THE CAMPBELLTON FORMATION, NEW BRUNSWICK, CANADA: A SEDIMENTOLOGICAL AND PALEOENVIRONMENTAL DESCRIPTION OF AN EARLY DEVONIAN (EMSIAN) VEGETATED LANDSCAPE

by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The Campbellton Formation, ~1 km thick, has long been recognized for early plants, arthropods, and fishes. The sedimentology of two basins is described with six facies associations to provide a framework for the fossil assemblages. The western basin contains aquatic fauna and coastal flora within a basal rhyolite breccia and coastal deltaic strata, and a braided river facies association is also present. Lower eastern basin strata primarily comprise lacustrine facies, where a thick marginal association deposited by sediment-laden underflows contains a lake-side plant assemblage. Other lacustrine associations include a fine-grained association in areas with restricted circulation, and a near-shore association. Upwards, a plant-rich fluvial landscape had wide sandstone and conglomerate channels and high-diversity wetlands containing terrestrial arthropods. A proximal alluvial facies association with hyperconcentrated flows contains plants and *Prototaxites*, possibly from adjoining uplands. All plants groups were well-established throughout the formation, with no apparent landscape partitioning between groups.

CHAPTER 1 — INTRODUCTION

The Campbellton Formation of northern New Brunswick, Canada, has long been of interest to paleontologists for its diverse and well preserved fossil assemblage of Early Devonian (Emsian to earliest Eifelian) age. First noted by Gesner (1843), the fossil occurrences received considerable attention through the later 1800s, and continue to yield world-class discoveries (Shear 1996; Miller et al. 2003; Gensel and Albright 2006). Remarkable preservation of early plants, fish, and arthropods has aided in morphological investigations into the body plans present during a crucial period of evolution. The Devonian was a time of increasing occupation of the terrestrial landscape as plants moved away from their aquatic origins to colonize new habitats. This has been referred to as the "Devonian Radiation" when many new clades emerged and thus may be the most significant period in plant evolution (Fig 1.1) (Bateman and DiMichele 1994). Concurrently, fish worldwide were becoming dramatically more abundant and diverse, giving rise to the designation of the Devonian as the "Age of Fishes". The Campbellton Formation represents an early stage in both of these processes. However, despite considerable historical interest in the fossil assemblage, the sedimentology has not been described in such a way as to complement the fossil record, as has been done at two other plant localities with similar ages and assemblages (Griffing et al. 2000; Hotton et al. 2001; Allen and Gastaldo 2006).

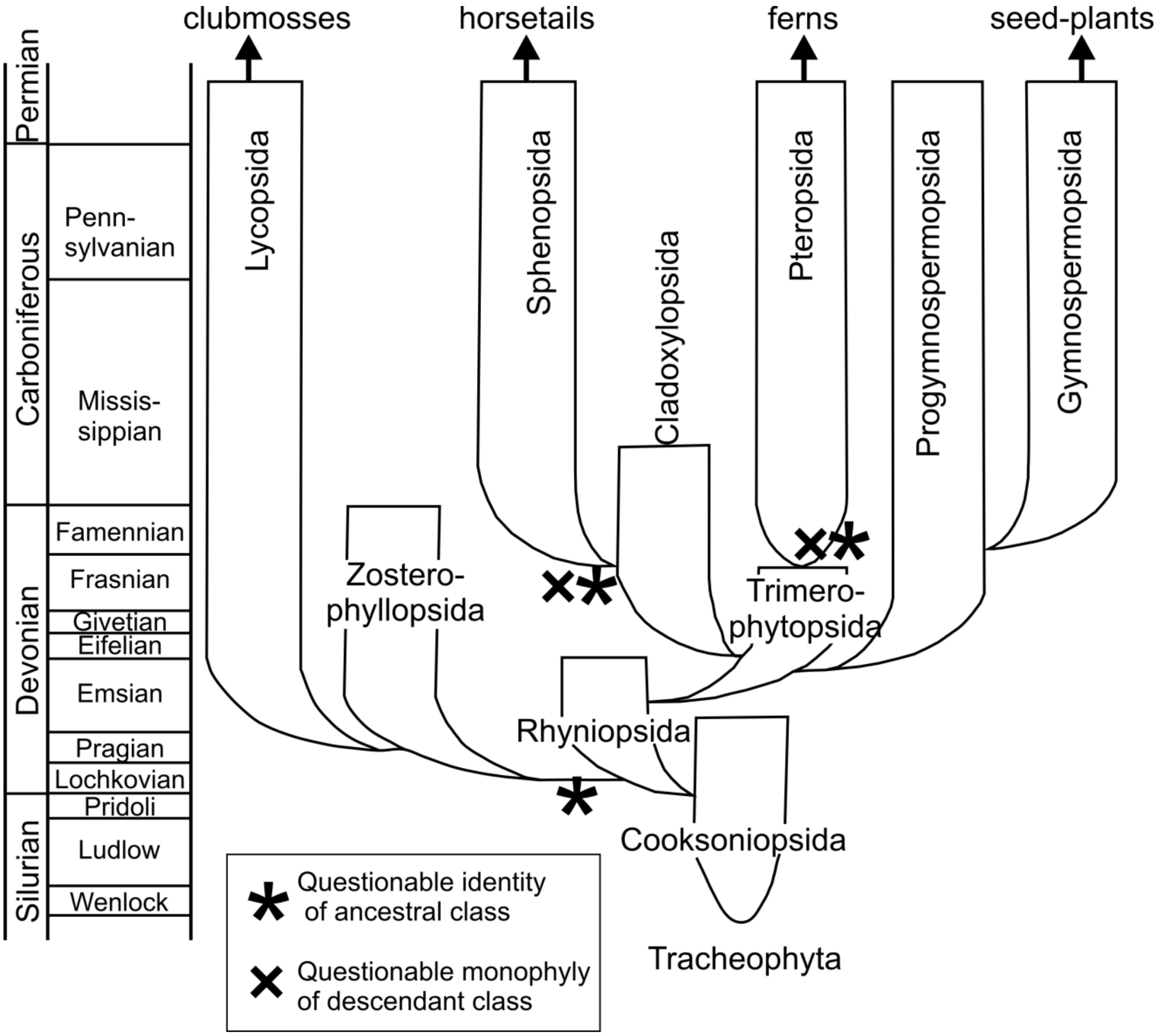


FIGURE 1.1: Phylogeny of tracheophytes from the Silurian to the Carboniferous. From Bateman and DiMichele 1994.

1.1 Objectives

This thesis addresses the sedimentology of the Campbellton Formation of New Brunswick, Canada and provides a paleoenvironmental context for the extraordinary fossil assemblage found within. By doing so, this thesis has the following objectives:

- To provide the first full stratigraphic assessment of the formation's thickness and lithology by determining the facies of all strata found within the Campbellton Formation, and identifying the genetic origin or paleoenvironment of each facies association.
- To form a paleoecological depiction of prominent fossil localities considering host rock features, taphonomy and their contextual position within the landscape.
- To assess whether the current view of environmental niche partitioning between plant clades as seen in localities of similar age is in accord with the distribution of the floral assemblage of the Campbellton Formation.
- To assess the degree of interaction between terrestrial vegetation and landscapes at this early but crucial phase in plant evolution.

1.2 Organization of Thesis

Chapter 2 provides a necessary background to the setting that existed during the Early Devonian including an outline of the regional Ordovician-Devonian tectonic situation, and an introduction to the evolutionary stages of important groups of plants, terrestrial arthropods, and fish. Two manuscripts form the body of this thesis and are presented as chapters 3 and 4. Chapter 3, entitled "The Campbellton Formation, New Brunswick, Canada: Paleoenvironments in an important Early Devonian terrestrial locality" provides the first comprehensive account of the formation and discusses the sedimentary features of the strata, and the paleoenvironments that can be inferred through a facies analysis. The manuscript by Kennedy and Gibling has been submitted for the Canadian Journal of Earth Sciences. Chapter 4, entitled "Paleoenvironmental inferences of the classic Early Devonian plant-bearing locality of the Campbellton Formation, New Brunswick, Canada" expands upon these broad paleoenvironmental interpretations at prominent plant localities, incorporates a literature review of the fossil record, and discusses various morphological features of plant fossils as they relate to the settings in which they are found. The manuscript by Kennedy, Gibling and Gensel is in preparation for submission to a paleontological journal. Chapter 5 considers future directions and remaining questions arising from the Campbellton Formation strata and chapter 6 presents the conclusions of this thesis. Several appendices are also attached. Appendix 1 provides a road map showing outcrop locations, road directions, and access points. Appendix 2 contains the methodology and data obtained from an electron microprobe analysis of one sample.

1.3 **Contributions of Author**

This study arises from two field seasons in August 2009 and August 2010. During the first field season, about two weeks were spent by the author measuring and describing strata on a bed-by-bed basis, with the supervision and assistance of M.R. Gibling. In-field discussions with P. Gensel, R. Miller, and S. Turner during both field seasons were instrumental in correctly placing fossils in the stratigraphic column. All subsequent drafting, facies analysis, and manuscript preparation were performed by the author, with

M.R. Gibling providing advice and editing. P. Gensel is a co-author of Chapter 4, having provided detailed plant locality information and identifications in the field, as well as comments on the chapter.

CHAPTER 2 — BACKGROUND

2.1 The Ordovician-Devonian Tectonic Setting of Eastern North America

The study area is located on the southern bank of where the Restigouche River meets Chaleur Bay (Fig. 2.1, Appendix 1). From the Ordovician to the Carboniferous, this region experienced multiple tectonic events related to the accretion of terranes and formation of Pangea. The result is a rather complicated suite of rocks trending NE-SW along the northeastern coast of North America, following the extent of the Appalachian Orogen. Before the Middle Ordovician, the stable continental margin of Laurentia faced into the Iapetus Ocean (Williams 1979). Subduction of oceanic crust beneath Laurentia and Avalonia resulted in a number of oceanic arcs that independently collided with the Laurentian margin to give rise to the Middle to Late Ordovician Taconic Orogeny (Van Staal 1994; Niocaill et al. 1997). These arcs form the Dunnage Zone of the northeastern Appalachians, and the Laurentian continental margin deformed as a result of their collision forms the Humber Zone (Williams 1979; Faure et al. 2004).

Following the Taconic Orogeny, the Gaspé Belt successor basin, the stratigraphy of which will be discussed further in Chapter 3, formed overtop the Humber and Dunnage zones. During initial stages of Gaspé Belt deposition from the Late Ordovician to the Wenlockian, marine regression was accomplished through basin filling by siliciclastic and carbonate turbidites passing upwards into shallow water carbonates (Bourque et al. 2000). By the Wenlockian, continued closure of the back-arc basin between Avalonia and the composite Laurentian margin meant that the Gander margin of Avalonia collided with the St. Lawrence promontory of Laurentia, causing localized erosion, extension, tilting, and sea-level fluctuations throughout the region (Bourque et al. 2000; Wilson et al. 2004; Wilson and Kamo in press). This disturbance is known as the Salinic Orogeny, and can be considered a forerunner to the Acadian Orogeny when the main stage of deformation related to the Avalonia-Laurentia collision occurred in this region.

With the arrival of the Acadian orogenic wedge, the Gaspé Belt transformed into a foreland basin with intra-plate volcanism in the Restigouche area related to the delamination of the Iapetus oceanic crust (Wilson et al. 2004). The collision occurred at an oblique angle, resulting in dextral transpression and a south-westward-migrating mountain chain, accompanied by a clastic wedge that also migrated over time (Rust et al. 1989; Ettensohn 2004). Pragian-Emsian foreland basin and intermontane clastics are found in the Gaspé Belt (Rust et al. 1989), Eifelian to Fammenian coarse deltaic deposits of the Catskill Delta complex are found in the vicinities of the New York and Virginian promontories, and Mississippian-Early Pennsylvanian deposits of the Price-Pocono/Grainger/Bordon deltaic complex are found as far south as the Illinois Basin (Ettensohn 2004). The Caledonian and Acadian orogenies brought together Baltica, Laurentia, and Avalonia into the amalgamated continent of Laurussia (or Euramerica) that had a long chain of high mountain ranges from which voluminous, mainly terrestrial, clastics of the Old Red Sandstone were shed.

The region of Gaspé and northern New Brunswick experienced later Devonian and Carboniferous events of tectonic activity and sedimentation, associated in part with the Alleghanian Orogeny in the final stages of Pangean assembly (Rust, 1984; Jutras et al. 2003; Jutras et al. 2005). These events include deposition of the Visean Bonaventure Formation, which rests unconformably on the Campbellton Formation. Although the latter probably experienced minor deformation after its deposition, it is in general undeformed and does not appear to have been deeply buried or metamorphosed.

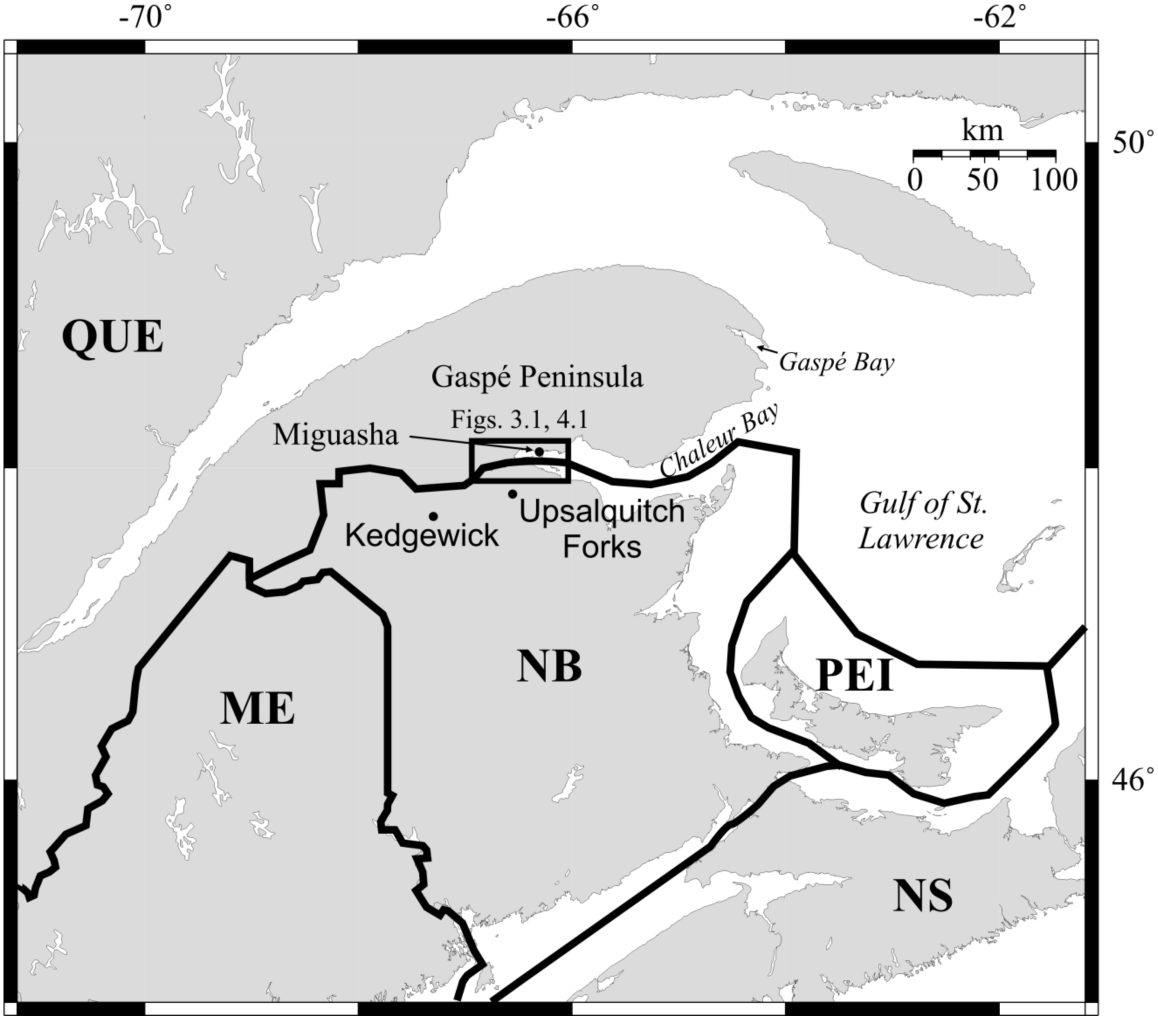


FIGURE 2.1: Map of the Maritimes region of eastern Canada showing the location of Chaleur Bay in the boxed area. QUE – Quebec. ME – Maine. NB – New Brunswick. PEI – Prince Edward Island. NS – Nova Scotia.

2.2 **Plant Evolution**

2.2.1. Laying the Groundwork

An initial period of landscape preparation, known as the Epeirophytic era, preceded plant evolution, during which terrestrial environments were occupied by organisms such as algae, bacteria, and fungi (Gray 1993). Among the oldest known examples of terrestrial life are mat-building microbes in 2.75 Ga fluviolacustrine strata of Australia (Rasmussen et al. 2009), and filamentous microbes with a possible cyanobacterial affinity in 1.2 Ga paleokarst in Arizona and 0.8 Ga paleokarst in southern California (Horodyski and Knauth 1994).

Embryophytes, which include all land plants, are thought to have monophyletically evolved in the Ordovician from charophycean green algae occupying fresh waters (Kenrick and Crane 1997a). The transition to a subaerial habitat required a number of critical innovations to evolve such as the internalization of organs for gas exchange and sexual reproduction, and the development of a protective, impermeable exterior surface (Kenrick and Crane 1997a). Early evidence of embryophytes comes from Middle Ordovician (Llanvirnian) cryptospore microfossils (two (dyad) or four (tetrad) conjoined spores) that were probably produced from very simple byrophytic land plants (Strother et al. 1996), as well as minute plant fragments and cryptospores thought to be of liverwort affinity from the Late Ordovician (Caradocian) (Wellman et al. 2003).

2.2.2. Stages of Plant Evolution in the Paleozoic

From the Ordovician to the Silurian (the Eoembryophytic era of Gray (1993)), embryophytes underwent a period of anatomical development to overcome terrestrial challenges, namely dehydration through evolution of a water-retaining cuticle, structural support through the use of turgor pressure and the development of new tissue types, and reproduction barriers through the alteration of generations (Bateman et al. 1998). The development of vascular tissue was a major advancement. Trilete and hilate spores, where the individual spores in tetrads and dyads have separated - characteristic of vascular plants - have been found in Late Ordovician (Ashgillian) sediments, about 20 million years earlier than the first mega-fossils of vascular plants (Steemans et al. 2009). However, plants of the bryophyte grade were likely more abundant than vascular plants until the appearance of the rhyniopsids in the Late Silurian (Gray 1993; Bateman et al. 1998). *Cooksonia* is often cited as the oldest vascular plant and is found in Wenlockian strata in Ireland (Edwards and Feehan 1980). However, Late Silurian (Ludlovian) strata of Australia contain *Baragwanathia* sp. which may be considered a lycopsid, suggesting that relatively complex early plants did not significantly lag behind the simplest forms (Gensel 1992).

After the appearance of the first vascular plants, a phase of morphological and behavioural evolution began (the Eutracheophytic era of Gray (1993)) during which the range, complexity, height, and ecosystem interactions increased (Bateman et al. 1998). The Devonian was a key period in this evolutionary development. Spores and megafossils became more diverse, and all tracheophytic lineages, except for the angiosperms, were established by the mid Permian (Gray 1993). Major innovations over this time include the development of enations, rooting structures, microphyllous and macrophyllous leaves, heterospory, secondary phloem and xylem, laminar leaves, fronds, and the seed habit (Banks 1970; Raven and Andrews 2010). The Campbellton Formation represents the very early stages of the Eutracheophytic era when primitive roots, enations and microphylls were common, heterospory and secondary tissues were extremely rare, and macrophyllous leaves, laminar leaves, fronds, and seeds had not yet developed.

2.2.3. Introduction to the Major Plant Groups of the Early Devonian

Early Devonian plants are commonly organized into several taxonomic groups: rhyniopsids, trimerophytes, and lycophytes (includes both zosterophylls and lycopsids). Broadly similar groups, usually bearing the same root word (Rhynio-, Trimero-, Lyco-, Zosteropyllo-), but a different suffix (-phyta, -psida) have been defined at various systematic taxonomic levels by numerous authors since Banks (1975a,b) identified four subdivisions (Rhyniophytina, Trimerophytina, Zosterophyllophytina, and Lycophytina). A good summary of these systematic treatments by different authors can be found in Kenrick and Crane (1997b, pgs. 96-99, 146, 186-187). It is now common to refer to three groups of tracheophytes: the lycophytes (zosterophylls and lycopsids), euphyllophytes (trimerophytes, sphenopsids, ferns, and seed plants), and rhyniopsids, although there is little consensus on the cladistic positions or systematic taxonomic placements of these groups (Gensel 1992; Doyle 1998; Kenrick and Crane 1997b; Taylor et al. 2009). Below, important morphological features of the Early Devonian taxonomic groups, the rhyniopsids, trimerophytes, zosterophylls, and lycopsids, are summarized from descriptions by Banks (1975a, b), Gensel and Andrews (1984) and Taylor et al. (2009), using morphological terminology illustrated in Fig. 2.2.

Rhyniopsids (Silurian-Devonian)

The rhyniopsids are among the simplest vascular plants, represented by the flora of the Rhynie Chert of Scotland, for which an overview can be found in Taylor et al. (2009 – Ch. 8). These are characterized by terminal sporangia on slender dichotomizing axes that bear no ornamentation. Roots are lacking, but anchorage is accomplished through horizontal dichotomizing rhizoids. Sporangia are elongate, sometimes branched, and are homosporous (produce uniformly sized spores). The xylem strand is solid and displays a centrarch maturation pattern. Some rhyniopsids may not be true vascular plants, but actually an intermediate between bryophytes and tracheophytes, and are thus referred to as Tracheophyta instead of Eutracheophyta. *Taeniocrada* sp. is the only rhyniopsid found in the Campbellton Formation.

Trimerophytes (Silurian-Devonian)

Trimerophytes bear many similarities to rhyniopsids, such as terminal sporangia and a solid strand of xylem with a centrarch maturation pattern, but are typically larger and more complexly branched. Fertile branches may branch many times before terminating in fusiform to elongate clustered sporangia. Branching may be monopodial or pseudomonopodial, and lateral branches may bifurcate or trifurcate. *Pertica dalhousii* (Fig. 2.3a, Fig. 2.4a), *Psilophyton princeps* (Fig. 2.3b, Fig. 2.4b), *P. charientos*, *P. coniculum* and *Trimerophyton robustius* (Fig. 2.4c) are trimerophytes found in Campbellton Formation strata.

Zosterophylls (Silurian-Devonian)

Zosterophylls are a basal lycophyte and tend to be small in stature compared to lycopsids. Smooth or spiny axes bifurcate in a pseudomonopodial fashion with both isotomous and anisotomous branches. The xylem is arranged in a strand that is round, elliptical, or terete (split into four regions of xylem), and displays an exarch maturation pattern. Homosporous reniform or globose sporangia, often dehisced, are borne laterally either directly attached to the axis, or on a short vascularized stalk. Zosterophylls found in the Campbellton Formation include *Oricilla bilinearis* (Fig. 2.3c), *Zosterophyllum divaricatum* (Fig 2.3d, Fig. 2.4d), *Sawdonia acanthotheca* (Fig. 2.4e) and *S. ornata* (*Sawdonia* sp. is shown in Figure 2.3e).

Lycopsids (Silurian-present)

The lycopsids share many similarities with the zosterophylls, to which they are closely related. Similarities include laterally borne reniform sporangia and exarch xylem maturation. The presence of microphylls, or small leaves with a single vascular strand, arranged helically around the axis, is the most significant synapomorphy, not shared with the zosterophylls. Sporangia are dehiscent and are borne on the upper surface of sporophylls (leafs, either microphyllous or megaphyllous that bear sporangia). Most early lycopsids are homosporous, but heterospory is seen in some later forms. Branching may be dichotomous or monopodial. “Pre-lycopsids” such as *Asteroxylon* sp., *Kaulangiophyton* sp. (Fig. 2.4f), and *Drepanophycus* sp. are morphologically similar to traditional lycopsids, but lack a vascularized leaf or leaf-associated sporangia (Gensel 1992). Among the groups presented here, lycopsids became the most successful with a thriving arborescent community in tropical Carboniferous wetlands (Edwards 1998), and several small forms are still present today. Lycopsids in the Campbellton Formation include *Drepanophycus spinaeformis* (Fig. 2.4g), *D. gaspianus* (*Drepanophycus* sp. is shown in Figure 2.5a), *Leclercqia complexa* (Fig. 2.4h), and *L. andrewsii* (*Leclercqia* sp. is shown in Figure 2.5b).

Incertae sedis

Several genera have been identified with a set of traits that cannot be placed among the fore-mentioned recognized groups. In the Campbellton Formation, these include *Chaleuria cirrosa* (Fig. 2.4i), possibly an early progymnosperm (Andrews et al. 1974), and *Oocampsa catheta* (Fig. 2.4j), representing an intermediate form between trimerophytes and progymnosperms (Andrews et al. 1975). *Bitelaria dubjanskii*, and *Loganophyton dawsoni* (Fig. 2.4k) are also incertae sedis that have been found within Campbellton Formation strata.

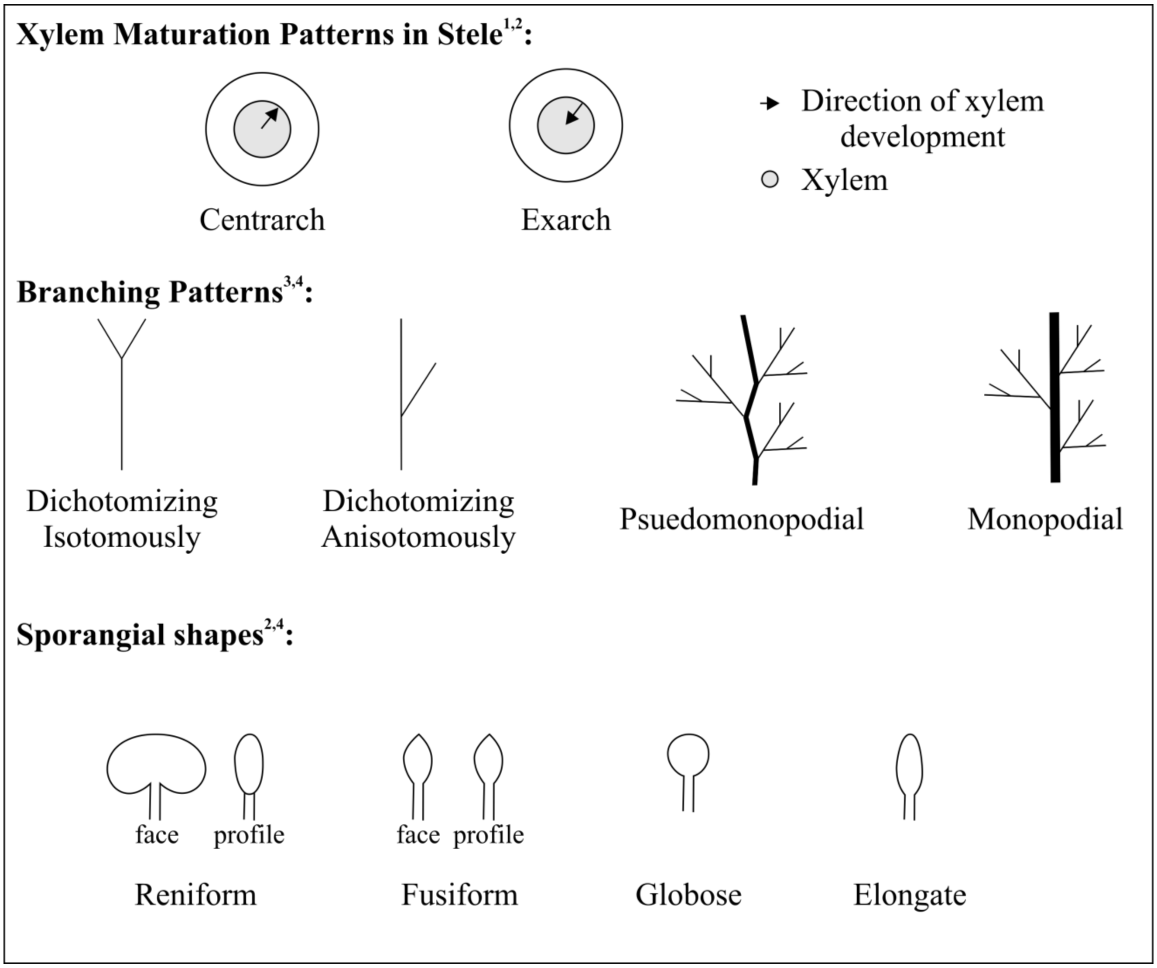


FIGURE 2.2: Simplified diagrams of major morphological terms applicable to Early Devonian plants. References are as follows. [1]Taylor et al. 2009. [2]Kenrick and Crane 1997b (pg. 115, 123). [3]Gensel et al. 2001.[4]Gensel and Andrews 1984.

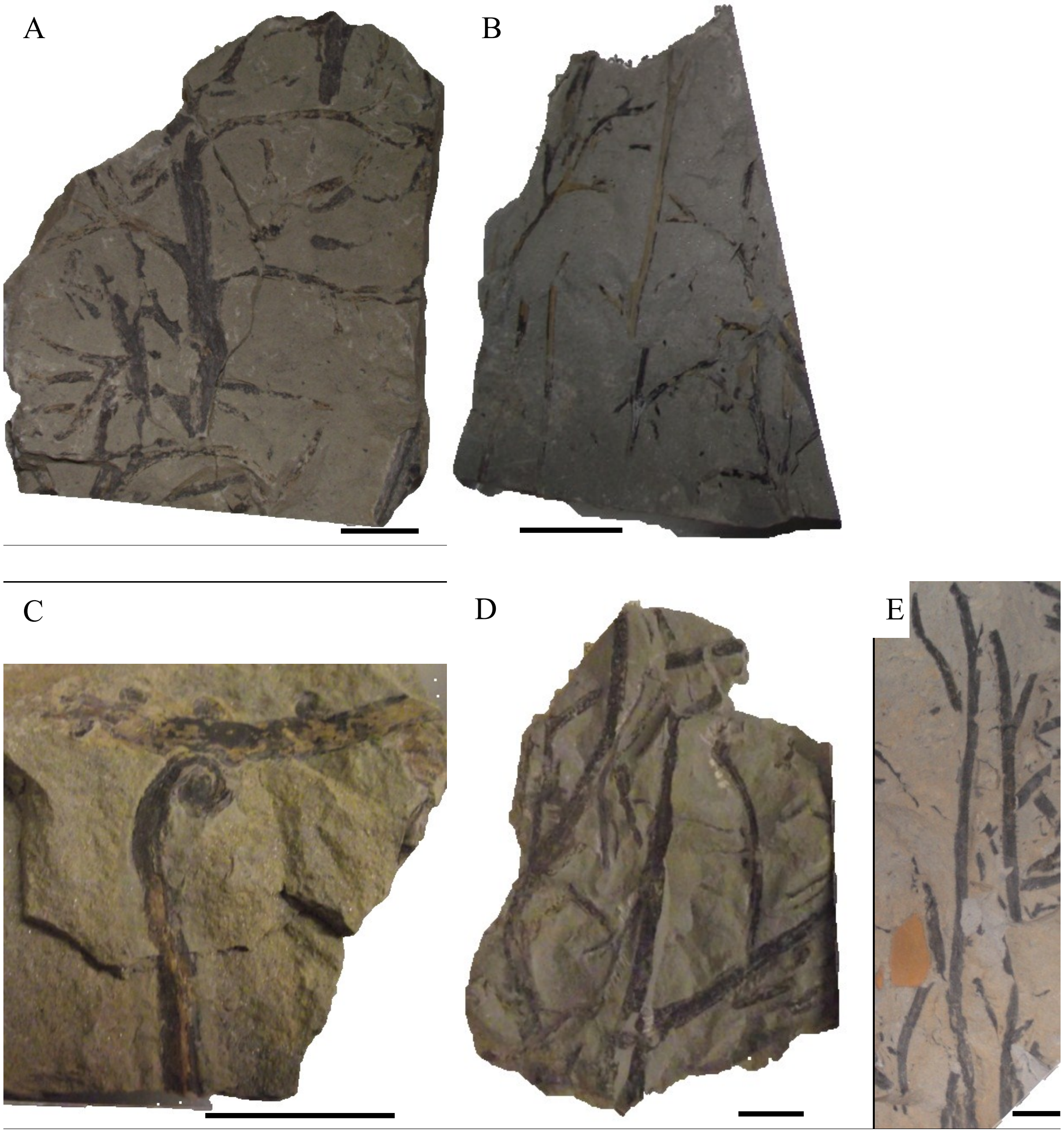


FIGURE 2.3: Examples of fossilized trimerophytes (A-B) and zosterophylls (C-E) from the Campbellton Formation. All scale bars are 2 cm. A) *Pertica dalhousii*. B) Thin, possible terminal, smooth stems of *Psilophyton princeps*. C) *Oricilla bilinearis* – horizontal stalk shows lateral sporangia. D) Stems of *Zosterophyllum divaricatum*. E) Vegetative *Sawdonia* sp. showing branching.

