Lower Paleozoic stratigraphic and biostratigraphic correlations in the Canadian Cordillera: implications for the tectonic evolution of the Laurentian margin[1]

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Abstract: The ancient Laurentian margin rifted in the latest Neoproterozoic to early Cambrian but appears not to have developed as a simple passive margin through a long, post-rift, drift phase. Stratigraphic and conodont biostratigraphic information from four platform-to-basin transects across the margin has advanced our knowledge of the early Paleozoic evolution of the margin. In northeastern British Columbia, two northern transects span the Macdonald Platform to Kechika Trough and Ospika Embayment, and a third transect spans the parautochthonous Cassiar Terrane. In the southern Rocky Mountains, new conodont biostratigraphic data for the Ordovician succession of the Bow Platform is correlated to coeval basinal facies of the White River Trough. In total, from 26 stratigraphic sections, over 25 km of strata were measured and > 1200 conodont samples were collected that yielded over 100 000 conodont elements. Key zonal species were used for regional correlation of uppermost Cambrian to Middle Devonian strata along the Cordillera. The biostratigraphy temporally constrains at least two periods of renewed extension along the margin, in the latest Cambrian and late Early Ordovician. Alkalic volcanics associated with abrupt facies changes across the ancient shelf break, intervals of slope debris breccia deposits, and distal turbidite flows suggest the margin was characterized by intervals of volcanism, basin foundering, and platform flooding. Siliciclastics in the succession were sourced by a reactivation of tectonic highs, such as the Peace River Arch. Prominent hiatuses punctuate the succession, including unconformities of early Late Ordovician, sub-Llandovery, possibly Early to Middle Silurian and Early Devonian ages.

Résumé : L'ancienne marge laurentienne a dérivé depuis le Néoprotérozoïque tardif jusqu'au Cambrien précoce, mais elle ne semble pas s'être développée comme simple marge passive au cours d'une longue phase de dérivation après la dérivation. Des informations stratigraphiques et biostratigraphiques sur des Conodontes provenant de quatre transects, de la plate-forme au bassin, à travers la marge ont permis d'avancer nos connaissances de l'évolution de la marge au Paléozoïque précoce. Dans le nord-est de la Colombie-Britannique, deux transects nordiques chevauchent la plate-forme de Macdonald jusqu'à la fosse de Kechika et le réentrant d'Ospika; un troisième transect chevauche le terrane parautochtone de Cassiar. Dans les Montagnes Rocheuses septentrionales, de nouvelles données biostratigraphiques des Conodontes pour la succession, à l'Ordovicien, de la plate-forme de Bow sont corrélées au faciès contemporain de bassin de la fosse White River. Au total, à partir de 26 coupes stratigraphiques, plus de 25 km de strates ont été mesurées et décrites et plus de 1200 échantillons de Conodontes ont été recueillis, fournissant plus de 100 000 éléments de Conodontes. Des espèces zonales clés ont été utilisées pour des corrélations régionales des strates du Cambrien terminal au Dévonien moyen le long de la Cordillère. La biostratigraphie restreint dans le temps au moins deux périodes d'extension renouvelée le long de la marge, au Cambrien le plus récent et à l'Ordovicien précoce tardif. Des volcaniques alcalins associés aux changements abrupts de faciès à travers l'ancien bris de plate-forme, des intervalles de dépôts de brèche de débris de pente et des écoulements distaux de turbidites suggèrent que la marge était caractérisée par des intervalles de volcanisme, d'effondrement de bassins et d'inondation des plates-formes. Les siliclastiques dans la succession tirent leur source d'une réactivation des sommets tectoniques tels que l'arche de Peace River. Des hiatus proéminents ponctuent la succession, incluant des discordances à l'Ordovicien tardif précoce, au sub-Llandovérien, possiblement au Silurien précoce à moyen et au Dévonien précoce.

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Introduction

Following the breakup of the supercontinent Rodinia in the Neoproterozoic (Hoffman 1991; Moores 1991; Unrug 1997; Handke et al. 1999; Karlstrom et al. 1999), the rifted western margin of Laurentia was the site of deposition for over 400 Ma, through the early and mid-Paleozoic. The lower Paleozoic stratigraphic succession accumulated as a westward thickening wedge along the length of the rifted Canadian Cordillera margin and has long been referred to as a passive margin succession. However, the strata document a history that is more complex, in which several periods of extension followed the main late Neoproterozoic rifting event (Thompson et al. 1987).

The Cambrian to Silurian deposits of the margin extend from southwest Alberta to northeastern British Columbia into the western Northwest Territories and Yukon Territory as shallow-water carbonates passing to the west into equivalent deep-water slope and basinal facies (Cecile and Norford 1993; Cecile et al. 1997) (Fig. 1). For much of the Cordillera, the Rocky Mountain Trench and Northern Rocky Mountain Trench – Tintina Fault mark the boundary between autochthonous strata deposited on cratonic North America and the parautochthonous and allochthonous terranes of the Cordillera.

In the past decade, knowledge of the evolution of the Canadian Cordilleran margin during the early Paleozoic has been advanced through several platform-to-basin transect studies. The detailed stratigraphy and conodont biostratigraphy established for the uppermost Cambrian through Devonian strata provide the temporal framework necessary to study the nature of the margin preserved in British Columbia and Alberta. Previous studies were based on reconnaissance style biostratigraphic determinations of relatively few conodont samples collected during regional mapping projects. It has been over a decade since the overview by Barnes et al. (1991) and later by Norford et al. (1997) of the regions and stratigraphic units of the Cordillera that have yielded Ordovician and Silurian conodont data.

More than one transect is necessary to understand the complex evolution of the ancient margin. The four transects across the margin (Fig. 1) are the result of eight seasons of fieldwork from 1990 to 1998. The work in the three northern transects was logistically challenging in remote, alpine terrain accessible only by helicopter, while the areas in the southern Cordillera were more accessible. In total, 26 sections were studied in detail, in which over 25 000 m of strata were measured and described and over 1200 conodont samples, averaging 2.5–4 kg each, were collected (Table 1). The taxonomic assignment of more than 100 000 conodont elements and recognition of key zonal species resulted in a constrained biostratigraphic framework for each transect.

In the southern Rocky Mountains (transect 1, Fig. 1), the fauna of a nearly complete Ordovician platformal succession of the Bow Platform was studied in Jasper National Park, Alberta (Ji and Barnes 1996; Pyle et al. 2003*a*). The formations of this section can be traced westward into the basinal equivalents of the White River Trough and correlated to the McKay Group (three transects of McKenzie McAnally and Barnes 1995) and Glenogle Formation (several sections studied by Norford et al. 2002). In the northern Rocky Mountains, two platform-to-basin transects from the Macdonald Platform to the Kechika Trough and its southern extension, called the Ospika Embayment, were studied (transects 2 and 3, Fig. 1). In conjunction with the Geological Survey of Canada's Central Foreland National Mapping (NATMAP) Project, a northeast–southwest, platform – shelfbreak – basin transect (transect 2, Fig. 1) contained several Ordovician–Devonian units (Pyle and Barnes 2001*b*; Pyle et al. 2003*b*). A revised and refined stratigraphic framework and conodont biostratigraphy of the Kechika and Skoki formations and Road River Group was established from transect 3 (Pyle and Barnes 2000, 2002). The most northern transect in British Columbia lies across the parautochthonous Cassiar Terrane (transect 4, Fig. 1). Pyle and Barnes (2001*a*) examined the correlative lower Paleozoic strata of this northward-displaced margin segment. The several recent publications by the authors cited in this paragraphs document the detailed stratigraphic framework and tight biostratigraphic control for the Upper Cambrian to Middle Devonian units along the Cordilleran margin.

