Swath-sounding techniques for near shore surveying

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Abstract

10 years ago, swath-sounding surveying was only affordable for ocean-scale research projects and some large budget oil and gas operations. Recently however swath-sounding equipment has seen significant developments where a combination of decreasing electronic costs and increasing power of personal computing has made the technique become a reality for lower budget, high resolution near shore surveying. For example, the high degree of bathymetric resolution and complete 3D coverage offered by the technique is providing new insights into complex sea floor geology and also allowing evaluations of dynamic sediment movements. In environmental habitat studies, both the bathymetry and co-located amplitude information is proving invaluable for habitat appraisal when the technique is used in combination with other acoustic methods and appropriate ground control from video, diver and sampling programmes. The method is outlined and limitations for surveying are discussed before three case histories are used to illustrate some of the potential applications of the technique.

Introduction

A swath-sounding system is one that is used to measure the depth to sea floor and amplitude of sonar return from the sea floor along a line extending outwards from the sonar transducer at right angles to the direction of motion of the sonar (Geen and Cunningham, 1998). As the sonar platform moves forwards, a profile of sweeps is defined as a ribbon-shaped surface of depth measurements known as a swath in a similar manner to a sidescan image of the seafloor. The final deliverables from a swath-sounding system are similar to those from a multi-beam survey however the mechanism for recording the data are different. The use of multibeam systems for both bathymetric mapping and analysis of seafloor type have been extensively reviewed in the literature (for example, Clarke et al., 1996; de Moustier, 1989). A basic outline of the swath-sounding technique is given here however only a brief comparison is made between swath-sounding and multi-beam as this has been discussed elsewhere (Davis et al., 1986; de Moustier and Matsumoto, 1993; Blacquiere and Van Woerden, 1998).

The acoustic signal is produced by the sonar in a similar manner to a sidescan acoustic pulse and is narrow in azimuth (that is, viewed from above), and wide in elevation (viewed from the side) (Geen and Cunningham, 1998). The difference between a sidescan and swath-sounding system is in the recording of the acoustic energy (De Moustier and Matsumoto, 1993). In a swath-sounding system a number of transducers or transducer staves are used to record the returned energy that is back-scattered from the seafloor. When this back-scattered sound is detected at the transducers, the angle it makes with the transducer is measured by recording the phase difference between transducers and a reference signal. Multiple staves ensure that both the angular measurement and the overall phase resolution are measured with high precision. The range for a reflector is calculated from the travel time to the reflector and back and the range and phase angle pair enable the location of the ensonified seabed patch to be known relative to the sonar transducer thus creating a 3D bathymetry map of the seabed. The range is measured using travel times to typically better than 0.05m and transducer angles to better than 0.05degree. As the transmit beam spreads in the water away from the sonar in a similar manner to the sidescan, the size of the footprint will also increase away from the sonar. Thus a footprint can be calculated with 234kHz transducers to about 0.87m at near range and 5.2m at 300m range along track and 5cm across track (table 1). The 117kHz transducer has an along track footprint of 1.5m at near range and 8.9m at 300m range with a 7.5cm across track dimension.

Table 1. Across track and along track resolution

	Across track range		Across track range	
Frequency (kHz)/beam width (degree)	50	300	50	300
117/1.7	1.5	8.9	0.075	0.075
234/1.1	0.9	5.8	0.050	0.050

Because phase difference is recorded a major advantage is realised with of the swath-sounding sonar in that there is no footprint spreading along the beam i.e. in the across track dimension. However, it should be noted that it may not be possible to achieve these across track dimensions in practice at far offsets due to energy loss. The maximum range limit is dictated by the nature of the seafloor and the grazing-angle limit where most of the energy is reflected away from the seafloor. Bottom types such as soft mud or peat can reduce the expected range by as much as 30 % however, sand, rock and shingle all give good sonar backscattering. A typical far range limit is about 7.5 times the water depth giving a total swath width of approximately 15 times the water depth. For seafloor classification this is an important issue as it is vital that similar size areas of the bottom are surveyed across a sonar record in order to be able to make meaningful comparisons (Monterey Bay). It should also be remembered that if there are slopes on the seafloor that fall away from the direction of the sonar beam these areas will fall into shadow zones and it is unlikely that they will be ensonified. Thus, obtaining true 100% coverage of the seafloor is rarely a practical achievement.

