# Arenigian (Early Ordovician) sea-level history and the response of conodont communities, western Newfoundland[1]

**Shunxin Zhang and Christopher R. Barnes**

**Abstract:** Four cluster analyses were performed, which recognized 17 conodont communities in the Arenigian (Lower Ordovician) of western Newfoundland. The analyses include 69 598 identifiable conodont specimens recovered from 153 conodont-bearing samples from four stratigraphical sections representing the environmental settings of the platform, upper proximal slope, lower proximal slope, and distal slope. The distribution of conodont communities along the platform to slope environmental gradient shows that sea-level changes simultaneously affected the development and replacement of the conodont communities in the different facies. The pattern of change in conodont communities allows an interpretation of sea-level change that is correlated precisely into the detailed graptolite biozonation. A gradual transgression lasted most of *Tetragraptus approximatus* Zone time, which was followed by a brief regression; a transgression–regression cycle occurred in the *T. akzharensis* Zone time; a major transgression caused a highstand during the entire *Pendeograptus fruticosus* Zone time, which was followed by a major regression in the early *Didymograptus bifidus* Zone time; *Isograptus victoriae lunatus* Zone time included repetitive oscillations of sea level; a severe regression in the earliest *I. i. victoriae* Zone time was represented by the St. George unconformity on the platform and the Bed 12 megaconglomerate on the slope, reaching the lowest sea level during the *I. i. maximus* Zone time. The Arenigian sea-level curve developed by this study only partly agrees with that from the Baltic region and central Australia based on trilobite communities.

**Résumé :** Quatre analyses typologiques ont été effectuées, elles reconnaissent dix-sept communautés de conodontes dans l'Arénigien (Ordovicien inférieur) de l'ouest de Terre-Neuve. Les analyses comprennent 69 598 spécimens identifiables de conodontes récupérés de 153 échantillons porteurs de conodontes à partir de quatre sections stratigraphiques qui représentent des environnements de plate-forme, de pente supérieure proximale, de pente proximale inférieure et de pente distale. La distribution des communautés de conodontes le long du gradient environnemental de plate-forme à celui de pente montre que les changements du niveau de la mer affectaient simultanément le développement et le remplacement des communautés de conodontes dans les différents faciès. Le patron de changement dans les communautés de conodontes permet une interprétation du changement du niveau de la mer qui est précisément corrélé à la zone biostratigraphique détaillée des graptolites. Une transgression graduelle a duré la plus grande partie de l'intervalle de temps correspondant à la Zone à *Tetragraptus approximatus*, laquelle a été suivie d'une courte régression; un cycle de transgression–régression a eu lieu dans l'intervalle de temps correspondant à la Zone à *T. Akzharensis*; une transgression majeure causée par une période de haut niveau durant tout l'intervalle de temps correspondant à la Zone à *Pendeograptus fruitcosus*, laquelle a été suivie par une régression majeure au début de l'intervalle de temps correspondant à la Zone à *Didymograptus bifidus*; l'intervalle de temps correspondant à la Zone à *Isograptus victoriae lunatus* comprenait des oscillations répétitives du niveau de la mer; une régression sévère au tout début de l'intervalle de temps correspondant à la Zone à *I. i victoriae* est représentée par la discordance de St. George sur la plate-forme et le mégaconglomérat du Lit 12 sur la pente, atteignant le plus bas niveau de la mer durant l'intervalle de temps correspondant à la Zone à *I. i. maximus*. Le graphique du niveau de la mer durant l'Arénigien, développé dans la présente étude, ne concorde qu'en partie avec ceux, basés sur des communautés de trilobites, de la région baltique et du centre de l'Australie.

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## Introduction

The Arenig was the second Series of the Ordovician System, but has recently been partially re-defined. The first appearance of the graptolite *Tetragraptus approximatus approximatus* defines the base of the Arenigian Stage, which will be renamed once the succeeding stage is approved by the Subcommission on Ordovician Stratigraphy (Berry 1992; Finney and Webby 2000). Cow Head Peninsula, western Newfoundland was proposed as the global stratotype for Arenigian Stage (Williams et al. 1994), but the section at Diabasbrottet, Mt. Hunneberg, Sweden, was selected in 2000 as the stratotype for the upper stage of the Lower Ordovician. The former boundary between Arenigian and Llanvirnian was earlier changed with the Darriwilian replacing the Llanvirnian–Llandelian and its base defined by the graptolite *Undulograptus austrodentatus* Zone. Thus, the term Arenigian is used herein for the stadial interval between the bases of the *T. approximatus approximatus* and *U. austrodentatus* zones, which is a more restricted interval than the traditional Arenig, pending designation of stadial revision of the Lower Ordovician (under review by the Subcommission in Ordovician Stratigraphy). Graptolite zones in the Pacific Province Arenigian are *T. approximatus approximatus*, *T. akzharensis*, *Pendeograptus fruticosus*, *Didymograptus* (*Didymograptellus*) *bifidus*, *Isograptus victoriae lunatus*, *I. v. victoriae*, and *I. v. maximus* (Williams and Stevens 1987, 1988).

Many sea-level fluctuations occurred during the Arenigian (Fortey 1984; Barnes 1984). Based on sequence stratigraphy, Ross and Ross (1992) recognized that the early Arenigian was a time when broad areas of the cratons were flooded and sea level was generally high, whereas the late Arenigian was a time of generally low sea level. A sea-level curve for the Arenigian, based on a compilation of Scandinavian ecostratigraphical data was established by Nielsen (1992*a*). An intercontinental correlation was made to the Victorian graptolite succession, southeast Australia, Valhallfonna Formation, Spitsbergen, Cow Head Group, western Newfoundland, and Pogonip Group, Utah based on sequence stratigraphy and ecostratigraphy (Nielsen 1992*b*). As a result, 14 major sea-level events were recognized using the relationship between paleoecology and biostratigraphy.

This present study documents changes in the conodont faunas and communities both in Arenigian parautochthonous and allochthonous facies, interprets this response in terms of sea-level change, and generates a more refined sea-level curve for Arenigian, based on closely sampled sections in western Newfoundland. The same method was used to establish sea-level curves for the Ashgillian–Llandovery sequence (Upper Ordovician – Lower Silurian) on Anticosti Island and the Merioneth–Tremadocian sequence (Upper Cambrian – Lower Ordovician) in western Newfoundland (Zhang and Barnes 2002, 2004). The principles of using conodont communities to establish sea-level curves are that (1) the same conodont community maintained its particular environmental preferences and water depths; (2) sea-level changes resulted in rapid lateral and vertical replacement of communities; (3) during periods of the relatively stable sea level, the communities maintained a stable development (Zhang and Barnes 2002). Another finding for this study is that the sea-level changes resulted in the conodont community changes in both parautochthonous and allochthonous facies synchronously.

## Review of earlier Arenigian stratigraphical correlations between parautochthonous and allochthonous facies

The Port au Port and St. George groups and Cow Head Group exposed in western Newfoundland (Fig. 1) have been interpreted as representing deposition on a carbonate platform and the adjacent continental slope from Middle Cambrian to Middle Ordovician time, respectively, (Hiscott and James 1985; James and Stevens 1986; James et al. 1989).

The Lower Ordovician St. George Group is a thick parautochthonous platform carbonate sequence comprising the Watts Bight, Boat Harbour, Catoche, and Aguathuna formations (Fig. 2). This sequence was deposited in a series of shallow subtidal and peritidal environments near the outer edge of a low-latitude continental margin. The entire sequence includes two unconformities separating two megacycles that reflect deposition in response to fluctuations in sea level (Knight and James 1987; James et al. 1989). The upper part of the Boat Harbour (= Barbace Cove Member of Knight and James 1987), Catoche, and Aguathuna formations form the upper megacycle and are of Arenigian age (Fig. 2).

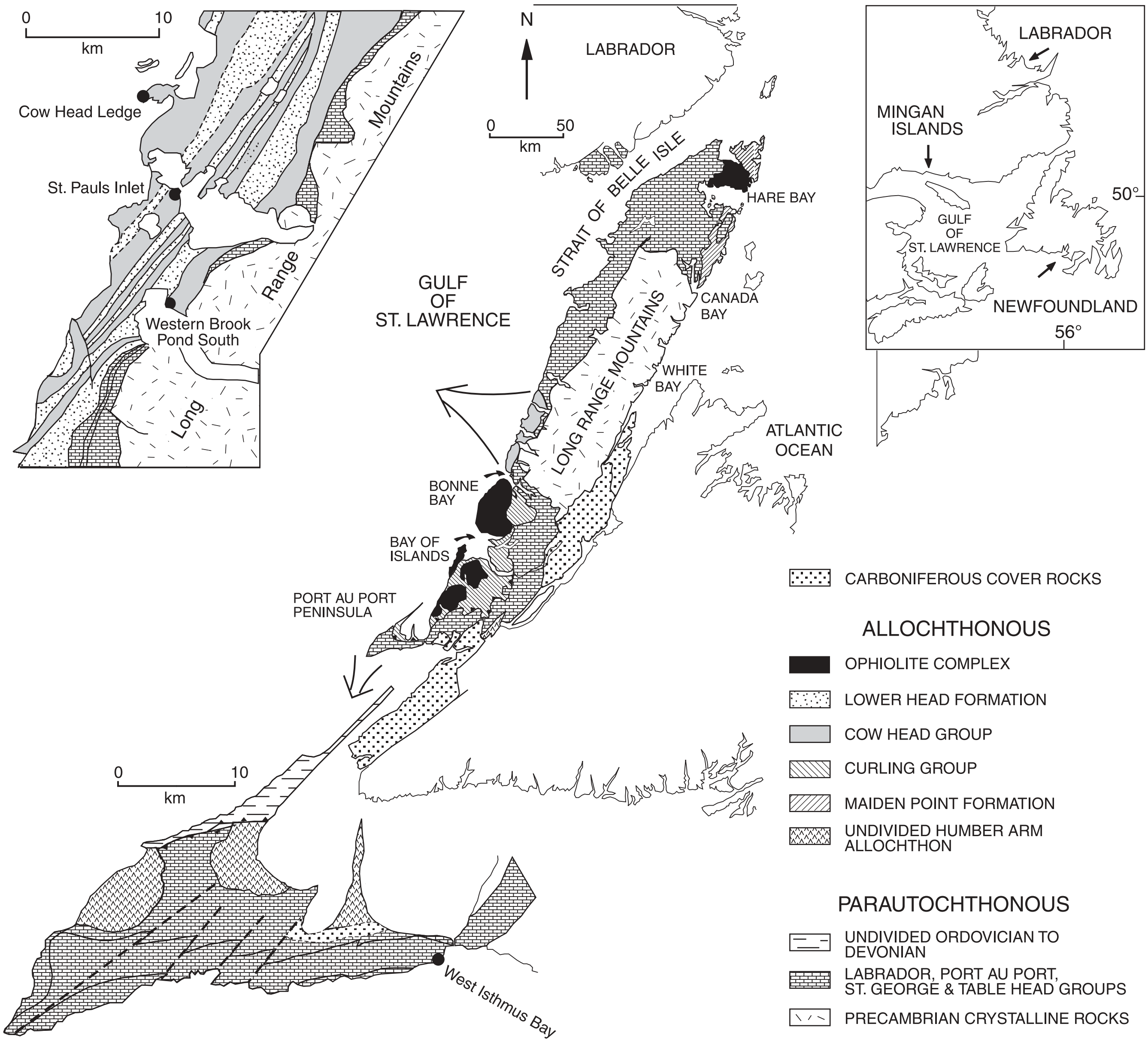
The Upper Cambrian and Lower Ordovician Cow Head Group is an allochthonous deep-water deposit and is composed of two different facies, i.e., proximal facies Shallow Bay Formation and distal facies Green Point Formation (Fig. 2). The Shallow Bay Formation is divided into the Downes Point, Tuckers Cove, Stearing Island, and Factory Cove members, and Green Point Formation into the Martin Point, Broom Point, and St. Pauls members. The Factory Cove and St. Pauls members include beds 9–13, which are of Arenigian age (Fig 2). This interval corresponds to the upper sequence of Phase 3 of James et al. (1989).

Williams and Stevens (1988) studied the graptolites from the different slope sections of beds 9–13, St. Pauls Member, Green Point Formation, Cow Head Group. Their biostratigaphy revealed that the bedded Bed 9 and conglomerate Bed 10 are of *Tetragraptus approximatus* and *T. akzharensis* zonal ages, the bedded Bed 11 is of *Pendeograptus fruticosus*, *Didymograptus bifidus*, and *Isograptus victoriae lunatus* zonal ages, and the bedded Bed 13 is of *I. v. victoriae* and *I. v. maximus* zonal ages (Fig. 2).

Graptolites are rarely preserved in the shallow-water carbonate sequence; hence it is difficult to correlate the allochthonous sequence to the parautochthonous sequence. Conodonts occur in abundance in both sequences, although they are affected by faunal provincialism (Barnes 1988; Pohler 1994; Ji and Barnes 1994*a*, 1994*b*; Johnston and Barnes 1999, 2000).

At the Port au Choix section, the Catoche Formation yielded *Clonograptus flexilis* and *Pseudophyllograptus* sp. A at 40–60 m and 90–105 m above the base of the formation, respectively (Williams et al. 1987). The range of *Clonograptus flexilis* is uncertain, but appears to span the uppermost Tremadocian and lower Arenigian, up to the *Pendeograptus fruticosus* Zone. However, it is most abundant in the uppermost Tremadocian and in the lowest Arenigian *Tetragraptus*

**Fig. 1.** The Humber Zone in western Newfoundland (geology modified from James and Stevens 1986; Ji and Barnes 1994*a*; Johnston and Barnes 1999). The sections included here are shown by black dots (top and bottom left insets).



