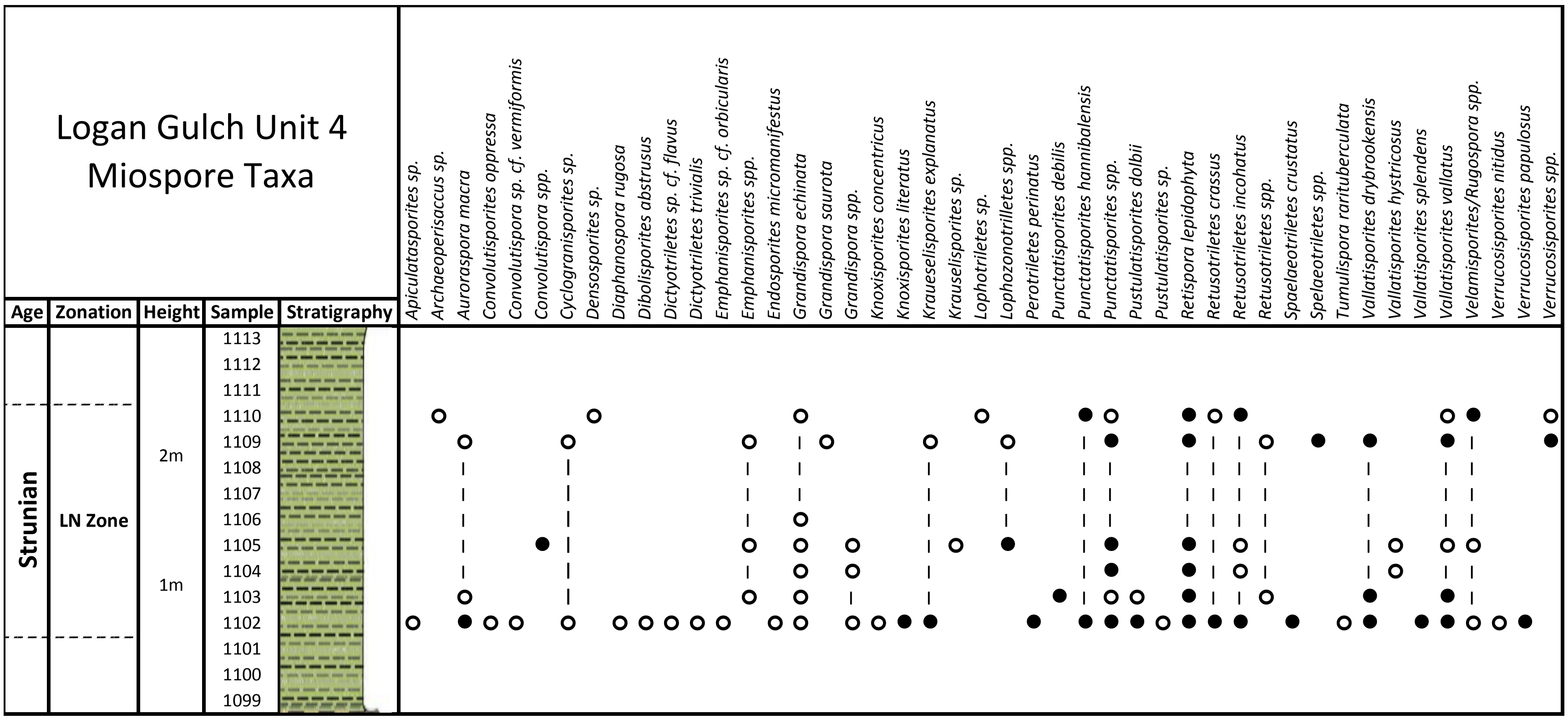

Figure 18: Stratigraphic ranges of miospore taxa in unit 4 of the Sappington Formation at the Logan Gulch locality. Open circles indicate the presence of one specimen; closed circles indicate the presence of two or more specimens.

4.2 Depositional Environments of the Sappington Formation

Unit 1

Unit 1 has four sub-lithofacies that may represent different depositional environments. Subunit “A” was reported as “unquestionably marine” (Sandberg et al., 1972). This is supported by the presence of conodonts (Gutschick et al., 1962). It was probably deposited in eutrophic conditions (Rodriguez, 2014). Subunit “B” is more oxidized, as evidenced by its commonly brownish black color, and is probably correlative to subunit “A” in a shallower environment (Rodriguez, 2014). Subunit “C” contains inarticulate brachiopods (Gutschick et al., 1962), conodonts (Gutschick et al., 1962), conchostrachans, scolecodonts, and poorly preserved miospores. Conodonts are indicative of marine environments, and scolecodonts are usually indicative of shallow marine environments (Szaniawski, 1996). In addition to the possibly shallow marine influences in the system, the presence of fresh water conchostrachans and miospores indicate that the system had some terrestrial influence (Kobayashi, 1972). The small grain size indicates a low energy environment. The grain size, the abundance of organic matter, the predominance of marine fossils but presence of freshwater conchostrachans, and the presence of commonly shallow-water scolecodonts likely indicate a restricted, shallow-water setting such as a lagoon for subunit “C”. Subunit “D” is a small, green shale containing marine fossils and lacking the high organic matter concentrations of other unit 1 subfacies. These characteristics may be indicative of a change to a less restricted environment that prevents the accumulation of large amounts of organic matter and permits more marine fossil deposition.

Unit 4

Unit 4 is a silty, dark green shale. It exhibits *Planolites* burrows, fresh water conchostrachans, bivalves, ostracodes, blastoids, clams, conodonts, and bryozoans within a siltstone channel-fill (Gutschick et al., 1962). In the surrounding shale, however, the Logan Gulch and Moose Creek localities exhibited diverse miospores, less diverse acritarchs, algal cysts, phytoclasts, and wood tissue in unit 4. Generally, there is a higher concentration of terrestrial palynomorphs and phytoclasts in comparison to marine palynomorphs. This indicates a high terrestrial influence in a marine depocenter.

