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# Late Ordovician–Early Silurian (Ashgillian–Llandovery) sea level curve derived from conodont community analysis, Anticosti Island, Québec

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## Abstract

Earlier workers have established sea level curves for the Ashgillian–Llandovery sequence on Anticosti Island, Québec, Canada, based on sedimentology and on brachiopod and reef communities. The complete Anticosti sequence has been collected for conodonts to provide a database of over 77 600 conodonts derived from 272 samples through the 800–1100 m sequence. This paper uses a statistical analysis of the database to establish the pattern of conodont communities and their interpreted water depths. This allows the establishment of a eustatic sea level curve for the sequence. This curve is in general agreement with those of the earlier workers, but is more detailed and better constrained stratigraphically given the large sampling program. The curve reflects more oscillating sea level changes for the whole sequence than those constructed earlier, and different water depths for certain intervals from those established earlier. The curve is valuable given that the Anticosti sequence is one of the most complete in the world for this interval, and its divergence from global eustatic curves for this interval is noted. © 2002 Published by Elsevier Science B.V.

*Keywords:* Ashgillian; Llandovery; eustasy; cluster analysis; conodonts

## 1. Introduction

Anticosti Island, located in the Gulf of St. Lawrence, eastern Canada, is underlain by Upper Ordovician (Ashgillian) and Lower Silurian (Llandovery) strata referred to the Vauréal, Ellis Bay, Becscie, Merrimack, Gun River, Jupiter and Chicotte formations (Fig. 1). The entire sequence is

represented by richly fossiliferous limestones, minor shales and siliciclastic sediments, totaling 800–1100 m in thickness with virtually no stratigraphic breaks. During the latest Ordovician and early Silurian, the Anticosti Basin was situated at paleolatitudes of 15–20° south of equator, and on the northwest margin of the Iapetus Ocean. Most of the Upper Ordovician and Lower Silurian sediments were deposited in a shallow, storm-influenced, open-marine sublittoral environment. The Anticosti Basin was subsiding slowly during this period to maintain a complete record of sedimentation and was relatively unaffected by post-Ta-

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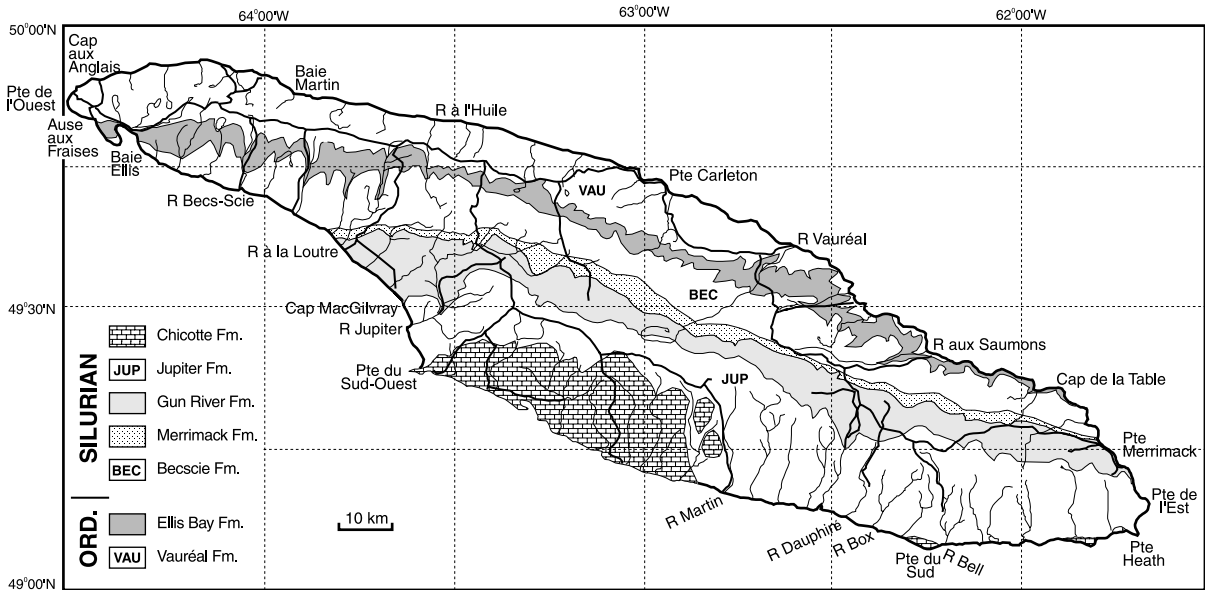


Fig. 1. Geological map of Anticosti Island showing formation outcrop pattern (from Jin and Copper, 1999).

conic orogenic clastic influx that affected the New York–Ontario region to the southwest. The stratigraphic sequence within the basin (Fig. 2), therefore, provides a sensitive indicator of subtle eustatic change through this time interval.

In this paper, we use the Ashgillian as a series and the Hirnantian/Gamachian as stages of the uppermost Ordovician. We recognize that the IUGS Subcommittee on Ordovician Stratigraphy is redefining and naming Ordovician chronostratigraphic units and that the redefined and possibly renamed Ashgillian will become the highest stage within a new Upper Ordovician series (Barnes, 1992) but these decisions have yet to be finalized.

The sea level fluctuations in the Anticosti Basin during Ashgillian and Llandovery time have been reconstructed by Johnson et al. (1981), Copper and Long (1998), Jin and Copper (1999) and Dewing (1999). Two different approaches have been used to identify sea level change. One is based on benthic fossil assemblages, mainly brachiopods, to interpret changes in water depth (Johnson et al., 1981; Jin and Copper, 1999; Dewing, 1999). The other is based mainly on the study of sequence stratigraphy, depositional environments and reef development (Sami and Des-

rochers, 1992; Copper and Long, 1989, 1990, 1998; Fig. 2).

This present study documents changes in the conodont faunas and communities and interprets this response in terms of sea level change. Conodont samples have been collected at closely spaced intervals through the entire sequence and the taxonomic descriptions have been completed. The temporal distribution of faunas has allowed a refined biostratigraphy. The spatial and temporal distributions in terms of community partitioning and evolution has been established (Zhang and Barnes, 2002b). We now utilize these latter data, along with the previous studies on stratigraphy, sedimentology, and benthic faunas, to generate a more refined eustatic sea level curve for this time interval.

The stratigraphic subdivisions for Vauréal, Ellis Bay, Becscie, Merrimack, Gun River, Jupiter and Chicotte formations in this study are mainly based on Bolton (1972), Petryk (1981a) and Uye-no and Barnes (1983). More recent subdivisions for the uppermost Vauréal and Ellis Bay formations (Long and Copper, 1987), Becscie and Merrimack formations (Copper and Long, 1989), and Jupiter Formation (Copper and Long, 1990) have been formally published (Fig. 2) based largely on

sections from the eastern part of the island. The conodont databases for the Vauréal, Ellis Bay, Jupiter and Chicotte formations adopted by this study were established by Nowlan and Barnes (1981), McCracken and Barnes (1981), Barnes (1988) and Uyeno and Barnes (1983) on the earlier subdivisions.

## 2. Methodology

### 2.1. Database

The database for this study consists of 272 con-

odont samples (av. 3 kg) from different sources: (1) 102 samples from the Ordovician Vauréal Formation which yielded nearly 50 000 disjunct conodont elements representing 35 multielement species (Nowlan and Barnes, 1981); (2) 47 selected samples from the Ellis Bay Formation at Baie Ellis that produced 3 600 conodont elements representing 21 multielement species, 15 of them extending from the Vauréal Formation (McCracken and Barnes, 1981); (3) 63 selected samples from the Becscie, Merrimack and Gun River formations which contain over 19 000 conodont elements (Zhang and Barnes, 2002a) representing 24 multielement species, several of which are

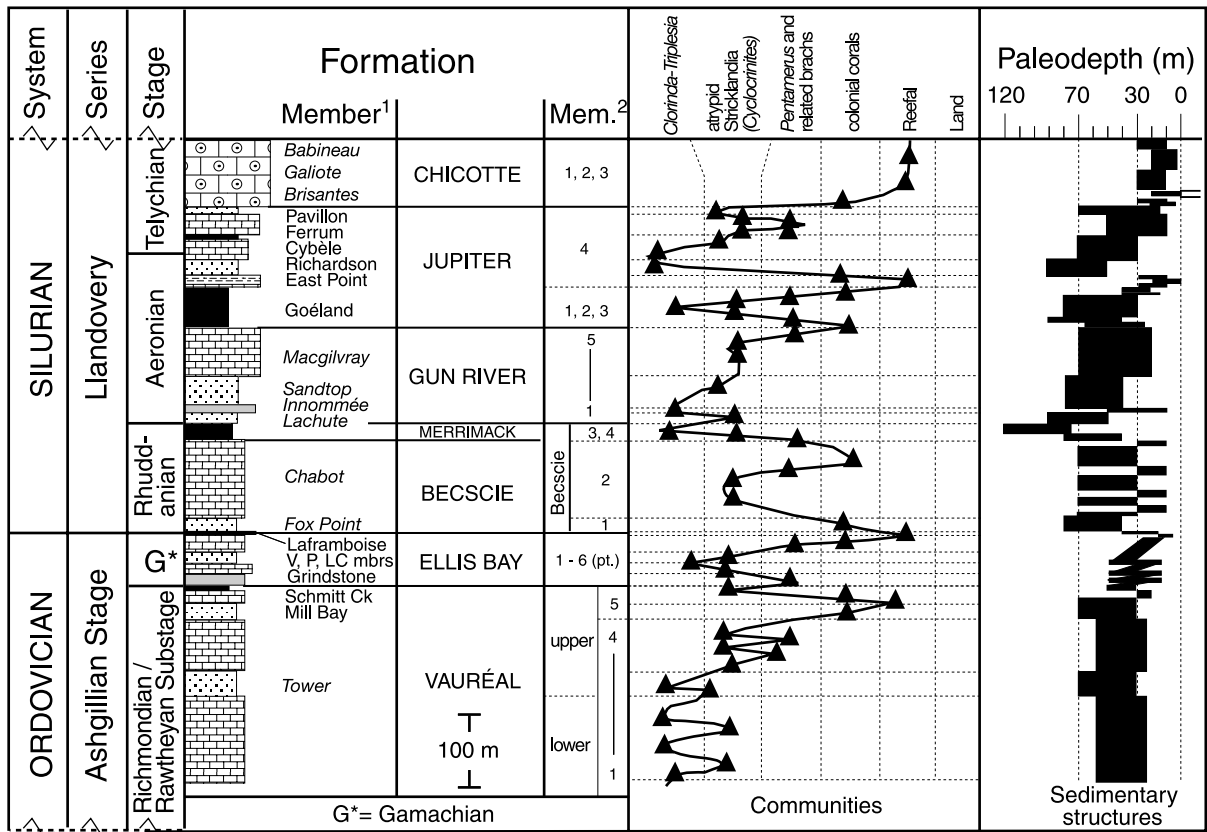


Fig. 2. Stratigraphic framework of the Anticosti succession, showing the main reef levels and brachiopod communities, and approximate sea level curve based on fossil data and sedimentology (modified from Copper and Long, 1998). Under Member<sup>1</sup>, the formal member names are shown in regular font, which is based on Long and Copper (1987) and Copper and Long (1989, 1990) (LC=Lousy Cove M.; P=Prinsta M.; V=Velleda M.); the informal member names are shown in italic font, which are from Copper and Long (1998); under Member<sup>2</sup>, the upper and lower members of the Vauréal Fm. are from Bolton (1972) and Nowlan and Barnes (1981), members 1–6 of Ellis Bay Fm. are from Bolton (1972) (member 6 includes only the lower 2m of the member as originally defined), members 1–4 of Jupiter Fm. are from Bolton (1972) and Uyeno and Barnes (1983) with others from Petryk (1981a).

new; (4) 60 samples from the Jupiter and Chicotte formations that contain over 5 000 conodont elements representing 33 multielement species (Uyeno and Barnes, 1983), most of which are different from those in the underlying Becscie, Merrimack and Gun River formations. In summary, the total database includes 272 samples that yielded over 77 600 conodont elements referred to 83 different species.

### 2.2. Data processing and program employed in the conodont community analysis

In analyzing the data to establish conodont communities, we have employed cluster analysis of the species abundance data (number of conodont elements for each species per kilogram) using SPSS version 6.1 for the Macintosh (SPSS, 1994). Both Q- and R-mode hierarchical cluster analyses were performed for both cases (samples) and variables (species). The recorded species abundance for each sample was divided into seven intervals (<1, 1–4, 5–9, 10–24, 25–49, 50–99, and  $\geq 100$ ). Pearson's correlation coefficient was used as an index of similarity and clusters were formed using the within-groups linkage method. The intervals of taxonomic counted abundance are expressed as a graded series of dots that are plotted at the intersection of certain species and samples. The community partitioning pattern is determined from the assemblages of dots representing distinctive groupings of samples and species. This methodology was adopted by Zhang and Barnes (2002b) and earlier by Westrop and Cuggy (1999) in a study of Late Cambrian trilobites.

Three analyses were designed and performed for the Vauréal Formation (Figs. 3 and 4), the Ellis Bay Formation (Figs. 5 and 6), and the combined Becscie, Merrimack, Gun River, Jupiter and Chicotte formations (Figs. 7–11). 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.

