J. Mar. Biol. Ass. U.K. (2003), **83**, 889–896
Printed in the United Kingdom

Influences of underwater bottom topography and geomorphology on minke whale (*Balaenoptera acutorostrata*) distribution in the Mingan Islands (Canada)

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Minke whale (*Balaenoptera acutorostrata*) distribution was derived from a 12 year observation programme in the Mingan Islands (Canada) and related to three geological features of the sea-floor: maximum depth, topography and geomorphology. Minke whale distribution was not uniform nor random in relation to maximum depth and topography, however, no evident trend was found. The most *prominent* factor was the presence of underwater sand dunes, where significantly more minke whales were observed than on any other bottom types. Because sand dunes are the favoured habitat of the minke whale major prey in the study area, an indirect link between minke whale distribution, geomorphology and substrate type is suggested.

INTRODUCTION

Marine habitats are heterogeneous over different spatial scales leading to non-random distribution of their inhabitants. Whale distribution is often, if not always, patchy on feeding grounds (Stern, 1999). Several studies demonstrated that whale concentrations were related to prey distribution (Whitehead & Carscadden, 1985; Murison & Gaskin, 1989; Payne et al., 1990), however, the effect of physical and geological features on cetacean distribution were seldom documented. In order to evaluate the influence of underwater topography on the distribution of dolphins (*Delphinus* sp.), Hui (1979) created an index of bottom relief (contour index). Hui (1979) carried out his study off the Pacific coast of Baja California (up to 200 km offshore at depths ranging from 2 to 2000 m) and observed that dolphins were mainly distributed in areas characterized by pronounced relief (Hui, 1979). Hui's index was later used to assess the influence of topography on the distribution of other cetacean species (Jaquet & Whitehead, 1996; Woodley & Gaskin, 1996). Woodley & Gaskin (1996) studied characteristics of right and finback whale habitat in the Bay of Fundy. They observed that uniform underwater topography, currents and water stratification influenced copepod density and hence the presence of right whales, but that finback whales tended to aggregate where the bottom topography was heterogeneous and the waters well mixed.

Ocean floor geomorphology is determined by structural geology, topography, sediment type, and hydrodynamic conditions. Because geomorphology is an integral part of the habitat and has a direct impact on prey distribution, it affects whales when foraging for prey. In fact, geomorphology and sediment type are determining factors in the presence of many benthic or nectobenthic minke whale (*Balaenoptera acutorostrata* Lacépède) prey such as sand lance (*Ammodytes americanus*, Scott & Scott, 1988) and herring (*Hareng harengus*, Maravelias, 1999), as well as pelagic fish during certain periods of their life cycle (e.g. spawning capelin, *Mallotus villosus*, on beaches, Parent & Brunel, 1976). Lynas & Sylvestre (1988) studied minke whale feeding behaviour in the St Lawrence Estuary and suggested that minke whales use currents, sometimes modulated by bottom topography, when feeding. In addition, Nordøy & Blix (1992) suggested that minke whales feed upon benthic prey (e.g. herring) directly on the bottom. Although the potential importance of geomorphology as a characteristic of whale habitat was mentioned by Smith & Gaskin (1983), such a study has never been attempted.

North Atlantic minke whales migrate north every summer to feeding grounds. They are commonly seen in the waters surrounding the Mingan Islands (Canada) from May to November. Data drawn from the Mingan Island Cetacean Study (MICS) database (1988–1999) revealed that minke whale distribution is patchy in this area (M.-J. Naud & R. Sears, unpublished data). The archipelago possesses highly heterogeneous bottom topography and geomorphology including cuestas, canyon, dunes systems, rock shelves, as well as deltaic and prodeltaic regions. The aim of this study was to assess the influence of maximum depth, bottom topography and geomorphology on small-scale (450 km^2) distribution of minke whales, around the Mingan Islands.