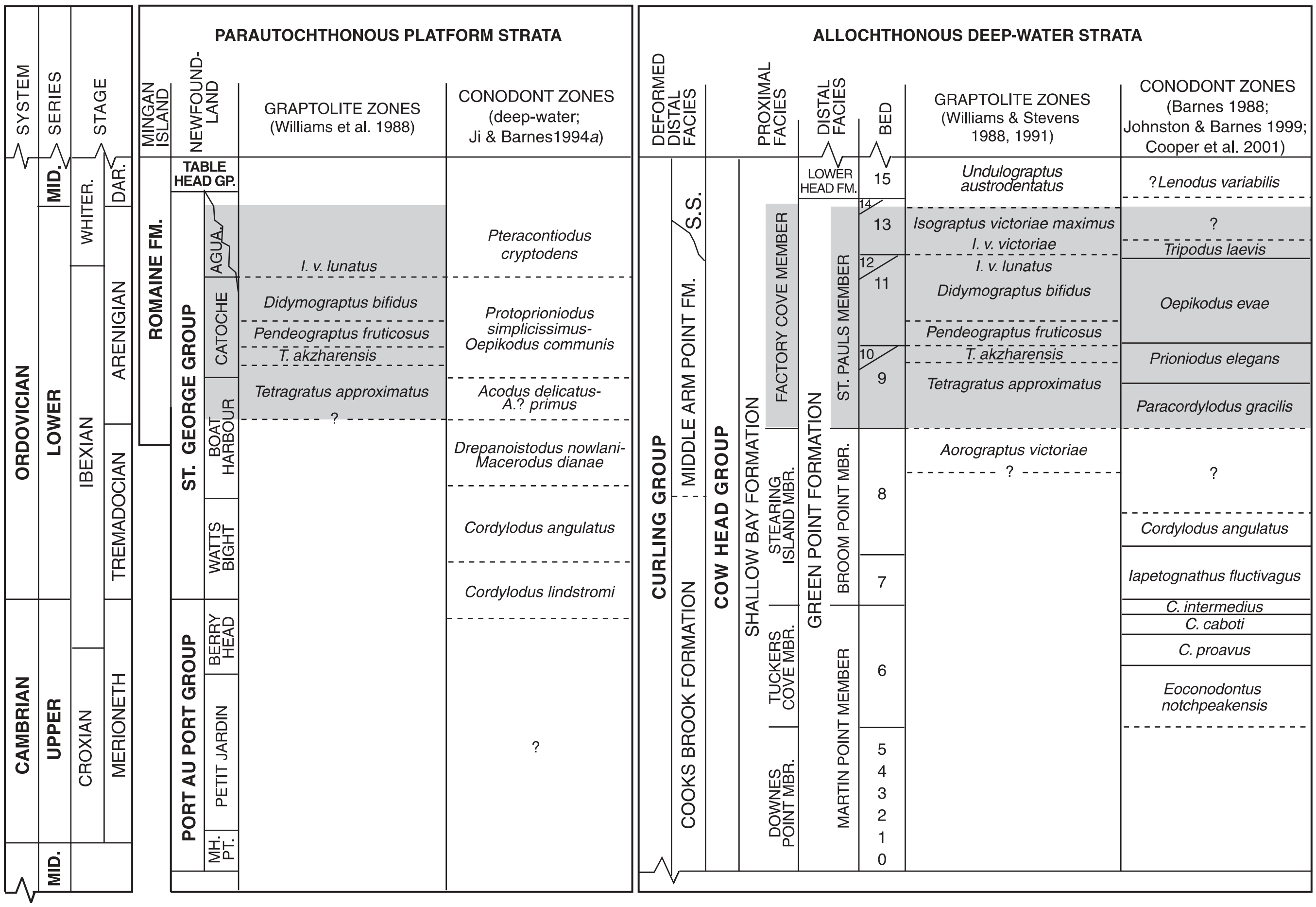

*approximatus* Zone (Williams et al. 1987). The appearance of *Pseudophyllograptus* sp. A indicates the *T. akzharensis* or *Pendeograptus fruticosus* Zone. *Didymograptus* (*Expansograptus*) *nitidus* was found near the boundary between the Catoche and Aguathuna formations. *D.* (*E.*) *nitidus* occurs in both the *P. fruticosus* and *D. bifidus* zones in the lower and middle Bed 11 of Cow Head Group (Williams and Stevens 1988, text-fig. 5). These graptolites established a stratigraphic correlation, where the Catoche Formation was correlated to the *Tetragraptus approximatus* and *T. akzharensis* zones and the Aguathuna Formation to the *Pendeograptus fruticosus* Zone (Williams et al. 1987).

At the Route 460 road section, western Port au Port Peninsula, *Didymograptus bifidus* was recovered from three closely spaced localities in a 3.5 m section from the top of the Catoche Formation, which Williams et al. (2000) considered to agree well with the earlier conclusions of Williams et al. (1987).

However, the present study considers that the discovery of *Didymograptus bifidus* established the *D. bifidus* Zone in the Costa Bay Member, Catoche Formation, as this species never appears below this zone. *Didymograptus bifidus* could even represent the *Isograptus victoriae lunatus* Zone, as it possibly occurs in this zone in slope facies — Western Brook Pond South and North sections (Williams and Stevens 1988, text-figs. 5, 7). Thus, it is possible to correlate the Aguathuna Formation to the *I. v. lunatus* Zone.

Based on the discovery of graptolites (Williams and Stevens 1988; Williams et al. 1987, 2000) and the conodont community pattern of both platform and slope facies and the inferred sea-level history, we agree that the interval from upper part of the Boat Harbour Formation through the Aguathuna

**Fig. 2.** Summary of the chronostratigraphy and biostratigraphy of sequences in western Newfoundland and the Mingan Islands (modified from James et al. 1989). Shaded area is the interval of this study. WHITER., Whiterockian; DAR., Darriwilian; GP., Group; FM., Formation; MBR., Member; S.S., sandstone; AGUA, Aguathuna Formation; MH. PT., March Point Formation.




Formation is of Arenigian age (Knight and James 1987; James et al. 1989). In detail, we correlate the Barbace Member, Boat Harbour Formation, and the lowest Catoche Formation with the *Tetragraptus approximatus* Zone; lower, middle and upper Catoche Formation with the *T. akzharensis*, *Pendeograptus fruticosus*, and *Didymograptus bifidus* zones; and the Aguathuna Formation with the *Isograptus victoriae lunatus* Zone (Fig. 2; also see discussion about sea-level history for detail).

## Database and statistical approach

### Database

The database for this study is based mainly on the four previous studies dealing with the Arenigian conodonts from western Newfoundland: the platform facies (Ji and Barnes 1994*a*), and those from upper and lower proximal slope to distal slope facies (Stouge and Bagnoli 1988; Johnston and Barnes 1999, 2000; Sullivan 1998). The lateral lithofacies reconstruction of James et al. (1989, fig. 16) is followed herein.

The database includes 69 598 identifiable conodont specimens recovered from 153 conodont-bearing samples (average 3 kg; barren samples are excluded) from four Arenigian sections spanning the *Tetragraptus approximatus approximatus* Zone to the *Isograptus victoriae maximus* Zone interval, and representing platform to distal slope facies.

(1) Platform facies. West Isthmus Bay section (Z2), 86 samples from the upper Boat Harbour, Catoche, and Aguathuna formations, which produced 15 325 conodont elements representing 33 multielement species (Ji and Barnes 1994*a*, appendix B, pp. 84–89).

(2) Upper proximal slope facies. The Ledge – Point of Head section, 17 samples from Bed 9, and lower Bed 11, Factory Cove Member, Shallow Bay Formation (Stouge and Bagnoli 1988, table 1), which yielded 18 454 conodont elements representing 68 multielement species. Additionally, the samples 2C and 2B from Bed 13, North Shore section (Fåhraeus and Nowlan 1978) are used in comparing the community changes, but not used in the cluster analysis.

(3) Lower proximal slope facies. The St. Pauls Inlet section, 39 samples from beds 9, 11, and 13, St. Pauls Member, Green Point Formation (Johnston and Barnes 1999, tables 1, 2), which contained 29 571 conodont elements representing 105 multielement species.

(4) Distal slope facies. Western Brook Pond South section, 11 samples from the upper Bed 11 and Bed 13, St. Pauls

Member, Green Point Formation (Sullivan 1998, appendix 1), which yielded 6248 conodont elements representing 23 species.

**Data processing and program employed in the conodont community analysis**

Cluster analysis was used by Zhang and Barnes (2002, 2004) to establish conodont communities, infer the sea-level changes, and determine Late Ordovician – Early Silurian and latest Cambrian – Early Ordovician sea-level history based on the conodont database of Anticosti Island, Quebec and western Newfoundland, respectively. The same methodology is adopted herein.

The raw data in the above-mentioned four databases are the actual number of specimens for each species of each sample, which were processed into the number of conodont elements for each species per kilogram and were divided into seven intervals (<1, 1–4, 5–9, 10–24, 25–49, 50–99, and ≥100) before running the cluster analysis. Both Q- and R-mode hierarchical cluster analyses were performed for both cases (samples) and variables (species) by SPSS version 6.1 for the Macintosh (SPSS 1994). Pearson's correlation coefficient was used as an index of similarity and clusters were formed using the within-groups linkage method. The analysis provides an output to readily visualize the conodont community patterns — these intervals of absolute element abundance are expressed as a graded series of dots that are plotted at the intersection of certain species and samples. The pattern of community partitioning is determined from the assemblages of dots representing distinctive groupings of samples and species.

Four R- and Q-type cluster analyses were designed and performed for West Isthmus Bay (Fig. 3), the Ledge – Point of Head (Fig. 6), St. Pauls Inlet (Fig. 8), and Western Brook Pond South (Fig. 10) sections. It must be emphasized, as in Zhang and Barnes (2002, 2004), the cluster analysis tends to divide an ecological gradient into discrete units, whereas the gradational nature of the conodont community groups is evident in the abundance data shown in the Q- and R-mode dendrograms.

Although a few species (e.g., the species of *Drepanoistodus*, *Drepanodus*, *Paroistodus*) are very abundant and play an important role in clustering samples statistically, they are considered to have had a pelagic mode of life and will be excluded in defining the conodont communities.

## Recognition of conodont communities and assemblage in different facies

The term community is used herein to denote an ecological association of taxa usually related to particular environmental parameters, and the term assemblage to a non-ecological association of taxa that are a mixture of taxa reflecting different environmental parameters.

**Platform communities**

Ji and Barnes (1994*b*) used Q-type cluster analysis of conodont presence–absence data from four sections of the platform facies to recognize six main conodont communities ranging from peritidal, through shallow subtidal to deep subtidal (Ji and Barnes 1994*b*, figs. 3, 4, 6, 15). The most continuous of the four sections – West Isthmus Bay section (Z2) is adopted in this study. The reason to re-study this section is that the following problems can be seen in the previous cluster analysis (Ji and Barnes 1994*b*): coding data by presence–absence could result in over-weighting the less important species, as no matter how abundant or how rare the conodont specimens in the samples, they play the same role in clustering the samples; recognizing conodont communities without R-type cluster analysis could produce subjective communities, as naming the communities is largely dependent on the researchers' understanding of the conodont faunas.

The platform deposits of the St. George Group include unconformity-bounded megacycles. Each megacycle is characterized by the same general sequence of deposition: (1) basal peritidal sediments, (2) middle subtidal facies, and (3) upper peritidal (Knight and James 1987; James et al. 1989). The platform communities recognized here were developed within the upper megacycle of Arenigian age and preserved in the Barbace Cove Member of Boat Harbour Formation, and Catoche and Aguathuna formations (Fig. 2).

The descriptions for platform communities are as follows; the lithofacies are based on Knight and James (1987); the figure references for the community partition and distribution are Figs. 3 and 4.

*Striatodontus prolificus* (*S.p.*) community

CLUSTERED SAMPLES: three consecutive samples.

DEFINING TAXON: *Striatodontus prolificus* (Ji and Barnes).

RANGE: occurs directly above the unconformity within the lower Barbace Cove Member, upper Boat Harbour Formation.

LITHOFACIES: the lower part of the grainy to muddy peritidal cycles.

DIVERSITY AND ABUNDANCE: 2–4 species, with 1–24 specimens/kg of each species.

SEA-LEVEL SIGNAL: representing the recovery of the conodont fauna after the latest Tremadocian regression.

*Colaptoconus quadraplicatus* (*C.q.*) community

CLUSTERED SAMPLES: 10 inconsecutive samples.

DEFINING TAXON: *Colaptoconus quadraplicatus* (Branson and Mehl).