### 2.3. Conodont community partitioning among Late Ordovician and Early Silurian conodonts

Several studies have discussed the ecological partitioning of conodonts in the Late Ordovician and Early Silurian. The pattern of conodont communities through this interval is also influenced strongly by the mass extinction, produced by the terminal Ordovician glaciation in North Africa that resulted in few species surviving through this event (Barnes and Bergström, 1988). Ordovician faunas are influenced severely by faunal provincialism; but certain provinces exhibit a separate conodont community pattern that generally shows an onshore to offshore community partitioning (e.g. Barnes and Fåhræus, 1975; Sweet and Bergström, 1974, 1984; Bergström, 1990; Pohler and Barnes, 1990). Faunal provincialism is far less pronounced in the Silurian, but the onshore–offshore pattern of conodont communities is still evident (e.g. Aldridge, 1976; Le Fèvre et al., 1976; Aldridge and Mabillard, 1981; McCracken and Barnes, 1981; Barrick, 1983; Idris, 1984; Aldridge and Jeppsson, 1984; Zhang and Barnes, 2002b). Although simple models involving partitioning as a function of distance from shore or water depth do not explain all the distribution patterns shown by Ordovician and Silurian conodonts, a few species – called ecological specialists by Aldridge and Jeppsson (1984) – appear to have been restricted to, or especially abundant in, particular nearshore or offshore environments. For example, Aldridge and Jeppsson (1984) argued that Llandovery species of *Icriodella* and *Distomodus* were specialists in nearshore environments, whereas those of *Decoricomus* and *Dapsilodus* as well as *Oulodus? fluegeli* were specialists in offshore environments. From these more general studies, it has been possible to use more detailed sampling strategies to examine statistically the distribution pattern of conodonts (see papers in Barnes, 1976; Clark, 1984), and more specifically for the Early Silurian of Anticosti Island (Zhang and Barnes, 2002b).

#### 2.4. *Shelly fossil communities, lithofacies and sea level curves*

Detailed studies of Late Ordovician and Early Silurian stratigraphy, sedimentology, and macrofaunas on Anticosti Island have been undertaken by Bolton (1972; includes a summary of earlier work), Barnes et al. (1981), Petryk (1981a), Lespérance (1981), Barnes (1989), Sami and Desrochers (1992), Copper and Long (1998), Jin and Copper (1999) and Dewing (1999). From the combination of stratigraphy, sedimentology, and faunal communities, various attempts have been made to establish a sea level curve for all or parts of this interval. A definite advantage is that this sequence is one of the most complete in the world and does not exhibit major tectonic or depositional change through this period. Being dominantly composed of limestones that can reveal subtle eustatic variations, the sequence is ideal to record those associated with the development, peak, and waning phases of the terminal Ordovician glaciation. Although prevailing thought is that the glaciation was restricted to the Hirnantian (late Ashgillian) (e.g. Brenchley et al., 1994), there is some evidence to suggest that ice accumulated through the Ashgillian (Barnes, 1986) to peak in the Hirnantian, and recent isotope and stratigraphic data suggest that three smaller glacial phases occurred within the Llandovery or into the early Wenlock (Grahn and Caputo, 1992; Azmy et al., 1998). The nature of eustatic change during the Late Ordovician–Early Silurian is of particular interest given the relationship to coupled ocean–atmosphere changes associated with the glaciation and given the apparent paradox of continental glaciation developing during a time when CO<sub>2</sub> levels were considered to be 14–18 times present atmospheric levels (Berner, 1994; Poussart et al., 1999).

Establishing sea level curves is fraught with difficulties, especially if the local area being considered has an active tectonic history. Assembly of regional curves to establish a global sea level curve has been attempted by several workers (e.g. Fortey, 1984; Ross and Ross, 1992 for the Ordovician; Ross and Ross, 1996; Loydell, 1998 for the Silurian; see also papers in Landing and

Johnson, 1998). The validity of these curves depends on the quality of both the regional data and the interpretations. The purpose of the present paper is to document the regional sea level curve for the Anticosti Basin based on new detailed conodont data, especially the pattern of conodont communities, for a region that could serve as a standard reference for the Llandovery (Barnes, 1989).

To refine the regional sea level curve for the Anticosti Basin, most of the characteristic species of the conodont communities recognized in this study have been used to establish the relative water depths. The latter have been estimated through the detailed studies of Llandovery sediments and brachiopods of Anticosti Island by Sami and Desrochers (1992), Copper and Long (1998), Jin and Copper (1999) and Dewing (1999). Their interpretations have been adopted as a reference to determine the interpreted water depths that each conodont community could represent.

### 3. Sea level changes during the Richmondian – analysis I for the Vauréal Formation

The Vauréal Formation consists of about 1100 m of thinly bedded lime mudstone, limestone, shale and minor sandstone, thickening by about 60 m beneath the south coast, as determined from drill-hole data (Roliff, 1968). The total thickness of the exposed upper Vauréal Formation is about 330–400 m and the conodont fauna was assigned to Fauna 12 of Richmondian age (Nowlan and Barnes, 1981).

The exposed Vauréal Formation is divided into lower and upper members by Bolton (1972), which was adopted by Nowlan and Barnes (1981). The lower member consists of gray shale with interbedded blue-gray to reddish gray or brown, fine-grained to dense limestone with intraformational conglomerate; the limestone beds increase in thickness upward and become nodular. The upper member is composed of gray, fine-grained to dense limestone with abundant intraformational conglomerate, gray shale partings and lenses, fine cross-bedding and channel-fill

structures. Small reefs occur in the upper part of the formation (Copper and Long, 1998). The sections at Rivière à l’Huile, and Cap aux Anglais and Pointe de l’Ouest measured by Nowlan and Barnes (1981) (Figs. 1 and 4) are equivalent to the lower and upper members, respectively. The lower member probably represents relatively unstable, deep subtidal conditions, whereas the upper member reflects a shallower subtidal environment (Nowlan and Barnes, 1981).

Earlier results of cluster analysis for the conodonts from the Vauréal Formation (Nowlan and Barnes, 1981) showed three clustered groups interpreted as representing three conodont ecozones – *Amorphognathus–Plectodina* predominating in the lower part of the formation, *Phragmodus* in the middle, and *Oulodus–Aphelognathus* in the upper part.

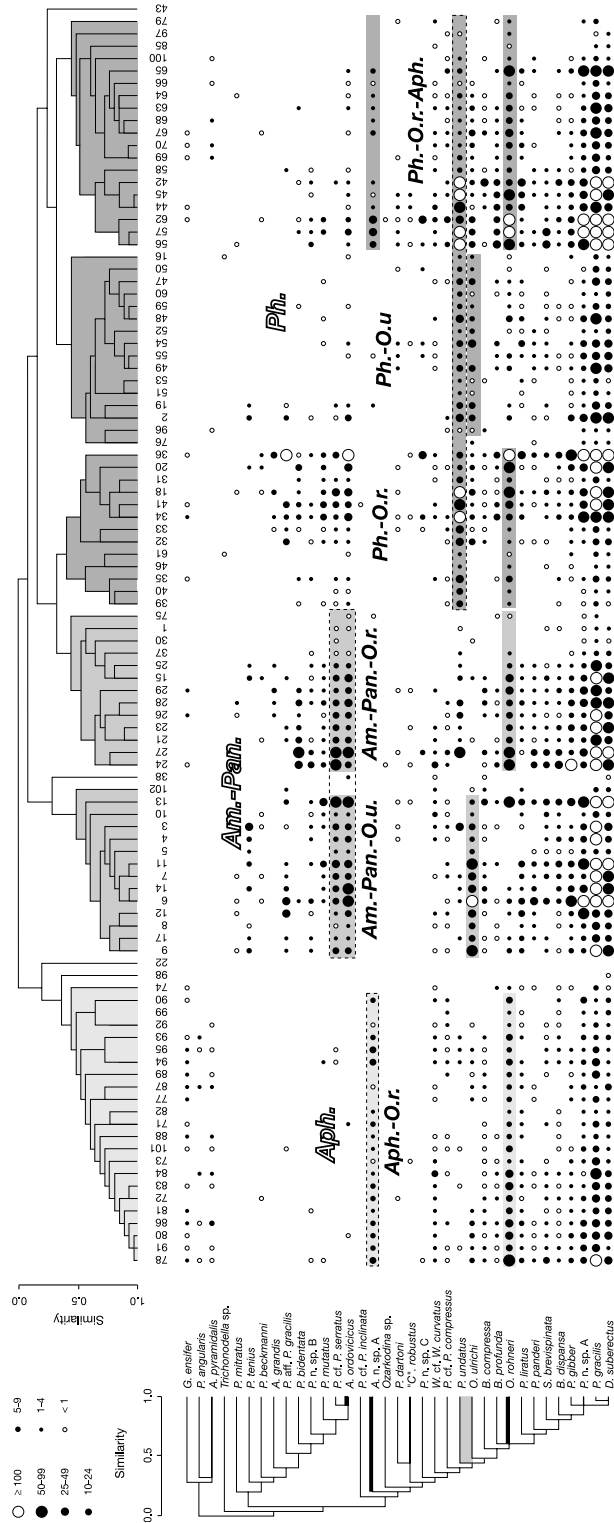
Analysis I (Figs. 3 and 4) employed the same database as used by Nowlan and Barnes (1981), which includes 102 samples producing 49 473 conodont elements from sections at Rivière à l’Huile, Cap aux Anglais, Point à la Goélette, Pointe de l’Ouest, and Anse aux Fraises at the western end of Anticosti Island (Figs. 1 and 4). These conodont elements were recognized as 35 species, most of which were identified as multielement apparatuses by Nowlan and Barnes (1981), and a few form species. Some of their multielement species, such as those of *Panderodus*, could perhaps be synonymized. However, in order to compare the results with those of Nowlan and Barnes (1981) all of these authors’ species names are retained in this analysis. Most of the conodont species from the Vauréal stratigraphically range through much of the formation and do not allow a precise biozonation. However, a repetitive ecological distribution of faunal associations of many species was

recognized by both Nowlan and Barnes (1981) and this study.

Cluster analysis in this study defined three clustered groups (Fig. 3, boxed in by dashed line and named in hollow letters), similar in composition to those of Nowlan and Barnes (1981). They are *Aphelognathus* n. sp. A (*Aph.*), *Amorphognathus ordovicicus–Panderodus* cf. *P. serratus* (*Am.–Pan.*) and *Phragmodus undatus* (*Ph*) associations. There was not a close relationship between *Amorphognathus ordovicicus* and *Plectodina* as suggested by Nowlan and Barnes (1981). The analysis also shows a similar stratigraphic distribution of different associations, whereby *Amorphognathus ordovicicus–Panderodus* cf. *P. serratus* (*Am.–Pan.*), *Phragmodus undatus* (*Ph*) and *Aphelognathus* n. sp. A (*Aph.*) dominated in the lower, middle and upper parts of the formation, respectively. The principal difference between the two analyses is that most of the samples from the upper part of the Cap aux Anglais section were grouped into the *Oulodus–Aphelognathus* ecozone (Nowlan and Barnes, 1981), but are grouped into the *Phragmodus undatus* association herein (Fig. 3, boxed in by dashed line and named in hollow letters).

One of the three ecozones recognized by Nowlan and Barnes (1981), *Oulodus–Aphelognathus*, was interpreted as representing a shallow subtidal environment. This is the same as the *Aphelognathus* n. sp. A (*Aph.*) association recognized in this study. The genus *Oulodus* appears not to have the same environmental preference as *Aphelognathus*, being present in almost all samples. However, the Q- and R-mode cluster analysis shows that the two Vauréal species of *Oulodus*, *O. rohneri* and *O. ulrichi*, always exhibit an antipathetic relationship to each other in terms of relative abundance

Fig. 3. Results of Q- and R-mode cluster analysis of 102 samples from Vauréal Formation (sample data from Nowlan and Barnes, 1981). Samples are in Q-mode clustering, taxa are in R-mode clustering order, and relative abundance of taxa are expressed as a graded series of dots. Intersections of Q- and R-clusters defined three conodont communities (boxed in by dashed line and named with hollow letters), indicated by the abbreviations: *Aph.*, *Aphelognathus* n. sp. A; *Am.–Pan.*, *Amorphognathus ordovicicus–Panderodus* cf. *P. serratus*; *Ph.*, *Phragmodus undatus*. Intersections of Q- and R-clusters defined six conodont communities by employing the species of *Oulodus* (shaded and named in bold italic; discussed in the text), indicated by the abbreviations: *Aph.–O.r.*, *Aphelognathus* n. sp. A–*Oulodus rohneri*; *Am.–Pan.–O.u.*, *Amorphognathus ordovicicus–Panderodus* cf. *P. serratus–O. ulrichi*; *Am.–Pan.–O.r.*, *Amorphognathus ordovicicus–Panderodus* cf. *P. serratus–Oulodus rohneri*; *Ph.–O.r.*, *Phragmodus undatus–Oulodus rohneri*; *Ph.–O.u.*, *Phragmodus undatus–Oulodus ulrichi*; *Ph.–O.r.–Aph.*, *Phragmodus undatus–Oulodus rohneri–Aphelognathus*.



- G. ensifer*
- P. angulatus*
- A. pyramidalis*
- Trichonodella* sp.
- P. mitratus*
- P. beckmanni*
- A. grandis*
- P. aff. P. gracilis*
- P. bidenata*
- P. mutatus*
- P. cf. P. serratus*
- A. oronocicus*
- P. cf. P. incincta*
- P. cf. P. incincta*
- Ocarodina* sp.
- P. dantoni*
- C. robustus*
- W. cf. W. curvatus*
- P. cf. P. compressus*
- P. undatus*
- O. unchi*
- O. prolifera*
- B. prolifera*
- O. rotneri*
- P. litatus*
- S. brevispinata*
- B. disparata*
- P. gibber*
- n. sp. A
- P. n. sp. A*
- D. subaeneus*

per sample. The species of *Oulodus* can be used to subdivide the community groups.

