FORAMINIFERAL EVIDENCE OF SUBAQUEOUS DEBRIS FLOWS AT ODP SITE 1033 (LEG 169S), SAANICH INLET, VANCOUVER ISLAND, CANADA

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ABSTRACT

The foraminiferal faunas of 150 Holocene-latest Pleistocene samples from ODP Site 1033 (Leg 169 S), Saanich Inlet, were quantified. Sediments of this anoxic inlet in southern Vancouver Island, British Columbia consist of varved clays interbedded with slightly coarser massive layers. The 25 species of benthic foraminifera found were predominantly shallow water, calcareous forms, although a few planktic foraminifera and rare arcellaceans, as well as deeper water dysoxic benthic forms were also recorded. Most samples contained an impoverished fauna (average of 25 to 30 individuals), but massive layers contained statistically higher numbers and diversity of foraminifera than varves. A high proportion (> 50 %) of the foraminiferal fauna in the massive units were also found to be either damaged or broken. Such a high proportion of broken/damaged foraminifera along with the presence of arcellaceans in the massive layers lend credence to the hypothesis that they were transported from well oxygenated shallower, and nearshore parts of the inlet and deposited on the anoxic bottom of Saanich Inlet during subaqueous debris flows. Subaqueous debris flows in the inlet are induced by both seismic and non-siesmic events. The varved sediments also contain broken specimens of foraminifera. Although intact benthic foraminifera within the varves are typical forms capable of withstanding dysoxic conditions and appear to be autochthonous, broken specimens are mostly shallow water types requiring higher levels of oxygen. They are transported to the deeper anoxic parts of the inlet during spring freshet along with mineral rich silt. It is difficult to distinguish between seismic and non-seismic debris flows as few recorded earthquakes in the region have been conclusively linked with massive layers.

Key words: Cascadia, Foraminifera, Varves, Anoxic, Paleoseismicity, Debris Flow

INTRODUCTION

Seismic activity related to subduction of the Juan de Fuca plate under the North American plate along the Cascadia subduction zone is a major cause for concern in Washington, Oregon and southern British Columbia (Riddinough and Hyndman, 1976; Hyndman *et al.*, 1996; Clague, 1996). Geophysical models predict that very large earthquakes (magnitude (M) $\geq$ 8) are rare, occurring approximately every 500 - 600 years at the boundary between the plate margins (Rogers, 1988; Atwater *et al.*, 1995; Hyndman, 1995). Smaller but still dangerous earthquakes are more frequent and tend to be centered within the plates (Shedlock and Weaver, 1991; Rogers, 1994). These geophysical models require extensive geologic ground testing to confirm their validity. The physical effects of Holocene palaeoseismic activity in this region have been studied in terms of sea-level changes, isostasy, and records of tsunamis (Long and Shennan, 1994, 1998; Hutchinson *et al.*, 1997; Clague *et al.*, 1999). Researches in tidal wetlands, coastal salt marshes and other coastal deposits have proven especially useful in interpreting Holocene palaeoseismic events in terms of the resulting geological and geomorphological changes, and environmental damages (Mathewes and Clague, 1994; Nelson *et al.*, 1995, 1996 a, 1996 b,1998; Shennan *et al.*, 1996; Reinhardt *et al.*, 1996). The geologic evidence of Palaeoseismicity caused by submarine slides, slumps and debris flows, has also been extensively studied (Middleton and

Hampton, 1976; Saxov and Nieuwenhuis, 1980). In particular, Hill *et al.*, (1980) discussed in detail the mechanism for deposition of thin bedded subaqueous debris flow deposits and sedimentological criteria for identifying them in sediments.

Both animal and plant microfossils and their stratigraphic distribution offer valuable evidence for sudden changes in coastal environments. Microfossils (pollen, diatoms and foraminifera) have been successfully used to identify seismically induced buried wetlands soils, sheets of sand and gravel deposited by tsunamis, and sand dykes generated by liquifaction during ground shaking (Nelson *et al.*, 1996 a, b; Mathewes and Clague, 1994; Shennan *et al.*, 1996; Guilbault *et al.*, 1995, 1996; Hemphill-Harley, 1995). Clague and Bobrowski (1999) provide an excellent review of the geological (including micropaleontological) signatures of earthquakes on the west coast of Canada.

The very well preserved varved sediments of Saanich Inlet on Vancouver Island offer an excellent opportunity to assess the long term history of possible seismic activity in this region. The silty, clayey massive layers interbedded with varves have been demonstrated to be the result of subaqueous debris flows triggered possibly by past earthquakes (Bobrowsky and Clague, 1990; Blais-Stevens *et al.*, 1997). Blais-Stevens *et al.*, (1997) have estimated that the average occurrence is one debris flow every hundred years. Banks (1997) on the basis of geotechnical study of Vancouver Island offshore sediments suggested that sediments are stable at normal gravity loads

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and a minimum M > 4.5 earthquake would be required to generate observed subaqueous gravity flows found in cores. Blais-Stevens and Clague (2001) determined that not all massive layers have been formed by seismically induced debris flows though. Some flows have resulted from gravity slumping of sediments along the steep margins of the inlet. For example, bioturbation can also destabilize substrates resulting in subaqueous sediment gravity flows (Hecker, 1980).

Saanich Inlet sediments have been extensively studied by geologists, geophysists, and geochemists. Results of these studies were published in a special volume (number 174, 2002) of Marine Geology and elsewhere (Bornhold *et al.*, 1998; Patterson and Kumar, 2002). The present study uses benthic foraminifera as proxies to show that massive layers result from subaqueous debris flows.

The long return time for major earthquakes in this region requires detailed analysis of proxy data from the geological record to determine the history of seismic activity. Blais-Stevens *et al.*, (1997) utilized the distribution of allochthonous benthic foraminifera in short piston cores from Saanich Inlet to determine the provenance of massive layers. The objective of this study is to similarly use benthic foraminiferal faunas recorded in very long cores obtained from Ocean Drilling Project (ODP) Site 1033 in Saanich Inlet to determine the applicability of foraminifera as proxy indicators of the frequency and magnitude of earthquake events during the Holocene.

Foraminifera are marine protists, but also inhabit brackish water environments. They are both planktic and benthic, and inhabit environments ranging from the intertidal zone to the deep ocean floor, and from polar region to the tropics. Distribution of benthic foraminifera is facies dependent, thus they are useful in paleoenvironmental, paleoceanographic and paleoclimatic studies. Benthic foraminiferal tests are calcareous, and their strength increases with increasing size and with level of physical environmental stress (Wetmore, 1987). Since most benthic foraminifera in Saanich Inlet are smaller and inhabit low-energy environments, their tests are relatively weaker. Once they move along with sediments during subaqueous debris flows, they tend to break into pieces or get physically damaged. Since massive layers are subaqueous debris flow deposits, broken or physically damaged tests of benthic foraminifera would be expected to be present in significant numbers. This study also attempts to use the ratio of broken/damaged benthic foraminifera to intact forms as a proxy for subaqueous debris flows.