MATERIALS AND METHODS

Study area

Data were collected in the Mingan Islands in the Gulf of St Lawrence, between 64°37′30″W and 63°54′45″W (Figure 1). The southern edge of the study area reached 50°11′00″N, while its northern limit was defined by the mainland coast (Figure 2). The site is composed of a

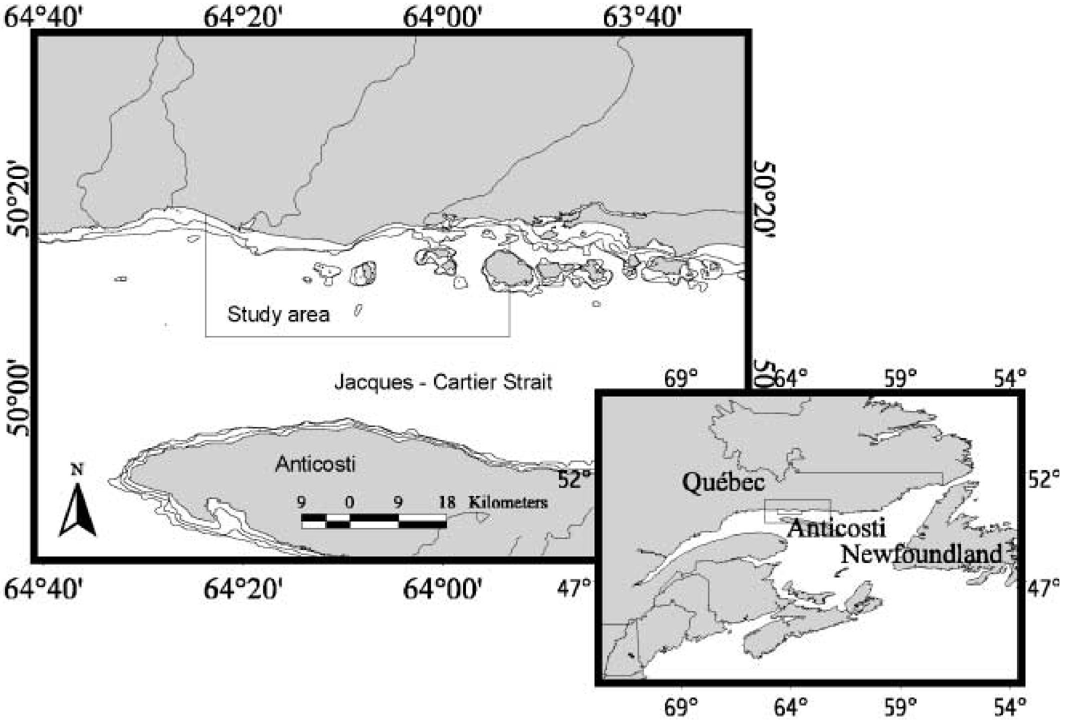

Figure 1. Location of the study area in the Gulf of St Lawrence, Canada.

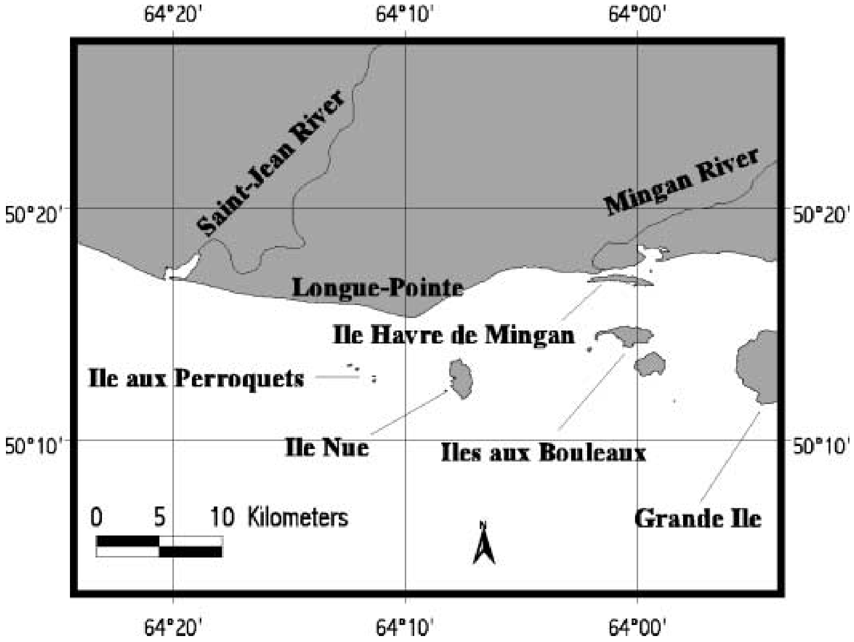

Figure 2. Detailed map of the western Mingan Islands.