Fig. 3 also shows a more detailed partition of communities by employing species of *Oulodus* (boxed in with shading and named in bold italics). The *Aphelognathus* n. sp. A–*Oulodus rohneri* (*Aph.*–*O.r.*) community, as with *Aphelognathus* n. sp. A (*Aph.*) in the upper part of the formation, cannot be subdivided further. The *Amorphognathus ordovicicus*–*Panderodus* cf. *P. serratus* (*Am.*–*Pan.*) community in the lower part of the formation can be divided into the *A. ordovicicus*–*P.* cf. *P. serratus*–*Oulodus rohneri* (*Am.*–*Pan.*–*O.r.*) and the *A. ordovicicus*–*P.* cf. *P. serratus*–*Oulodus ulrichi* (*Am.*–*Pan.*–*O.u.*) community. The *Phragmodus undatus* community in the middle part of the formation can be divided into the *Phragmodus undatus*–*Oulodus rohneri* (*Ph.*–*O.r.*), the *P. undatus*–*O. ulrichi* (*Ph.*–*O.u.*) and the *P. undatus*–*O. rohneri*–*Aphelognathus* n. sp. A (*Ph.*–*O.r.*–*Aph.*) communities. Both the first and last of these groups, *Ph.*–*O.r.* and *Ph.*–*O.r.*–*Aph.*, contain *O. rohneri*, but it is easy to differentiate them on the basis of *Aphelognathus* n. sp. A that appears in 12 of the 19 samples of the group *Ph.*–*O.r.*–*Aph.*

Based on the depositional interpretations of Bolton (1972), Nowlan and Barnes (1981), Petryk (1981a) and Copper and Long (1998), *Amorphognathus* from the lower part of the formation and *Aphelognathus* from the upper part of the formation preferred relatively deeper and shallower water, respectively. Elsewhere, Leatham (1997) also found that *Aphelognathus*-dominated faunas characterize more nearshore environments. Nowlan and Barnes (1981) revealed that *Phragmodus* appears in high abundance in deeper water settings. Seddon and Sweet (1971) and Barnes and Fåhræus (1975) also suggested that *Phragmodus* was usually a relatively deep water, subtidal inhabitant. Thus, *Phragmodus*, *Amorphognathus* and *Aphelognathus* represent three different subtidal water depths from deeper to shallower.

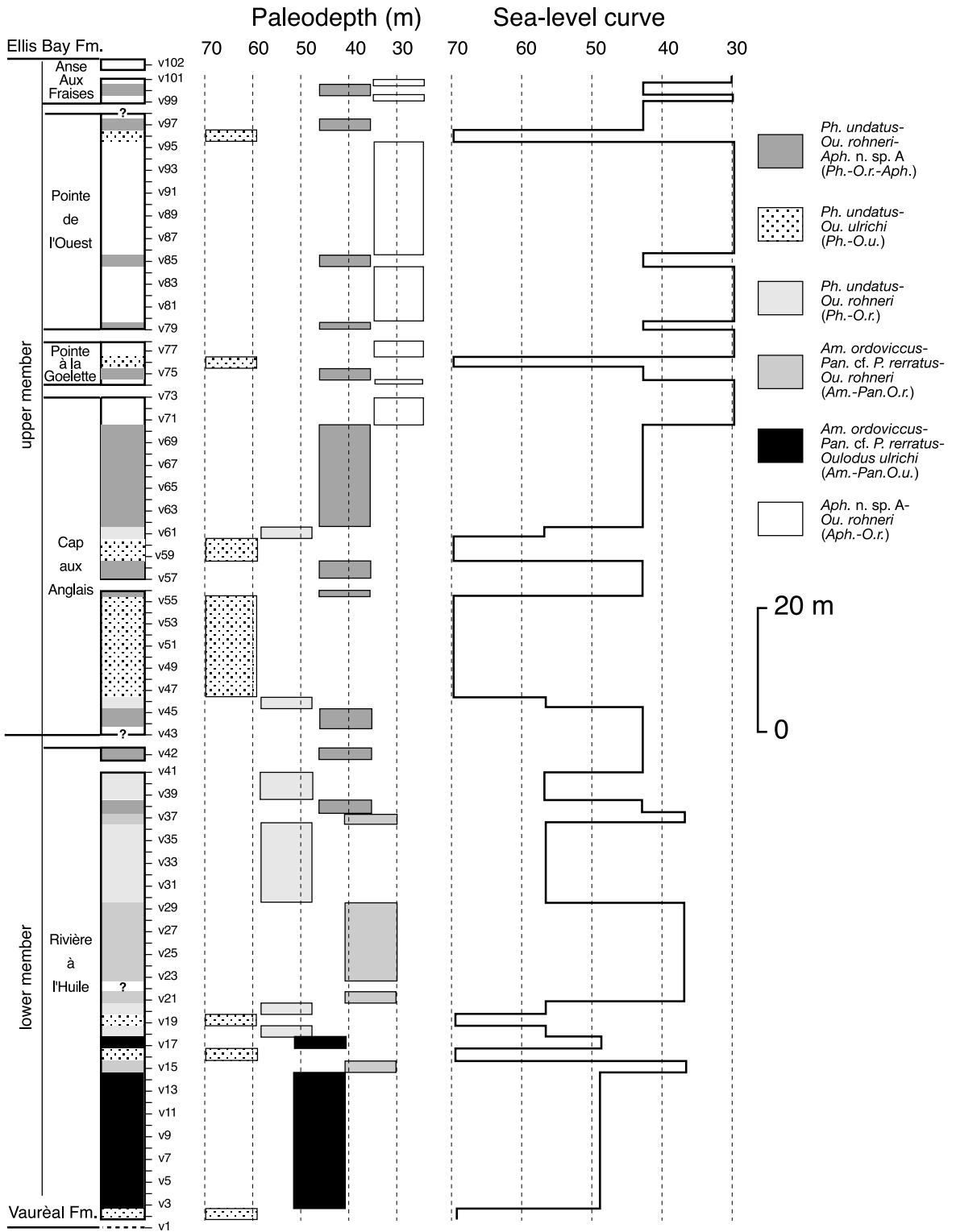
The question remains whether the associations dominated by the above-mentioned three genera

could represent the same water depth, but differentiated by some other environmental factors. A possible answer comes by considering the distributional pattern of *Oulodus* species. As indicated above, *Aphelognathus* had the shallowest environment preference among *Phragmodus*, *Amorphognathus* and *Aphelognathus*, and can be used as an indicator to distinguish the water depth difference between *Oulodus ulrichi* and *O. rohneri*. Twenty-three samples are grouped in the *Aphelognathus* n. sp. A–*O. rohneri* community, each contains 1–99 specimens of *O. rohneri*, but only 11 samples yield < 1–4 specimens (per kg) of *O. ulrichi*. Thus, *O. rohneri* had a stronger shallow water preference than *O. ulrichi*. From this, it is inferred that the communities of *Amorphognathus ordovicicus*–*Panderodus* cf. *P. serratus* (*Am.*–*Pan.*) and *Phragmodus undatus* (*Ph.*), which both contain more *O. ulrichi*, indicate deeper water than those yielding more *O. rohneri*. The *P. undatus*–*O. rohneri*–*Aphelognathus* n. sp. A (*Ph.*–*O.r.*–*Aph.*) community is the shallowest of the three communities within the *Phragmodus undatus* community because of the presence of *Aphelognathus* n. sp. A.

Among all six conodont communities, *Aphelognathus* n. sp. A–*Oulodus rohneri* (*Aph.*–*O.r.*) and *Phragmodus undatus*–*Oulodus ulrichi* (*Ph.*–*O.u.*) represent the shallowest and deepest Vauréal environments, respectively (Figs. 4 and 12). Species abundance and diversity are both lower in these two extreme communities than in the others. For example, the species number in community *Aph.*–*O.r.* ranges from 7 to 21 (per kg) which is comparable to that of community *Ph.*–*O.u.* which ranges from 5 to 16. The specimen number of the characteristic species in these two communities is below 50 in almost all samples. All other intermediate communities have higher species abundance and diversity (Fig. 3). Copper and Long's (1998) sea level curve, established using macrofossils and sediments, indicates that the paleobathymetry for the Vauréal Formation ranged from 20 to 70 m. Based on this, it can be inferred

Fig. 4. Inferred paleodepth and sea level changes based on the distribution of the six conodont communities identified by cluster analysis through a composite section from five different sections of Vauréal Formation.





that the habitat of *Aphelognathus* n. sp. *A-Oulodus rohneri* (*Aph.-O.r.*) and *Phragmodus undatus-Oulodus ulrichi* (*Ph.-O.u.*) was about 20 and 70 m below the sea level, respectively. All other communities were between these two depths (Figs. 4 and 12).

Within upper member of the Vauréal Formation, a new genus *Gamachignathus* appeared, that was represented by two species, *G. ensifer* McCracken, Nowlan and Barnes and *G. hastatus* McCracken, Nowlan and Barnes (McCracken et al., 1980). This genus became a dominant faunal component of the overlying Ellis Bay Formation (McCracken and Barnes, 1981). In the Vauréal Formation samples, the number of specimens of one species, *G. ensifer*, is low, being equal to or lower than 4. Of the 29 samples that include the genus, 17 occur in the *Aphelognathus* n. sp. *A-Oulodus rohneri* (*Aph.-O.r.*) community (Fig. 3). It is absent in the *A. ordovicicus*-*P. cf. P. serratus-Oulodus rohneri* (*Am.-Pan.-O.r.*) and *Phragmodus undatus-Oulodus ulrichi* (*Ph.-O.u.*) communities. Therefore, it is concluded that *G. ensifer* preferred shallow water.

The general distribution of conodont communities through the five sections of the Vauréal Formation (Fig. 4) indicates that the Rivière à l'Huile section was deposited in intermediate depths, the lower part of the Cap aux Anglais section in the deepest depths, and the upper part of the Cap aux Anglais section and Pointe de l'Ouest sections in the shallower depths. This reflects a sea level history of deepening in the early Vauréal and shallowing in late Vauréal times. Fig. 4 shows the detailed distribution of conodont communities on sample-by-sample basis, and the derived sea level curve, which reveals that each major deepening or shallowing phase included several minor phases of shallowing or deepening.

#### 4. Sea level changes during the Gamachian – analysis II for the Ellis Bay Formation

The Ellis Bay Formation conformably overlies the Vauréal Formation. Its conodont fauna was designated as Fauna 13 and proposed as being representative of the type Gamachian Stage of

the Cincinnati Series, latest Ordovician (and equivalent to the Hirnantian of the Ashgillian Series) (McCracken and Barnes, 1981). The Ellis Bay Formation is the thickest and most complete section of Hirnantian-equivalent age in the world. It represents the main phase of terminal Ordovician glaciation, and the alternating members are considered to reflect at least three cycles of glacial-interglacial cycles (McCracken and Barnes, 1981; Petryk, 1981b; Barnes, 1988). The thickness of the Ellis Bay Formation varies between 53 m and 96 m (Bolton, 1972), and the formation was divided into six members by Bolton (1972) based on argillaceous content. Members 1, 3 and 5 consist of shale with interbeds of argillaceous limestone, whereas members 2, 4 and 6 consist predominantly of limestone with shale interbeds or partings. Petryk (1981a) made adjustments to the member divisions, introducing two thin members from the lower part of Bolton's member 6 and incorporating most of that member into the overlying Becscie Formation. The depositional environments are represented by three main lithofacies: (a) nearshore, arenaceous and calcareous deposits at Rivière aux Saumons; (b) intermediate, argillaceous and calcareous deposits at Rivière Vauréal; and (c) offshore, alternating argillaceous and calcareous deposits at Baie Ellis (McCracken and Barnes, 1981). The present study deals only with offshore lithofacies, its conodont fauna being dominated by *Gamachignathus ensifer* and *G. hastatus*.

Analysis II employed part of the database as used by McCracken and Barnes (1981) to include 47 samples producing 3600 conodont elements from the lower to middle part of the Ellis Bay Formation at the Baie Ellis section (i.e. the Ellis Bay Formation as defined more restrictively by Petryk (1981a)). These conodont elements were assigned to 21 species, most of which were identified as multielement apparatuses by McCracken and Barnes (1981), and few form species. As discussed in analysis I, although a few multielement apparatuses are in need of revision, all species names are retained for use in this analysis.

The cluster analysis performed by McCracken and Barnes (1981) involved all samples from the three different lithofacies (a–c above), and they

recognized communities A, B, C, D, and E. These reflect the distribution of conodont communities from east to west across the island. Most samples from the Baie Ellis section are grouped in community A, which generally represents an offshore environment.

In comparison with the Vauréal Formation, the Ellis Bay Formation has a less abundant and diverse conodont fauna. Of the 21 species present, the most productive samples only produce 14 species. The cluster analysis in this study identifies four communities (Fig. 5), namely the *Gamachignathus ensifer* (*G.e.*), *Phragmodus undatus* (*Ph.*), *G. ensifer*–*G. hastatus*–*Panderodus panderi* (*G.e.–G.h.–P.p.*), and *G. ensifer*–*G. hastatus* (*G.e.–G.h.*) communities.

As indicated earlier, members 1, 3 and 5 consist of shale with interbeds of argillaceous limestone and represent deeper, presumed interglacial phases, whereas members 2, 4 and 6 consist predominantly of limestone with shale interbeds or partings and represent the shallower, presumed glacial phases. The lithofacies suggest three cycles of deepening–shallowing. To interpret the relative water depth of each community represented, there are some noteworthy trends in the pattern of communities and lithofacies.

Of the four communities recognized herein, when the distribution of two of them, *Gamachignathus ensifer* (*G.e.*) and *G. ensifer*–*G. hastatus*–*Panderodus panderi* (*G.e.–G.h.–P.p.*), is plotted against the different lithofacies of members 1 and 2 (Fig. 6), the former is the major component in member 1, and the latter in member 2. Hence, firstly it is inferred that the *Gamachignathus ensifer* (*G.e.*) community represents a deeper water habitat than the *G. ensifer*–*G. hastatus*–*Panderodus panderi* (*G.e.–G.h.–P.p.*) community.

