Multibeam surveys: a major tool for geosciences

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Abstract: Since the early 1990's, the development of multibeam surveys has provided a very new and precise way of describing the morphology and nature of the underwater world ! We must consider that these surveys are now an integral part of any underwater study either in marine, estuarine, fluvial or lacustrine environments. This presentation will elude not only on establishing the major role which can be played by multibeam surveys in geosciences studies but will also elaborate on the necessity to acquire a systematic multibeam-quality map of the underwater of Canada in a manner similar to what is provided by aerial photography.

Résumé: Depuis le début des années 1990, les levés multi-faisceaux nous ont permis d'obtenir des images précises des fonds marins ce qui nous a permis d'améliorer grandement notre capacité à bien définir la géomorphologie sous-marine. Ces levés nous fournissent aujourd'hui, tant dans les environnements marins, lacustres que fluviaux, une qualité d'imagerie équivalente à celle que l'on peut obtenir sur terre à partir de photographies aériennes. Une illustration faite à partir de plusieurs exemples pris un peu partout dans le monde vient illustrer le potentiel énorme de cet outil pour les géosciences. De plus, on espère, par cette démonstration, initier une concertation pan-canadienne qui nous permettra d'acquérir une connaissance inégalée du patrimoine sub-aquatique canadien.

Introduction

Since the early 1990's, the use of multibeam surveys has increased exponentially. If there is one field of application which has been revolutionise by this technique it is in Earth sciences. We should now consider that underwater investigations can henceforth be done with similar perspective as of aerial photographs (Locat et al. 1999). In fact, we would like to take this opportunity to showcase the use of multibeam surveys in geosciences and stress the need for establishing a long term programme to provide a complete vision of Canada's underwater heritage.

The demonstration of the potential of multibeam surveys for geosciences will be mostly done using recent research activities carried in Canada and elsewhere in the World on various landslide prone areas. We will first look at a few examples from California, Spain, and along the St. Lawrence River and Gulf, with a particular look to the Upper Saguenay Fjord. This later area will show how multibeam surveys have led to a major discovery about postglacial seismic activity in the area (Locat 1999). Finally, we will briefly present some ideas in support of initiating a programme to map Canada's underwater over the next 10 years.

Seafloor Geomorphology Using Multibeam Techniques

One of the major achievements of the last decade has been the rapidly rising use of multibeam surveys in both marine and fresh water environments. For example, if the analysis of sub-aerial landslides must be done with an adequate knowledge of the morphology and stratigraphy, not withstanding the mechanical properties and pore water conditions, for submarine landslides, it is only recently that we can count on similar type of data. Until recently, most of the analyses had to rely on side-scan sonar and seismic surveys which had a major limitation due to the complexity of integrating them into a homogeneous system whereby the inherent morphological distortions due to the data acquisition process would be corrected. With the development of multibeam techniques, Differential Global Positioning Systems (DGPS, Lee *et al.* 1991, Mitchell 1991, Li and Clark 1991, Prior 1993, Hughes Clarke *et al.* 1996) we can now produce precise bathymetric maps of near air-photographic quality (Bellaiche 1993, Urgeles *et al.* 1997). Multibeam techniques use acoustic signal emitted from a series of transmitter mounted on the hull of a vessel. The greater the number of transmitters and higher frequencies will provide more precise bathymetric coverage. There are various techniques such as the CLORIA/Seabeam (e.g. Mitchell 1991; Moore and Normark 1994), Tobi and EM-series (Hughes Clarke *et al.* 1996) techniques. Bathymetry data from multiple sources can also be merged together (Orange 1999). Since most of the examples provided herewith were obtained by mean of EM1000, we will focus on this technique to illustrate the methodology.