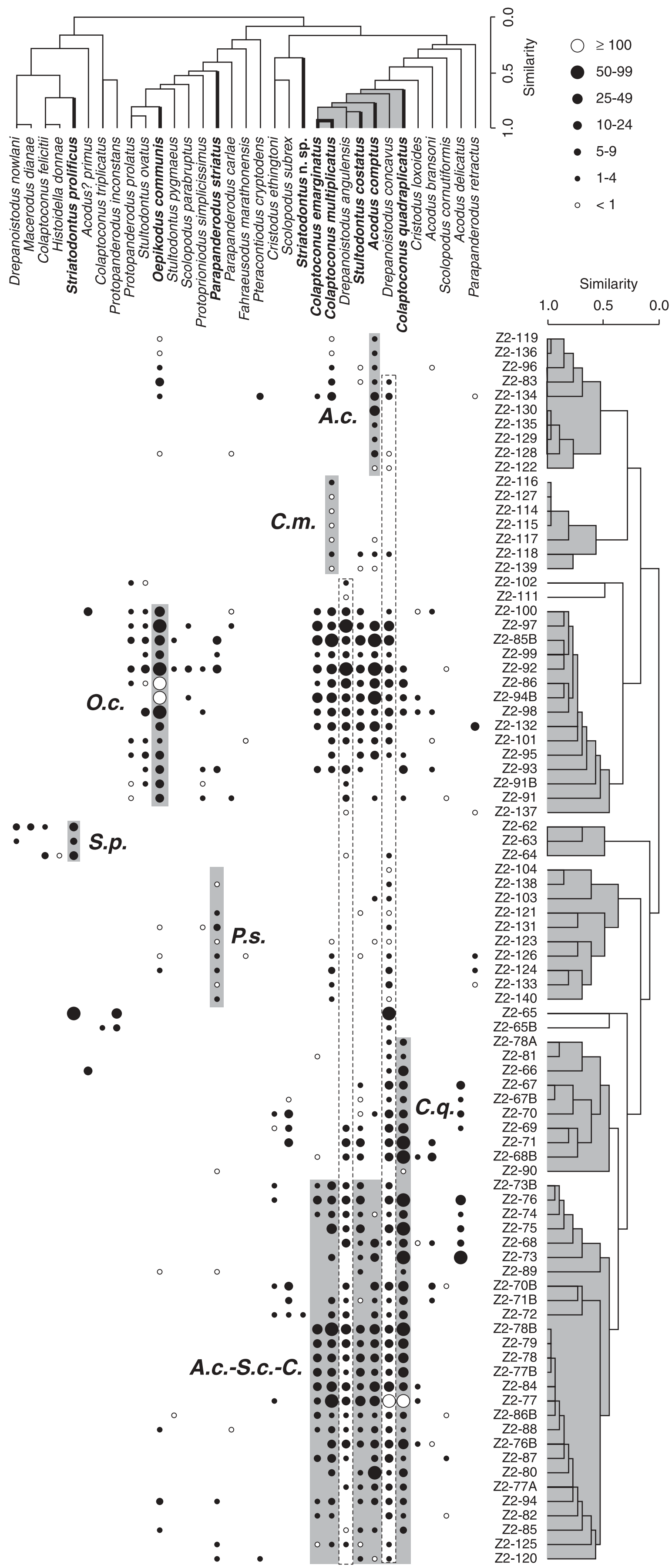
RANGE: *C. quadraplicatus* is common and dominant in several communities in upper Boat Harbour and lower Catoche formations, but the community is restricted to the middle Barbace Cove Member, Boat Harbour Formation.

LITHOFACIES: the grainy to muddy peritidal cycles.

DIVERSITY AND ABUNDANCE: 2–7 species, each with 1–99 specimens/kg.

SEA-LEVEL SIGNAL: representing a short period of relatively stable shallow peritidal environment.

*Acodus comptus – Stultodontus costatus – Colaptoconus* (*A.c.–S.c.–C.*) community


0.0
0.5
1.0
Similarity
≥ 100
50-99
25-49
10-24
5-9
1-4
< 1
Drepanoistodus nowlani
Macerodus dianae
Colaptoconus feliciti
Histoidella donnae
Striatodontus prolificus
Acodus? primus
Colaptoconus triplicatus
Protopanderodus inconstans
Protopanderodus prolatus
Stultodontus ovatus
Oepikodus communis
Stultodontus pygmaeus
Scolopodus parabruptus
Protoprioniodus simplicissimus
Parapanderodus striatus
Parapanderodus carlae
Fahraeusodus marathonensis
Pteracontiodus cryptodens
Cristodus ethingtoni
Scolopodus subrex
Striatodontus n. sp.
Colaptoconus emarginatus
Colaptoconus multiplicatus
Drepanoistodus angulensis
Stultodontus costatus
Acodus comptus
Drepanoistodus concavus
Colaptoconus quadraplicatus
Cristodus loxoides
Acodus bransoni
Scolopodus cornutiformis
Acodus delicatus
Parapanderodus retractus
Similarity
1.0 0.5 0.0
A.c.
C.m.
O.c.
S.p.
P.s.
C.q.
A.c.-S.c.-C.
Z2-119
Z2-136
Z2-96
Z2-83
Z2-134
Z2-130
Z2-135
Z2-129
Z2-128
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Z2-116
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Z2-117
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Z2-139
Z2-102
Z2-111
Z2-100
Z2-97
Z2-85B
Z2-99
Z2-92
Z2-86
Z2-94B
Z2-98
Z2-132
Z2-101
Z2-95
Z2-93
Z2-91B
Z2-91
Z2-137
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Z2-123
Z2-126
Z2-124
Z2-133
Z2-140
Z2-65
Z2-65B
Z2-78A
Z2-81
Z2-66
Z2-67
Z2-67B
Z2-70
Z2-69
Z2-71
Z2-68B
Z2-90
Z2-73B
Z2-76
Z2-74
Z2-75
Z2-68
Z2-73
Z2-89
Z2-70B
Z2-71B
Z2-72
Z2-78B
Z2-79
Z2-78
Z2-77B
Z2-84
Z2-77
Z2-86B
Z2-88
Z2-76B
Z2-87
Z2-80
Z2-77A
Z2-94
Z2-82
Z2-85
Z2-125
Z2-120

**Fig. 3.** Q- and R-mode cluster analysis of 86 samples from the platform facies (Barbace Member, Boat Harbour, Catoche, and Aguathuna formations at West Isthmus Bay section). Samples in Q-mode clustering order, taxa in R-mode clustering order and relative abundance of taxa as a graded series of dots. Intersections of Q- and R-clusters define conodont communities: *A.c.*, *Acodus comptus*; *C.m.*, *Colaptoconus multiplicatus*; *O.c.*, *Oepikodus communis*; *S.p.*, *Striatodontus prolificus*; *P.s.*, *Parapanderodus striatus*; *C.q.*, *Colaptoconus quadraplicatus*; *A.c.–S.c.–C.*, *Acodus comptus – Stultodontus costatus – Colaptoconus*. The dashed boxes are communities not discussed here. The data extracted from appendix B of Ji and Barnes (1994*a*).

CLUSTERED SAMPLES: 27 inconsecutive samples.

DEFINING TAXA: *Acodus comptus* (Branson and Mehl), *Stultodontus costatus* (Ethington and Brand), *Colaptoconus multiplicatus* (Ji and Barnes), and *C. quadraplicatus*.

RANGE: first and last appearance in the middle Barbace Cove Member, Boat Harbour Formation, and basal Aguathuna Formation, respectively, with several consecutive samples in the upper Boat Harbour and the lower Catoche formations.

LITHOFACIES: grainy to muddy peritidal cycles and shallow subtidal to peritidal cycles.

DIVERSITY AND ABUNDANCE: 4–9 species, each with 5–99 specimens/kg in most samples.

SEA-LEVEL SIGNAL: the consecutive samples representing periods of relatively stable subtidal to peritidal environment.

*Oepikodus communis* (*O.c.*) community

CLUSTERED SAMPLES: 14 samples, basically consecutive.

DEFINING TAXON: *Oepikodus communis* (Ethington and Clark).

RANGE: middle Catoche Formation, in the approximate interval of units 6–10 at the Catoche type section and units 8–14 at the Catoche reference section (Knight and James 1987), with 1 exceptional sample (Z2-132) from Aguathuna Formation.

LITHOFACIES: interpreted as subtidal skeletal-rich muds and subtidal skeletal-peloid-rich muds.

DIVERSITY AND ABUNDANCE: 5–15 species, several of them common in the *A.c.–S.c.–C.* community, each with 5–99 specimens per kg in most samples.

SEA-LEVEL SIGNAL: the abundant *Oepikodus communis*, together with the lithology, the diversity of the community and the consecutive samples indicating a stable and highest sea level.

*Colaptoconus multiplicatus* (*C.m.*) community

CLUSTERED SAMPLES: five consecutive samples from upper Catoche Formation and two others from Aguathuna Formation.

DEFINING TAXON: *Colaptoconus multiplicatus*.

RANGE: mainly restricted to the upper Catoche Formation that roughly correlates to unit 14 at the type section and unit 18 at the reference section.

LITHOFACIES: dolomitized shallow subtidal facies.

DIVERSITY AND ABUNDANCE: 1–4 species, each with < 1 specimens/kg in most samples.

SEA-LEVEL SIGNAL: shallower water environment than that interpreted by Knight and James (1987), possibly peritidal to supratidal.

*Acodus comptus* (*A.c.*) community

CLUSTERED SAMPLES: 10 inconsecutive samples.

DEFINING TAXON: *Acodus comptus* (Branson and Mehl) that is also common in both the *A.c.–S.c.–C.*, and *O.c.* communities.

RANGE: first appears in the lower Catoche Formation, then alternates with the *Parapanderodus striatus* community (see discussion later in the text) from top of the Catoche through the Aguathuna formations.

LITHOFACIES: interpreted as a peritidal cycle.

DIVERSITY AND ABUNDANCE: 1–7 species, each with < 1–24 specimens/kg in most samples.

SEA-LEVEL SIGNAL: probably representing a water depth between subtidal and peritidal.

COMMENTS: the *Acodus* community recognized by Ji and Barnes (1994*b*) included *Acodus comptus*, *A. delicatus* Branson and Mehl, and *A.*? *primus* Ji and Barnes; the database (Ji and Barnes 1994*a*) and Fig. 3 show that only two samples contain *A.*? *primus* scattered among the different communities recognized in this study; both Figs. 3 and 5 show that *A. comptus* and *A. delicatus* exhibit a clear pattern of mutual exclusion, which may be caused by subtle environmental changes, thus the *Acodus* community of Ji and Barnes (1994*b*) was incorrectly established.

*Parapanderodus striatus* (*P.s.*) community

CLUSTERED SAMPLES: 10 inconsecutive samples.

DEFINING TAXON: *Parapanderodus striatus* (Graves and Ellison).

RANGE: first appears directly above the base of Aguathuna Formation and extends up to the exposed top of the formation.

LITHOFACIES: dolostone-dominated peritidal succession.

DIVERSITY AND ABUNDANCE: 1–7 species, each with < 1–4 specimens in most samples.

SEA-LEVEL SIGNAL: representing the shallowest peritidal to supratidal environment; the alternation with *A.c.* community indicating an oscillating sea level.

### Upper proximal slope communities

The upper proximal slope facies is represented by beds 9–13, Factory Cove Member, Shallow Bay Formation. The cluster analysis employed 17 samples from Bed 9, and lower Bed 11 at Ledge – Point of Head section (Stouge and Bagnoli 1988, table 1) that is part of Cow Head North – Point of Head section

**Fig. 4.** Inferred sea-level curve based on the distribution of the conodont communities identified by cluster analysis through Barbace Cove Member, Boat Harbour Formation, and Catoche and Aguathuna formations at West Isthmus Bay section. The graptolite distribution is from Williams et al. (1987) and Williams et al. (2000). M., Member; Fm., Formation.