Mud deposition, an accumulation of relatively high concentrations of terrestrial organic matter compared to marine organic matter, and the presence of *Planolites* burrows suggests that deposition was in a low energy, probably somewhat restricted environment that was oxygenated enough to allow for bioturbation and near enough to shore to preserve a diverse assemblage of miospores. Planolites and other horizontal burrows are commonly seen in low energy embayments, such as lagoons, as are muddy sediments and organic matter accumulation (Boggs, 2006). Evidence for a bay setting is strengthened by the presence of marine fossiliferous channel-fill in shale containing very few marine macrofossils (Rodriguez et al., 1962). This channel was probably an inlet from the open ocean into the bay system. Since unit 4 sediments are rich in terrestrial organic matter and may have contained the fresh to brackish water *Bottryococcus* algae, there were probably a few small channels also bringing terrestrial sediments and organic matter from the shore into the bay, possibly creating localized areas of variable salinity.

Unit 6

Unit 6 overlies an unconformity and a basal lag (Isaacson et al., 2014; Rodriguez, 2014). It exhibits high concentrations of amorphous organic matter, some small phytoclasts, and few palynomorphs at both the Trident and Moose Creek sections. Moose Creek exhibited poorly preserved miospores but usually well preserved acritarchs. Preservation of acritarchs seems to be favored over miospores, possibly indicating a distal setting. This is also supported by the presence of degraded phytoclasts and miospores, which become damaged with transport (Tyson, 1995). Because unit 6 overlies a basal lag that is likely transgressive in nature since it overlies an unconformity, and because deposition and preservation seems to favor marine biota, it likely represents an anoxic offshore environment.

Further study across the basin is necessary to confirm these depositional environment hypotheses. A basinwide study would elucidate lateral environmental changes and basin evolution characteristics within the Central Montana Trough. If combined with geochemical studies on organic matter provenance, palynology and palynofacies analysis could prove to be a powerful tool to determine the depositional environments of these units.

4.3 Global Paleoclimatic and Paleobiologic Implications

4.3.1 Correlation with the Bakken Formation (figure 19)

Correlation between the Sappington and Bakken formations still remains imprecise above the Lower Bakken and Sappington unit 1. The Lower Bakken contains the LV zone (Playford and McGregor, 1993), which at present, has not been found in the Sappington Formation. Recovery from unit 1 has been unsuccessful in terms of palynostratigraphy, but subunits 1A, 1C, and 1D are better preserved than 1B, and should be investigated further before ruling out the possibility of palynostratigraphic dating. Lithologies unfavorable for both conodont and palynomorph extraction make it difficult to find the base of the LN zone in both formations. While the upper limit of the LN zone has probably been found in the Sappington Formation (Isaacson et al., 2014), it has not yet been found in the Bakken Formation (Playford and McGregor, 1993), precluding correlation at this time. The Upper Bakken, like unit 6, is most likely in the early Tournaisian HD zone (Playford and McGregor, 1993; di Pasquo et al., 2012), but the HD zone may extend down into units 2 or 3 of the Bakken Sandstone (Thrasher et al., 1987). Unfortunately, until the biostratigraphies of these formations are refined, correlations will remain imprecise.

4.3.2 Global Correlation (figures 19 and 20)

Retispora lepidophyta has been found worldwide at the end of the Devonian, and is an index fossil for the latest Devonian (Loboziak and Melo, 2000). It has a very short range, and its disappearance marks the end of the Devonian (Streel, 1986). For this reason, it is used frequently in biostratigraphic correlations at the D-C boundary across the world. Figure 19 presents correlations between the Sappington Formation, its neighboring Bakken Formation, the Hangenberg Shale in Germany, the Curuá Group in Brazil, and the Zhangdon and Yali formations in Tibet. Three dark shales are seen in three of these groups, while Brazil and Tibet display shales that are not necessarily organic rich. This could be a result of proximal glaciation, tectonic activity, or environments that are not conducive to preservation of organic matter. As is with the lower shales in the Sappington and Bakken formations (figure 19), biostratigraphic correlations may not match lithostratigraphic correlations, so even if there are three black shales present at two localities, they may not exactly match biostratigraphically (Hartenfels and Becker, 2009). This could indicate different timings of anoxia or refugia allowing for extended ranges of species

The lower dark shales, seen in four localities, belong to the VCo zone. The shales likely represent global oceanic anoxia associated with the Dasberg biotic event. This event took place during eustatic transgression and was not caused by a glacial advance (Hartenfels and Becker, 2009). A glacial advance followed the Dasberg Event at the base of the LL zone (Isaacson et al., 2008). The much larger Hangenberg event at the base of the LN zone was associated with a glacial advance (Walliser, 1996; Caputo et al., 2008). This event is much more difficult to correlate in western North America due to lithologies unsuitable for preservation of conodonts and palynomorphs. At the start of the Mississippian, a series of at least three glaciations occurred prior to transgression and deposition of early Tournaisian HD zone black shales that may correlate with the *crenulata* event (Caplan and Bustin, 1999). In order to determine whether these biotic events truly correlate with the Sappington Formation shales, they must be located. Until we find the events within the shales, we must rely on approximate lithologic and biostratigraphic correlations that may or may not be up-to-date or accurate.