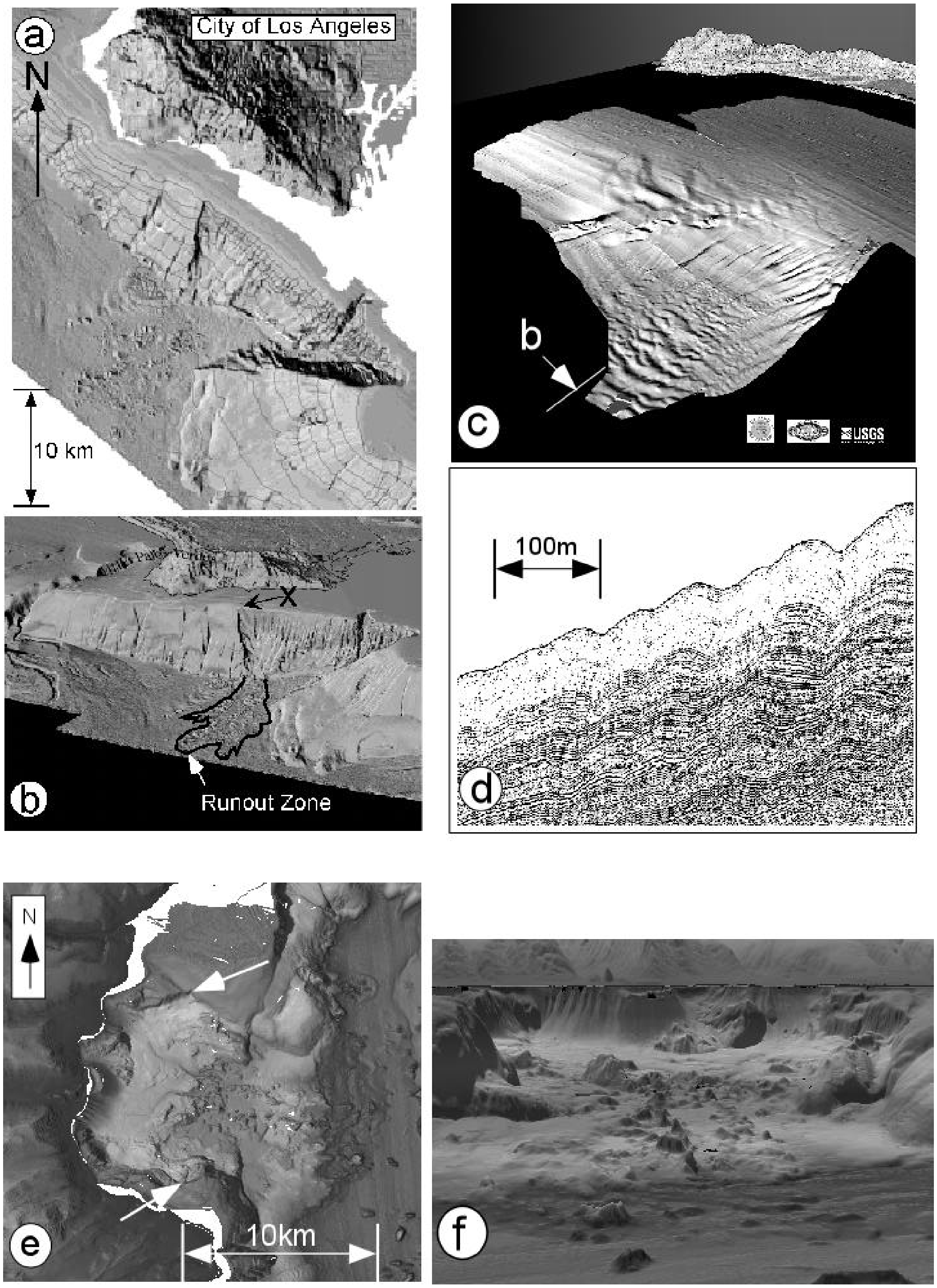

Figure 1. Palos Verdes slide, (a): plane view, (b): 3D view; Eel River Margin, California (see Gardner et al. 1999 and Lee et al. 1999 for discussion), (c): bathymetry sun illuminated 3D map, d: Huntec seismic section with the location shown as "b" in (c); Lake Tahoe debris avalanche (see Gardner et al. 1998 for details), (e): plan view of the debris avalanche area, arrows pointing at lineament intersections, (f): 3D view looking towards the west.

The EM1000 works at a frequency of 95 kHz, producing a fan of 60 beams with 2.4° by 3.3° beam widths over a total angular swath sector of 150°. While the sonar can operate in water depths ranging from as little as 3m to up to 1000m, this system is at his best for water depths between about 10 to 600m. The EM3000, a more portable and recent version of shallow water multibeam system, can be used for water depths of less than 100m. The sonar is capable of resolving a water depth at an accuracy as little as 10 cm. The EM1000 can be mounted on a vessel a small as 8 m (Gardner et al. 1998).

The data is collected along path in order to cover all the survey area with an overlap percentage depending on the accuracy required. In most cases, an overlap of 20% is correct. This overlap assures a minimum of data redundancy and helps increase the precision of the measurements. The ship speed can be as high as 18 knots without loss of accuracy. Precise differential positioning, tide data and data correction related to ship movement are essential. In addition, the acoustic velocity is corrected by a series of acoustic profiles taken during the survey. If space permits, data post acquisition treatment can be completed onboard and maps produced rapidly.

United States and European Examples

Over the last ten years, the United States Geological Survey (USGS) has been intensively involved in mapping the sea floor in the so-called Exclusive Economic Zone (EEZ, Mitchell 1991). It intensified with the GLORIA program after which were added multibeam surveys (e.g. EM100 and EM1000, Gardner et al. 1998). The following examples are related to underwater mass movements and sediment transport studies.

Palos Verdes slide, California, USA

The Palos Verdes slide (Figure 1a and b), off Los Angeles, had long been recognised on reflection seismic logs (Hampton *et al*. 1996). The slide took place along a steep escarpment and travelled a distance of about 10 km on the sea floor. The head scarp, controlled by a fault, is about 500m high with a slope angle between 15° and 20°. The debris were dispersed over a wide area shown in figure 4b. From seismic records (Hampton *et al.* 1996, Locat et al. 2000) the thickness of the debris deposit varies from about 20 m in the lower part of the slope to less than 1m, 10 km away from the base of the slope, with an average thickness of 5 to 10m. In the area of the recent mass movement, we observe that the degradation of the slope is progressing towards the North (as shown by the “x” in Figure 1b).