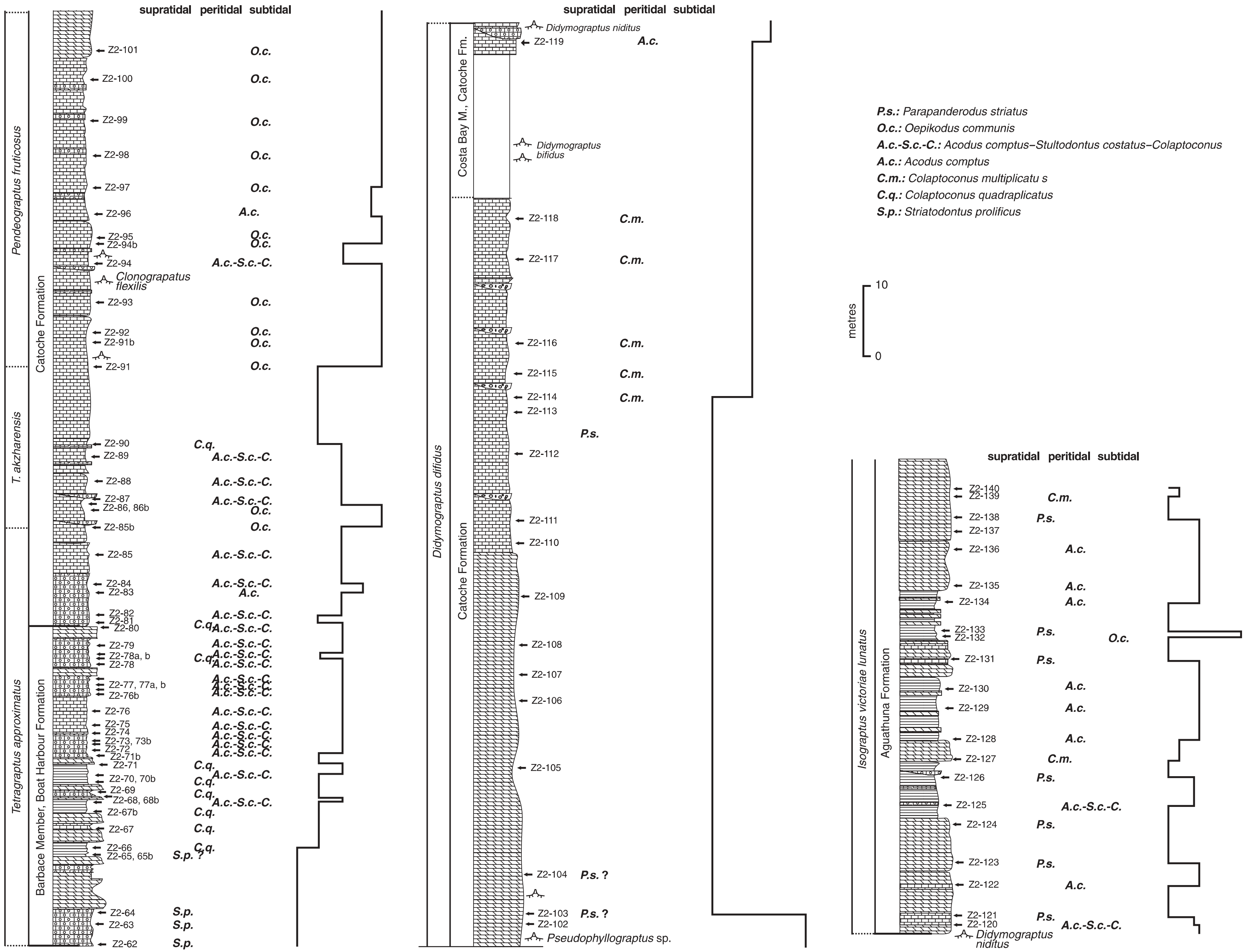
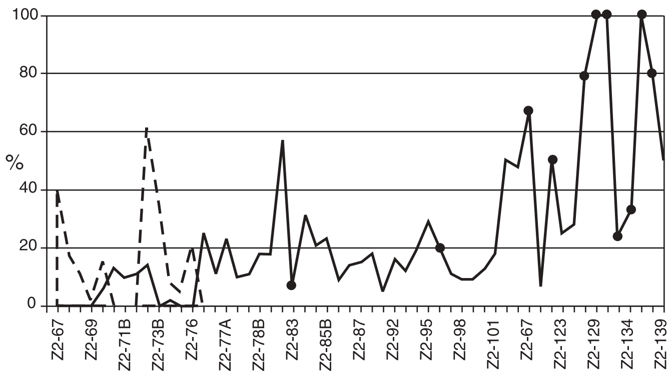


**Fig. 5.** Relative abundance of *Acodus comptus* (solid line) and *A. delicatus* (dashed line) displays a mutually exclusive pattern; black dots are samples grouped under the *A. comptus* community in Fig. 3.




described by James and Stevens (1986). Five communities are recognized statistically from Bed 9 and lower Bed 11 (Figs. 6, 7). The community within Bed 13 is recognized by non-statistical analysis based on the collection of Fåhraeus and Nowlan (1978).

The descriptions for upper proximal slope communities are as follows; the lithofacies and division of units are based on James and Stevens (1986); the figure references for the community partition and distribution are Figs. 6 and 7.

*Tripodus albani – Prioniodus oepiki* (*T.a.–P.o.*) community

CLUSTERED SAMPLE: 1 (CH4A).

DEFINING TAXON: *Tripodus albani* Stouge and Bagnoli, and *Prioniodus oepiki* (McTavish).

RANGE: unit 9.5 in lowest Bed 9, equivalent to lower *Tetragraptus approximatus* Zone.

LITHOFACIES: shale with conglomerate lenses.

DIVERSITY AND ABUNDANCE: 21 species, the two nominate species with over 100 specimens/kg.

SEA-LEVEL SIGNAL: representing the basal Arenigian transgression in the upper proximal slope facies.

COMMENTS: Williams et al. (1999) reported a conodont fauna from the level lower than CH4A at the same section, which is closely similar to the *T.a.–P.o.* community. It is likely that the community can be recognized from the lower level within the *Tetragraptus approximatus* Zone.

*Prioniodus adami – Paracordylodus gracilis* (*P.a.–P.g.*) community

CLUSTERED SAMPLES: four consecutive samples.

DEFINING TAXA: *Prioniodus adami* Stouge and Bagnoli, and *Paracordylodus gracilis* Lindström.

RANGE: units 9.6–9.9 in lower Bed 9 representing lower *Tetragraptus approximatus* Zone.

LITHOFACIES: ribbon to parted limestone and mudstone with conglomerate in unit 9.7.

DIVERSITY AND ABUNDANCE: 18–23 species, most species with 1 – >100 specimens/kg.

SEA-LEVEL SIGNAL: further transgression that brought *P. gracilis* into upper proximal slope.

*Prioniodus elegans – P. hyalinus* (*P.e.–P.h.*) and *P. elegans – Oepikodus communis* (*P.e.–O.c.*) communities

CLUSTERED SAMPLES: five and four samples forming the two communities, respectively, most of them consecutive.

DEFINING TAXA: *Prioniodus elegans* Pander and *P. hyalinus* Stouge and Bagnoli for the *P.e.–P.h.* community, and *P. elegans* and *Oepikodus communis* for the *P.e.–O.c.* community.

RANGE: units 9.14 and 9.17 in upper Bed 9 corresponding to the upper *Tetragraptus approximatus* Zone and *T. akzharensis* Zone.

LITHOFACIES: mainly ribbon to parted lime mudstone with shale and conglomerate in units 9.14 and 9.15.

DIVERSITY AND ABUNDANCE: 18–32 and 15–25 species in *P.e.–P.h.*, and *P.e.–O.c.* communities, respectively; the *P. elegans* with 25 – ≥100 specimens/kg.

SEA-LEVEL SIGNAL: the appearance of *P. elegans* reflects a deeper water environment (Barnes and Fåhraeus 1975; Fortey and Barnes 1977; Dubinina 1991) than the previous two communities; *P. hyalinus* being replaced by *O. communis* probably reflected a subtle change to a deeper water depth.

*Oepikodus evae – Periodon flabellum* (*O.e.–P.f.*) community

CLUSTERED SAMPLES: three consecutive samples.

DEFINING TAXA: *Oepikodus evae* (Lindström) and *Periodon flabellum* (Lindström).

RANGE: units 11.1–11.4 of the lowest Bed 11, equivalent to the *Pendeograptus fruticosus* Zone.

LITHOFACIES: dominated by shale.

DIVERSITY AND ABUNDANCE: 23–32 species, the two nominate species with over 100 and 25–100 specimens/kg in each sample, respectively.

SEA-LEVEL SIGNAL: abundant *O. evae* and *P. flabellum* have been well known as representatives of an Arenigian transgression (Barnes and Fåhraeus 1975; Fortey and Barnes 1977; Nielsen 1992*b*; Johnston and Barnes 1999), which is supported by the invasion of a diverse graptolite fauna to the upper proximal slope.

*Periodon aculeatus – P. flabellum* (*P.a.–P.f.*) community

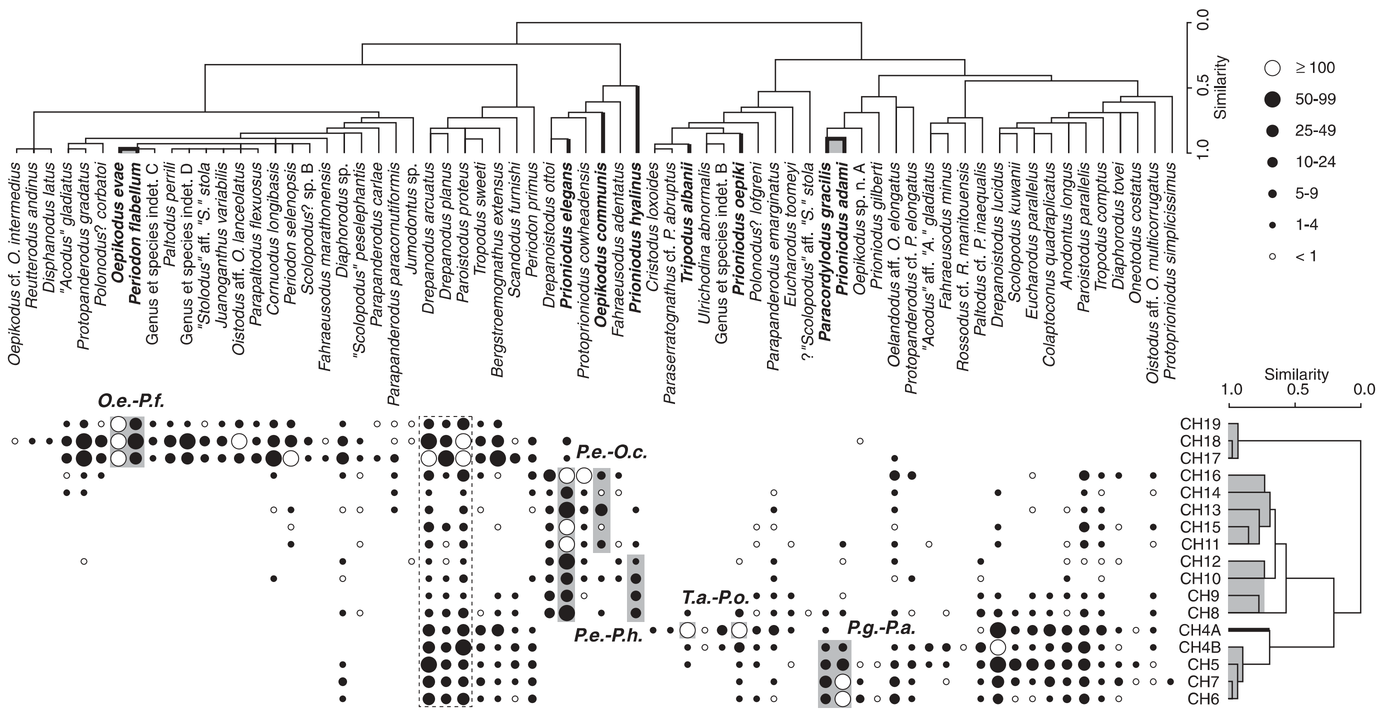
SAMPLES USED: two samples (2C, 2B) from the collection of Fåhraeus and Nowlan (1978).

DEFINING TAXA: *Periodon aculeatus* Hadding and *P. flabellum*.

RANGE: unit 1, Bed 13, correlated to the *Isograptus victoriae victoriae* Zone.

LITHOFACIES: parted to ribbon grainstone.

**Fig. 6.** Q- and R-mode cluster analysis of 17 samples from the upper proximal slope facies (Bed 9 and lower Bed 11, Factory Cove Member, Shallow Bay Formation at the Ledge – Point of Head section). Samples in Q-mode clustering order, taxa in R-mode clustering order, and relative abundance of taxa as a graded series of dots. Intersections of Q- and R-clusters define conodont communities: *O.e.–P.f.*, *Oepikodus evae – Periodon flabellum*; *P.e.–O.c.*, *Prioniodus elegans – Oepikodus communis*; *P.e.–P.h.*, *Prioniodus elegans – Prioniodus hyalinus*; *T.a.–P.o.*, *Tripodus albani – Prioniodus oepiki*; *P.g.–P.a.*, *Paracordylodus gracilis – Prioniodus adami*. The data are from table 1 of Stouge and Bagnoli (1988).




DIVERSITY AND ABUNDANCE: 5–9 species, the nominate species comprising 88%–97% of the community.

SEA-LEVEL SIGNAL: changes from *O.e.–P.f.* to *P.a.–P.f.* community and from shale to grainstone reflect a significant change of water depth from deep to shallow, supporting the observation of regional shallowing producing a change from a *Prioniodus* to a *Periodon* community made by Fortey and Barnes (1977) and Johnston and Barnes (1999).

### Lower proximal slope communities

Eight communities are recognized by the cluster analysis through beds 9–13, St. Pauls Member, Green Point Formation at St. Pauls section (Johnston and Barnes 1999, 2000), which represents the lower proximal slope facies (James et al. 1989) (Figs. 8, 9).

The descriptions for lower proximal slope communities are as follows; the lithofacies and division of units are based on James and Stevens (1986); the figure references for the community partition and distribution are Figs. 8 and 9.

*Paracordylodus gracilis* (*P.g.*) community and Midcontinent assemblage (M.a.)

CLUSTERED SAMPLES: nine and three alternating samples in *P.g.* community and Midcontinent assemblage, respectively.

DEFINING TAXON: *Paracordylodus gracilis* for *P.g.* community and several Midcontinent Realm (Pohler and Barnes 1990) species for Midcontinent assemblage.

RANGE: alternating occurrences in units 48–52, Bed 9 representing the *Tetragraptus approximatus* Zone.

LITHOFACIES: from shale, parted limestone to parted grainstone.

DIVERSITY AND ABUNDANCE: 4–26 species in *P.g.* community and 15–35 species in the Midcontinent assemblage; most of species with < 1–9 specimens/kg.

SEA-LEVEL SIGNAL: *P. gracilis* is indicative of deep water; the appearance of the Midcontinent species in the grainstone unit suggests a brief sea-level drop in the late *T. approximatus* time caused the Midcontinent fauna either to have migrated or to have been transported to a deeper environment setting.

*Oepikodus evae – Periodon flabellum* (*O.e.–P.f.*) community

CLUSTERED SAMPLES: five consecutive samples.

DEFINING TAXA: *Oepikodus evae* and *Periodon flabellum*.

RANGE: the units 59–63 of the middle Bed 11, correlated to the lower *Didymograptus bifidus* Zone.

