PHYSICAL, MAGNETIC, SEDIMENTOLOGICAL, GEOCHEMICAL, ISOTOPIC AND MICROPALEONTOLOGICAL FEATURES OF RAPIDLY DEPOSITED LAYERS IN THE SAGUENAY FJORD, QUÉBEC: FROM 7200 CAL BP TO THE 1996 AD FLOOD LAYER

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ABSTRACT: Sedimentological, geochemical, isotopic and micropaleontological properties of surface and sub-surface sediments cored in the Saguenay Fjord and adjacent Baie des Ha!Ha! allowed the identification of several rapidly deposited layers (RDL). The most recent ones in box-cored sediments include layers deposited during the 1996 AD flood, the 1988 AD earthquake and the 1971 AD landslide of St-Jean-Vianney. Short-lived isotope (^{228}Th, ^{210}Pb and ^{137}Cs) measurements suggest discrete mixing, notably on top of these layers, but all were buried rapidly enough to preserve most of their original isotopic signature. Analyses of foraminifers collected before and after the 1996 AD flood indicate that the recolonization of surface sediments by the benthic microfauna was almost immediate, with increased species diversity as compared to pre-flood sediments, suggesting that the 1996 AD flood layer has played a role in isolating the underlying contaminated sediments. A total of 14 RDL likely resulting from high magnitude (>6) earthquakes during the last ~7200 calibrated years BP were also recognized in a 38 m-long piston core from the inner basin of the Fjord. They include a ~16-m thick layer associated with the great historical earthquake of 1663 AD.

RÉSUMÉ : L'analyse des propriétés sédimentologiques, géochimiques, isotopiques et micropaléontologiques de plusieurs carottes sédimentaires ainsi que de sédiments de surface prélevés dans le fjord du Saguenay et la baie des Ha!Ha! a permis d'identifier plusieurs couches accidentelles. Les couches accidentelles les plus récentes observées dans les carottes-boîtes ont été déposées à la suite de la crue de 1996 AD, du séisme de 1988 AD et du glissement de terrain de St-Jean-Vianney en 1971 AD. Les profils de radio-isotopes à courte période (^{228}Th, ^{210}Pb and ^{137}Cs) indiquent un mélange discret, en particulier au sommet de ces couches, mais leur enfouissement semble avoir été suffisamment rapide pour qu'elles aient conservé quasi-intactes leurs signatures isotopiques. L'analyse des foraminifères prélevés dans le sédiment accumulé avant et après la crue de 1996 AD indique une recolonisation rapide des sédiments par la microfaune benthique après 1996, avec une diversité des espèces plus élevée qu'avant la crue. La couche de crue de 1996 AD semble ainsi avoir joué un rôle isolant sur les sédiments contaminés sous-jacents. Une carotte sédimentaire de 38 m de longueur prélevée dans le basin central du fjord du Saguenay a révélé la présence d'au moins 14 couches accidentelles probablement liées à des séismes de grande magnitude (>6) survenus au cours des derniers ~7200 ans dont une de ~16 m d'épaisseur qui est associée au grand séisme historique de 1663 AD.

1. INTRODUCTION

The Saguenay Fjord has been marked by several natural disasters over the last few centuries. These include the 1663 (M≈7.0) and 1988 (M=6) earthquakes, the 1924 Kénogami and 1971 Saint-Jean-Vianney landslides and the catastrophic flood of 1996, which swept more than 15 x 10^6 m^3 of sediment into the Saguenay Fjord (Lapointe et al. 1998). Previous studies have revealed the presence of thick sediment deposits associated with these events, varying from several centimeters to several meters in the Baie des Ha!Ha! and inner basin of the Saguenay Fjord (Smith and Walton 1980; Syvitski and Schafer 1996; St-Onge et al. in press). These deposits generally consist of light grey homogenous silty clays that contrast sharply with the dark grey, bioturbated background sediments.

Following the 1996 flood, a collaborative research project was undertaken in order to evaluate the efficiency of the newly deposited flood layer to isolate the underlying sediments, which were highly contaminated by industrial activity (Pocklington and Leonard 1979). Our contribution to this project was 1) to develop tracers of Holocene rapidly deposited layers (RDL) such as the 1996 flood layer, 2) to evaluate the effect of mechanical mixing by bioturbation at the interface between the 1996 flood layer and the underlying contaminated sediments, and 3) to evaluate the impact of the 1996 flood on the benthic microfauna. In this paper, we present the physical, magnetic, sedimentological, geochemical, isotopic and micropaleontological signature of RDL deposited during the last 7200 calibrated years BP, with a special attention to the 1996 AD flood layer and its impact on benthic microfaunal re-settling.