The purpose of this paper is to interpret the early Paleozoic evolution of the rifted western Laurentian margin through detailed stratigraphy and conodont biostratigraphy from four platform-to-basin transects. This study reports new conodont biostratigraphic data and a revised correlation for transect 1. A synthesis of the stratigraphic revisions and temporal constraints on the ages of several new Ordovician and Silurian formations within transects 2, 3, and 4 is presented and correlated with units in transect 1. In addition, the regional study addresses the apparent non-passive nature of the margin by relating, through space and time, the abrupt lateral facies changes, associated shelfbreak events, occurrence of volcanics, and nature of unconformities across the transects.

The Cordilleran margin

The timing and nature of the rifting events that created the Cordilleran margin of Laurentia are controversial. A brief review of the evidence for two rifting events in the Neoproterozoic illustrates that the margin is more complex than that of a simple passive margin. The lower Paleozoic succession that accumulated on the rifted margin contains evidence to support a tectonic evolution complicated by further extensional events.

Colpron et al. (2002) reviewed the evidence for the initial rifting of the interior of Rodinia (Hoffman 1991) that resulted in the development of the Windermere Supergroup along the margin of Laurentia (Ross 1991). The breakout of Laurentia from Rodinia has been estimated at ca. 700 Ma (Powell et al. 1993), ca. 725 Ma (Unrug 1997), and ca. 755 Ma (Wingate and Giddings 2000) from tectonic reconstructions and from 762 to 728 Ma based on geochronologic constaints from the syn-rift sediments of the basal Windermere Supergroup (Ross et al. 1995).

In conflict with these ages are those derived from quantitative analyses of early Paleozoic subsidence of the western North American miogeocline that began ca. 600 Ma (Bond and Kominz 1984; Bond et al. 1985). In addition, evidence for a younger, early Cambrian separation event as suggested by Sears and Price (2000) is further constrained in the southeastern Canadian Cordillera within the Hamill–Gog Group (Bond et al. 1985; Devlin and Bond 1988; Lickorish and Simony 1995) and syn-rift volcanics from the Hamill Group

Fig. 1. Map showing early Paleozoic paleogeography, distribution of platformal and basinal rocks, occurrences of lower Paleozoic volcanic rocks, and lines of platform-to-basin transects (1 to 4). NRMT, Northern Rocky Mountain – Tintina Fault (modified from Cecile et al. 1997).

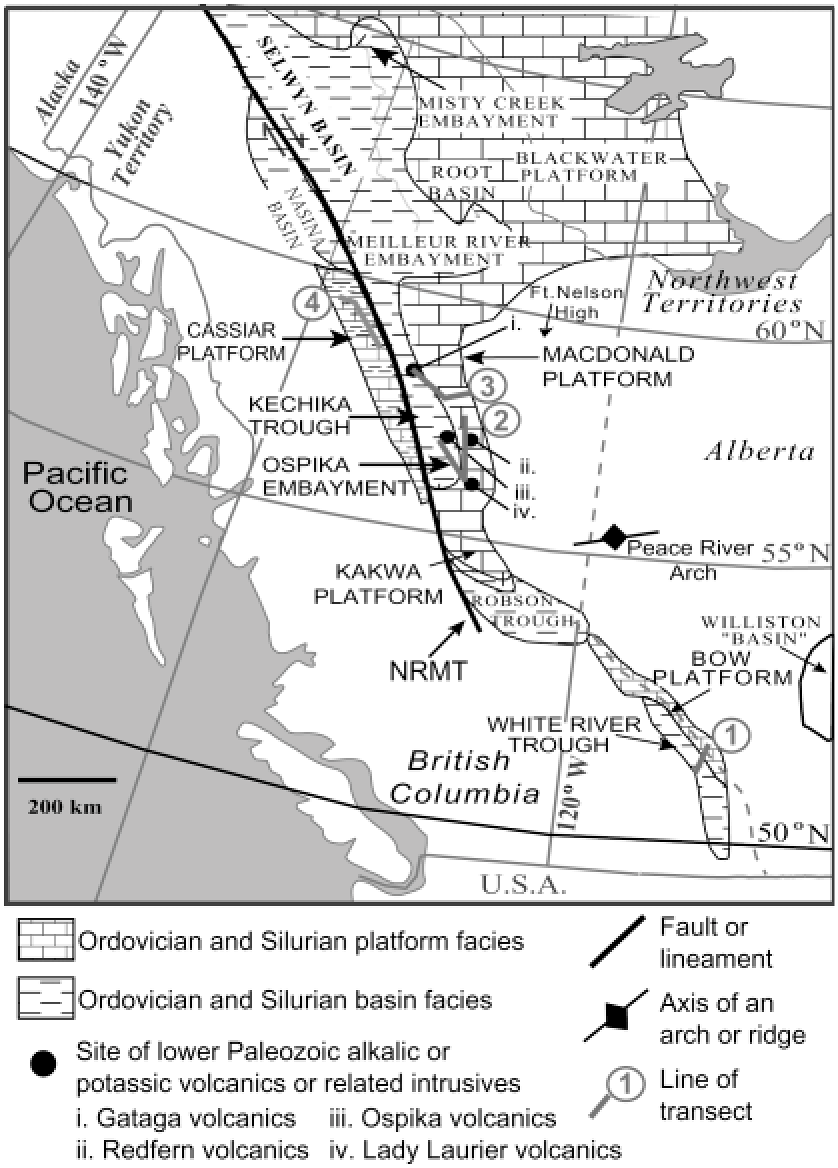


Table 1. Summary of stratigraphic data collected from four transects in the Cordillera.

	1. Southern transect	2. Northeastern transect	3. Northern transect	4. Cassiar Terrane transect
No. of sections studied	4	10	9	3
Approximate total thickness of strata measured and described (m)	ca. 4 000	8 850	9 000	3 000
Total conodont samples (2.5–4 kg each)	539	257	320	85
Conodont elements recovered	ca. 65 000	16 876	38 600	926
No. of genera and species	ca. 70 genera, ca. 130 spp.	81 genera, 139 spp.	69 genera, 185 spp.	21 genera, 31 spp.

dated at 569.6 ± 5.3 Ma (Colpron et al. 2002). Colpron et al. (2002, their fig. 6) proposed a model in which two separation events occurred along the margin, accounting for the differences in the nature and timing of Windermere-age and Hamill–Gog-age events.

In the early Paleozoic, subsequent periods of renewed extension, rifting, and post-rift subsidence occurred along the margin, which cannot be explained by a single continental rifting and separation event (Thompson et al. 1987). A tectonic model for the Cordillera, proposed by Cecile et al. (1997), attributes the variation in paleogeography and depositional history along the length of the margin to divisions of the Cordilleran Miogeocline into crustal blocks of alternating upper- and lower-plate segments of a rifted margin. The four transects lie within an upper plate segment of the margin characterized by a narrowly preserved miogeocline and dominated by paleogeographic highs. The Peace River Arch, the southern boundary of the Ospika Embayment, was a source of clastics deposited along the Cordilleran margin from the latest Middle Cambrian to Middle Devonian during times of emergence and periodic activation (Norford 1991; Ross et al. 1993; Gehrels et al. 1995). Other highs, such as the Fort Nelson High (Norford et al. 1966; Ross et al. 1993; Rigby et al. 1998), northeast of the Ospika Embayment, may have shed clastics across the Macdonald Platform and into the Ospika Embayment. The tectono-stratigraphic framework was also influenced by eustatic sea-level changes. In the Ordovician, the North American margin experienced eustatic sea-level change with the largest incursions occurring in the Caradocian (Barnes 1984).