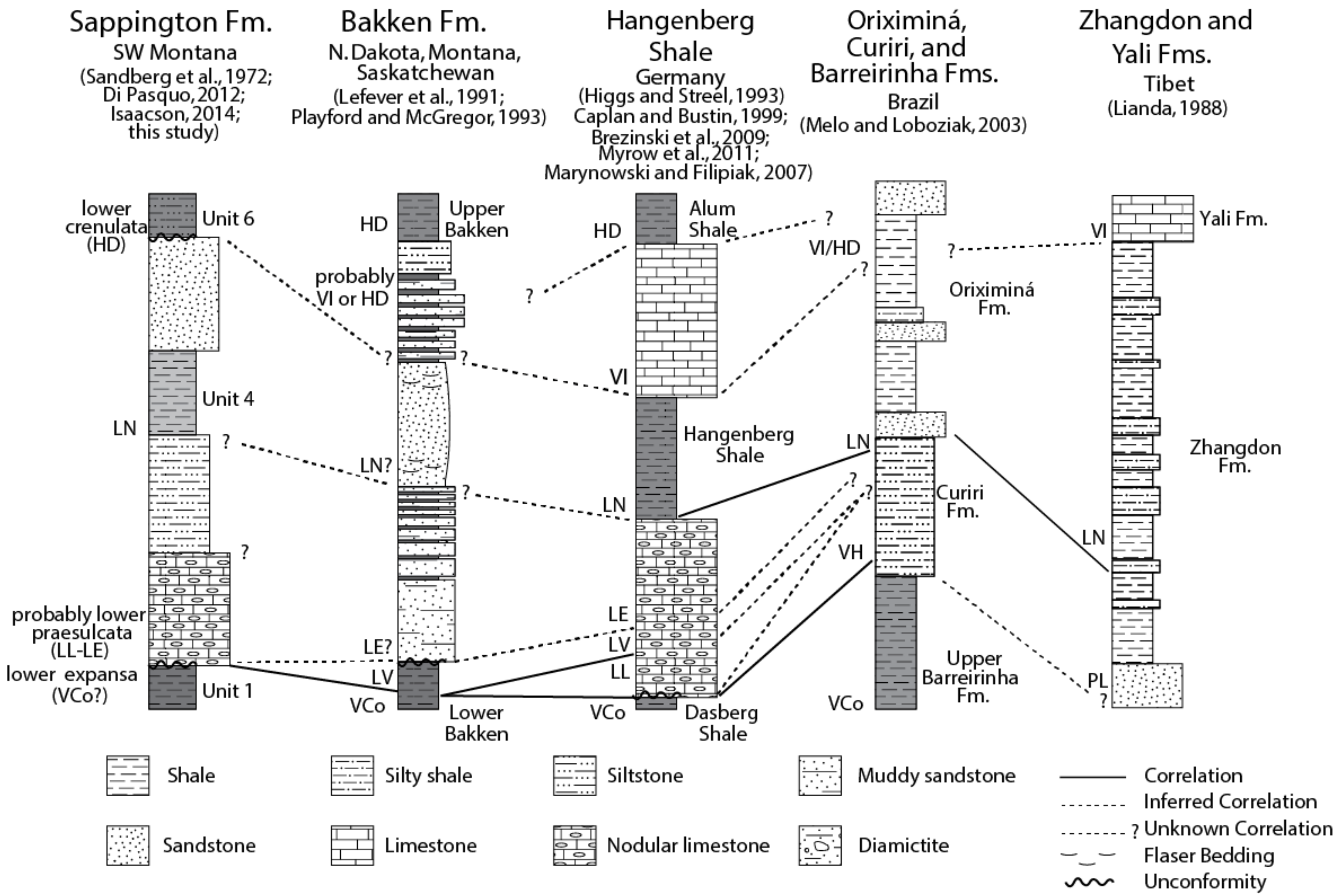

Figure 19: Correlation between the Sappington Formation and other D-C boundary formations worldwide. Zonations are listed to the left of each column and unit names are listed to the right.