Secondly, based on analysis I for the Vauréal Formation, the *Phragmodus undatus* (*Ph.*) community is interpreted as having the deepest water preference among the four communities in analysis II.

Thirdly, the differences between communities *Gamachignathus ensifer*–*G. hastatus*–*Panderodus panderi* (*G.e.–G.h.–P.p.*) and *G. ensifer*–*G. hastatus* (*G.e.–G.h.*) are: (a) the former contains *P. panderi* whose elements are robust and have a

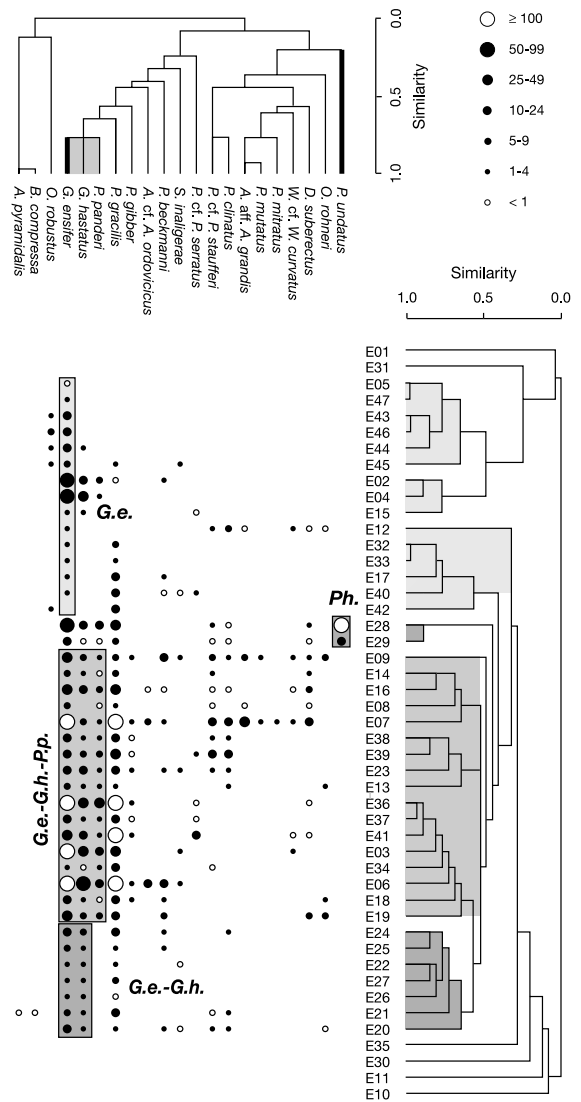


Fig. 5. Results of Q- and R-mode cluster analysis of 47 samples from Ellis Bay Formation (sample data from McCracken and Barnes, 1981). Samples are in Q-mode clustering, taxa are in R-mode clustering order and relative abundance of taxa are expressed as a graded series of dots. Intersections of Q- and R-clusters defined four conodont communities (shaded), indicated by the abbreviations: *G.e.*, *Gamachignathus ensifer*; *Ph.*, *Phragmodus undatus*; *G.e.–G.h.–P.p.*, *Gamachignathus ensifer*–*G. hastatus*–*Panderodus panderi*; *G.e.–G.h.*, *Gamachignathus ensifer*–*G. hastatus*.

strong cusp curvature, which is probably part of an apparatus with *P. liratus* (Nowlan and Barnes) and *P. cf. P. staufferi* (Branson, Mehl and Branson) of McCracken and Barnes (1981); and (b)

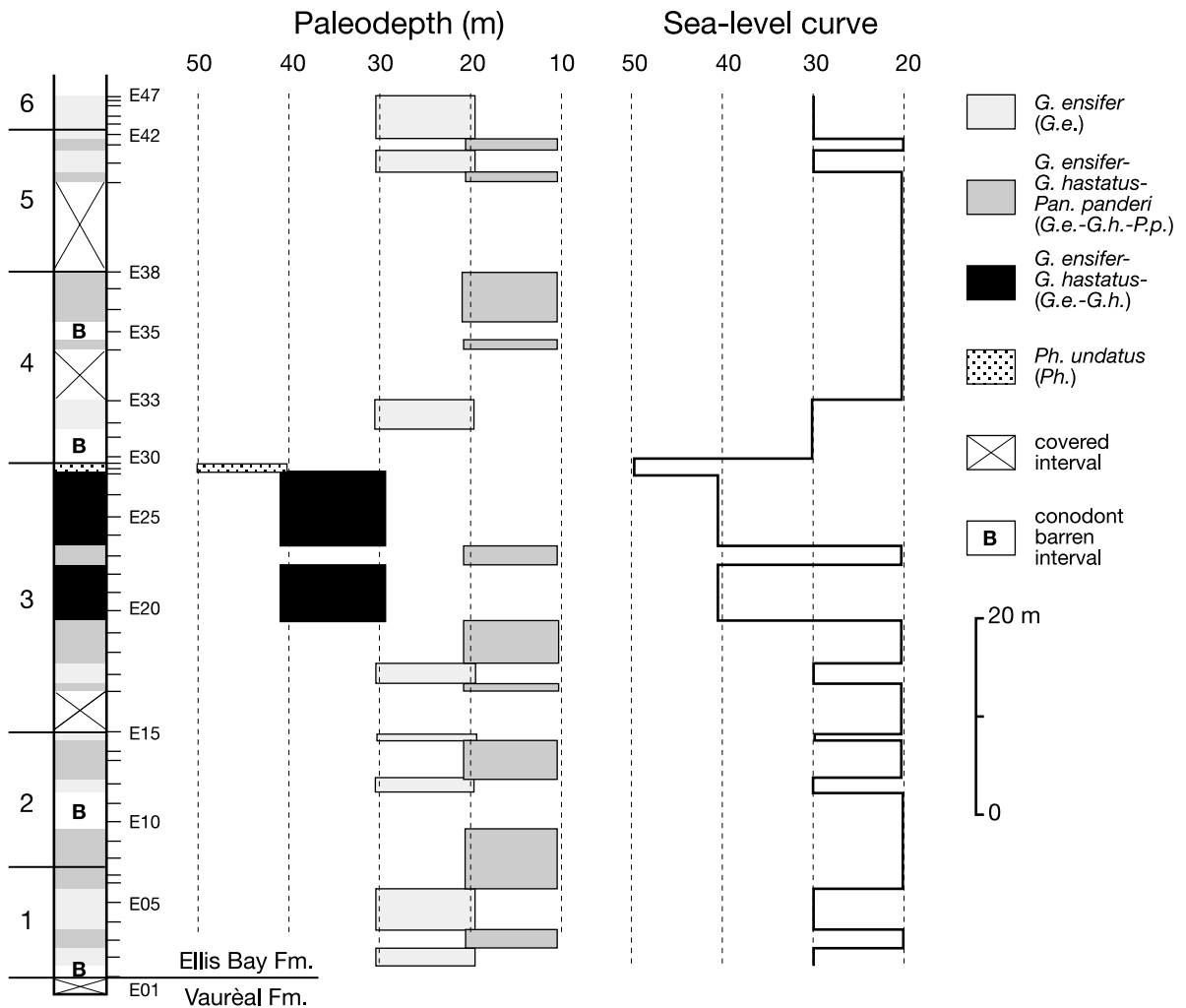


Fig. 6. Inferred paleodepth and sea level changes based on the distribution of the four conodont communities identified by cluster analysis through Ellis Bay Formation at Ellis Bay.

the abundance of *G. ensifer* and *G. hastatus* in the former is higher than the latter. There is no definitive evidence to tell which, if either, preferred deeper water. However, the *G. ensifer*–*G. hastatus* community only appears in member 3, and the *Phragmodus undatus* (*Ph.*) community appears at the top of member 3 that represents the deepest water interval (Copper and Long, 1998). Thus, the *G. ensifer*–*G. hastatus* (*G.e.*–*G.h.*) community represents a deeper water setting than the *G. ensifer*–*G. hastatus*–*Panderodus panderi* (*G.e.*–*G.h.*–*P.p.*) community.

Although four communities can be recognized

through the Ellis Bay Formation (Fig. 6), most of them suggest shallower environments than those represented in the Vauréal Formation, as almost all samples from the Ellis Bay Formation produce elements of *Gamachignathus* which mainly appears in the shallowest conodont community, *Aphelognathus* n. sp. A–*Oulodus rohneri* (*Aph.*–*O.r.*). Therefore, most of the Ellis Bay Formation communities represent the same water depth as *Aphelognathus* n. sp. A–*Oulodus rohneri* (*Aph.*–*O.r.*), or shallower. Based on the interpretation of macrofossils and sediments by Copper and Long (1998), the water depth ranged from 10 to 50 m for the

Ellis Bay Formation. The presence of *Phragmodus undatus* in upper member 3 probably indicates a water depth greater than 50 m. Fig. 6 summarizes the four community distributions through time and space, and the interpreted sea level curve. The cyclicity of sea level oscillations is more pronounced numerically in the Ellis Bay Formation than for any equivalent interval in thickness in the Vauréal Formation, likely in response to the glacio-eustatic changes in the Hirnantian interval.

### 5. Sea level changes during the Llandovery – analysis III for the Becscie, Merrimack, Gun River, Jupiter and Chicotte formations

The Becscie, Merrimack, Gun River, Jupiter and Chicotte formations comprise the Llandovery strata on Anticosti Island, which are 525–565 m in thickness (Petryk, 1981a). The Llandovery conodont fauna is totally different from that of Ashgillian sequence, with only a few coniform species extending from the Ordovician (McCracken and Barnes, 1981; Zhang and Barnes, 2002a).

The conodonts from the Becscie, Merrimack, and Gun River formations received preliminary study by Fåhræus and Barnes (1981) and detailed study by Zhang and Barnes (2000, 2002a), and those for the Jupiter and Chicotte formations were reported by Uyeno and Barnes (1983). The more recent multielement taxonomy has tended to reduce the species number, especially for the coniform species, than that of the Vauréal and Ellis Bay formations. The coniform species, especially those of *Panderodus*, occur in almost every Anticosti sample, and are of limited help in the partition of conodont communities.

The database for analysis includes 27 samples yielding 4130 specimens from the Becscie and Merrimack formations at the Rivière aux Saumons and Rivière Jupiter sections, 36 samples producing 14947 specimens from the Gun River Formation at the La Loutre coast and Rivière Jupiter sections (both from Zhang and Barnes, 2002a), and 60 samples containing 5762 specimens from the Jupiter and Chicotte formations that are mainly from sections along the south coast derived from Uyeno and Barnes (1983).

The following revisions have been made for the database of Uyeno and Barnes (1983): (a) the specimen number of coniform species was recounted, so the total specimen number is 5762 rather than 5116 as published; (b) *Oulodus* sp. A is assigned as *Ou. panuarensis* Bischoff; (c) *Walliserodus sancticlairei* is included in *Walliserodus curvatus* (Branson and Branson); (d) *Oulodus* sp. is included in *Ou. sigmoideus* Zhang and Barnes; and (e) *Oulodus? fluegeli* subsp. A is considered a synonym of *Ou.? expansus* (Armstrong).

Thus, the database of analysis comprises 123 samples and 42 species that were identified from 24839 conodont specimens using sections that span the Llandovery sequence. The analysis produced 11 conodont communities (Fig. 7), which are named as *Panderodus unicostatus* (*P.u.*), *Icriodella inconstans*–*Ozarkodina gulletensis*–*Aulacognathus bullatus* (*I.-O.-A.*), *Ozarkodina strena*–*Rexroadus nathani* (*Oz.s.-R.n.*), *Apsidognathus tuberculatus*–*Pterospathodus celloni*–*P. pennatus procerus*–*Carniodus carnulus*–*Ozarkodina polinclinata* (*A.-P.-P.-C.-O.*), *Ozarkodina aldridgei* (*Oz.a.*), *Ozarkodina oldhamensis*–*Rexroadus kentuckyensis* (*Oz.o.-R.k.*), *Panderodus* sp. (*P. sp.*), *Icriodella deflecta*–*Oulodus jeannae*–*Ozarkodina pirata* (*I.d.-Ou.j.-Oz.p.*), and *Panderodus recurvatus* (*P.r.*), *Oulodus* cf. *Ou.? fluegeli*–*Pterospathodus siluricus*–*P. posteritenuis*–*Decoriconus fragilis* (*O.-P.-P.-D.*), and *Ozarkodina pirata* (*Oz.p.*) communities.