Similar to the sidescan sonar, the number of pings or hits on a target is defined by the ping rate and speed advance of the sonar over the seafloor of survey. The ping rate is determined by the furthest range limit and speed of beam in the water (table 2). High survey speeds will result in poorer target definition or poorer quality images of the target as discussed for the sidescan sonar and shown in table SB1. Some swath-sounding systems alternate transmitting between each side of the sonar to avoid interference, thus the ping rate is effectively halved. However, the distance between pings indicated in the table can be halved if only one side or transducer is used.

Table 2. Distance between pings (alternate pinging for port and starboard transducers)

	Range		
Survey Speed (kts)	50	100	200
4	0.26	0.53	1.07
8	0.53	1.07	2.10

In addition to a determination of the location of a reflecting target on the seafloor, the amplitude of the returned signal can be measured with the swath-sounding system (Geen, 1998). This amplitude data can be used in one of two ways. Either it can be treated as a sidescan record, that is as a time series to produce a qualitative image of the seafloor or it can be processed using the bathymetric information for the point on the seafloor from which each individual reflection is measured. In this latter case the recorded amplitude is compared with the source signal after compensation for energy losses during the travel path such as loss of signal to the water column, spherical beam spreading and the incidence angle for scatter or reflectance from the sea floor (Goodfellow, 1996). It is only since the development of this type of sonar with high fidelity co-location of bathymetry and amplitude that these compensations for amplitude loss have been possible. The processing of this type of amplitude data is currently the focus of research activities at a number of institutions and may represent and important new use of the swath-sounding and multibeam sonar (English Nature, 2000; Clarke et al., 1996; Canepa and Bergem, 1998).

Because of the high fidelity of depth measurements with swath-sounding systems they have been used for a number of survey objectives in a variety of locations over the last 5 years. The types of survey include offshore hydrocarbon pipeline and telecommunication cable route planning, dredge analysis of harbours, estuaries and ports, resource evaluation, environmental surveying (Geen, 1998). The range of users includes engineering companies, hydrographic surveyors and environmental assessors. Three examples are given to illustrate the use of swath-sounding systems. Different survey parameters were used for each survey but each data set was processed using similar protocols which included final bathymetric surfaces interpolated using a using triangular irregular network (TIN).

Plymouth Harbour

A swath-sounding survey was conducted at Plymouth Harbour for English Nature using the Submetrix System 2000 sonar with 234kHz transducers. The primary objective of the survey was to produce a data set of bathymetry and sea-bottom amplitude for comparison with other remotely sensed geophysical data and ground truth data of biological habitats from video and grab sampling. The final deliverables included a bathymetric chart for a 5.5km north-south strip and 3km east-west strip of the harbour together with amplitude data over key areas of bottom habitat. The survey was conducted over a calm two day period in January, 2000.

For this survey a Trimble RTK differential GPS system was used for navigational information. The swath-sounding system was deployed in a bow-mount configuration together with DMS 205 motion reference unit. Tidal corrections were provided by a continuous-logging tide gauge and models from the hydrographic office. Sound velocity measurements were made before and during the survey for correction of the sonar data. Survey lines were located to give 100% overlap between swaths running both north-south and east-west. The acquisition parameters resulted in final position errors of less than 1m over the entire survey and in places less than 0.4m. Height information gave errors of less than 1m for all the area with less than 0.2m for at least 40% of the area.

Results - Bathymetric Data

The bathymetric chart for the total Plymouth harbour data set is shown in figure 1. A number of interesting features are shown on the chart. To the north of the outer breakwater, two large circular depressions were mapped that have been formed by the differential scour produced by mooring buoys from the Navy warship moorings. The depressions have a 0.5m topographic expression with a further 1m scour indicated at the point that the chains are attached to the seafloor. Heterogeneous rock skerries were mapped extending from each of the major promontories on the east side of the harbour with gently sloping bathymetry from the north to the south over the remainder of the survey. One aspect of the survey program was to determine the repeatability of the swath-sounding system. In order to test this, a key area at the centre of the site was chosen for repeat surveying over the two day survey period using a number of different line orientations and directions. Figure 2a shows the bathymetry for the calibration area surveyed in a north-south direction and figure 2b shows the same area surveyed in an east-west direction.