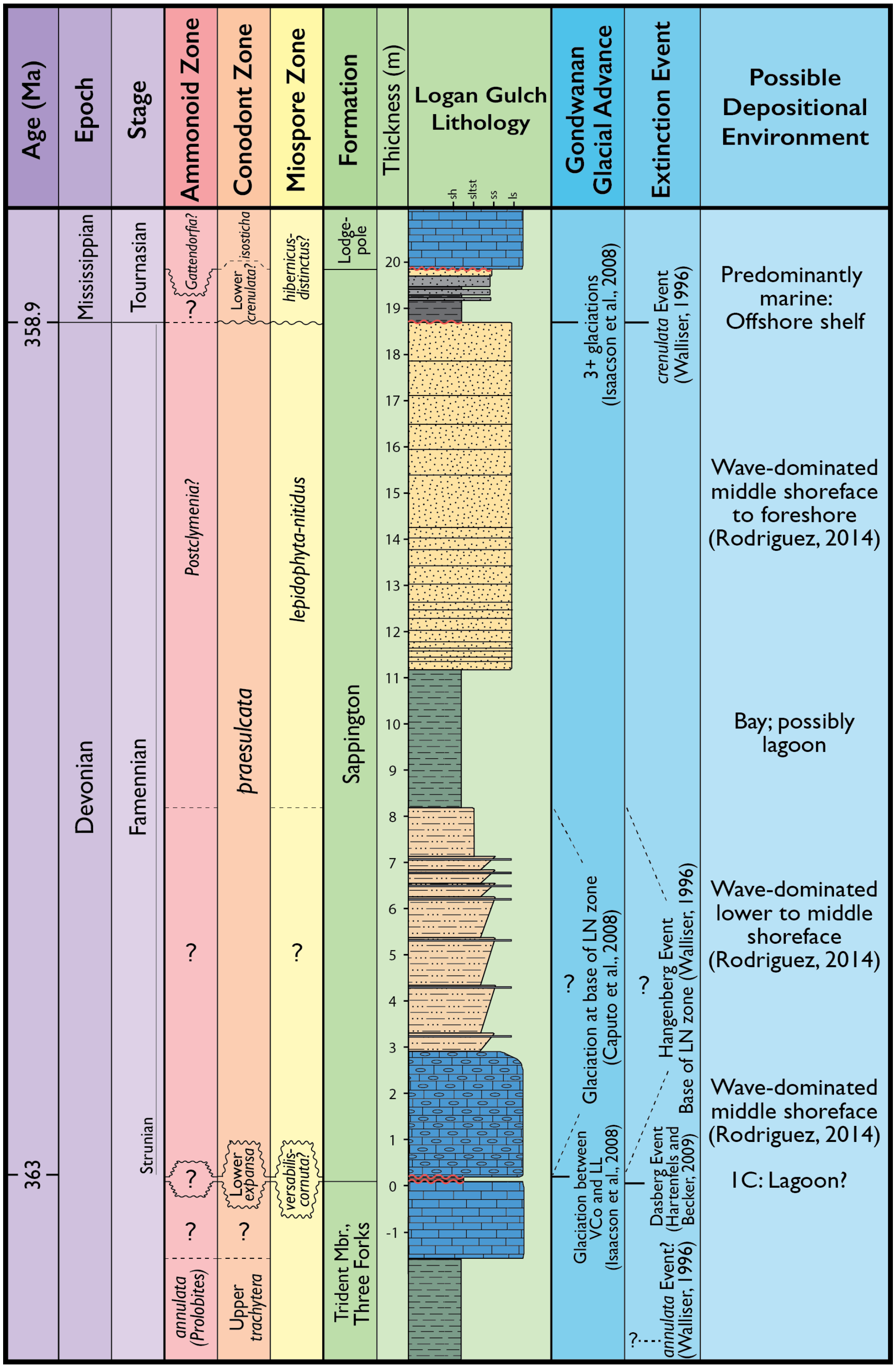

Figure 20: Possible correlation between glacial advances, extinction events, and depositional environment changes. Dotted lines indicate boundaries of age uncertainty. Uncertain ages are indicated by question marks, while possible ages derived from correlation with other biota are indicated by a zone name followed by a question mark. Wavy lines indicate unconformities (red) and possible gaps in the biostratigraphic record (black). Geologic ages are from Cohen et al., (2014) and Streel et al. (2006). Biostratigraphic ages are from this study, Sandberg et al. (1972), Korn and Titus (2006), di Pasquo et al. (2012), and Isaacson et al. (2014).

5. CONCLUSIONS

1. The Sappington Formation encompasses the Devonian-Carboniferous boundary. Previous biostratigraphic studies based on conodonts, brachiopods, and palynology conflict on where the boundary occurs within the formation. This study is the first in-depth study of the palynology of the Sappington Formation.

2. Samples were collected systematically from five localities: Nixon Gulch, Antelope Hill, Red Hill, Logan Gulch, Moose Creek, and Trident. These samples were processed using standard palynological processing techniques (Traverse, 2007).

3. Unit 1, a brownish black shale, was unproductive in all locations likely because of its easily weathered nature. Unit 4, a slightly calcareous shale, was the most productive, yielding miospores and acritarchs in three localities: Logan Gulch, Frazier Lake, and Moose Creek. Unit 6, a greyish black siltstone to sandy siltstone, was largely unproductive for biostratigraphy but contained a few palynomorphs at Moose Creek and phytoclasts at other localities. Logan Gulch and Moose Creek were the most productive sections, both yielding the Strunian index fossil *Retispora lepidophyta*. Moose Creek also yielded long-ranging acritarchs in unit 6. Nixon Gulch, Antelope Hill, and Trident were all barren, likely as a result of weathering or less suitable depositional conditions for preservation. Red Hill was barren as a result of an andesite sill carbonizing the organic matter.

4. Unit 4 is dated as late Strunian because it contains both *Retispora lepidophyta* and *Verricosisporites nitidus,* placing it in the LN Zone. The Devonian-Carboniferous boundary was not located in this study, but is concluded to be above unit 4. Taking into account the latest Strunian age of units 4 and 5 (Isaacson et al., 2014), the Tournaisian age of unit 6 (di

Pasquo et al., 2012; Isaacson et al., 2014), and the presence of a an unconformity and a lag at the base of unit 6 (Rodriguez, 2014), the D-C boundary is concluded to be at the base of unit 6.

5. Unit 1 may represent a lagoon, as evidenced by the presence of both freshwater and marine macrofossils, mud deposition, and organic matter accumulation. Unit 4 likely represents a somewhat restricted embayment as evidenced by a general predominance of terrestrial organic matter sedimentation except for an inlet containing marine macrofossils. Unit 6 most likely represents an offshore shelf environment as evidenced by a basal transgressive surface (Rodriguez, 2014), few poorly preserved miospores, and few, but well preserved, acritarchs.

6. Correlation between the Bakken and Sappington formations remains imprecise above Sappington unit 1 and the Lower Bakken, but the LN zone has been recognized in both formations, allowing correlation between Sappington unit 4 and either unit 1 or 2 of the Bakken Sandstone.

7. Anoxic events are visible in the Sappington Formation that may allow correlation with other D-C boundary formations worldwide. The Dasberg Event is tentatively correlated with deposition of unit 1 and the *crenulata* event is tentatively correlated with deposition of unit 6. These will require further paleontological and geochemical investigation to confirm possible associations. The exact location of the Hangenberg event has not been located yet in the Sappington Formation because the base of the LN zone has not yet been ascertained.