series of calcareous sub-marine cuestas (cliffs, 80 to 114 m high) from the northern Ordovician formation of the Lower St Lawrence. Cuestas are oriented east–west, and are cut by a series of valleys perpendicular to the shore in north–south direction. The valleys represent the prolongation of actual rivers drainage basin during a low stand period (Desrochers & James, 1988). The three main valleys possess a mean length of 10 km, width of 2.8 km and depth of 100 m. The cuestas' back is formed by a bedrock outcrop partially covered by erosion lag associated with shell fraction. Glacial erosion of ancient deposits provided sediment for the formation of the sandy Saint-Jean River pro-delta and Mingan River delta. A continuation of these formations penetrates into the three valleys and covers the bottom with fine sediment (Long et al., 1981). Hydrodynamic, tidal and long-shore current impacts the area by transporting the sediments. Tides (micro-tidal to meso-tidal) flow from the east through the islands and are channelled out, creating currents, which sometimes reach a speed of 1 m s^{-1}. The main sediment drift is from west to east and is directly related to the dominant west-south-west summer winds. Saint-Jean

River pro-delta sediments are eroded by wave action, transported along the shoreline and create a large sub-marine dune field (Reid, 1987). In contrast, sand migrating from the Mingan River is transported perpendicular to the shoreline and is blocked to the south by the first cuestas (Laroche, 1983). The varying geomorphology found in the archipelago differs in its topography, depth, and substrate, and form habitats suitable for many minke whale (*Balaenoptera acutorostrata*) prey.

Whale observation method

In order to achieve our objectives, data representing 12 years of observations were drawn from the MICS database. Sighting data were collected between 1988 and 1999 from June to October during daylight hours. There was little variation in observation methods during those 12 years. In general, whale observations were made at sea from one to five rigid hulled inflatable boats. There were at least two observers per boat, which travelled at an average velocity of $7.7\,\mathrm{m\,s^{-1}}$ (15 knots). Regular stops were made to visually and acoustically search for whales. Boat tracks were determined each morning, according to wind direction and speed, and based on previous days sightings of large whales located outside the area considered in the present study. When two or more boats were involved, they predominantly followed a parallel track separated by 1.9 to 5.6 km (one to three nautical miles), depending on visibility. Total counts and positions of sightings were checked to avoid recounts. From 1988 to 1990, observers carried out an hour of observation from the lighthouse located on Perroquets Island each day. In August of 1998, a single dedicated boat with two observers carried out a line transect survey. The transect lines covered the study area in a north–south orientation 3.5 km apart. The transect study sighting rates were tested against the results from previous years and because no significant differences were found (*t*-test, $P>0.05$), the two data sets were combined.

Positions were taken using 'Global Positioning System' (GPS) or by triangulation using compass bearings of prominent landmarks. Fieldwork was carried out in wind speeds of $10.3\,\mathrm{m\,s^{-1}}$ (20 knots) or less and sea state of zero to four (but mostly below three) on the Beaufort scale. The survey effort was determined by calculating the time spent in the study area each day. Because daily effort was concentrated on offshore distribution of large whales (including minke), most boat tracks only passed through the present study area, with relatively less observation time within the islands. However, each day the track line varied enough through the study area as to afford wide coverage in the vicinity of the islands. Effort (hours searched per day) was plotted against the relative minke whale density (sightings/hour searched). The regression slope, which was not significantly different from zero ($P=0.125$), demonstrates randomness of distribution of effort in relation to minke whale density.

Sources of geological data

Part of the geological data used for this study was collected by the Institut National de Recherche Scientifique (INRS)-Océanologie during a study carried out in 1980 (Long et al., 1981). Sonar, seismic, and sediment sampling were used to create bathymetric, geomorphological and sediment maps of the area. Bathymetric and geomorphological data reported in several MSc theses (Université du Québec à Rimouski, Rimouski, Canada) were also used for the present study.

Data analysis

A rectangular grid (35×13 squares), where each square represented $1\,\mathrm{km}^2$ (using UTM—Universal Transverse Mercator) was overlaid on bathymetric and geomorphologic maps. Two quantitative indices (maximum depth 'M' and topography or contour index 'CI'), and one qualitative index (geomorphology 'G') were defined, and a value or category was given to each square of the grid. Maximum depth was estimated from isobaths found on bathymetric maps. The contour index (Hui, 1979) reflects the intensity of sub-marine relief and is defined as follows:

$$\mathrm{CI} = 100^{*}((\mathrm{M}-\mathrm{m})/\mathrm{M}) \qquad (1)$$

where M = maximum water depth in metres below sea level (mbsl) and m = minimum depth in metres (mbsl). A high CI value indicates a pronounced bottom relief while CI value of zero indicated a flat bottom. Both M and CI were divided in classes of 20 m as follow: M in seven classes (0–$20\leqslant$; 20–$40\leqslant$; >40–$60\leqslant$; >60–$80\leqslant$; >80–$100\leqslant$; >100–$120\leqslant$; >120–$140\leqslant$) and CI in five classes (0–$20\leqslant$; >20–$40\leqslant$; >40–$60\leqslant$; >60–$80\leqslant$; >80–$100\leqslant$). Finally G was divided into seven exclusive categories describing underwater geomorphology: (1) cuestas (cliff); (2) valley; (3) dune system; (4) rock outcrop; (5) deltaic sediment complex (including transient sand formations); (6) pro-deltaic sediment (mud associated with ancient fluvial deposit); (7) other (used when morphology was unknown or different from the major categories).

In order to compare the indices with the distribution of minke whales, the total number of minke whale observations was calculated for each km^2. Sighting positions were transformed from geographic co-ordinates to UTM using 'Geodetic Survey Routine–UTM and Geographic' software. A mean number of observations per km^2 for each class or category of the indices was then calculated. The means were not normally distributed, even after the usual transformations. Variation between mean observations per km^2 for each class or category was tested with Kruskal–Wallis non-parametric test, and differences in mean were located using the Mann–Whitney *U*-test.

RESULTS

Spatial distributions of the three indices and of minke whales (*Balaenoptera acutorostrata*) are shown in Figure 3. The first map (Figure 3A) shows a general land–offshore depth increase. The greatest depths are reached in the valleys between Ile Nue and Iles aux Bouleaux and between Iles aux Bouleaux and Grande Ile (see Figure 2 for island names). Two other large valleys are found on the western end of the site, and a small one is located between Ile Nue and Ile aux Perroquets. The map illustrating the contour index (topography; Figure 3B)