Results - Amplitude Data

The amplitude data was processed in a manner similar to that for a sidescan sonar with time varying gain applied to each transducer stave individually. The final sidescan output was then compared at a number of different grid resolutions (0.2, 0.5 and 1.0m bins) in order to test the system resolution and also the errors associated with the position fixing. While the 0.2m bin showed some fine detail, significant areas were missing between the lines (shown as empty pixel spaces) and the data was further compromised at the end of the lines by large data gaps. No discernible differences were seen between the 0.5m and 1m bins. Because of the navigational errors associated with the Trimble RTK GPS, grid resolutions less than 1m give a false impression of the data having a higher positional precision than it actually does. Thus for habitat appraisal based on the bathymetry and amplitude combined response, a final data grid size of $1m^2$ was used appropriate.

The results of amplitude data for the area are given in figure 3 as a mosaic summary equivalent to the bathymetric charts. From this chart it can be seen that even with a 100% overlap in swaths, amplitude artefacts were obvious as along-track signatures. These survey artefacts will have a profound influence on the data for classification if full amplitude correction is not conducted as the artefacts represent the strongest events in the records. None the less, even with this data, many bottom features can be identified such as the complexity in the rock skerries striking out from the two headlands in a southwest direction.

Results - Seabed Classification

Supervised classification was conducted following image processing techniques on the combined data sets of bathymetry and amplitude with 67% weight for bathymetry and 33% for amplitude. First histograms of combined spectral peaks were produced to identify significant classes within the data. These significant classes, representing different acoustic responses from the bottom, were then used to pick training sites for the classification routines. Representative sites for training were manually located on typical or type example locations for training the classification routines. Three training sites were chosen per class with the sites chosen where the bottom type was know from grab or video sampling, however, the acoustic classification map (figure 4) represent only acoustic signatures of bathymetry and amplitude. At each training site a polygon was digitised around each of the sites with a minimum of 400, $1m^2$ pixels in each polygon. The parallelepiped method was used to classify individual pixel with relation to the know signatures at the training sites. The classification scheme produced six distinct groups or clusters of bottom type. Broadly these types were located based on their bed rock outcrop (group 1), the bedrock outcrop/sand or mud boundary conditions (group 2), sand or coarser grained regions (group 3), regions of mud (group 4), an unknown region (group 5) and regions where the sonar data was beyond the survey limits of the equipment usually in very shallow water (group 6).

Discussion

While the theoretical limits of ensonified areas for the Submetrix 2000 system gives individual bottom pixel or image patches on the sea floor of 12cm sides, the practical resolution of the system is limited by a number of other survey parameters. These other survey parameters such as the errors in navigation information, the angles of the beams compounding errors at the end of the beams are all present with any sonar system. When the errors are compounded, it can be demonstrated that positional accuracy for features on the bottom are often only known at best to 50cm and on average to 1m. For this reason, any comparison of remote sensing techniques should be made at 1m. A further issue with sea floor classification into habitat types is introduced with the ground truth data. The ground truth sampling locations are only as good as the navigation system plus the error in not knowing exactly where on the bottom the sample has been taken from. Despite these limitations, the swath-soundingmapping provided high resolution, repeatable bathymetry and images of the seafloor that were acquired in a short survey period.

Loch Sunart

The western sea-lochs hold important information for evaluating past climatic changes in northern latitudes. This information includes high fidelity undisturbed records of sedimentary sequences together with palaeo-landscape relics that indicate the actions and extent of previous glacial limits. The swath-soundingsurvey was conducted using the 234kHz transducers with the primary objective of resolving topographical features on the bed of the loch. A secondary benefit resulted from the survey subsequent to the acquisition as the data provided valuable information for biologists studying critical habitats in this candidate Special Areas of Conservation (an EC protected habitat area). The survey was conducted during a relatively calm period in June, 2000.

For this survey navigation was provided by a Racal Skyfix differential GPS and tide control from the hydrographic office. The sonar was bow mounted together with a DMS 205 motion reference unit. Survey lines were oriented parallel to the long dimensions of the loch with line separations of 100m. This line spacing was necessary for the deep sections where depths in excess of 100m result in greatly reduced ensonified areas. Unfortunately in the deepest part of the loch the return sonar signal is very weak from the fine-grained muds and it is recommended that for future work in these conditions lower frequency transducers are used.