Prior to the initiation of the detailed stratigraphic and conodont biostratigraphic studies over the past decade, the nature of this segment of the early Paleozoic Laurentian margin could not be fully assessed. Regionally, the tectonic influences on the facies trends and sedimentation patterns across the transects indicate at least two phases of extension, from the Early to Middle Cambrian and from the Middle Ordovician to Middle Devonian (Pyle and Barnes 2000). The following sections review the stratigraphic framework for the southern and northern transects and the parautochthonous Cassiar Terrane that form the basis for regional tectonic and stratigraphic interpretations.

Stratigraphic framework, transect 1

Resting on the sub-Cambrian unconformity are clastics of the Hamill–Gog Group, which are in turn overlain by a westward thickening miogeoclinal wedge, bounded by the sub-Devonian unconformity (see fig. 5 in Bond and Kominz 1984), that developed on a subsiding margin (Aitken 1981). The late Lower and Middle Cambrian units form a series of sedimentary grand cycles, each cycle consisting of an alternation of thick, shale-dominated, recessive half-cycle that grades into a carbonate-dominated, resistant half-cycle (Aitken 1966, 1968) (see fig. 7.14 in Fritz et al. 1991). These cyclical upward-shallowing events represent a shift in deposition from a deeper water facies belt to a cratonward, carbonate-dominated belt in response to eustatic sea-level change and (or) local tectonic controls.

The Upper Cambrian is well exposed in the southern Canadian Rocky Mountains, the lithostratigraphic framework of which has been established by Aitken (1966, 1968), and Aitken and Greggs (1967). Four complete grand cycles occuring in ascending order, these are the Pika; Arctomys and Waterfowl; Sullivan and Lyell; and Bison Creek and Mistaya formations (Aitken 1966; Ludvigsen and Westrop 1985). The Bison Creek and Mistaya grand cycle is overlain by the Survey Peak Formation.

Transect 1 contains one platform section (Wilcox Pass) and three key basinal sections (of McKenzie McAnally and Barnes 1995), in which over 4000 m of strata have been sampled extensively for conodonts (539 samples, Table 1). The stratigraphic framework discussed in detail later in the text is based on new data obtained from the Wilcox Pass Section.

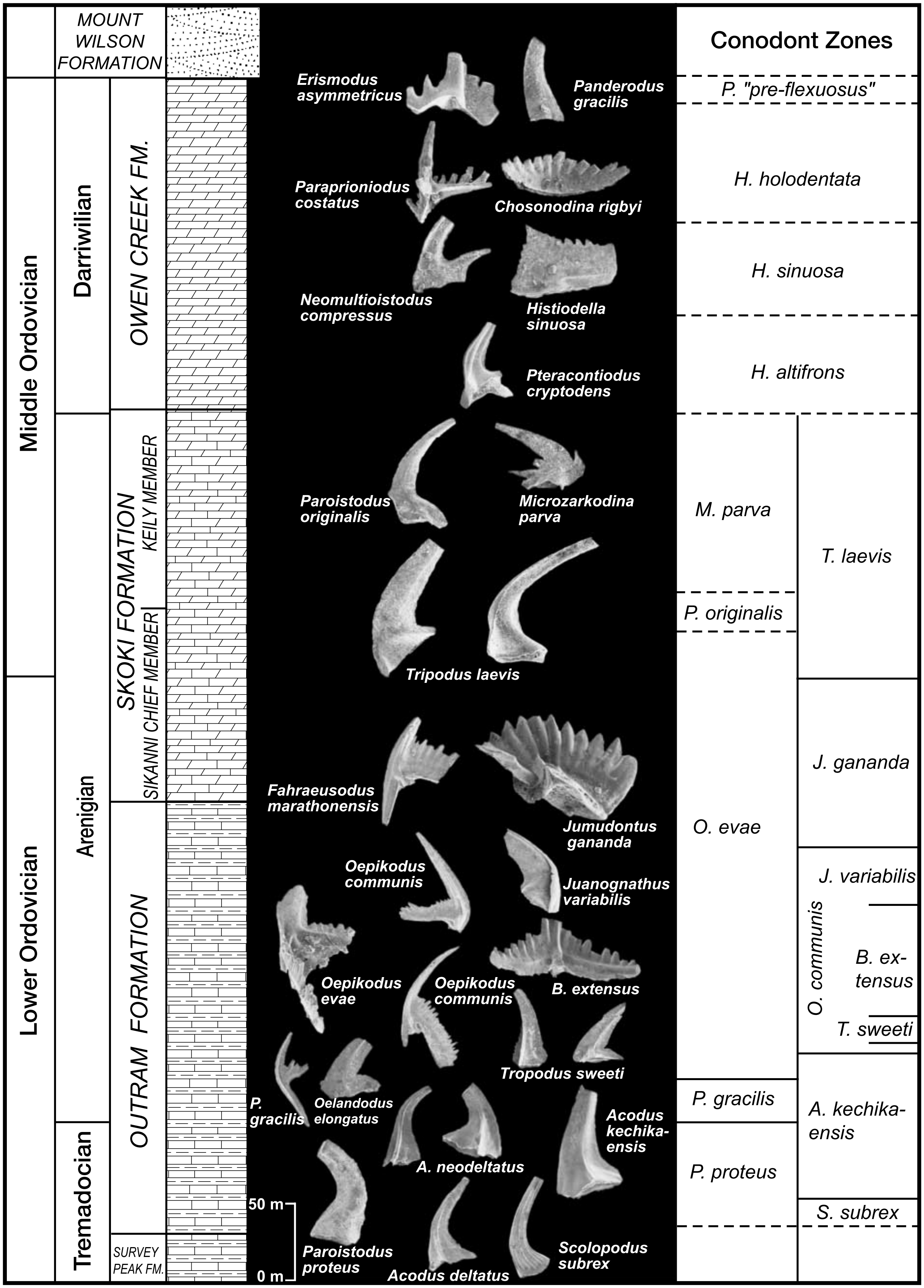
The Wilcox Pass Section, Jasper National Park, Alberta, exposes a nearly complete carbonate platform sequence, over 1000 m thick, of latest Cambrian to Middle Ordovician age. The formations of the Wilcox Pass Section can be traced westwards into the offshore equivalents of the White River Trough (Fig. 1). Deposition of the Survey Peak followed the termination of the underlying uppermost Cambrian grand cycle, and its four informal members in turn comprise a grand cycle. A flooding surface at the base of the Basal Silty member represents the drowning of the carbonate bank during a relative rise in sea level in the latest Cambrian (Ji and Barnes 1996). The formation is shallows upward to the Upper Carbonate member (uppermost Tremadocian).

This section presents new detailed conodont biostratigraphic data for the overlying succession at Wilcox Pass, which represents the standard reference section for the Lower–Middle Ordovician of the southern Canadian Cordillera (Pyle et al. 2003*a*) (Fig. 2). The Outram Formation (*Scolopodus subrex* Zone, Tremadocian, to *Jumudontus gananda* Zone, Arenigian) is the base of the next grand cycle, composed of dark grey shale, calcareous siltstone, thick-bedded limestone, and limestone pebble conglomerate. It ranges from 170 to 443 m thick within the southern Rocky Mountains. The lower contact with the Survey Peak Formation is gradational. The upper contact with the Skoki Formation is gradational (Aitken and Norford 1967) and contains alternations of the dominant lithologies of each formation such that the base of the Skoki Formation is estimated at 583 m above section base at Wilcox Pass.