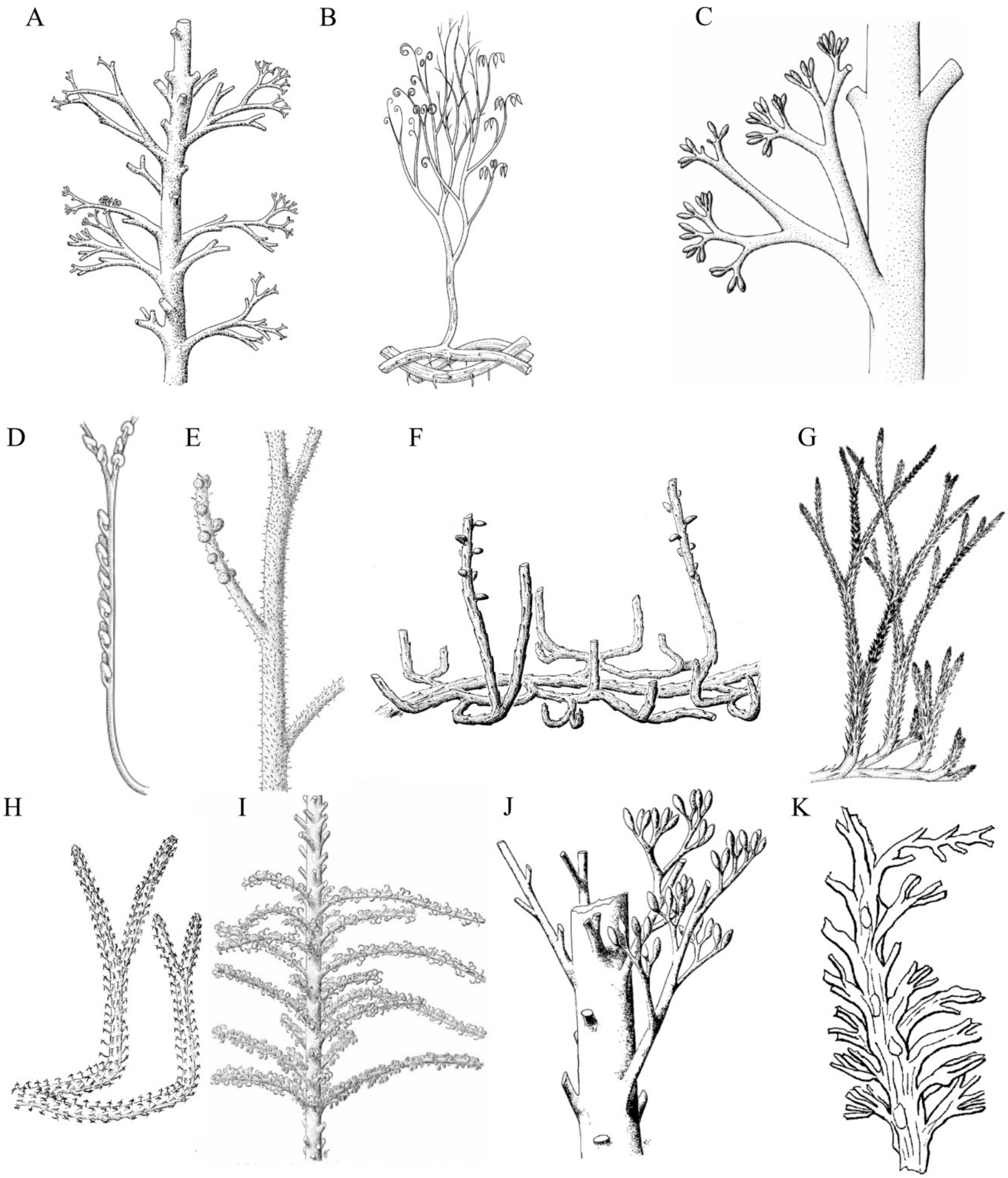


Figure 2.4: Reconstructions of selected plants found within the Campbellton Formation. A) *Pertica dalhousii* (Doran et al. 1978). B) *Psilophyton princeps* (Taylor et al. 2009). C) *Trimerophyton robustius* (Taylor et al. 2009). D) *Zosterophyllum divaricatum* (Kenrick and Crane 1997b). E) *Sawdonia acanthotheca* (Gensel et al. 1975). F) *Kaulangiophyton akantha* (Gensel et al. 1969). G) *Drepanophycus spinaeformis* (Taylor et al. 2009). H) *Leclercqia complexa* (Kenrick and Crane 1997b). I) *Chaleuria cirrosa* (Andrews et al. 1974). J) *Oocampsa catheta* (Andrews et al. 1975). K) *Loganophyton dawsoni* (Krausel and Weyland 1961)

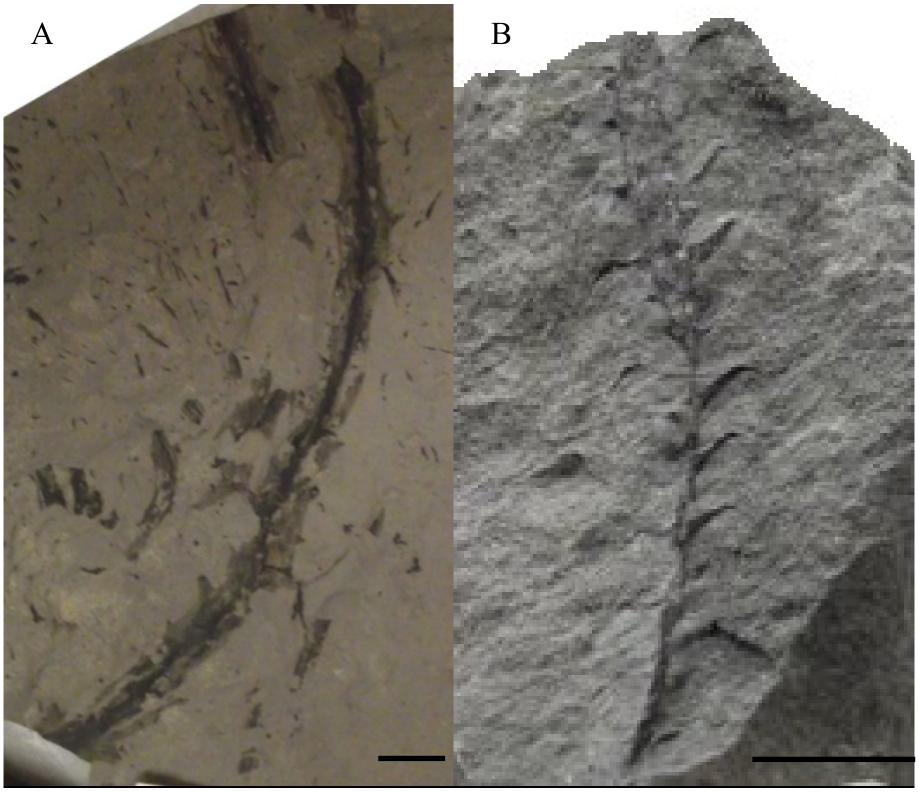


FIGURE 2.5: Examples of fossilized lycopsids from the Campbellton Formation. All scale bars are 2 cm. A) *Drepanophycus* sp. showing dark vascular strand within a broad axis and microphylls. B) *Leclercqia* sp. showing very fine microphyllous leaves.

2.3 Terrestrial Arthropods

First appearing in aquatic habitats during the Cambrian, arthropods transitioned to land in the Cambro-Ordovician, as demonstrated by the occurrence of putative terrestrial burrows in strata of this age (DiMichele and Hook 1992; Shear and Selden 2001). By the Late Silurian, body fossils of trigonotarbid arachnids and myriapods appear in the rock record (Rolfe 1985; Jeram et al. 1990). True ecosystems involving these terrestrial arthropods are found in Early Devonian and younger strata, but there are few localities until the early Middle Devonian (DiMichele and Hook 1992). Important locations containing these early terrestrial arthropods include the Pridolian Ludford Lane deposit in Shropshire, England, the Rhynie Chert of Scotland, Alken an der Mosel of Germany, and the Battery Point Formation of Gaspé Bay, Canada (Shear and Selden 2001).

Only two subphyla of Arthropoda had made it to land by the Early Devonian: Chelicerata and Uniramia (Atelocerata). Arachnids, belonging to subphylum Chelicerata due to distinctive chelicerae near the mouth, in the Early Devonian were represented by the orders Scorpionida, Trigonotarbida, and Acari, but several more orders appear soon after in the Middle Devonian locality of Gilboa, northeastern USA (Shear and Selden 2001). The earliest aquatic scorpions had become amphibious by the Early Devonian (Rolfe 1985) and the earliest air-breathing scorpion, likely no longer than 9-9.5 cm, is found in Emsian strata of the Campbellton Formation (Shear et al. 1996). Trigonotarbid spiders resemble heavily armoured spiders lacking a silk-spinning apparatus and lived from the Silurian to Permian where they subsisted as carnivorous litter dwellers, sometimes taking shelter in empty sporangia as seen in the Rhynie Chert (Rolfe 1985; Chaloner et al. 1991). The Rhynie Chert also contains the earliest fossils of mites (order

Acari) which were likely detritivores, fungivores, or microherbivores (Shear and Seldon 2001; Habgood et al. 2004).

Uniramians include myriapods and hexapods. Myriapods are likely among the oldest terrestrial animals, diversifying into the clearly terrestrial Diplopoda (millipedes), Chilopoda (centipedes) and Arthropleurida by the Early Devonian. Millipede body fossils are found as early as the Silurian (Wenlock), and due to a detritivorous diet were probably important soil-forming agents (Almond 1985; Shear and Selden 2001). Centipedes, found in the Pridolian of Ludford Lane, are more likely to have been carnivorous (Shear and Kukalovà-Peck 1990; Shear and Selden 2001). Arthropleurida was first seen as a 15-20 cm long body fossil in the Emsian of Alken an der Mosel, and a precursor form, *Eoarthropleura*, is inferred from trackways in Upper Silurian strata of Newfoundland, and is first known from a body fossil in Emsian strata of the Campbellton Formation (Shear and Kukalovà-Peck 1990; Shear et al. 1996). Hexapods, which today have a wide variety of forms including most insects, were in the Early Devonian mostly restricted to detritivorous collembolans (springtails) seen from the Rhynie Chert (Shear and Kukalovà-Peck 1990) and archaeognathans (bristletails) from Gaspé Bay (Labandeira et al. 1988).

2.4 **Fish**

The Devonian has been referred to as the "Age of Fishes" for an intense period of diversification of vertebrates in aquatic habitats. The Upper Devonian is best represented by Miguasha National Park on the northern shore of the Bay of Chaleur opposite the Campbellton Formation outcrops, a UNESCO World Heritage Site for the Age of Fishes. Both agnathan and the gnathostome fish occupied waters worldwide during the

Devonian. Perhaps the oldest, arising as early as the Ordovician, are the agnathans, or jawless fishes which include the extinct ostracoderms characterized by tough plated covering, and living cyclostomes (lampreys and hagfish) (Forey and Janvier 1993; Purnell 2001). Most ostracoderms are thought to have been filter feeders or microphagous, eating only small pieces of detritus, but some, the thelodonts and heterostracans in particular, show evidence of macrophagy and even predation, without the advantage a hinged jaw (Forey and Janvier 1993; Purnell 2001). Jawless fish in the Campbellton Formation are limited to the cephalaspid genus *Yvonaspis* sp. (Fig 2.6a).

The development of jaws in the gnathostomes gave rise to a dramatic increase in diversity among vertebrates. Major groups of gnathostomes in the Early Devonian include the chondrichthyans, the placoderms, the acanthodians, and the sarcopterygians; however the cladistic placement of the latter three is controversial. Oldest microfossil evidence of shark-like cartilaginous fish (chondrichthyans) comes from Ordovician (Caradoc) scales from Colorado (Sansom et al. 1996). By the early Devonian, the dentition patterns suggest that predation and scavenging were dominant feeding strategies (Turner and Miller 2008). Placoderms are almost exclusively known from Devonian strata where the characteristic armoured plating, which was probably involved in feeding, locomotion, and structural support, is commonly well-preserved (Young 1986). Late Silurian to Early Permian acanthodians, known for their paired, spine-supported fins, are often fossilized as isolated spines and scales (Purnell 2001). These fish were probably very good swimmers, possibly with an air bladder to control buoyancy, and as such are distributed world-wide (Young 1986). Sarcopterygians are recognized for their lobe-fins and are found in Devonian and younger shallow freshwater and marine deposits

(Thomson 1969). Lobe fins gave rise to the Amphibia, and Miguasha is known for its representation of this group, best represented by *Eusthenopteron foordi.* In the Campbellton Formation, one placoderm genus, *Phlyctaenius* sp. (Fig 2.6b), several acanthodians including *Ankylacanthus incurvis* (Burrow et al. 2008) and *Climatius latispinosis* (Fig. 2.6c), and the chondrichthyans *Protodus jexi* (Turner and Miller 2008) and *Doliodus problematicus* (Miller et al. 2003) have been found near Atholville.

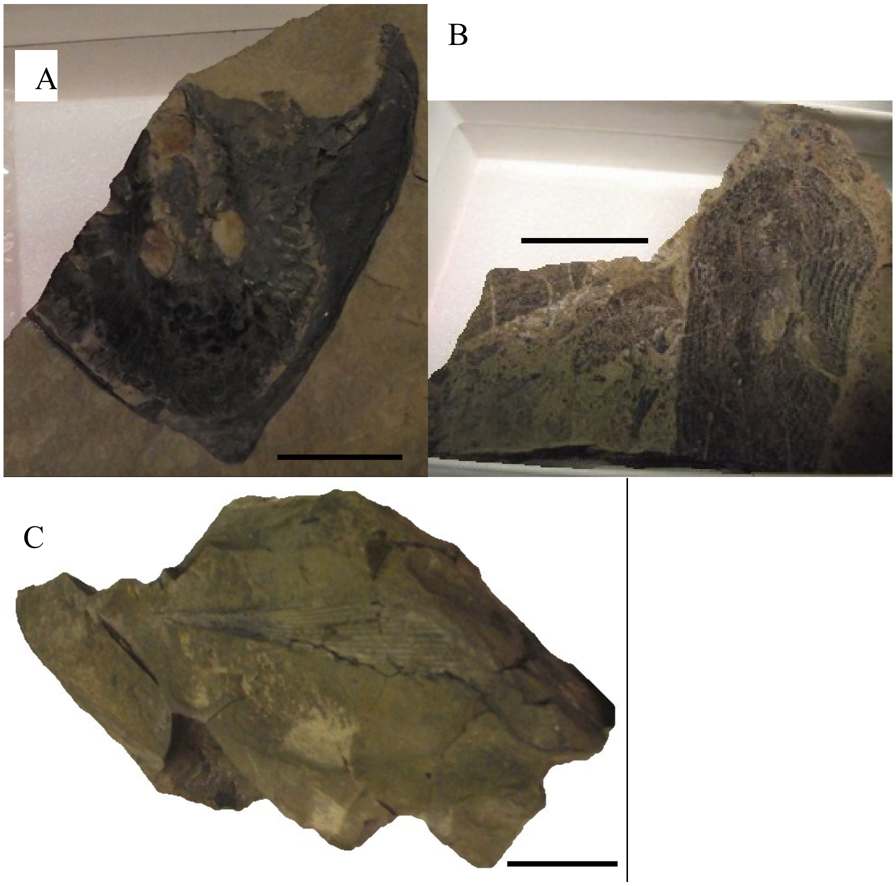


FIGURE 2.6: Fish fossils of the Campbellton Formation. All scale bars are 2 cm. A) Head shield of *Yvonaspis* sp. B) Dermal plate of *Phlyctaenius* sp. C) Spine of *Climatius latispinosis*.

2.5 Consequences of the Terrestrialization Process on Earth Systems

The greening of the land as driven by increasing arborescence, increased size and complexity of root systems, and the growing use of the seed habit throughout the Devonian had a number of substantial effects on earth systems, as summarized by Algeo et al. (2001). Resulting impacts on the carbon cycle and weathering regimes led to several land-atmosphere-ocean interactions as outlined below.

Throughout the Devonian and Carboniferous, atmospheric CO_2 significantly decreased, mirrored by an increase in atmospheric O_2 (Berner 2003, 2006). Plants with planate megaphyllous leaves were probably responsible for much of the drawdown of CO_2 through photosynthesis and organic carbon burial (Beerling et al. 2001), in conjunction with accelerated silicate weathering brought on by large roots (Berner 1997, 2003). Although plants were first present on land in the Ordovician, this sudden decrease in atmospheric CO_2 was delayed until the end of the Devonian, when vegetation had achieved significant density and when Acadian mountain-building resulting in oxidation of organic matter had subsided (Malkowski and Racki 2009).

Early pedogenesis mainly occurred by burrowing arthropods, microbes, and fungi, processing thin layers of soil. More efficient rooting systems were able to mechanically and chemically weather deeper silicates, liberating nutrients and causing eutrophication and ensuing widespread ocean anoxia in Middle to Late Devonian oceans (Algeo et al. 1995, 2001; Algeo and Scheckler 1998). Rooted vegetation decreased runoff and increased bank stabilization, promoting a meandering channel style over a braided style where sediment yield was low, and chemical weathering produced more compositionally mature, mud-rich fluvial sediments (Cotter 1978; Davies and Gibling 2010).

CHAPTER 3 — THE CAMPBELLTON FORMATION, NEW BRUNSWICK, CANADA: PALEOENVIRONMENTS IN AN IMPORTANT EARLY DEVONIAN TERRESTRIAL LOCALITY

3.1 Abstract

Strata of the Campbellton Formation, nearly 1 km thick and known for its diverse fossil assemblage of early plants, arthropods, and fish, can be divided into six facies associations, interpreted as: 1) restricted lacustrine, 2) marginal lacustrine, 3) near-shore lacustrine, 4) coastal-deltaic, 5) sandy to gravelly alluvial plain, and 6) gravelly proximal alluvial environments. Lacustrine deposits with restricted circulation, due to depth or stagnation, have fine-grained beds with well-preserved organic material. The marginal lacustrine facies association is the most abundant and consists of beds of massive siltstone and very fine sandstone, interbedded with conglomerate. The latter is interpreted to have been shed from older volcanic units forming the basin walls. The near-shore lacustrine association is characterized by rippled sandstones with microbialites. Alluvial strata are present as interbedded imbricate to non-imbricate conglomerates, trough cross-stratified sandstone, and siltstone which may be barren or only locally preserve plant fossils. Rare exposures of thickly bedded imbricate to weakly imbricated cobble-boulder conglomerates with sandy plant-bearing lenses are interpreted as products of hyperconcentrated debris flows. In the western basin, a well-developed braided-fluvial system had paleocurrents flowing WNW. Coastal-deltaic deposits, containing aquatic vertebrates and invertebrates, had paleocurrents flowing towards the ESE, suggesting a small, confined, body of fresh or brackish water. In the eastern belt, lacustrine facies are prevalent in lower parts of the formation, representing a large open lake. Alluvial facies dominate the upper part of the formation, representing an eastward-

flowing axial braided river system, with proximal alluvium shed transversely from the basin margins. Although most of the strata have a volcanic provenance, one outcrop in the lacustrine beds shows evidence that volcanism was still active during deposition of the Campbellton Formation.

3.2 **Introduction**

On the southern shore of the Restigouche River in New Brunswick, Canada, near the head of Chaleur Bay, a narrow belt of the Emsian to Eifelian Campbellton Formation is exposed (Ami 1900; Fig. 3.1). This formation has long been of interest to paleontologists due to its rich assemblage of fossilized fish (Whiteaves 1881; Traquair 1890; Woodward 1892; Burrow et al. 2008; Turner and Miller 2008), invertebrates (Jones 1889; Miller 1996, 2007a, 2007b) and plants (Dawson 1871; Andrews et al. 1974, 1975; Gensel and Albright 2006). Strata from this formation host the oldest articulated chondrichthyan (Miller et al. 2003), early terrestrial macroarthropods (including two myriapods and the earliest air-breathing scorpion; Shear et al. 1996; Wilson 2006), and 14 genera of plants representing the rhyniopsids, lycopsids, trimerophytes, and zosterophylls, as well as several plants of uncertain affinity (Gensel and Andrews 1984; Gensel and Kasper 2005). Early work on the sedimentology was performed by Alcock (1936) who recognised black shales, sandstones, and conglomerates between Mission Point and Campbellton, buff sandstones west of Dalhousie Junction, and sandstone and volcanically-derived conglomerate west of Dalhousie, as well as the clastic outcrop belt on the north shore of Chaleur Bay as belonging to the Gaspé Sandstone Group. Despite the paleobiological significance of the formation, the only newer accounts of its sedimentology are those of Dineley and Williams (1968) and Gamba (1990), who presented measured sections and facies interpretations in a regional survey of formations bordering Chaleur Bay. This paper presents new information on the formation's thickness, facies spectrum, and paleoflow patterns, and places the remarkable fossil discoveries within a paleoenvironmental context.

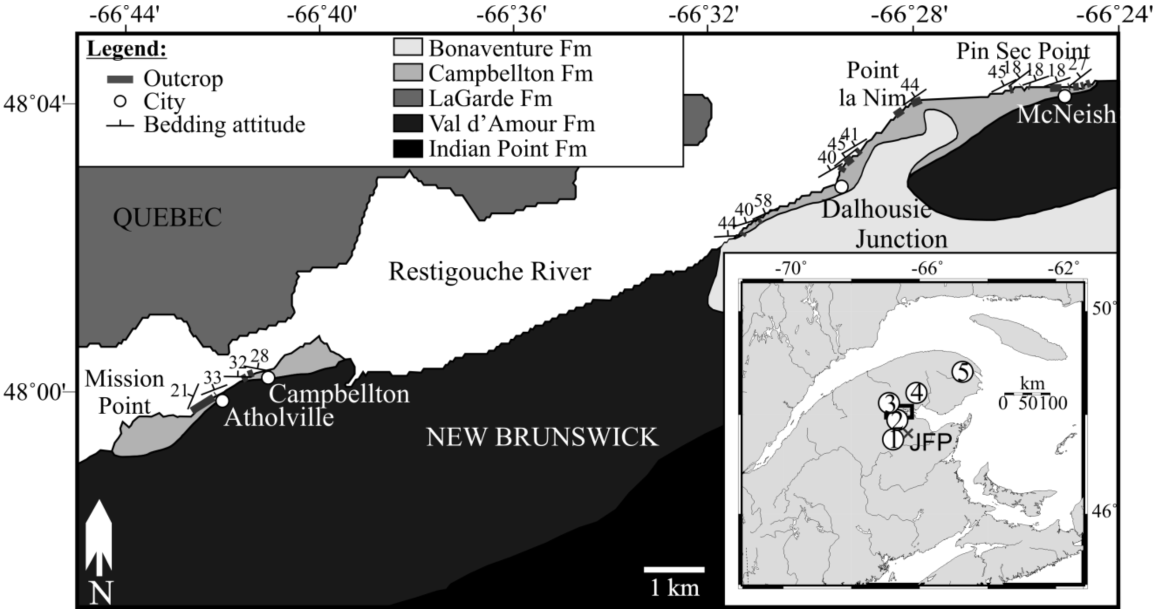


FIGURE 3.1: Location and geology of the Campbellton Formation and region. Geology from Wilson et al. (2004). Circled numbers in inset map refer to stratigraphic columns in Figure 3.2. JFP – Location of the Jerry Ferguson Porphyry.

3.3 Geologic Setting

The basal beds of the Campbellton Formation unconformably overlie rhyolites of the Val d'Amour Formation (Dalhousie Group) (Wilson et al. 2005). Rhyolites near the top of the formation have been dated with a concordant U-Pb zircon age of 407.4 ± 0.8 Ma (Wilson et al. 2004), giving a lower age limit of latest Pragian (Early Devonian) for the Campbellton Formation (International Commission on Stratigraphy 2009). The Atholville beds in the lowermost Campbellton Formation (Dineley and Williams 1968) contain a spore assemblage in the *Emphanisporites annulatus – Camarozonotriletes sextantii* assemblage zone of Richardson and McGregor (1986), suggesting a mid Emsian age (McGregor 1989, in Gamba 1990). Beds stratigraphically higher contain spores from the *Grandispora* subzone of the *douglastownense-eurypterota* zone (Richardson and McGregor 1986), indicating a late Emsian to earliest Eifelian age (Gensel 1982; Wellman and Gensel 2004). Thus, the formation appears to be mainly of Early Devonian age, possibly extending into the Middle Devonian (Fig. 3.2). Gamba (1990) identified several members within the formation, but these have not been formally recognised or mapped, and they are not used here.

The Campbellton Formation lies within the Gaspé Belt (Fig. 3.2), a broad tract of mainly sedimentary rocks deposited in a post-Taconic successor basin during the Acadian Orogeny. The Gaspé Belt crops out from the Gaspé Peninsula through to southern Maine. Early stages of basin fill include turbidite deposits, shelf sandstones, and platform carbonates, reflecting regression through the Ashgillian to the Wenlockian (Bourque et al. 2000; Wilson et al. 2004). In the mid Wenlockian, collision of Ganderia and Laurentia during the Salinic orogeny (van Staal et al. 2009) uplifted crustal blocks and caused localized erosion that in the Restigouche area resulted in a 5-6 million year hiatus between lower and upper Chaleurs Group strata (Wilson et al. 2004; Wilson and Kamo in press). The Salinic event was followed by widespread extensional collapse with transgression during which reefal strata of the West Point Formation were overlain by deep water facies of the Indian Point Formation (Bourque et al. 2000).

Palinspastic reconstruction of the Lochkovian Gaspé Belt depicts a foreland basin setting associated with the Acadian orogenic wedge, with uplift in the far southeast Chaleur Bay synclinorium (Bourque et al. 2000). By the Pragian, deep-water strata were deposited in the Upper Gaspé Limestone and Fortin Group in the northern Gaspé Belt, while outer shelf or slope turbidites were deposited in the Wapske Formation in the southern Chaleur Bay synclinorium, leaving the Restigouche area between these two basins as a relative topographic high (Wilson et al. 2004). The Pragian Val d’Amour Formation, about 6 km thick, directly underlies the Campbellton Formation, and consists of terrestrial clastic and subaerial volcanic rocks, passing from mafic to felsic upsection, except near Dalhousie where shallow subaqueous volcanic rocks and minor shallow marine carbonates are present (Wilson et al. 2005). An intra-plate tectonic setting for the Val d’Amour Formation volcanics is inferred based on Zr-Nb-Y and Zr-Ti-Y discrimination plots of basalts and andesites (Wilson et al. 2005). Volcanic rocks equivalent to the Val d’Amour Formation also crop out as the Black Cape - Dalhousie Volcanics in the southern Gaspé Peninsula of Quebec (Dostal et al. 1993).

Dextral transpression associated with the Acadian Orogeny resulted in a series of open to closed folds, shortening and thickening the Gaspé Belt significantly (Malo and Kirkwood 1995). In Maine and New Hampshire, the position of the deformation front by the base of the Emsian (406-408 Ma) has been constrained using paleontologically dated foreland basin turbidites and an isotopically dated plutonic belt to a NE-SW trend that, if extended linearly, would project through Chaleur Bay (Bradley and Tucker 2002). A 401 ± 1 Ma U-Pb zircon age from the intrusive Jerry Ferguson Porphyry located near Upsalquitch Forks (McCutcheon and Bevier 1990) implies significant thickening of the crust due to Acadian deformation in the Campbellton area during the Emsian. The unconformity between the Val d'Amour Formation and the Campbellton Formation also indicates uplift and erosion at the beginning of the Emsian (Wilson et al. 2004). During later stages of the Acadian Orogeny much of the Gaspé Sandstones Group was deposited as coastal or alluvial successions in the foreland clastic wedge (Battery Point and Malbaie formations) and as alluvial or lacustrine successions in intermontane basins (Campbellton, LaGarde and Pirate Cove formations) (Rust et al. 1989).

By the middle Emsian, the Acadian highlands and orogenic wedge lay in close proximity to the Campbellton area, probably resulting in a rugged mountainous landscape. The alluvial LaGarde and Pirate Cove formations on the north shore of Chaleur Bay are considered equivalent to the Campbellton Formation (Dineley and Williams 1968). Paleocurrents for the LaGarde Formation show westward paleoflow of proximal alluvium and northward paleoflow of distal alluvium (Gamba 1990) whereas the alluvial-fan deposits in the Pirate Cove Formation show paleoflow to the southeast (Rust et al. 1989). The apparent location of topographic highs to the north, east, and south near the study area suggests deposition in an intermontane basin. Emsian dates for Acadian orogenic events elsewhere in the region suggest that Campbellton Formation deposition was synorogenic (Bradley and Tucker 2002), but the precise cause of subsidence has not been determined, nor which faults in the area may have been active at this time.

Given a paleolatitude of about 35°S (Niocaill and Smethurst 1994), this area may have experienced a subtropical climate, possibly with monsoonal weather patterns, as has been suggested for nearly contemporaneous Gaspé Sandstone Group strata in Gaspé Bay, Quebec (Griffings et al. 2000).