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PLATES

Plate 1:

Logan Gulch Unit 4: 1102
1) *Dictyotriletes* sp. cf. *flavus* Keegan, 1977
2) *Retispora lepidophyta* (Kedo) Playford, 1976
3) *Verrucosisporites papulosus* Hacquebard, 1957
4) *Grandispora echinata* Hacquebard emend. Utting, 1987
5) *Dictyotriletes trivialis* (Naumova) Kedo, 1963
6) *Knoxisporites concentricus* (Byvsheva) Playford and McGregor, 1993
7) *Cyclogranisporites* sp.
8) *Verrucosisporites papulosus* Hacquebard, 1957
9) *Vallatisporites drybrookensis* Playford and McGregor, 1993
10) *Endosporites micromanifestus* Hacquebard, 1957
11) *Retispora lepidophyta* (Kedo) Playford, 1976
12) *Diaphanospora rugosa* (Naumova) Byvsheva, 1985
13) *Convolutispora oppressa* Higgs 1975

Plate 2:

Logan Gulch Unit 4: 1102
1) *Gorgonisphaeridium winslowiae* Staplin, Jansonius, and Pocock, 1965
2) *Maranhites stockmansii* (Martin) Martin, 1984
3) *Cymatiosphaera chelina* Wicander and Loeblich, 1977
4) *Duvernaysphaera tenuicingulata* Staplin, 1961
5) *Gorgonisphaeridium ohioense* (Winslow) Wicander 1974
6) *Cymatiosphaera* sp. 1
7) *Maranhites insulatus?* Burjack and Oliveira, 1989
8) *Stellinium micropolygonale* Stockmans and Willière, 1962
9) *Gorgonisphaeridium absitum* Wicander, 1974
10) *Cymatiosphaera* sp. 1
11) *Gorgonisphaeridium evexispinosum* Wicander, 1974

Plate 3:

Logan Gulch Unit 4: 1102
1) *Punctatisporites hannibalensis* Wicander and Playford, 2013
2) *Emphanisporites* sp. cf. *orbicularis* Turnau, 1986
3) *Perotriletes perinatus* Hughes and Playford, 1961
4) *Pustulatisporites dolbii* Higgs, Clayton, and Keegan, 1988
5) *Pustulatisporites* sp.
6) *Vallatisporites drybrookensis* Playford and McGregor, 1993
7) *Kraeuselisporites explanatus* (Luber and Waltz) Azcuy and di Pasquo, 2005

Logan Gulch Unit 4: 1103
8) *Grandispora echinata* Hacquebard emend. Utting, 1987

Logan Gulch Unit 4: 1105
9) *Vallatisporites hystricosus* (Winslow) Wicander and Playford, 2013
10) *Convolutisporites* sp.
11) *Emphanisporites rotatus* McGregor, 1973
12) *Lophozonotriletes* sp.
13) *Convolutisporites* sp.
14) *Kraeuselisporites* sp.

Plate 4:

Logan Gulch Unit 4: 1109
1) *Grandispora saurota* (Higgs, Clayton, and Keegan) Playford, 1963
2) *Navifusa* sp.
3) *Auroraspora macra* Sullivan, 1968

Logan Gulch Unit 4: 1110
4) *Densosporites* sp.
5) *Archaeoperisaccus* sp.

Moose Creek:
6) *Micrhystridium stellatum* (unit 6) Deflandre, 1945
7) Scolecodont (unit 1)
8) *Gorgonisphaeridium* sp. (unit 6)
9) Unidentified (unit 6)
10) Unidentified, altered with GIMP to remove background (unit 6)