MATERIAL AND METHODS

Twelve cores (1H to 12H) of varying length were taken at ODP Site 1033 (Hole 1033B) in 238 m of water in the southern narrower part of the inlet (Fig. 1). Each core was partitioned into 1.5 m sections and numbered from the top. The lowermost

Fig.1. Map of Sanich Inlet showing location of ODP site 1033 (modified after Patterson and Kumar, 2002).

section of each core was a shorter core catcher (CC). Details of the standard ODP methods employed for coring and core handling are outlined in Bornhold and Firth *et al.* (1998) and Westbrook *et al.*, (1994).

Massive layers interbedded with varves occur only in Holocene and youngest Pleistocene sediments (11,668-12,336 ^{14}C yr BP) penetrated by cores 1H to 6H, 0 - 48.1 meters below sea floor (mbsf). Therefore, samples from below this level are not included in this study. The lithology of core sediments, ^{14}C dates and identified biofacies are given in Fig. 2. The details about ^{14}C dates of various core samples are listed in Table 1. Cores were split and analyzed for color using a Minolta spectrometer. The core was also CAT-scanned to reveal details of internal structure and composition, such as the presence of stratified and dispersed sand, ice rafted debris and subtle variations in lithology (Bornhold and Blais-Stevens, 1997).

Sub-sampling for this research was done at the Pacific Geoscience Centre (PGC), Sydney, British Columbia. The sand fraction of 150 samples from cores 1H to 6H was obtained by washing 15 cc core sediment through a 63mm sieve and drying at low temperature. The resultant sample residues were very small, usually ranging from < 0.001 g to 0.7 g (rarely ≥ 1.0 g) out of 15 cc of core processed. A few processed samples did not have any measurable sand fraction.

Table 1: ^{14}C dates of studied core at site 1033 B, obtained from Lawrence Liversmore Laboratory. Both radiocarbon years and corrected calender years are provided. Reservoir correction value applied is 801 ± 23 years (after Robinson and Thomson, 1981).

Core Section Interval (cm)	Sample	Taxon	^{14}C age (yr BP)	Calibrated ^{14}C age (yr BP)
169S-1033B-				
2H-7, 28	Shell	Bivalvia *Compsomyax subdiaphana*	2,420 ± 60	1,407-1,715
3H-5, 144	Charcoal		2,940 ± 50	2,892-3,316
5H-1, 8	Charcoal		5,430 ± 50	6,059-6,389
6H-2, 15	Shell	Bivalvia *Macoma calcarea*	8,880 ± 50	8,929-9,226
6H-2, 60	Shell	Bivalvia *Axinopsida serricata*	9,030 ± 50	9,078-9,388
6H-2, 90	Shell	Bivalvia *Axinopsida serricata*	9,150 ± 50	9,246-9,474
6H-4, 110	Shell	Bivalvia *Axinopsida serricata*	10,190 ± 70	10,304-10,879
6H-5, 135	Shell	Bivalvia *Macoma calcarea*	10,600 ± 60	10,952-11,452
6H-5, 141	Shell	Bivalvia *Macoma calcarea*	10,700 ± 50	11,003-11,643
6H-6, 13	Shell	Bivalvia *Macoma calcarea*	10,710 ± 60	11,000-11,687
6H-6, 88	Shell	Bivalvia *Macoma calcarea*	11,050 ± 60	11,668-12,336

All foraminifera in each sample were picked and transferred to slides for identification. Total number of foraminifera, total number of complete specimens, total number of broken/damaged specimens and number of specimens of various foraminiferal species were recorded for each sample (Table 2) for statistical treatment of the data. A non parametric sign test (Mendelhall and Beaver, 1994) was carried out on the foraminiferal counts to see if there was any significant difference between faunas recorded from the varves and massive layers (Table 3). Integrated Q- and R- mode cluster analysis of the 58 samples from cores 1033B and 1034B with statistically significant number of specimens and 23 benthic foraminiferal species with significant populations were used to define five biofacies (Patterson and Kumar, 2002). Fig. 2 shows the distribution of biofacies in the core 1033B.

Identification of foraminifera was primarily based in illustrations in the *Atlas of Common Benthic Foraminiferal Species from Quaternary Shelf Environments of Western Canada* (Patterson *et al.*, 1998). The foraminifera identified in this core are illustrated in Patterson and Kumar (2002).

SAANICH INLET AND ITS SEDIMENTARY RECORD

Saanich Inlet is a 26 km long and 0.4 to 7.6 km wide inlet on the southern coast of Vancouver Island. Surface sediments surrounding Saanich Inlet were deposited during the Wisconsinan glaciation and the Holocene (Blyth and Rutter, 1993; Blyth *et al.*, 1993). The inlet is a single basin separated from the oceanic waters of Haro Strait by a bedrock sill at the north end in Satellite Channel (Holland, 1980). The average depth of the inlet is 120 m and its maximum depth is 238 m. The sill at the mouth of the inlet rises to 70 m below the water surface, restricting deep-water circulation. The lower part of the water column, below 70 m, is anoxic (Bornhold *et al.*, 1998). High primary productivity in the inlet during spring and summer, sluggish estuarine circulation and the presence of abundant fresh water from Fraser River into Haro Strait, further

contribute to the development of bottom water anoxia almost year round in the inlet. The anoxia leads to an absence of most benthic fauna, thus preserving the seasonal record of deposition as fine laminae alternating between an organic-rich plankton fall and terrigenous sediments (Bornhold and Firth *et al.*, 1998). The distribution of the various modern sediment types, sedimentary environments and their associated foraminiferal biofacies were documented. These data have been invaluable in identifying the source of various foraminiferal species found in the Saanich Inlet cores.

Cores recovered from Site 1033B can be broadly divided into two sedimentary units (Fig. 2). The uppermost approximately 50 m of sediments are a laminated sequence of Holocene olive-gray diatomaceous mud overlying a pre-Holocene sequence of dense, massive to irregularly laminated glaciomarine mud (older than about 12 k yr BP) containing poorly sorted sand lenses and dropstones, as well as graded and contorted sand and silt beds (Bornhold *et al.*, 1998).

The Holocene sediments are rhythmically-laminated varves of various thickness (5-15 mm thick) as is common in coastal settings at temperate latitudes. Such laminated sediments can provide ultra-high resolution information, providing valuable data on seasonal scale processes as well as intra and inter annual variability (Kemp, 1996). The observed sequence in Saanich Inlet is related to late fall and winter, early spring, and late spring and summer deposition respectively. Unit thickness vary considerably reflecting changes in the amount and seasonal distribution of runoff in nearby watersheds, and in primary productivity (Gross *et al.*, 1963; Sancetta and Calvert, 1988; Bobrowsky and Clague, 1990; Blais-Stevens *et al.*, 1997).