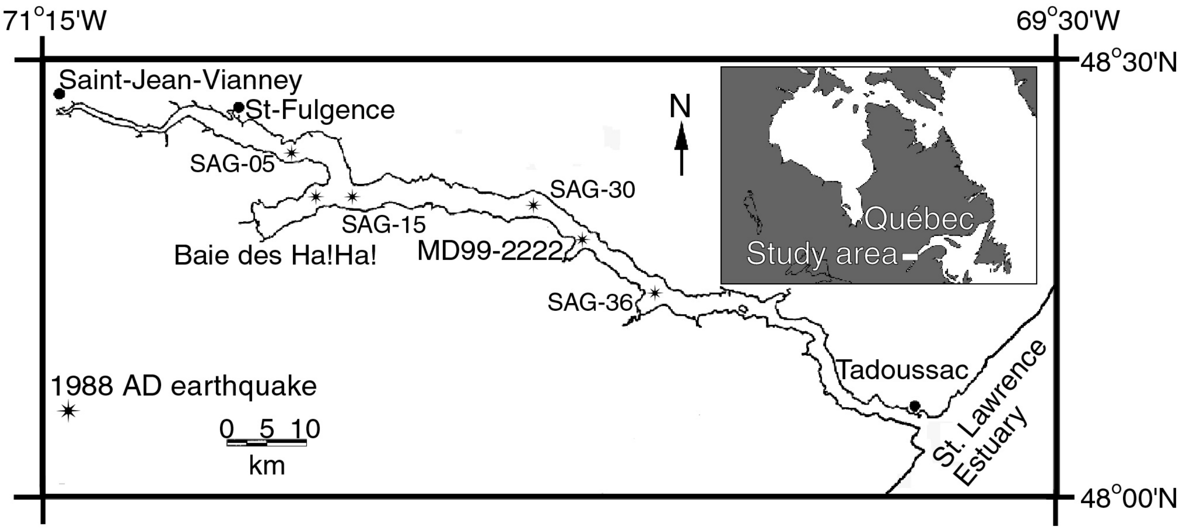

Figure 1. Map of the Saguenay Fjord showing the location of coring sites discussed in the text and that of the epicenter of the 1988 AD earthquake (M=6).

2. GEOLOGICAL SETTING

The Saguenay Fjord is a long (90 km) and narrow (1-6 km) submerged valley extending from Saint-Fulgence to Tadoussac (Fig. 1). The Fjord occupies an ancient tectonic depression in the Precambrian rocks of the Canadian Shield (Drainville 1968), which was accentuated by advances and retreats of glaciers in the Late Quaternary. Following deglaciation at around 10 000 ^{14}C years BP, saline waters of the Laflamme Sea occupied the glacioisostatic depression. During this interval, a thick cover of light grey, slightly carbonated clays was deposited in the Fjord (Lasalle and Tremblay 1978). High-resolution seismic reflection profiles reveal the presence of a thick Quaternary sequence filling the Fjord (Praeg and Syvitski 1991). The sequence averages 800 m in thickness, and ranges up to 1300 m in the intermediate basin. Modern sedimentation rates range from 7 cm/yr near Saint-Fulgence to less than 0.1 cm/yr in the deepest part of the inner basin (Smith and Walton 1980; Zhang 2000).

3. PHYSICAL, MAGNETIC, SEDIMENTOLOGICAL AND GEOCHEMICAL TRACERS

A 38 m-long Calypso piston core (core MD99-2222; Fig. 1) was raised from the deepest part of the Saguenay Fjord inner basin during the 1999 IMAGES-V (International Marine Past Global Change Study) expedition. One of the objectives was to identify the RDL prior to the one associated with the 1663 earthquake. This seismic event generated about 3 km^3 of landslides and submarine slides over most of the inner basin of the Fjord (Syvitski and Schafer 1996), while a landslide at the head of the Fjord dammed the river with about 0.2 km^3 of material (Legget and Lasalle 1978). Syvitski and Schafer (1996) proposed that the dam breached during the following spring freshet, contributing to very high suspended particulate matter concentrations, which generated an estimated 28-day-long hyperpycnal flow and the deposition of a 2 to 10 meter thick turbidite.