LITHOFACIES: from shale, limestone, grainstone to lenticular conglomerate.

DIVERSITY AND ABUNDANCE: 31–46 species, with *O. evae* having 50 – ≥100 specimens/kg.

SEA-LEVEL SIGNAL: the community appeared later in the lower

**Fig. 7.** Inferred sea-level curve based on the distribution of the conodont communities identified by cluster analysis through Bed 9 and lower Bed 11, Factory Cove Member, Shallow Bay Formation at the Ledge – Point of Head section. The graptolite distribution and the zonation are from Williams and Stevens (1988, text-fig. 4). S, shallow; D, deep; L, low; H, high.; bk, black; gn, green; gy, grey; rd, red.

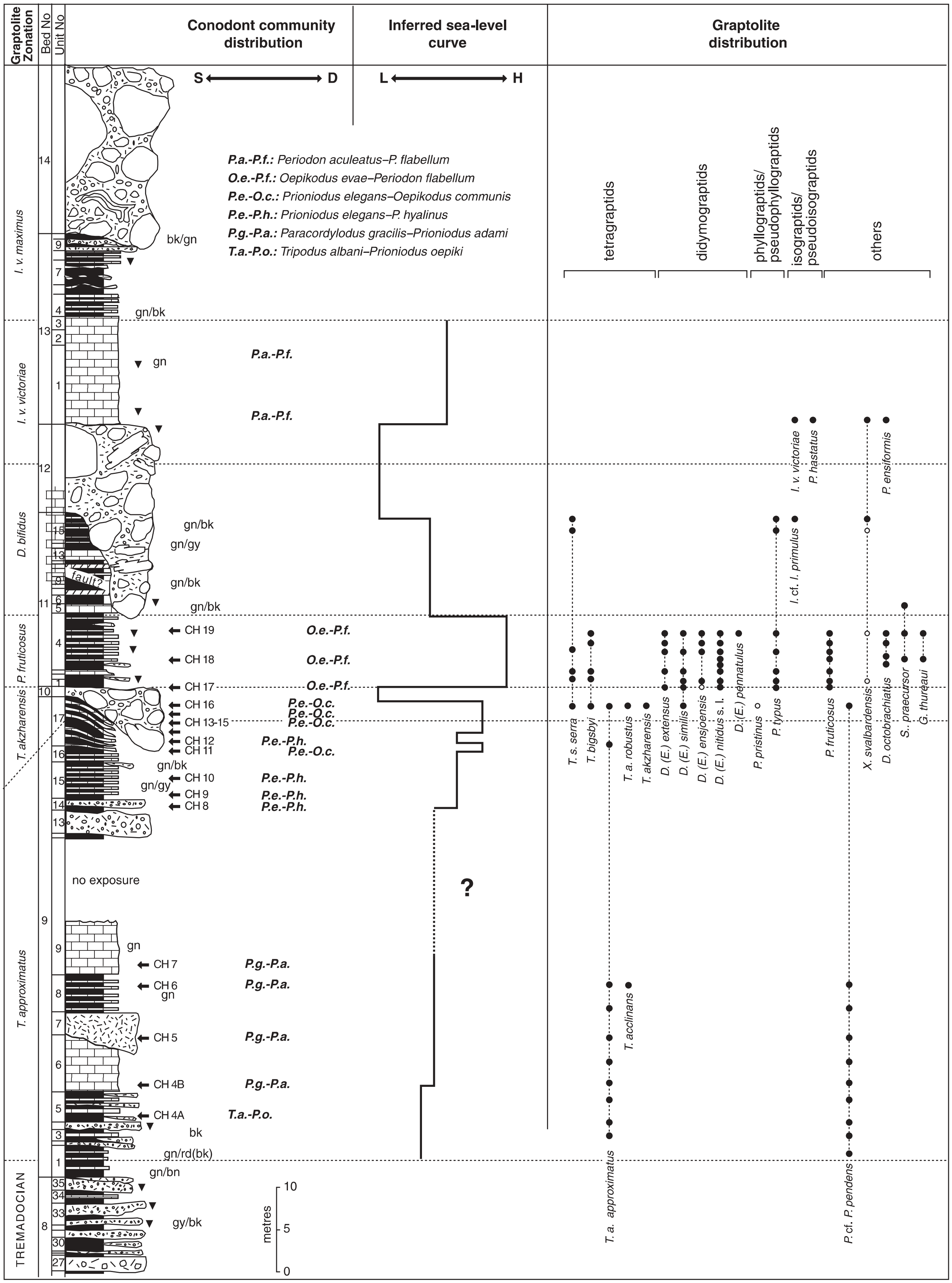
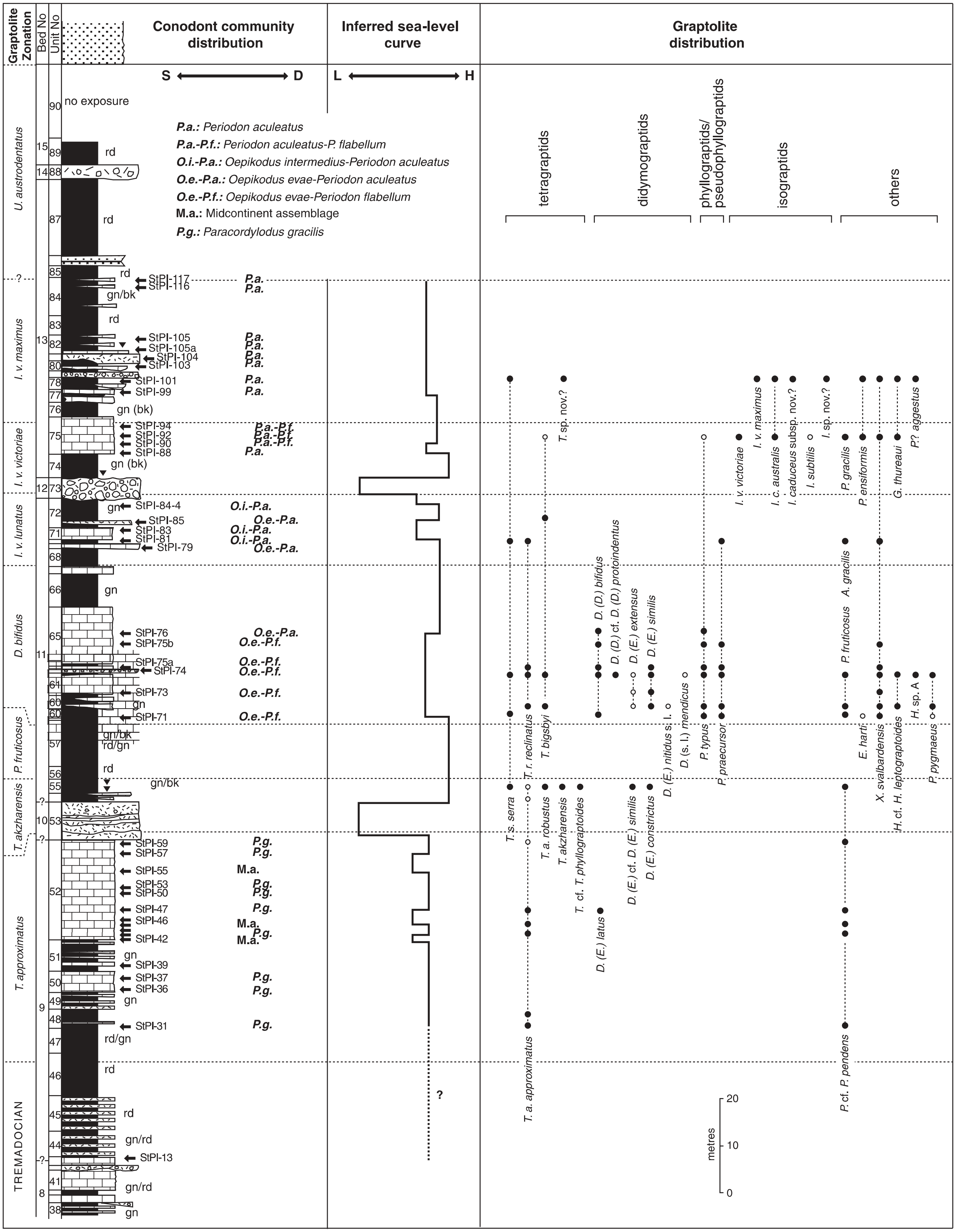


**Fig. 8.** Q- and R-mode cluster analysis of 17 samples from the lower proximal slope facies (beds 9, 11, and 13, St. Pauls Member, Green Point Formation, at St. Pauls section). Samples in Q-mode clustering order, taxa in R-mode clustering order and relative abundance of taxa as a graded series of dots. Intersections of Q- and R-clusters define conodont communities: *P.a.*, *Periodon aculeatus*; *P.a.–P.f.*, *Periodon aculeatus – P. flabellum*; *O.i.–P.a.*, *Oepikodus intermedius – Periodon aculeatus*; *O.e.–P.a.*, *Oepikodus evae – Periodon aculeatus*; *O.e.–P.f.*, *Oepikodus evae – Periodon flabellum*; M.a., Midcontinent assemblage; *P.g.*, *Paracordylodus gracilis*. The data are from tables 1 and 2 of Johnston and Barnes (1999).

**Fig. 9.** Inferred sea-level curve based on the distribution of the conodont communities identified by cluster analysis through beds 9, 11, and 13, St. Pauls Member, Green Point Formation at St. Pauls section. The graptolite distribution and the zonation are from Williams and Stevens (1988, text-fig. 10). Abbreviations the same as Fig. 7.



proximal slope than in the upper proximal slope, reflecting a community shift to respond the sea-level fall.

*Oepikodus evae – Periodon aculeatus* (*O.e.–P.a.*) community

CLUSTERED SAMPLES: three inconsecutive samples.

DEFINING TAXA: *Oepikodus evae* and *Periodon aculeatus*.

RANGE: units 65, 69, and 72 in middle and upper Bed 11, equivalent to upper *Didymograptus bifidus* and *Isograptus victoriae lunatus* zones.

LITHOFACIES: grainstone, conglomerate, and shale.

DIVERSITY AND ABUNDANCE: 5–7 species, each with 1–9 specimens/kg.

SEA-LEVEL SIGNAL: decrease of both diversity and abundance in both conodont and co-occurring graptolite, and replacement of *Periodon flabellum* by *P. aculeatus* may reflect a sea-level drop.

*Oepikodus intermedius – Periodon aculeatus* (*P.i.–P.a.*) community

CLUSTERED SAMPLES: three inconsecutive samples.

DEFINING TAXON: *Oepikodus intermedius* (Serpagli) and *Periodon aculeatus*.

RANGE: units 71 and 72 in the uppermost Bed 11, correlated to the *Isograptus victoriae lunatus* Zone.

LITHOFACIES: parted limestone and shale with conglomerate.

DIVERSITY AND ABUNDANCE: 29 and 35 species with two nominate species having 10 – >100 specimens/kg (except for B11-83).

SEA-LEVEL SIGNAL: *O. evae* replaced by *O. intermedius* reflects a subtle sea-level drop, and *P.i.–P.a.* community alternating with the *O.e.–P.a.* community reflects an oscillating sea level.

*Periodon aculeatus – P. flabellum* (*P.a.–P.f.*) community

CLUSTERED SAMPLES: three consecutive samples.

DEFINING TAXA: *Periodon aculeatus* and *P. flabellum*.

RANGE: unit 75, lower Bed 13, correlated to the upper *Isograptus victoriae victoriae* Zone.

LITHOFACIES: parted grainstone.

DIVERSITY AND ABUNDANCE: 31–34 species with the two nominate species having 10–100 and > 100 specimens/kg.

SEA-LEVEL SIGNAL: reappearance of *P. flabellum* and recovery of species diversity and abundance indicate that the sea level returned to the similar level represented by the *O. evae – P. flabellum* community.

*Periodon aculeatus* (*P.a.*) community

CLUSTERED SAMPLES: nine samples with eight consecutive.

DEFINING TAXON: *Periodon aculeatus*.

RANGE: mainly in units 77–84, middle Bed 13, correlated to the *Isograptus victoriae maximus* Zone.

LITHOFACIES: shale with minor conglomerate and dolostone.

DIVERSITY AND ABUNDANCE: almost a monospecific community dominated by the nominate species having 1 – ≥100 specimens/kg in different samples.

SEA-LEVEL SIGNAL: the dominant *P. aculeatus* suggests a community shift in response to the sea-level drop (Fåhraeus and Barnes 1975; Fortey and Barnes 1977; Pohler et al. 1987; Pohler 1994; Johnston and Barnes 1999).

**Distal slope communities**

The distal slope facies section Western Brook Pond South is only partly exposed (James and Stevens 1986), and productive conodont samples are restricted to upper Bed 11 to the base of Bed 13, St. Pauls Member, Green Point Formation (Sullivan 1998, appendix 1). Three conodont communities are recognized from this interval; the descriptions for them are noted in this subsection of text; the lithofacies and division of units are based on James and Stevens (1986); the figure references for the community partition and distribution are Figs. 10 and 11.

*Oepikodus evae – Periodon aculeatus* (*O.e.–P.a.*) community

CLUSTERED SAMPLES: two inconsecutive samples.

DEFINING TAXA: *Oepikodus evae* and *Periodon aculeatus*.

RANGE: units 23 and 24, Bed 11, correlated to the uppermost *Didymograptus bifidus* Zone; the community spans the interval of middle *D. bifidus* to middle *Isograptus victoriae lunatus* zones in the lower proximal slope (Figs. 8, 9).