Sedimentation rates for the varved sediments have been estimated at between 4 and 6 mm per year (Gucluer and Gross, 1964; Blais *et al.*, 1997). According to Bobrowski and Clague (1990), average varve thickness over the past 1,400 years has been 4 mm. Although varve thickness varies significantly, dark brown terrigenous dominated varves vary in thickness from 1

Table 2: Foraminiferal distribution in the samples. (V= varves, M= massive layers, B= breccia, MB= massaive and breccia, IL= indistinct laminae, MM= massive muds, FS= fine sand, S= sand)

Sample No.	Total number of specimens	Complete specimens	Broken specimens	Cribroelphidium microgranulosum	Cribroelphidium excavatum	Cribroelphidium halladense	Cribroelphidium foraminosum	Buccella frigida	Lobatula fletcheri	Stainforthia feylingi	Buliminella eligantissima
2H5/127-130 V	17	6	11	0	5	2	0	5	4	0	0
2H5/139-140 M	186	105	81	0	24	3	0	12	30	84	0
2H5/143-146 ?	41	24	17	0	7	2	0	8	7	10	0
2H5/146-149 ?	56	36	20	0	12	3	0	16	11	4	0
2H6/30-33 V	5	5	0	0	1	0	0	1	1	1	0
2H6/44-47 M	8	6	2	0	3	0	0	2	0	1	2
2H6/49-52 M	12	7	5	0	4	0	0	2	2	1	3
2H6/54-57 M	18	11	7	0	5	0	0	5	2	2	0
2H6/60-63 M	63	45	18	0	11	1	2	19	10	11	0
2H6/65-68 M	25	20	5	0	4	1	3	4	3	5	2
2H6/81-85 V	12	10	2	0	2	1	0	5	2	0	0
3H2/55-58 V	9	5	4	0	3	1	0	3	4	0	0
3H2/63-66 M	29	18	11	0	12	3	0	6	3	0	2
3H2/66-69 M	17	14	3	0	3	2	0	3	2	4	2
3H2/77-80 M	10	7	3	0	2	2	0	1	3	0	0
3H2/83-86 M	31	25	6	0	9	3	0	5	5	1	2
3H2/88-91 M	27	21	6	0	6	3	0	3	10	1	0
3H2/94-97 M	38	27	11	0	10	2	2	15	3	1	0
3H2/98-101 B	45	30	15	0	7	3	1	14	12	3	0
3H2/102-105 V	6	4	2	0	2	0	0	3	1	0	0
3H2/106-108 M	26	17	9	0	7	0	0	5	5	2	6
3H2/110-113 V	18	12	6	0	4	2	0	4	6	0	0
3H3/67-70 V	49	28	21	0	8	2	1	11	3	2	0
3H3/80-83 M	1	1	0	0	0	0	0	0	0	1	0
3H3/87-90 V	16	9	7	0	6	0	0	2	4	0	0
3H3/95-98 M	2	2	0	0	0	0	0	0	0	0	0
3H3/99-102 M	29	20	9	0	8	0	1	8	7	3	0
3H3/103-106 B	36	20	16	0	5	0	1	20	3	1	0
3H3/106-109 B	26	13	13	0	8	1	2	9	2	1	0
3H3/113-116 V	9	5	4	0	4	0	0	3	0	0	0
3H5/10-14 M	33	18	15	0	4	4	3	8	5	3	0
3H5/14-18 M	37	18	19	1	8	1	1	9	14	2	0
3H5/21-24 V	11	4	7	0	3	1	0	3	3	0	0
3H5/60-63 V	17	6	11	0	4	0	0	8	1	0	0
3H5/77-80 M	12	7	5	0	3	0	0	1	1	5	0
3H5/90-93 M	30	12	18	1	10	4	1	5	5	1	0
3H5/102-105 M	27	15	12	0	2	2	0	8	7	4	0
3H5/109-112	29	7	22	0	3	0	0	10	11	1	0
3H5/117-120 M	43	5	38	3	10	2	2	11	10	1	0
3H5/124-126 B	66	21	45	3	10	3	2	18	15	3	0
3H5/127-130	6	0	6	0	3	0	0	1	2	0	0
3H7/11-14 V	19	7	12	0	3	2	0	3	11	0	0
3H7/16-19 M	40	39	1	0	1	1	0	0	0	36	0
3H7/25-28 V	18	5	13	0	2	1	0	4	8	0	0
3H7/42-45 M	4	2	2	0	0	0	0	1	1	2	0
3H7/46-49 M	8	5	3	0	0	0	0	2	2	4	0
3H7/59-62 M	26	9	17	2	5	0	0	4	13	0	0
3H7/63-66 M	28	10	18	0	5	1	1	6	4	9	0
3H7/73-76 M	25	20	5	0	0	1	0	2	1	19	0
3H7/76-79 M	49	22	27	0	7	5	0	12	8	9	0
3H7/79-82 M	19	9	10	0	1	0	0	5	4	4	0
3H7/86-89 V	15	0	15	1	3	1	0	3	6	0	0
4H1/1-4 M	19	7	12	0	2	0	0	3	11	1	0
4H1/6-9 M	24	6	18	0	4	1	1	6	9	1	0
4H1/11-14 M	28	8	20	0	8	0	0	7	13	0	0
4H1/17-20 M	26	11	15	0	4	2	0	6	7	1	0
4H1/23-26 M	34	8	26	0	2	2	0	15	7	0	0
4H1/26-29 M	29	16	13	0	4	0	0	10	4	0	0
4H1/42-45 B	51	19	32	3	8	1	0	13	14	0	0
4H1/45-48 B	13	6	7	0	3	0	0	6	2	1	0
4H1/51-54 V	12	4	8	0	3	0	0	3	1	0	0
4H1/136-139 V	11	3	8	0	1	0	0	5	3	0	0
4H1/140-142 M	69	17	52	0	2	0	0	36	29	0	0
4H1/143-146 V	14	5	9	0	1	0	0	5	1	0	0
4H2/0-4 V	12	6	6	0	0	1	0	2	2	1	0
4H2/4-8 M	7	2	5	0	1	0	0	2	3	0	0
4H2/10-13 V	20	7	13	0	1	3	0	3	7	0	0
4H2/24-27 M	25	4	21	0	1	1	0	12	7	1	0
4H2/30-33 M	33	15	18	0	3	2	0	9	6	5	0
4H2/36-39 M	42	13	29	0	5	0	0	20	8	0	0
4H2/42-45 M	34	12	22	0	6	0	0	8	10	0	0
4H2/47-50 M	39	13	26	0	3	0	0	12	8	1	0
4H2/51-54 B	60	25	35	1	10	1	0	11	16	1	0
4H2/56-59 V	29	21	8	0	1	0	0	2	4	0	0
4H2/109-112 V	18	6	12	0	1	1	0	4	6	1	0
4H2/127-130 M	12	3	9	0	3	0	0	5	0	2	0
4H2/131-134 M	14	7	7	0	1	0	0	2	6	4	0
4H2/135-138 M	38	13	25	5	5	0	0	6	12	0	0
4H2/147-150 V	7	2	5	10	2	0	0	2	2	0	0