The Skoki Formation was named by Walcott (1928) and has been divided into four formal members by Pyle and Barnes (2000, 2001*b*). The formation is 250 m thick at Wilcox Pass and is divided into two members recognized in the northern Rocky Mountains: the Sikanni Chief and Keily members. The base of the Skoki Formation lies in the *J. gananda* Zone, Arenigian, and the formation ranges into the *Histiodella altifrons* Zone, earliest Darriwilian. Its lower contact with the Outram Formation is gradational, and its upper contact with the Owen Creek Formation is paraconformable. Based on the Wilcox Pass Section, the Sikanni Chief Member (126 m thick) is medium grey, rubbly weathering, thin- to thick-bedded dolostone with thin interbeds of lime mudstone to grainstone. Chert occurs in discontinuous beds and as stringers. Abundant, large macluritid gastropods (described by Rohr et al. 1995) and large oncolites, 1.5–2.0 cm in diameter, are abundant in the upper part of the member. A lithologic change to dark grey weathering lime mudstone and yellow-grey weathering, mottled, massive dolostone of the Keily Member (124 m thick) occurs at 709 m above the base of the section. The Redfern Member (of Pyle and Barnes 2000) in the northern Rocky Mountains is equivalent in lithology and fauna to the Owen Creek Formation.

The Owen Creek Formation was formally defined by Norford (1969) at its type locality, Mount Wilson, southwest Alberta. Regionally, the formation ranges in thickness from 46 to 199 m, and its contact with the underlying Skoki Formation

Fig. 2. Biostratigraphy of the Ordovician Outram, Skoki, and Owen Creek formations, Wilcox Pass Section, Alberta, showing the key zonal species used for the regional correlation in Fig. 3. Revisions to the standard Atlantic Realm (left column) and Midcontinent Realm (right column) conodont zonations are after Pyle and Barnes (2002).



is paraconformable with evidence of channel filling and karstification at some sections. At Wilcox Pass, the formation is 205 m thick and has a conformable lower contact with the Skoki Formation (at 833 m above section base), marked by a change in weathering colour from grey to yellow-grey. The Owen Creek Formation ranges from the *H. altifrons* Zone to the *Phragmodus "pre-flexuosus"* Zone and is, therefore, Darriwilian in age. The dominant lithology is pale weathering, well-bedded, aphanitic dolostone and thick-bedded dolostone in upward shallowing cycles about 10 m thick that contain alternations of shallow subtidal to intertidal, thin-bedded, mottled dolostone to supratidal, laminated, and mud-cracked dolostone. Interbeds of sandy dolostone that contain scattered, rounded quartz grains are common and minor chert stringers occur in some beds. The upper beds of the formation contain dolomitic sandstone with cross-laminae. The upper contact with the light grey to white, thin- to thick-bedded, partly cross-stratified quartz sandstone of the Mount Wilson Formation is conformable, but erosional surfaces between the two formations are locally developed (Norford 1969).

The Mount Wilson Formation (up to 460 m thick) marks a profound lithologic change from the platformal carbonates to pure, grey to white quartzite. The formation lies conformably to disconformably over the Glenogle, Skoki, and (or) Owen Creek formations (Aitken et al. 1972). Undiagnostic conodonts of Middle or Late Ordovician age were reported by Norford (1969). The Beaverfoot Formation (up to 540 m thick) is mottled, thick-bedded to massive dolomitic limestone and dolostone that is conformable to disconformable with the Mount Wilson Formation. The Tegart Formation is upper Llandovery in age and overlies the Beaverfoot Formation (Norford 1994) (Fig. 3).

The McKay Group (ca. 3000 m thick) is the offshore lateral facies equivalent of the Bison Creek, Mistaya, Survey Peak, and Outram formations (Mott et al. 1986) that accumulated outboard of a hinge zone (Kicking Horse Rim) and thinned continental crust beneath the middle to outer part of the Bow Platform (Bond and Kominz 1984), resulting from a drift stage following a rifting event 600–555 Ma. The McKay Group contains eight units that comprise four grand cycles of a lower shale-dominated part and upper limestone-dominated part (Mott et al. 1986). It is conformable with the underlying Jubilee Formation and gradationally conformable with the black shale of the Glenogle Formation or disconformable with the Mount Wilson or Beaverfoot formations (Reesor 1973). The lower part of the upper McKay Group spans the Cambrian–Ordovician boundary through the *Cordylodus* zones (McKenzie McAnally and Barnes 1995), and the uppermost part of the McKay Group lies within the *Prioniodus elegans* Zone of the Atlantic Realm and *Oepikodus communis* Zone of the Midcontinent Realm (Norford et al. 2002). The Glenogle Formation extends into the *"Glyptograptus" euglyphus* Zone and correlative *Pygodus serra* Zone (upper Darriwilian) (Norford et al. 2002).

Stratigraphic framework, transects 2 and 3

As in the southern Cordillera, the lower Paleozoic strata of the Macdonald Platform – Kechika Trough transects accumulated on a subsiding continental margin and formed a westward thickening wedge. The important differences documented across transects 2 and 3 are (1) the ancient shelf break is preserved, and (2) units cut out by erosion in the southern Rockies are present in the north, although significant unconformities occur in the succession.

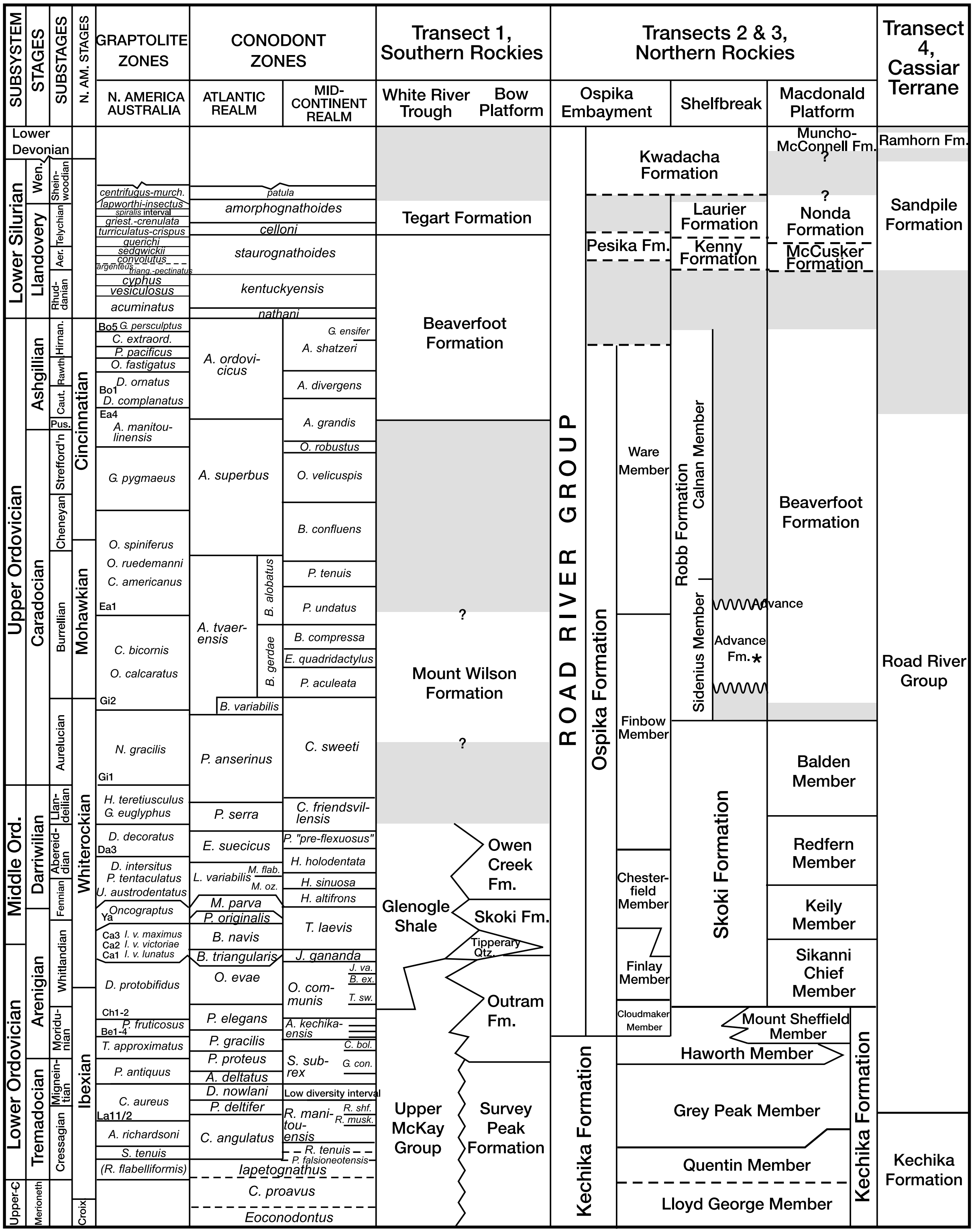
Lower to Middle Cambrian units in the Kechika Trough have been mapped as a composite Cambrian unit called "Gog Group and younger rocks," where archaeocyathids were absent, and assignment to the Gog Group could not be ascertained (Ferri et al. 1996). Ferri et al. (1996) also reported Lower Cambrian volcanic subunits (tuffs). In the northern Kechika Trough, a thick clastic-carbonate succession is similar to rift-to-drift deposits of the southern Cordillera (Post and Long 2000). The overlying Middle and Upper Cambrian succession in the Kechika Trough contains unnamed, interfingering carbonate and siliciclastic units (Fritz et al. 1991), the deposition of which may have been controlled by periodic fault-controlled extension, uplift, and subsidence (Ferri et al. 1996).