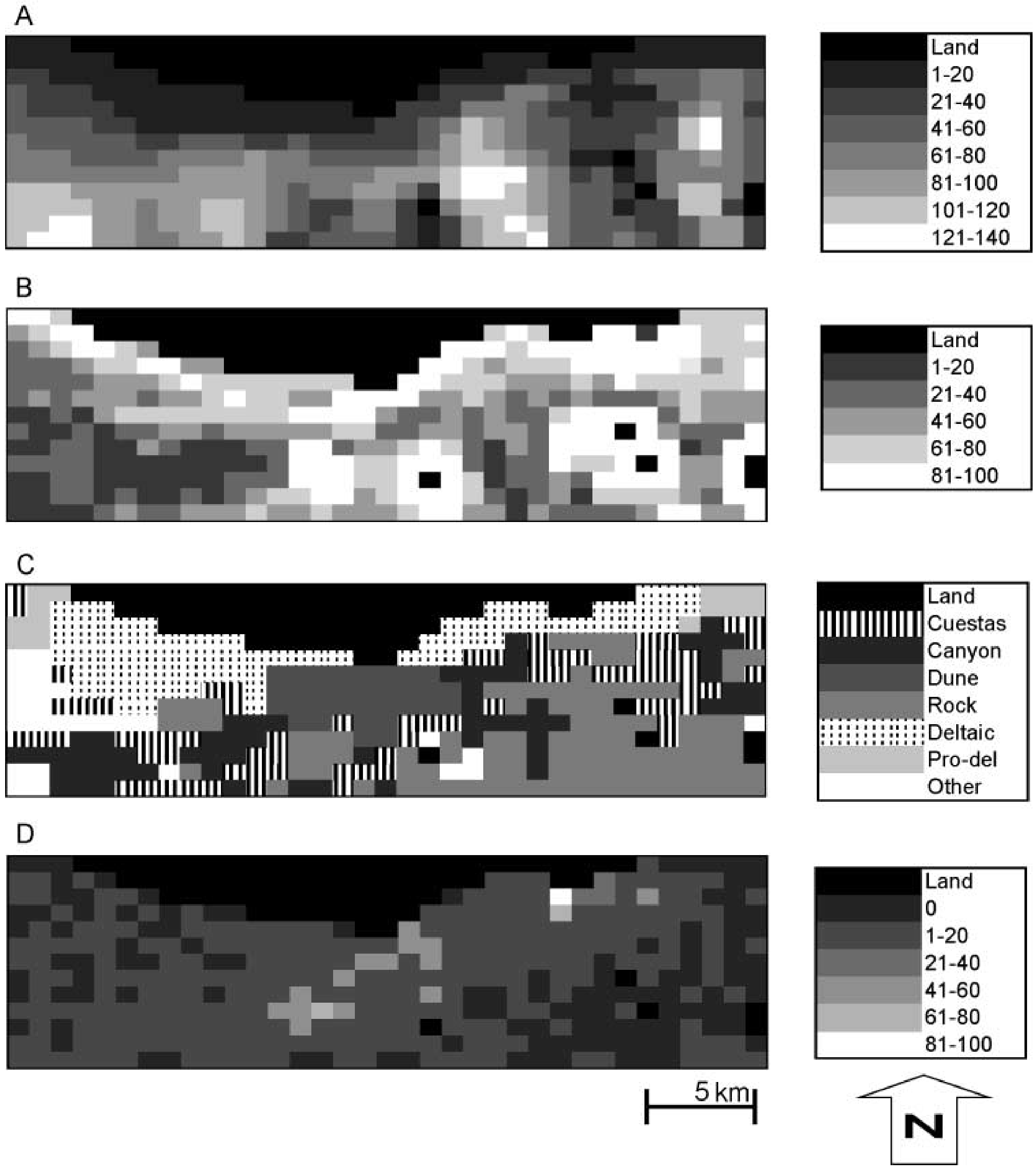

Figure 3. Grid maps of the distribution of the geological indices and minke whale observation (each square represents 1 km^2); (A) maximum depth (metres); (B) topography (contour index; unit-less, a value of one represents a flat sea-floor while a value of 100 represents pronounced sea-floor relief); (C) geomorphology (categories); and (D) minke whales observation (total sighting per km^2 for 12 years).

highlights pronounced relief surrounding the islands, in front of Mingan harbour and in front of Longue-Pointe. Conversely, flat areas are found in valleys and on the western end of the site. The geomorphology map (Figure 3C) shows that cuestas are cut by the valleys and often prolonged by rock shelf. Rocky bottoms are also present on the eastern end of the study area. The region near the land corresponds mainly to deltaic and pro-deltaic environments, with the exception of large sub-marine dunes (up to 15 m high) beginning at the tip of Longue-Pointe (30 to 90 m depth). The last map shows the distribution of minke whale observations (Figure 3D). The highest numbers of sightings are located near Mingan harbour, around Ile aux Perroquets and in front of Longue-Pointe.

Data analysis *indicated* that minke whale distribution was not uniformly spread over the different classes or categories of maximum depth, topography and geomorphology (Figures 4, 5 & 6).

Figure 4 shows the distribution of mean minke whale observations per km^2 between the different maximum depth-classes. The Class 2 ($>$20–40$\leqslant$) was the depth-class most frequented by minke whales, with a mean of 7.1 (23%) observations per km^2. From there, the mean number of observations per km^2 decreased with increasing