Eel River Margin, California, USA

The Eel River Margin example was obtained as part of a study related to a multidisciplinary effort aimed at understanding the process by which sedimentary strata are deposited, modified and ultimately preserved in the stratigraphic record (STRATAFORM project, Nittrouer 1999). One component of this study is to understand sediment stability and transport (Lee *et al.* 1999). In such a case, the detailed description of the morphology is an essential part of the analysis (Goff *et al.* 1999). The 3D bathymetry picture shown in Figure 1c represents the study area which can be divided into two parts. The Northern sector, located to the north of the anticline (a small sea mount in the middle on the slope), which presents a regular slope with more or less regularly spaced gullies. The Southern sector is characterised by a semi-circular feature which may represent the amphitheatre of a large shear-dominated retrogressive failure (Fig. 1d, Gardner *et al.* 1999) or a large deep seated submarine failure (Lee *et al.* 1981, Lee *et al.* 1999, Orange 1999). The water depth range in this image is from zero to about 200 m near the shelf break to about 500 m near the base of the slope. The slope itself is at an angle of about 3° to 6° and the slope break is about 20 km from the shoreline.

Lake Tahoe Rock Avalanche, California/Nevada, USA

Lake Tahoe is located at the boundary between California and Nevada. The lake is at an elevation of 1900m. The multibeam sonar survey (Figure 1e and 1f) of the lake was carried out in 1998 (Gardner *et al.* 1998). For this work, the EM1000 was mounted on a small vessel (8 m long). Lake Tahoe, one of the deepest lakes in the United States, is located between two major faults, including the Sierra Nevada fault which is located about two kilometres west of the lake. Most rocks in the area were produced by volcanic activity. The landscape itself has been, locally, modified by glaciers. The head-scarp of the slide is about 5 km wide and the debris reached a distance of up to about 10 km near the centre of the lake. Some lumps of isolated debris are of the order of 100 m in length. The north flank in the starting zone appears to be limited by strong lineament systems intersecting at an angle of about 130° (see arrows in Figure 1e).

Canary Islands Rock Avalanches, Spain

The Canary Islands submarine slides (Urgeles *et al.* 1997) were initiated along the flanks of the islands (Figure 2). The avalanche spreads from an elevation of about 1000m above sea level to a depth (below sea level) between 3000 and 4000m with a run out distance at about 50 km. The La Palma rock avalanche is also partly visible on the left side of the Figure 2. These large scale mass movements involve very large volumes (few cubic kilometres) and cover large areas of the sea floor (up to 2600 km^2), and run-outs reaching 70 km (Urgeles *et al.* 1997). This type of mass movement is very similar to those reported by Moore and Normark (1994) for the Hawaiian Islands.

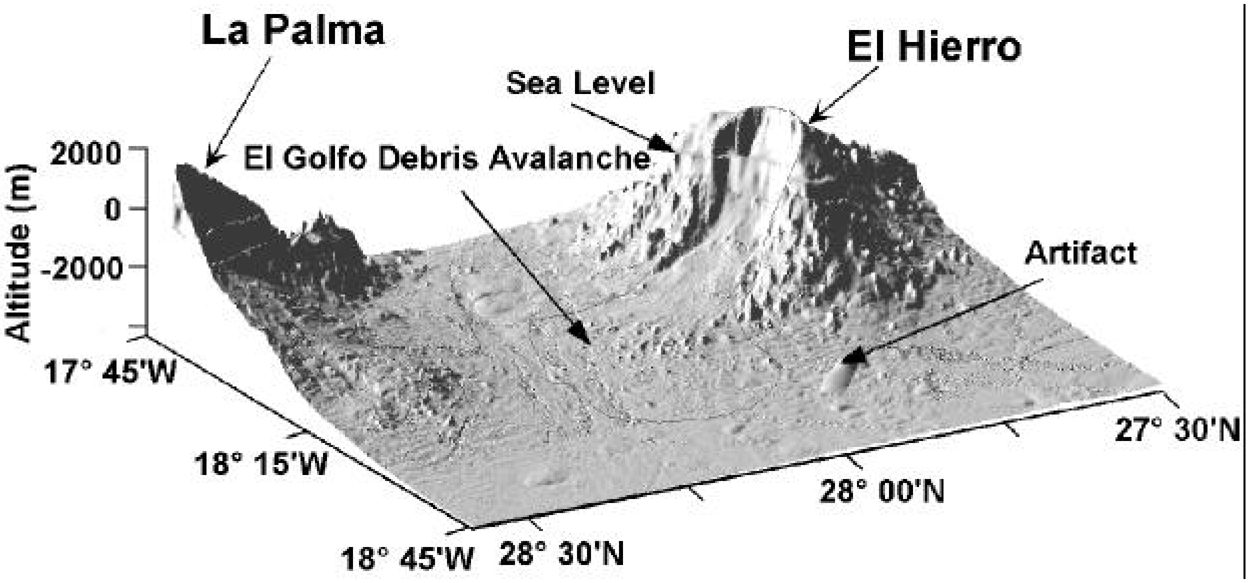

Figure 2. El Golfo debris avalanches off El Hierro Island (Canary Islands, Spain, Urgeles et al. 1997)