A number of minette lamprophyre dikes, rich in biotite and potassium feldspar, are present in the study area (Bachinski and Simpson 1984). These dikes do not intrude the Visean Bonaventure Formation, and are probably similar in age to lamprophyre dikes in the Kedgwick region of northern New Brunswick that were dated at 378.5±1.9 Ma (R. Wilson pers. comm. 2011).

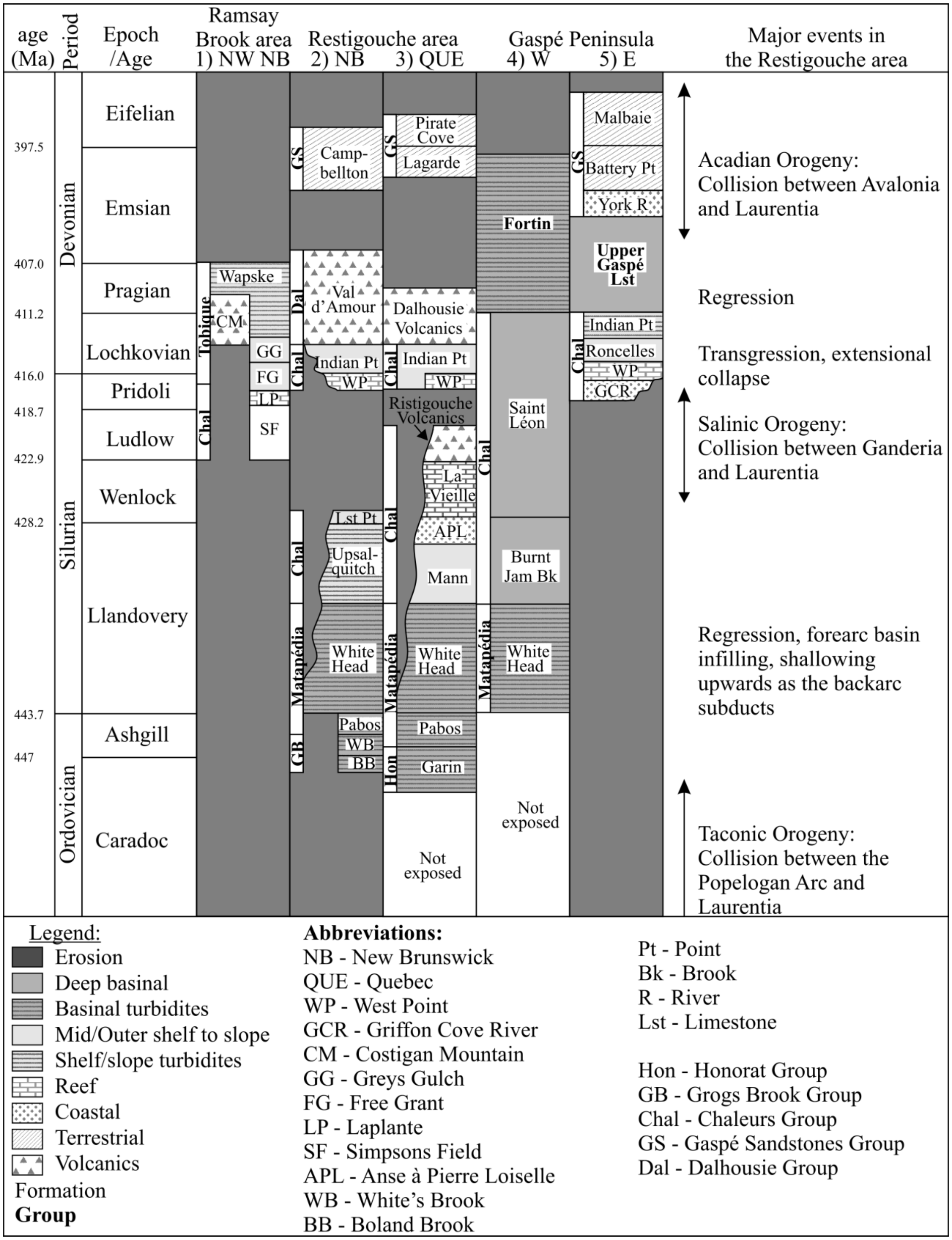


FIGURE 3.2: Regional stratigraphic correlation chart of five locations within the Gaspé Belt. See Figure 3.1 inset map for locations of stratigraphic columns. Dates for age boundaries are from ICS International Stratigraphic Chart 2009. Data for column 1 Ramsay Brook area are modified from Wilson and Kamo (2008); columns 2 and 3, and main events in the Restigouche area are from Wilson et al. (2004); columns 4 and 5 are modified from Bourque et al. (2000); and the upper part of column 5 from Rust et al. (1989).

3.4 **Methodology**

Outcrop in the study area is sporadic, with long intervals of no exposure (Fig. 3.1), making the construction of a representative stratigraphic column challenging. The eastern outcrop belt includes a strike section 4 km long, from McNeish to Point la Nim. Most outcrops are accessible at all but the highest tides, allowing 221 m of strata to be described on a unit-by-unit basis, with respect to their stratigraphic thickness, bedding thickness and style, bedding orientation, colour, basal contact, sedimentary structures, clast size and shape, sorting, paleocurrents, and fossil occurrences. To aid description, 37 samples were examined in thin section, and one sample was analyzed using an electron microprobe (JEOL JXA8200 Superprobe). Using the data collected, facies were defined according to a scheme adapted from Miall (1996) with some modifications to more accurately describe the Campbellton Formation (Table 3.1). The stratigraphic relationships through intervals of no-exposure between outcrops were trigonometrically determined using the attitude of beds and outcrop positions found using a handheld GPS accurate to ~3 m or by pace-and-compass where outcrops were closely spaced. These observations are plotted using SedLog Version 2.1.4 (Zervas et al. 2009) into a stratigraphic log with six sections (Figs. 3.3-3.4), representing an estimated thickness of 82 m in the western belt (sections I-II) and 938 m in the eastern belt (sections III-VI).

Conglomerate provenance was compared between selected beds using clast counting techniques. Seven sets of 50 clasts greater than 1 cm in diameter and in the pebble to cobble size range were collected from within a single sedimentation unit less than a few decimetres thick, corresponding to a ribbon of strata (Howard 1993). The clasts were fractured to obtain a fresh surface, and examined under a binocular microscope for colour, grain size, phenocryst presence, and mineral composition. Where an igneous affinity could be determined, aphanitic or porphyritic rocks were classified mainly by groundmass colour where leucocratic rocks (rhyolites and ash tuffs) were termed “felsic”, mesocratic rocks (andesites, dacites) were termed “intermediate”, and melanocratic rocks (basalts) were termed “mafic”. For coarse igneous rocks, the provisional IUGS field classification of plutonic rocks was used where “felsic” lithologies include granitoids and syenitoids, and “intermediate” lithologies are mainly dioritoids (Le Maitre 2002). Sedimentary clasts, where encountered, were described as carbonate if they effervesced with hydrochloric acid, or siliciclastic if they did not. Crystalline quartz is also present. Seven thin sections of clasts were made to confirm identifications. Statistical methods outlined by Howard (1993) were applied to determine the counting error at 95% confidence using a student t-distribution, however this technique may inaccurately estimate the counting error for very small (<0.1) or very large (>0.9) proportions.

Thirty-two paleocurrent measurements were taken from clearly developed imbrication within facies Gh and Gt and from the dip direction of cross-stratification in facies Sr and St (see facies descriptions below). For imbrication, beds were selected where numerous inclined clasts were stacked against each other and where sufficient three-dimensional exposure was available to confirm the true dip direction of the inclined clast groups. These conditions were met by a small proportion of conglomerate beds. For cross-stratification, sites were only selected where the three-dimensional crescent form of the cross sets as viewed from above could be discerned, allowing trough axes to be measured accurately. In each bed containing imbrication or cross-stratification, the paleoflow azimuth suggested by the overall trend of indicators was measured so as to make corrections due to bedding dip and orientation unnecessary. Tectonic rotation of blocks between outcrops was assumed to be negligible and, although minor faults are present, no major faults within the Campbellton Formation have been observed. Thus, local faulting is not considered to have affected local paleocurrent measurements. A more quantitative approach was hampered by a scarcity of clear paleoflow indicators, but measurements were selectively taken only on clear, well-developed features.

	Facies	Characteristics	Process	Contextual Interpretation
Siltstones to fine sandstones				
Fm	Massive siltstone to fine sandstone	Red, grey, or mottled red and grey Massive to graded Medium bedding thickness, commonly lenticular Plant fragments rare to abundant, <5 cm long	Suspensional fall out into standing water	Lake margin; Well mixed deep lake; Abandoned fluvial channels
FSi	Interlensing siltstone, sandstone, and very fine conglomerate	Red, grey, greenish grey Medium bedding thickness	Short lived higher energy events depositing thin coarse layers	Storm or density-flow layers on lake margins
Fl	Laminated siltstone to fine sandstone	Grey, red Current-ripple cross-lamination and planar lamination Thinly bedded Plant material common, mostly disseminated fragments, but can be up to 10 cm long	Where rippled, indicates current present Planar lamination could result from lake overturn	Deep to marginal lake with regular variations in productivity, stratification, and sedimentation
Fo	Organic rich shale and siltstone	Dark grey to black, Finely laminated, fissile Rich in carbonaceous material, largely amorphous Thinly bedded	Anoxic with high organic matter accumulation	Stratified deep lake or stagnant waters
Medium to coarse sandstones				
St	Trough cross-bedded sandstone	Grey Erosional and sharp contacts common Occasional pebbly foresets (10-20 cm high), ripple cross-laminated sets Thinly to medium bedded Plant fragments small (<5 cm, 2 cm average)	Unidirectional persistent flow	Low to mid energy 3D fluvial dunes
Sr	Ripple cross-laminated sandstone	Grey Asymmetric ripple cross-lamination, both climbing and planar sets Thinly bedded Organic material typically defines lamina, usually disseminated	Unidirectional flow	Low energy currents
Sm	Massive medium to coarse sandstone	Grey Massive or graded beds Bed boundaries lenticular to planar, erosional surfaces common Thinly to medium bedded Disseminated organics	Sediment gravity flow	Lake margin rapid suspensional settling or subaqueous debris flows; Fluvial bank collapse
Sh	Horizontally bedded sandstone	Horizontally laminated and plane-bedded sandstone Parting lineation rarely present	Upper flow regime	Flood events

TABLE 3.1: A summary of Campbellton Formation facies descriptions and interpretations.

Table 3.1 Continued.

	Facies	Characteristics	Process	Contextual interpretation
Conglomerates				
Gms	Matrix-supported massive or graded conglomerate	Poorly sorted pebbles to cobbles No imbrication Bedding absent or very poorly defined and thick Well rounded clasts	Variable strength debris flow	Alluvial debris flows; Minor presence as subaqueous debris flows in lake settings
Gh	Clast-supported horizontally stratified conglomerate	Granules to boulders Crude horizontal stratification of grain size, common minor sand lenses, and grading Imbrication common, but weak Medium to thickly bedded	Moderate sorting by fluid flow	Bedload deposits as longitudinal bars
Gt	Trough cross-bedded conglomerate	Granules to cobbles Foresets, lag deposit in troughs, trough cross-bedding Some coarse sandy lenses	Unidirectional channelized flow	Alluvial channel fills or gravel bedforms with curved crests
Gcg	Clast-supported granule conglomerate	Well sorted granules Clasts flattened parallel to bedding Thin (<2 cm) lenses of mud or fine sandstone common Commonly scour into underlying sediments Medium bedding thickness	Cohesionless subaqueous grain flows	Marginal lake
Other facies				
	Pyroclastic	Maroon, white, and mottled Fine grained Poorly bedded Devitrification and hematization prevalent		Localized pyroclastic flows
	Coal	Black Thinly bedded	Plant accumulation and compression	Shallow areas with abundant plant material
	Breccia and fissure fill	Dark grey shales of argillaceous micrite Fragments of fish, ostracods, eurypterids, gastropods and plants Locally containing angular rhyolite clasts	Fill of irregular subaqueous rhyolite surface	

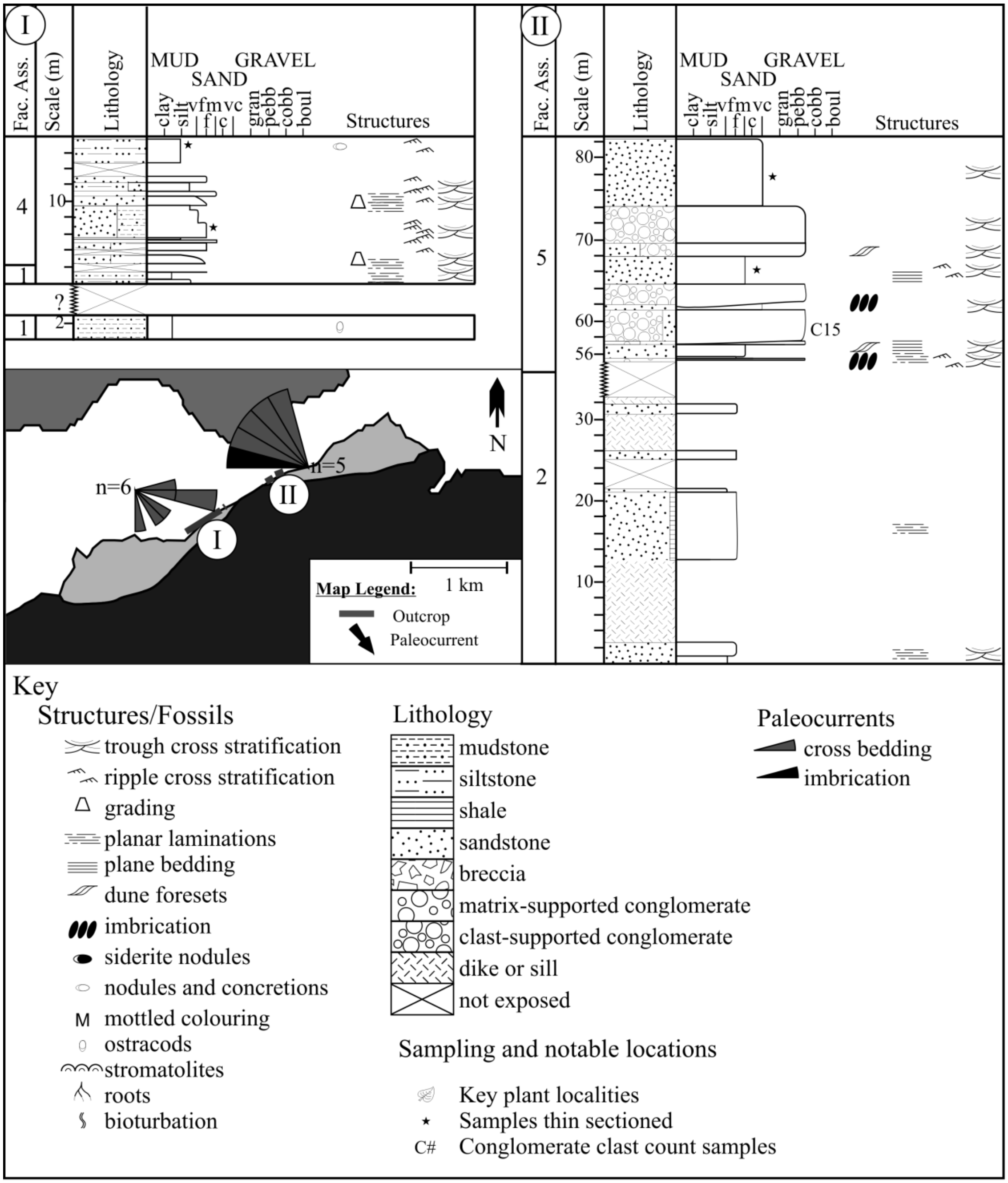


FIGURE 3.3: Western Belt stratigraphy, sedimentology, and paleocurrents. Circled roman numerals in inset map refer to section numbers. Plotted with SedLog v2.1.4.

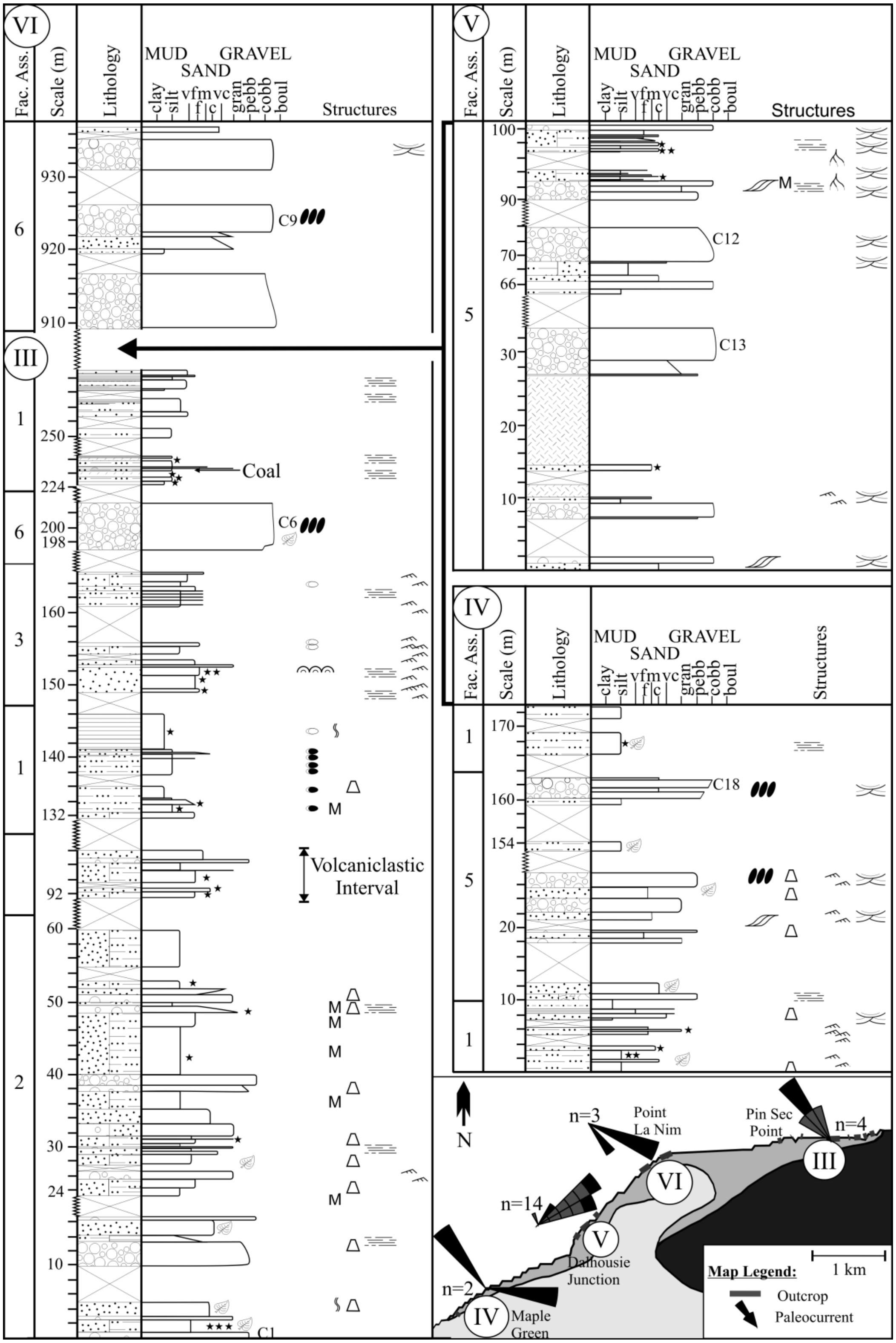


FIGURE 3.4: Eastern Belt stratigraphy, sedimentology, and paleocurrents. Circled roman numerals in inset map refer to section numbers. Note the large gap between III and VI is partially filled by sections IV and V. See Figure 3.3 for legend. Plotted with SedLog v2.1.4.

3.5 **Facies Associations**

Twelve facies were identified in the outcrops, including strata of mud to boulder grade (Table 3.1). They are described below, and interpreted in the context of six facies associations, which are distinguished by facies proportions (Fig. 3.5) in outcrop (Figs. 3.6, 3.7). Major facies are those that constitute over 20% of each association, while minor facies comprise from 5% to 20%. Facies associations are interpreted as 1) restricted lacustrine, 2) marginal lacustrine, 3) near-shore lacustrine, 4) coastal-deltaic, 5) sandy to gravelly alluvial plain and 6) gravelly proximal alluvium. As discussed below, a few faunal elements in the basal part of the western outcrop belt may have a marine affinity, but strata elsewhere are interpreted as terrestrial due to the absence of such taxa, as well as the lack of any clearly marine sedimentological features. Here, "lacustrine" refers to any landlocked body of water, regardless of scale, and thus includes both large lakes with well-developed stratification, and pond-like lakes, that are much smaller.

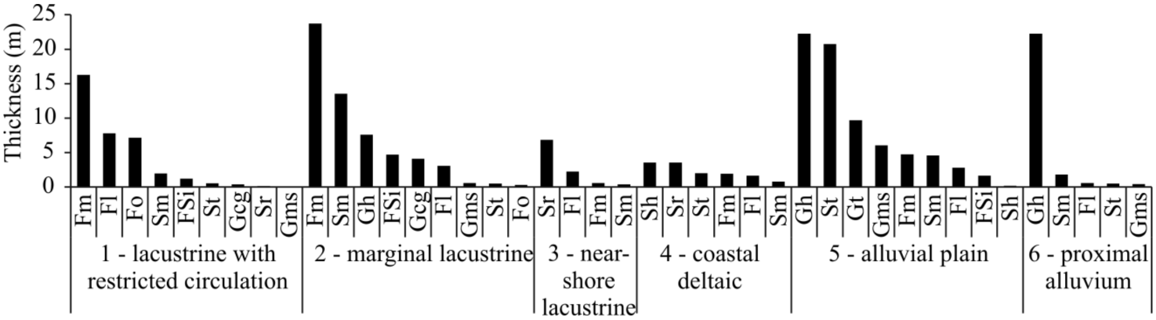
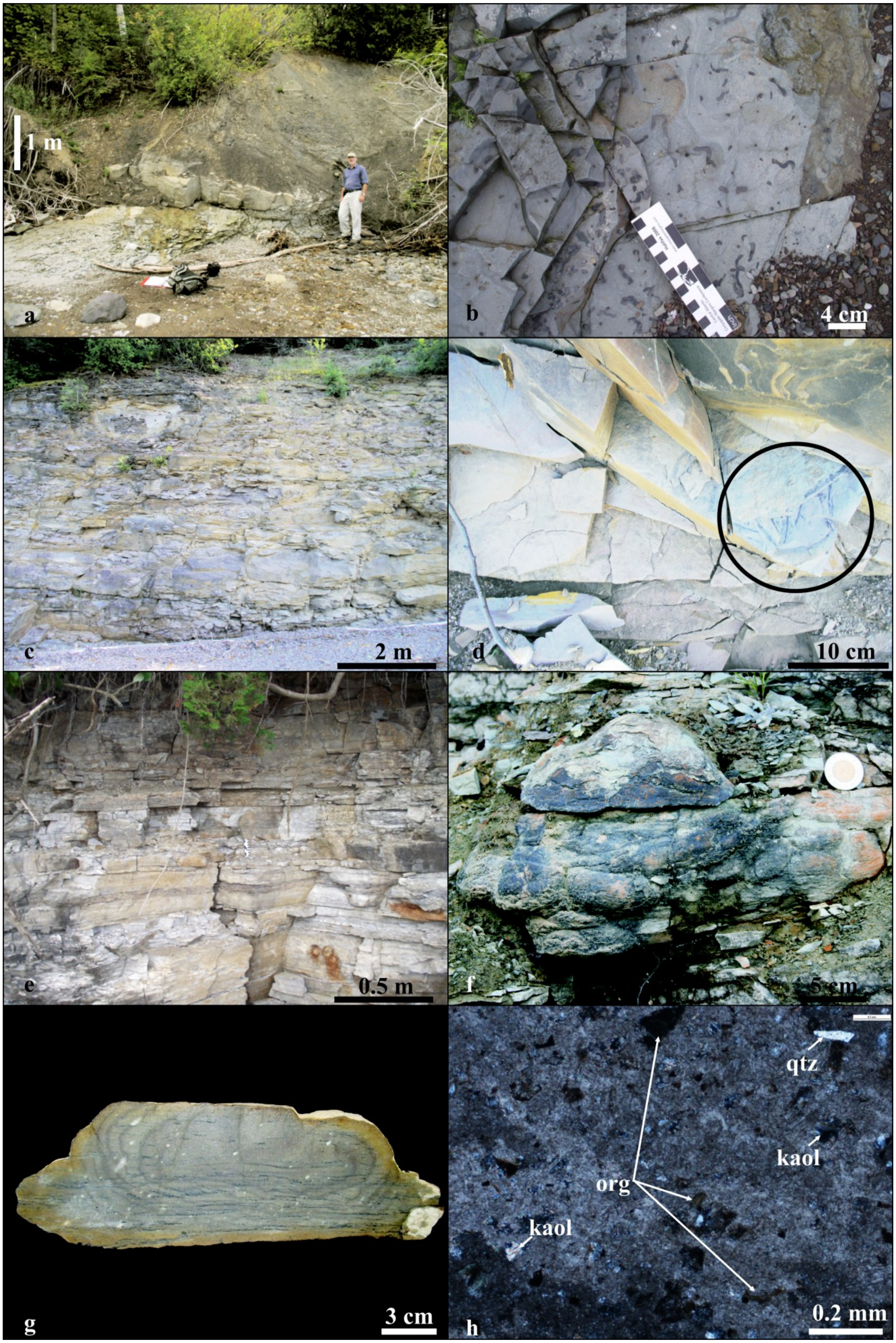


FIGURE 3.5: Facies proportions within each facies association. See Table 3.1 for facies codes.

FIGURE 3.6: Photo plate of features seen in associations 1-3. A) Association 1 deep lacustrine with restricted circulation showing dark, friable shales (facies Fo), poorly exposed in upper bank. B) Bedding plane view of siderite nodules in deep lacustrine facies association showing the unusual elongate and sinuous shape of nodules. C) Association 2 marginal lacustrine beds. Note lenticular form of grey and red siltstone and sandstone beds (facies Fm and Sm), which are generally massive and medium bedded. D) Association 3 marginal lacustrine beds showing bedding surfaces of siltstone (facies Fl) with abundant well-preserved plant material (circled). E) association 3 tabular nearshore beds of ripple cross-laminated sandstone (facies Sr) with finer interbeds of siltstone (facies Fl). F) Microbialite dome shown in outcrop within association 3. G) Cross section through microbialite, showing flat top and internally flat-lying to slightly wavy laminae with low mounded forms and one prominent set of ripple cross-lamination. H) Photomicrograph of an association 3 microbialite in cross polarized light. Quartz grains (qtz), kaolin-group minerals (kaol), organic detritus (org) are indicated.


1 m
a
b
4 cm
c
2 m
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10 cm
e
0.5 m
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g
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org
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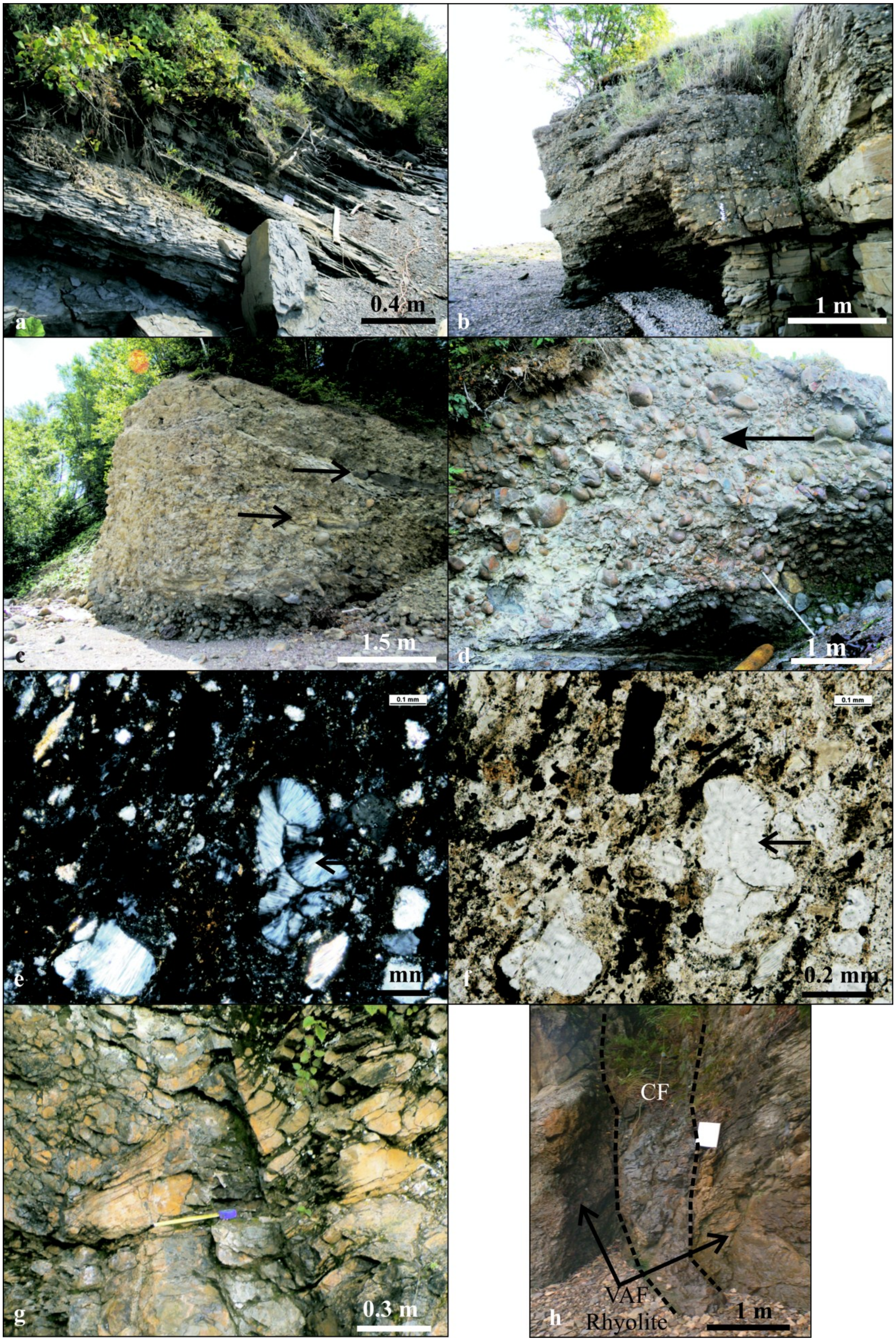
h
0.2 mm

FIGURE 3.7: Photo plate of features seen in associations 4-6. A) Association 4 coastal-deltaic beds, with interbeds of ripple cross-laminated sandstone (facies Sr), horizontally laminated sandstone forming some well-cemented units (facies Sh), and recessive units of mudstone (facies Fm and Fl); the topmost exposed bed is a unit of Sr and Sh with an erosive base, representing a small distributary channel. B) Association 5 braided river beds in section II, comprising interbeds of weakly stratified clast-supported conglomerate (facies Gh) and trough cross-bedded sandstones (facies St, at base of exposure). C) Association 6 hyperconcentrated flow deposits at Pin Sec Point, showing stacked, poorly defined units of cobble to boulder conglomerate (facies Gh); arrows point to isolated sandy lenses containing plant debris (facies Sm), which define the tops of gravel units laid down during high-flow events. D) Well imbricated hyperconcentrated flow deposits comprising only volcanic clasts at Point la Nim with arrow indicating direction of paleoflow inferred from imbrication. E), F) Photomicrographs of vermiform kaolin-group minerals under cross-polarized and plane-polarized light, respectively, arrows point to large book of vermiform kaolin-group crystals. G), H) Brecciated and fissured (dashed line) unit representing the contact between the Val d'Amour Formation (VAF) and fissure fill shales with fish fragments (not visible) of the Campbellton Formation (CF).


a
0.4 m
b
1 m
c
1.5 m
d
1 m
e
0.1 mm
mm
f
0.1 mm
0.2 mm
g
0.3 m
CF
VAF
Rhyolite
h
1 m

3.5.1. Facies Association 1: Lacustrine with Restricted Circulation

Description

Thin occurrences of association 1 are found in sections I, III, and IV, consisting primarily of fine-grained facies Fm, Fo, and Fl (Fig. 3.6a). Facies Fm is a thinly to medium bedded grey siltstone to very fine sandstone with a massive to weakly graded texture. One interval of this facies contains abundant siderite nodules 2-5 mm in diameter, arranged in an unusual vermiform pattern where elongate and sinuous black nodules appear on discrete planes in a homogeneous to slightly graded grey siltstone (Fig. 3.6b). Facies Fl contains grey and red siltstone and fine sandstone with planar laminae defined by finely comminuted organic material and slight grain-size variations. Beds may include rare plant fragments as long as 10 cm. Facies Fo includes dark grey to black, finely laminated mudstone and siltstone with carbonaceous material, in units that may be several metres thick. Thin sections show compressed layers of organic material, with pods of claystone, less than 0.75 mm wide and 0.3 mm high, alternating with bands of siltstone. Carbonized films derived from plant fragments are the source of most of this carbonaceous material, and plant axes can still be discerned in several beds. Rare beds of trough cross-bedded and massive sandstone (facies St and Sm), as well as lenses of coarse to fine sandstone (FSi), are present locally. Two low-rank coal seams, each less than 10 cm thick, are also included within this association.