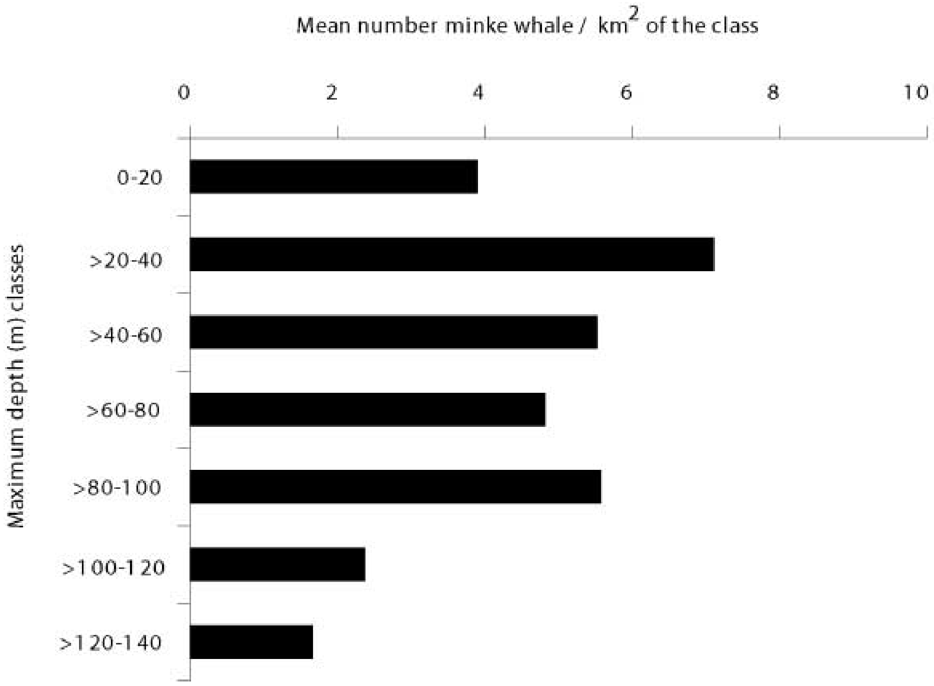

Figure 4. Mean number of observations of minke whales per km^2 for each class of the maximum depth index (in metres).

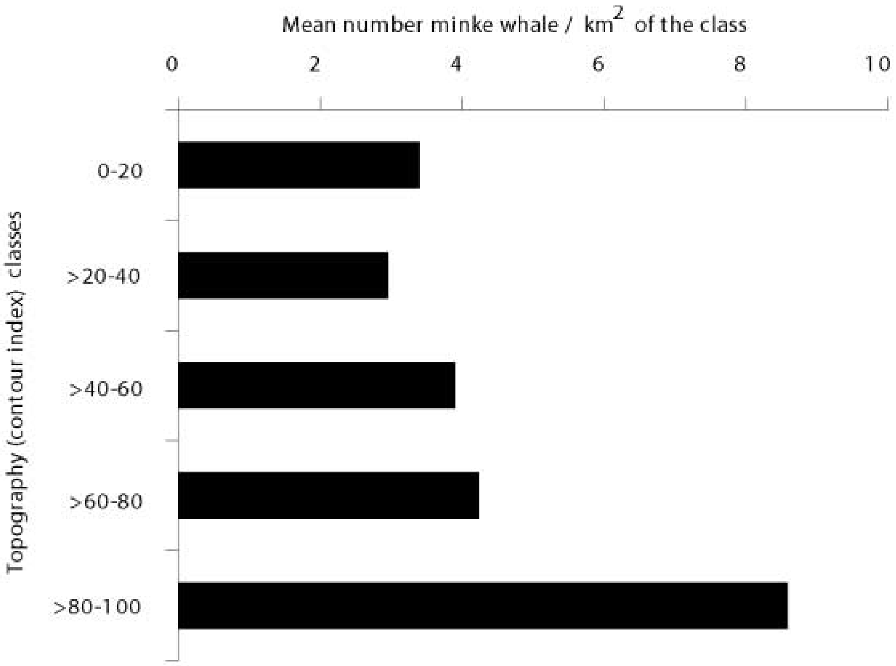

Figure 5. Mean number of observations of minke whales per km^2 for each class of the topography index (contour index, Hui 1979). The contour index is a unit-less indices, a value of zero represents a flat sea-floor and a value near 100 represents a pronounced sea-floor relief.

depth to reach a mean of 1.6 (5.3%) at Class 7 (>120–140⩽; Figure 4). The Kruskal–Wallis test found a significant difference (df=6, Criteria=19.717, P=0.003) between mean minke whale observations across maximum depth-classes. However, a posteriori Mann–Whitney U-tests did not show a clear trend to explain this significant difference (Table 1).

Minke whales were more frequently observed over regions of heterogeneous sub-marine relief (Figure 5). Besides a slight increase in mean number of observations between Classes 3 & 4 (>40–6⩽ and >60–80⩽) of the contour index, Class 5 (>80–100⩽) had the highest mean. The mean for this class was 8.6 (37.3%), compared to 4.2 (18.3%) for Class 4, the class possessing the second highest mean (Figure 5). Variance analysis showed significant differences between the means of the contour index classes (df=4, Criteria=10.087, P=0.039), however, no clear relation between the mean observations and the CI classes was *determined* from Mann–Whitney U-test results (Table 1).