High-resolution physical (density, color reflectance and digital X-radiography), magnetic (susceptibility and inclination), sedimentological (detailed description and grain size) and geochemical ($CaCO_3$) analyses revealed the presence of at least 14 RDL (Fig. 2), including a 16-m thick layer associated with the 1663 AD earthquake (Fig. 2). These RDL are easily recognizable by their sandy bases, light grey color, high $CaCO_3$ content and low basal paleomagnetic inclinations, contrasting sharply with the dark grey bioturbated background sediments. The light grey color and the high $CaC0_3$ contents indicate the incorporation of Laflamme Sea clays (St-Onge and Hillaire-Marcel 2001), whereas the low paleomagnetic inclinations at the base of the RDL indicate an energetic depositional process, the magnetic particles being plastered horizontally because of high flow velocity and rapid sediment accumulation. Based on the chronology derived from paleomagnetic secular variations and paleointensity correlations and one ^{14}C date, St-Onge et al. (in press) estimated the age at the base of the core to be about 7200 calendar years BP.

Using digital X-radiography and grain size analyses at <1 cm spacing, St-Onge et al. (in press) showed that six RDL (RDL 2, 5, 6, 8, 12 and 13), ranging from 7 cm to 1 m in thickness, are fining upward and likely resulted from the transformation of earthquake-triggered slumping. Earthquakes that produced RDL in the Saguenay Fjord are likely to have a magnitude higher than 6.75 assuming that their epicenter is located near the one of the 1988 earthquake (Fig. 1), which had a magnitude of 6 and did not produce any significant landslides or submarine slides in the deepest part of the inner basin (Urgeles et al. 2002). Six additional RDL (RDL 1, 3, 7, 9, 10 and 11), ranging from 40 cm to 16 m in thickness, have a similar fining upward basal unit, but are overlain by a coarsening upward unit that underlies a second fining upward unit. The two units at the top are associated with the deposition of a flood-induced hyperpycnal flow. By analogy with the 1663 event, such beds are inferred to result from the breaching and rapid draining, during the spring freshet, of a natural dam generated by an earthquake-triggered landslide (see St-Onge et al. in press for details). On these grounds, the RDL record of core MD99-2222 suggests that the frequency of major earthquakes significantly decreased during the late Holocene, after 4000 calendar years BP.