The stratigraphic units studied across transects 2 and 3 are the shallow-water platform succession of Kechika, Skoki, Beaverfoot, McCusker, and Nonda formations (uppermost Cambrian to Lower Silurian). The shelf to basin facies of the laterally extensive Kechika Formation (upper Cambrian to lower Ordovician) extend without abrupt facies changes from the platform to a broad, gently dipping ramp. The well-developed shelf break transition occurs in the Lower Ordovician, as facies of the platformal succession overlying the Kechika Formation change abruptly into slope-to-basin equivalents of the Road River Group (Lower Ordovician to Middle Devonian) (Fig. 3). The units that preserve the ancient shelf-break facies, the Robb, Kenny, and Laurier formations, were the focus of Transect 2 and include the transitional and off-shelf equivalents of the Upper Ordovician to Lower Silurian Beaverfoot, McCusker, and Nonda formations (Fig. 3). In total, 19 sections and nearly 19 000 m of strata were studied (Table 1) (Pyle and Barnes 2000, 2001*b*, 2002, 2003).

The Kechika Formation thickens westwards (200–1400 m) from the Macdonald Platform to Kechika Trough. It abruptly overlies shallow-water Cambrian units and represents deposition on a broad ramp with gradual lateral facies changes. It contains five members of typically light grey to brown weathering, calcareous shale with interbedded limestone. The lower part of the Kechika Formation contains the Cambrian–Ordovician boundary and its upper, conformable contact with the Skoki Formation is Early Ordovician (Arenigian) in age (Pyle and Barnes 2000, 2002). The Skoki Formation is locally over 1000 m thick and is typically thick-bedded to massive, light grey weathering dolostone, limestone, and shale. It contains a variety of subtidal platform facies, such as burrow-mottled dolostone; oncolitic and macluritid gastropod-rich dolostone; and laminated sandy dolostone. The uppermost member of the Skoki Formation is early Late Ordovician in age (Caradocian), but the Skoki Formation is commonly unconformably overlain by the Beaverfoot Formation.

The abrupt platform-to-basin transition is recorded in the lateral facies changes from the Skoki Formation to the lower part of the Ospika Formation of the Road River Group. The Ospika Formation (455 m thick) consists of five members and preserves spectacular transitional facies locally, in which

Fig. 3. Biostratigraphic correlation of the uppermost Cambrian to Lower Silurian units from the four transects in Fig. 1. Chronostratigraphy after Webby (1998) and Cooper et al. (2001). Standard graptolite zonation for the North America and Australia and standard conodont zonation from Webby (1995), with revision to the Lower Ordovician conodont zonation from Pyle and Barnes (2002). Refined correlation for the Lower to Middle Ordovician platformal succession of the southern transect 1 from this study based on Ji and Barnes (1996), Pyle et al. (2003*a*), and Norford et al. (2002), with information from Norford (1969, 1994) for the Upper Ordovician and Lower Silurian. The correlation of units from the northern transects 2 and 3 from Pyle and Barnes (2000, 2001*b*) and for the Cassiar Terrane (transect 4) from Pyle and Barnes (2001*a*) and Gabrielse (1998). Shading indicates hiatuses and * indicates that the Advance Formation (Norford 1996) was not examined in this present study.



debris flows containing clasts of Skoki Formation lithologies are interbedded with black shale. The initiation of Ospika Formation sedimentation represents an abrupt deepening phase in the late Early Ordovician (Pyle and Barnes 2000).

The platform succession of Beaverfoot, McCusker, and Nonda formations (Early Silurian) overlie the Skoki Formation and correlate to the off-shelf succession of the Robb, Kenny, and Laurier formations (Pyle and Barnes 2001*b*, 2003). The Beaverfoot Formation (ca. 200 m thick, Late Ordovician) consists of shallow platform dolostone and contains a unit of sandy dolostone and laminated sandstone at its base. The McCusker Formation (223 m thick at its type section, Early Silurian) occurs through a narrow belt in the study area of transect 2. It unconformably overlies the Beaverfoot Formation and consists of yellow-grey weathering, thin-bedded limestone, dolostone, and shale. The Nonda Formation (335 m thick, Early Silurian) rests unconformably on Precambrian, Cambrian, and Ordovician strata, and conformably overlies the McCusker Formation locally. It is typically composed of medium, grey-weathering, siliceous dolostone, dolomitic siltstone, sandstone, and quartzite, with rare limestone beds. It is unconformably overlain by dolostone and quartzite of the Muncho–McConnell Formation.

The transitional facies of the Robb Formation (481 m thick, Late Ordovician) contain quartzite, dolostone, and shale in the stratigraphic position between the Skoki and Nonda formations and correlate in part to the Beaverfoot Formation. It is also correlative to the uppermost member of the basinal Ospika Formation, the Ware Member. The Robb Formation is unconformably overlain by the Kenny Formation (ca. 200 m thick), a recessive unit of dark-weathering, thin-bedded limestone, siltstone, and shale. The Kenny Formation is coeval with the McCusker and Nonda formations. At a spectacular section within transect 2, carbonaceous lime mudstone of the Kenny Formation interfingers with debris flow deposits of the Nonda Formation (Pyle and Barnes 2001*b*). The Laurier Formation (161 m thick at its type section, Early Silurian) unconformably overlies the Kenny Formation. It contains mainly medium grey-weathering, thick-bedded, slope debris breccias in a series of flow deposits, the clasts of which are mainly of Nonda Formation lithologies (Pyle and Barnes 2001*b*). The Kenny and Laurier formations correlate in part to the slope to basinal Pesika Formation (230 m thick at its type section, Early Silurian in age) of the Road River Group, a locally preserved unit of thin-bedded limestone, shale, and thin-bedded slope breccia. The Pesika Formation is conformably to unconformably overlain by the Kwadacha Formation, an extensive unit in the Ospika Embayment. It is 300 m thick at its type section and is a resistant, orange to brown weathering siltstone unit. The unit, that ranges in age from latest Early Silurian to Early or Middle Devonian, may correlate in part to the Nonda Formation and overlying Muncho–McConnell Formation (Pyle and Barnes 2000).