LITHOFACIES: shale, limestone and mudstone.

DIVERSITY AND ABUNDANCE: five and 11 species with nominate species having 5–49 specimens/kg.

SEA-LEVEL SIGNAL: lacking comparison from lower level of the same section.

*Periodon aculeatus* (*P.a.*) community

CLUSTERED SAMPLES: seven inconsecutive samples.

DEFINING TAXON: *Periodon aculeatus*.

RANGE: units 24–52, upper Bed 11 to lower Bed 13, equivalent to the interval from uppermost *Didymograptus bifidus* Zone to lower *Undulograptus austrodentatus* Zone.

LITHOFACIES: shale dominated.

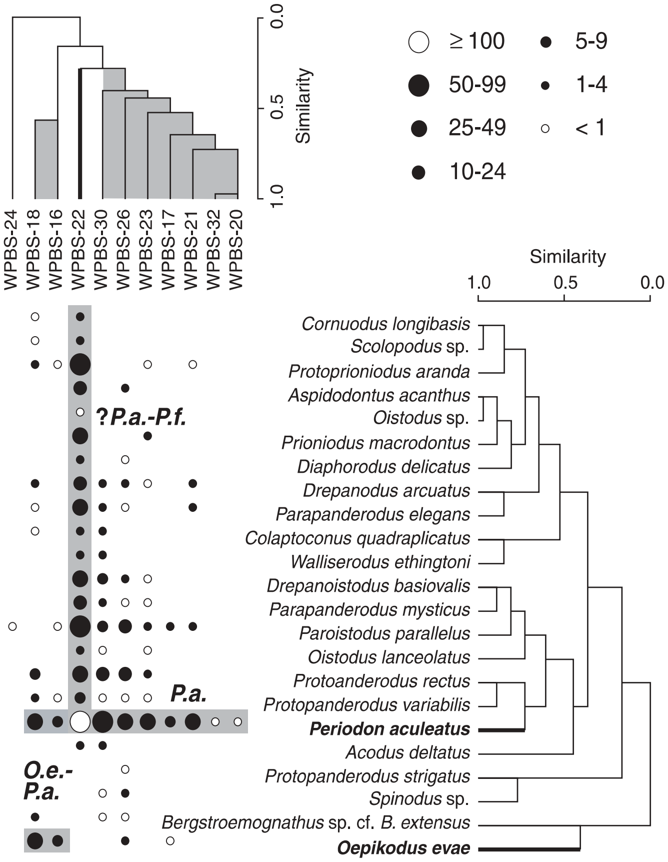
DIVERSITY AND ABUNDANCE: dominated by the nominate species having < 1 – 99 specimens/kg.

SEA-LEVEL SIGNAL: see description for the community of the same name in the lower proximal slope.

? *Periodon aculeatus – P. flabellum* (*P.a.–P.f.*) community

CLUSTERED SAMPLE: 1 (WPBS-22).

**Fig. 10.** Q- and R-mode cluster analysis of 17 samples from the distal slope facies (upper Bed 11 and Bed 13, St. Pauls Member, Green Point Formation at Western Brook Pond South section). Samples in Q-mode clustering order, taxa in R-mode clustering order, and relative abundance of taxa as a graded series of dots. Intersections of Q- and R-clusters define conodont communities: *P.a.*, *Periodon aculeatus*; ?*P.a.–P.f.*, *Periodon aculeatus – P. flabellum*; *O.e.–P.a.*, *Oepikodus evae – Periodon aculeatus*. The data are from appendix 1 of Sullivan (1998).




DEFINING TAXON: no specimens of *Periodon flabellum* found in the sample, the community assignment is questioned; compared to the *P.a.–P.f.* community in the lower proximal slope, both having several species in common and having a similar species diversity and abundance.

RANGE: unit 34, lower Bed 13, correlated to lower *Isograptus victoriae maximus* Zone.

LITHOFACIES: parted limestone.

DIVERSITY AND ABUNDANCE: 19 species with most having 1–100 specimens/kg.

SEA-LEVEL SIGNAL: the community appeared in the distal slope later than in the lower proximal slope (*Isograptus victoriae victoriae* Zone) indicating a community shift from lower slope to distal slope, hence suggesting a sea-level drop.

## Interpretation of Arenigian sea-level history deduced from changes in lithofacies, conodont communities, and graptolite faunas

A general Arenigian sea-level history in western Newfoundland was depicted by Barnes (1984) based on lithology and biostratigraphy. Three main transgressions are represented by beds 9, 11, and 13 of Cow Head Group that were correlated to the Boat Harbour, lower Catoche and upper Catoche formations, respectively. These transgressions were separated by two major regressions represented by the megabreccias of beds 10 and 12, which were correlated to the interval between the Boat Harbour and Catoche formations and middle Catoche Formation by Barnes (1984), and to the interval of upper Catoche and lower Aguathuna formations later by James et al. (1989). Based on the stratigraphy of St. George Group, the Barbace Cove Member, Boat Harbour Formation, Catoche and Aguathuna formations were formed in a megacycle reflecting a transgressive–regressive couplet (Knight and James 1987; James et al. 1989).

Ji and Barnes' (1994*b*) study on conodont communities from the St. George Group recognized one first-order and three second-order transgressive–regressive cycles in the upper Boat Harbour to Aguathuna formations. Pohler's (1994) study on conodont biofacies from the upper slope and shelf-break suggested that the lower Bed 11 represents a highest sea level during Arenigian. The conodont paleoecology study of the lower slope facies of Johnston and Barnes (1999) recognized the *elegans–evae* transgression in Bed 9 and lower Bed 11, and the Whiterock regression in upper Bed 11 and Bed 13, respectively. An integration of the data from these conodont paleoecological studies from different facies enables a revised and more detailed assessment of Arenigian sea-level history.

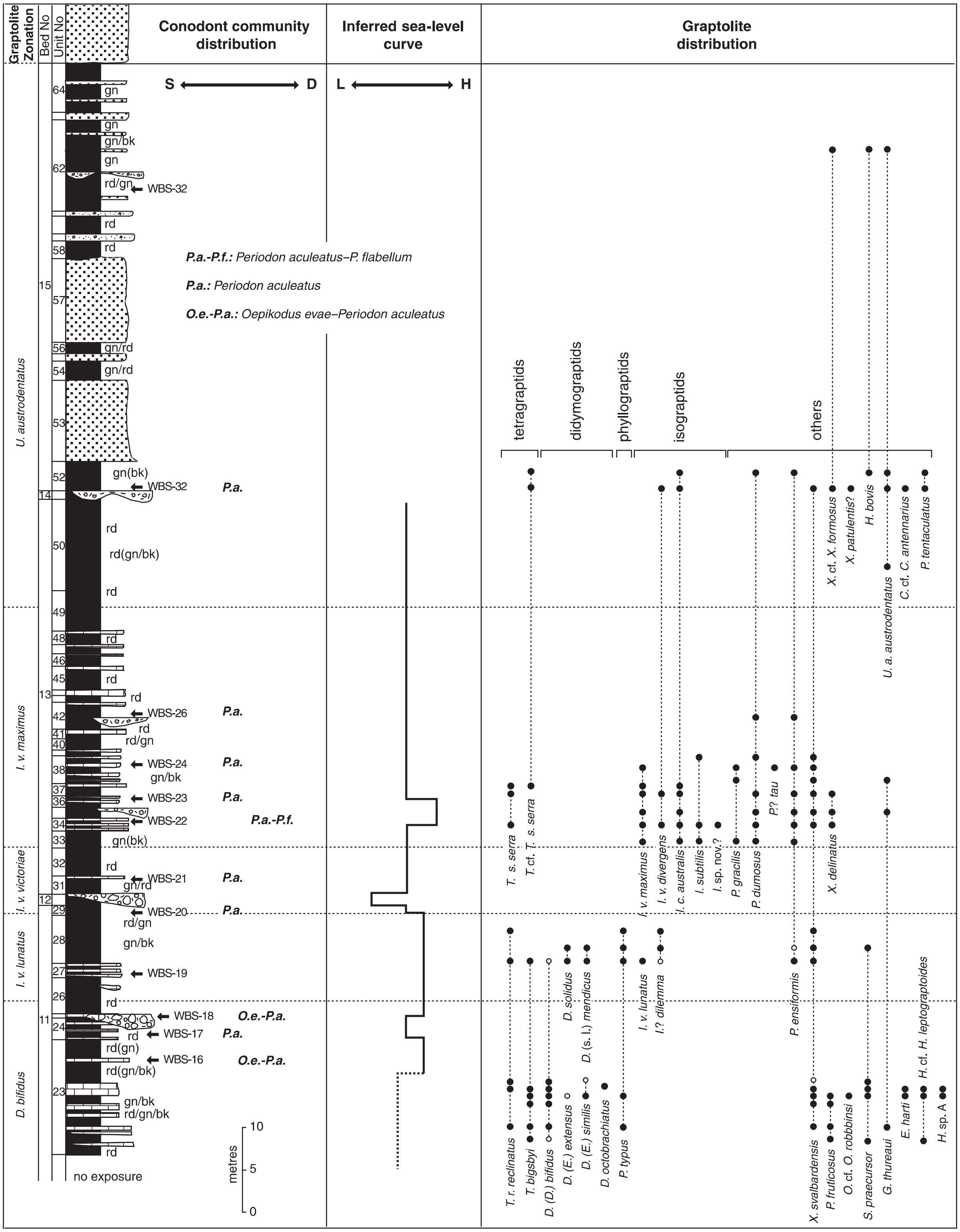
It must be stressed that an important prerequisite for the following discussion is the temporal framework established by Williams and Stevens (1988) based on the graptolite biozonation for each slope section. This biozonation is difficult to apply to the platform facies where graptolites are scarce, but the conodont biozonation for the slope (Johnston and Barnes 1999) can be correlated to both the graptolite biozonation and the platform conodont biozonation of Ji and Barnes (1994*a*).

### *Tetragraptus approximatus* Zone time: a prolonged transgression resulting in sequential community replacement and terminating with a brief regression

Although no early Arenigian graptolites are found in the platform facies Barbace Cove Member, Boat Harbour Formation, a widespread subaerial disconformity represented by breccias, quartz-pebble conglomerate, and paleokarst marks its lower boundary (Knight and James 1987), which has been taken to mark the Tremadocian–Arenigian boundary (James et al. 1989; Knight et al. 1991).

Conodont communities in the upper proximal slope displayed a successive change during the *Tetragraptus approximatus* Zone time. The four communities of *Tripodus albani – Prioniodus oepiki*, *Paracordylodus gracilis – Prioniodus adami*, *Prioniodus elegans – P. hyalinus*, and *P. elegans –*

**Fig. 11.** Inferred sea-level curve based on the distribution of the conodont communities identified by cluster analysis through upper Bed 11 and Bed 13, St. Pauls Member, Green Point Formation at Western Brook Pond South section. The graptolite distribution and the zonation are from Williams and Stevens (1988, text-fig. 7). Abbreviations the same as Fig. 7.



*Oepikodus communis* appeared in ascending order in the Ledge – Point of Head section, and the *P. elegans – P. hyalinus* community recurred by the end of *T. approximatus* Zone time (Figs. 7, 12). The community changes from *gracilis*-dominated to *elegans*-dominated, and then from *hyalinus*-dominated to *communis*-dominated, coinciding with the earlier phase of the *elegans–evae* transgression (Johnston and Barnes 1999). The *hyalinus*-dominated community that re-invaded the upper proximal slope may represent a brief sea-level drop by the end of *T. approximatus* Zone time.

A similar pattern of community changes occurs on the platform in the Barbace Cove Member, Boat Harbour Formation and lowest Catoche Formation. The community changed from *Striatodontus prolificus* to *Colaptoconus quadraplicatus*, then to *Acodus comptus – Stultodontus costatus – Colaptoconus*, then to *A. comptus* (Figs. 3, 4). The latter contains the first appearance of *Oepikodus communis* that probably originated from an Atlantic lineage (see later discussion). Such a change reflects a shift of the community diversity from low to high and an influx of Atlantic-realm components. Increasing platform diversity is considered as one of the biological effects during a transgressive phase onto the craton, and times of transgression may appear as times of provincial breakdown (Fortey 1984). If the four successive communities in the platform facies represent a gradual transgression, then the recurrence of *A. comptus – S. costatus – Colaptoconus* community may indicate a brief regression comparable to the recurrence of *Prioniodus elegans – P. hyalinus* community in the upper proximal slope. The two series of community changes in both platform and upper proximal slope suggest that they were affected by the same transgressive–regressive phase. If correct, the recurrence of the *A. comptus – S. costatus – Colaptoconus* community after the *A. comptus* community should correlate to latest *T. approximatus* Zone time, i.e., lower Catoche Formation (Fig. 12). Within such a biostratigraphic framework, the initial transgressive phase can be implied from the appearance of *Oepikodus communis* in the different facies.

Ethington and Repetski (1984, fig. 5) summarized the occurrences of certain species superimposed on the Lower Ordovician lithofacies map of the US., which shows *Oepikodus communis* distributed from shallow-water dolomite facies to the deeper water limestone facies. In the open shelf deposits, it is one of the most abundant taxa, and it usually co-occurred with those species that are known in shallow subtidal facies. In the outer shelf or upper slope deposits, this species is rare. It is unknown whether this species was indigenous to deeper environments or was transported there from the slope and shelf (Ethington and Repetski 1984).