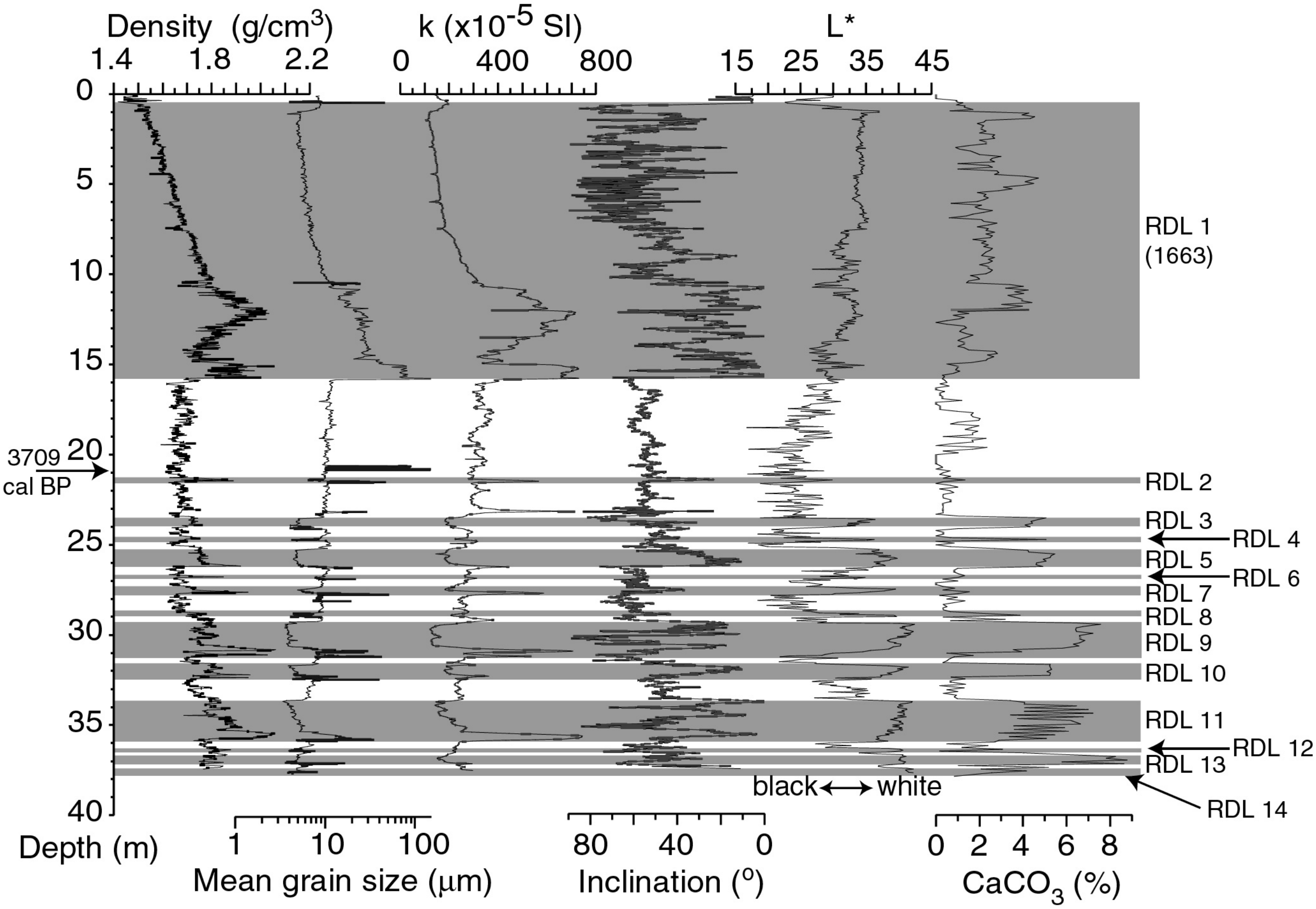

Figure 2. Physical properties of rapidly deposited layers (RDL) in core MD99-2222. The grey zones correspond to RDL. RDL 1 is associated to the 1663 AD earthquake. Wet bulk density and low field volumetric magnetic susceptibility (k) were measured using a GEOTEK™ MSCL (Multi Sensor Core Logger). The color index (L*) that ranges from 0 (black) to 100 (white) was measured using a Minolta™ hand-held spectrophotometer. Inclinations were calculated by principal component analysis using 4 to 9 alternating field (AF) demagnetization steps at peak fields of 10-50 mT using a 2-G Enterprises™ Model 755 cryogenic magnetometer at the University of California, Davis. The $CaCO_3$ content was analyzed with an automated Bernard calcimeter, whereas the grain size analyses were made with a Malvern™ Supersizer "S" at the Université de Bordeaux 1. Detailed data are reported by St-Onge et al. (in press).

4. ISOTOPIC TRACERS

Box cores collected in 1997 at sites SAG-05, SAG-15 and in the Baie des Ha!Ha! (Fig. 1) were analyzed at 1 cm-intervals for their radioisotopic content (^{228}Th, ^{210}Pb, ^{137}Cs). Results permitted to identify RDL based on low activity values of these isotopes (e.g., Fig. 3; see Savard 2000). The 1996 RDL flood layer is identified at the three sites, whereas an RDL assigned to the 1998 earthquake is observed at SAG-5 and in the Baie des Ha!Ha!. One other RDL is only distinguished at SAG-15 and is assigned to the 1971 St-Jean-Vianney landslide. A smoothing in the radioisotope profiles is generally observed at the boundaries of most RDL, notably at their top as seen in the Baie des Ha!Ha!, suggesting that some biological mixing occurred after their deposition. In the long term, based on the radioisotope profiles, some remobilization of the contaminated sediment buried by the 1996 flood layer cannot be discarded. However, the relatively well preserved radioisotope profiles of the 1988 and 1971 RDL along with the decimeter to meter thick RDL observed in core MD99-2222 spanning the last 7200 calibrated years BP indicate limited mixing of RDL with the underlying sediments. This is especially true for sites with high sedimentation rate or thick RDL.