A high number of minke whales was observed in the region dominated by dune geomorphology (Figure 6). The mean for this category was 13.8 (40.8%) compared

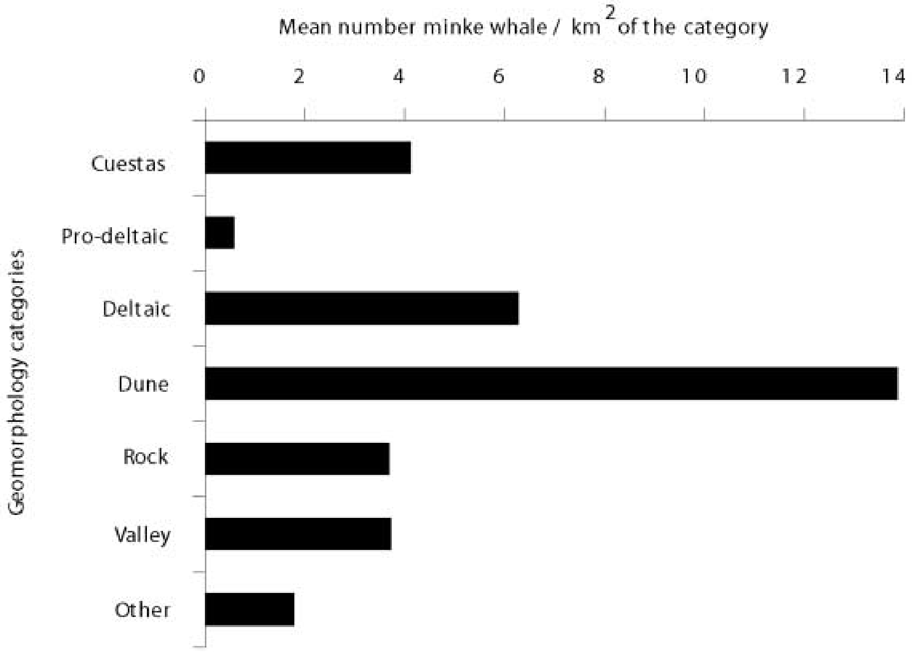

Figure 6. Mean number of observations of minke whales per km^2 for each category of the geomorphologic index.

Table 1. *Results of Mann–Whitney* U*-tests on the means of the different classes or categories of maximum depth (M), topography (contour index, CI) and geomorphology index (G). Values are probabilities, significant differences (*P*<0.05) are shown in bold type.*

Class M	0–20⩽	>20–40⩽	>40–60⩽	>60–80⩽	>80–100⩽	>100–120⩽	>120–140⩽
0–20⩽	1.000	0.088	0.687	0.541	**0.000**	0.803	0.398
>20–40⩽		1.000	0.214	0.306	0.087	0.195	0.076
>40–60⩽			1.000	0.87	**0.001**	0.959	0.317
>60–80⩽				1.000	**0.005**	0.795	0.254
>80–100⩽					1.000	**0.001**	**0.001**
>100–120⩽						1.000	0.273
>120–140⩽							1.000

Class CI	0–20⩽	>20–40⩽	>40–60⩽	>60–80⩽	>80–100⩽
0–20⩽	1.000	**0.023**	0.524	0.175	0.576
>20–40⩽		1.000	**0.048**	0.502	**0.009**
>40–60⩽			1.000	0.282	0.314
>60–80⩽				1.000	0.052
>80–100⩽					1.000

Category G	Cuestas	Deltaic	Pro-deltaic	Dune	Rock	Valley	Other
Cuestas	1.000	0.280	**0.000**	**0.000**	**0.003**	0.529	**0.007**
Deltaic		1.000	**0.003**	**0.000**	0.084	0.876	0.107
Pro-deltaic			1.000	**0.000**	**0.025**	**0.004**	0.067
Dune				1.000	**0.000**	**0.000**	**0.000**
Rock					1.000	0.073	0.633
Valley						1.000	0.087
Other							1.000

to 6.3 (18.4%) for the second highest category, deltaic (Figure 6). Results from the Kruskal–Wallis test demonstrated a highly significant difference (df=6, Criteria=72.335, P=0.000) between the means of the seven categories, and here, a Mann–Whitney U-test clearly highlighted the significant differences. The mean for dune was significantly higher than all other categories (P=0.000; Table 1).

DISCUSSION

Results showed that the distribution of minke whale (*Balaenoptera acutorostrata*) observations was not uniform among the different classes and categories of geological characteristics. Moreover, distribution of observations across the geomorphology categories was significantly biased toward the category dune.