Interpretation

Horizontally laminated siltstone and mudstone, where laminae are sharp and preserve organic debris, are characteristic of a basinal lacustrine environment (Gaylord et al. 2001). Such associations are frequently recognized in deep-water, ancient lacustrine successions containing massive to laminated black mudstones with silty laminae deposited as distal turbidites (Changsong et al. 1991; Basilici 1997; Gaylord et al. 2001; Cas et al. 2001). Reducing conditions during times of stably stratified deep water would have preserved organic matter in chemical isolation, until mixing events re-oxygenated the deep waters. The original water depth could not be established for the facies association, although the prevailing fine grain size suggests fairly deep water (Fig. 3.6a). However, some occurrences, particularly in proximity to fluvial beds, could represent stagnant pond-like settings in a fluvial landscape. In such a setting, plant and terrestrial arthropod material would have collected under conditions of restricted circulation and with few significant sources of siliciclastic detritus other than rare density flows of facies Sm or flood events of facies St (Nichols and Uttamo 2005). The two coal seams in particular were probably deposited in a shallow pond with rafted plant debris. Since the coal occurrences are isolated exposures, and in one case in contact with a sill, their stratigraphic context is not clear.

3.5.2. Facies Association 2: Marginal Lacustrine

Description

Association 2 is the most voluminous component of the Campbellton Formation, making up a large portion of section III. The most representative occurrence of this association is near McNeish in a cliff section (Fig. 3.6c) where 37 m of decimetre- to metre-thick beds are lenticular over distances of metres to a few tens of metres, and are frequently interrupted by minor faults. This association is dominated by massive siltstone and sandstone of facies Fm and Sm. Both facies consist of red, grey, or red and grey mottled strata in medium beds with massive to graded textures and sharp, planar to broadly lenticular contacts. Coarser lenses within these beds are rare, but where present are usually granule conglomerate. Siltstone and sandstone units are poorly sorted with hematite-coated grains (in reddish coloured rocks), a clay-rich matrix, numerous unidentifiable organic fragments, and grains that are almost entirely altered to kaolin-group minerals (confirmed using an electron microprobe; Appendix 2). Megascopic plant fragments in either facies are rare, and are typically less than 1 cm long. At one locality, fragments up to 30 cm long were present both throughout beds of a grey and pink siltstone, and concentrated on bedding planes (Fig. 3.6d).

Minor constituents, from most abundant to least abundant, include facies Gh, FSi, Fl, and Gcg, which introduces considerable heterogeneity into this association, in marked contrast to facies association 1. The first of these, facies Gh, is a granule to pebble conglomerate in thin to medium lenticular beds that commonly fine upward. Clasts here are well rounded, typically highly altered volcanic lithologies, and the conglomerate is cemented by calcite. Facies FSi contains interbedded lenses 1-6 cm thick of coarse sandstone and fine conglomerate in siltstone or fine sandstone. Comminuted plant fragments are common, and a maximum fragment length of 15 cm was observed. Facies Fl is a grey laminated siltstone to very fine sandstone, with common plant fragments of length 2 cm or less, and more rarely up to 15 cm. Facies Gcg is a granule conglomerate containing distinctive platy clasts of a variety of original volcanic lithologies, some with relic flow-banding textures and devitrified groundmass, altered to hematite, clays, and carbonate. The conglomerate beds commonly incorporate 1-2 mm muddy lenses, and show an erosional base. Finely laminated, organic-rich beds of facies Fo, which are characteristic of facies association 1, are rare.

Interpretation

This association is interpreted as a marginal lacustrine association, occurring somewhat offshore but generally above the oxycline. A marginal setting is supported by numerous coarse-grained beds (in contrast with deep-water association 1 beds), a lack of ripple cross-lamination suggesting a depth below wave base, and the prevalence of red, grey, and mottled massive and graded siltstone and sandstone (facies Fm, Sm) which suggests settling from suspension through a well-mixed water column. Conglomerates are commonly reported in ancient lake sequences with hydrothermal activity, likely related to adjacent tectonically active terrain, resulting in underflows of high-density turbidity currents and sediment-gravity flows (Gaylord et al. 2001; Bohacs et al. 2000). Plant fragments in several facies were probably from nearby plant stands, either washed in during floods, or slumped and buried rapidly by suspensional fall out and sediment-laden underflows. Facies Association 2 resembles strata described by Gürel and Kadir (2008) from a lake margin that had thickly bedded red mudstone interbedded with thin conglomerates and sandstones, degraded minerals, and intensive alteration producing clay minerals.

3.5.3. Facies Association 3: Near-Shore Lacustrine

Description

Association 3 was found only in a single 16 m interval of section III (Fig. 3.6e), where it consists predominantly of facies Sr and Fl. Facies Sr comprises grey coarse siltstone to medium sandstone with asymmetric ripple cross-lamination, defined by finely comminuted organic material accumulated in troughs and on the lee faces of ripples. Although section III is mainly detrital with planar, laterally continuous beds of siliciclastic material, it has a significant calcareous component in the form of microbialite formations within facies Sr (Fig. 3.6f-h). These internally very weakly or unlaminated leiolites (sense of Riding 2000) were coalescent, low domal forms up to 10 cm tall and 30 cm in diameter with a mammillated surface. They occur in discrete levels where up to 10 dome-forms can be seen along a 20 m bedding surface. Internally, fine, discontinuous laminae with cross-laminae are present in some instances (Fig. 3.6g), with some poorly developed convex-up surfaces, but internal stratification is generally cryptic. Numerous plant fragments less than 2 cm long appear to have been trapped inside the stromatolites near the base and in laminae. Thin sections of the microbialite revealed that the majority of the sample consists of patchy large anhedral calcite crystals with only minor detritus that includes organic material, rounded quartz grains, pitted feldspar grains, and vermiform kaolin-group minerals (Fig. 3.6h). The great predominance of carbonate within these bodies strongly supports a microbial, rather than a purely concretionary, origin. Facies Fl is interbedded with the rippled facies, and differs mainly in the finer grain size of siltstone to very fine sandstone. Both facies Sr, Fl, and minor facies Fm contain cm-scale calcite nodules.

Interpretation

The prevalence of current-rippled sandstone, transported plant fragments, and microbialites point to a relatively shallow depth of deposition compared to previously-discussed facies associations. Microbialites are a common feature of both modern (Winsborough et al. 1994) and ancient (Link et al. 1978) shallow lacustrine environments. The association of these domal microbialites with cross-laminated siliciclastic beds may indicate periods or areas of low sediment influx which would have permitted microbialite growth (Link et al. 1978). The large proportion of carbonate minerals to detritus suggests that these were essentially skeletal stromatolites made by calcite-secreting microorganisms, similar to thrombolites (Kennard and James 1986).

3.5.4. Facies Association 4: Sandy Coastal-Deltaic

Description

Association 4 includes most beds in section I, referred to previously as the “Atholville Beds” (Dineley and Williams 1968) or “Atholville Member” (Gamba 1990) (Fig. 3.7a). This association consists predominantly of facies Sh and Sr. Facies Sh is typically a buff-grey fine to medium sandstone with thick intervals of planar laminae that truncate underlying ripple cross-laminated beds. Facies Sr consists of fine to medium sandstone with thick beds of ripple cross-lamination including climbing ripples, and calcite nodules.

Minor facies are St, Fm, Fl, and Sm which are repetitively interbedded with the thicker sandstone bodies. Facies St commonly has an erosional base, and occasionally contains scattered pebbles, while facies Fl shows some weak current-ripple lamination.

Facies Fm and Sm are broadly lenticular units that include beds with shark spines, placoderm plates, eurypterid fragments, and scattered plant fossils up to 5 cm in length (Miller 1996, 2007a, 2007b). Nearly all beds contain abundant comminuted plant material.

Two general packages of strata can be recognized, alternating on a scale of several metres: broadly channelized coarser bodies, and interbedded fairly planar beds of mudstone and sandstone. The channel-like units include coarser, thicker units of Sh and Sr, and show erosive features such as the truncation of climbing ripple sets by 20-30 cm sets of planar lamination. The associated interbedded mudstone and sandstone units lack clear channel geometry, and consist primarily of 2-10 cm thick alternate beds of either facies Sm or St with Fm. Although distinct thinning or thickening upwards trends of bedding are not clear, bedding thicknesses alternate on a 50 cm scale between 2 cm thick beds of sandstone and mudstone, and 5-10 cm thick beds of sandstone with 1-3 cm beds of mudstone.

Interpretation

The association includes beds deposited by moderate to high energy current flow, with transported terrestrial fossils, articulated and disarticulated aquatic fossils, mild channelling, and massive fine-grained units that represent suspensional settling. This suggests a sandy deltaic environment with distributaries avulsing and shifting over time, creating the alternation between channel sandstones and interdistributary planar mudstones and sandstone, similar to a proximal mouthbar association (Pollard et al. 1982; Farquharson 1982).

3.5.5. Facies Association 5: Sandy to Gravelly Braided Alluvial Plain

Description

Association 5 occurs in sections II, IV and V, characterized by near-equal proportions of major facies Gh and St (Fig. 3.7b). Facies Gh is a granule to cobble grade clast-supported conglomerate, found in thick lenticular beds with weak horizontal stratification caused by grain size changes, and with local development of imbrication. Sandy lenses, with transported plant fragments, are common in nearly all exposures. Facies St is a grey medium to coarse trough cross-bedded sandstone, commonly with erosional contacts with the unit below. Plant material is abundant on many exposed surfaces, and is usually comminuted, but it is also common for fragments up to 7 cm long to be preserved.

Minor facies are Gt, Gms, and Fm. Facies Gt is much like facies Gh, but is typically more structured, containing clear scours, cross-stratification within clast-bearing beds, and sandstone lenses. Beds in facies Gms are more poorly sorted with only weak stratification, and are typically 25-75 cm thick. Facies Fm is interbedded most commonly with facies St. In several beds in section V, facies Fm shows signs of pedogenic development with small glaebules 1-2 mm in diameter and rooted horizons with near-vertical rooting structures that penetrate a few millimetres into the substrate.

Several important distinctions between association 5 beds in the eastern and western belts were noted. In the western belt (section II), sublithic arenites (largely facies St and Sh) form uninterrupted units up to 3 m thick with trough cross sets typically 20-40 cm thick. These are cut by channel fill units of cobble conglomerate (Gh and Gt) up to 4 m thick. Facies Gh contains laterally extensive sandstone sheets up to 10 cm thick, locally at low angles to bedding. Facies Gt contains some solitary planar-cross sets up to 1 m thick, with down flow-dipping foresets. There are almost no mudstone beds.

In contrast, eastern belt association 5 beds (sections IV, V) tend towards poorer sorting, with fewer well-developed bedforms, and a significant mudstone component. Units of both conglomerate and sandstone are rarely thicker than 1 m, arranged in 4-10 m thick bodies. Sandstone units are poorly sorted, feldspathic wackes with poorly-developed ripple cross-sets a few centimetres thick. Conglomeratic beds have erosional bases, but do not display concave-up channel forms cut into the underlying sandstones, and can be traced laterally with minor thickness variation at the outcrop scale. The steep orientation of bedding in this region (as high as 58°) as well as poor exposure complicates efforts to determine bedding morphology or cross bedding direction, and consequently most units were classified as Gh, since cross-stratification was not evident. Mudstone, in the form of facies Fm, is a significant component, forming poorly indurated organic-rich beds that can be over 1 m thick, with well indurated thinner beds in areas of possible pedogenesis. Data on paleocurrents and clast provenance provide another means of discrimination between outcrop belts, and are discussed below.

Interpretation

Association 5 represents a braided alluvial plain environment. Terrestrial sedimentation is supported by the occurrence of a shallow, weakly developed soil horizon at one location, and an abundance of organic material in sandy bedload deposits and floodplain mudstones. The overall association has comparable proportions of facies as the humid tropical alluvial system described by Evans (1991) who characterised sheet-like gravel bedload stream deposits in the Chumstick Formation of Washington State, USA, as having 50% conglomerate (mainly Gh with lesser Gt), 40% sandstone (mainly Sm, and Sh with lesser St, and sandstone with low-angle lamination) and only 10% mudstone.

Section II in the western belt shows evidence of strong flood events that deposited thick successions of facies St, Sr, and Sh sandstone, which were eroded by broad channels filled with facies Gh and Gt conglomerate. Units of Sh represent upper plane-bed sedimentation, implying rapid flow and/or shallow depth, and the abundance of gravel indicates high flow competence. Units of dominantly Gh are repeatedly interstratified with lenses of sandstone that represent shallow channels filled during waning flow, implying that high flow events were intermittent, and Gt is interpreted as the deposits of channel-base dunes and unit bars within channels. There are no signs of fine-grained floodplain deposits or lateral accretion structures. Fluvial systems with this range of features and style of sedimentation can be broadly matched with braided rivers in western Canada, including parts of the Kicking Horse River, Donjek River, and the South Saskatchewan River (Williams and Rust 1969; Hein and Walker 1977; Cant and Walker 1978). None of these modern rivers provides an ideal analogue for facies association 5, in part because the proportions of sand and gravel vary considerably within reaches of these modern systems and also because they are fed in part by snowmelt.

Fluvial sections IV and V in the eastern belt can also be compared to modern gravel-bed braided rivers, but may be considered as shallower, lower energy systems, perhaps more distal or less confined than those of section II. Features that support this interpretation include the presence of fine sediment containing abundant plant material deposited in inactive tracts (facies Fm, Fl, or FSi interbedded with thin layers of facies Sm, or St during floods), immature feldspathic sandstones, and shallow channel beds in the active tract (Rust 1978). Some sandier units resemble thin, extensive flood successions from central Australia (Williams 1971).

3.5.6. Facies Association 6: Gravelly Proximal Alluvium

Description

Association 6 is found in sections III and VI, and is characterized by the predominance of facies Gh (Fig. 3.7c). Gh here differs from other occurrences primarily in having a cobble to boulder clast size, with boulders up to 70 cm in intermediate diameter. Imbrication may be well-developed, as in section VI, or weak, as in section III. Units 4-6 m thick have poorly defined beds 1.5-3 m thick, with some heterogeneity in matrix content tending towards remarkably well-rounded clasts that are poorly sorted and clast supported. Sandy lenses 30 cm thick are present and contain scattered pebbles, grading, lamination, and plant fossils. Facies Sm is a minor constituent, and appears as thick beds of coarse sandstone with weak grading and scattered pebbles.

Interpretation

This association may be considered to have formed in a higher energy, more proximal alluvial environment than association 5, with high-density flows of large cobbles and boulders that have already undergone significant rounding. The presence of weak stratification, local imbrication, and clast support suggest at least a partly fluidized transport mechanism, as opposed to a cohesive debris-flow deposit (Benvenuti and

Martini 2002). The random to weak clast fabric, moderately to poorly sorted texture, and lack of cross stratification is characteristic of hyperconcentrated flows where clasts are carried in an interstitial fluid of water and sediment (Smith 1986). Similar deposits are common in volcanic settings, alluvial fans, fluvial settings, and proglacial areas where there is abundant sediment available and water discharge can be high volume, flowing rapidly, and highly seasonal.

3.6 **Provenance**

Clast counting techniques were used to compare conglomerate clast provenance through the formation. Proportions of 9 major lithologies are illustrated in Figure 3.8 with the associated counting error at 95% confidence. Although the counting error is high, from this, it is apparent that igneous (mostly volcanic) material predominates in four samples, and forms about half the clasts in two other samples. The sample from the conglomerate in the western belt (C15) is lithologically more diverse than samples from the eastern belt, with significant amounts of quartz and felsic porphyritic or phaneritic igneous lithologies. Beds at stratigraphically higher locations (C9, C12, C13) have a greater proportion of intermediate igneous lithologies than those lower in the section (C1, C18), which have proportions of siliciclastic lithologies or felsic porphyry that exceed the porphyritic intermediate lithology. Sample C6, although stratigraphically lower than sample C18, bears similarities to samples C9, C12, and C13.

Paleocurrents, presented in the inset maps of Figures 3.3 and 3.4, were not uniform. In the western belt, they show two opposing directions of flow, with imbrication and dune-scale foresets in association 5 fluvial strata (section II) directed to the northwest and trough cross-beds and ripple cross-sets of association 4 deltaic strata (section I) building to the east and southeast. In the eastern belt, paleocurrents deduced from weak conglomerate imbrication and trough cross-bedding generally shift from the northwest (association 6 in section III and association 5 in lower section IV), to east and northeast in association 5 section IV and V, respectively, to southeast in association 6 (section VI) up section. Because of a paucity of paleoflow indicators, these paleocurrents are not statistically rigorous, but to compensate, only well-developed features were measured.

In summary, the eastern belt paleoflow patterns suggest that the lowermost lacustrine successions contain hyperconcentrated-flow deposits transported to the northwest, probably shed from a proximal source. The younger and more westerly fluvial successions developed east-flowing drainage, probably along axial basinal systems, with hyperconcentrated debris shed from the north, probably from the conjugate basin margin. These results are consistent with westward and northward paleocurrents in the LaGarde Formation (Gamba 1990) and southward paleocurrents in the Pirates Cove Formation (Rust et al. 1989), both located to the north of the Campbellton Formation. The results are also consistent with the prevailing stress regime due to the Acadian Orogeny as implied by the NE-SW orientation of major fold hinges in the Gaspé Belt. There appears to be no strong correlation between paleoflow directions in the conglomerates, and clast lithology.

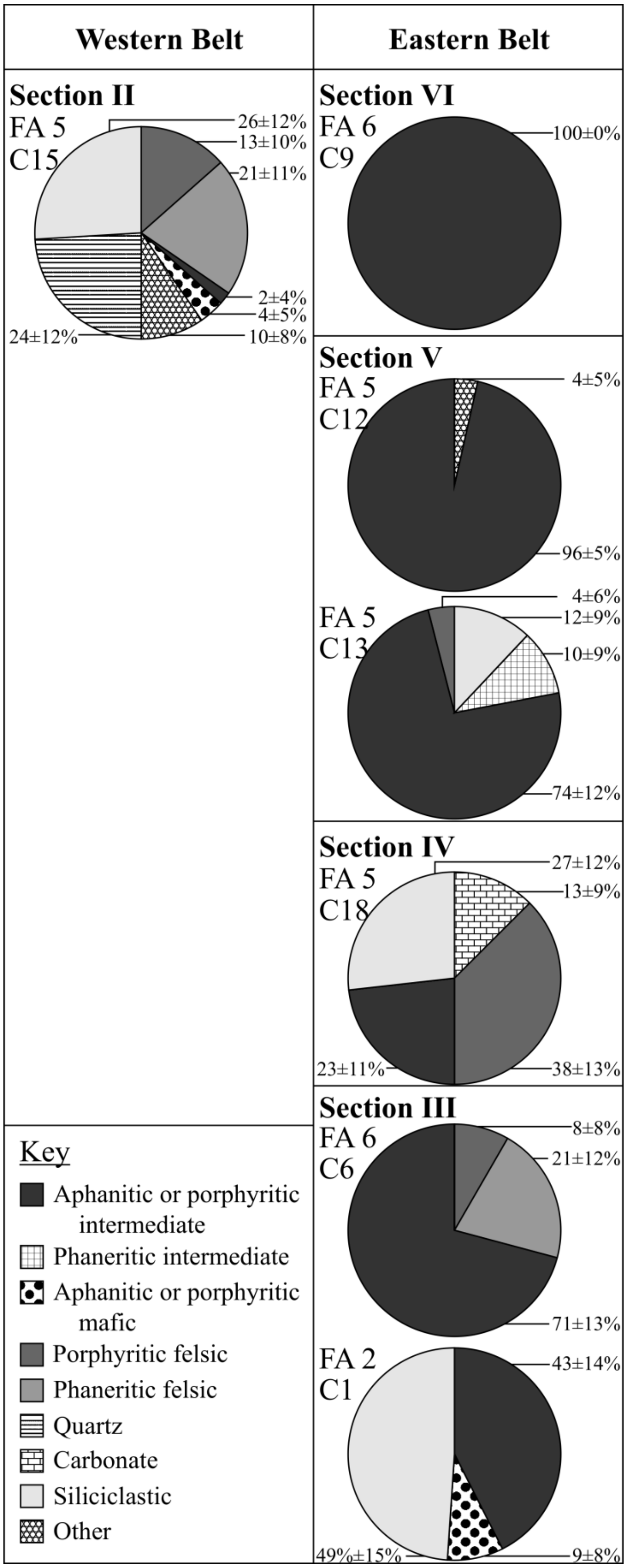


FIGURE 3.8: Proportions of lithologies found as clasts within conglomerates. See Figures 3.3 and 3.4 for locations of each sample within the stratigraphic column.

3.7 Alteration

As noted above, Campbellton Formation sandstones and conglomerates are predominantly volcaniclastic in composition. Some intervals of section III (facies associations 2 and 3) show intensive alteration clearly visible under a petrographic microscope. Included amongst the alteration products are significant amounts of large vermiform kaolin-group crystals (Fig. 3.7e, f) with a composition of $Al_2Si_2O_5(OH)_4$ confirmed through electron microprobe analysis. This mineral replaces detrital feldspars in every thin section cut from beds below 165 m, but was rare in the rest of the formation. In one instance, kaolin-group minerals form clasts in a pebble conglomerate with carbonate cement. Formation of authigenic kaolinite occurs during diagenesis, during which meteoric fluids that are rich in organic acids or CO_2 may dissolve feldspar and promote kaolinite precipitation (Lanson 2002). Alteration of lake sediments to clay minerals that include kaolinite, smectite and illite has been observed in lakes where an acidic environment for alteration was created by leaching of basement rocks and this may have been the case here (Gürel and Kadir 2008).

Igneous sills in section III showed pervasive alteration to carbonate and chlorite, to the point where the original mineralogy is completely obscured. Carbonate alteration is abundant in the lower parts of section III and in the Atholville breccia, particularly affecting rhyolite clasts with relict glassy or flow-banded igneous textures.

3.8 Western Belt Stratigraphy and Paleoenvironments

The western belt has three main areas of outcrop; the basal contact, section I near Atholville, and section II near Campbellton (Fig. 3.3).

The western belt contains the stratigraphically lowest strata, including an exposed contact with the underlying Val d'Amour Formation rhyolite, that is located between sections I and II. This contact is a highly brecciated and fissured angular unconformity (Fig. 3.7g, h; Wilson et al. 2005), overlain by angular and exclusively rhyolitic clasts in a dark micritic matrix that contains gastropods, ostracods, eurypterids, plants, spores, and fish (Whiteaves 1881; Jones 1889; Woodward 1892). The underlying rhyolites have dips of up to 70°, much higher than the 21-33° observed in the western belt of the Campbellton Formation, and an age of 407.4 Ma compared to a mid Emsian spore age of the Atholville beds (Wilson et al. 2004; McGregor 1989 in Gamba 1990), suggesting a hiatus of about 5 million years. Previously, this contact has been described as subvertical (Gamba 1990), or as a bed of breccia with the same attitude as the Campbellton Formation beds (Dineley and Williams 1968). Here we consider the contact to be a fissured and uneven rhyolite surface that was drowned and filled with pockets of breccia with weak layering consistent with the attitude of Campbellton Formation strata. In mudstones above the brecciated rhyolite and fissured zone, ostracodal micrite with plant material is present, but other fossil material is sparse.

Section I is dominated by strata of association 4, interpreted as a coastal deltaic sequence with ESE paleoflow. These beds contain both aquatic fauna and plant fragments, most often within massive siltstone; however, it is difficult to determine if this delta was feeding into a lacustrine, brackish, or marine environment. The acanthodian genus *Ankylacanthus* is considered predominantly a marginal marine taxon, living in shallow water deltas, estuaries, and lagoons, but other early gyracanthids are also found in terrestrial waters (Turner et al. 2005; Burrow et al. 2008). Gastropods *Cyclora* *valvatiformis* and *C. imbricata* (Whiteaves 1881) have been identified as nonmarine (Morris 1985), and the ostracods *Primitia mundula* and *P. scaphoides* are also probably nonmarine (Gray 1988). However, rare occurrences of prasinophytes (Blieck and Cloutier 2000) and acritarchs (McGregor 1989; in Gamba 1990) have been reported, suggesting brackish water or marine incursions. The frequency of well-preserved plant fossils, as well as the proximity of section I to clearly fluvial section II strata, suggests that if this were a marine environment, it was marginal.

Section II contains beds of associations 2 and 5. The finely laminated beds of association 2 were poorly exposed and only accessible at low tide, and were intruded by lamphrophyre dikes and sills; consequently, any environmental interpretation is tentative. However, beds of association 5 are well exposed in cliff sections with trough cross-stratification of both sands and gravels, repetitive sandy lenses in pebble-cobble conglomerates, and channel bodies. This outcrop of association 5 is unlike fluvial beds in the eastern belt. Sediments are texturally more mature, with well sorted sublithic arenite and polylithic well-rounded conglomerates. Imbrication indicating a northwesterly paleoflow suggests that a paleotopographic high lay between this section and the eastern belt, where fluvial strata tend to record paleoflow generally to the east.

3.9 Eastern Belt Stratigraphy and Paleoenvironmental Synthesis

3.9.1. Mainly Lacustrine Sedimentation: Section III

Section III is the most complete and most extensive section, recording 259 m of mainly lacustrine strata. The contact with the underlying Val d'Amour Formation is not exposed, but regional mapping suggests that it closely underlies the lowermost exposures, without any indication that faults are present. The lake basin is bordered by the alluvial Pirate Cove and LaGarde formations to the north and the older Val d'Amour Formation to the south, yielding a present-day width of no more than 6 km. However, there are no clear constraints to the east and west, and it is uncertain how far the lake basin may have extended. The basal 98 m consists entirely of association 2, representing a thick marginal lacustrine succession. Lower lacustrine beds contain laminae rich in the particularly well preserved carbonized films of plant fragments in massive siltstone, probably transported and buried by density flows. Important plant taxa include *Drepanophycus spinaeformis*, *D. gaspianus*, *Psilophyton princeps*, *Sawdonia acanthotheca*, and *Zosterophyllum divaricatum* and these probably lived on the lands immediately surrounding the lake basin (Gensel and Andrews 1984). The presence of conglomerate lenses suggests a steep-sided basin (Bohacs et al. 2000) possibly with ongoing tectonism and deepening that caused conglomerates to become less common upwards. Siltstones and very fine sandstones are clay-rich with abundant authigenic kaolin-group minerals. The predominance of advected terrigenous material with plant debris, rather than autochthonous evaporites or carbonates, suggests that this lake lay within a hydrologically open basin where sediment and water input exceeded the rate of tectonic subsidence (Bohacs et al. 2000).

Above association 2, there is evidence of active volcanism at one exposure where microscopic analysis shows intensively altered and devitrified felsitic fragments, fiamme, and angular porphyritic grains. In outcrop, these are poorly bedded red and white strata, 10-30 cm thick, commonly with leached rinds around grains. These were probably small localized pyroclastic flows. Although the bulk of sediment in the Campbellton Formation are resedimented volcaniclastics, no evidence was found to suggest active volcanism at any other location.

Deepening of the lake basin at 132 m culminated in association 1 deposits passing upsection from massive grey siltstones with siderite nodules, to well laminated dark-coloured mudstones. The upward transition in this section suggests a progressive deepening and chemical isolation of the basin from oxygen. Although siderite nodules are rare in modern lake sediments, they have been found in deep lakes where CO_2 and Fe^{+2} have accumulated to high concentrations (Bernard and Symonds 1989). The most prominent bed of dark shale, several metres thick (Fig. 3.6a), lacks well-preserved plant material, which may indicate deposition at some distance from the shore.

At 149 m, evidence for shallowing occurs in the transition from deep water shale to ripple cross-laminated siltstone and sandstone of association 3. The presence of mound-like carbonate microbialites suggests shallow water during periods of limited clastic supply, possibly away from major sediment point sources.

A cobble-boulder conglomerate unit of association 6 is found at Pin Sec Point with weak imbrication showing paleoflow to the northwest and crude stratification with at least five thick sandy lenses (Fig. 3.7c). This conglomerate is reported to contain large clasts of *Prototaxites* (Boyce et al. 2007). Specimens of *Drepanophycus spinaeformis* and *Psilophyton princeps* were recovered from coherently transported blocks of interbedded sandstones and shales (Li et al. 2000) and *P. coniculum* from within clasts of the conglomerate which may have been eroded from older formations (Trant and Gensel 1985).

Above this conglomerate there is a return to fine-grained strata of association 1 where organic material accumulated to form at least two 9 cm thick planar coal-like seams. These beds would seem to represent shallow ponds with little sediment influx aside from rafted organic debris. Two igneous sills (heavily altered to calcite) intruded these beds, with one directly in contact with one of the coal seams.

3.9.2. Mainly Alluvial Sedimentation: Sections IV, V, VI

Fluvial intervals are better developed to the west and higher in the section, although they may be considered to begin as low as the first association 6 appearance. Variations in strike within beds of section IV and V make accurate placement relative to sections III and VI difficult, but an estimate is shown in Figure 3.9.