Fig. 7 shows that some communities are grouped by few species, but are represented in many samples, whereas other communities are grouped by more species, but involve fewer samples. This suggests that the former communities, such as *Panderodus unicostatus* (*P.u.*), *Ozarkodina strena*–*Rexroadus nathani* (*Oz.s.-R.n.*), *Ozarkodina aldridgei* (*Oz.a.*), *Ozarkodina oldhamensis*–*Rexroadus kentuckyensis* (*Oz.o.-R.k.*), *Icriodella deflecta*–*Oulodus jeannae*–*Ozarkodina pirata* (*I.d.-Ou.j.-Oz.p.*), and *Panderodus recurvatus* (*P.r.*) were more persistent and had a wider environmental tolerance than the latter group. Some, such as *Ozarkodina strena*–*Rexroadus nathani* (*Oz.s.-R.n.*), *Ozarkodina oldhamensis*–*Rexroadus kentuckyensis* (*Oz.o.-R.k.*), and *Icriodella deflecta*–*Oulodus jeannae*–*Ozarkodina pirata* (*I.d.-*

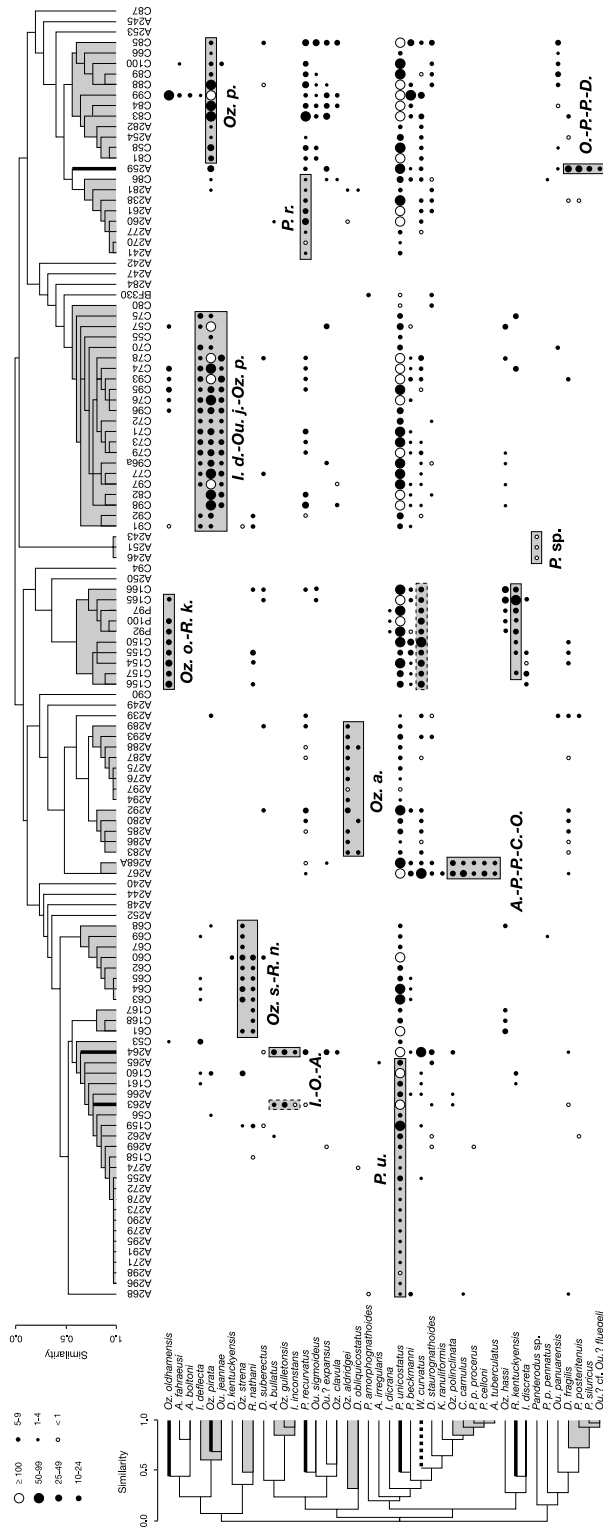


Fig. 7. Results of Q- and R-mode cluster analysis of 123 samples from Becscie, Merrimack, Gun River, Jupiter and Chicotte formations (sample data of Becscie, Merrimack, Gun River formations using C-samples from Zhang and Barnes (2002a); sample data of Jupiter and Chicotte formations using A-samples from Uyeno and Barnes, 1983). Samples are in Q-mode clustering, taxa are in R-mode clustering order, and relative abundance of taxa are expressed as a graded series of dots. Intersections of Q- and R-clusters defined 11 conodont communities (shaded), indicated by the abbreviations: *P.u.*, *Panderodus unicostatus*; *I.-O.-A.*, *Icriodella inconstans*–*Ozarkodina gulletensis*–*Aulacognathus bullatus*; *Oz.s.-R.n.*, *Ozarkodina strena*–*Rexroadus nathani*; *A.-P.-P.-C.-O.*, *Apsidognathus tuberculatus*–*Pterospathodus celloni*–*P. pennatus procerus*–*Carniodus carnulus*–*Ozarkodina polinclinata*; *Oz.a.*, *Ozarkodina aldridgei*; *Oz.o.-R.k.*, *Ozarkodina oldhamensis*–*Rexroadus kentuckyensis*; *P. sp.*, *Panderodus* sp.; *I.r.-Ou.j.-Oz.p.*, *Icriodella deflecta*–*Oulodus jeannae*–*Ozarkodina pirata*; *P.r.*, *Panderodus recurvatus*; *O.-P.-P.-D.*, *Oulodus?* cf. *Ou.?* *fluegeli*–*Pterospathodus siluricus*–*P. posteritenuis*–*Decoriconus fragilis*; *Oz.p.*, *Ozarkodina pirata*.

*Ou.j.-Oz.p.*), had a more stable development than the others (Figs. 7–10). As a species, *Panderodus unicostatus* has the widest distribution within the Llandovery fauna, occurring in almost every sample, but as a community it only groups 23 samples out of 123. The *Panderodus unicostatus* (*P.u.*) community may represent both the shallowest and the deepest water depths, in which other conodonts are rare or absent. Thus, the development and replacement of conodont communities in the Early Silurian appears to be more complex than those of the Late Ordovician.

### 5.1. Sea level changes in the Rhuddanian

The Becscie and Merrimack formations represent Rhuddanian strata (Fig. 8). The Becscie was divided into four informal members by Petryk (1981a), the lower two were assigned as the Fox Point and Chabot members by Copper and Long (1989) and the upper two members were incorporated into the Merrimack Formation by Copper and Long (1989).

The *Ozarkodina oldhamensis*–*Rexroadus kentuckyensis* (*Oz.o.-R.k.*) community exhibits stable and dominant development throughout member 1 (=Fox Point Member of Copper and Long, 1989). It is characterized by a relatively high species diversity, most of samples yielding 5–9 species. *Walliserodus curvatus*, *Rexroadus kentuckyensis* and *Ozarkodina oldhamensis* are three dominant species.

Idris (1984) used nine points (A–I) to divide the nearshore to offshore gradient for the Llandovery of the Oslo region, Norway. He showed that *Walliserodus curvatus* had a preference for deeper waters, being most common in the environment

furthest offshore (Point A), represented by the deeper water *Clorinda* brachiopod community. In a detailed conodont paleoecological study of the Anticosti Llandovery (Zhang and Barnes, 2002b), the same community was also recognized by the same statistical method, and interpreted to have been prevalent at or below storm wave base. The abundance of *W. curvatus* in the *Oz.o.-R.k.* community (10–99 specimens per kg in all samples) stands in contrast with its low abundance in the *G.e.-G.h.-P.p.* community (>1–4 specimens per kg in 5 samples out of 17), which is interpreted as a shallow water community in the Ellis Bay Formation. Thus, the occurrence of the *Oz.o.-R.k.* community in member 1, Becscie Formation, indicates a significant deepening after the latest Ordovician Ellis Bay Formation. In addition, the dominant lithofacies LF2 (homogenous, laminated mudstone) of member 1 also indicates relatively deep water, interpreted as being below storm wave base (Sami and Desrochers, 1992).

The *Ozarkodina strena*–*Rexroadus nathani* (*Oz.s.-R.n.*) community replaced the *Ozarkodina oldhamensis*–*Rexroadus kentuckyensis* (*Oz.o.-R.k.*) community near the boundary between members 1 and 2 (member 2 = Chabot Member of Copper and Long, 1989). It developed through member 2 and the lower part of the Merrimack Formation (=members 3 and 4, Becscie Formation of Petryk, 1981a), being only replaced briefly by the *Panderodus unicostatus* and *Ozarkodina pirata* communities in the lower and upper parts of member 1. Except for the main components of the community, the obvious differences between the two neighboring communities are that: (a) the *Ozarkodina strena*–*Rexroadus nathani* (*Oz.s.-R.n.*) community has a lower species diversity and

abundance, most samples producing 2–5 species whose specimen numbers range from 1 to 24, mostly 1–9; and (b) all samples comprising the *Ozarkodina strena*–*Rexroadus nathani* (*Oz.s.*–*R.n.*) community lack *Walliserodus curvatus*. These communities both indicate shallowing. *Oz. strena* is a newly described species from Anticosti Island (Zhang and Barnes, 2002a) and *R. nathani* does not have a wide distribution like *W. curvatus*. However, Idris (1984) found that *R. cf. R. nathani* (referred to as *Oulodus cf. Ou. nathani*) ranged between Points D and H representing water depths characterized by the *Stricklandia* to *Pentamerus* brachiopod communities. Lithofacies LF4 (laminated mudstone–grainstone facies) is predominant in member 1 (Sami and Desrochers, 1992), which has abundant wave-formed structures and excellent preservation of tempestites indicating deposition above storm wave base but below fairweather wave base in approximate water depths of 30–70 m. These features all indicate that there was a shallowing upward trend from members 1 and 2 (Fig. 11).

Besides LF4, member 2 also includes lithofacies LF5 (laminated calcisiltite–grainstone facies) that was deposited above storm wave base and probably near fairweather wave base, in approximately 10–30 m of water (Sami and Desrochers, 1992). This indicates that the whole member 2 was formed in relatively shallow water. However, this shallowing trend was not constant, but was interrupted by periodic deepening events indicated by the *Ozarkodina pirata* (*Oz.p.*) community. There is no direct evidence to establish the water depth for this community. However, the following reasons suggest a relatively deep water preference for the *Oz. pirata* (*Oz.p.*) community: (a) among 123 samples in analysis, 12 are grouped as the *Oz. pirata* (*Oz.p.*) community; among these 123 samples, 12 contain *Oulodus? expansus* that is generally related to outer shelf and upper slope facies (Armstrong, 1990; Jowett and Barnes, 2000), and

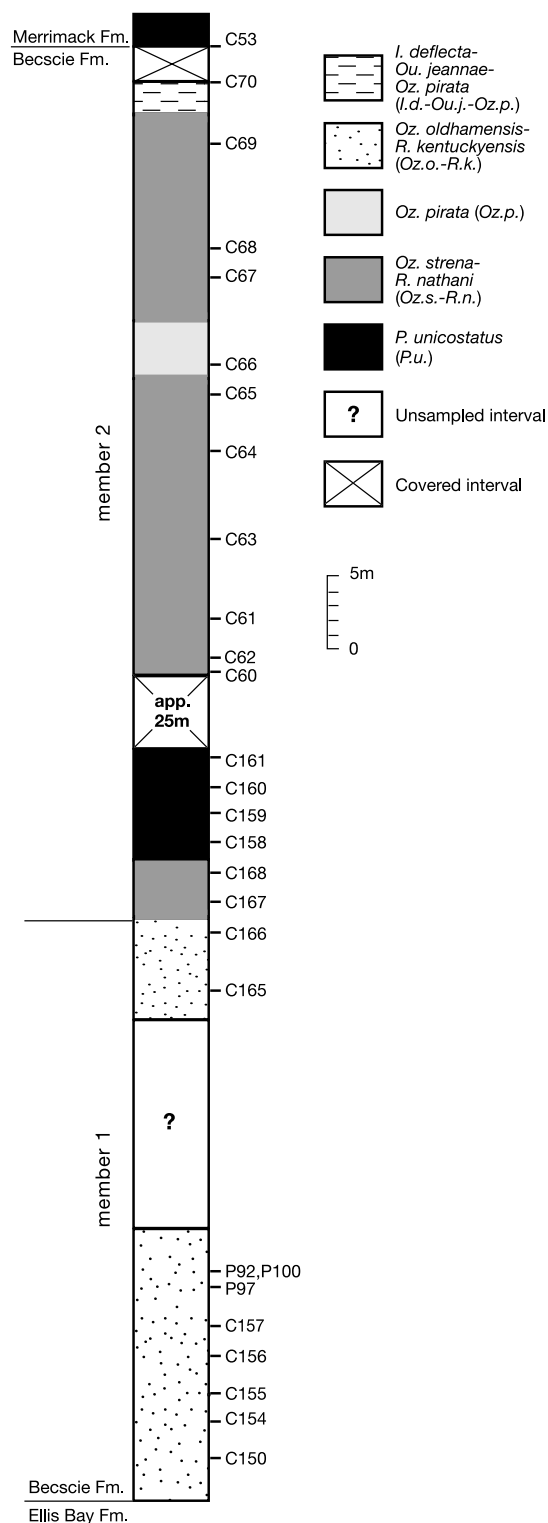


Fig. 8. Distribution of the conodont communities identified by cluster analysis through the Beccschie and Merrimack formations.



five of these 12 are assigned to the *Oz. pirata* (*Oz.p.*) community (Fig. 7); and (b) the five samples containing *Oulodus? expansus* in the *Oz. pirata* (*Oz.p.*) community show the highest abundance of *Ou.? expansus* (1–24 specimens per kg) among the 12 samples.

The presence of the *Panderodus unicostatus* (*P.u.*) community in the upper part of Merrimack Formation and near the boundary between the Merrimack and Gun River formations may indicate the deepest water depth in the sequence. This is supported by the presence of the LF1 lithofacies (calcareous mudstone–shale facies) in the upper Merrimack Formation, which is indicative of below-normal storm wave base (Sami and Desrochers, 1992). One sample from this interval (C57), not grouped in the *P. unicostatus* community, contains the first appearance of *Oulodus? expansus* which is generally associated elsewhere with outer shelf and upper slope facies (Armstrong, 1990; Jowett and Barnes, 2000). The Merrimack to Gun River transition may represent oscillating eustatic conditions as five samples from this interval (C70, C53, C55, C56, C57) are alternately grouped in the *P. unicostatus* (*P.u.*) and the *Icriodella deflecta*–*Oulodus jeannae*–*Ozarkodina pirata* (*I.d.*–*Ou.j.*–*Oz.p.*) community, the latter likely being indicative of more shallow water (see discussion below).