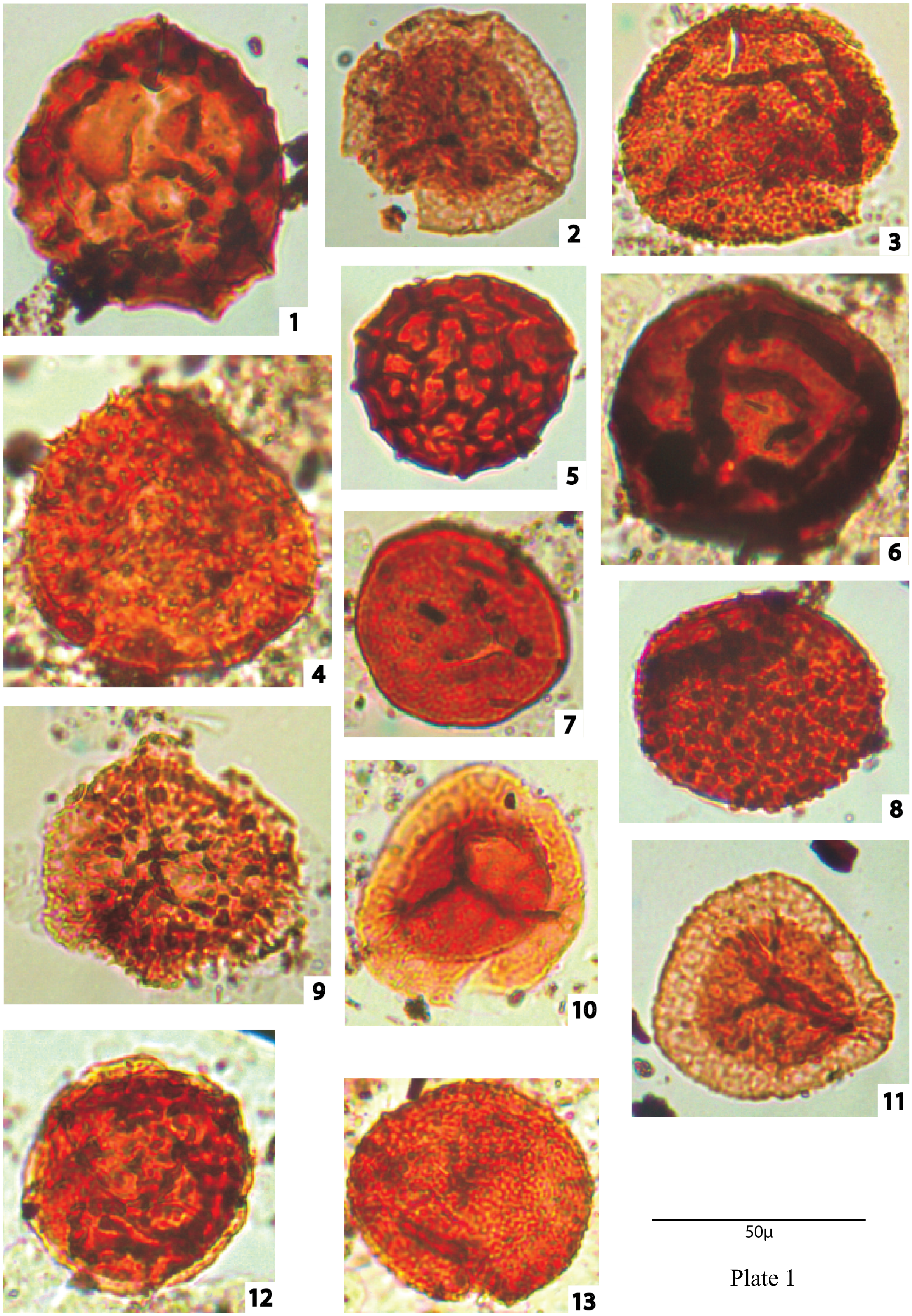
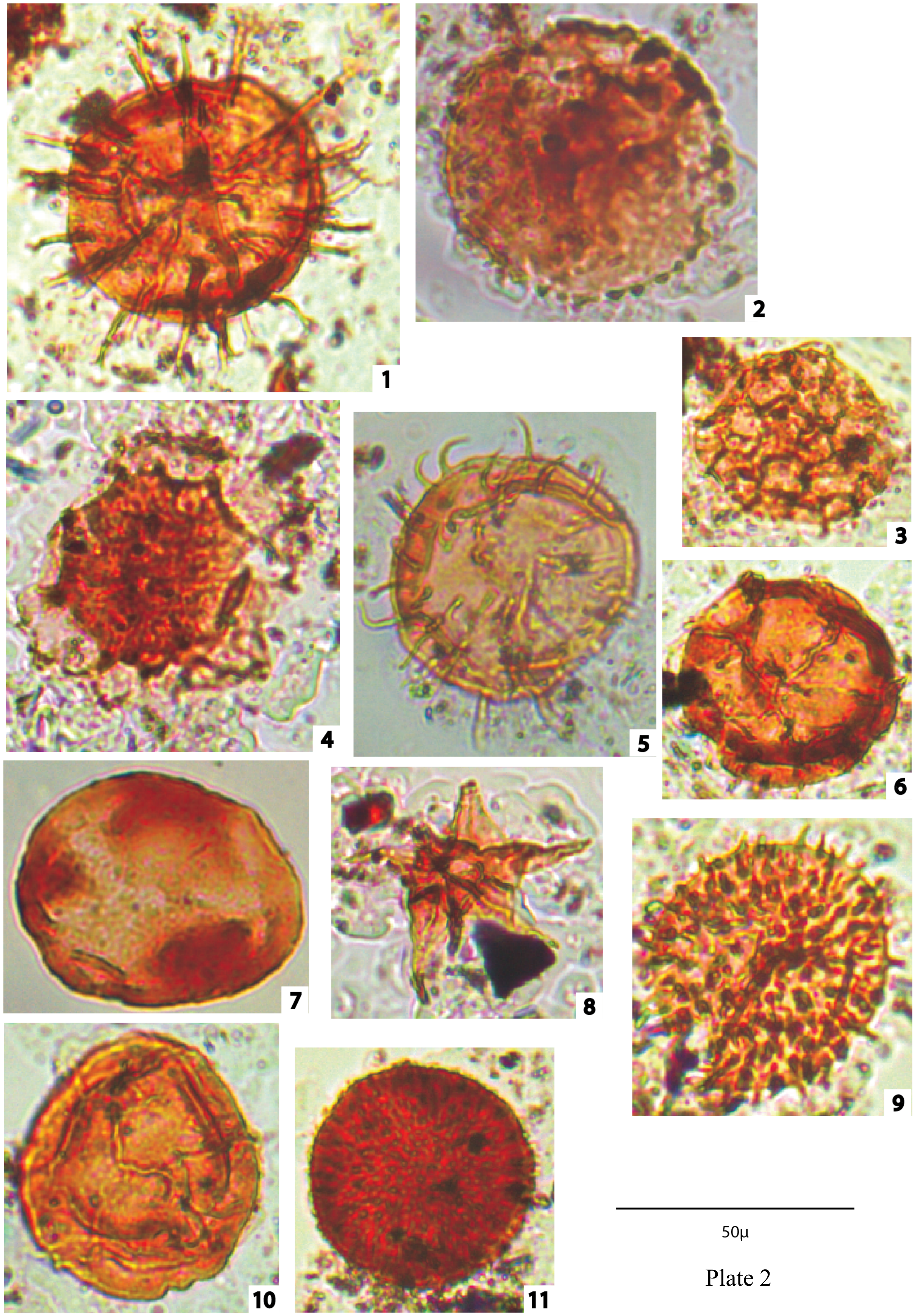