Section IV near Maple Green is a complex sequence, yet holds a great deal of importance to paleobotany as these beds have yielded a more diverse, well-preserved, plant assemblage than the lacustrine localities. Thickness estimates of non-exposed intervals suggest that the measured section lies several hundred metres above the formation base (Fig. 3.9). This section contains points A, B, and C of Andrews et al. (1974), and locality F of Gensel and Andrews (1984) where plants have been collected by a number of authors (Andrews et al. 1975; Gensel et al. 1975; Doran et al. 1978; Johnson and Gensel 1992; Wellman and Gensel 2004; Gensel and Kasper 2005; Gensel and Albright 2006; among others). Abundance and diversity of plants in these outcrops is generally higher than in lacustrine facies (Gensel and Andrews 1984). In addition two myriapod specimens *Gaspestria genselorum* and *Eoarthropleura* as well as fragments of mesoscorpian cuticle were found (Shear et al. 1996; Wilson 2006). Exposure is discontinuous and beds are typically poorly indurated. The lowermost 30 m probably represents localized ponds of association 1 within a highly vegetated landscape, trapping sediment and permitting thick mats of plant cuticle to accumulate amongst rippled sandstones and graded beds. There are no evident rooted horizons, but the good preservation suggests that these remains were not far travelled and may be considered parautochthonous. The remainder of the section alternates between weakly imbricated fluvial conglomerates and floodplain siltstones rich in well preserved plant cuticles.

Section V near Dalhousie Junction is dominated by association 5 deposits. Imbricated conglomerates here show paleoflow to the northeast. Near the top of the section, evidence of rooted horizons with glaebules can be seen in an indurated purplish-grey siltstone interstratified with trough cross-stratified coarse sandstones that represent the fills of shallow channels; plant debris in this section is rare. This section contains the only clear evidence of paleosol development in the Campbellton Formation.

The uppermost beds are found in section VI at Point la Nim where association 6 cobble-boulder conglomerates create a headland. These conglomerates resemble those seen at Pin Sec Point, but are more strongly imbricated with a sense of flow to the east-southeast (Fig. 3.7d). Similar to Pin Sec Point, clasts are well rounded and volcanic in origin, and the conglomerate is crudely stratified.

Fine grained strata in these fluvial sections tend to be less altered than the siltstones of association 2 and 3, and more compositionally immature than the association 5 strata of the western belt. Angular feldspars in arkosic greywackes or siltstones are readily preserved without alteration to kaolin-group minerals, although localized chlorite alteration is common.

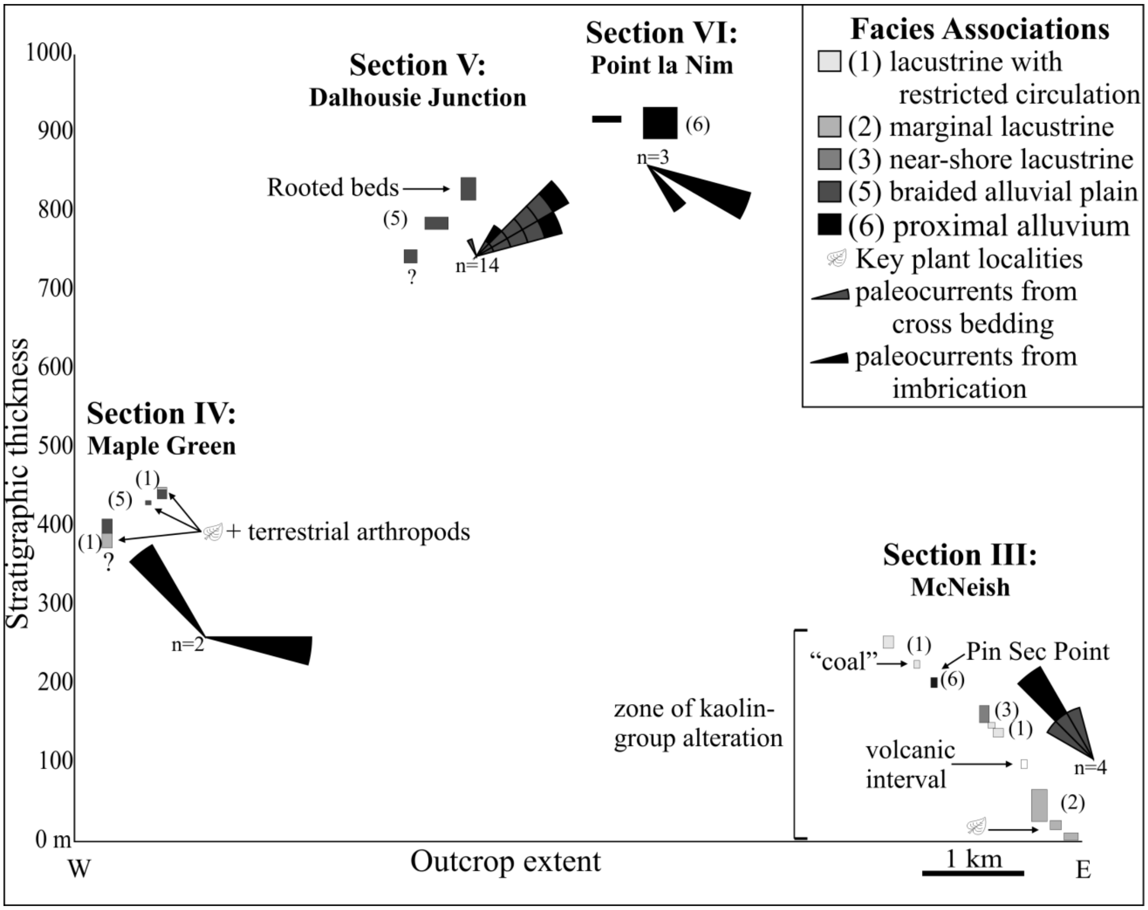


FIGURE 3.9: Schematic cross-sectional overview of the observable strata in the Campbellton Formation looking north. Shaded areas give a sense of the actual outcrop extent where height represents the stratigraphic thickness and width represents the lateral extent of outcrops, which has been exaggerated by 20% for visibility. Stratigraphic positions of sections IV and V relative to sections III and VI are approximations due to the variability of strikes within sections. Important plant localities, paleocurrents, and other notable features are indicated.

3.10 **Basinal Evolution**

There seems little reason to suggest that the western belt is closely related to the eastern belt, aside from a similar age as determined by spore and plant assemblages. In the western belt, the braided river system is polylithic with no axial floodplain deposits preserved. Paleocurrents are to the northwest, where flow may have fed into a body of water containing an aquatic, and possibly brackish, assemblage of fish and invertebrates. The stratigraphically equivalent beds in the eastern belt are primarily lacustrine with virtually all material having a volcanic provenance. This suggests that a topographic high separated the two belts during initial stages of deposition, perhaps as a result of a rough orogenic and volcanic landscape causing the two basins to have disparate sediment sources. The transition upwards from an intermontane lacustrine to primarily fluvial setting may reflect a decrease in subsidence rate with the cessation of the Acadian Orogeny, or an increase in sedimentation rate which led to basin-filling. Eastern belt association 5 fluvial beds with a prevailing paleoflow to the east include abundant fine floodplain sediments, organic-rich beds suggesting poor drainage with swampy areas, primitive soils, and a more immature clast assemblage. Intercalated with fluvial beds are association 6 hyperconcentrated flows, likely from a proximal source, with paleoflows at high angles to the generally eastward paleoflow of axial fluvial beds. We infer that the association 5 (and some association 1) beds represent axial drainage with hyperconcentrated flows washing transversely down the sides of the basin onto the alluvial plain.

In terms of a modern analogue, the general geologic setting of the Campbellton Formation is comparable with the continental collision between the Arabian and Eurasian plates at 13 Ma giving rise to Upper Miocene-Quaternary volcanic rocks throughout the Caucasus Mountain ranges and the eastern Anatolian plateau (Dilek et al. 2010). This region holds numerous, often fault bounded or lava-dammed lakes at a range of depths and altitudes. Lake Van at 38.5° N in eastern Turkey, provides an analogue for the lacustrine beds of the Campbellton Formation. Volcanic deposits occur to the north and west of Lake Van which is a closed lake basin reaching depths of 451 m (Degens et al. 1984). Unusually large microbialite features made by coccoid cyanobacteria can be found in shallow areas on the eastern and northern near-shore (Kempe et al. 1991). Lacustrine shelf sediments are being deposited at an average of 20 m depth in wide margins, and at up to 250 m depth on narrow margins. The shelf occupies 72% of the lake bottom surface area, characterized by geomorphic relicts of alluvial channelling and erosion that presumably represent periods of low lake level. Laminated beds are interrupted by turbidites, volcanic tuffs, and small lenticular subaqueous slump features (Degens et al. 1984). Sublacustrine slope and basin environments were also identified. Despite regular overturning events, sediment cores taken from depths of 17 m to 400 m were all from an environment with reducing bottom waters. Well-developed braided fluvial systems can also be seen in the Kura-Aras river basin with axial eastward flowing rivers draining into the Caspian Sea and with numerous proximal transverse tributaries.

In the Early Devonian weathering rates associated with the early stages of root evolution would have been modest, reducing nutrient cycling to lakes and oceans, and limiting the formation of paleosols, which makes the assessment of paleoclimate difficult (Algeo and Scheckler 1998). Sedimentation styles in fluvial systems of the Campbellton Formation are indicative of periodic high-intensity floods which may suggest seasonal discharge. A monsoonal climate was suggested for the Battery Point Formation in Gaspé Bay (Griffing et al. 2000). Although the environmental tolerances of taxa are poorly understood, thick accumulations of cuticular material may suggest humid conditions, with several plant taxa capable of dwelling in well drained proximal alluvium.

3.11 **Conclusions**

Two alluvial associations, three lacustrine associations, and a deltaic association were defined to describe the strata of the Campbellton Formation, which is largely Early Devonian in age and about 1 km thick. A western possibly brackish basin directly overlying the formation contact was confined by deltaic sediments to the west and fluvial conglomerates to the east, and appears to be lithologically and ecologically distinct from an eastern fluvial-lacustrine basin. The eastern basin received large amounts of volcanic debris, probably eroded from a rugged upland composed of the underlying Val d'Amour Formation, which likely contributed to rapid burial and fossilization of plant material. Here, a lower mainly lacustrine succession comprised largely marginal strata that preserve some evidence of the fluctuation of water levels, resulting in periods of deep water with restricted circulation, or shallow water conditions. Upwards, braided fluvial sediments with a plant-bearing floodplain and numerous small shallow ponds dominate. Axial braided systems are interrupted by transversely derived deposits of proximal alluvium in the form of boulder conglomerates, also bearing plant material. The strata formed within an intermontane basin during the closing stages of the Acadian Orogeny, although the tectonic context of the Campbellton Formation is not fully resolved.

3.12 Acknowledgments

This research was funded by a postgraduate scholarship to Kennedy from the Natural Sciences and Engineering Research Council of Canada (NSERC), an NSERC Discovery Grant to Gibling, and a Geological Society of America student research grant to Kennedy. The research benefited greatly from field consultations with Pat Gensel, Randy Miller, Reg Wilson and Bob Gastaldo, and we thank them for their helpful assistance. Reviews from Darrel Long and Guy Plint greatly assisted us in improving the manuscript. The authors thank Dan MacDonald for microprobe work, Gordon Brown for thin section preparation, and the residents of Dalhousie Junction for generously facilitating outcrop access.

CHAPTER 4 — PALEOENVIRONMENTAL INFERENCES FROM THE CLASSIC EARLY DEVONIAN PLANT-BEARING LOCALITY OF THE CAMPBELLTON FORMATION, NEW BRUNSWICK, CANADA

4.1 Abstract

The colonization of the terrestrial landscape by vegetation was a critical period in Earth history. Although this began as early as the Ordovician, the Early Devonian heralded an acceleration of diversity and dispersal across the landscape. The Emsian Campbellton Formation represents a subtropical basin comprising two parts: a coastal environment, and a fluvial-lacustrine intermontane environment. Although recognized for a rich fossil assemblage since the mid 19th century, this is the first attempt to correlate that fossil record with physical attributes of the environment as depicted by the sedimentology. Marginal lacustrine beds contain a parautochthonous collection of plants assumed to have been washed in from lakeside plant stands and buried by density flows. Shallow, oxygen-depleted lakes or ponds subjected to fluctuations in water level collected a more diverse assemblage from the surrounding flooded marsh than collected by the lake margin. Plants within fluvial sandstones were subjected to harsh, ephemeral conditions, and as such typically display poorer preservation. Although some plants showed adaptations to drier environments, there is little evidence of landscape partitioning as has been demonstrated in contemporaneous localities between rhyniopsids, trimerophytes, zosterophylls, and lycopsids, all of which are here found in nearly every identified setting. Plant occupation of upland areas is suggested by the occurrence of plant-bearing strata within blocks transported cohesively by hyperconcentrated flows.

4.2 **Introduction**

The Paleozoic colonization of the landscape by vascular plants was among the most significant transformations affecting the terrestrial realm. Evidence of land plants is found as early as the Ordovician (Wellman et al. 2003), but by the Early Devonian, continuing proliferation of vegetation began to profoundly influence global processes. The floral assemblage began diversifying through adaptations such as increased stature, rooting structures, lateral branches, and primitive leaves that together increased survivorship in a wider range of environments than was previously possible (Raymond 1987). Resultant vegetative cover affected Earth processes by contributing to a dramatic drawdown in atmospheric CO_2 (Mora et al. 1996; Berner 2003, 2006), stabilizing fluvial environments (Cotter 1978; Davies and Gibling 2010), and triggering ocean anoxic events (Algeo et al. 1995). At the same time, terrestrial ecosystems developed where nutrients were cycled between floral and faunal elements (Chaloner et al. 1991; Labandeira 1998, 2007). Throughout this initial radiation of tracheophytes, plant diversity remained low compared to the floral assemblages dominated by pteridophytes and gymnosperms that appeared in the Late Devonian (Niklas et al. 1983). Studying the terrestrialization of plants and the subsequent effects on Earth processes requires researchers to consider both paleoenvironmental and paleobiological factors by looking at snapshots of plant-bearing landscapes. Examples of this approach for Early Devonian localities include descriptions of the Cap-aux-Os Member of the Battery Point Formation on the Gaspé Peninsula (Griffing et al. 2000; Hotton et al. 2001), the Trout Valley Formation of Maine (Allen and Gastaldo 2006), and the Rhynie Chert of Scotland (Rice et al. 2002).

Here, we add the Emsian Campbellton Formation of New Brunswick to this list as an example of an intermontane fluvial-lacustrine environment. Relatively undeformed and unmetamorphosed, the formation contains a remarkable assemblage of early plants and some of the first coals on Earth, along with well-preserved fish and arthropods that have received attention from paleontologists since the mid 1800s. However, until recently, the lack of a detailed stratigraphic and sedimentological framework for the formation limited its usefulness for investigating the environments inhabited by Early Devonian biota. With such a framework now in place (Kennedy and Gibling, submitted), we discuss the ecosystem of the Campbellton Formation and the contribution of organisms across a range of paleoenvironments from alluvial fans to lowland river plains and lakes.

4.2.1. Location and Geologic Setting

A series of small coastal outcrops of the Campbellton Formation is found on the southern shore of the Restigouche River and Bay of Chaleur, New Brunswick (Fig. 4.1). Spore assemblages span the mid Emsian *annulatus-sextantii* assemblage zone (McGregor 1989 in Gamba 1990) to the late Emsian to early Eifelian *Grandispora* subzone of the *douglastownense-eurypterota* zone (Gensel and Andrews 1984; Richardson and McGregor 1986). The Campbellton Formation is one of the uppermost units of the post-Taconic Gaspé Belt, and directly overlies the Lochkovian to Pragian Val d'Amour Formation, which consists of a 6 km thick succession of terrestrial strata and subaerial volcanic rocks representing intraplate volcanism (Wilson et al. 2005). The deformation front of the Acadian Orogeny at 406-408 Ma (early Emsian) was located in central

Maine, striking NE-SW, and had progressed about 60 km northwards by 394 Ma (early Eifelian), likely overshooting the Restigouche area and causing active faulting and heightened topography in the region (Bradley and Tucker 2002). Plutonism occurred in the late Emsian (401 ± 1 Ma) in central New Brunswick, which provides a regional age for lithospheric thickening accompanying mountain building (McCutcheon and Bevier 1990). The clastic wedge produced by this orogeny in the foreland basin and in intermontane regions produced the Gaspé Sandstones Group, in which the Campbellton Formation is included (Rust et al. 1989). Although the Acadian Orogeny was responsible for the open folding of the Restigouche syncline (Wilson et al. 2004), there is little metamorphism or cleavage developed within the Campbellton Formation.

Several formations within the Gaspé Sandstones Group are roughly synchronous with the Campbellton Formation (Fig. 4.2). On the north side of the Restigouche River, the LaGarde and Pirate Cove formations consist mainly of alluvial deposits with southeastward paleoflows of alluvial fans, westward paleoflows of proximal alluvium, and northward paleoflows of distal alluvium, all shedding from surrounding topographic highs (Rust et al. 1989; Gamba 1990). About 170 km to the northeast in Gaspé Bay, the Battery Point Formation is interpreted as a coastal plain transitioning upwards through distal alluvium to proximal alluvium with paleocurrents that reflect westward migration of the Acadian Orogeny (Rust et al. 1989; Griffing et al. 2000).

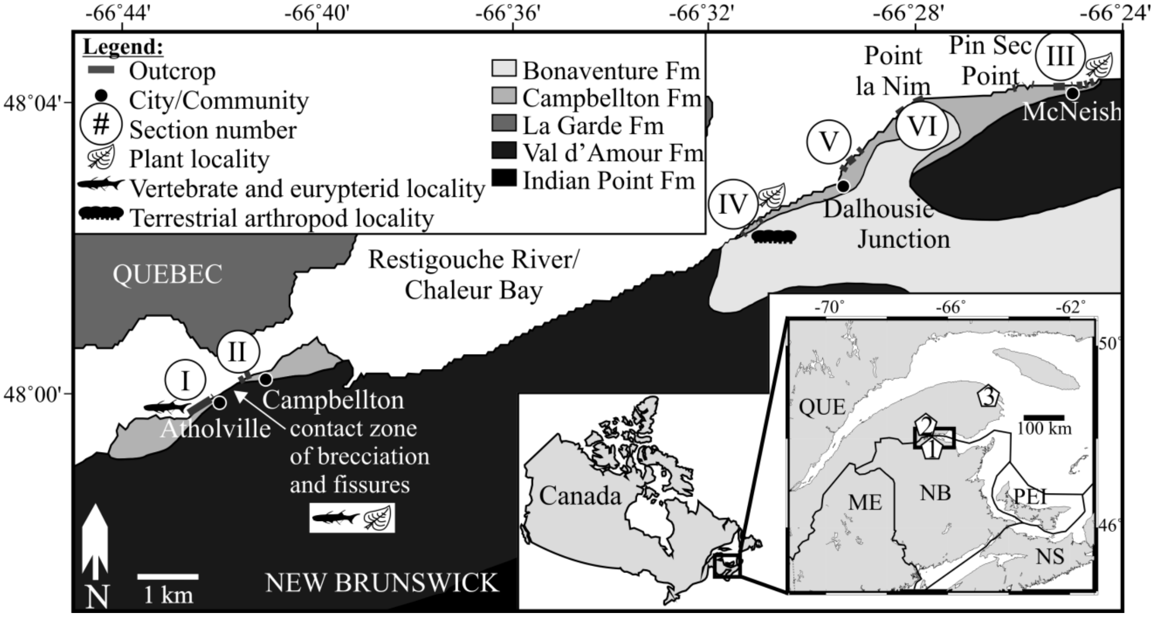


FIGURE 4.1: Geologic map of the Campbellton Formation and surroundings showing section locations and locations of major fossil localities. Geology from Wilson et al. (2004). Numbers in pentagons on the inset map refer to stratigraphic columns presented in Fig. 4.2. QUE – Quebec; NB – New Brunswick; NS– Nova Scotia; PEI – Prince Edward Island; ME – Maine, USA.

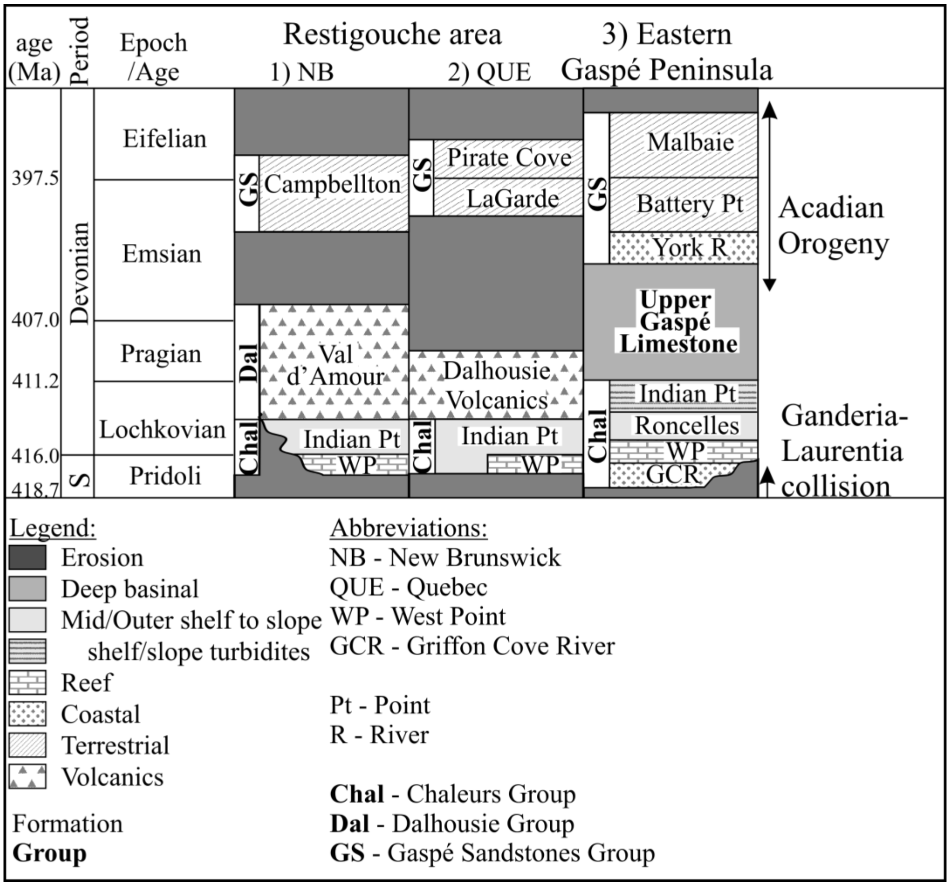


FIGURE 4.2: Pridolian to Eifelian Gaspé Belt stratigraphic correlation chart for three locations indicated on the inset map in Figure 4.1. Dates for age boundaries are from the ICS International Stratigraphic Chart 2009. Data for columns 1 and 2 are from Wilson et al. (2004); column 3 is modified from Rust et al. (1989) and Bourque et al. (2000).

4.2.2. Summary of Sedimentological Work

Beds of sandstone, shale, and conglomerate were first noticed cropping out on the southern shore of Chaleur Bay in a survey of the habitable and economic lands of New Brunswick by Gesner (1843). In the following half century, these beds were briefly mentioned in numerous field reports (Logan 1844, 1846; Ells 1881, 1883), and noted for their fossil assemblage (Dawson 1871; Whiteaves 1881). Ami (1900) later designated the outcrops as the Campbellton Formation, which was recognized by Alcock (1936) as belonging to the Gaspé Sandstones Group. Strata near Atholville were described and established as equivalent to parts of the LaGarde Formation on the northern shore of the Chaleur Bay by Dineley and Williams (1968). Gamba (1990) described mainly fluvial facies of a large swathe of outcrop including rocks that were later divided between the Val d'Amour, Campbellton, and LaGarde formations because of differences in age and geographical position.

The most recent treatment (Chapter III, Kennedy and Gibling, submitted) delineated six depositional settings (Table 4.1) complete with detailed stratigraphic sections reflecting sub-environments of a mainly fluvial-lacustrine system with possible marine connections. Two sub-basins were identified on the basis of lithological and paleobiological differences and paleocurrent data: the western belt (Fig. 4.3a) and the eastern belt (Fig. 4.3b). The western belt (sections I and II) directly overlies the formation contact and contains possibly brackish deltaic sandstones and siltstones to the west and braided alluvial plain conglomerates to the east. The eastern belt (Sections III to VI) is dominated by volcanic lithologies that fill an intermontane lake basin that transitions upwards to an alluvial basin with eastward paleoflows of axial braided alluvium and northward and southward transverse flows of proximal alluvium. Lacustrine strata were deposited in settings with restricted circulation, marginal settings at intermediate depth, and near-shore shallow water settings. It is from this study that the following discussion will build.

	Brief Description	**Interpretation**
1 – Lacustrine with restricted circulation	Massive or laminated siltstone, very fine sandstone, and beds enriched in carbonaceous material.	Low-energy deposition, reducing waters. May represent deep basinal waters with stable stratification or shallower stagnant waters.
2 – Marginal lacustrine	Lensing red and grey massive or graded siltstone and very fine sandstone interbedded with granule to cobble conglomerate.	High sedimentation rates and little subsequent reworking at intermediate depths.
3 – Near-shore lacustrine	Ripple and finely laminated tabular sandstone with microbialite layers.	Shallow water with weak wave action and low sedimentation.
4 – Coastal deltaic	Interbedded trough cross-stratified sandstone and mudstone, and lenticular-bedded sandstone with climbing ripples and planar laminations.	Shifting of distributary channels over time with periods of variable discharge.
5 – Braided alluvial plain	Horizontally bedded and trough cross-stratified granule to cobble clast-supported conglomerate interbedded with trough cross-stratified and planar laminated sandstone.	Broad and shallow braided channels subjected to frequent large-scale flooding events.
6 – Proximal alluvium	Cobble-boulder conglomerate with weak horizontal bedding and rare sandstone lenses.	High-energy hyperconcentrated flows where large volumes of sediment are remobilized by abrupt increases in water discharge.

TABLE 4.1: Summary of the facies associations of the Campbellton Formation.

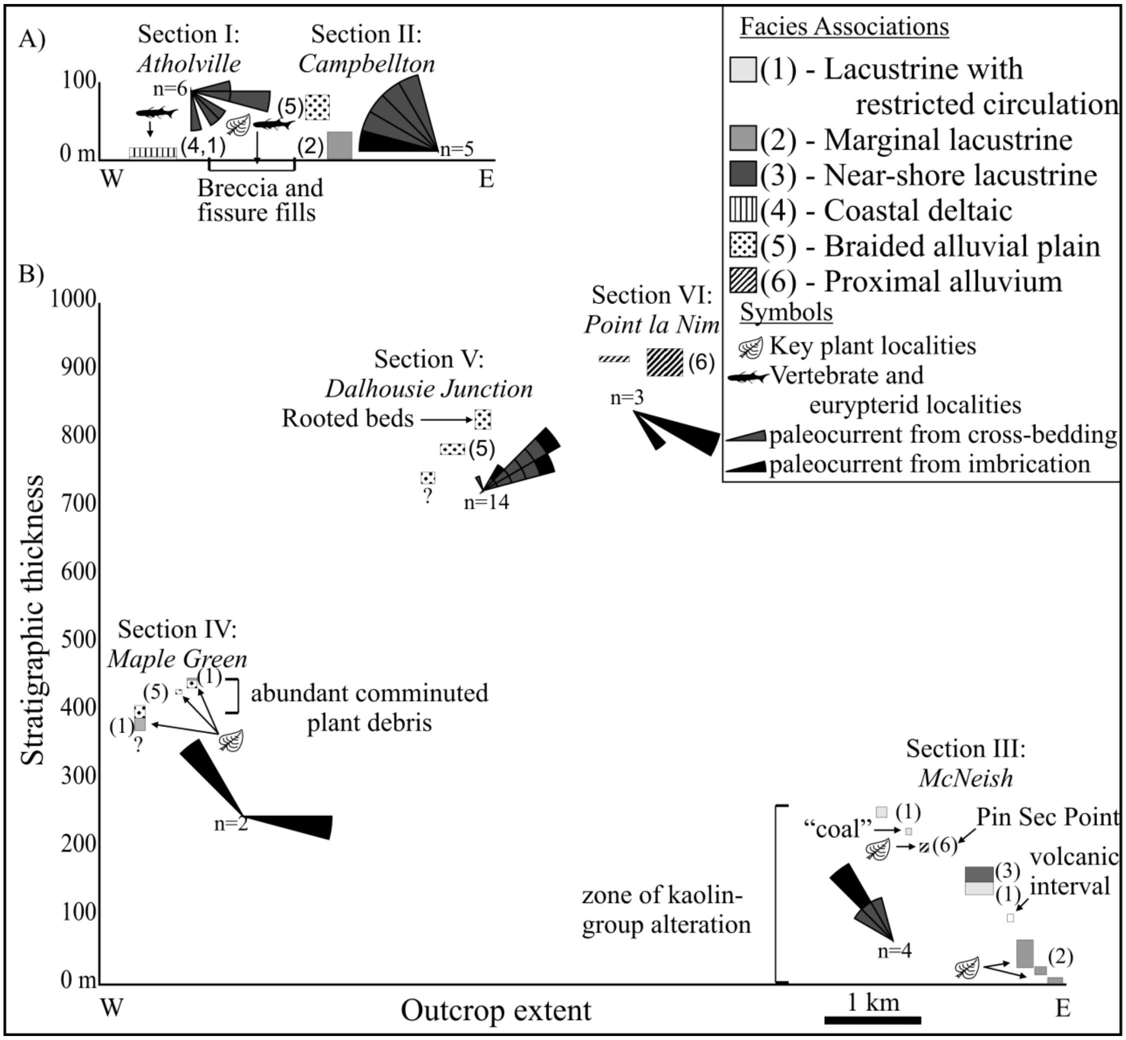


FIGURE 4.3: Summary of Campbellton Formation stratigraphy, geographical extent of outcrops, major fossil localities, and paleocurrents. A) The western belt. B) The eastern belt. Note that stratigraphic relationships between sections IV and V relative to sections III and V are uncertain, but approximations are shown. The geographic extent of each outcrop has been exaggerated by 20% for clarity. Data from Kennedy and Gibling (submitted).

4.2.3. Brief History of Paleontological Work

Interest in the fossils of the Campbellton Formation was instigated with the discovery of plant- and fish-bearing beds in the breccia near Campbellton. Dawson (1871) reported on several species of plant material within hard black shales, sandstones, and brecciated units. These are the same beds that were extensively sampled from in order to obtain the specimens identified by Whiteaves (1881, 1883), prompting a number of researchers to report on the vertebrate assemblage (Traquair 1890, 1893; Woodward 1892). It was not until the latter half of the 20th century that interest was renewed in plant-bearing beds and, for the first time, in beds located within the eastern belt (Hueber 1967; Grierson and Hueber 1967). Since then, new plant material has been regularly discovered, culminating in a rich floral assemblage comprising representatives of each of the three prominent Emsian clades: rhyniopsids, trimerophytes, and lycophytes (including both zosterophylls and lycopsids) (Gensel and Andrews 1984 and references in Tables 4.2, 4.3). Given the extensive body of literature on the fossil discoveries of the Campbellton Formation, and the newly completed sedimentological descriptions, we now have an opportunity to offer a more complete environmental reconstruction than has previously been possible.