4H4/50-53 V	14	5	9	0	1	0	0	5	1	1	0
4H4/61-64 M	9	1	8	0	3	0	0	0	5	0	0
4H4/64-67 B	24	10	14	0	3	2	0	7	5	0	0
4H4/83-86 V	22	9	13	2	1	0	0	4	4	1	0
4h6/87-90 V	30	16	14	0	1	1	0	7	12	1	0
4H6/92-95 M	23	9	14	0	2	1	0	3	14	1	0
4H6/95-98 B	36	11	25	1	5	2	0	15	11	0	0
4H6/99-102 V	30	16	14	2	1	0	0	6	16	0	0
4H7/63-66 V	35	19	16	2	6	0	0	10	11	0	0
4H7/74-77 M	17	5	12	2	2	0	0	3	8	0	0
4H7/77-79 B	63	26	37	2	8	2	0	16	15	12	0
4H7/80-83 V	17	4	13	0	2	0	0	5	4	0	0
5H1/60-63 V	52	28	24	0	0	0	0	8	20	4	0
5H1/70-74 M	108	108	0	0	3	0	0	3	6	85	0
5H1/74-78 MB	25	16	9	0	0	0	0	9	6	3	0
5H1/86-89 V	20	8	12	0	0	0	0	7	7	0	0
5H2/26-29 DL	45	10	35	0	7	0	0	15	9	0	0
5H2/36-39 IL	1	1	0	0	1	0	0	0	0	0	0
5H2/43-46 IL	2	2	0	1	0	0	0	0	0	0	0
5H2/49-52 IL	2	0	2	0	1	0	0	2	0	0	0
5H2/54-57 IL	3	0	3	0	0	0	0	1	2	0	0
5H2/66-69 DL	1	1	0	0	0	0	0	0	0	0	0
5H3/88-91DL	0	0	0	0	0	0	0	0	0	0	0
5H3/93-96DL	0	0	0	0	0	0	0	0	0	0	0
5H3/104-107 DL	0	0	0	0	0	0	0	0	0	0	0
5H4/63-66 IL	1	1	0	0	0	0	0	0	0	0	0
5H4/82-85 M	0	0	0	0	0	0	0	0	0	0	0
5H4/85-88 M	3	3	0	0	0	0	0	0	0	3	0
5H4/94-97 M	52	30	22	1	2	0	0	10	7	26	0
5H4/106-109 M	51	28	23	0	0	0	0	7	6	34	0
5H4/112-115 M	22	8	14	0	1	0	0	4	1	12	0
5H4/115-118 M	63	21	42	0	6	3	0	31	12	4	0
5H4/126-129 M	28	17	11	0	1	1	0	10	3	9	0
5H4/146-149 M	44	21	23	1	2	3	0	9	17	0	0
5H5/2-5 M	560	392	168	0	135	20	5	200	135	35	0
5H5/8-11 M	1088	979	109	0	208	40	8	392	208	144	0
5H5/14-17 M	736	662	74	0	176	0	0	160	224	64	0
5H5/25-28 ID	33	30	3	0	4	0	0	10	1	12	0
5H5/58-62 V	48	48	0	0	10	2	0	12	0	18	0
5H5/64-68 M	132	110	22	0	6	0	0	24	0	102	0
5H5/68-72 MB	102	90	12	0	20	2	2	6	0	48	0
5H5/74-78 V+IL	114	113	1	0	0	0	0	30	12	48	0
5H5/109-112 DL	24	15	9	0	2	0	0	4	0	1	0
5H5/113-116 M+IL	104	64	40	0	0	0	0	24	0	32	0
5H5/126-129 IL	40	32	8	0	0	0	0	0	8	24	0
5H5/133-136 M	9	5	4	0	2	0	0	3	1	2	0
5H5/139-142 L	16	12	4	0	4	0	0	12	0	0	0
5H7/52-55 V+DL	104	64	40	0	8	0	0	24	0	16	0
5H7/57-60 M	120	112	8	0	0	0	0	32	0	56	0
5H7/67-70 IL	64	56	8	0	0	0	0	8	0	40	0
6H1/53-56 IL	40	40	0	0	0	0	0	8	0	0	0
6H1/57-60 M	152	96	56	0	40	6	0	32	0	56	0
6H1/67-70 IL	10	7	3	0	4	1	1	3	0	0	0
6H1/103-105 C	0	0	0	0	0	0	0	0	0	0	0
6H2/132-135 IL	13	7	6	0	1	0	0	3	1	0	0
6H2/145-148 M	184	64	120	0	20	0	0	92	48	12	0
6H3/9-12 M+B	20	6	14	0	4	0	0	8	1	2	0
6H3/12-15 IL	8	4	4	0	2	0	0	2	1	0	0
6H5/7-10 IL	120	96	24	0	16	0	0	24	0	40	0
6H5/11-14 M	1	1	0	0	0	0	0	0	0	0	0
6H5/16-19 M	69	48	21	0	6	3	0	9	9	27	0
6H5/24-27 IL	176	136	40	8	32	8	0	0	0	40	0
6H5/57-61 IL	180	162	18	0	6	0	0	0	0	78	0
6H5/70-73 YD	528	420	108	4	88	16	8	12	0	0	0
6H5/84-87 YD	0	0	0	0	0	0	0	0	0	0	0
6H5/100-103 YD	1	1	0	0	0	0	0	0	0	1	0
6H5/112-115 YD	0	0	0	0	0	0	0	0	0	0	0
6H5/126-129 M+YD	88	80	8	0	16	0	0	0	0	0	0
6H6/29-32 MM	104	72	32	0	0	0	0	24	0	72	0
6H6/78-81 MM	40	40	0	0	0	0	0	0	0	0	0
6H6/127-130 MM	224	192	32	0	0	0	0	16	0	208	0

Fissurina spp.	Trochammina nana	Trochammina charlottensis	Planktics stella	Nonionella pacifica	Bolivinella agglutinata	Siphonaperta	Others
0	0	0	0	0	0	0	Agglutinated sphere (? Arcellaceans) (1)
9	12	3	3	0	3	0	Islandiella helenae (3)
1	5	0	0	0	0	0	Arcellaceans (1)
3	7	0	0	0	0	0	0
0	0	0	0	1	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0