A new formation of the Road River Group called the Deserters Formation is Early to Middle Devonian in age and was studied as part of Transect 2 (Pyle et al. 2003*b*). The formation unconformably overlies the Kwadacha Formation and contains mainly argillaceous, crinoidal limestone with interbeds of black shale, siltstone, dolostone, and intervals of tuff. The formation is regionally restricted and represents distal carbonate turbidite deposits of a linear sub-basin of the Ospika Embayment that experienced extension in the Lower to Middle Devonian. The formation is the age equivalent in part to the Stone and Dunedin formations of the Macdonald Platform to the east, and is flanked by carbonate facies of the Akie Reef (McIntyre 1992) to the west.

Stratigraphic framework, transect 4 (Cassiar Terrane)

The study of an east–west transect across the parautothonous Cassiar Terrane examined over 3000 m of lower Paleozoic strata in three sections, from which 85 conodont samples were collected (Table 1) (Pyle and Barnes 2001*a*). The Cassiar Terrane lies west of the Northern Rocky Mountain Trench fault (Fig. 1) and is a margin segment that has been displaced along the fault by a minimum of 500 km (Price and Carmichael 1986) or up to 900 km from the Kakwa Platform (Gabrielse 1985). Estimates indicate movement up to a maximum of 1700 km, based on Cambrian stratigraphy (Pope and Sears 1997) or over 2000 km, based on paleomagnetic data of overlying Slide Mountain Terrane (Richards et al. 1993). Although the amount of displacement of the terrane remains controversial, the detailed study of the stratigraphy and its conodont fauna by Pyle and Barnes (2001*a*) advanced the knowledge of its geological history. The age of the Kechika Formation – Road River Group boundary within the terrane, established by conodont biostratigraphy, is older within the Cassiar succession (*R. manitouensis* Zone, middle Tremadocian) compared with that east of the NRMT (*P. gracilis* Zone, lower Arenigian) (Fig. 3). This may help establish the initial position of the terrane if a similar aged boundary for the onset of Road River Group sedimentation is established on a section of the margin (?Kakwa Platform) (Pyle and Barnes 2001*a*).

Regional correlations

Although the general stratigraphic framework is known for the lower Paleozoic of the Canadian Cordillera, this detailed regional stratigraphic and conodont biostratigraphic framework provides for precisely constrained correlation of units (Fig. 3). The integration of conodont and graptolite zonations, where both fossil groups were recovered in the offshore facies, allows precise correlation between the two schemes. In addition, for the Lower Ordovician platformal succession in the southern Rocky Mountains, the conodont biostratigraphy is integrated with trilobite and acritarch zonations of Dean (1989) and Martin (1992), respectively (see Ji and Barnes 1996 and Pyle et al. 2003*a*). The biostratigraphy established for the Outram, Skoki, and Owen Creek formations from the Wilcox Pass Section (Fig. 3) illustrates the importance of conodont faunas for biostratigraphy, particularly from the dolomitic units where other zonal fossils are rarely preserved.

The details of the correlation of units from the platform to basin, as discussed in the previous sections for each transect, is summarized in Fig. 3. In transect 1, the lower part of the upper McKay Group spans the Cambrian–Ordovician boundary (McKenzie McAnally and Barnes 1995) and correlates to the Survey Peak and Outram formations. A key revision within Transect 1 is the precise ages of the Outram, Skoki, and Owen Creek formations. The contact of the Outram formation with the underlying Survey Peak Formation was previously reported as coeval with the McKay–Glenogle contact to the west (Slind et al. 1994), which marks a rapid deepening phase. The conodont data from this study and from that by Norford et al. (2002) indicate that the lower part of the Glenogle Formation is coeval with the upper part of the Outram Formation. The conodont data from the Wilcox Pass section established that the Survey Peak Formation and lower part of the Outram Formation are correlative to the Kechika Formation in transect 3. The exact age of the base of the Kechika Formation of the Cassiar Terrane has not been ascertained.

The upper part of the Outram Formation is also partly equivalent to the Skoki Formation (*O. communis* Zone) of the northern Rockies. The base of the Skoki Formation is diachronous, such that in the southern Rockies, it lies within the *J. gananda* Zone (latest Arenigian) and in the *O. communis* Zone (middle Arenigian) in the northern Rockies. The new data from the Wilcox Pass section also establishes that the overlying Owen Creek Formation is equivalent to the Redfern Member of the Skoki Formation of the Macdonald Platform.

Just as the McKay Group is overlain by deeper-water facies of the Glenogle Formation in the south, the Kechika Formation – Road River Group transition occurs in the north. This Middle Ordovician deepening phase and pronounced shelfbreak development is best observed in the Skoki–Ospika Formation transition in the northern transects. The base of the Road River Group in the Cassiar Terrane is older (Tremadocian) than its correlative facies in the northern Rockies (Arenigian).

The hiatus of late Middle – Late Ordovician age lies at the base of the quartzite of the Mount Wilson Formation. This hiatus correlates in part to that at the base of the Beaverfoot Formation of the Macdonald Platform; however, the uppermost unit of the Skoki Formation and its basinal equivalent, the Finbow Member of the Ospika Formation, bridge some of this time gap in the north (representing the early Late Ordovician). The Beaverfoot Formation of northern Rockies is time equivalent to the Mount Wilson Formation and the Beaverfoot Formation of the southern Rockies. The sands of the Mount Wilson Formation and base of the northern Beaverfoot Formation also formed deposits preserved within the shelfbreak succession, assigned to the Robb Formation, and extend into the Ospika Embayment as the uppermost member of the Ospika Formation, the Ware Member.

In the Macdonald Platform, the Beaverfoot Formation is overlain unconformably by the Lower Silurian McCusker and Nonda formations. In contrast, the Beaverfoot Formation of the Bow Platform extends into the Lower Silurian and is overlain by the Tegart Formation, which is time equivalent to the Nonda Formation. Lower Paleozoic strata younger than the Tegart Formation have been removed by erosion, represented by the sub-Devonian unconformity in the southern Rockies. In the northern Rockies, the Lower Devonian Muncho–McConnell Formation unconformably overlies the Nonda Formation and may correlate in part to the Kwadacha Formation and Deserters Formation of Early–Middle Devonian age (not shown in Fig. 3). The Kwadacha Formation may record continuous sedimentation locally through the Silurian, but elsewhere unconformably overlies the Ordovician Ospika Formation and is unconformably overlain by the Deserters Formation.

Depositional and tectonic history

The detailed stratigraphic revision from this large regional study provides constraints on the timing of depositional and tectonic events during the early Paleozoic. The evidence from the stratigraphic record, specifically the abrupt platform-to-basin facies changes, occurrence of Middle Ordovician and Middle Devonian alkalic volcanics, influx of siliciclastic material from reactivated arches, and significant unconformities that punctuate the succession, indicate that extensional tectonism persisted during the early Paleozoic, after the proposed initial rifting of Rodinia in the Neoproterozoic and the breakup unconformity of the basal Cambrian. This discussion focuses on the outcrop-based interpretations of key stratigraphic surfaces and hiatuses that represent major shifts in depositional trends primarily related to regional tectonic controls. The overprint of the eustatic history is not addressed in detail here, but will be discussed in a forthcoming paper.