Examples from Québec

Îles de la Madeleine

Following four surveys (1995, 1996, 1998 and 1999) at the Îles de la Madeleine, an interesting compilation has revealed a spectacular morphological signature. The bedrock formations in the area consist mostly of red sandstone while sand is the main Quaternary deposits which has been derived from the sandstone. The area covered in Figure 3a shows a shallow shelf consisting of draping sand over folded bedrock. The windblown style of the sand covering over the bedrock is well illustrated in 1 (Figure 3b) where the sand appears to slowly migrate over the folded bedrock ridges (2 in Figure 3b). The enlargement shown in Figure 3b reveals the presence of a fault in the folded bedrock. Some synclinal of anticlynal ridges (4) appears visible at the scale given in Figure 3a. Finally a small mound is visible at point 5 in Figure 3a which is a disposal point for dredged material.

Head of the Laurentian Channel, Tadoussac

The Laurentian Channel extends from the mouth of the Saguenay Fjord to the Continental shelf between Newfoundland and Nova Scotia. A multibeam survey carried out in 1997, near the mouth of the Saguenay Fjord, has provided a dramatic view of the head of the Laurentian Channel with the complex morphology composed of bedrock outcrops and Quaternary deposits. The origin of the channel could be complex to determine. This part of the St. Lawrence River is a major convergence centre for glacial flow where ice from the Upper St. Lawrence Valley would meet with the glacier coming out of the Saguenay Fjord. The morphology of the head (1 in Figure 4) of the channel resembles very much that of a canyon which could have been eroded at the time that there was large volumes of water and sediments being carried out into the St. Lawrence River system. It is also known that glaciers stood in the upper part of the Saguenay Fjord at least until about 10000 years ago (Lasalle and Tremblay 1978). We do not know the nature of the underlying geological formations in this area, but the morphology of the feature indicated in 2 is typical of a major mass movement with its scarp, low angle slope and a hummocky ground or deformed ridges. This slide could have taken place in the marine deposits and could have been caused by either erosion, glacial loading or seismic activity (Hampton et al. 1996). Clearly, one could easily find some targets for a seismic survey or a coring programme!