In western Newfoundland, the first appearance of *Oepikodus communis* is in the middle *Tetragraptus approximatus* Zone in the lower proximal slope (sample StPI-39, Figs. 8, 9), in the upper part of the zone in the upper proximal slope (sample CH8, Figs. 6, 7), and in the uppermost part of the zone or lowest *T. akzharensis* Zone in the platform (sample Z2-83, Figs. 3, 4). Thus, from lower proximal slope to platform, the first appearance of the species was progressively younger, suggesting that the species originated in deep water and migrated onto the platform with the early Arenigian transgression.

This transgressive phase reflected by the community changes is coincident with the aerobic phase reflected by the slope lithofacies (James and Stevens 1986) and with the Barbace Cove Member, Boat Harbour Formation and the lower Catoche Formation (Knight and James 1987; James et al. 1989; Knight et al. 1991), but the regression during the late *Tetragraptus approximatus* Zone time was not recognized.

In the lower proximal slope, the *Paracordylodus gracilis* community exhibits a relatively stable development, except for the brief occurrence of components of the Midcontinent fauna. These Midcontinent elements may have been introduced by the transportation or migration, but more likely transportation, as they are preserved in the grainstone and are not recognized in the equivalent upper proximal slope section.

### *Tetragraptus akzharensis* Zone time: transgression, or regression, or transgression–regression?

Uppermost Bed 9 is characterized by the recurrence of the *Prioniodus elegans – Oepikodus communis* community and an "explosion" in terms of graptoloid diversity and numbers (Williams and Stevens 1988) in the upper proximal slope, which occurred in the *Tetragraptus akzharensis* Zone (Williams and Stevens 1988). On the platform, *Oepikodus communis* was abundant and is the characteristic species of the *O. communis* community (Figs. 3, 4,12). In the present interpretation, the conodont community changes and the graptoloid explosion reflect a transgression.

The question arises whether the transgression lasted for the entire *Tetragraptus akzharensis* Zone time, or only for the earlier part. As noted by Williams and Stevens (1988), this zone occurs within strata below Bed 10 at Cow Head but above the breccia bed referred to Bed 10 by James and Stevens (1986) at St. Pauls Inlet (Figs. 7, 9). "It is unclear whether this indicates inaccuracy in lithostratigraphical correlation, or differential erosion of sediments underlying (at St. Pauls Inlet) and overlying (at Cow Head) Bed 10" (Williams and Stevens 1988, p. 6).

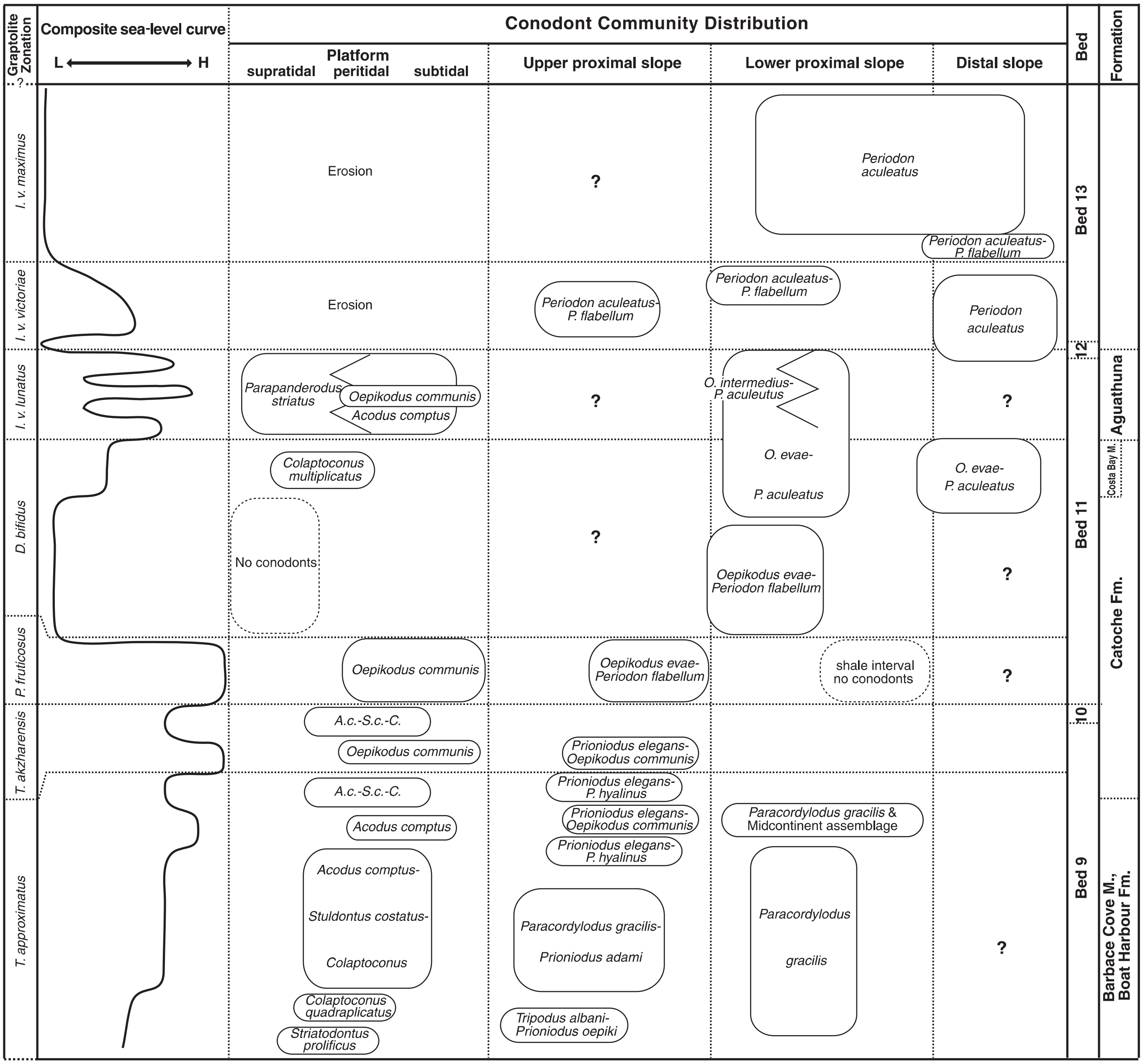
Analyzing the conodont community change on the platform, it is evident that the brief transgression in early *T. akzharensis* Zone time was followed by a regression reflected by the *Acodus comptus – Stultodontus costatus – Colaptoconus* community that replaced the *Oepikodus communis* community, and in turn was replaced by the *C. quadraplicatus* community. This regression may have caused the graptolites of the *T. akzharensis* Zone to migrate from upper proximal slope to lower proximal slope to remain in a similar water depth or temperature, resulting in the same graptolite fauna found below Bed 10 in Cow Head and above Bed 10 in St. Pauls Inlet.

The conodont community changes on the platform, together with the likely graptolite migration from upper proximal slope to lower proximal slope, suggest that a transgression of early *T. akzharensis* Zone time was followed by a regression in late *T. akzharensis* Zone time.

### *Pendeograptus fruticosus* and early *Didymograptus bifidus* Zone time: "*evae*" representing a transgression everywhere? When?

A chert cap covering Bed 10 of the Cow Head Group was interpreted as a marine flooding event reflecting the "*Oepikodus evae transgression*," representing the highstand, rather than

**Fig. 12.** Summary of conodont community distribution through space and time during Arenigian time in western Newfoundland with an inferred composite sea-level curve based on the distribution of the conodont communities and the graptolite fauna. *A.c.–S.c.–C.*, *Acodus comptus – Stultodontus costatus – Colaptoconus*; L, low; H, high; M., Member; Fm., Formation.




the initial transgression that occurred within the *Tetragraptus akzharensis* Zone (Nielsen 1992*b*). Based on conodont studies from St. Pauls Inlet, Johnston and Barnes (1999) concluded that beds 9 and 11 represent maximum transgression and termed it the "*elegans–evae* transgression."

The typical Atlantic-realm conodont species, *Oepikodus evae*, has been widely accepted as a deep-water representative (Fortey and Barnes 1977). The *Oepikodus evae – Prioniodus flabellum* community has an interesting distribution in the slope facies in western Newfoundland. It appeared in the upper proximal slope directly above the breccia Bed 10 and was developed through the entire *Pendeograptus fruticosus* Zone (Fig. 7). A diverse graptolite fauna with 13 species has been found within this zone in the Ledge – Point of Head section (Williams and Stevens 1988). However, within this interval no conodont and graptolites were found in the shale-dominated units 56 and 57 (James and Stevens 1986) in the lower proximal slope section at St. Pauls Inlet (Fig. 9). This suggests that during *P. fruticosus* Zone time the St. Pauls environment was too deep or anoxic for most animals to live. Hence, the *P. fruticosus* Zone is considered to represent the highest sea level during the Arenigian in western Newfoundland.

The highest sea level resulted in a stable diverse conodont community developed on the platform, reflected by the continuous presence of the *Oepikodus communis* community (Fig. 4) and the invasion of the pelagic trilobites *Carolinites* and *Opipeuter* (Fortey 1979) in the lower middle Catoche Formation. Comparing the communities representing the highest sea level suggests that the lower middle Catoche Formation correlates to the *P. fruticosus* Zone but not to the *Tetragraptus approximatus* Zone, as suggested by Williams et al. (1987).

On the platform, *Didymograptus bifidus* was found in the upper Catoche Formation (Williams et al. 1994), which confirmed the presence of *D. bifidus* Zone. A dramatic event affected the conodont communities from *Pendeograptus fruticosus* Zone to the lower *D. bifidus* Zone. The diverse *Oepikodus communis* community disappeared suddenly, followed by an interval lacking conodonts in the upper middle Catoche Formation, except for the brief appearance of the *Colaptoconus multiplicatus* community (Fig. 4). This conodont community change was accompanied by the disappearance of the pelagic trilobites *Carolinites* and *Opipeuter* (Fortey 1979) in the upper Catoche Formation.

Although the database of Stouge and Bagnoli (1988) excludes conodonts within or younger than the *D. bifidus* Zone from the upper proximal slope section at the Ledge – Point of Head, there is enough evidence to prove that the *Oepikodus evae – Prioniodus flabellum* community migrated from upper proximal slope to lower proximal slope (Figs. 7, 9). Such a change can be also found among the graptolite faunas. Within the Arenigian, in the upper proximal slope, the most diverse graptolite fauna occurred in the *Pendeograptus fruticosus* Zone, but in the lower proximal slope, it occurred in the lower *D. bifidus* Zone, including species such as *Tetragraptus serra serra*, *T. bigsbyi*, *D. extensus*, *D. similes*, *Pendeograptus fruticosus*, *Phyllograptus typus*, and *Sigmagraptus praecursor* (referred to as the *fruticosus* fauna in the following discussion). Except for the appearance of *D. bifidus*, the graptolite fauna in the lower *D. bifidus* Zone in the lower proximal slope is almost the same as the *fruticosus* fauna in the *P. fruticosus* Zone in the upper proximal slope, and this diverse fauna also occurs in the lower *D. bifidus* Zone in the distal slope (Fig. 11), but totally disappeared in the lower *D. bifidus* Zone of the upper proximal slope.

The migration of the *Oepikodus evae – Prioniodus flabellum* community and the *fruticosus* fauna from upper proximal slope to lower proximal slope suggests a regression during the early *D. bifidus* Zone time. Thus, the *O. evae – P. flabellum* community only represents the "*evae*" transgression at certain times and locations, marking a transgression in upper proximal slope during *fruticosus* Zone time, but a regression in lower proximal slope during early *bifidus* Zone time.

### Late *Didymograptus bifidus* Zone time: transgression

*Didymograptus bifidus* was found in the Costa Bay Member, Catoche Formation, a unit interpreted to represent a shelf-wide marine incursion of Iapetan Ocean waters onto the shelf (Williams et al. 1994). Based on the changes of conodont communities and graptolite faunas, this interval is probably of upper *D. bifidus* Zone.

On the platform, the *Colaptoconus multiplicatus* community and monospecific graptolite fauna of *D. bifidus* occurred sequentially in the upper Catoche Formation, with *C. multiplicatus* showing a stable development (Fig. 4). The upper proximal slope lacks firm conodont evidence, but a graptolite fauna with *Tetragraptus serra serra*, *Phyllograptus typus*, and *Xiphograptus svalbardensis* that returned after a graptolite-barren interval in the lower *D. bifidus* Zone (Fig. 7). In the lower proximal slope, the *Oepikodus evae – Periodon aculeatus* community replaced the *O. evae – P. flabellum* community, with an obvious decrease in graptolite diversity (Fig. 9). In the distal slope, the *O. evae – P. aculeatus* community occurred, but with no graptolites. Both the conodont community and graptolite faunal changes indicate a shift towards the platform, suggesting a transgression in late *D. bifidus* Zone time and supporting the interpretation of an important marine flooding event onto the platform at this time (Williams et al. 1994).

### The *Isograptus victoriae lunatus* Zone time: frequent sea-level oscillations

The Aguathuna Formation, overlying the Catoche Formation, may belong to the *Isograptus victoriae lunatus* Zone, as *D. bifidus* was found in the Costa Bay Member, uppermost Catoche Formation (Williams et al. 1994).