0	1	0	2	0	0	0	0
0	5	0	2	1	1	0	0
0	1	0	0	0	2	0	0
2	0	0	0	0	0	0	0
0	0		0	0	0	0	0
0	2	0	2	0	0	0	0
1	0	0	0	0	0	0	0
0	1	0	0	1	0	0	0
0	1	0	2	0	1	0	Islandiella helenae (2)
0	1	0	2	0	0	1	0
0	0	0	5	0	0	0	0
2	0	0	3	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	Arcellaceans (1)
0	0	0	2	0	0	0	0
1	0	0	17	1	1	1	Arcellaceans(1); Rosalina columbiensis (1)
0	0	0	0	0	0	0	0
2	1	0	1	0	0	0	0
0	0	0	0	0	1	0	Lagena striaticollis (1)
0	0	0	1	0	1	0	0
3	0	0	0	0	2	1	0
3	0	0	0	0	0	0	0
1	0	0	0	0	1	0	0
1	1	0	1	0	2	0	Miliammina fusca (1)
0	1	0	0	0	0	0	0
0	1	0	0	0	0	0	0
2	2	0	0	0	0	0	0
0	0	0	1	0	0	0	Arcellaceans (1)
0	2	0	1	0	0	0	0
2	2	0	0	0	0	0	0
0	0	0	2	1	1	0	0
o	0	0	1	1	1	0	Lagena striaticollis(1);
2	5	0	0	1	0	0	Miliammina fusca (1); Rosalina columbiensis (3)
0	0	0	0	0	0	0	0
0	1	0	0	0	0	0	0
1	1	0	0	0	0	0	0
1	1	0	1	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	2	0	0	0	0	0	0
2	0	0	0	0	0	0	Arcellaceans (1)
0	2	0	0	0	0	0	0
1	3	0	1	0	0	0	Miliammina fusca (1); Arcellaceans (2)
3	2	0	0	0	0	0	0
0	1	0	0	0	0	0	0
0	1	0	0	0	0	0	0
1	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0
1	1	0	4	0	0	0	0
0	0	0	7	0	0	0	Miliammina fusca (1)
1	2	0	8	0	0	0	0
0	4	1	7	0	0	0	0
0	0	0	1	0	0	0	0
1	0		3	0	0	0	Miliammina fusca (1)
0	2	0	0	0	0	0	Buliminella sp. (1)
0	0	0	2	0	0	0	0
1	3	0	3	0	0	0	0
2	3	0	1	0	0	0	0
0	1	0	0	0	0	0	0
0	4	0	2	0	0	0	0
0	1	0	2	0	0	0	0
0	2	0	6	0	0	0	0
0	2	0	5	1	0	0	0
0	5	0	3	1	0	0	0
1	4	0	8	1	0	0	0
0	1	0	19	0	0	0	0
1	1	0	20	0	0	0	0
1	1	0	3	0	0	0	0
0	0	0	1	1	0	0	0
0	1	0	0	0	0	0	0
0	1	0	8	0	0	0	Arcellaceans (1);
0	0	0	0	0	0	0	0
1	1	0	4	0	0	0	0
0	0	0	0	0	0	0	Islandiella helenae (1)
0	3	0	2	1	0	0	Rosalina columbiensis (1)
0	2	0	8	0	0	0	0
0	2	0	6	0	0	0	0
0	1	0	1	0	0	0	0
0	1	0	1	0	0	0	0
0	0	0	5	0	0	0	0
1	3	0	5	0	0	0	0
0	0	0	2	0	0	0	0
5	0	0	8	0	0	0	0
1	0	0	3	0	0	0	Arcellaceans (1); Rosalina columbiensis (1)
0	0	0	8	0	0	0	Agglutinated spheres (12)

3	0	0	0	0	0	0	Agglutinated spheres (8)
1	2	0	4	0	0	0	0
0	0	0	6	0	0	0	0
0	2	0	12	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	7	0	0	0	4	0	Miliammina fusca (1);
0	0	0	0	0	0	0	Miliammina fusca (4)
1	0	0	0	0	2	0	0
3	0	0	0	1	0	0	Miliammina fusca (1), Islandiella helenae (2)
0	0	0	0	2	1	0	Islandiella helenae (2)
1	0	0	0	0	1	0	Miliammina fusca (1); Islandiella helenae (2);
0	0	0	0	5	0	5	Euuvigerina juncea(5);Cassidulina reniforme(5);Angulogerina sp. (5);Buliminella (5)
8	8	0	16	16	0	8	Buliminella sp. (32)
0	0	0	48	16	0	0	Homalohedra sp.(16);Buliminella sp. (16); Quinqueloculina sp. (16)
0	0	0	4	0	2	0	0
0	0	0	6	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	18	0	0	0	Euuvigerina ? sp. (6)
0	6	0	18	0	0	0	0
0	0	0	17	0	0	0	0
0	0	0	16	32	0	0	0
0	0	0	8	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	56	0	0	0	0
8	0	0	16	8	0	0	0
0	0	0	16	0	0	0	0
0	0	0	24	0	8	0	0
0	0	0	0	8	8	0	0
0	0	0	0	0	0	0	Favulina melo (1)
0	0	0	0	0	0	0	0
0	0	0	8	0	0	0	0
4	4	0	0	0	0	0	? Buliminella sp.(4)
1	1	0	3	0	0	0	0
0	0	0	3	0	0	0	0
0	8	0	0	24	0	8	0
1	0	0	0	0	0	0	0
3	0	0	3	0	0	0	? Buliminella sp. (9)
0	8	0	0	80	0	0	0
0	0	0	0	96	0	0	0
4	0	0	0	300	0	36	Nonionella digitata (60)
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	72	0	0	0
0	0	0	0	8	0	0	0
0	0	0	0	40	0	0	0
0	0	0	0	0	0		0

to 4.5 mm and comprise 1-3 separate laminae. The paler, light olive-green biogenic rich varves vary in thickness from 2 to 20 mm and may contain up to 16 individual laminae (Dean *et al.*, 2001).

Inter-annual differences in the number of sub-laminae result from the presence or the absence of (1) distinct silt layers, (2) pelletised/diatom "hash" layers, (3) intact, un-pelletised diatom assemblages, (4) monospecific diatom blooms, and (5) exotic diatoms, such as *Thalassiothrix* mats, indicating ocean input (Dean *et al.*, 2001). SEM sediment fabric studies also provide some evidence of micro-benthic bioturbation, probably due to episodes of bottom water renewal resulting from the flow of oxygenated, higher salinity, oceanic water over the sill (Dean *et al.*, 2001).

The laminated sediments are interrupted by thin (< 1-3 mm), light gray clay laminae and thicker massive intervals, a few cm to few tens of cm thick. The clay laminae appear between winter and summer layers and were deposited during abnormally high spring floods from the Cowichan River. They are more abundant in the northern part of the inlet than southern part, providing further corroboration that the major source of clastic sediments into the inlet is from north and northwest (Bornhold *et al.*, 1998).

During the early Holocene, after initiation of diatomaceous mud deposition, there was a brief period of rapid deposition of gray terrigenous clays with sharp lower contacts. The gray

clay bed occurs as a massive layer with a sharp base and grades upward into diatomaceous mud in core 6H-5 between 67 and 123 cm. There is palynological and silicoflagellate evidence suggesting a major terrestrially derived input of nutrients and fresh water during its deposition (Melissa McQuoid, personal communication, 1999). This interval has been interpreted to represent Fraser River plume into Saanich Inlet (Blais-Stevens *et al.*, 2001).

According to Bornhold *et al.*, (1998) the massive units are considered to result from episodic debris flows caused by slope failure along the inlet sidewalls. There are more massive layers in the southern part of the inlet (44 at Site 1033) than northern part (22 at Site 1034), where walls are less steep. As might be intuitively inferred, this difference in failure rate is due to the lower stability of fine grained sediments on the steeper slopes.