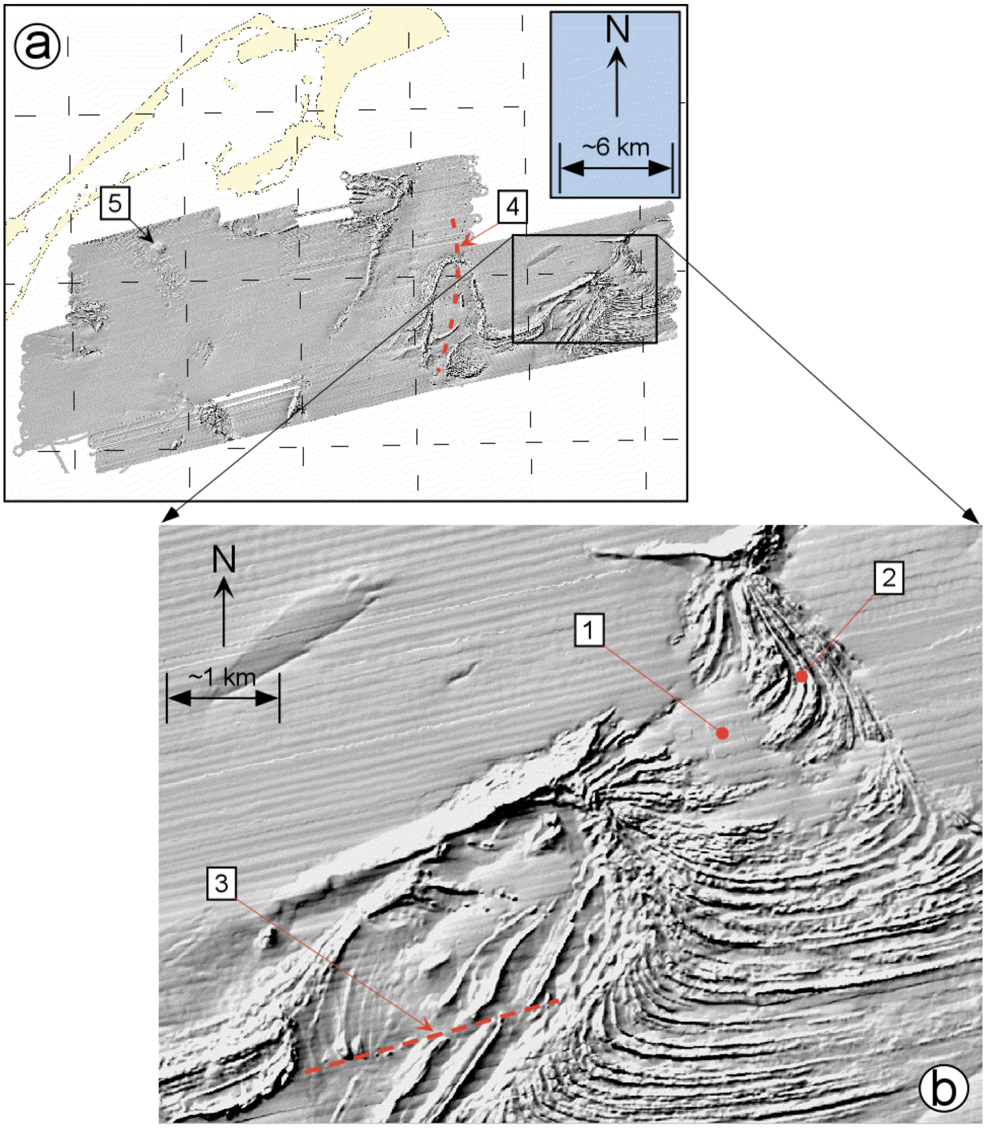

Figure 3. (a): Multibeam sonar bathymetry at Grande Entrée Island, illumination with a direction at 315° and elevation at 45° ; (b): enlargement of the Goodwin Shoal sector (1995, 1996, 1998, 1999, F.G. Creed).

Upper Saguenay Fjord

The Saguenay Fjord was one of the first sites where a multibeam sonar survey was carried out to map submarine landslides (Couture *et al.* 1993, Hampton *et al.* 1996). It is located 200 km Northeast of Québec City, Canada. The area provides a fairly quiet environment so that sea conditions are nearly perfect so as to ensure the best results. The same area was also re-visited in 1997 after a major flood event (Kammerer *et al.* 1998) and in 1999 (Figure 4, see also Schmitt et al. 2000). The Saguenay Fjord survey covers the upper part of the fjord at water depths ranging from 0 to 225 m.

The Saguenay Fjord region has frequent major earthquakes (*e.g.* 6.3 in 1988), the largest historic one occurring in 1663 (Locat and Leroueil 1988, Locat and Bergeron 1988, Pelletier and Locat 1993, Syvitski and Schafer 1996) for which an equivalent Richter Scale of 7 was given. It is believed that this earthquake triggered a series of major land and submarine slides, the largest sub-aerial one being the St. Jean Vianney slide totalling a volume of more than 200 millions cubic metres. At the same time, major submarine landslides took place in the upper reaches of the fjord. The complex morphology of this part of the fjord is related to both the major catastrophic sedimentation due to the sub-aerial mass movements material being deposited in the fjord and to the synchronous occurrence of many submarine landslides and their related mass movements (see Fig. 5a, 1: flow, 2: slump, 3: flow, 4: fan accumulation, 5: flow, and in Fig. 5b, 6: slides and spreads). This major catastrophic event is responsible for the deposition of a 5 to 15 m thick turbidite in the deeper part of the fjord, few kilometres to the East (Perret et al. 1995). At the mouth of the Bras Nord lies a large submarine fan which is dissected by two channels (4 in Fig 5a and 5e) and the ridge between show low amplitude mega-ripples composed of a sandy silt. The only plausible explanation for the extensive submarine landslide delineated in Figure 5e is that it resulted from a major seismic event, likely the 1663 earthquake. This slide is bounded to the west by a scarp (point 7 in figure 5e) which is crossed by an underlying fault (point 9 in Figure 5e).