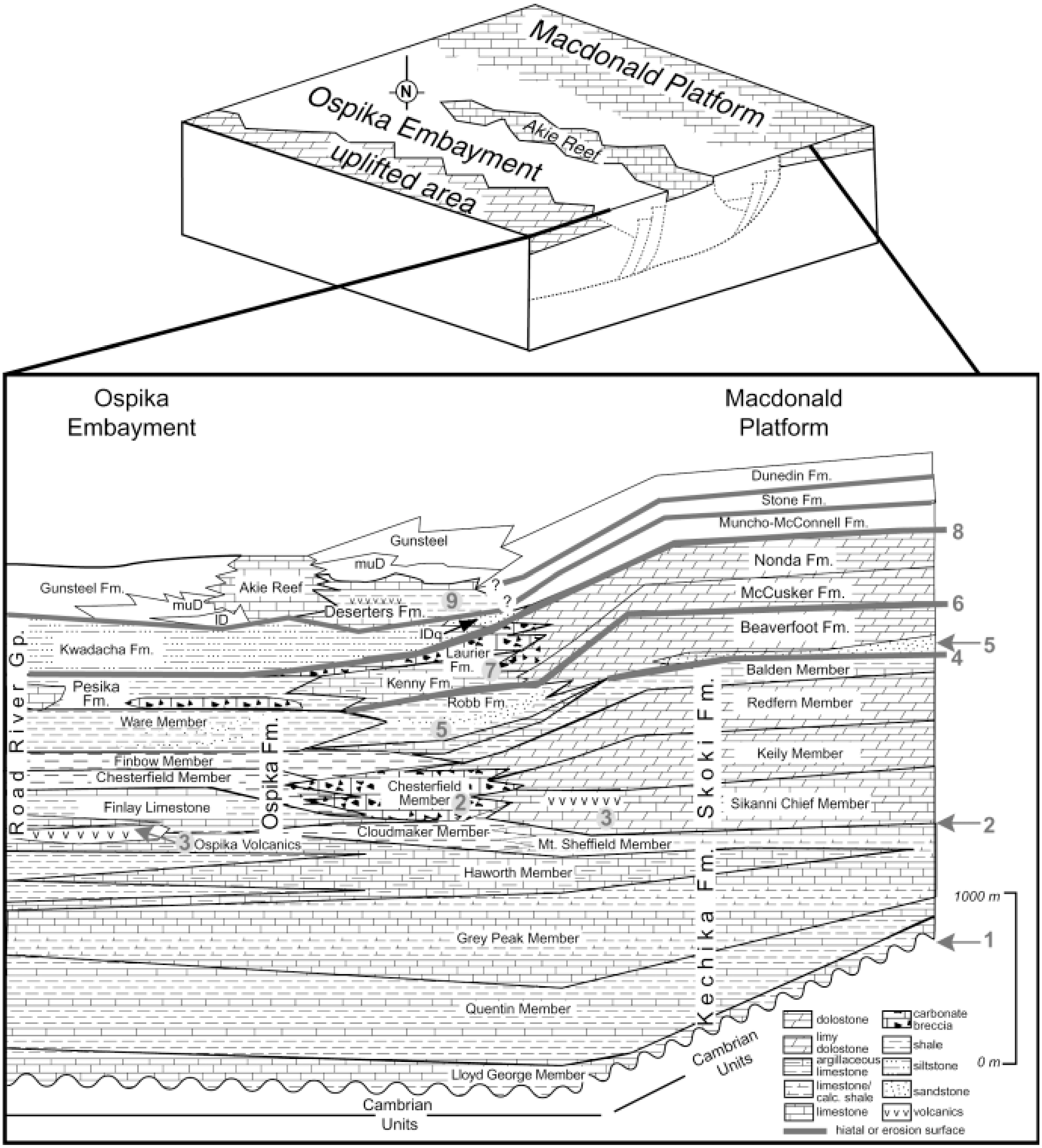
Although the Cambrian successions of transects 2 and 3 have not been described and interpreted in detail previously and were not the focus of this present study, there are several factors that indicate periods of extension with the development of rifted and rotated fault blocks. On the Macdonald Platform, Taylor and Stott (1973) described Lower Cambrian syndepositional extension faults with up to 1500 m displacement, overlain by Ordovician strata. Ferri et al. (1996) described units of tuffs with subordinate submarine alkalic flows and volcaniclastics, typical of the rift-related volcanic sequences documented elsewhere in the lower Paleozoic of the northern Cordilleran miogeocline (Goodfellow et al. 1995). Fritz et al. (1991) described the laterally distinct Upper Cambrian units that developed in the Kechika Trough, in which block faulting may account for both the development of clean carbonates free of terrigenous clastics, as well as the varying degrees of erosion at the top of the Upper Cambrian units prior to Kechika Formation sedimentation.

The evidence for episodes of extensional tectonism in the early Paleozoic, illustrated in a representative cross-section from transects 2 and 3, highlights the major events (Fig. 4). These numbered events are summarized as follows:

(1) The initiation of sedimentation of the Kechika and Survey Peak formations and coeval thick upper McKay Group represents a flooding surface and deepening event that may be associated with a latest Cambrian phase of post-rift thermal subsidence. Just as the Survey Peak changes laterally to the upper McKay Group from east to west in transect 1, the Kechika Formation shows a westward change in depositional environment from platform to shelf and deep shelf as part of the subsidence phase and differentiation of platform and basin strata from the latest Cambrian to Early Ordovician (MacIntyre 1992). Within the Kechika Trough, the abrupt vertical facies change from shallow-water clastics to the thick succession of distal, carbonate-dominated facies of the Kechika Formation may be the result of renewed subsidence.

(2, 3) Depositional changes are more abrupt in the late Early Ordovician (Arenigian), as seen in the Skoki Formation to Ospika Formation transition. The steepening of the shelf-break margin is recorded in the transitional facies of the Chesterfield Member, where preserved, that include thick debris flow breccias containing large clasts and blocks of

Fig. 4. Schematic east–west cross-section from the platformal succession, through the preserved shelfbreak succession to the basinal facies of the Ospika Embayment, southern Kechika Trough, based on transects 2 and 3 (modified from Cecile and Norford 1979; MacIntyre 1992; and Pyle and Barnes 2000). The numbered events and heavy grey lines representing hiatal or erosion surfaces correspond to the numbered events in the discussion. lDq, lD, and muD are Devonian map units of MacIntyre (1992). Transect spans horizontal distance of ~ 200 km, but no scale is implied in the cross-section.



Skoki Formation lithologies, conglomerate, and distal turbidites interbedded with black shale. Shelf-break facies are not as sharply preserved in the southern Rockies, but a correlative deepening phase is recorded in the Arenigian with the initiation of black shale deposition of the Glenogle Formation and interbeds of carbonate derived from the correlative Outram

Formation to the east. Although these depositional events associated with the pronounced development of the shelfbreak do not necessarily require a tectonic cause, a renewed phase of extension is supported by the occurrence of volcanics at two intervals in the Ordovician within transects 2 and 3 (event 3, Fig. 4). The Ospika Volcanics (Arenigian, Lower Ordovician) occur at the Kechika Formation – Road River Group boundary. On the Macdonald Platform, an interval of altered volcanics occurs in the Skoki Formation (Darriwilian, Middle Ordovician). In the Ospika Embayment, volcanics likely related to those in the Skoki Formation occur within the lower Ospika Formation (Darriwilian, Middle Ordovician). The extent of the Ospika volcanics through the axis of the Kechika Trough along a northwest-trending belt and their composition suggests they represent submarine volcanic flows along reactivated fault zones during episodes of extension (MacIntyre 1998).

(4) An early Late Ordovician transgressive pulse is recorded in the transitional facies of the base of the Robb Formation that onlap the platform carbonate of the uppermost member of the Skoki Formation. The upper part of the Skoki Formation is only preserved locally beneath a Late Ordovician unconformity. An unconformity of similar age lies below the Mount Wilson Formation in the southern Cordillera. The relative sea-level rise was possibly in response to basin foundering related to the extensional events of the Middle Ordovician compounded by a possible superplume event near the Darriwilian–Caradocian boundary (Barnes, in press). The latter paper provides various lines of evidence in support of a superplume event, one consequence being the most widespread cratonic submergence by epeiric seas during the Phanerozoic.