On the platform, the two main conodont communities *Parapanderodus striatus* and *Acodus comptus* communities alternated through the entire Aguathuna Formation, except for three other conodont communities appearing briefly. The former community may represent a shallower water environment than the latter. A similar pattern can be found among the conodont communities in the lower proximal slope where the *Oepikodus intermedius – Periodon aculeatus* and *O. evae – P. aculeatus* communities replaced each other repeatedly. The former may have been adapted to a shallower environment than the latter (see earlier discussion). Such similar patterns of repeating replacement of conodont communities in both platform and slope suggest an oscillating sea level during the *Isograptus victoriae lunatus* Zone time. This probably reflected the instability during the earlier phases of the Taconic Orogeny resulting in the foundering of the margin and subduction of oceanic crust onto the margin (James et al. 1989). Overall, the conodont communities in both platform and slope indicated relatively lowered sea level.

### St. George unconformity and Bed 12: a major regression

An erosional unconformity on the top of Aguathuna Formation, the St. George unconformity (James et al. 1989; Knight et al. 1991), represents a lowstand peak. Conodonts from the overlying basal Table Head Formation, above the erosional surface indicate an early Darriwilian, Middle Ordovician age (Stouge 1984). The coeval Bed 12 deep-water megaconglomerate, which can be traced to the most distal slope, could be the result of seismicity and margin faulting (James and Stevens 1986), but was likely the lowstand peak correlative to the initiation of the St. George unconformity.

### The *Isograptus victoriae victoriae* Zone and *I. v. maximus* Zone times: a period of slow regression

Directly above Bed 12 at the Ledge – Point of Head and St. Pauls Inlet sections, chert layers represent marine flooding after the regression reflected by Bed 12 (James and Stevens 1986). However, this transgression was brief and was followed by a prolonged, slow regression within the *Isograptus victoriae victoriae* and the *I. v. maximus* zones.

At the Ledge – Point of Head, the upper proximal slope section, the *Periodon aculeatus – P. flabellum* community first occurred almost directly above Bed 12 along with *Isograptus victoriae victoriae* in the lower *I. v. victoriae* Zone, and disappeared in the middle of the zone (Fig. 7). At St. Pauls Inlet, the lower proximal slope section, the first appearance of the *P. aculeatus* – *P. flabellum* community was in the upper *I. v. victoriae* Zone, which was later than the first appearance of *I. v. victoriae*, and its last appearance was at the top of the *I. v. victoriae* Zone (Fig. 9). At Western Brook Pond South, the distal slope section, the ?*P. aculeatus* – *P. flabellum* community appeared in the lower *I. v. maximus* Zone along with a diverse isograptid-rich graptolite fauna (Fig. 11). The initial appearance of the *P. aculeatus* – *P. flabellum* community was progressively younger along a depth gradient from upper proximal slope to distal slope, which reflected a community migration towards a deeper environment setting. Such a migration is similar to that during the *bifidus* time, and suggests a regression. The diverse isograptid-rich graptolite fauna was closely related to the last appearance of *P. aculeatus* – *P. flabellum* community in the distal slope, which does not support the conclusion that change of didymograptid-rich to isograptid-rich graptolite fauna was connected to rapid sea-level events, i.e., shallow to deep (Nielsen 1992*a*, fig. 3).

Except for the early *Isograptus victoriae maximus* Zone time, the sea level remained stable and at a relatively low level during rest of this zone time, as the *Periodon aculeatus* community maintained a stable development both in the lower proximal slope and distal slope (Figs. 9, 11).

## Comparison to the global Arenigian sea-level history

An Arenigian sea-level history was reconstructed based mainly on the trilobite paleoecology of the Komstad Limestone and Huk Formation of Scandinavia and the Horn Valley Siltstone of central Australia, where eight major transgression–regression cycles were recognized (Nielsen 1992*a*, 1992*b*). They were correlated widely to Scandinavia, central Australia, Victoria (Australia), Spitsbergen, western Newfoundland, Utah, and Britain (Nielsen 1992*b*). The sea-level curve for the early Arenigian, as reconstructed by Nicoll et al. (1992) based on Canning Basin and Amadeus Basin, Australia, is quite similar to that of Nielsen (1992*a*, 1992*b*). A comparison between the sea-level curve constructed by Nielsen (1992*b*, fig. 1) and a new curve developed by this study is shown in Fig. 13.

**Aspects of agreement**

(1) The brief regression related to the uppermost *Tetragraptus approximatus* Zone can be recognized by a hiatus in Canning Basin and Amadeus Basin, Australia (Nicoll et al. 1992), which is related to the regression peak (B) at the top of trilobite *Megistaspis planilimbata* Zone.
(2) The transgression in the early *T. akzharensis* Zone time can be related to the initial phase 2 (base of *Megistaspis* aff. *estonica* Zone) of the Billingen transgression.
(3) The transgression during the *Pendeograptus fruticosus* Zone time, the “*evae*” transgression, was considered as the highest sea level, which is at the base of the zone, peak 3.
(4) A transgression in the early *Isograptus victoriae lunatus* Zone time can be related to the transgression peak 4 at the base of *Megistaspis estonica* Zone.
(5) A major regression, represented by the St. George unconformity on the platform and Bed 12 in the slope, occurred during the latest *I. v. lunatus* Zone time and earliest *I. v. victoriae* Zone time. This is recognized as regression peak C at the base of *Megistaspis polyphemus* Zone.
(6) Both curves show a shallowing-up trend and a frequent sea-level oscillation pattern within the *I. v. lunatus* Zone – *M. estonica* Zone.

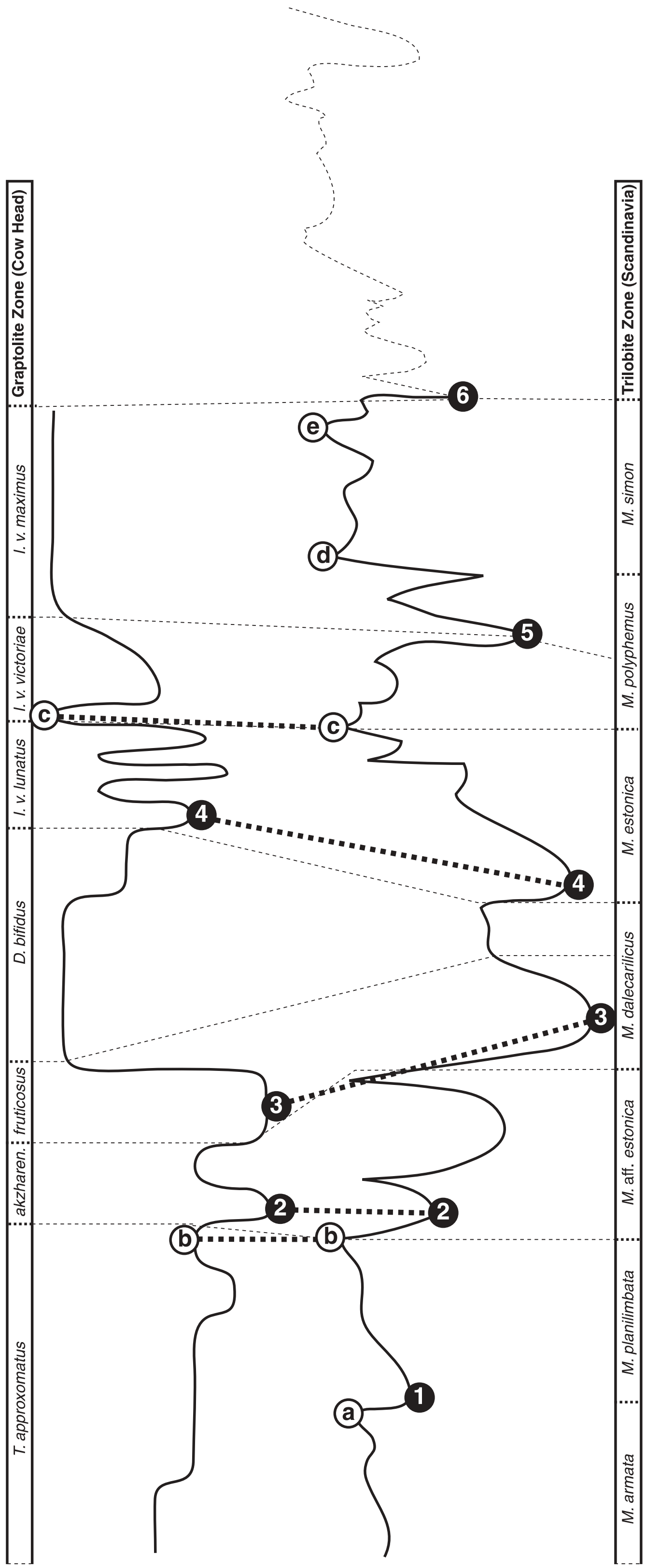
**Aspects of disagreement**

(1) Overall, although early Arenigian was a period of relatively low sea level, the boundary interval of Tremadocian–Arenigian was a period of increasing relative sea level. This event is of global significance, since it has been recorded in Australia (Nicoll et al. 1988), China (Chen 1988) and North America (Vail et al. 1977; Hallam 1984), western Argentina (Beresi 1992), and also recognized earlier by Barnes (1984), Barnes et al. (1995), and Fortey (1984), and now by this present study in western Newfoundland with a consecutive community replacement in the *Tetragraptus approximatus* Zone (Fig. 12). The regression peak A at the top of *Megistaspis polyphemus* Zone is recognized by a hiatus in the Amadeus Basin, which is related to the middle *T. approximatus* Zone. It is doubtful that this event has worldwide significance.
(2) Although a regression and a transgression were not recognized as peaks in the middle and upper *Megistaspis* aff. *estonica* Zone, which roughly correlates to the upper *Tetragraptus akzharensis* Zone, the curve developed by Nielsen (1992*a*, 1992*b*) obviously displays this couplet. However, only regression is recognized in this interval herein.
(3) A regression was not identified as a peak in the upper *Megistaspis dalecarilicus* Zone that is correlated to the *Didymograptus bifidus* Zone, but the curve developed by Nielsen (1992*a*, 1992*b*) shows a relatively low sea level in this interval. However, a major early regression coupled by a late transgression is identified by this study.
(4) A shallowing-upward trend is recognized in the *Isograptus victoriae victoriae* Zone in western Newfoundland; however, this is opposite to the deepening-upward trend within this time interval (lower *Megistaspis polyphemus* Zone) recognized by Nielsen (1992*a*, 1992*b*).
(5) Although the two curves show a relatively low sea level during the *Isograptus victoriae maximus* Zone – upper *Megistaspis polyphemus* and *M. simon* zones, sea level maintained a stable pattern in western Newfoundland, rather than a fluctuating pattern.

## Conclusions

Western Newfoundland provides a series of nearly complete and fossiliferous stratigraphic sections of Arenigian (Early Ordovician) age. The valuable records of sea-level changes are preserved in the two different sequences, parautochthonous (St. George Group platform facies) and allochthonous (Cow

**Fig. 13.** Comparison between the sea-level curves constructed by Nielsen (1992*a*, 1992*b*; on the right hand) and this study (on the left hand). 1–7 and a–g were used by Nielsen (1992*a*, 1992*b*) to list the transgression and regression peaks, respectively. Transgression peak 7 and regression peaks f and g are not included in this study.




Head Group slope facies). The present study is the first attempt to recognize statistically a complex pattern of conodont communities from 69 598 identifiable conodont specimens discovered from 153 conodont-bearing samples from four sections. It complements a similar study for Tremadocian strata in western Newfoundland (Zhang and Barnes, 2004). The study allows the reconstruction of sea-level history, given that the changes in the conodont communities responded to the sea-level changes both stratigraphically from older to younger and geographically along the depth gradient from platform to slope.

(1) Several major sea-level fluctuations are recognized by analyzing conodont community changes among the parautochthonous and allochthonous faunas. The sea-level changes synchronously affected the two different faunal groups, conodonts and graptolites.

(2) Analyzing the approximately synchronous sea-level changes results in a more precise stratigraphic correlation between parautochthonous and allochthonous sequences of Arenigian age. Barbace Cove Member, Boat Harbour Formation can be roughly related to the *Tetragraptus approximatus* Zone; Catoche Formation to the *T. akzharensis*, *Pendeograptus fruticosus*, and *Didymograptus bifidus* zones, instead of *T. approximatus* and *T. akzharensis* zones of Williams et al. (1987); Aguathuna Formation to the *Isograptus victoriae lunatus* Zone, instead of *P. fruticosus* Zone of Williams et al. (1987).

(3) It is not always reliable to use a particular fauna as a signal to identify a transgression or regression. A more reliable way is to analyze the faunal change within space and time. For example, the *Oepikodus evae – Prioniodus flabellum* community did not always represent the "*evae*" transgression (Nielsen 1992*b*); it could have migrated to a deeper geographic setting through a regression.

(4) The sea-level history in western Newfoundland can be depicted as follows: a transgression started in early *Tetragraptus approximatus* Zone time, lasting for most of this time interval, which was followed by a brief regression by the end of this time; a transgressive–regressive cycle occurred in *T. akzharensis* Zone time; a major transgression caused a highstand that remained during the entire *Pendeograptus fruticosus* Zone time, which was followed by a major regression in early *Didymograptus bifidus* Zone time; sea level recovered from a lowstand in late *D. bifidus* Zone time; frequent fluctuations of sea level occurred during *Isograptus victoriae lunatus* Zone time; a severe regression in the earliest *I. v. victoriae* Zone time was represented by the St. George unconformity on the platform and by Bed 12 megaconglomerate on the slope, after which sea level gradually dropped and reached its lowest level during the *I. v. maximus* Zone time.

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