Plate 1



50μ

Plate 2

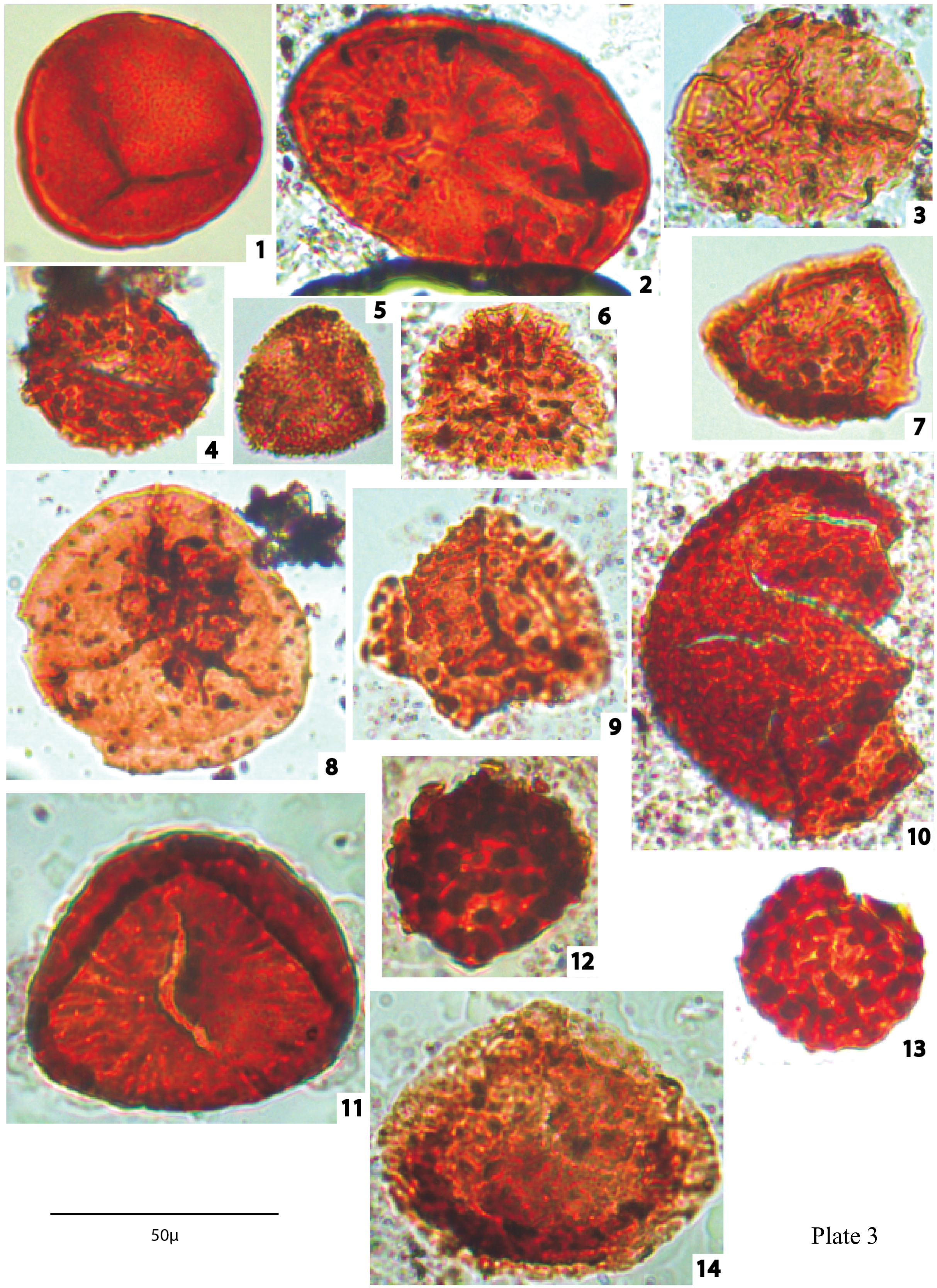


Plate 3

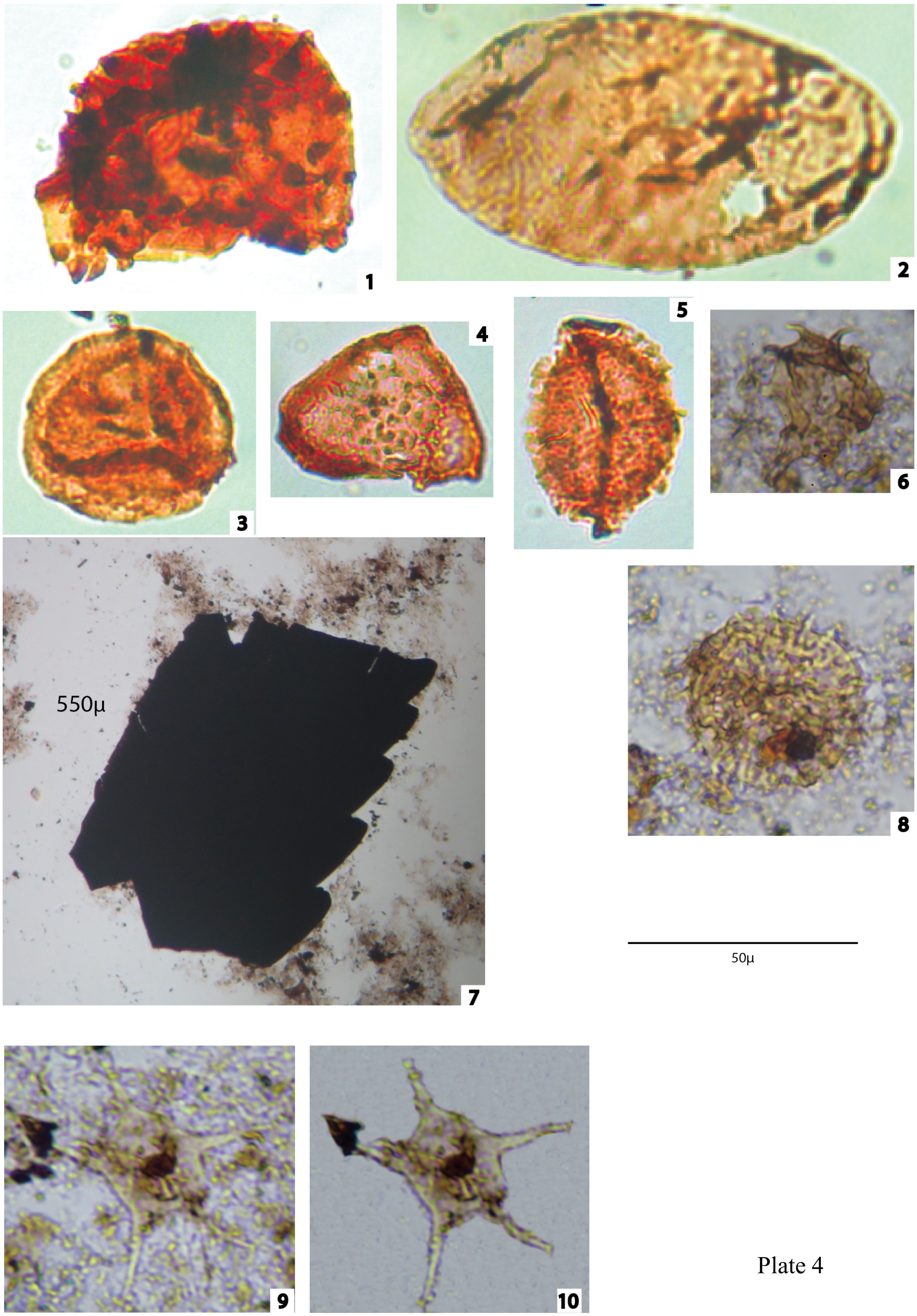


Plate 4

APPENDIX

Specimen Counts at Logan Gulch

Specimen counts are listed underneath a species' corresponding sample number.

Marine palynomorphs	**Strunian**						
Taxa **Sample Numbers (CICYTTP-Pl)**	**1102**	**1103**	**1104**	**1105**	**1106**	**1109**	**1110**
Cymatiosphaera chelina Wicander and Loeblich, 1977	1						
Cymatiosphaera sp. 1 (similar to D*ictyotidium araiomegaronium* Hashemi and Playford 1998)	6						
Cymatiosphaera spp.	2			2			2
Dictyotidium sp.							1
Duvernaysphaera tenuicingulata Staplin, 1961	1						
Duvernaysphaera sp.		1					
Gorgonisphaeridium absitum Wicander 1974	2		1			3	3
Gorgonisphaeridium evexispinosum Wicander 1974	1						
Gorgonisphaeridium ohioense (Winslow) Wicander 1974	8	2	1				1
Gorgonisphaeridium plerispinosum Wicander 1974	3	1		1			
Gorgonisphaeridium sp.						1	
Gorgonisphaeridium winslowiae Staplin, Jansonius, and Pocock, 1965	2						
Navifusa sp.							1
Stellinium micropolygonale (Stockmans and Willière) Playford 1977	4						
Verhyachium downeii Stockmans and Williere, 1962	2						
Maranhites stockmansii (Martin) Martin, 1984	1						
Maranhites sp.(insulatus) Burjack and Oliveira, 1989	1						
Leiosphaeridia spp.	10	3		1		2	1
Botryococcus?							1

Miospores	**Strunian**						
Taxa Sample Numbers (CICYTTP-Pl)	**1102**	**1103**	**1104**	**1105**	**1106**	**1109**	**1110**
Apiculatasporites sp.	1						
Archaeoperisaccus spp.							1
Auroraspora macra Sullivan, 1968	2	1				1	
Convolutispora cf. vermiformis (Hughes and Playford 1961; similar to *Diaphanospora perplexa* Balme and Hassel 1962)	1						
Convolutispora oppressa Higgs, 1975	1						
Convolutispora spp.				2			
Cyclogranisporites sp.	1					1	
Densosporites sp.							1
Diaphanospora rugosa (Naumova) Byvsheva, 1985 (similar to *D. perplexa)*	1						
Dibolisporites abstrusus (Playford) Playford, 1976	1						