4.3 **Methods**

Detailed observations of the sedimentology and stratigraphy were made during two field seasons in the summers of 2009 and 2010, as described in Kennedy and Gibling (submitted). Semi-quantitative information on plant fragments included the maximum fragment length visible in a unit, the quality of preservation as fragmental, comminuted, or matted, and the frequency rated as rare, common, or abundant. Fragmental plant material was well preserved as carbonized films several centimetres in length, comminuted plant material was present as mm-scale plant debris, and matted plant material occurred where numerous plant axes compressed upon themselves to make flakey layers of carbonized films. Identification of plant taxa relied on descriptions of plant localities within the published literature (references in Tables 4.2, 4.3) as well as in-field identifications made by P. Gensel. Thin sections were cut of 37 rock samples to determine petrography.

4.4 **Paleoenvironments at Key Fossil Localities**

Three main fossil localities will be referred to in this paper: sections I, III, and IV to correspond to Kennedy and Gibling (submitted). A thorough description of facies associations, sections, and outcrop localities can be found in that work. Sections not discussed in detail here (sections II, V, VI) are generally poor in macrofossils, but contribute to the overall basinal assessment.

4.4.1. Section I and Basal Breccia

The beds of the western outcrop belt near Campbellton and Atholville contain a diverse fossil assemblage of plants, vertebrates, molluscs, and arthropods. Many of these can be found in a basal breccia composed exclusively of rhyolite clasts in an indurated grey calcareous mudstone, which marks an angular unconformity with the underlying Val d’Amour Formation. Rhyolite in the upper Val d’Amour Formation has been radiometrically dated to the uppermost Pragian (407.4 ± 0.8 Ma) (Wilson et al. 2004) whereas the lowermost Campbellton strata have a mid Emsian spore assemblage (McGregor in Gamba 1990) suggesting a hiatus of approximately 3-5 Ma. During this time, the rough and uneven rhyolite surface was tilted, submerged, and filled by Campbellton Formation muds and organisms (Fig 4.4a).

The breccia passes upward into plant-, fish- and ostracod-bearing sandstone beds that have been largely lost through present day coastal erosion. Plant specimens include fragments of the trimerophytes *Psilophyton princeps* and *Trimerophyton robustius* and the lycopsids *Drepanophycus spinaeformis* and *Leclercqia complexa* (Dawson 1871; Hopping 1956; Grierson and Hueber 1967; Gensel and Albright 2006), suggesting that this locality was in close proximity to land. The plants were transported either by air or on water to a low-energy environment where they could settle through the water column without excessive mechanical degradation.

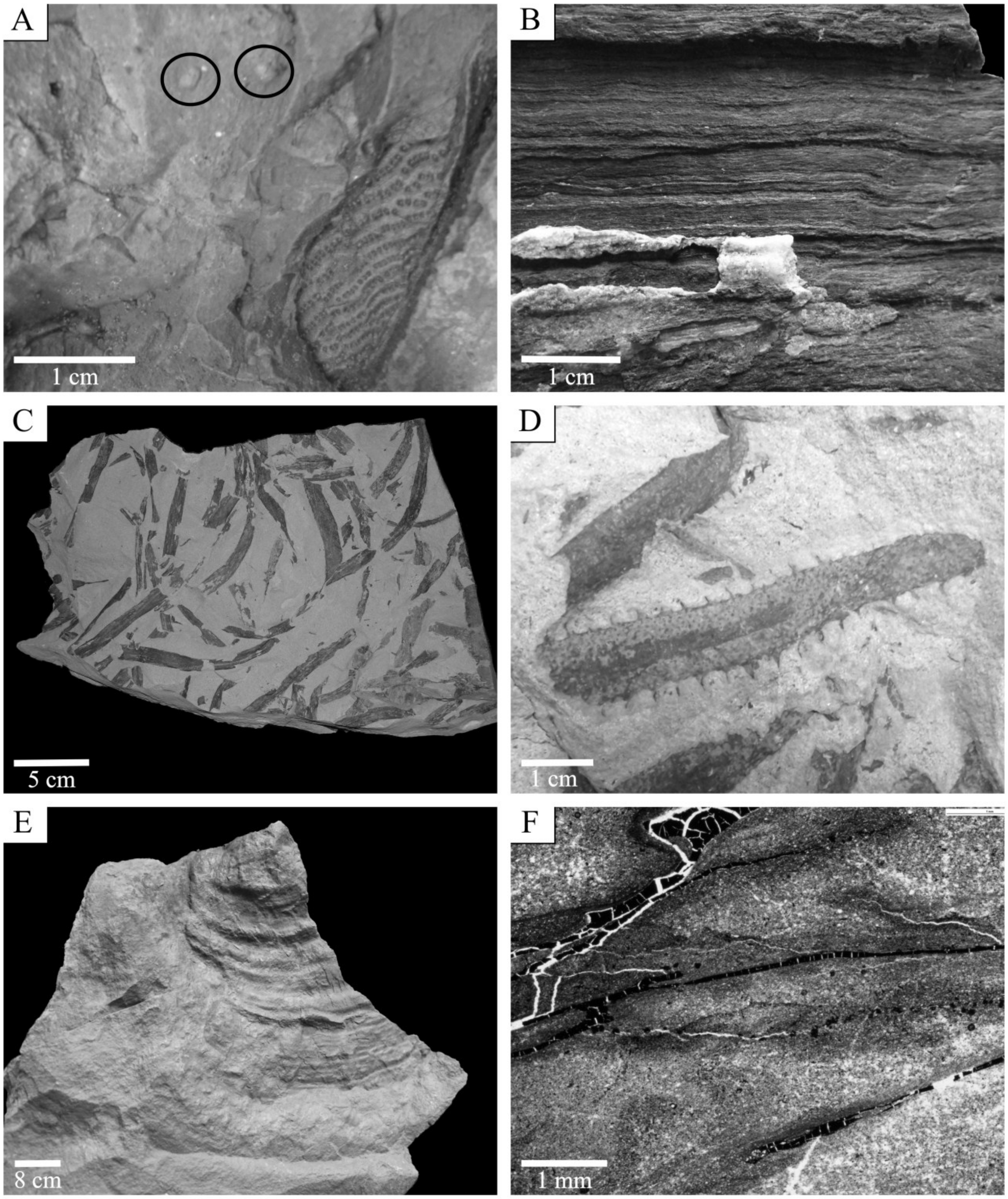


FIGURE 4.4: Examples of fossilization within the Campbellton Formation. A) An impression of a dermal plate fragment of a fish in the mudstone matrix of the breccia unit near Atholville, NB. Ostracods are circled. B) Finely laminated coaly rock from section III showing dark laminae of tracheophyte cuticle and pale laminae of silt. C) Carbonized compression fossils of *Taeniocrada* cf. *dubia* in the lower beds of section III with a moderate degree of axis alignment. D) Apical region of *Sawdonia* sp. illustrating exceptional preservation of enations and a trace of the vascular strand. E) Putative scratch circle. F) Photomicrograph of a plant-bearing unit from the lower siltstone beds of section IV where grain size decreases with proximity to plant axes.

4.4.2. Section III

Section III incorporates a series of outcrops from the community of McNeish to about 200 m west of Pin Sec Point (Fig. 4.1). Although there are many intervals of non-exposure, the similarity of strike through the area allows a single stratigraphic section to be constructed (Fig. 4.5). Paleoenvironments include a restricted lacustrine setting where poor circulation at depth led to oxygen depletion, a marginal lacustrine setting that represents an intermediate depth between the near-shore and lake centre, a shallow near-shore environment with microbialite growth, and a proximal alluvial setting with coarse hyperconcentrated flows (Fig. 4.3) (Kennedy and Gibling, submitted). Plant debris is preserved as comminuted material within nearly all of these settings, and also as large well-preserved fragments in the marginal lacustrine deposits and proximal alluvium, as discussed below. Two coal seams (Fig. 4.4b), each less than 10 cm thick, noteworthy as being among the oldest coals known, are located in an isolated outcrop interpreted to represent a restricted lacustrine setting, and warrant further consideration.

The lower strata of this section (Fig. 4.5) are nearly equivalent stratigraphically to the Section I beds, but are sedimentologically distinct and contain many well preserved plant compression fossils. The strata are characterized by lenticular interbedded conglomerates and red and grey coarse siltstones, the latter containing compression fossils of plants. The siltstone beds are composed of up to 70% clay-rich matrix with coarse-silt-sized clasts of quartz, pitted feldspar, and carbonate, along with large amounts of fine-sand-sized authigenic vermiform kaolin-group minerals and organic detritus. The clay-rich matrix commonly contains hematite in mottled and solid red siltstones, but in these beds, details of plant morphology have commonly been destroyed. Interbedded conglomerates contain clasts of very well-rounded volcanic and siliciclastic rock types. Plant debris delineates very fine, faint lamination in siltstone beds. Well-preserved large fragments up to 30 cm long are found throughout siltstone beds, often with a preferred axis alignment (Fig. 4.4c, 4.4d). A list of specimens found in these marginal lacustrine beds can be found in Table 4.2. On the beach below these outcrops, a loose slab bore markings that resembled a scratch circle made by a flexible, anchored organism, but it is not clear from where in the section it came from, or what kind of organism made it (Fig. 4.4e).

The sediment source region was predominantly volcanic as demonstrated through sandstone and conglomerate lithology, in accord with proximity to the Lochkovian-Pragian Val d'Amour Formation and Dalhousie Volcanics (Wilson et al. 2004). When considered with contemporaneous regional mountain building of the Acadian Orogeny, the coarse volcaniclastic deposits suggest that steep topography surrounded the basin. As such, sediment was readily available and rapidly transported from the land surrounding the lake to the lake margin by sediment-laden underflows and suspensional settling, which would have brought lake-side plant taxa into the lake.

A second noteworthy plant locality occurs upsection at Pin Sec Point where a cobble-boulder conglomerate 6 m thick protrudes to form a slight headland. This conglomerate exhibits weak imbrication in a few lenses, suggesting paleoflow to the northwest, and at least five major coarse sandstone lenses, and is interpreted as a series of hyperconcentrated flows. Large plant-bearing blocks of interbedded shale and sandstone that appear to have been transported cohesively as part of the flow (Hueber 1967) are visible among the conglomerates only at extremely low tides. These blocks contain spores in the *annulatus-sextantii* spore zone, which is contemporaneous with the rest of the formation, and are reported to contain moderately aligned, two and three-dimensional carbonized films of *Drepanophycus spinaeformis* with rhizomes and *Psilophyton princeps* (Hueber 1967; Li et al. 2007). Within the conglomerate itself, fragments of *Prototaxites* have been found (Hotton 2001; Boyce et al. 2007 and specimens in the New Brunswick Museum), as well as aligned permineralizations of *P. coniculum* isolated from within carbonate clasts (Trant and Gensel 1985). This unusual assemblage of plant-bearing blocks and carbonate clasts in a boulder conglomerate suggests a derivation from the slumped banks and paleosols of upstream regions, possibly within the adjoining uplands.

Organic-rich facies containing the aforementioned coal seams are also found within this section among heavily altered igneous sills and carbonaceous siltstones. The seams are planar, low rank, and are devoid of any well preserved macroscopic plant remains. Plentiful coalified material was present in loose blocks on the beach, suggesting that more coal horizons may exist under the overburden. The outcrop is interpreted to represent infilling of shallow ponds where plant debris accumulated in calm stagnant waters with minimal detrital input.

	Taxon	**Lacustrine (L) or Alluvial (A)**	**Reference**
Tracheophytes			
Zosterophylls	*Zosterophyllum divaricatum*	L	Gensel 1982a
	Sawdonia acanthotheca	L	Gensel et al. 1975
Trimerophytes	*Psilophyton princeps*	L, A	Hueber 1967
	Psilophyton coniculum	A	Trant and Gensel 1985
Lycopsids	*Drepanophycus spinaeformis*	L, A	Grierson and Hueber 1967; Li et al. 2000
	Drepanophycus gaspianus	L	Grierson and Hueber 1967
Rhyniopsids	*Taeniocrada* cf. *dubia*	L	P. Gensel, this study
Other			
	Spongiophyton minutissimum	L	Gensel et al. 1991
	Pachytheca	L	Gensel and Andrews 1984
	Prototaxites	A	Hueber 2001

TABLE 4.2: Fossils reported within section III beds. Attribution of lacustrine or alluvial represents the inferred paleoenvironment of plant-bearing beds, as set out in Kennedy and Gibling (submitted).

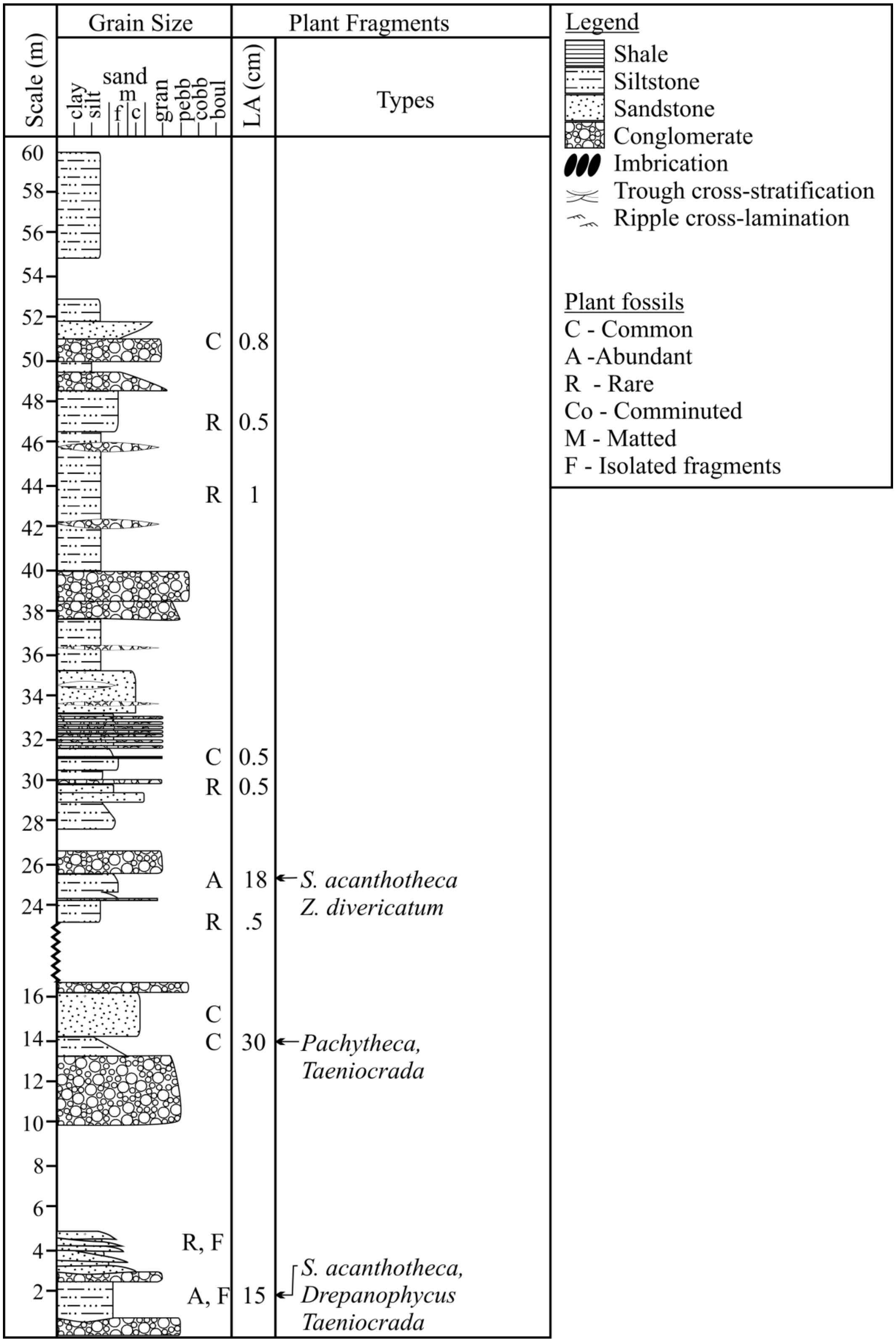


FIGURE 4.5: Stratigraphic log of beds in the marginal lacustrine facies association of section III showing sedimentological features and plant occurrences. LA – long-axis length of plant fragments.

4.4.3. Section IV

The third important plant-bearing section is section IV (Fig. 4.6a) in which poorly indurated outcrops are exposed sporadically west of Dalhousie Junction and east of Maple Green from 066° 31.309' W to 066° 30.912' W (Fig. 4.1). Two main environments are found here: a low-energy setting representing shallow stagnant water, and a high-energy fluvial setting. There is no evidence for *in situ* vegetation in these outcrops, nor are there obvious signs of subaerial exposure surfaces where vegetation may have grown. All plants reported from these outcrops are listed in Table 4.3, most of which are placed at least to a generic level into appropriate beds (Figs. 4.6a-c).

The lower and upper parts of this section are considered predominantly shallow lacustrine beds surrounded by wetland. These are characterized by black, green, and grey shales and occasional lithic greywacke lenses with alteration of detrital minerals to chlorite. Plants are preserved primarily in three lithologies: green or grey micaceous siltstone with plant fragments isolated in the matrix, black paper shales of matted organic material, and fine to coarse interlensed sandstones (Figs. 4.6a, b). The siltstones consist of 30-60% matrix clays with clasts of muscovite, quartz, and plagioclase. In thin section, sediment tends to fine towards the isolated plant axes (Fig. 4.4f), suggesting a preliminary coating with mud during transportation.

Although some beds contain a monospecific floral assemblage, most were multispecific. Both vegetative and fertile specimens were found, sometimes within the same layer. Matted organic layers preserve plant axes with little sediment between compressions, sometimes preserving axes that have retained enough strength to be extracted from the matrix. These observations and the high degree of preservation suggest low oxygen levels to prevent degradation, low sedimentation rates, and short distances from growth stands of dense vegetation. Greenish-grey sandstone lenses, no thicker than 30 cm at maximum width and extending several metres laterally, with faint cross-lamination and isolated plant fragments several centimetres in length, may represent low-energy channels that traversed the wetland. All plant materials appear transported but, given the level of detail preserved, they evidently were not subjected to extensive mechanical or biological degradation during transport, or exposure to oxygen after final deposition (Spicer 1989). One outcrop (Locality F of Gensel and Andrews 1984) that in the past was highly productive, producing *Loganophyton dawsoni*, *Oricilla bilinearis*, a spiny *Psilophyton* species, *Drepanophycus spinaeformis*, *D. gaspianus*, *Bitelaria dubjanskii*, and *L. complexa*, appears to have been lost through coastal erosion, but from descriptions (Gensel and Albright 2006) it is assumed to closely resemble the basal beds of section IV.

Taken as a whole, the sedimentary facies are similar to those described for water-saturated floodplains and shallow marshy ponds (Wing 1984; Bashforth et al. 2010). Limitations in organic matter accumulation from plants in this setting meant that no peat formed, so these herbaceous plants grew in a mineral-substrate marsh where fluctuating ground and surface waters interacted directly with sediment and were thus probably alkaline with high nutrient availability (Zoltai and Vitt 1995). Thin layers of paper shale may point to periods of low rainfall and high evaporation where little runoff resulted in low sedimentation rates (DiMichele and Gastaldo 2008), but humid conditions likely prevailed for much of the season such that the water table was above the horizon of plant burial in order to maintain anoxia (Gastaldo and Demko 2011). Two coarsening upwards sequences, 1.5 m to 2 m in thickness, are recognized in Fig. 4.6b that may represent infilling of shallow hollows in the wetland.

The mid portion of section IV has characteristics of a braided-fluvial environment with lenticular imbricated conglomerates, trough cross-stratified sandstones, and fine floodplain material. These strata are similar to those seen in section V where purplish siltstones contain traces of rooting structures, but where few macrofossils of plants are seen. Again, because of sporadic outcrop, sizable parts of the stratigraphic column are missing and others are isolated, making contextual interpretations imprecise. Nearly all plants here are preserved as isolated fragments with long axis lengths of up to 15 cm within trough cross-stratified or thin graded, very fine sandstone beds. One small stream-cut outcrop of grey siltstone contains six named taxa with specimens commonly preserved at 10-20 cm in length. These strata likely represent a return to a low-energy, water-logged floodplain or shallow lake.

	Taxon	**Reference**
Tracheophytes		
Zosterophylls	*Oricilla bilinearis*	Gensel 1982b
	Sawdonia ornata	Gensel and Albright 2006
Trimerophytes	*Pertica dalhousii*	Doran et al. 1978
	Psilophyton charientos	Gensel 1979
	Psilophyton sp.	Hueber 1967; Andrews et al. 1974; Gensel and Albright 2006
	Psilophyton princeps	Hueber 1967
Lycopsids	*Drepanophycus gaspianus*	Grierson and Hueber 1967; Gensel and Albright 2006
	Drepanophycus spinaeformis	Grierson and Hueber 1967; Gensel and Albright 2006
	Drepanophycus sp.	Andrews et al. 1974
	Leclercqia complexa	Gensel et al. 1975; Gensel and Albright 2006; Wellman et al. 2009
	Leclercqia andrewsii	Gensel and Kasper 2006; Wellman et al. 2009
	Kaulangiophyton	Andrews et al. 1974; Gensel and Andrews 1984
Rhyniopsids	*Taeniocrada* cf. *dubia*	P. Gensel, this study
Incertae Sedis	*Loganophyton dawsoni*	Gensel and Andrews 1984
	Bitelaria dubjanskii	Johnson and Gensel 1992; Johnson 1992
	Chaleuria cirrosa	Andrews et al. 1974
	Oocampsa catheta	Andrews et al. 1975; Wellman and Gensel 2004
Invertebrates		
Myriopods	*Eoarthropleura*	Shear et al. 1996
	Gaspestria genselorum	Wilson 2006
Mesoscorpion	Unnamed	Shear et al. 1996
Thallophyte	*Spongiophyton minutissimum*	Gensel et al. 1991

TABLE 4.3: Reported fossils attributed to section IV.

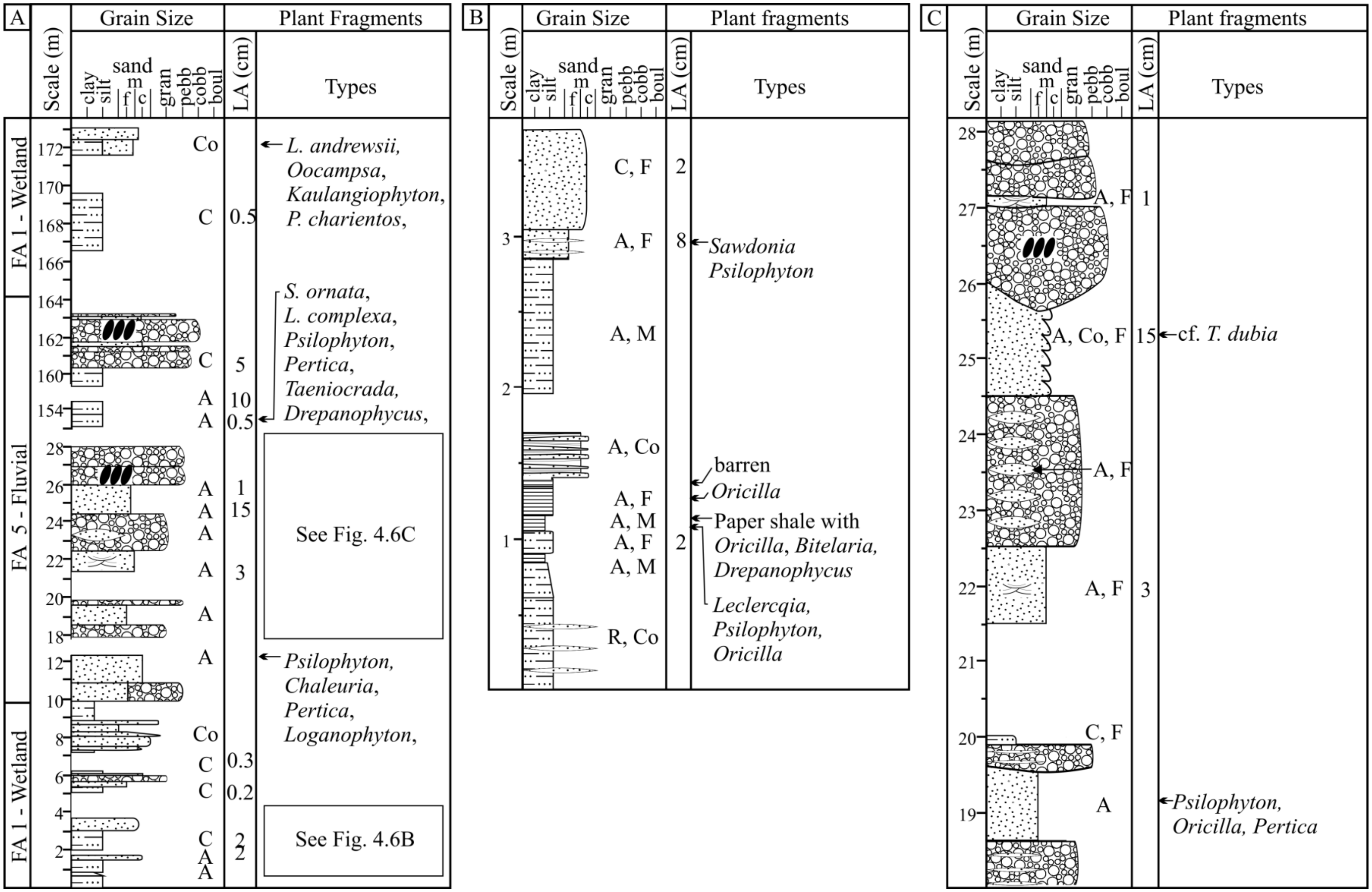


FIGURE 4.6: Stratigraphic logs showing sedimentological features and plant occurrences. A) Section IV, complete. B) Details of the lower lacustrine beds of section IV. C) Details of a segment of fluvial strata. LA – long-axis length of plant fragments. FA – Facies Association. See Figure 4.5 for the legend.

4.4.4. Taphonomic Caveats

The expansion of terrestrial plants during the Early Devonian represents a unique situation, perhaps comparable in the modern world only to primary successions on volcanic or deglaciated landscapes. Because taphonomic guidelines for assessing the paleoecology of plant communities most often deal with well-established communities such as those seen in the Late Devonian and onwards, a few considerations for the Campbellton Formation's more primitive assemblage should be stated. Firstly, the relatively short stature of these plants may be preservationally advantageous since greater proportions of the complete plant are preserved compared to the numerous fragments of leaves or branches of large arborescent forms. Similarly, short flexible plants are less likely to break from shear stresses like wind than tall rigid plants with strengthened stems, which may cause early herbaceous specimens to be more complete than larger, more recent specimens (Niklas and Speck 2001). Parts like the sporangia on fertile plants that may easily disarticulate, if preserved attached as is often seen in the Campbellton Formation, give a good indication of immediate burial and limited transportation (DiMichele and Gastaldo 2008). There is little chance that any of the specimens were deposited and later reworked because resistant woody tissues had not yet developed (Gastaldo and Demko 2011). It is doubtful that any plant fragments present in the Emsian were resistant enough to withstand long distances of transport, so true allochthonous assemblages are probably rare. The depositional environment itself may also influence the interpretation of plant assemblages because environments like crevasse splays on floodplains can contain fragments washed from far away while wetlands often contain autochthonous or parautochthonous assemblages (Gastaldo et al. 1987; DiMichele and

Gastaldo 2008). Charcoalified plant fossils preserving fine detail have been observed in earlier formations (Glasspool et al. 2006), but none were observed in the Campbellton Formation strata, perhaps suggesting that wildfire was still a relatively rare event.

Although lacustrine deposits are relatively rare in the sedimentary record, the Campbellton Formation may have been shielded from excessive erosion throughout much of its existence. After initial deposition in an intermontane basin and folding into an open syncline, the region largely remained a depocentre with only minor periods of erosion. The eastern part of Chaleur Bay formed the westernmost extension of the Maritimes Basin (Jutras and Prichonnet 2002). By the Visean, coarse clastics of the Bonaventure Formation were laid down in a paleovalley occupying much of the Chaleur Bay region (Zaitlin and Rust 1983). Following the formation of Pangea, the study area was located rather centrally, and therefore had a fairly high preservation potential until the Jurassic (Ingersoll and Busby 1995).

4.4.5. Summary: Inferred Vegetated Environments of the Campbellton Formation

From the above environmental interpretations of plant-bearing deposits, five general environments can be inferred in which plant stands grew (Fig. 4.7, Table 4.4). These are lake-side, wetland, riparian, upland, and coastal settings near possibly brackish waters. Marginal lacustrine sediments accumulated large, well-preserved fragments suggesting that most identifiable plant fossils were parautochthonous, although the likely hydrologically open character (Kennedy and Gibling, submitted) would also have permitted far-travelled highly comminuted plant material to collect. The assemblage of the lake-side taxa is relatively low in diversity compared to alluvial settings, with only two zosterophyll species, one lycopsid species, one trimerophyte species, one rhyniopsid species, *Spongiophyton minutissimum*, *Pachytheca*, and *Prototaxites*.

In contrast, the highly productive wetland setting contains a more diverse assemblage where different beds have different assemblages representing either changes in transportation energy or changes in population over time. Shallow ponds with little sedimentation collected only immediate pond-side taxa such as *Oricilla* (zosterophyll), *Drepanophycus* sp. (lycopsid), and *Bitelaria dubjanskii* (incertae sedis). Because burial here would have been a slow process, dysaerobic or anaerobic conditions of shallow stagnant water likely prevented microbial degradation. During moist stages when muddy sediment was remobilized, siltstone beds were laid down that contain fragments such as *Leclercqia andrewsii, L. complexa* (lycopsids), *Psilophyton princeps* (trimerophyte), *Oricilla bilinearis*, *Sawdonia ornata* (zosterophylls), and *Drepanophycus* sp. (lycopsid). These taxa are well preserved, suggesting transportation in non-turbulent water and over relatively short distances, perhaps along the fringes of the marsh. In low-energy channels, unstructured sandstone beds with lenses of *P. princeps* (trimerophyte), *S. ornata* (zosterophyll), *L. andrewsii* (lycopsid), *Kaulangiophyton* (lycopsid-like) and *Oocampsa catheta* (incertae sedis) may represent an assemblage transported either from outside or from within the marsh. This wetland environment also contains all known terrestrial arthropods found within the Campbellton Formation.

Riparian habitats are considered more ephemeral, and plants transported from such an environment are seen mainly in trough cross-stratified sandstones representing bars or bedload dunes interbedded with channel conglomerates. Turbulent water inherent to this environment would have preferentially destroyed weak stems or those that were not buried fairly rapidly. Preserved taxa include *Taeniocrada* cf. *dubia* (rhyniopsid), *Pertica dalhousii* (trimerophyte), *Psilophyton princeps* (trimerophyte), *Oricilla* (zosterophyll), *Chaleuria* (incertae sedis), and *Loganophyton dawsoni* (incertae sedis).