Bathymetric results

The inner and middle sections of the loch are shown in figure 5 together with summaries of the bedrock geology. The inner loch shows clear over-deepening at its western end as a result of glacial pinching controlled by the more resistant pelitic bands at the narrows before the loch turns to the northwest. It is postulated from observations made on land (Greene, 1995) that this represents the seaward (western) limit of the Loch Lomand re-advance in this part of Scotland and this is collaborated by the shallow bathymetry and sea-bottom features that are evident to the west of the narrows. Similar overdeepening with a shallow lip or sill has been observed in many fjords in Norway (ref). At the eastern end of the inner loch, De Geer type glacial moraines are inferred from their shape which is similar to debris deposited by grounded ice in front of glaciers, Baffin Island (Boulton, 1986). These moraine ridges with steep proximal sides and shallow distal sides are also clearly identified from an analysis of the amplitude data (figures 6a, and 6b) and bathymetric slopes (figure 6c, 6d and background image). The high resolution offered by the swath-sounding survey has allowed not only a new bathymetric chart for the inner and middle lochs but new insights for environmental reconstruction of the Quaternary history of the area.

Megget Reservoir

In 1999 a bathymetric survey was conducted of the Megget Reservoir in the Southern Uplands of Scotland. The reservoir has a volume of 63,722 Megalitres and was constructed in 1983 as the main drinking water supply serving Lothian Regions and the city of Edinburgh. In 1997-98 the reservoir was drained to 25% of its capacity in order to conduct repair work on the face of the dam. A number of slump features were noted during the drainage process and it was postulated that the process of refilling could trigger further slumps. The primary objectives of the bathymetric survey were to assess if further slumping had occurred during re-fill and to map the amount of sedimentation in the deep part that was not visible on draining since the reservoir was constructed. The final bathymetric charts would therefore be compared to initial engineering maps of the reservoir bottom, that is the old land surface prior to flooding of the river valley.

Because the reservoir is a drinking water supply it was a requirement of the survey conditions to use the only powered boat allowed on the reservoir as a survey platform. The size of this boat did not allow for bow or side mounting the System 2000 transducers and so they were suspended with a motion reference unit beneath two floatation buoys and secured to the side of the boat. A temporary wet-weather housing was constructed over the open boat to protect the electronics and the survey was only made possible by a relatively calm period of weather. GPS navigation was provided by a Trimble unit and sound velocity profiles measure prior to the survey. A line spacing of 100m was used in order ensure 50% overlap between swaths.

The bathymetric chart (figure 7a) shows the reservoir floor to be gently sloping to from the west to the dam in the east with a step approximately half way down the reservoir where depths drop to greater than 40m. Many features were observed that remain from conditions before the glen was flooded such as the old road in the western half of the reservoir and a number of burrow pits. The meander channel of the western river courses can also be seen crossing the floor of the reservoir in the shelf area at the western end. A number of features were also evident particularly on the south shore of the reservoir and on steeper slopes on the north shore that were not present before the reservoir was constructed. The geometry of these features is characteristic of slumping events and this is reconfirmed with the difference or cut-fill map (figure 7b) between the old topography and the bathymetry from the swath-sounding survey.

Discussion

The swath-sounding sonar system provides very high resolution bathymetry when used in conjunction with differential GPS and a motion reference unit. The sonar can be deployed on a wide range of vessels of opportunity for a variety of survey objectives. The 234kHz sonar transducers have an effective survey depth of 100m and the 117kHz transducers a survey depth of 250m. Under typical survey conditions this manifests itself as $0.25m^2$ and $1m^2$ ensonified patches with 25 and 50cm depth resolution where full differential GPS and motion reference is available. The high bathymetric survey fidelity and the repeatability of the survey method are of particular advantage to users who wish to record small bathymetric variations but also need to measure changes in bathymetry over time. Furthermore, with nearly 100% coverage at swath widths of up to 15 times the water depth the method can be highly cost-effective for surveying large areas. The method has some bathymetric resolution limitations at very steep bottom slope angles but is particularly effective where slopes are gentle. The amplitude data, which is recorded simultaneously and co-located with the bathymetric information, contains additional semi-quantitative information on bottom type. Current research programmes at a number of institutions aim to utilise this data for full quantitative remote bottom classification.