The study area extends to 10 km offshore and includes depth ranging from 0 to 130 m. Figure 4 shows that maximum number of observations occurred in shallow water at depths between 20–40 m, and then decreased. However, the *post-hoc* Mann–Whitney *U*-test did not support this trend statistically. Hoelzel et al. (1989) stated that 80% of their observations of feeding minke whales in the San Juan Islands (USA) were located over moderate slopes at depths ranging from 20 to 100 m despite the fact that waters around the islands are predominantly 100–320 m deep. Our data differ from the observations made by Hoelzel et al. (1989), which may be due to geographical differences. Compared to the Mingan archipelago, the San Juan Islands are located further offshore, are less affected by river systems, with a maximum depth three times greater.

In the Mingan Islands, minke whales are more often observed in areas with bottom topography of pronounced relief rather than flat areas (Figure 6). Hui (1979) studied dolphins (*Delphinus* sp.) in the waters off southern California, in an area about 100 times larger than the present study (450 km^2). His results were quite similar to ours, with a greater abundance of dolphins in regions with a pronounced sub-marine topography, and a uniform distribution of observations between different depth-classes. According to Hui (1979), this pattern reflects the link existing between high biological productivity and heterogeneous topography (e.g. upwelling promoted by high bottom relief but independent of absolute depth). During a study conducted in the Bay of Fundy (site about 1000 km^2), Woodley & Gaskin (1996) observed higher numbers of finback whales (*Balaenoptera physalus*) in shallow areas (40 m) with heterogeneous bottom topography. Woodley & Gaskin (1996) suggested that these areas presented a maximal accumulation of euphausiid (*Meganyctiphanes norvegica*) and Atlantic herring (*Hareng harengus*), two prey species of the finback whale. Kasamatsu et al. (2000) also found that minke whale distribution in the Bellingshausen and Amundsen Seas (Antarctica) at a scale some 2000 times larger than our study, was not uniform over the different topography. *As in our study*, however, statistical analyses did not support the observed trend. They suggested that other factors could have produced this apparent effect and that spatial patterns cannot be explained by topography alone.

High bottom relief in the Mingan Islands is associated with two different categories of geomorphology: cuestas (cliffs) and dune (up to 15 m high, in 30 to 90 m of water), both leading to a high variation in depth over short distances (1 km^2). Data showed that minke whales were observed statistically more frequently in areas where dune was the dominant geomorphology. The observed relation could depend on the choice of prey for a particular habitat. Minke whales of the Mingan Islands have been observed feeding on capelin (*Mallotus villosus*) and sand lance (*Ammodytes* sp.) (MICS, unpublished data). These fish species have shown clear preferences for habitat with sandy substrate along the North Shore of the Gulf of St Lawrence—where the Mingan Islands are located (Parent & Brunel, 1976)—in littoral and offshore waters of Newfoundland (Carscadden et al., 1989), as well as off Nova Scotia (Scott, 1982). Sand lance live buried in the sand except when feeding, while capelin, a pelagic species, comes out on sandy beaches to spawn (Parent & Brunel, 1976; Scott & Scott, 1988). The second geomorphology type most frequented by minke whales in the study area was deltaic, which also possesses sandy substrate (in shallower water, 0 to 20 m). The high number of minke whale observations where dune and deltaic geomorphologies dominate could be due to their prey's preference for a sandy substrate. Smith & Gaskin (1983) previously suggested the possibility of an indirect link between the distribution of a harbour porpoise and substrate type.

Results suggest that neither the maximum depth nor the topography can explain by themselves the aggregation of minke whales in specific areas of the Mingan archipelago. However, the number of observations between different geomorphology types indicated a clear trend; there were more minke whale sightings where there were dunes than in other areas. Geological features, by affecting the availability, distribution and concentration of prey can modulate the distribution of minke whales. The results of this study demonstrate for the first time that sea-floor geomorphology can influence the distribution of a species of cetacean on a local scale. Sea-floor characteristics are an integral part of a minke whale's habitat and can be used as tools to predict their local distribution, at least on feeding grounds. Future studies on this species' habitat should consider this aspect of the environment.

We would like to thank all the present and past team members of the Mingan Island Cetacean Study (MICS) and students of Université du Québec à Rimouski for their effort and perseverance in collecting the data over the years. Special thanks to S. Angel and T. Doniol-Valcroze for their help in analysing this data set. Finally thanks to J. Pellerin, L. Measures, D.E. Sergeant, M. Hale and anonymous referees for constructive comments on earlier drafts of this manuscript. Financial support was provided by MICS.

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Submitted 21 April 2002. Accepted 9 June 2003.