Most specimens found in proximal alluvium appear to be reworked from other environments, which prohibits discovering the growth environment other than to suggest locally elevated water tables in upland localities. However, given the coherent nature of the angular blocks and reported alignment of fossils (Hueber 1967), it can be presumed that *P. princeps* and *D. spinaeformis* grew in a current-influenced, likely elevated, riparian setting bordering a steep gradient such that plant materials could slump into a sediment-gravity flow after initial deposition. Specimens found within lenses were degraded and unidentifiable, but may represent clearer evidence of upland vegetation.

The plant locality in the western belt with *D. spinaeformis, L. complexa*, *P. princeps*, and *T. robustius* was probably coastal and therefore stressed by salinity from seaspray, but again, the clearly allochthonous nature of plants that occur mixed with aquatic fauna limits our ability to infer the growth setting. Continuing collection and identification will add resolution to this story.

Suggested growth environment	**Genera present**	**Location designations in previous literature**
Lakeside	*Taeniocrada* *Psilophyton* *Sawdonia* *Zosterophyllum* *Drepanophycus* *Pachytheca* *Spongiophyton* *Prototaxites*	M, N
Wetland	*Psilophyton* *Oricilla* *Sawdonia* *Drepanophycus* *Leclercqia* *Bitelaria* *Kaulangiophyton* *Loganophyton* *Oocampsa* *Spongiophyton* *Gaspestria* *Eoarthropleura* Scorpion	B, D, E, F, H
Riparian	*Taeniocrada* *Psilophyton* *Oricilla* *Pertica* *Chaleuria* *Loganophyton*	A, G
Upland	*Psilophyton* *Drepanophycus* *Spongiophyton* *Prototaxites*	K, L
Coastal	*Psilophyton* *Trimerophyton,* *Drepanophycus* *Leclercqia* *Loganophyton*	

TABLE 4.4: A summary of genera inferred from each environment and the designation given to these localities in previous literature (Andrews et al. 1974; Gensel and Andrews 1984; Gensel et al. 1991).

4.5 **Discussion**

4.5.1. Tracheophyte Innovations and Ecology

From this assessment, representatives of each plant clade occupied a range of environments from high-energy ephemeral systems to relatively stable low-energy systems. It becomes worthwhile to consider why this might be and what influence various morphological features may have contributed to the distribution. Foremost among these are adaptations that permitted greater structural support and desiccation resistance as plants moved away from saturated substrates. Some adaptations limited possible environments, while others allowed plants to be more versatile and opportunistic. This allows us to consider the system using both environmental requirements of plant traits and sedimentological evidence to evaluate the distribution of genera observed.

Mechanical support for the maintenance of stature against gravity and wind stresses (Niklas and Speck 2001) was important in the competition to acquire sunlight. Early tracheophytic rhyniopsids are thought to have been supported mainly by hydrostatic turgor pressure in the cortex, limiting occupation to water-logged or even subaquatic substrates (Bateman et al. 1998). This placed considerable constraints on habitable environments, as water had to be permanently accessible to prevent wilting. By the Early Devonian, many tracheophytes reached heights that required additional non-hydrostatic support from a lobed stele (e.g. *Zosterophyllum* sp., *Drepanophycus* sp., and *Pertica* sp.), intertwining of stems and lateral branches (e.g. *Pertica* sp., *Trimerophyton* sp.), the hypodermal sterome (e.g. *Psilophyton* sp., *Zosterophyllum* sp., *Leclercqia* sp.), and in rare instances from the xylem itself (e.g. *L. complexa*) (Bateman et al. 1998; Gensel et al. 2001). It is hypothesized that reliance on turgor pressure to maintain a competitive stature drove the evolution of measures to evade desiccation, such as root systems that could access deeper water sources and increased thicknesses of cuticle and subepidermal tissues that impeded transpiration (Bateman et al. 1998). Secondary xylem of woody plants may have been present in rare instances in plants similar to trimerophytes and progymnosperms, which would have both provided mechanical support and increased the efficiency of fluid conduction (Gerrienne et al. 2011).

Roots have the additional advantage of anchoring plants in high-energy environments where poorly rooted taxa may be endangered by flooding or winds. Although there is little evidence of rooting structures within the Campbellton Formation, aside from two horizons among fluvial beds (Fig. 4.3), several of the Campbellton taxa have been found in other contemporaneous localities with rooting structures. High-energy ephemeral environments that included longitudinal bars and sandstone sheets laid down by floods from the Fort Prével Member of the Battery Point Formation have traces up to 90 cm long that may have been created by large plants similar to *Drepanophycus* sp., *Psilophyton* sp., or *Pertica* sp. (Elick et al. 1998). Rhizomatous growth forms that may also act to anchor the plant have been found in *Sawdonia ornata* and *Drepanophycus* spp. (Gensel et al. 2001). Adventitious roots are described for *Drepanophycus spinaeformis* (Hueber 1992; Li et al. 2000), and putative structures have been found with *S. ornata* in New Brunswick, *Zosterophyllum* sp. on Bathurst Island (Gensel et al. 2001), and *Taeniocrada langii* in Germany (Schweitzer 1980). Large rooting structures attributed to *Prototaxites* are found in river bars, on floodplains, and in well-developed paleosols (Hillier et al. 2008). Short branch-like buds on *Bitelaria dubjanskii* may have helped initiate shoot regrowth if the plant were knocked over, demonstrating another method of surviving an unpredicted environmental change (Johnson and Gensel 1992; Gensel et al. 2001).

The development of leaf forms, mainly microphyllous leaves in early lycopsids and precursors to megaphyllous leaves in trimerophytes, presents another important adaption. The slight increase in surface area arising from these extensions offered an advantage by facilitating photosynthesis and allowing individuals in dense plant stands to intertwine lateral branches for support (e.g. *Pertica* sp. and *Trimerophyton* sp.) (Doran et al. 1978), while providing a sheltered habitat for early arthropods (Chaloner et al. 1991). The shapes of microphyllous leaves such as those of *L. complexa* may have functioned as drip-tips in the capture of meteoric water in arid climatic belts on either side of the equator (Meyer-Berthaud et al. 2003). Megaphyllous leaves, which required more stem strength to support than was generally found in the Emsian, later arose from lateral branches in genera like *Pertica* (Bateman et al. 1998). However, leaves with large surface areas at a time when tropospheric temperatures were warm would not have been effective at energy dispersion, and were not energetically favoured (Raven and Andrews 2010).

Reproductive strategies of tracheophytes at this time relied on a free-sporing life cycle in which the sporophyte released large quantities of spores, and fertilization within the gametophyte generation required proximity to water. Nearly all vascular plants were homosporous, but *Chaleuria cirrosa*, an aneurophytalean early progymnosperm, presents the earliest known example of heterospory (Andrews et al. 1974), a trait which later became an important precursor to the seed habit (Bateman and DiMichele 1994). In *Chaleuria*, both microspores and megaspores are found within a single sporangium (anisosporous) but one "gender" tends to dominate (Andrews et al. 1974).

Environmentally, both heterospory and homospory require fairly moist conditions and dense stands to facilitate fertilization, but the heterosporous life cycle is more closely restricted to wet, possibly semi-aquatic settings (Bateman and DiMichele 1994). The development of spore ornamentation and tough wall coverings may be linked to spore dispersal via arthropods and the need for survivorship as spores passed through the digestive tract or were caught on the body (Kevan et al. 1975).

Terrestrial arthropods are rare within the Campbellton Formation, and have so far been found only within organic-rich floodplain strata of section IV. However, the presence of arthropods here as well as in other contemporaneous formations allows some paleoecological considerations. Most arthropods were likely detritivores, consuming litter and aiding soil formation (Almond 1985; Shear and Kukalovà-Peck 1990). *Gaspestria genselorum* is among those that had a detritivorous trophic habit, burrowing through soft earth and litter (Wilson 2006). A high proportion of coprolites in the Rhynie Chert are thought to belong to detritivores rather than to herbivores or omnivores, suggesting that detritivory was the dominant feeding strategy (Labandeira 1998). However, some arthropods including collembolans, mites, and insects may have participated in herbivory on live stems (e.g. on *Psilophyton* sp.) and sporangia of herbaceous plants, as well as on woody mycelial tissue of *Prototaxites* leaving wounds that later healed over (Banks and Colthart 1993; Labandeira 2007). Early scorpions such as the one found in the Campbellton Formation could have been carnivorous (Shear et al. 1996). Plant cover in turn provided a sheltered and humid microclimate for arthropods (Chaloner et al. 1991), and some adaptations such as enations may have helped with spore dispersal by allowing arthropods to easily climb the stems of plants in order to consume sporangia (Shear and Seldon 2001).

Several of these morphological traits show interesting distributions when compared to the environments in which they are found within the Campbellton Formation. *Leclercqia* sp. has a particularly advanced set of traits including a well-supported stem with structural reinforcements, microphyllous leaves, and possible rooting structures and is found repeatedly in beds associated with wetland flooding. It, therefore may have lived in relatively dry areas of the marsh that were only periodically inundated with water. *Chaleuria* should have been constrained to a consistently wet habitat by its heterosporous life cycle, but is found with two trimerophyte genera in fluvial strata, which are generally associated with ephemerally dry growth conditions (Hotton et al. 2001). *Drepanophycus* sp. and *Psilophyton* sp. are both relatively tall plants that appear in most environments, perhaps aided by rooting systems demonstrated for *Drepanophycus* sp., but which are merely suspected for *Psilophyton* sp. (Hueber 1992; Elick et al. 1998; Gensel et al. 2001). Considering the water requirement for turgor pressure in most rhyniopsids, it is surprising that *Taeniocrada* cf. *dubia* is found in riparian, lake-side, and wetland localities where water saturation may have varied. This may be a result of the tendency for any smooth broad-stemmed plant to be referred to this genus, or it may indicate the former presence of rooting structures as have been observed in at least one species of *Taeniocrada* not observed in the Campbellton Formation (Schweitzer 1980), despite the conventional view that rhyniopsids lacked roots (Banks 1985).

4.5.2. Emsian-Eifelian Phytogeography of Laurentia

Phytogeographical provinces in Devonian times can be identified using megascopic fossil plant remains (Raymond 1987). The Campbellton Formation is located in the south Laurussian phytogeographic province, which has an assemblage distinct from other Emsian-Eifelian localities in northern Laurussia-Siberia, China, Australia, and Kazakhstan-north Gondwana. Differences in assemblages can be explained by latitudinal climatic zonation and separation of southern Laurussia from other low-latitude localities (China) by geographic barriers (Tethys Sea, Rheic Ocean) (Raymond 1987). A list of Ordovician to Lochkovian localities and Middle Devonian localities can be found in Edwards and Wellman (2001) and Berry and Fairon-Demaret (2001), respectively, while many Early Devonian sites are discussed in Gensel and Andrews (1984).

Several contemporaneous localities within the same phytogeographic province are found with similar plant assemblages to a generic level. In the Trout River Formation of Maine, USA, 12 plant taxa are reported from a low-diversity fluvial-estuarine environment where trimerophytes including *Pertica quadrifaria, Psilophyton princeps*, and *P. forbesii* dominated (Allen and Gastaldo 2006). The Cap-aux-Os Member of the Battery Point Formation on the Gaspé Peninsula of eastern Quebec similarly represents a fluvial-coastal plain, but has perhaps the clearest evidence of linkages between plant clades and specific environmental preferences (Griffing et al. 2000; Hotton et al. 2001). Here, zosterophylls were found mainly in a vegetative state in fine-grained facies of dysaerobic, water- saturated marshes and backswamps, and were probably rarely subjected to dry conditions, despite having xeromorphic characteristics such as a tough cuticle and sunken stomata. Trimerophytes were often found in a fertile state in ephemeral habitats such as on channels bars and margins where rapid growth, permitted by a thin cuticle, was favoured by an inherently unstable fluvial environment (Hotton et al. 2001). Fragments of *Spongiophyton minutissimum* and *Prototaxites* were thought to have been transported from upland environments. Alluvial strata on the north shore of Chaleur Bay appear in the LaGarde and Pirate Cove formations (Dineley and Williams 1968; Rust 1989). The LaGarde Formation is lithologically similar to the higher beds of section II (Dineley and Williams 1968), but contains fragments of ostracoderms, placoderms, small invertebrates, *P. princeps*, and *Prototaxites* (Dawson 1882), whereas the Pirate Cove Formation contains an abundance of root traces but only comminuted plant debris (Rust et al. 1989).

The Campbellton Formation presents a more complex setting. Plant clades do not appear to be strongly partitioned within the landscape, and tend to be found across a variety of settings (Fig. 4.7). However, some of this may be explained by taphonomic bias as all preserved specimens are parautochthonous or allochthonous; none are unquestionably found in their growth positions. Moreover, 5 out of 13 plant genera found here do not fit well into any established clade and therefore cannot easily be included in a model of clade niche partitioning. Fluvial strata contain rhyniopsids and trimerophytes, similar to the assemblage in fluvial beds in Trout Valley (Allen and Gastaldo 2006), as well as zosterophylls. Stable lake margins in the Campbellton Formation have a lower diversity compared to the wetland and, although abundance has not been quantified, this setting may have been dominated by zosterophylls as in the Cap-aux-Os Member, with instances of *Psilophyton* sp. and *Taeniocrada* sp.. Paper shales likely represent relatively dry periods when little precipitation and thus little overland flow provided sediment to small topographic depressions that were surrounded mainly by zosterophylls (DiMichele and Gastaldo 2008). Organic-rich micaceous siltstone beds found in association with these paper shales suggest periods of high rainfall where the surrounding marsh may have been inundated such that a more diverse assemblage from both wet and dry parts of the marsh was transported to local topographic lows. A steep topographic gradient required for hyperconcentrated flows in section III, which contains blocks with *Drepanophycus spinaeformis* and *Psilophyton princeps,* may suggest occupation of upland regions, but there is also a temporal discontinuity between when the plants grew and when they were entrained in the hyperconcentrated flow in what was likely a fairly tectonically active landscape. Discoveries of *Prototaxites* sp. and *Spongiophyton minutissimum* in these beds are consistent with their occurrence in fluvial beds in the Cap-aux-Os Member.

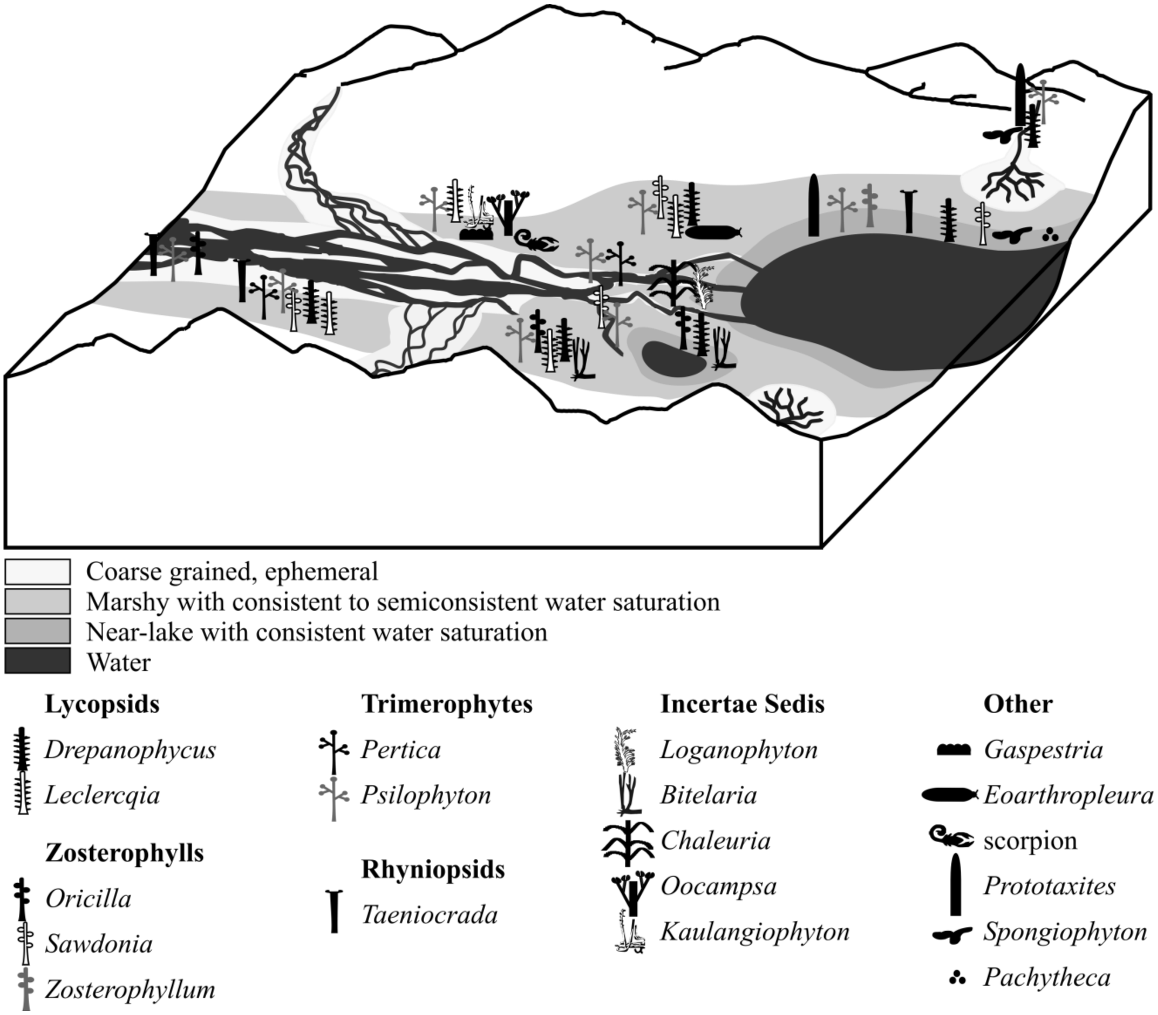


FIGURE 4.7: Reconstruction of the landscape represented by the eastern belt of the Campbellton Formation. Groupings of plants represent individual localities, some of which have the same or similar environmental interpretations, but slightly different assemblages. Note that plant heights and topographic features are not to scale.

4.5.3. Earth Systems

Over the course of the Devonian, the process of terrestrial plant expansion through enhanced plant diversity and versatility culminated in a number of climatic upsets. At the Silurian-Devonian boundary, high sea levels and primary productivity in both the terrestrial and marine realm led to increased carbon burial and temporary associated cooling (Malkowski and Racki 2009). In the Lochkovian, eustatic regression and high weathering rates associated with tectonic uplift from the Caledonian Orogeny reversed this process through oxidation of carbon-rich sediments to CO_2, causing a shift to a greenhouse state that persisted until the Fammenian (Malkowski and Racki 2009). High rates of carbon burial and silicate weathering led to widespread ocean anoxia that devastated marine communities in the Late Devonian biotic crisis (Algeo et al. 1995, Algeo and Scheckler 1998). Atmospheric levels of carbon dioxide were 11 times pre-industrial levels in the mid Emsian rising to 16 times in the Frasnian, but had dropped to 6 times by the end of the Fammenian, levelling off at near pre-industrial levels in the Carboniferous (Berner 2006). The Campbellton Formation therefore would seem to represent a time when the atmospheric carbon cycle was only moderately affected by plant growth and this signal was largely overprinted by large-scale perturbations. By the end of the Devonian to Carboniferous times, proliferating vegetation and enhanced chemical weathering contributed to a dramatic decrease in CO_2 levels.

4.6 **Conclusion**

From the preceding discussion, it is clear that the database of environmentally constrained early plant sites needs to be broadened in order to more completely understand early plant evolution and the effects it had on the expansion of plants across the terrestrial realm. The Early Devonian (Emsian) Campbellton Formation contributes to this by offering a distribution of clades that is more variable than those found to date at other localities of the same age and with similar assemblages. This difference may represent taphonomic issues of non-autochthonous assemblages, as well as a fundamental ecological difference between the coastal settings studied and the intermontane setting presented here. By the Emsian, vegetation was well established and beginning to spread to niches outside of those for which they were initially ideally adapted. The greatest diversity and abundance of plants is seen in dysaerobic shallow pond-like beds where plants were likely derived from surrounding marshy areas with a fluctuating, but probably predominantly high, water table. Fewer genera were found in fluvial beds of a braided river, where plant material was probably derived from riparian zones, but the taxa included members from each clade as well as some of unknown affinities. Some genera, such as *Psilophyton* sp. and *Drepanophycus* sp.*,* were found in nearly every environment including proximal environments with *Prototaxites* sp. and *Spongiophyton minutissimum*, indicating their versatility in colonizing a variety of terrains as well as their profusion both here and in other localities. Others like *Oocampsa catheta* and *Bitelaria dubjanskii* were found in a single environment.

4.7 Acknowledgements

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CHAPTER 5 — DISCUSSION AND REMAINING QUESTIONS

5.1 Other Fossiliferous Localities of the Campbellton Formation

The fossils of the Atholville beds are mentioned in the above manuscripts, but have not yet been completely addressed. As opposed to other Campbellton Formation localities, vertebrates dominate the assemblage, which also includes plant fragments, gastropods, ostracods, and eurypterids (Table 5.1). Fossils are located dominantly in two areas: the basal breccia, and uppermost beds of section I (Fig. 5.1).

The basal brecciated and fissured unit contains many of the invertebrate and vertebrate fossil discoveries. Fish and eurypterids are preserved as compression or impression fossils, often as fragments of ecdysed exoskeleton, dermal plates, fin spines, and teeth, or more rarely as articulated specimens. Small invertebrates such as the ostracods *Primitia mundula* and *P. scaphoides* (Jones 1889) and the gastropods *Cyclora valvatiformis* and *C. imbricata* (Whiteaves 1881; Morris 1985) are numerous and tend to be preserved complete. It is possible that some of these organisms took shelter in the crevices and fissures of relatively young rhyolite submerged in quiet waters, similar to aquatic ecosystems in modern subtidal rocky coasts and seamounts. The breccia passes upward into ostracodal calcareous mudstone and plant-, fish- and ostracod-bearing sandstone beds, the latter largely lost through coastal erosion.

To the west of the contact, section I crops out as broadly channelized units of ripple cross-laminated and planar-laminated medium sandstone interbedded with units of trough cross-stratified medium sandstone and massive siltstone and sandstone. The succession is capped by ~2 m of indurated fossiliferous siltstone containing fish and eurypterid fossils. This facies suite is attributed to a sandy delta with shifting channels where thick mudstone packages represent localities away from large distributaries in calm water with little wave action.

Within section I, most preserved vertebrate and eurypterid fossils are found in the uppermost units of massive grey siltstone. These include the anterior end of the oldest known partially articulated chondrichthyan (Miller et al. 2003; Maisey 2009), and a moulted exoskeleton of the large eurypterid *Pterygotus anglicus* (Miller 1996, 2007a). The delicate nature of preserved articulated specimens as well as the fine grain size suggests quiescent environmental conditions. Well-preserved fossils are rare within the interbedded sandstones and siltstones below, although compression fossils of pterygotid eurypterids in sandstone, putative arthropod traces and unidentifiable comminuted plant debris have been found (Miller 1996).

Taxa with marine (prasinophytes and acritarchs), marginal marine (*Ankylacanthus*), and nonmarine (*Cyclora* and *Primitia*) affinities (Morris 1985; Gray 1988; Blieck and Cloutier 2000; Burrow et al. 2008) have all been found in the basal breccia and in section I, which may suggest that water here was brackish or fresh with marine incursions, but this remains unresolved.

Pterygotus anglicus is a pterygotid eurypterid, a group of powerful swimmers that travelled vast distances across the ocean to become well-distributed around the globe (Tetlie 2007). Most pterygotids were probably marine, but they appear to have been able to make at least short trips into brackish waters of estuaries and lagoons, and some species may have even travelled up rivers into lakes (Kjellesvig-Waering 1964). It is unclear whether their occurrence in fresh water and marginal environments was due to a life-long habitation, a temporary pursuit of prey, or a regular migration in order to undergo ecdysis and reproduce (the mass-moult-mate hypothesis of Braddy 2001). The pterygotids were active hunters with chelicerae that were particularly well-suited among the eurypterids for defense and capture of prey and transfer of food to the mouth region (Kjellesvig-Waering 1964). Stereoscopic vision due to anteriorly placed compound eyes with overlapping fields of vision may have helped pterygotids to track their prey (Selden 1985). The presence of *Pterygotus* sp. in active deltaic channels where no fish appear could be a demonstration of their ability to swim through fresh or brackish waters, and against currents.

Fish appear in the breccia and in the uppermost mudstone unit, but have not been found in any coarser deltaic strata (Fig. 5.1). These environments were marginal, and from the unstructured fine grained nature of the sediments, were low energy settings. Little is known of the life habits of individual genera found in the Campbellton Formation, but some general inferences may be made. Sharp, stabbing teeth in *Protodus jexi* suggest it was predatory or scavenging, and could have been capable of breaking through flesh of anything else in the seas at that time, except for perhaps large eurypterids (Turner and Miller 2008). Little is known of the feeding habits of cephalaspid ostracoderms like *Yvonaspis* spp., but like most agnathans, these probably dwelt in bottom-waters or in soft substrates and were filter feeders or microphagous (Janvier 1985). *Phlyctaneous* spp., as an arthrodire placoderm, may have had bony outgrowths in the mouth for eating smaller fish (Young 2003).

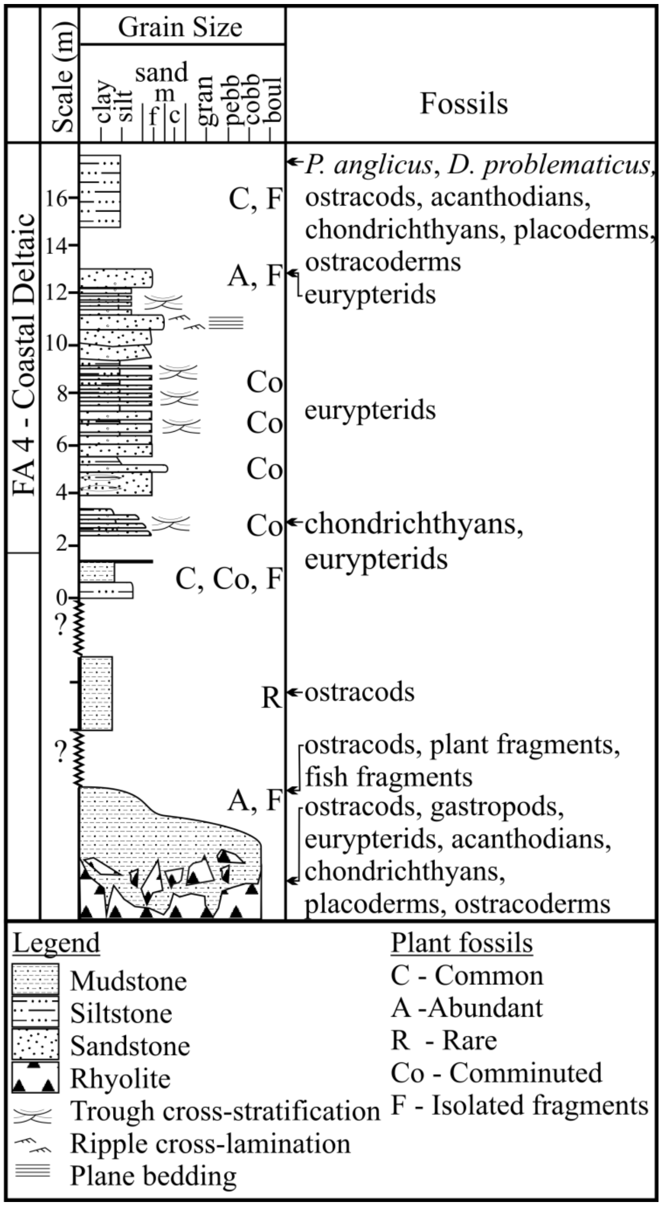

FIGURE 5.1: Stratigraphic logs of section I and the contact zone showing sedimentological features and fossil occurrences. FA – Facies Association.

	Taxon	**Reference**
Tracheophytes		
	Psilophyton princeps	Dawson 1871
	Trimerophyton robustius	Dawson 1871; Hopping 1956
	Drepanophycus spinaeformis	Dawson 1871; Grierson and Hueber 1967
	Leclercqia complexa	Gensel and Albright, 2006
	Loganophyton dawsoni	Krausel and Weyland 1961
Vertebrates		
Ostracoderms	*Yvonaspis campbelltonensis*	Whiteaves 1881; Woodward 1892, Traquair 1893; Pageau 1969; Belles Isles 1989
	Yvonaspis jexi	Traquair 1893, Pageau 1969
Placoderms	*Phlyctaenius acadicus*	Whiteaves 1881; Traquair 1890, 1893; Woodward 1892
	Phlyctaenius atholi	Young 1983, Pageau 1969
	Phlyctaenius stenosus	Young 1983
Acanthodians	*Ankylacanthus incurvis*	Traquair 1890; Woodward 1892; Burrow et al., 2008
	Homacanthus gracilis	Whiteaves 1881
	Climatius latispinosis	Whiteaves 1881; Woodward 1892; Pageau 1969
	Mesacanthus semistriatus	Woodward 1892; Pageau 1969
	Cheiracanthus costellatus	Traquair 1893; Pageau 1969
Chondrichthyans	*Protodus jexi*	Woodward 1892; Traquair 1893; Turner and Miller, 2008
	Doliodus problematicus	Woodward 1892; Traquair 1893; Miller et al., 2003; Turner, 2004; Maisey et al., 2009
	Ctenacanthus ornatus	Pageau 1969
Invertebrates		
Eurypterids	*Pterygotus* sp.	Whiteaves 1881
	Pterygotus anglicus	Miller 1996; Miller, 2007a, 2007b
Ostracods	*Primitia mundula*	Jones 1889
	Primitia scaphoides	Jones 1889
Gastropods	*Cyclora valvatiformis*	Whiteaves 1881
	Cyclora imbricata	Whiteaves 1881
Other		
	Spirorbis	Whiteaves 1881
	Prototaxites	Dineley and Williams 1968

TABLE 5.1: Reported plant and animal fossils found within Section I and the basal breccia.

5.2 **Coal-Bearing Strata**

Early surveyors of the Campbellton strata reported 5-10 cm thick coal seams which were rumoured to have been mined out by early French settlers (Gesner 1843), but these were deemed to not have any economic value and have not been of interest since (Ells 1881). However, given the age of the formation, these coals are noteworthy as among the oldest coals known. Older coals are extremely rare, but inertinite in humic coals has been found in Ordovician and Silurian strata of Estonia (Diessel 2010). This region may have been particularly favourable to coal formation, as Lochkovian to Pragian coals have also been found in the Val d'Amour Formation (Wilson et al. 2004).

The coal-bearing strata of the Campbellton Formation occur in a single outcrop which has been assigned to facies association 1, and were likely deposited in fairly shallow water where rafted plant material could accumulate. Two sills intrude this outcrop, each with pervasive alteration of igneous crystals to calcite. There appears to be no clear link between these sills and the dated lamprophyre dikes that intruded lower parts of section III, so it is unclear when they may have intruded. Loose pieces of coal litter the beach, and it might be expected that more seams would be found below the overburden. These sills obscure much of the outcrop, therefore little environmental context is possible. No rootlets or paleosols are apparent. Other sediment types found in the outcrop include dark grey to black siltstone and shale, and an 11 cm thick lenticular body of medium to coarse sandstone (Fig. 5.2a,b). Coals in outcrop were dull and appeared to be made out of layers of compressed cuticular material. In thin section, very thin silty laminae were observed, separating layers of organic material (Fig. 5.3).