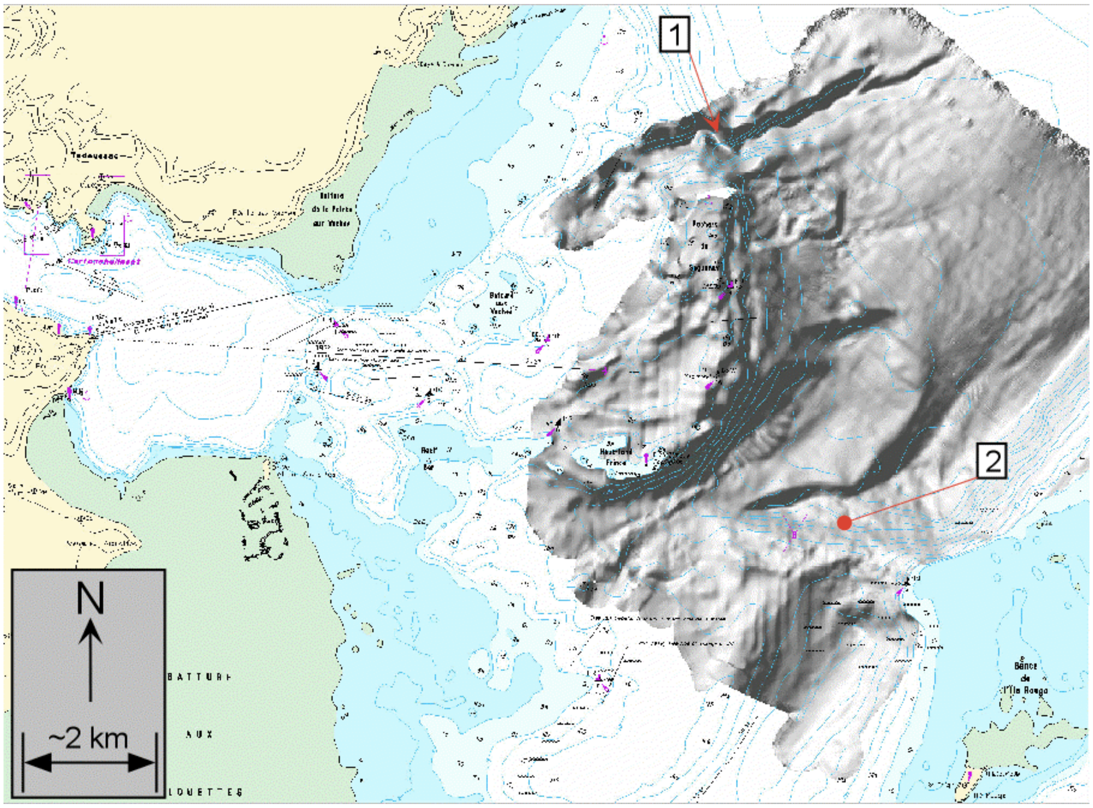

Figure 4. Multibeam bathymetry at the head of the Laurentian Fan; illumination at 315° and elevation at 45° (F.G. Creed 1997).

The finding of the fault, for which the probable position is shown in Figure 5e, is quite significant. Indeed, it initially came to be speculated upon when the escarpment was first observed at the time of the 1993 multibeam survey. Only later, after another multibeam survey, done in 1997, was it possible to use a high resolution seismic system (SEISTEK). An example of the seismic line is shown in Figure 6b along with the 1999 mulibeam survey. In 1999, knowing the the ship was at the right place, we made the following postulate: if there is a fault under the sea floor below us, it must show on the fjord's wall. Then, we looked at the escarpment, about 100 m in front of us, and found this spectacular fault (Figure 6b and 6c). This fault can be traced as much as 400 m inland over the plateau. This is one of the very few evidence of recent seismic activity in the area and this discovery will guide any further site investigation which would be required to check for any seismic hazard.