Dictyotriletes sp. cf. flavus Keegan, 1977	1						
Dictyotriletes trivialis (Naumova) Kedo, 1963	1						
Emphanisporites cf. orbicularis Turnau, 1986	1						
Emphanisporites rotatus McGregor, 1973				1			
Emphanisporites spp.		1				1	
Endosporites micromanifestus Hacquebard, 1957	1						
Grandispora echinata Hacquebard emend. Utting, 1987	1	1	1	1	1		1
Grandispora saurota (Higgs, Clayton, and Keegan) Playford and McGregor, 1993						1	
Grandispora spp.	1		1	1			
Knoxisporites concentricus (Byvsheva) Playford and McGregor, 1993	1						
Knoxisporites literatus? (Luber and Waltz) Playford, 1963	2						
Kraeuselisporites explanatus (Luber and Waltz) Azcuy and di Pasquo, 2005	4					1	
Krauselisporites sp.				1			
Lophotriletes sp.							1
Lophozonotriletes spp.				1		2	
Perotriletes perinatus Hughes and Playford, 1961	2						
Punctatisporites hannibalensis Wicander and Playford, 2013	4						3
Punctatisporites spp.	10	1	2	2		3	1
Pustulatisporites dolbii Higgs, Clayton, and Keegan, 1988	8	1					
Pustulatisporites sp.	1						
Retispora lepidophyta (Kedo) Playford, 1976	30	2	3	2		6	5
Retusotriletes crassus Clayton, Johnston, and Smith, 1980	2						1
Retusotriletes incohatus Sullivan, 1964	8		1	1			2
Retusotriletes spp.		1				1	
Spelaeotriletes crustatus Higgs, 1975	2						
Spelaeotriletes spp.						2	
Tumulispora rarituberculata (Luber) Playford, 1991	1						
Vallatisporites drybrookensis (morphon) Playford and McGregor, 1993	5	2				3	
Vallatisporites hystricosus (Winslow) Wicander and Playford, 2013			1	1			
Vallatisporites splendens Staplin and Jansonius, 1964	3						
Vallatisporites vallatus Hacquebard, 1957	5	2		1		4	1
Vallatisporites spp.				1		1	
Velamisporites/Rugospora spp.	1			1			2
Verrucosisporites nitidus Playford, 1964	1						
Verrucosisporites papulosus Hacquebard, 1957	2						
Verrucosisporites spp.						2	1
Total Palynomorphs	**210**	**19**	**11**	**20**	**1**	**35**	**30**