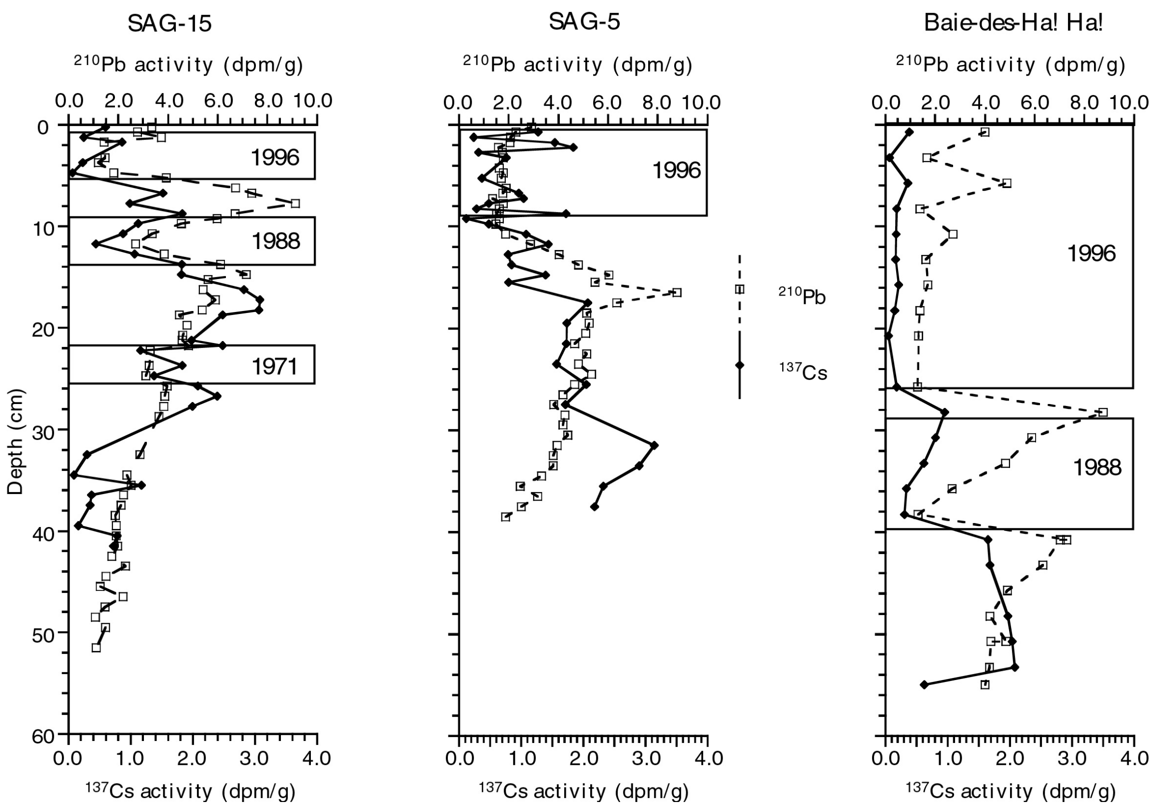

Figure 3. ^{210}Pb and ^{137}Cs activity profiles in box cores collected at sites SAG-05 and SAG-15 and in the Baie des Ha!Ha! (cf. Savard 2000). ^{210}Pb measurements were made after chemical treatment, purification and deposition on a silver disk following routine procedures at GEOTOP by alpha counting of the daughter ^{210}Po (Zhang, 2000). ^{137}Cs measurements were done directly on dried and ground sediments by gamma counting.

5. MICROPALEONTOLOGICAL TRACERS

Benthic foraminifera were analyzed in a box core collected at site SAG-30 in 1997, and in surface sediment samples collected at sites SAG-15, SAG-30 and SAG-36 in 1994, 1997, 1998 and 1999, with the aim of evaluating the impact of the 1996 flood on the benthic microfauna (Leduc et al. 2002). The analysis of the first 10 cm of the box core from SAG-30 revealed a significant decrease of *Spiroplectammina biformis* relative to *Adercotryma glomerata* (Fig. 4). Such a decline in the abundance of *S. biformis*, which is an opportunistic and tolerant species, has been associated with the reduction of industrial discharge into the Fjord since the 1970's, following implementation of new governmental regulation (Schafer et al. 1991; Leduc et al. 2002).