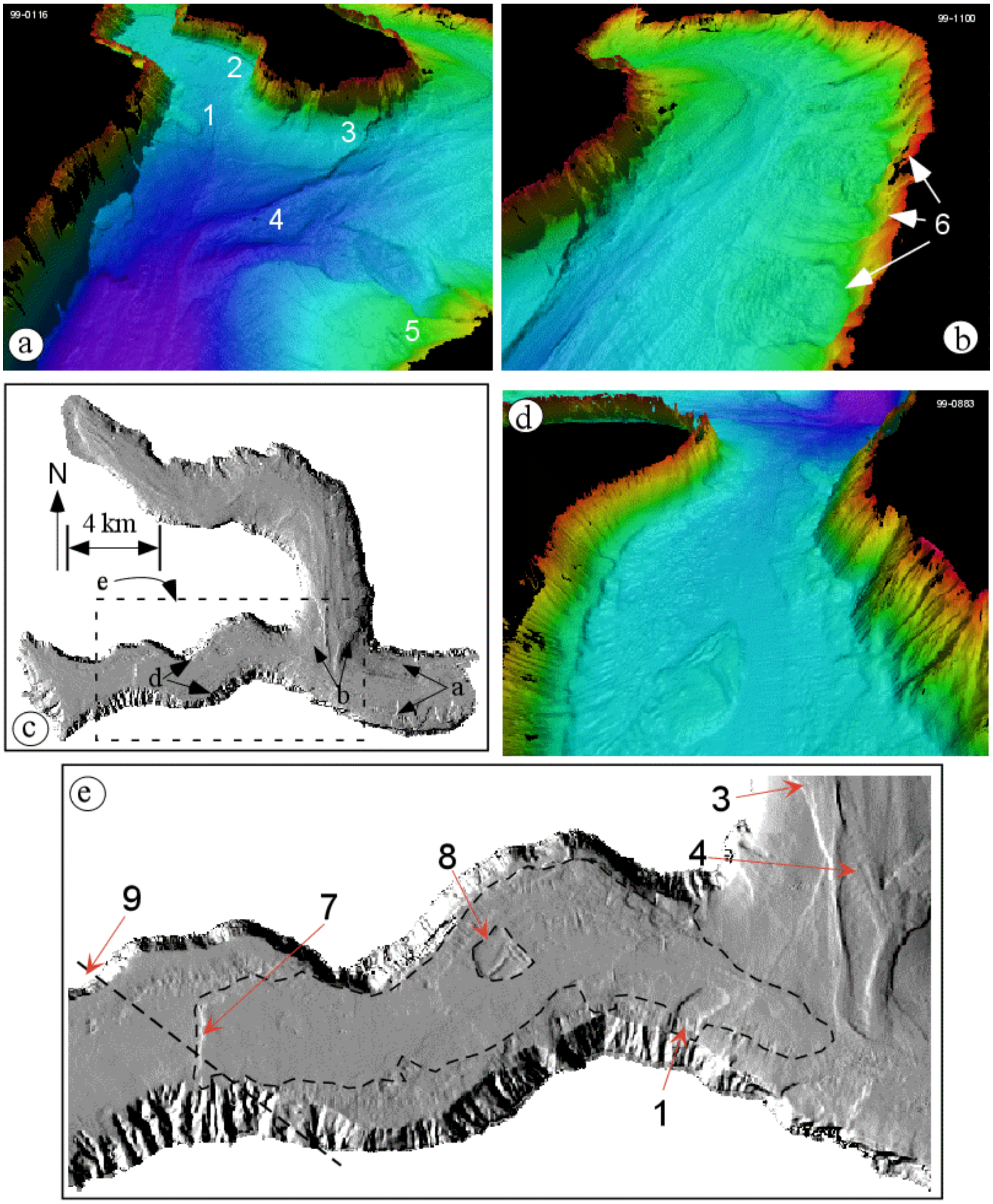

Figure 5. Morphological analysis of the upper part of the Saguenay Fjord, Québec, Canada, illustrating the use of 3D representation of multibeam sonar bathymetry from the 1999 survey. In (a), we can see various types of landslides: spread (1), slide (2), Flows (3 and 5). Also identify is major fan (4) deposited by the flow generated after the 1663 submarine slide. In (b) we can see three spreads (6) originating from the East wall. The width in the middle of (a) is about 6 km, and about 4 km in (b). In (e) a large liquefaction failure has been map and is limited to

the West by a 8 metre escarpment controlled by an underlying fault (Locat 1999). The water depth range from 0 to 225 m, and views angle of (a), (b), and (d) are given in (c).

So, the access to excellent sea floor bathymetry has provided a unique data base which enabled us to better understand the sea floor morphology and carry a scientific procedure leading to a significant geoscientific discovery (Locat 1999).

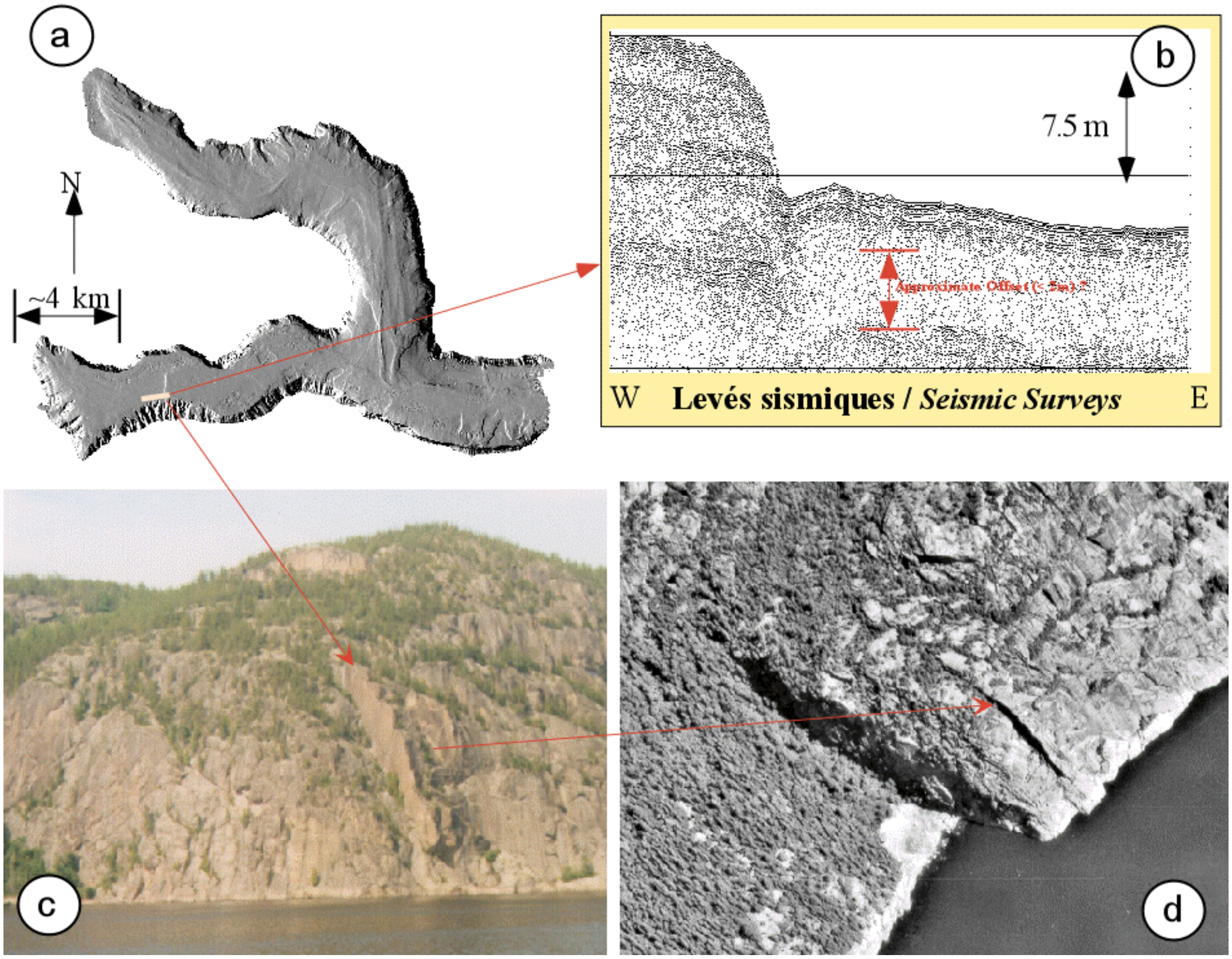

Figure 6. The escarpment, View of the postglacial fault seen from the fjord and its trace on an aerial photograph.