## 5.2. Sea level changes in the Aeronian

The Gun River Formation and members 1–4 (lower part) of the Jupiter Formation (of Uyeno and Barnes, 1983) are of Aeronian age (Fig. 9). Members 1–4 approximate to the Goéland, East Point and Richardson members of Copper and Long (1990). As noted above, the first appearance of the *Icriodella deflecta*–*Oulodus jeannae*–*Ozarkodina pirata* (*I.d.*–*Ou.j.*–*Oz.p.*) community is in the uppermost Becscie Formation (C70), i.e. near the Rhuddanian–Aeronian boundary, and it dominates throughout the Gun River Formation. Among all the communities recognized in analysis, the *Icriodella deflecta*–*Oulodus jeannae*–*Ozarkodina pirata* (*I.d.*–*Ou.j.*–*Oz.p.*) community has the highest species diversity and abundance. Most samples contain 3–8 species, and the char-

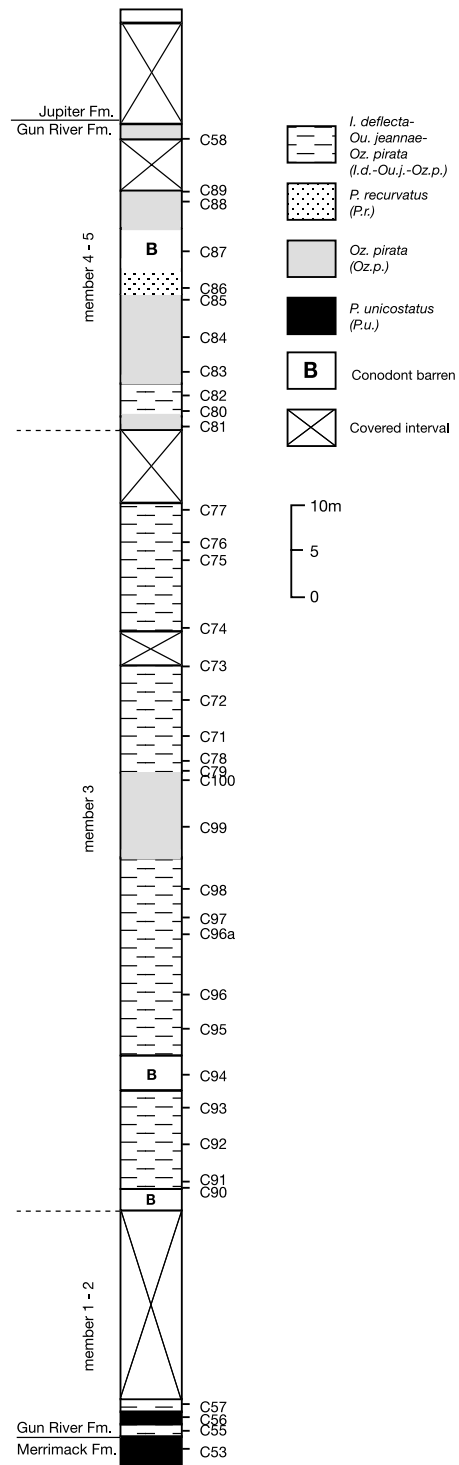


Fig. 9. Distribution of the conodont communities identified by cluster analysis through the Gun River Formation.

acteristic species in most samples are represented by over five specimens, and *Oz. pirata*, in particular, by between five and over 100 specimens.

Within this community, the best indicator of water depth is *Icriodella deflecta* Aldridge. Idris (1984) made a detailed study of the early Llandovery conodont faunas of the Oslo Region, Norway, and found *Icriodella discreta* Pollock, Rexroad and Nicoll and *I. deflecta* to be especially common in shallow water deposits displaying channeling, ripple marks, and lenses of pebbly biosparite. In analysis, 18 of 22 samples within the *Icriodella deflecta*–*Oulodus jeannae*–*Ozarkodina pirata* (*I.d.*–*Ou.j.*–*Oz.p.*) community produce 1–24 specimens of *I. deflecta*. The second richest community with *I. deflecta* is the *Ozarkodina strenna*–*Rexroadus nathani* (*Oz.s.*–*R.n.*) community in the upper part of the Becscie Formation, where four of 11 samples yield 1–4 specimens of *I. deflecta*. As interpreted above, the habitat of the *Ozarkodina strenna*–*Rexroadus nathani* (*Oz.s.*–*R.n.*) community was probably above storm wave base but below fairweather wave base. Based on the species abundance of *I. deflecta*, it can be inferred that the habitats of both the *Icriodella deflecta*–*Oulodus jeannae*–*Ozarkodina pirata* (*I.d.*–*Ou.j.*–*Oz.p.*) and *Ozarkodina strenna*–*Rexroadus nathani* (*Oz.s.*–*R.n.*) communities were similar. The Gun River Formation consists primarily of rhythmic micrites and shales representing a quiet, deeper water setting (Copper and Long, 1998) with stricklandiid brachiopods in low abundance (Jin and Copper, 1999). Additionally, the *Icriodella deflecta*–*Oulodus jeannae*–*Ozarkodina pirata* (*I.d.*–*Ou.j.*–*Oz.p.*) community contains the most abundant representation of *Ozarkodina pirata* (a relatively deep water representative as mentioned above) among all communities, which suggests that the *I.d.*–*Ou.j.*–*Oz.p.* community represents slightly deeper water than the *Ozarkodina strenna*–*Rexroadus nathani* (*Oz.s.*–*R.n.*) community.

The *Icriodella deflecta*–*Oulodus jeannae*–*Ozarkodina pirata* (*I.d.*–*Ou.j.*–*Oz.p.*) community was briefly replaced by the *Ozarkodina pirata* (*Oz.p.*) community in the middle part of the Gun River Formation, and then eventually replaced by it in the upper part of the formation. This indicates

that sea levels during Gun River time were moderately high, but increased briefly in the middle and again at the end.

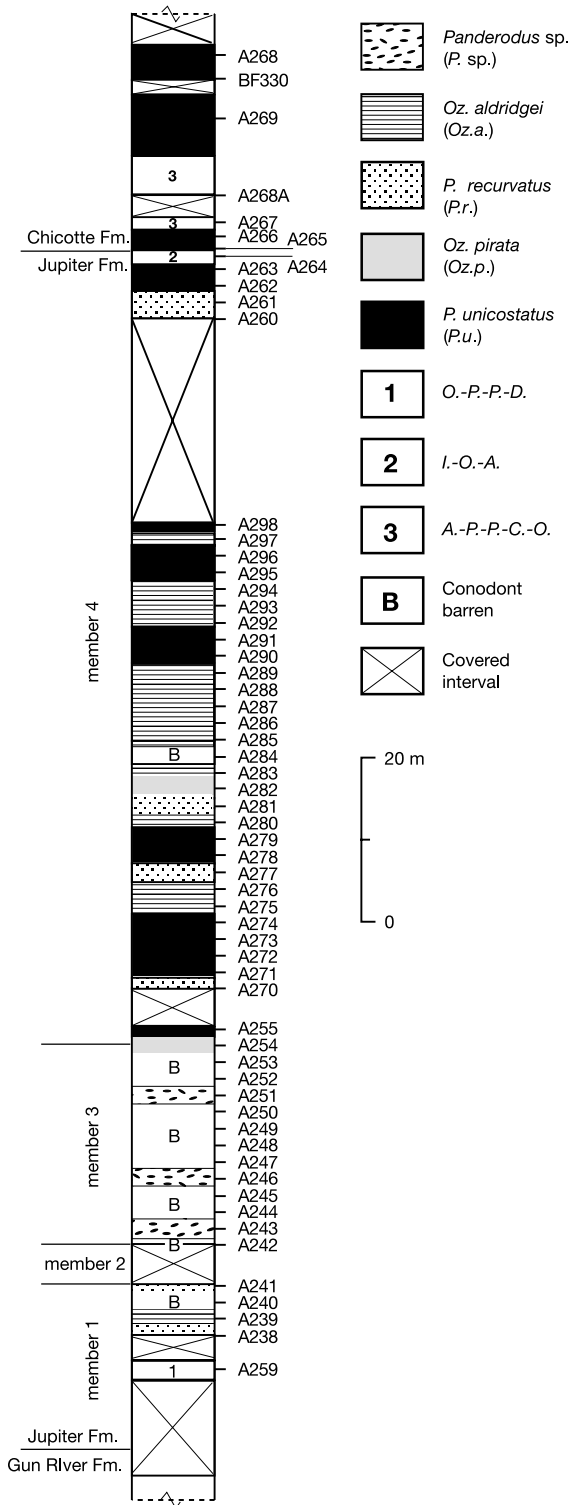
A study of the brachiopods (Jin and Copper, 1999) shows a development of the *Pentamerus* community near the top of Gun River Formation and at the base of the Jupiter Formation, indicating a shallowing event near the formational boundary. Unfortunately, no conodont collections came from the base of Jupiter Formation.

The lowest sample (A259) from the Jupiter Formation contains a special conodont community, i.e. the *Oulodus?* cf. *Ou.?* *fluegeli*–*Pterospathodus siluricus*–*Pterospathodus posteritenuis*–*Decoriconus fragilis* (*O.*–*P.*–*P.*–*D.*) community. It is the only sample among 123 in analysis yielding *Ou.?* cf. *Ou.?* *fluegeli* and having the highest abundance of *D. fragilis* (10 specimens per kg). These two species were interpreted as being specialists of offshore environments (Aldridge and Jeppsson, 1984). Hence, the *O.*–*P.*–*P.*–*D.* community in the middle part of member 1 in the Jupiter Formation, represents a relatively high sea level (Fig. 11).

Two other communities, *Panderodus recurvatus* (*P.r.*) and *Ozarkodina aldridgei* (*Oz.a.*), first appeared alternately in the upper part of member 1, Jupiter Formation (Fig. 10). Member 2 of the Jupiter Formation is not exposed on the south coast. Member 3 yields only conodonts of the *Panderodus* sp. (*P.r.*) community, represented by just three tiny specimens of *P. sp.* found in three samples, respectively. Member 3 comprises shale, locally sandy, which may represent a local clastic influx from the Canadian Shield to the north and probably a brief period of shallowing (Uyeno and Barnes, 1983). This interpretation is supported by the discovery of land-derived microfossils in the member (Duffield, 1985). This member probably represents the lowest sea level on Anticosti during the Llandovery (Fig. 11).

### 5.3. Sea level changes in the Telychian

Telychian strata are exposed on Anticosti Island as member 4 ( $\approx$  Cybèle, Ferrum and Pavillon members of Copper and Long, 1990) of the

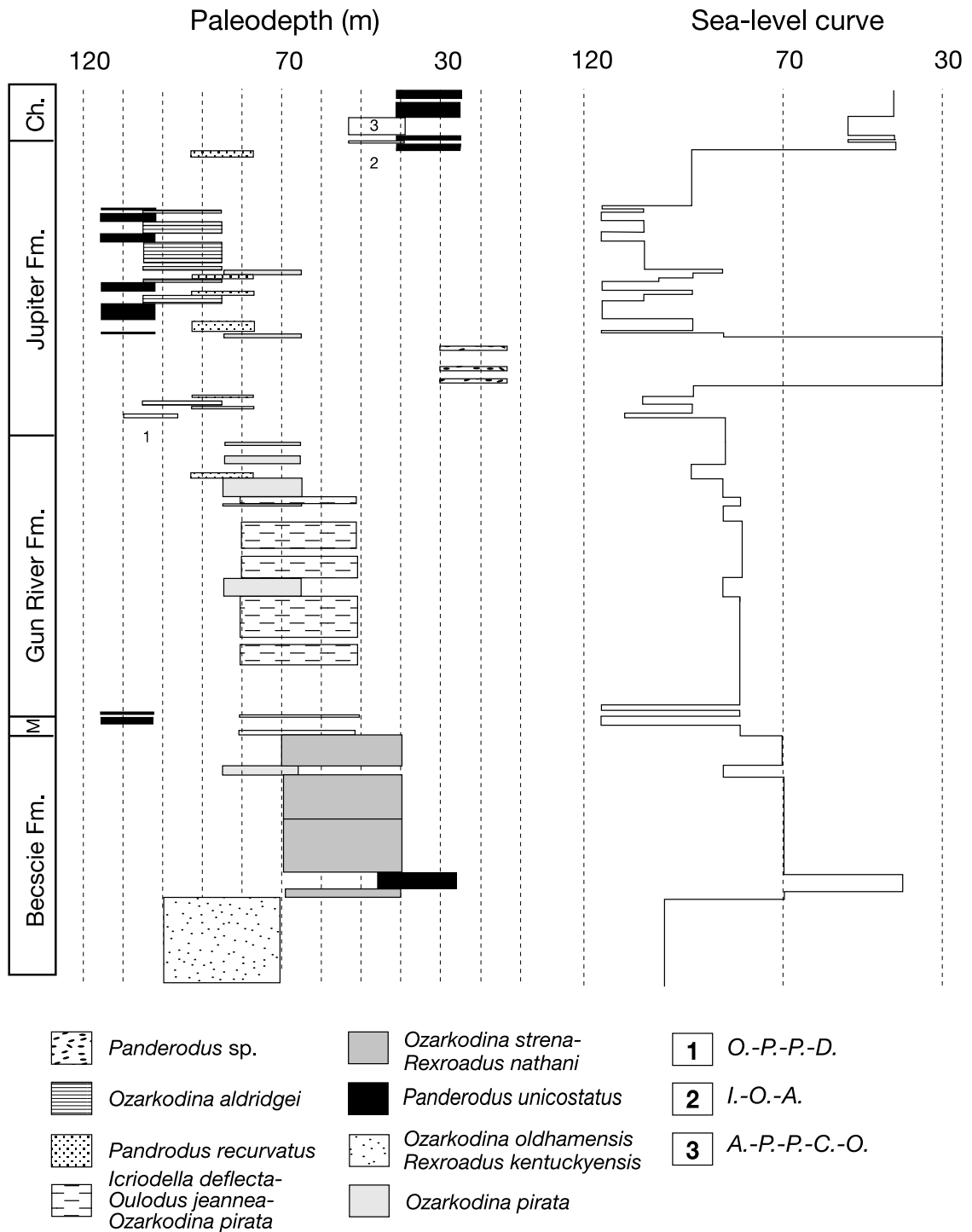


Jupiter Formation and the lower part of Chicotte Formation (Fig. 10); there is no clear evidence of uppermost Telychian or of Wenlock age strata. The pattern of conodont communities through member 4 of the Jupiter Formation is quite different from those in the underlying strata. Four conodont communities, *Panderodus unicostatus* (*P.u.*), *Panderodus recurvatus* (*P.r.*), *Ozarkodina aldridgei* (*Oz.a.*) and *Ozarkodina pirata* (*Oz.p.*), replaced each other in a repetitive pattern (Figs. 10 and 11).