(5) The Upper Ordovician quartzite deposits of the Mount Wilson Formation, those within the Beaverfoot and Robb formations, and within the Ware Member of the Ospika Formation were likely sourced by reactivated tectonic highs such as the Peace River Arch to the east or Fort Nelson High to the northeast of transect 2 (Norford et al. 1966; Ross et al. 1993; Rigby et al. 1998). These deposits represent substantial volumes of mature quartz sand that were distributed across the platform margin and extended into the slope and basin (Norford 1991).

(6) The transgressive phase during the Late Ordovician terminated with a period of erosion in the latest Ordovician – Early Silurian over much of the study area, likely related to the terminal Ordovician Gondwanan glaciation. The erosion is represented by an unconformity beneath the Nonda Formation, or beneath the McCusker Formation where this unit is locally preserved, and extends into the slope facies beneath the Kenny, Laurier, and Pesika formations. The sub-Nonda Formation or sub-Llandovery unconformity is regional and cuts Ordovician strata northward and westward from the study area such that the Nonda Formation overlies locally Precambrian strata, such as the Fort Nelson High (Norford et al. 1966; Norford 1991). A large Paleozoic positive feature referred to as the Muskwa High is a structural culmination that is unconformably overlain by Silurian strata within the Central Foreland region (Cecile et al. 2000), north of transect 3.

(7) Further margin extension in the Early Silurian is suggested by the prominent interfingering relationship of the platform carbonates of the Nonda Formation with the carbonaceous limestone of the Kenny Formation, representing deposition on a steepened ramp (Pyle and Barnes 2001*b*). The overlying composite debris flows within the Laurier Formation (event 7, Fig. 4) were sourced by the upper Nonda Formation and may represent another period in which the shelfbreak was pronounced. This event does not require a tectonic cause, but the association of contemporaneous volcanics with carbonates of the Silurian Nonda south of the study area (Taylor et al. 1972) may suggest another phase of extensional tectonism similar to that recorded in the late Early to Middle Ordovician (events 2 and 3).

(8) Additional Silurian and Devonian events are less well constrained. A post-Nonda hiatus was followed by the deposition of the Muncho–McConnell Formation (event 8, Fig. 4), which has a prominent marker bed of cross-bedded quartzite at its base that also overlies the Laurier Formation (Legun 2000). The hiatus in marine deposition and basinward shift of shallow-water quartzite facies may suggest uplift and emergence of the platform. The Nonda Formation is entirely cut out by various unconformities south of 56°N (Norford 1991). It is not known if any of the Muncho–McConnell Formation lies in the Silurian. The Kwadacha Formation is at least as old as latest Llandovery to early Wenlock based on graptolite collections (Norford 1980) and extends into the Lower Devonian based on conodont collections (Ferri et al. 1995). The Kwadacha is interpreted to overlie the Laurier Formation and may then imply a period of Lower Silurian erosion rather than sub-Llandovery or sub-Devonian as previously thought, but correlation of these siltstone units is tenuous (Pyle and Barnes 2001*b* and references therein). The Kwadacha Formation is a peculiar unit present only within northeastern British Columbia and contains clastic facies and sedimentary structures of proximal turbidites (Insley 1990) that may imply uplift of a western source area.

(9) The Lower–Middle Devonian Deserters Formation (of Pyle et al. 2003*b*) represents deposition in a restricted, northwest-trending, linear sub-basin of the Ospika Embayment, bounded by uplifted areas that developed carbonate banks such as the Akie Reef to the west (Pigage 1986; MacIntyre 1992, 1998) and the carbonate terrace consisting of the Stone and Dunedin formations to the east (Fig. 4). The Akie Reef discontinuously overlies the Kwadacha Formation (MacIntyre 1998) as does the Deserters Formation (Pyle et al. 2003*b*), which indicates a hiatus of Early Devonian age. The overlying Middle to Upper Earn Group contains extensive evidence of uplift and erosion such as abrupt facies changes, slump breccias, anomalous facies thickening, and sedimentary exhalative deposits (MacIntyre 1998). The Deserters Formation contains similar stratigraphic evidence of renewed tectonic activity, such as an interval of tuff (Eifelian age) associated with distal carbonate turbidite deposits and debris flows. In addition, the distribution of sandstone and dolostone of the Lower Devonian Wokkpash Formation roughly surrounds the Muskwa High and may suggest emergence of this feature (Cecile et al. 2000). The Devonian is clearly a complex time, which is attributed to the change in tectonic regime of the Cordillera to extensional or strike-slip faulting associated with the Antler Orogeny (Root 2001 and references therein). In the southern Cordillera, syndepositional deformation in Middle Devonian strata and the lack of pre-Devonian strata may be due to uplift and erosion associated with the Antler Orogeny (Root 2001).

Our observations on Silurian and Devonian stratigraphic events suggest the "sub-Devonian unconformity" that cuts out much of the Ordovician–Silurian strata from northwestern Alberta and northeastern British Columbia is a complex series of regional tectonic events that merit further study.

The older age of the Kechika Formation – Road River Group boundary within the Cassiar Terrane (mid-Tremadocian) compared with that of the autochthon (lower Arenigian) indicates the diachroneity of the onset of Road River Group sedimentation. If a similar age range of this boundary within the authochon is discovered, it may help establish the initial position of the Cassiar Terrane (Pyle and Barnes 2001*a*). The hiatus at the top of the Road River Group in the Cassiar Terrane is post-Caradocian (Fig. 3) and may correlate to the sub-Nonda (sub-Llandovery) Event 6, but the extent of the hiatus is poorly constrained. The conodont biostratigraphy established for the parautochthonous Cassiar Terrane demonstrates the significance of conodont studies in resolving regional tectonic issues.

Conclusions

(1) New conodont biostratigraphic data for the Ordovician succession of the Bow Platform are established and clarify the ages of the Outram, Skoki, and Owen Creek formations.

(2) The Survey Peak – Outram Formation contact does not correlate with the contact of the McKay Group and Glenogle Formation of the White River Trough as assumed previously. Rather, the base of the Glenogle Formation, marking a deepening phase, is diachronous from middle to late Arenigian and correlates to the upper part of the Outram Formation. The Redfern Member of the Skoki Formation in the northern Rocky Mountains is equivalent in lithology and fauna to the Owen Creek Formation that overlies the Skoki Formation in the southern Rockies.

(3) Regional correlation along the Cordillera from the Bow Platform – White River Trough to the Macdonald Platform – Kechika Trough and Ospika Embayment is refined. The time equivalency of the upper McKay Group, Survey Peak Formation, and Kechika Formation during a deepening phase initiated in the latest Cambrian and the onset of the Glenogle and Ospika formations during a second deepening phase in the early Arenigian has been established.

(4) Building on the proposal by Colpron et al. (2002) to explain a second episode of rifting dated at ca. 570 Ma, our refined correlations suggest at least two later episodes of renewed extension along the margin, in the latest Cambrian and late Early Ordovician (Arenigian).

(5) The stratigraphic record of tectonic activity along the margin includes localized volcanic activity, abrupt facies changes and extensional events that persisted from the Early Ordovician to Middle Devonian, siliciclastic influx from reactivated paleotopographic highs in the Late Ordovician, Early Silurian, and Early Devonian, and a number of prominent hiatuses including unconformities of early Late Ordovician, sub-Llandovery, Early Devonian, and possibly Early to Middle Silurian ages.

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