Impact of Multibeam Surveys on Research Planning

In most projects where multibeam survey was available, it impacted on many facets of the research work.. If we take the case of the Saguenay Fjord, the knowledge of the fine sea floor morphology is now directly taken into account in any sampling or monitoring program. For example, if you are interested in sampling recent sediments to monitor temporal changes, you want to make sure that the sample are taken in an area where little mass movements took place. Similarly, if you want to look at bottom currents, as for the case of erosion of contaminated sediments, you want to now the local morphology as it would directly influence current patterns and characteristics.

In 1997, we had a cruise on the Saguenay Fjord, aboard the Martha L. Black, and just the week before we had completed the EM1000 survey. Having the bathymetry maps, like in Figure 5e, was an invaluable tool in fine tuning either the coring program and the seismic survey. For the first time, we were carrying site investigations not to explore but to answer specific questions related to the identification of the various features evidenced by the morphology (landslides, channels, etc…).

It is clear that the information contained in multibeam survey maps is of a quality that now approaches that of aerial photographs and is increasingly being requested for many types of activities. Precise morphological underwater maps are valuable instruments not only for scientists (geology, biology, engineering, etc…) but also to regional planners, environmentalists, sports people, fisherman and tourists. These are some of the reasons leading into the necessity to have a concerted effort aimed at acquiring this type of information about underwater World !

A Millenum Project: Mapping Canada's Underwater Landmass

In response to the above comment about the necessity of a concerted effort we would like to propose, for discussion, the establishment of a major project aimed at acquiring knowledge about Canada's underwater landmass. The main objective of this programme would be to acquire first knowledge on the morphology of sub-aquatic Canadian landmass. A large area of the Canadian landmass is covered with water. If only we consider the 350 km (200 miles) economic zone along the shoreline of Canada, the Great Lakes, the Arctic Archipelago, it represents about 1/10th of the total landmass. Compare to the landmass above water, the underwater part of the territory is almost unknown. Since the early 1990s, imaging techniques have been developed to such a level that it is now possible to acquire underwater images of the land mass of such a quality that it approaches that of aerial photography or satellite imagery (e.g. radar). Anyone who has been using these underwater remote sensing methods cannot do without them anymore!

Major users who would benefit from the availability of this information are involved in various fields such as: Resources, Transportation, Environment, Communications and Culture. In fact, about the same who uses land remote sensing information will be using its underwater equivalent. It is therefore proposed here to set up a programme with the mandate to: complete the mapping of the underwater landmass of Canada over a period of 10 years. The initial strategy to plan this work would be to:

1. Evaluate the interest and support (1999-2000).
2. Structure a Working Group who will develop the proposal (submitted by the end of 2000).
3. Official launching of the project (Early 2001).
4. Termination of the project (2010).

The initial working group could include people from: (1) data acquisition (e.g. CHS), (2) data analysis and treatment and technological development (e.g. Ocean Mapping Group in Fredericton, developing industry, CHS and the Department of National Defense), (3) university participants interested in underwater research (e.g. Laval, MUN, Uvic, UBC, etc..), governments (DFO, Natural Resources Canada, DND, etc..) and the industry (Oil and gas, communication, energy etc…).

This working group could come up with a team approach similar to that used for a project LITHOPROBE with had support from government, the industry and NSERC to explore the deep nature of the lithosphere via a complex program of reflection seismic surveys across Canada. This committee would in particular, look after selecting priorities for the site selection. For recent discussions, it appears that few "regional" initiatives are taking place (e.g. Scotian Shelf, and parts of the Great Lakes). So, some priorities are being addressed but there is no concerted effort. Of great importance would be the fact that all the data would be made available in a manner similar to that of aerial photographs, with minimum cost to the users.

Carrying this work over a 10 year period will also sustain the technological development in the field of underwater acoustics mapping and data analysis.

Conclusions

We hope that the above presentation has fostered the essential role now played by multibeam bathymetry maps in the planning and making of geoscientific research. This would certainly also apply to other disciplines like marine biology, coastal and marine engineering, or to more social activities like sports fishing or underwater activities like diving.

From the above presentations and discussion we would like to conclude that:

1. Multibeam surveys now provide a realistic view of the underwater morphology of the landmass to a quality approaching that of aerial photography.
2. The use of multibeam survey is essential to any geoscientific activity and positively impact on any research planing.
3. A concerted effort is required in Canada to acquire a knowledge of the underwater landmass to a degree similar to what is available from aerial photography.

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