One sample of this coal was analysed for vitrinite reflectance, yielding a value of 0.4%. Examples of macerals seen during this procedure are shown in Figure 5.4a,b. This value agrees well with measurements of thermal maturity from the Val d'Amour Formation, which include a vitrinite reflectance value of 0.4%, and a thermal alteration index of 3.1 in lower parts of the formation and 2.7 in higher parts (Wilson et al. 2004). Based on these limited analyses, coals in both formations are the rank of hard lignite, while spores in the Val d'Amour Formation may suggest hydrocarbon generation in the gas condensate or oil window zone (Héroux et al. 1979).Coals are primarily formed by the accumulation of vegetation in a waterlogged non-oxidizing setting, where little tissue degradation occurs. Over a long period of time, exposure to heat and pressure causes molecules such as cellulose to degrade and be removed from the incipient coal while other molecules persist. Lignin is a critical component of coal, and can be found in the cell walls of all vascular plants, but is particularly abundant in secondary cell walls of vascular plants (Niklas 1981). It is for this reason that coals do not become abundant until after the Middle Devonian, when lignophytes with secondary xylem developed (Edwards 2003), although precursors to lignophytes may be present from the Pragian-Emsian boundary onwards (Gerrienne et al. 2011). Secondary xylem in the Emsian was extremely rare and it may be expected that coal formation was unusual, and required a prolonged fairly dense vegetation cover of small herbaceous plants that were common at the time. From the present study, *Psilophyton* sp. and *Drepanophycus* sp. are likely candidates as components for some of these early coals as they are abundant, but any of the wetland taxa listed in Table 4.5 may have contributed. In the Campbellton Formation, at least one coal occurrence is in direct contact with a sill where the additional heat may have acted to volatilize gases and restructure the coals, ultimately raising their grade (Melenevsky et al. 2008). Both the Val d'Amour and Campbellton formation coals present an interesting early occurrence, and require further examination.

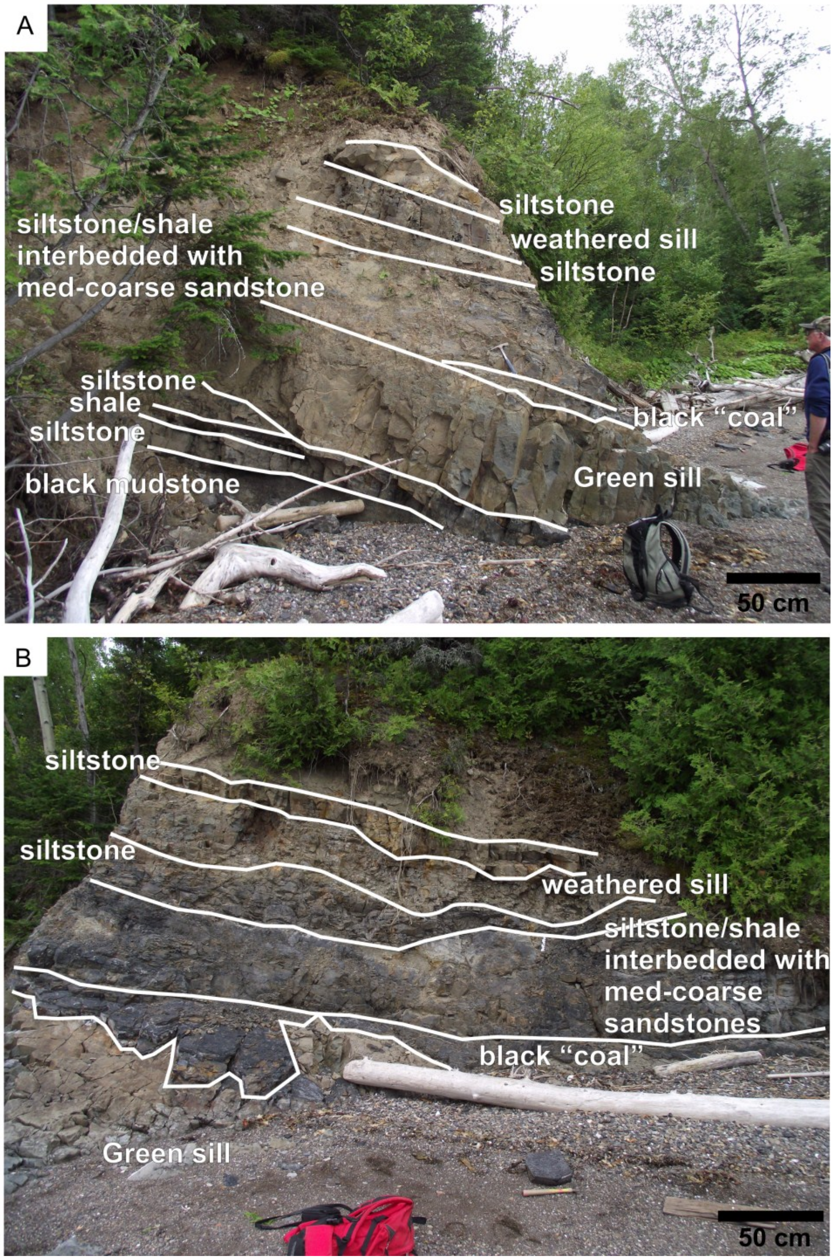

FIGURE 5.2: Outcrop photograph of coal-bearing strata. A) and B) are the same outcrop shown from the perspectives of A) cross section perpendicular to strike, and B) cross section nearly parallel to strike.

FIGURE 5.3: Photomicrograph of a coal seam under plane-polarized light. Thin silty laminae separating coaly layers of organic material are apparent.

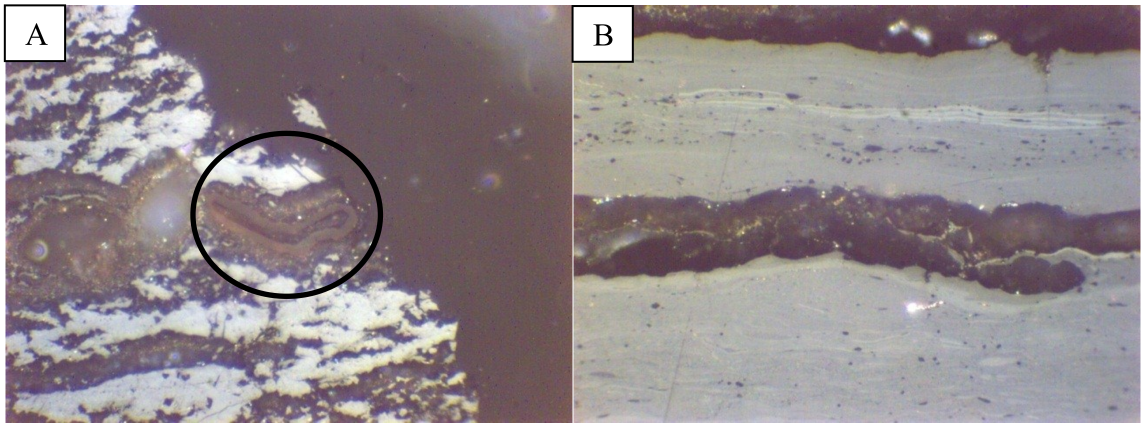

FIGURE 5.4: Examples of coal macerals under reflected light. A) Spore (circled) surrounded by pyrite. B) Vitrinite macerals.

5.3 **Regional Stratigraphy**

A large ribbon-like swathe of clastic strata, 2-4 km wide stretching from Campbellton, New Brunswick through to Drapeau, Quebec has incorporated three formations with ages spanning the middle Emsian to early Eifelian, all with terrestrial deposits. Two of these, the Campbellton and LaGarde formations, are so similar that there have been several attempts to combine them into a single formation (Dineley and Williams 1968, Gamba 1990). The LaGarde and Pirate Cove formations on the north arm of the Restigouche syncline dip southwards, and the Campbellton Formation on the south arm dips northwards with no evidence of a fault under Chaleur Bay. Detailed stratigraphic columns of both the LaGarde (Gamba 1990) and Pirate Cove (Dineley and Williams 1968; Zaitlin 1981) formations have been created, and it would seem reasonable to attempt a preliminary correlation among the three.

Several sections within the LaGarde Formation were described by Gamba (1990) who divided the strata into the Pointe à la Garde and Pointe à Bourdreau members. Gamba's sections F, H, J-N, A, and B can reasonably be considered part of the LaGarde Formation, although several other sections included in the Pointe à la Garde member are inconsistent with these sections and have been excluded. Two depositional systems were recognized: a transverse proximal gravelly braidplain flowing westwards, and a northward flowing longitudinal sandy braidplain. Clast composition is largely volcanic, with smaller components of vein quartz, granite, siliciclastics, and jasper clasts. This is comparable to the clast composition of section II of this study, which is the only conglomerate in the study area to contain vein quartz, and it has been suggested that section II of the Campbellton Formation and the basal LaGarde Formation beds are equivalent (Dineley and Williams 1968; Gamba 1990). This relationship has the following implications: 1) the LaGarde Formation and section II are likely isolated from contemporaneous lacustrine beds in the eastern belt of the Campbellton Formation beds by an upland area that, during early stages of Campbellton Formation deposition, lay near Pointe à la Garde, 2) a major tectonic reorganization occurred between this time and the deposition of sections IV and V, and the Pirate Cove Formation, 3) the occurrence of a deltaic deposits with south-eastward flowing paleocurrents west of the LaGarde Formation and section II appears to oppose the alluvial topographic gradient, and the relationship between these sections is unclear.

The Pirate Cove Formation (545 m thick) consists of 5 units interpreted as: 1) alluvial braidplain or the interlobe area of an alluvial fan with ephemeral flashfloods, 2) mid to distal alluvial fan, 3) distal alluvial fan or proximal braidplain, 4) braidplain, 5) gravel-dominated distal braidplain (Zaitlin 1981). A normal fault to the northwest was interpreted as controlling many of these processes; however, it is not clear if this fault was active during Campbellton deposition. Clast composition in the Pirate Cove Formation is predominantly micrite, with minor fossiliferous limestone, sandstone, and volcanics and is therefore markedly different than any of the Campbellton Formation conglomerates, possibly reflecting late uplift of carbonate strata. Most of this formation occurs east of the Campbellton Formation, in the vicinity of Miguasha, suggesting that eastward flowing fluvial systems of sections IV and V were deposited before the fault to the north became active.

The broad relationships between these three formations are tenuous, and more field work may help clarify the timing of events. Faulting may have controlled many of these interactions, but few faults have been identified as candidates. Better correlation between formations is needed to understand the interactions between each formation and ongoing tectonism.

5.4 Basin Formation

The tectonic processes that may have responsible for the existence of such a basin remain uncertain. Detailed structural evidence of the tectonic movements within the Campbellton Region is presented in Craggs (2008). The Restigouche Syncline is bounded to the south by the Black Lake Fault, and to the north by the Sellarsville Fault, with the Squaw Cap, Suger Loaf, and Sellarsville East faults cutting through the south and north limbs of the syncline, but not affecting the Campbellton, Pirate Cove, or LaGarde formations. The Sellarsville Fault is interpreted as a post-Middle Devonian reverse fault, and may not have been active during Campbellton deposition (Malo and Kirkwood 1995). The Squaw Cap and Black Lake faults, however, may have been active during Salinic extension, and reactivated during late Acadian dextral strike-slip motion (Wilson et al. 2004). The McKenzie Gulch Fault is a major NE-SW striking fault that terminates at the Black Lake Fault. It was initiated during Salinic deformation, and was reactivated as a reverse fault during Acadian deformation, so may be a more likely candidate. Two large dextral transcurrent faults are also in the vicinity of Chaleur Bay, and may have had a component of vertical motion (Wilson et al. 2004). These are the Restigouche Fault of the Gaspé Peninsula, which is the western extension of the Grand Pabos Fault, and the Rocky Brook-Millstream Fault of New Brunswick. Most folding in the Restigouche area was late Early to Middle Devonian. Early Devonian Acadian faulting throughout the

Gaspé Belt was complex, and it may be that the cause of basin formation in the Campbellton area can only be understood by knowing the timing and sense of motion on some of these faults with higher precision than is currently available.

CHAPTER 6 — CONCLUSIONS

The strata of the Campbellton Formation represent an almost 1 km thick clastic succession. Western outcrops represent a possibly brackish basin confined by deltaic deposits to the west and braided river deposits to the east. Eastern outcrops represent an intermontane basin isolated from the western basin, filled with lacustrine strata transitioning upwards to fluvial strata. The lowermost beds are predominantly thick marginal lacustrine facies, with restricted lacustrine facies and shallow water lacustrine facies. Upwards, deposits of an axial braided river system with a well-vegetated wetland floodplain occur. Proximal alluvium transverses the valley. Most material in the eastern outcrop belt is volcanic in origin, and alteration is pervasive in the lower lacustrine beds.

Plant fossils are primarily found in five settings. A marginal, possibly brackish environment contains a low-diversity plant assemblage representing growth in coastal regions and is intermixed with an aquatic fossil assemblage. A marginal lacustrine environment collects plants from the lake perimeter, and thus represents the lake-side assemblage. Shallow, dysaerobic ponds derive a plant assemblage from surrounding marshlands and tend to have the highest diversity. Fluvial strata contain an assemblage that represents short-lived riparian growth stands. Proximal alluvium contains blocks and clasts containing plants entrained from upland locations.

The distribution of both specific plant fossils and groups of plant fossils within the Campbellton Formation vary from other localities by having fairly diverse assemblages in all recognized environments. All clades are represented in lakeside, riparian, and wetland settings, but coastal and upland settings have no reported rhyniopsids or zosterophylls. The wetland setting contains the most diverse assemblage including several species of incertae sedis and terrestrial arthropods. The trimerophyte *Psilophyton princeps* and the lycopsid *Drepanophycus spinaeformis* seem particularly resilient and are both found in every plant-rich environment.

From this locality, it can be seen that the Emsian landscape was more extensively vegetated than is generally thought. Plants interacted with many different environments and were not necessarily restricted to low-lying coastal and alluvial plains. As what was probably a tectonically active landscape with short periods of volcanism, floods, high topographic gradients, and few signs of developed soils, the Campbellton Formation represents a relatively hostile environment compared to the Battery Point or Trout River formations, yet this does not seem to have significantly hindered the dispersal of vegetation.

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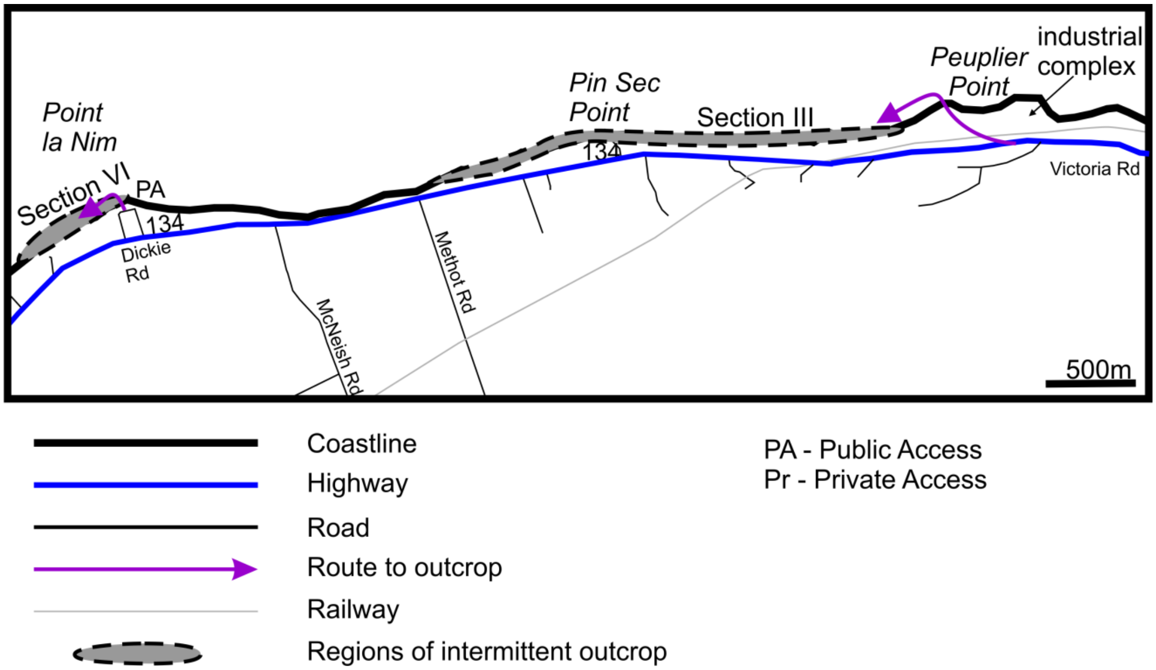
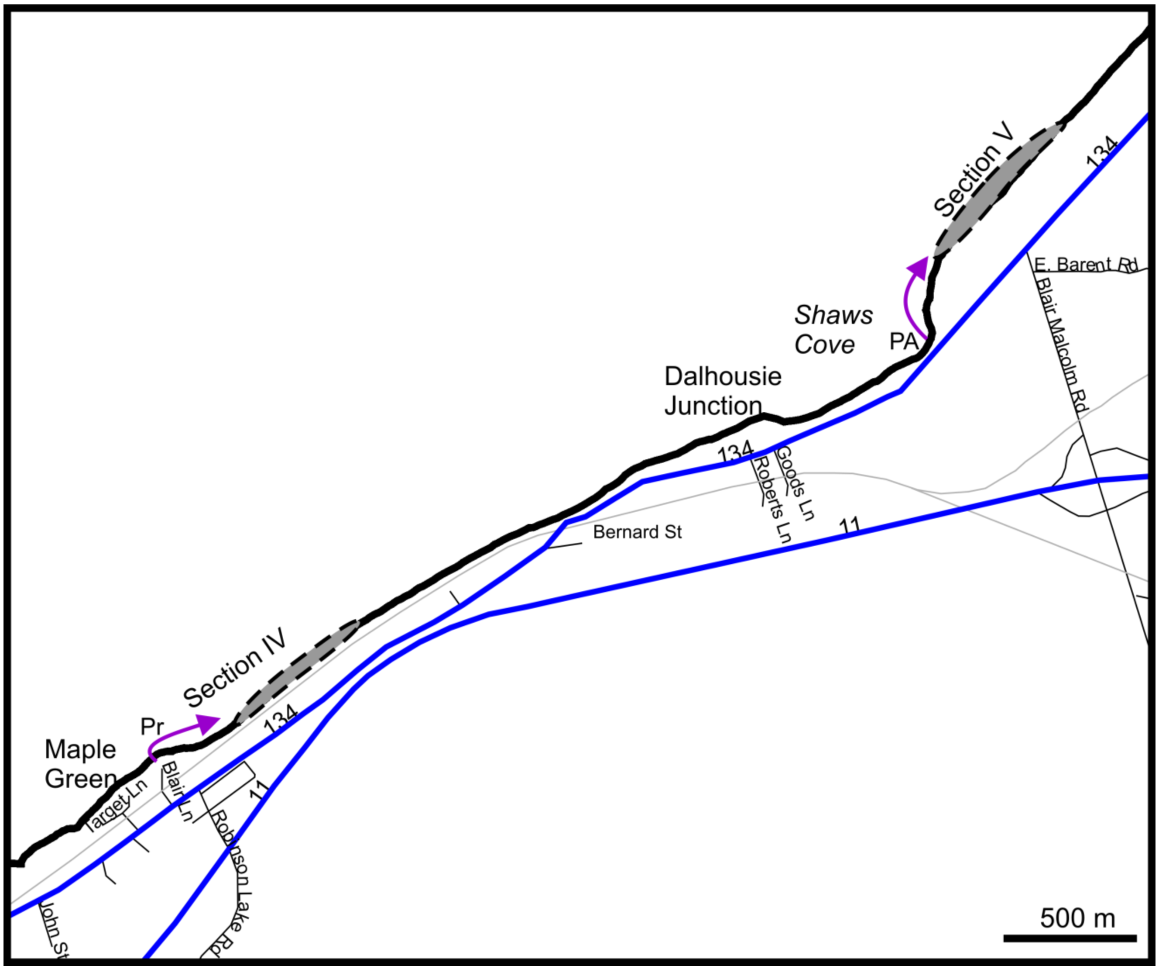
APPENDICES

Appendix 1: Access to Outcrops



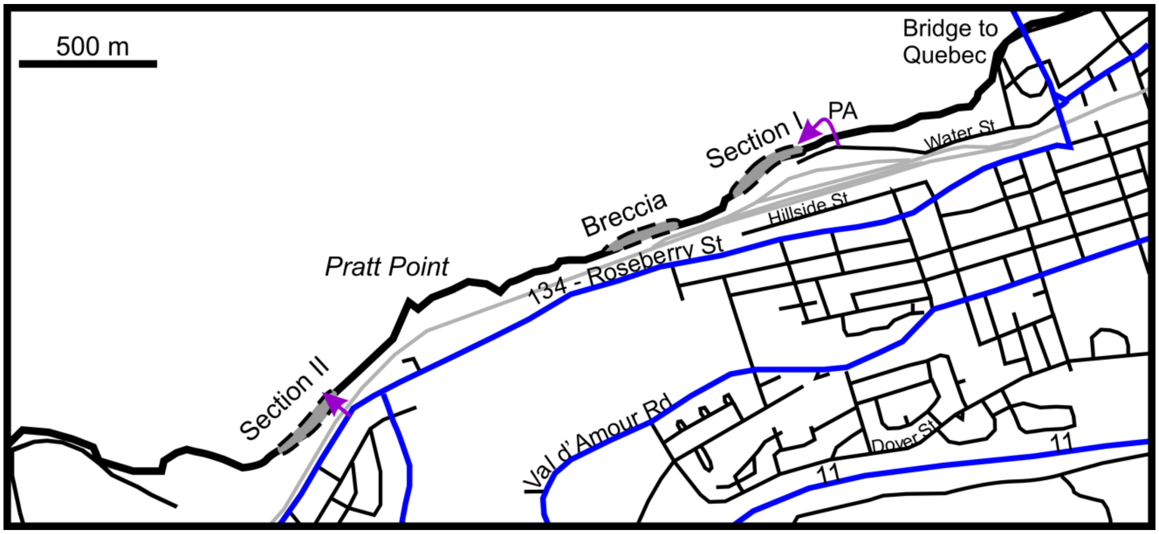
Access to Section III is most easily done by parking at the top of a gated gravel road that descends on the north side highway 134, about 800 m west of the outskirts of Dalhousie. After walking down the gravel road, there is a path that follows the outside of the fence around the industrial complex, which will lead to Peuplier Point. Tides may hinder reaching all of the section from this entrance due to dikes protruding into the water, but some residents of the area have stairways descending from their property to the coast that they may permit the use of.

Access to Section VI, at Point la Nim, is public from Dickie Rd.



Access to Section V is public from Shaws Cove where a ramp leads from the road. High tide may limit access.

Access to Section IV is best done at the end of Blair Road where a number of residents may grant permission to cut through their properties. At the seastack, head east, past a large outcrop of red conglomerate (Bonaventure Formation). Outcrop at Section VI is generally poorly exposed, and occurs intermittently. Some outcrop is available up stream cuts, or behind slumped banks.



Access to Section I and the breccia is best done through a public access point where Water Street turns into a small gravel parking area, leading to the beach. Heading west, large cement blocks may complicate passage at high tide, but these can be bypassed by taking a steeper route closer to the end of Water St. Similarly, passage around the breccia at high tide can be difficult.

Section II can be accessed either by walking from section I at moderate and low tides, or by parking at the confluence of the railway and Highway 134 (Roseberry Street). The path down is not clearly marked, the brush is thick in places, and care should be used crossing the railway track.

GPS coordinates of outcrops as of August 2009:

Note: Rapid coastal erosion causes outcrop exposure to change from year to year.

Section I	48.0005N 66.7028W → 48.0000 66.7040W 47.9969N 66.7115W → 47.9958 66.7131W – Fish beds
Section II	48.0036N 66.6921W → 48.0029 66.6936W 48.0040N 66.6915W → 48.0045 66.6897W
Section III	48.0669N 66.4102W → 48.0666N 66.4115W – Plant beds 48.0663N 66.4126W → 48.0661N 66.4134W – Plant beds 48.0660N 66.4140W → 48.0659N 66.4161W 48.0660N 66.4174W → 48.0659N 66.4178W – Volcanics 48.0657N 66.4201W → 48.1656N 66.4241W – Microbialites 48.0661N 66.4308W → 48.0662N 66.4314W – Pin Sec Point 48.0661N 66.4338W → 48.0660N 66.4339W – Coals 48.0653N 66.4370W → 48.0652N 66.4379W
Section IV	48.0556N 66.48118W → 48.0549N 66.4823W – Rootlets 48.0537N 66.4838W → 48.0524N 66.4859W 48.0517N 66.48682W → 48.0507N 66.4878W
Section V	48.0361N 48.0361W → 48.0366N 66.5211W – Plant beds 48.0388N 66.5168W – Plant beds 48.0390N 66.5163W → 48.0395N 66.5152W – Plant beds
Section VI	48.0627N 66.4684W → 48.0616N 66.4716W – Point la Nim 48.0601N 66.4748W → 48.0587N 66.4774W
Breccia	48.0021N 66.6946W → 48.0014N 66.6980W – Fish and plant beds

Appendix 2: Electron Microprobe

Methodology

One sample was analyzed with an electron microprobe (Jeol JXA8200 Superprobe) to aid in mineral identification. A polished thin section was carbon coated and analysed with K_α x-rays using the following standards: sanidine (for K, Al, and Si); Cr-metal (for Cr); jadeite (for Na); pyrolusite (for Mn); kanganui kaersutite (for Ca, Mg, Ti); garnet (for Fe); and Ni-metal (for Ni). A 10 µm spot size was analysed with a 15 kV accelerating voltage and a beam current of 20 nA for a counting time of 20 s on peak, and 10 s on both the upper and lower background. Intensities were counted at full-width at half maximum using a ZAF matrix correction.

Data: Mass %

K_2O	Cr_2O_3	Na_2O	SiO_2	MnO	CaO	TiO_2	MgO	Al_2O_3	FeO	NiO	Total	Comment
12.5992	0	3.0335	63.5076	0.0248	0.0358	0.0636	0.0036	18.8601	0.153	0.0305	98.3118	Sanidine 53 ctrl
0.0301	0.0204	0	39.2383	0.5163	4.3284	0.0809	11.3612	23.233	22.3135	0.0502	101.1722	Garnet12442 ctrl
0.0353	0.0212	0	46.4314	0	0.0086	0	0	38.0339	0.2075	0.0077	84.7456	KK striped grain 3
0.033	0.017	0.0108	46.4167	0.0041	0.0524	0.01	0	38.1258	0.4088	0.0198	85.0984	KK striped grain 3b
0.0652	0.0102	0.0084	45.6634	0	0.0143	0	0	37.999	0.3079	0.0227	84.0911	KK striped grain 4a
0.038	0.0012	0.0087	45.4411	0	0.0396	0	0	37.9911	0.1647	0.021	83.7055	KK striped grain 4b
0.038	0.007	0.0021	45.4532	0.0012	0.0215	0	0.0034	37.3422	0.1247	0	82.9934	KK striped grain 5a
0.2133	0.0186	0.0257	45.4953	0	0.01	0	0.0195	37.8514	0.1416	0	83.7755	KK striped grain 5b
0.0539	0.0123	0.0222	45.7497	0	0.0262	0	0	37.6106	0.1924	0	83.6674	KK striped grain 6a
0.9022	0.0328	0.0704	45.9454	0	0.0635	0.0431	0.0645	37.8573	0.2414	0	85.2207	KK striped grain 6b
0.4037	0.0254	0.0288	46.0362	0	0.04	0.0373	0.1924	36.832	0.7477	0	84.3436	KK striped grain 7a
0.5787	0.0333	0.0412	45.9009	0.0106	0.0629	0.0408	0.2564	36.9683	1.0055	0	84.8987	KK striped grain 7b
0.1616	0	0.0157	46.7725	0	0.0372	0	0.0486	37.9588	0.4331	0	85.4276	KK striped grain 8a
0.553	0.0228	0.024	45.6968	0	0.0167	0.0366	0.0403	37.8385	0.2126	0	84.4414	KK striped grain 8b
0.0991	0.0381	0.0143	44.5464	0	0.0701	0.005	0.0054	36.7959	0.4009	0.0129	81.9882	KK striped grain 9a
0.4363	0.0418	0.0066	45.6638	0.0041	0.0248	0	0.0538	37.3634	0.2656	0.0089	83.8692	KK striped grain 9b
0.4375	0.0518	0.0355	44.6132	0	0.0296	0.0395	0.072	37.1568	0.2977	0	82.7337	KK striped grain 10a
0.172	0.0175	0.0066	44.0693	0.016	0.0372	0.0129	0.0361	36.8974	0.2155	0	81.4806	KK striped grain 10b
0.0747	0.0012	0	46.7539	0	0.0148	0.0237	0.0228	38.2555	0.2262	0	85.3729	KK striped grain 11a
0.0761	0.0175	0.0226	46.3073	0	0.0424	0	0.0394	37.7785	0.2753	0	84.5592	KK striped grain 11b
0.1136	0.0328	0.0126	46.6216	0	0.0243	0.0043	0.0158	37.8579	0.4472	0	85.1301	KK striped grain 12a
0.0516	0.0123	0	46.7162	0	0.0696	0	0.0236	38.2649	0.538	0.0037	85.68	KK striped grain 12b
1.087	0.0506	0.0304	46.0528	0	0.1722	0.0315	0.243	36.114	1.0071	0.0164	84.8051	KK striped grain 13a
0.4121	0.0376	0.0399	45.1873	0.003	0.1087	0.0294	0.0776	36.7153	0.521	0.0083	83.1403	KK striped grain 13b
11.5591	0	3.055	63.1471	0	0.0125	0.0174	0.0008	18.5162	0.1523	0.0056	96.466	Sanidine 53 ctrl

Results:

	K_2O	**Cr_2O_3**	**Na_2O**	**SiO_2**	**MnO**	**CaO**	**TiO_2**	**MgO**	**Al_2O_3**	**FeO**	**NiO**	**H_2O**	**Total**
Average mass % for unknown mineral “striped grain”	0.274	0.023	0.019	45.797	0.002	0.045	0.014	0.055	37.528	0.381	0.006	15.856	84.144
STD DEV n=22	0.296	0.015	0.017	0.734	0.004	0.038	0.017	0.076	0.593	0.253	0.008	1.132	1.132
Molecular ratio to Al	0.008	0.000	0.001	2.071	0.000	0.002	0.000	0.004	1.000	0.014	0.000	2.391	
Cation proportion	0	0	0	2.1	0	0	0	0	2	0	0		

$2Si^{+4}$, $2Al^{+3}$, charge balanced by $7O^{-2}$

$Si_2Al_2O_7 \cdot 2.4H_2O \rightarrow Si_2Al_2O_5(OH)_4$

Note: 0.4 H_2O remained after elucidation of this chemical formula. This discrepancy is most likely due to impurities in the platy crystal structure and the assumption that all mass unaccounted for is H_2O.