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Figure Captions

Figure 1) Bathymetry for Plymouth Harbour

Figure 2a) bathymetry from north-south lines through calibration area, 2b) bathymetry from east-west lines through calibration area

Figure 3) Amplitude returns for Plymouth Harbour

Figure 4) Bottom type classification for Plymouth Harbour based on bathymetry and amplitude

Figure 5) Inner and mid-loch bathymetry for Loch Sunart together with bedrock geology and the limits of ice re-advance during the last re-advance

Figure 6a) and 6b) Amplitdue response over de Geer moraine features in Loch Sunart; 6c) slope angel measured from bathymetry; 6d) slope aspect measured from bathymetry over moraine features. Backdrop is bathymetry of inner loch

Figure 7a) bathymetry of the Megget Reservoir in elevation above OD; 7b) net loss and gain (cut and fill) within reservoir

Figure 1

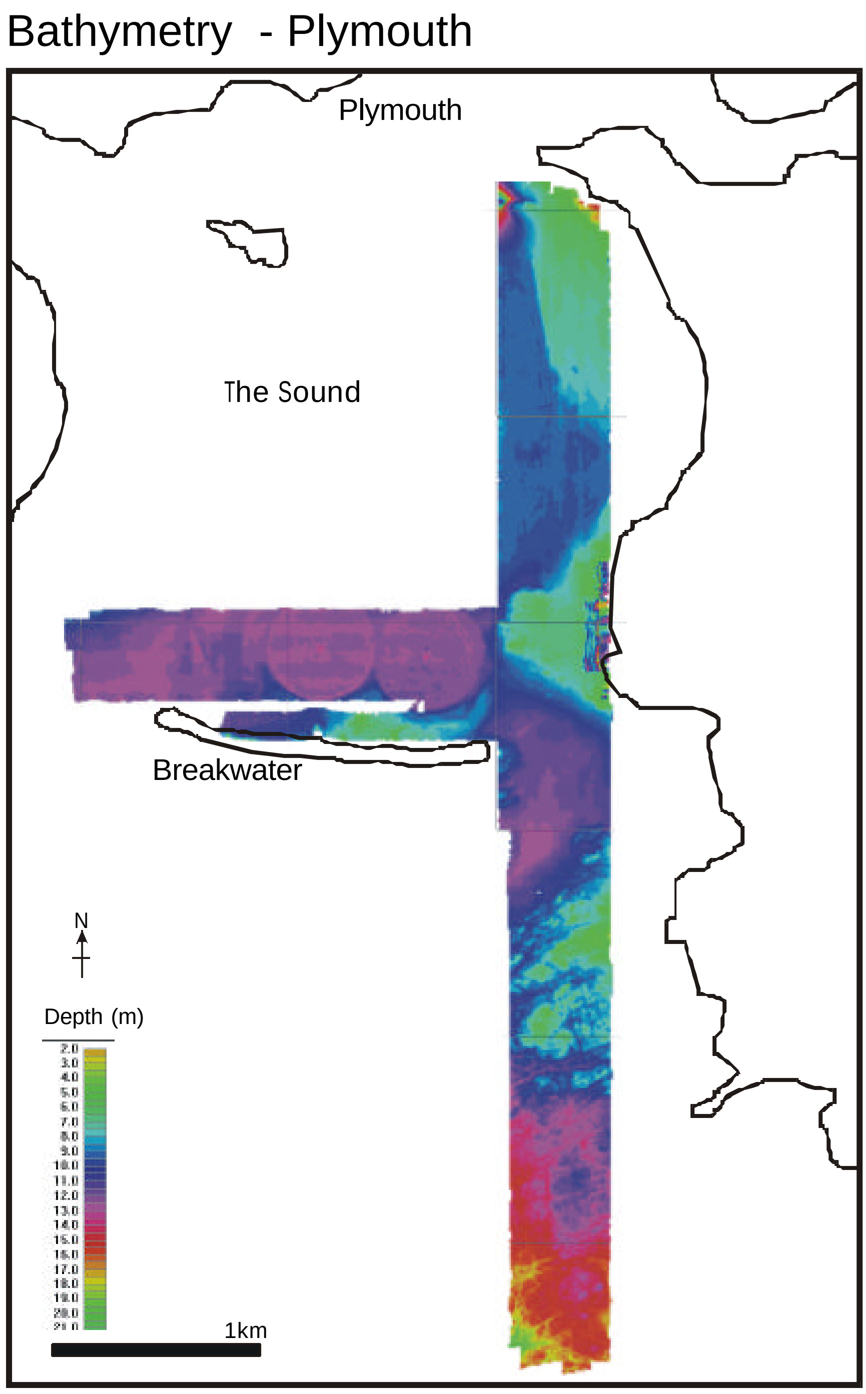


Figure 2a

North-south lines

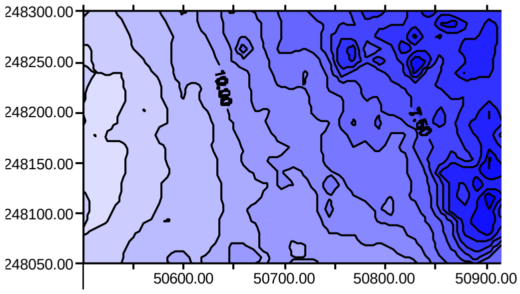
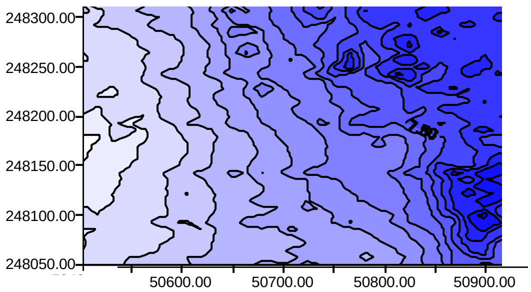