Massive layers result from subaqueous debris flows, and they can be triggered either by seismic events or by gravity slope failure. It is difficult to conclude that all massive layers are seismically generated. Blais-Stevens and Clague (2001) proposed that extensive debris flow deposits emplaced by single large failure or many smaller coincident failures, probably have a seismic origin. On the basis of various chronological controls like radiocarbon dates, varve counts, and the first appearance of the diatom *Rhizosolenia* in 1940 in Saanich Inlet (McQuoid and Hobson, 1997), debris flow deposits were linked to the known earthquakes. For example, massive layers were observed in Saanich Inlet that can be linked to the AD 1946 large crustal earthquake of central Vancouver Island (magnitude 7.3) and AD 1700 earthquake of Cascadia subduction zone (magnitude 8-9) off the coast of Vancouver Island, Washington and Oregon. Other massive layers in cores 1033 and 1034 were dated to about AD 1600, 1500, 1250, 1150, 850, 800, 450, 350, 180 and BC 200, 220, 500, 900 and 1050 were probably also related to earthquakes (Blais-Stevens and Clague, 2001).

A diatom marker horizon dated to 1940 AD provides chronological control for the youngest massive layer. A white volcanic ash layer (1.5-2.0 cm thick) occurs at 37 m depth, and is dated at 7,645 yr BP. This ash layer was deposited following the eruption of Mount Mazama (Crater Lake, Oregon). The lowermost part of this sequence is not well laminated and contains a rich bivalve fauna suggesting a 2-3 k yr period when during the earliest Holocene well oxygenated waters characterized the inlet at all water depths (Bornhold *et al.*,1998; Blais-Stevens *et al.*, 2001). Foraminifera occur in most of the samples from cores 2H to 7H, but the samples below this level are usually barren. Only 9 of 86 samples examined from cores 8H to 12 H contain foraminifera.

RESULTS

One hundred and fifty samples from the upper 48.1 mbsf (cores 1H to 6H) were examined from Site 1033B, of which 68 samples were from massive layers, and 31 from varves. The rest were from distinct or indistinct laminae, breccia or various combinations of different kinds of layers (Table 2). Foraminiferal tests occur both in varves and the massive layers, with typically impoverished foraminiferal assemblages found throughout (Kumar and Patterson, 1998, 1999, 2002). On average, only between 25 to 30 specimens per 15 cc were observed in these samples, and a few samples were barren. However, some samples in cores 5H and 6H contained significantly higher numbers of foraminifera (100 - 500 individuals per 15 cc and rarely even higher, see Table 2). The foraminiferal taxa were predominantly benthic, calcareous, shallow water forms. Planktic foraminifera were usually rare, although in a few varves and laminated samples from cores 3H-3, 4H-2, 5H-2, 5H-5 and 5H-7 they occur in significant numbers (10-50 % of the sample assemblage). Rare specimens of arcellaceans (freshwater testate rhizopods) were also observed, but only in the massive layers.

To determine whether there was a statistical difference between the faunas found in the varves and massive layers, a nonparametric statistical sign test (Mendenhall and Beaver, 1994) was conducted on the mean values of total number of foraminifera found in the massive and varved layers (Table 3). The difference between the foraminiferal populations in the massive and varved layers is significant, $p < 0.05$ (calculated value of $p = 0.0352$), with foraminifera being more abundant and diverse in the massive layers than the varves (Figure 3). Species diversity observed in these samples (both massive and varved sediments) was also low, with most samples containing only 5 to 10 species.

A large proportion (> 50 %) of the observed foraminiferal specimens in both massive and varved sediments were damaged or broken (Table 2). In some samples observed from the massive layers all foraminiferal specimens were broken. A few varved sediment samples were dominated by either planktic foraminifera or unbroken specimens of the benthic foraminiferal species *Stainforthia feylingi.*

The most common species of foraminifera observed were *Cribroelphidium excavatum, C. halladense, Lobatula fletcheri, Buccella frigida, B. tenerrima, Nonionella stella and Stainforthia feylingi.* Other less common and rarer species were *Cribroelphidium microgranulosum, C. foraminosum, Homalohedra guntheri, Lagena striatocollis, Bolivinellina pacifica, Fissurina copiosa, F. lucida, Trochammina charlottensis, T. nana, Siphonaperta stalkeri, Lagena striaticollis, Miliammina fusca, Buliminella elegantissima, Nonionella digitata, Astrononion galloway, Rosalina columbiensis,* and *Hyalinonetrion clavatum.* Most of these species are shallow water forms and characterize well oxygenated environments, with the exception of some of the bolivinid forms and *Stainforthia feylingi* which are known to

Table 3: Mean of total number of foraminifera in massive layers and varves

Core No.	Depth (m)	Mean of Total Number of Forams (Massive Beds / Varves)
2H5	6.6-8.1	186 / 17
2H6	8.1-9.6	25 / 10.5
3H2	11.6-13.1	25.42 / 11
3H3	13.1-14.6	18.8 / 24.66
3H5	16.1-17.6	34.62 / 11.33
3H7	19.1-19.6	24.87 / 17.33
4H1	19.6-21.1	31.44 / 12.33
4H2	21.1-22.6	30.8 / 17.2
4H4	24.1-25.6	16.5 / 18
4H6	27.1-28.6	29.5 / 30
4H7	28.6-29.1	40 / 26
5H1	29.1-30.6	66.5 / 36
5H2-5H4	30.6-35.1	32.87 / 5.5
5H5	35.1-36.6	390.14 / 45.83
5H7-6H3	38.1-43.1	119 / 39.83

inhabit dysoxic and suboxic environments on the British Columbia shelf (Patterson *et al.*, 2000).

DISCUSSION

Foraminiferal Assemblages

Patterson and Kumar (2002) defined five benthic foraminiferal biofacies that characterize the late Pleistocene to Recent succession at ODP Site 1033B (Fig. 2). These biofacies document three paleoceanographic phases of this inlet. During the earliest phase (latest Pleistocene – earliest Holocene) gray clay, silt and sand layers were deposited, and the inlet was oceanographically controlled by the influence of cold, low-salinity water associated with deglaciation as indicated by the presence of *Nonionella stella* (Biofacies 3), *Islandiella norcrossi* (Biofacies 4), and *Cribroelphidium excavatum* (Biofacies 5). Early Holocene sediments are olive-gray diatomaceous mud characterized by *Stainforthia feylingi* (Biofacies 2) and represent the presence of low oxic to suboxic bottom conditions in the inlet. Finely-laminated sediments characterize mid Holocene to Recent sediments indicating the development of anoxic conditions at the bottom of the inlet. A *Lobatula fletcheri – Buccella frigida* dominated biofacies characterizing this section is allochthonous and was derived by down-slope transport from shallower, oxygenated regions of Saanich Inlet.