The *Panderodus recurvatus* (*P.r.*) community first appeared in the upper part of the Gun River Formation. This community has its closest relationship with the *Ozarkodina pirata* community; both are linked by *P. recurvatus*, which suggests that the water depth for the *P. recurvatus* community was similar to that of the *Ozarkodina pirata* (*Oz.p.*) community. In analysis III, both *Icriodella deflecta*–*Oulodus jeannae*–*Ozarkodina pirata* (*I.d.*–*Ou.j.*–*Oz.p.*) and *Ozarkodina pirata* (*Oz.p.*) communities contain abundant *Ozarkodina pirata*. The *Ozarkodina pirata* (*Oz.p.*) community yields more abundant *Oulodus? expansus* than any other communities, and consequently the water depth of the *Ozarkodina pirata* (*Oz.p.*) community was deeper than that of the *Icriodella deflecta*–*Oulodus jeannae*–*Ozarkodina pirata* (*I.d.*–*Ou.j.*–*Oz.p.*) community as discussed earlier. Thus, the water depth of the *P. recurvatus* community that generally lacks *Ozarkodina pirata* should be deeper than that of the *Ozarkodina pirata* (*Oz.p.*) community.

The *Ozarkodina aldridgei* (*Oz.a.*) community originates in the Jupiter Formation and *Oz. aldridgei* is a characteristic species. The distinctive Pa element of *Oz. aldridgei* is similar to that of *Oz. oldhamensis* that is most common in the *Ozar-*

Fig. 10. Distribution of the conodont communities identified by cluster analysis through the Jupiter and Chicotte formations (O.-P.-P.-D. = *Oulodus?* cf. *Ou.?* *fluegeli*–*Pterospathodus siluricus*–*P. posteritenuis*–*Decoriconus fragilis* community; I.-O.-A. = *Icriodella inconstans*–*Ozarkodina gulletensis*–*Aulacognathus bullatus* community; A.-P.-P.-C.-O. = *Apsidognathus tuberculatus*–*Pterospathodus celloni*–*P. pennatus* *procerus*–*Carniodus carnulus*–*Ozarkodina polinclinata* community).



*kodina oldhamensis*–*Rexroadus kentuckyensis* (*Oz.o.*–*R.k.*) community in the early Rhuddanian. A cladistic analysis suggests that *Oz. oldhamensis* and *Oz. aldridgei* shared a common ancestry, and the latter is interpreted as being transformed through the pseudoextinction of the former by the acquisition of an additional derived character state of basal cavity (located at about mid-length of the blade) (Zhang and Barnes, in preparation). Hence, *Oz. aldridgei* and *Oz. oldhamensis* probably preferred a similar water depth below storm wave base. The other characteristic species are *Decoriconus fragilis* and *Dapsilodus obliquicostatus* (Branson and Mehl). Both of these are rare through the whole Llandovery on Anticosti Island; among 123 samples in the analysis, eight of 19 yielding *D. fragilis* and three of five producing *D. obliquicostatus* are grouped under the *Oz. aldridgei* (*Oz.a.*) community. This indicates that the water depth of *D. obliquicostatus* and *D. fragilis* is also equivalent to that of the *Oz. aldridgei* (*Oz.a.*) community. A strikingly high proportion of *D. obliquicostatus* was documented by Aldridge and Mabillard (1981) in the most offshore localities across the Early Silurian shelf of the Wales/Welsh Borderland area. *Decoriconus fragilis* is also common in more offshore areas of this shelf (Aldridge and Jeppsson, 1984). A similar dominance has been also noted in other areas, for instance, North Greenland (Armstrong, 1990) and Arctic Canada (Jowett and Barnes, 2000), where the outer shelf and upper slope communities contain *D. obliquicostatus* and *D. fragilis*. Thus, the *Ozarkodina aldridgei* (*Oz.a.*) community represents a deep water environment, perhaps deeper than that of the *Ozarkodina oldhamensis*–*Rexroadus kentuckyensis* (*Oz.o.*–*R.k.*) community in the early Rhuddanian.

The common characteristic of the four communities in member 4 of Jupiter Formation is the low species diversity and abundance. Most samples from this interval grouped under the *Pan-*

*derodus unicastatus* (*P.u.*) community only produce the eponymous species, with low abundance (one to four specimens per kg). This suggests deeper water than that of the *Ozarkodina aldridgei* (*Oz.a.*) community, with the latter being likely the deepest community of the Llandovery Anticosti conodonts except for the *P. unicastatus* community. Most of the 14 samples grouped under the *Ozarkodina aldridgei* (*Oz.a.*) community contain two to four species, only one (A239) produced eight species, and most of these are only represented by less than one to nine specimens per kg. Similarly, most samples from this interval grouped under the *P. recurvatus* (*P.r.*) community also show a lower species diversity and abundance than other samples from the Gun River Formation. The *P. unicastatus* (*P.u.*), *Oz. aldridgei* (*Oz.a.*), *P. recurvatus* (*P.r.*) and *Oz. pirata* (*Oz.p.*) communities through member 4 of the Jupiter Formation indicate four different but alternating water depths from deep to shallow, but still deeper than any other communities from the underlying strata. This pattern suggests more oscillating sea levels than seen in the underlying strata.

Near the Jupiter–Chicotte boundary, two short-lived communities can be recognized. They are *Icriodella inconstans*–*Ozarkodina gulletensis*–*Aulacognathus bullatus* (*I.–O.–A.*) and *Apsidognathus tuberculatus*–*Pterospathodus celloni*–*P. pennatus procerus*–*Carniodus carnulus*–*Ozarkodina polinclinata* (*A.–P.–P.–C.–O.*). Each is represented by only two adjacent samples. Among the former, *Oz. gulletensis* and *I. inconstans* have been interpreted as nearshore inhabitants during the pre-*amorphognathoides* and post-*amorphognathoides* intervals, respectively (Aldridge and Mabillard, 1981). However, *Au. bullatus* may not have a strong environmental preference, and occurs widely in small numbers almost everywhere as recorded by Armstrong (1990). In that study, the relative abundance peaks of *C. carnulus* dur-

Fig. 11. Inferred paleodepth and sea level changes based on the distribution of the 11 conodont communities identified by cluster analysis through Becscie, Merrimack, Gun River, Jupiter and Chicotte formations (M = Merrimack Fm.; Ch = Chicotte Fm.; *O.–P.–P.–D.* = *Oulodus?* cf. *Ou.?* *fluegeli*–*Pterospathodus siluricus*–*P. posteritemis*–*Decoriconus fragilis* community; *I.–O.–A.* = *Icriodella inconstans*–*Ozarkodina gulletensis*–*Aulacognathus bullatus* community; *A.–P.–P.–C.–O.* = *Apsidognathus tuberculatus*–*Pterospathodus celloni*–*P. pennatus procerus*–*Carniodus carnulus*–*Ozarkodina polinclinata* community).

ing the *amorphognathoides* interval and *P. celloni* during the pre-*amorphognathoides* interval are related to a more offshore environment (Aldridge and Mabillard, 1981) than their presence in the *Icriodella inconstans*–*Ozarkodina gulletensis*–*Aulacognathus bullatus* (*I.–O.–A.*) community.

The crinoidal grainstone of the uppermost Jupiter and lower Chicotte formations is possibly an initial indication of a regional shallowing phase (Uyeno and Barnes, 1983) corresponding to shallow shoal bank environment.

### 6. Discussion

#### 6.1. Ashgillian–Llandovery sea level curve for Anticosti Island

Fig. 12 summarizes the Anticosti conodont community distribution through time and space. Fig. 13 illustrates the sea level curve derived from Ordovician–Silurian conodont communities from the Ashgillian–Llandovery sequence on Anticosti Island. It also compares with the smoothed sea

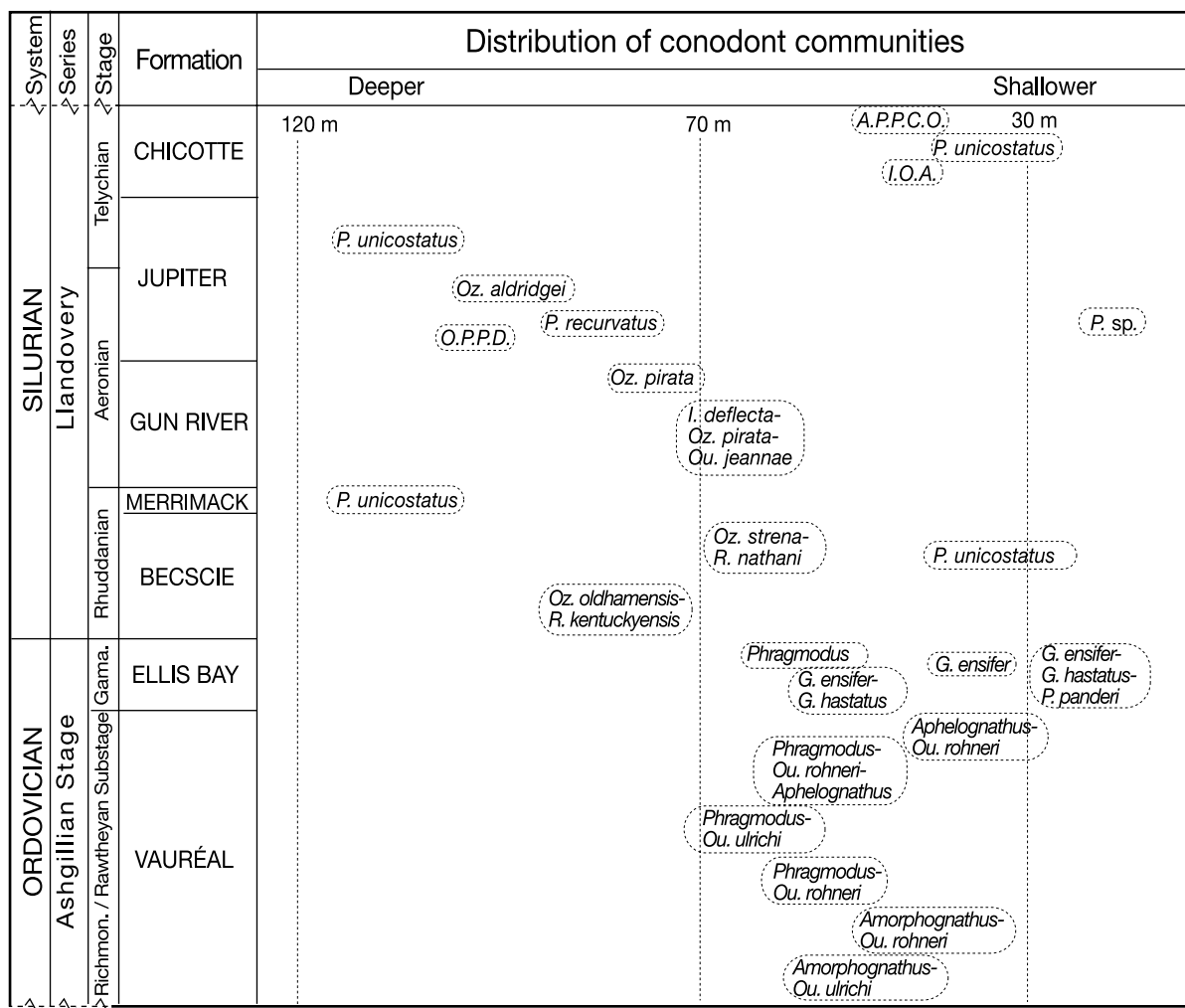


Fig. 12. Summary of conodont community distribution through space and time during the Late Ordovician and Early Silurian on Anticosti Island (*O.P.P.D.* = *Oulodus?* cf. *Ou.?* *fluegeli*–*Pterospathodus siluricus*–*P. posteritenuis*–*Decoriconus fragilis* community; *I.O.A.* = *Icriodella inconstans*–*Ozarkodina gulletensis*–*Aulacognathus bullatus* community; *A.P.P.C.O.* = *Apsidognathus tuberculatus*–*Pterospathodus celloni*–*P. pennatus*–*Procerus*–*Carniodus carnulus*–*Ozarkodina polinclinata* community).