Figure 2b

East-west lines



Depth contour interval 0.5m

Figure 3

Amplitude - Plymouth

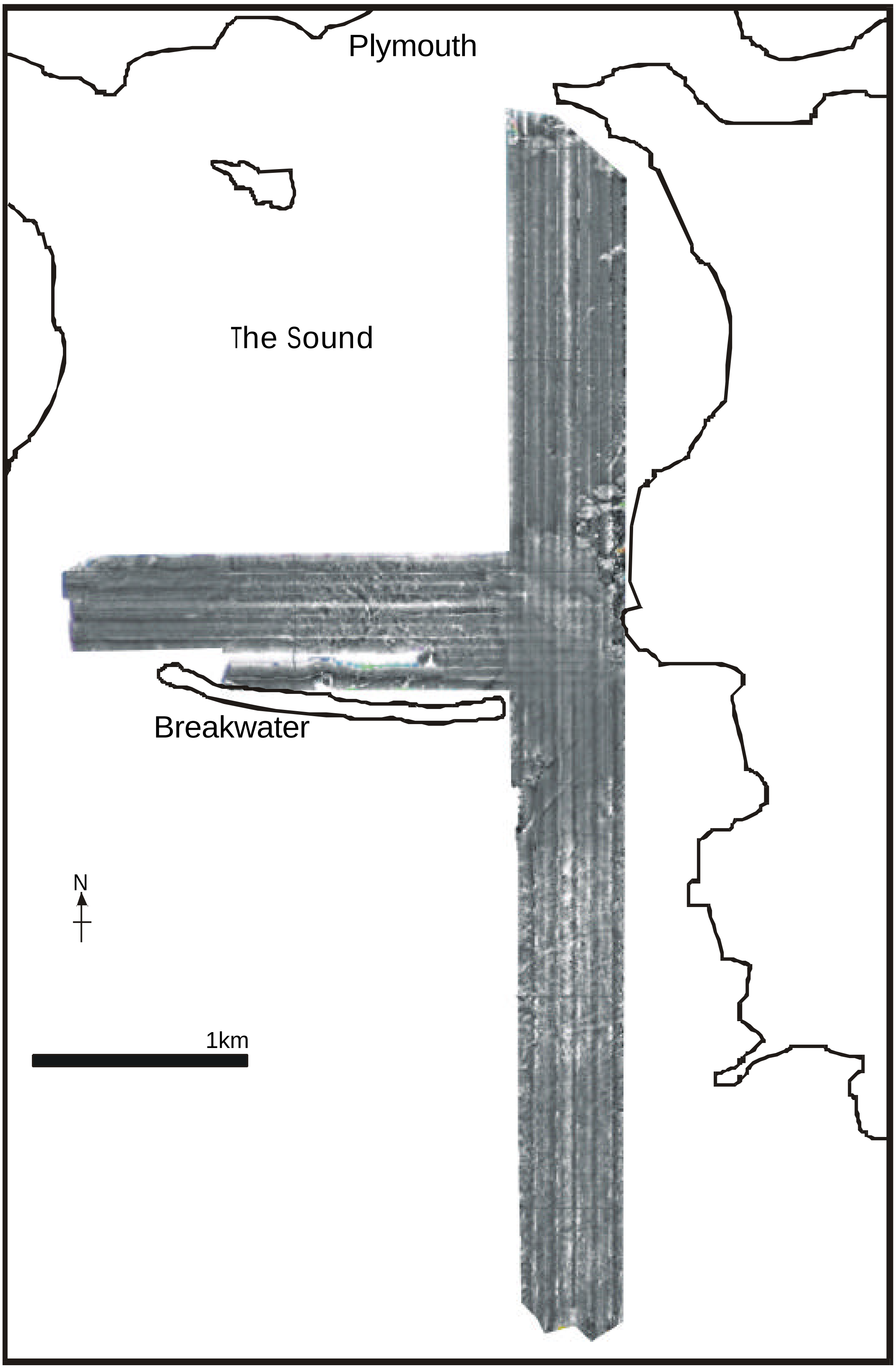


Figure 4

Bottom Classed Groups - Plymouth