The foraminiferal composition within varves and massive layers does not vary considerably. and correlates well with the *Lobatula fletcheri* assemblage described from modern shallower well oxygenated regions of Saanich Inlet by Blais-Stevens and Patterson (1998). This assemblage is characterized by a calcareous fauna, and always contains *Lobatula fletcheri*. This assemblage was subdivided into the *Stainforthia feylingi*
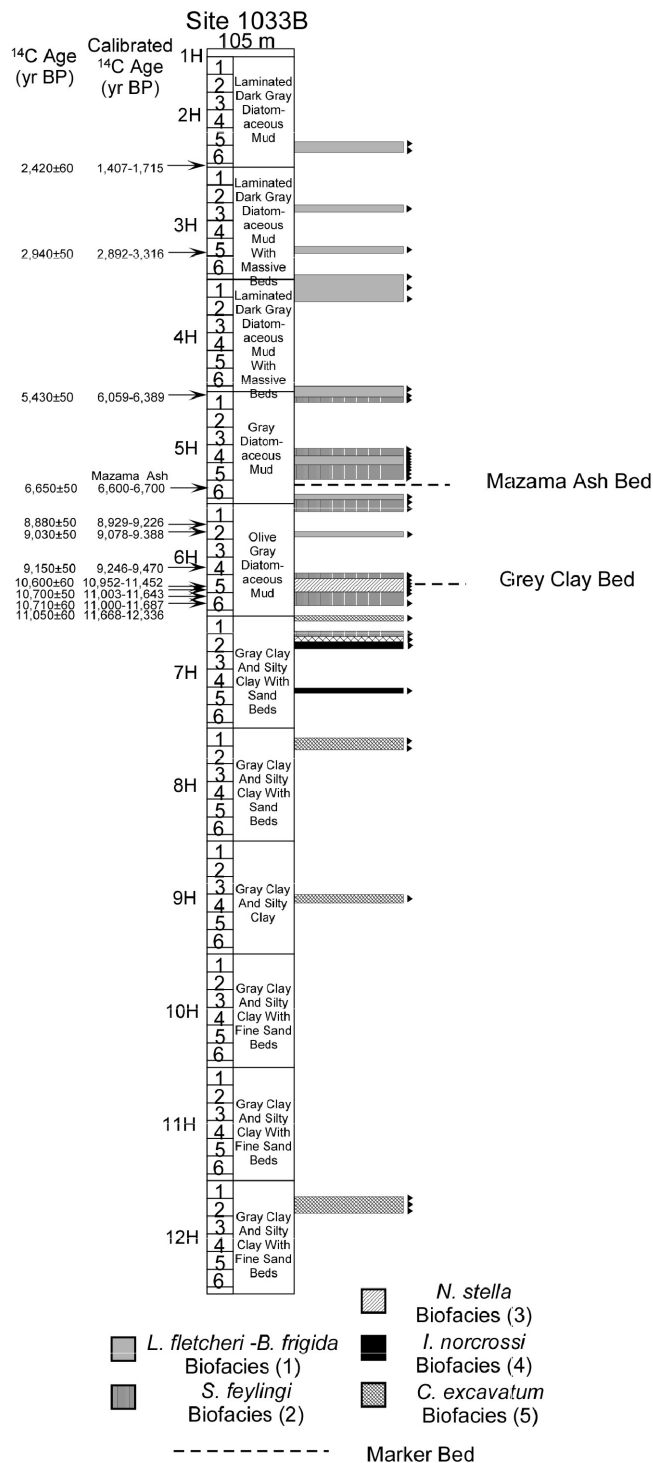
Fig. 2. Late Quaternary lithology, chronology and foraminiferal biofacies for cores from site 1033B (modified after Patterson and Kumar, 2002).

and *Buccella frigida* sub-assemblages. The *Stainforthia feylingi* sub-assemblage occurs in deep water, low oxygen environment (basin trough) whereas the *Buccella frigida* sub-assemblage characterizes shallow water (< 20 m) normal marine environments (bays), and has a patchy distribution probably due to vagaries of water circulation in this restricted basin. At depths of 20-50 m, *Buccella frigida* and *Stainforthia feylingi* occur in approximately equal abundance (Blais-Stevens and
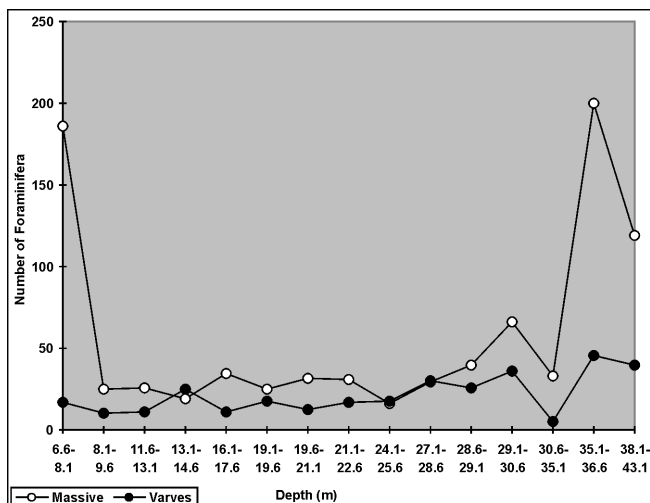
Fig. 3 Abundance of foraminifera in massive layers and varves.

Patterson, 1998). Other important taxa identified by Blais-Stevens and Patterson (1998) and found in significant numbers in core 1033B include *Cribroelphidium* spp. and *Miliammina fusca. Cribroelphidium* spp. dominate modern assemblages in the inlet at depths of < 5 m. In addition, dissolved *Cribroelphidium* spp. tests, identified by their linings, are found in most deeper water samples (> 5 m). These linings become more abundant with increasing depth and are thus a significant component of deep water assemblages. *Miliammina fusca* characterizes brackish waters with salinities < 20 ‰ dominates agglutinated foraminiferal assemblages of shallower bays and areas of fresh water discharge.

Foraminiferal composition of the samples from core 1033B indicate that sediments of the massive layers were derived from diverse and varied environments ranging from nearshore, shallow, well oxygenated, marine and/or brackish waters to deeper water environments low in dissolved oxygen. For example, the occurrence of *Buccella frigida* and *Stainforthia feylingi* together in several samples indicates that they were derived from deeper waters. Evidence of slumps derived from shoreline sediments is indicated by the presence of *Miliammina fusca* and fresh or brackish water arcellaceans (centropyxids, difflugids and agglutinated spheres). These observations further support the view that massive layers for the most part represent subaqueous debris flows.

In this study, foraminifera were consistently observed both in massive and varved layers from core 1033B (Table 2). This is in sharp contrast to the results of Blais *et al.*, (1997) who observed foraminifera only in the massive layers of short piston cores from Saanich Inlet. This discrepancy is difficult to explain. However, the number of foraminiferal specimens found in samples from sections 2H-5, 2H-6 and 3H-2 (6.6 - 13.1 m) are particularly meager, and correspond with the interval examined in the previous study. As the lateral distribution of these low abundance benthic foraminiferal populations in these varves is undoubtedly very uneven, the results of the two studies are probably not as incompatible as it seems. As indicated by the sign test results, there are statistically higher numbers of foraminifera found in the massive layers indicating that the hypothesis that these massive units are derived by subaqueous debris flows remains valid.