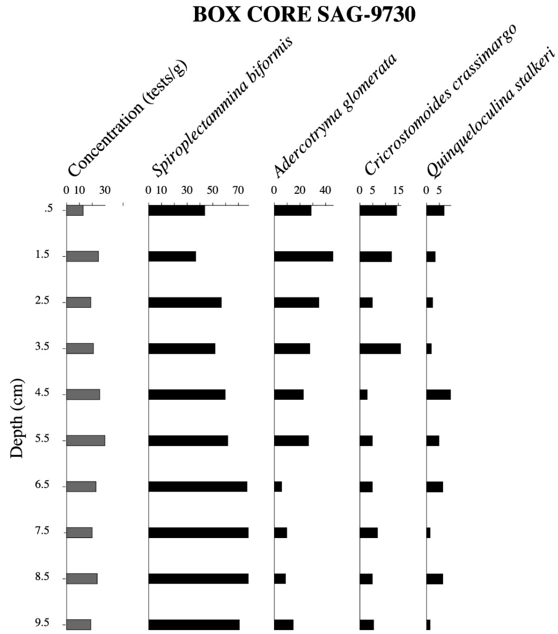

Figure 4. Concentration of benthic foraminifera and percentage of dominant species in a 1997 box core from site SAG-30 (Leduc et al. 2002).

The analysis of the surface sediment samples collected in the inner basin indicate that the 1996 flood had a major impact on foraminiferal populations. In the 1997 samples, the concentrations and species diversity are low, with dominance of the opportunistic taxon *S. biformis* (Fig. 5).

From 1998 to 1999, the concentration and the species diversity record a significant increase, and *S. biformis* is replaced by a variety of less tolerant taxa at each site (Fig. 5). This temporal evolution indicates a rapid recolonization of the sediment by benthic foraminifera and the setting of conditions suitable for a more diverse microfauna. Assuming that *S. biformi*s is indicative of polluted environments (Schafer et al 1991), its clear decline from 1997 to 1999 could be seen as an evidence for an improvement of the benthic environment after the 1996 flood.

6. CONCLUSIONS

In this paper, we have shown that numerous rapidly deposited layers (RDL) are well preserved in the Saguenay Fjord sediments since ~7200 cal BP. These RLD are easily recognizable by their physical, magnetic, sedimentological, geochemical, isotopic and micropaleontological properties. Foraminiferal analyses before and after the 1996 flood indicate that the recolonization of the sediments by the benthic foraminifera was rapid, that the assemblages are now more diversified and that the 1996 flood layer seems efficient in isolating the underlying contaminated sediments. Furthermore, the analysis of the long core reveals that only two major earthquakes were recorded in the Saguenay Fjord during the last ~4000 years, suggesting that the 1996 flood layer is probably seismically stable.

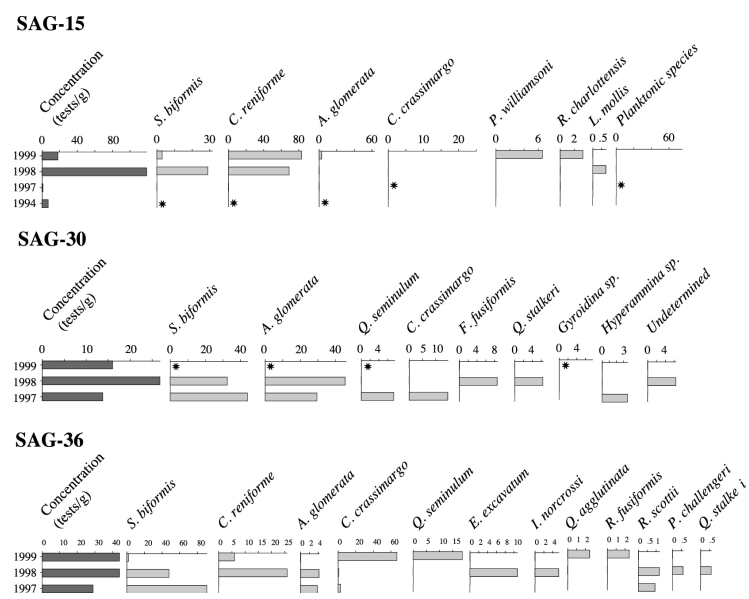

Figure 5 (previous page). Concentration of benthic foraminifera and percentage of main taxa in surface sediment samples collected at sites SAG-15, SAG-30 and SAG-36. The asterisks indicate the presence, but the sum of specimens counted was too low (<25) to calculate meaningful percentages. Data are from Leduc et al. (2002).

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