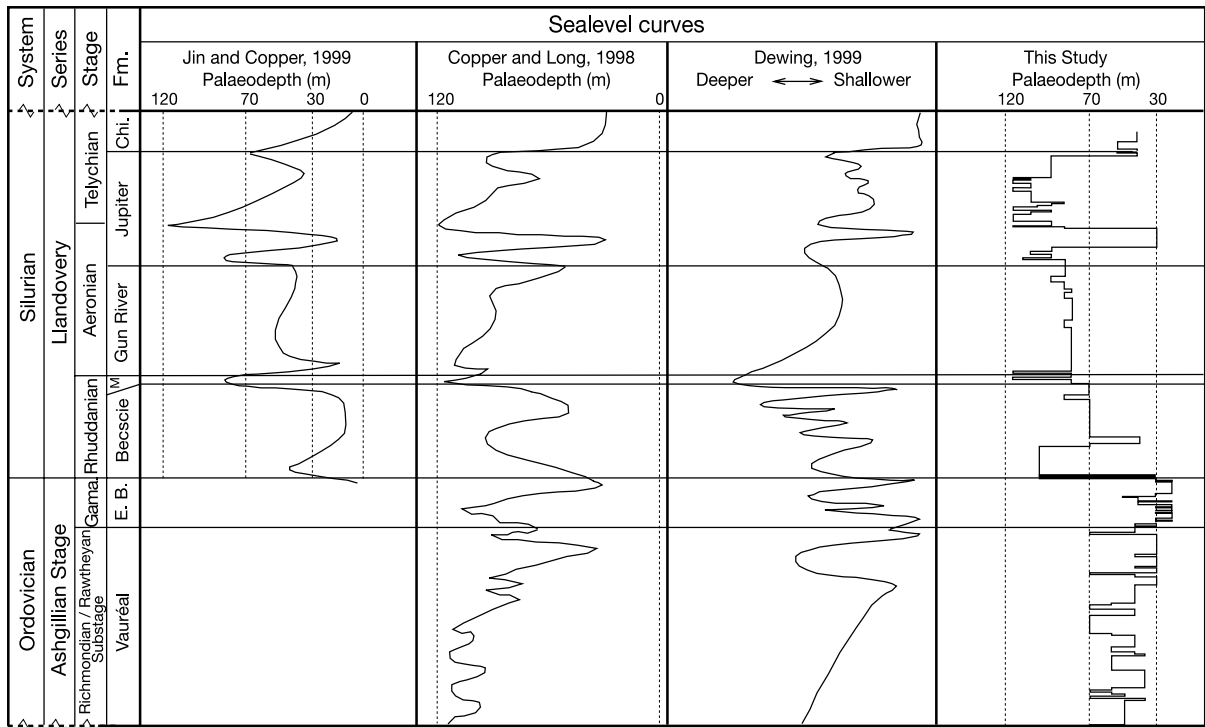


Fig. 13. Comparison of the sea level curve and paleodepths inferred by the distribution of conodont communities with those inferred by macrofossils and sediments through the Upper Ordovician and Lower Silurian sequence on Anticosti Island (M = Merrimack Fm.; Ch = Chicotte Fm.).

level curves proposed previously by Copper and Long (1998), Jin and Copper (1999), and Dewing (1999) based on sediments and brachiopod and reef communities. These different authors used slightly different formational thicknesses, and Fig. 13 adjusts the thickness of each formation used by Copper and Long (1998), Jin and Copper (1999), and Dewing (1999) to match the same scale.

There is some contradiction between sea level curves and the paleodepths for the Vauréal Formation established by Copper and Long (1998). Fig. 2 (modified from Copper and Long, 1998) shows the paleodepths of the Vauréal as occurring between 20 and 70 m, with two shallow to deep cycles based on sedimentary structures. However, the sea level curve based on the paleocommunities is deeper, almost as deep as that of Merrimack Formation (maximum 120 m), with sea level gradually shallowing from lower to upper Vauréal

with six secondary shallow to deep cycles (Fig. 13). Dewing's (Fig. 13) sea level curve exhibits a gradual shallowing without any significant deepening or shallowing events in the lower and middle part of Vauréal. However, it shows a sharp deepening in the upper part of the formation, contrary to that of Copper and Long (1998). The sea level curve proposed herein is similar to that of Copper and Long (1998), but shows more variations of deepening and shallowing.

The sea level curve for the Ellis Bay Formation of Copper and Long (1998), Dewing (1999) and this study are similar, although this study shows a more oscillating pattern in the lower part of the formation than the former two.

Dewing (1999) recognized three small regressive cycles within an overall transgression through the Beccsie and Merrimack formations, based largely on the curve of Sami and Desrochers (1992). Both Jin and Copper (1999) and Copper and Long

(1998) recognized one major regression in this interval. The curve derived from the conodont community pattern for this interval supports that of Jin and Copper (1999) and Copper and Long (1998) with only minor differences, but not that of Dewing (1999).

The conodont communities in the few samples from the Merrimack Formation are similar to those of the upper Becscie Formation, which does not reflect the deepening phase suggested by brachiopod community evidence. However, the rapid replacement of conodont communities does suggest a major transgression in the upper part of Merrimack Formation and near the Merrimack–Gun River boundary (Rhuddanian–Aeronian boundary), slightly later than that recognized by Jin and Copper (1999), Copper and Long (1998) and Dewing (1999).

In the Gun River interval, conodont communities remained relatively constant, only punctuated by other communities representing deeper water in the upper part of the formation. This is a similar pattern to that suggested for the brachiopod communities.

In the lower Jupiter Formation interval, the sea levels constructed by different authors show a similar pattern with two major transgressions and one regression. However, in the middle and late Jupiter interval, this study reveals a much more oscillating sea level pattern than do the others. This study does not recognize a transgression near the boundary between the Jupiter and Chicotte formations, contrary to the other studies. A marked regression occurred in the lower Chicotte interval, associated with the widespread crinoidal shoal facies, recognized by all authors.

## 6.2. Comparison to the Ashgillian–Llandovery global sea level curve

Based on sequence stratigraphic correlations of key Ordovician sections in North America and Europe, Ross and Ross (1992) concluded that Upper Ordovician sequences were deposited during a series of transgressions–regressions that were associated with generally high eustatic sea levels (Mohawkian and Cincinnati). The changes of Richmondian conodont communities on Anticosti

Island reflect these eustatic sea level changes. According to Ross and Ross (1992), a global sea level drop occurred in the Gamachian with only one brief transgression. This may be reflected in the brief appearance of the *Phragmodus undatus* community in the middle Ellis Bay Formation.

The sudden changes in conodont communities near the Ordovician–Silurian boundary and the stable development of new Llandovery conodont communities on Anticosti Island do not support the conclusion of Ross and Ross (1992) that, after the Gamachian, sea level gradually rose through a series of transgressions and regressions at the beginning of the Silurian. The pattern of conodont communities suggests a rapid rise of sea level in the beginning of the Silurian (Fig. 14).

Highest Llandovery sea level is reached near the Rhuddanian–Aeronian boundary (between the Merrimack and Gun River formations), as reflected in the appearance of the *Panderodus unicostatus* community along with *Oulodus? expansus*, a deep water specialist species. This highstand probably correlates with the upper *Coronograptus cyphus* Zone and lower *Demirastrites triangulatus* Zone, which approximates to the highstand recognized by Johnson (1996) and Johnson et al. (1991) that they correlated with the *C. cyphus* Zone, but does not support a lowstand recognized by Ross and Ross (1996) (Fig. 14).

Loydell (1998) considered that sea level reached a maximum in the early Aeronian *Demirastrites triangulatus* to early *Diplograptus magnus* zones. However, recent stratigraphic and isotopic data suggests that a minor glaciation occurred in South America at or close to the *D. triangulatus* Zone (Grahn and Caputo, 1992; Grahn, 1996; Caputo, 1998; Veizer et al., 1999) which supports the likelihood of an early Aeronian regression. The *Atavograptus atavus* Zone on Anticosti Island equates approximately with the *D. triangulatus* Zone (Zhang and Barnes, 2002a) and in this interval conodont communities indicate a stable development in relatively shallow water (Fig. 14).

The development and replacement of conodont communities indicate two highstands in the latest Aeronian. The first one is earlier than the graptolite *Stimulograptus sedgwickii* Zone, and the second one coincides with the first appearance of *S.*



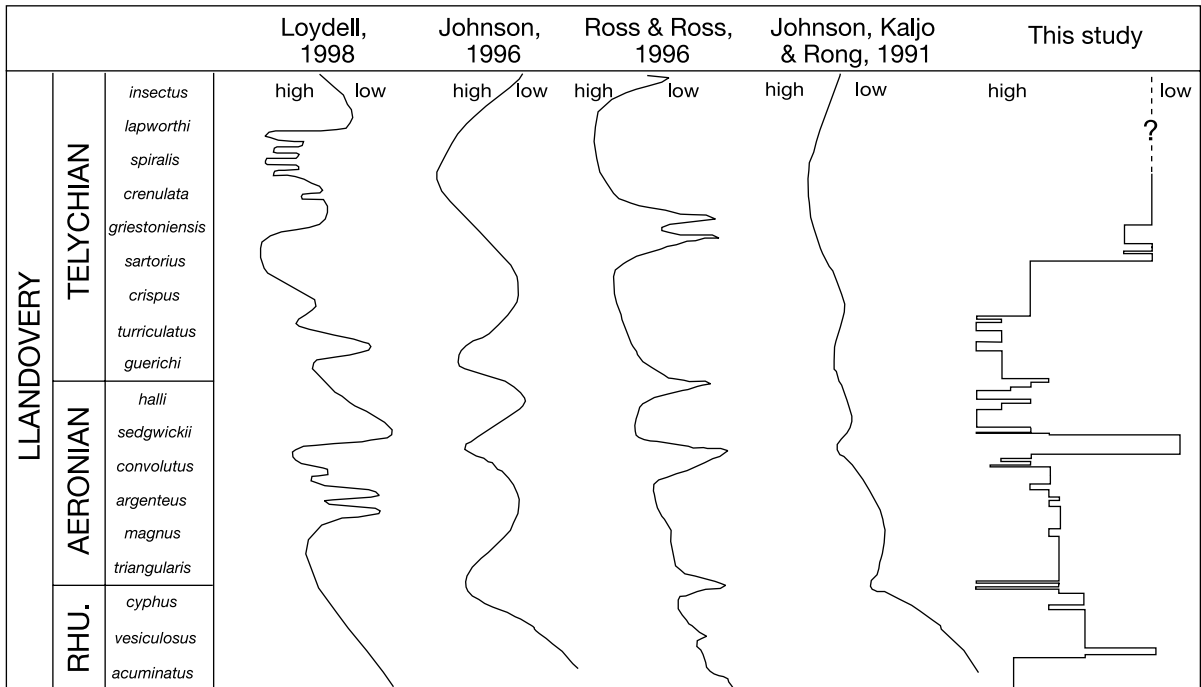


Fig. 14. New sea level curve inferred by the distribution of Anticosti Llandovery conodont communities (right), compared with other proposed global Llandovery sea level curves (modified from Loydell, 1998). Zones are drawn arbitrarily as of equal duration (as in Loydell, 1998), but this creates a slightly different duration of chronostratigraphic units from that used in Figs. 11 and 13.

*sedgwickii*. Between these two highstands, there is a pronounced lowstand represented by the *Panderodus* sp. community, which was also recognized by Ross and Ross (1996); a lowstand is correlated with the *S. sedgwickii* Zone by Loydell (1998) (Fig. 14). The latest Aeronian glaciation recorded in South America is also correlated with this graptolite zone by Veizer et al. (1999).

No zonal graptolites have been found in the Chicotte Formation, so precise correlation is difficult. On the basis of conodont and brachiopod biostratigraphy (Barnes, 1989), the Chicotte ranges at least as high as Telychian C<sub>5</sub> and the graptolite *Monoclimacis crenulata* Zone. The lowstand recognized by the conodont communities in the Chicotte Formation is contrary to the highstand related to *M. crenulata* Zone and conodont *Pterospathodus amorphognathoides* Zone recognized by Ross and Ross (1996) and Johnson (1996).

## 7. Conclusions

Anticosti Island, Québec, provides the most complete and fossiliferous section in the world for the Ashgillian–Llandovery (Upper Ordovician–Lower Silurian) interval. The predominantly limestone succession accumulated in the gently subsiding Anticosti Basin and preserves a valuable record of changing sea levels. Earlier workers have derived sea level curves based on aspects of stratigraphy and sedimentology, and or brachiopod and reef communities. Virtually the entire sequence has been sampled in detail for conodonts, and underpinned by taxonomy. The resulting database of over 77 600 conodonts secured from 272 samples has allowed, using paleoecological statistical analysis, the recognition of a complex pattern of conodont communities. These are correlated to paleobathymetry as inferred from the known details of the stratigraphy, sedimentology

and macrofossil communities. From the spatial and temporal distribution of conodont communities derived from this detailed sampling base, a refined sea level curve has been established for the Anticosti sequence. It is compared to sea level curves developed by other workers that were based on sedimentary structures, and brachiopod and reef communities with which it is in general agreement, but shows more subtle changes and is better constrained stratigraphically. The Anticosti sea level curve is also compared to the global eustasy curves developed recently for this interval by other workers.

Some distinct patterns have emerged from the analysis and the interpretations, namely:

- Each conodont community maintained its particular environmental preferences and interpreted water depths through this interval.
- Sea level changes resulted in the rapid displacement of communities.
- During periods of relatively stable sea level, the communities likewise maintained a stable development and typically had a relatively high species diversity and abundance during these brief periods of stasis.
- During periods of oscillating sea level, different communities were replaced rapidly and typically had a relatively low species diversity and abundance.
- The *Panderodus unicostatus* community tolerated both the extreme deep and shallow water environments represented in the sequence that other conodont communities avoided, likely due to the eurytopic nature of this species.

The main periods of regression in the sequence can be correlated relatively well to the intervals of eustatic lowstand generated by the Gondwana glaciation, for both the main glacial events in the Hirnantian/Gamachian and in the three brief intervals in the Llandovery that are also indicated by the recently documented oxygen isotope excursions.

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