Specimen Damage

A large proportion of foraminiferal specimens were observed to be either broken or otherwise damaged in many samples. As mentioned earlier, foraminiferal test strength increases with size and with the level of physical environmental stress (Wetmore, 1987). Species living in coarse unconsolidated sediment typically have stronger tests than similarly sized individuals from low-energy habitats. These observations suggest a possible explanation for the high proportion of damaged foraminiferal specimens in these samples. Since most living foraminiferal species inhabit low-energy environments in this inlet (Blais and Patterson, 1998), their tests are relatively thin walled. During subaqueous sedimentary flows, tests and coarse sediment particles collide with each other, resulting in significant breakage of tests. This provides an explanation for the high proportion of damaged specimens in the massive layers.

Damaged specimens were also observed in the varves. The dark silt and clay layers within varves are terrigenous in origin and deposited during fall and spring freshets. This terrigenous sediment is derived from the Cowichan River to the north, Fraser River freshet, Goldstream River in the south and the Fraser River. The broken tests in the varved layers result from the transport of these weaker shelled tests from shallower depths to the bottom of the inlet during fall and spring freshet.

Oxygen as a Limiting Factor

Some species, notably *Stainforthia feylingi, Nonionella stella,* and *Bolivinellina pacifica* were usually observed intact in the varves (Table 2). These species are known to inhabit dysoxic, deeper water, benthic environments in Santa Barbara basin off southern California and Effingham Inlet, Vancouver Island. (Douglas,1981; Douglas and Heitman, 1979; Bernhard *et al.*, 1997; Patterson *et al.*, 2000). *Stainforthia feylingi,* common in Arctic to cold boreal environments (Knudsen and Seidenkrantz, 1994), also characterizes low oxygen environments (Alve, 1990) and in Saanich Inlet it is found abundantly in water depths > 50 m (Blais-Stevens and Patterson, 1998). It has been demonstrated that meiofaunal taxa are less affected by hypoxia than macro and megafauna, and among the meiobenthos hard shelled foraminifera are most resistant to prolonged anoxia (Moodley *et al.*, 1997). These foraminifera thus provide a valuable tool for assessing marine paleo-oxygen conditions (Kaiho, 1994; Sengupta *et al.*, 1996; Bernhard *et al.*, 1997, Patterson *et al.*, 2000).

Measured dissolved oxygen levels in the deeper waters in Saanich Inlet generally range from 0.0 mL/L at the bottom to 0.5 mL/L between the 100 - 150 m depth (Herlinveaux, 1962). Although, oxygen concentrations at the bottom of the basin increase to 0.5 mL/L in late summer when deeper parts of the basin are flushed (Herlinveaux, 1962; Blais-Stevens and Patterson, 1998). More comprehensive data (unpublished) on the monthly dissolved oxygen levels in Saanich Inlet during 1953 to 1996 by D. Stucchi, (Fig. 3 in Barnhold and Firth *et al.*, 1997) indicate that dissolved oxygen concentration at the bottom of the inlet ranges between 0.0 to only 0.2 mL/L and not 0.5 mL/L as observed by Harlinveaux, 1962). These data clearly indicate that the bottom of this inlet is not absolutely anoxic.

Kaiho (1994) developed a calcareous benthic foraminiferal dissolved-oxygen index. The five oxygenation levels demarcated are; "high oxic", "low oxic", "sub oxic", "dysoxic" and "anoxic" for oxygen levels of 3 - 6, 1.5 - 3, 0.3 - 1.5, 0.1 - 0.3, 0 - 0.1 mL/L respectively. Thus bottom waters in the Saanich Inlet could be classified as "dysoxic" to "anoxic" and specimens of *Stainforthia feylingi, Nonionella stella*, and *Bolivinellina pacifica* found intact in the varves (Table 2) are no exception, but prove that these species of benthic foraminifera are capable of inhabiting very low oxygen environments.

Paleoseismic Events

Initially it was not clear whether the massive beds were products of in situ liquefaction of varves, oxygenation of bottom waters and resultant bioturbation of sediments, or sediment gravity flows (Bobrowski and Clague, 1990). Particle-size data indicate that many massive beds are coarser than the bounding varves, supporting an allogenic origin (Bobrowski and Clague, 1990; Blais-Stevens and Patterson,1997). Blais-Stevens and Patterson (1997) gave the following reasons for a gravity flow origin of massive beds, (1) basal contacts of massive beds are sharp, and some are clearly erosional, (2) one massive bed has a gravelly base that truncates underlying varves, (3) some massive beds contain varve intraclasts, (4) a zone of brecciated varves marks the base of many massive beds, and (5) most massive beds contain benthic foraminifera, which implies that the sediment was transported downslope from above the anoxic zone (< 150 m depth). The massive beds are relatively thin (maximum thickness 110 cm) and ascribed to localized submarine sediment gravity flows, rather than large inlet-wide turbidity currents because (1) none of the beds exhibit sedimentary structures and textures typical of a turbidite, (2) there is no normal or inverse grading , (3) about half the beds contain a basal zone of brecciated varves, which were probably formed by shearing at the base of debris flow, and (4) varve intraclasts show no apparent fabric (Blais-Stevens and Patterson,1997).

There are two possible causes for the sediment flows, (1) as sediments build up on submarine slopes, they may exceed the critical angle of repose and slide or flow into deeper water, and (2) sediments may fail when shaken during earthquakes, which would depend on the amount of sediment on the walls of the inlet, the strength of the sediments, the acceleration and period of seismic waves, and the duration of shaking Blais-Stevens and Patterson,1997).

CONCLUSIONS

Benthic foraminifera are useful in distinguishing sediments of massive layers which originated by subaqueous sediment flows from annually deposited varved layers in an anoxic basin. The two distinguishing characters are: (1) massive layers contain larger numbers and relatively higher diversity of benthic foraminifera than varves, and (2) varves contain intact, autochthonous specimens of deeper water dysoxic foraminiferal species in addition to some allochthonous forms, whereas massive layers contain only allochthonous foraminiferal fauna derived from different environments of the inlet.

The foraminiferal fauna of ODP core 1033B was impoverished with low absolute numbers and species diversity in most samples. Most observed species were derived from shallow, well oxygenated coastal environments although in situ species occurring in the deeper lower oxygen environments were also found.

A large proportion of the foraminiferal specimens were either broken or damaged. This is mainly due to collision of thin walled tests with sediment particles during subaqueous sediment flows. Transport of these forms from shallower environments to the deeper parts of the inlet during spring freshets also causes breakage.

Occurrence of autochthnous intact specimens of *Stainforthia feylingia*, *Nonionella stella*, and *Bolivina pacifica* in the varves deposited in "dysoxic" to "anoxic" environments indicate that these species of benthic foraminifera are capable of inhabiting even in very low oxygen environments.

ACKNOWLEDGMENTS

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