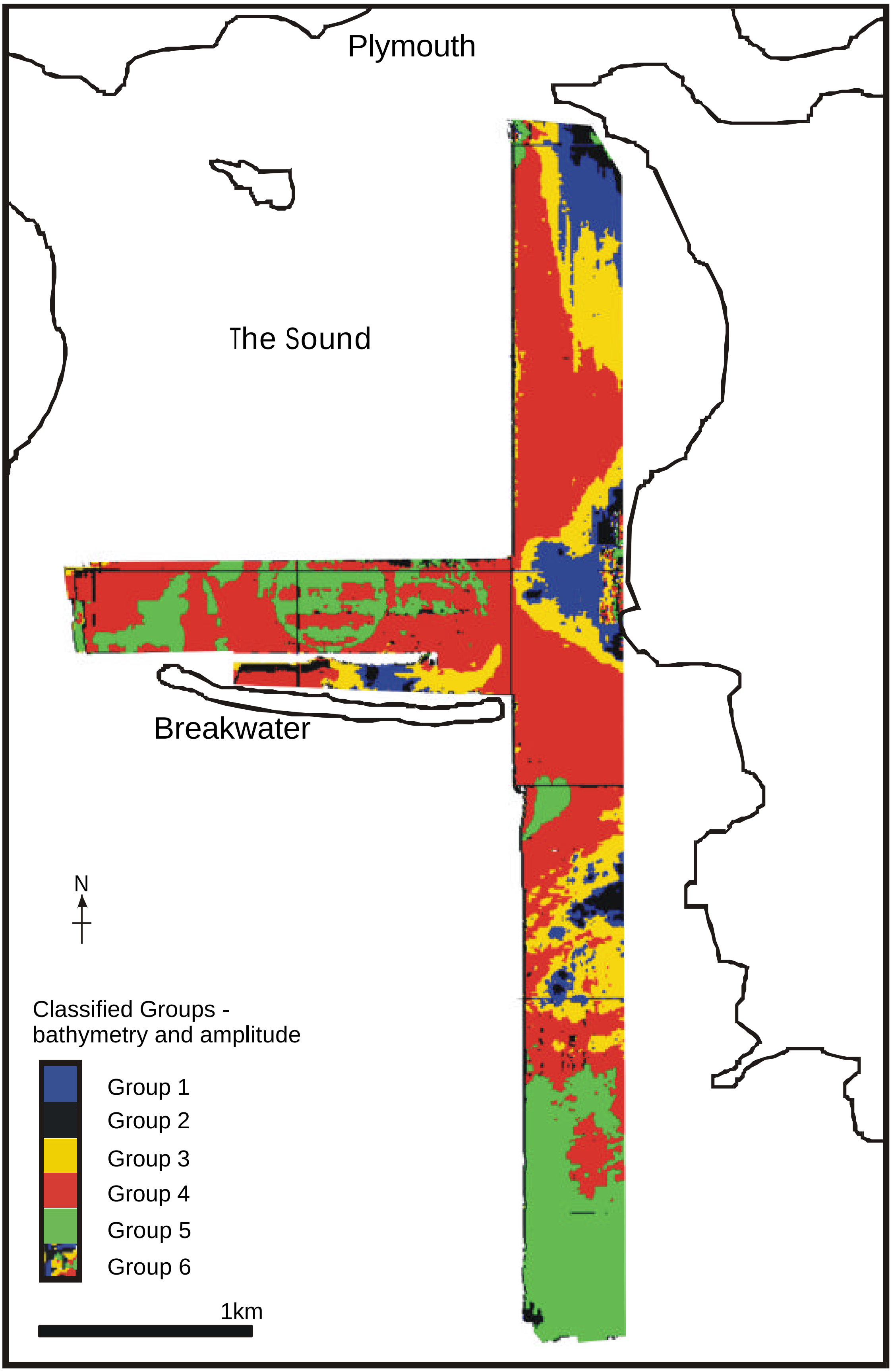
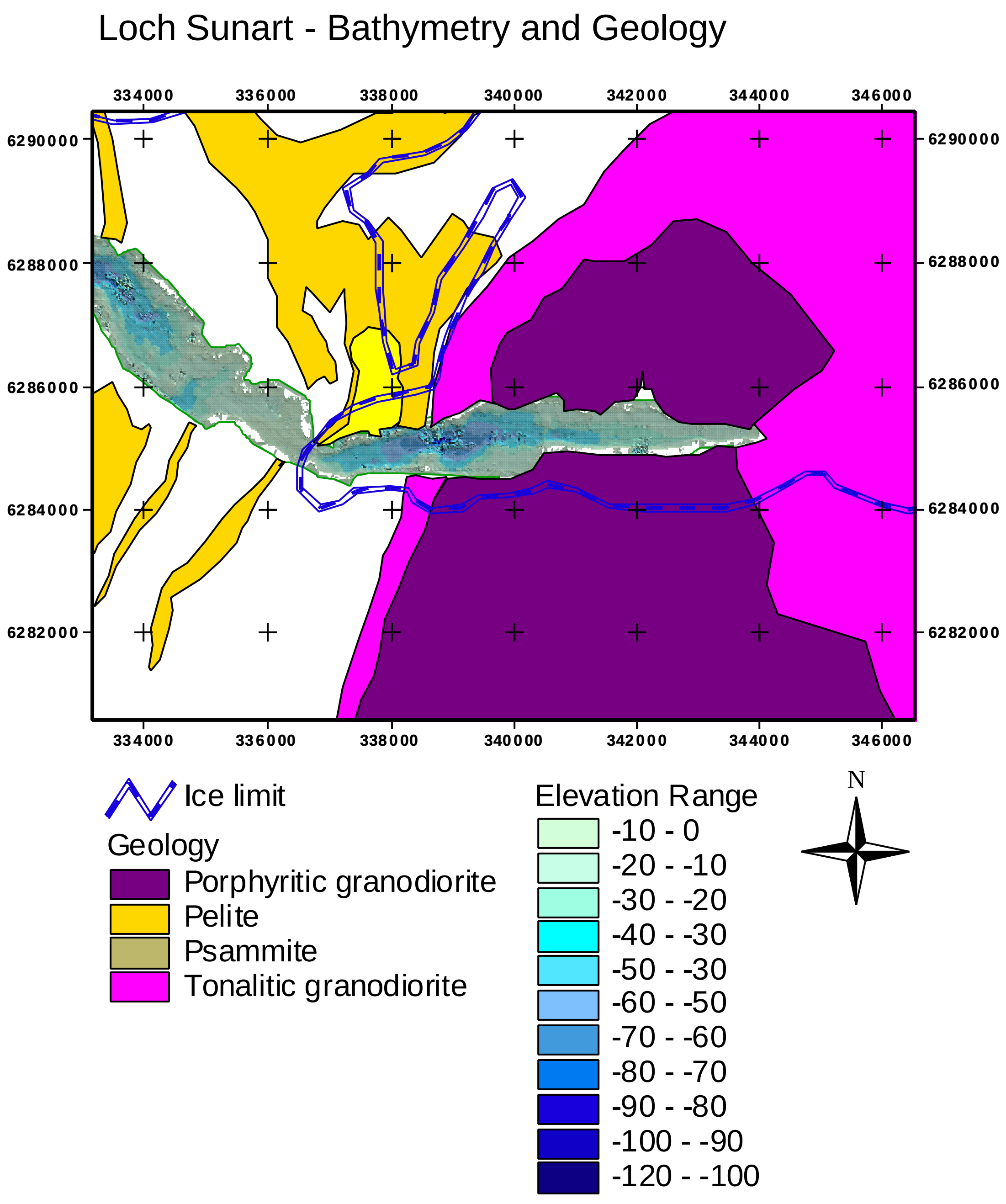
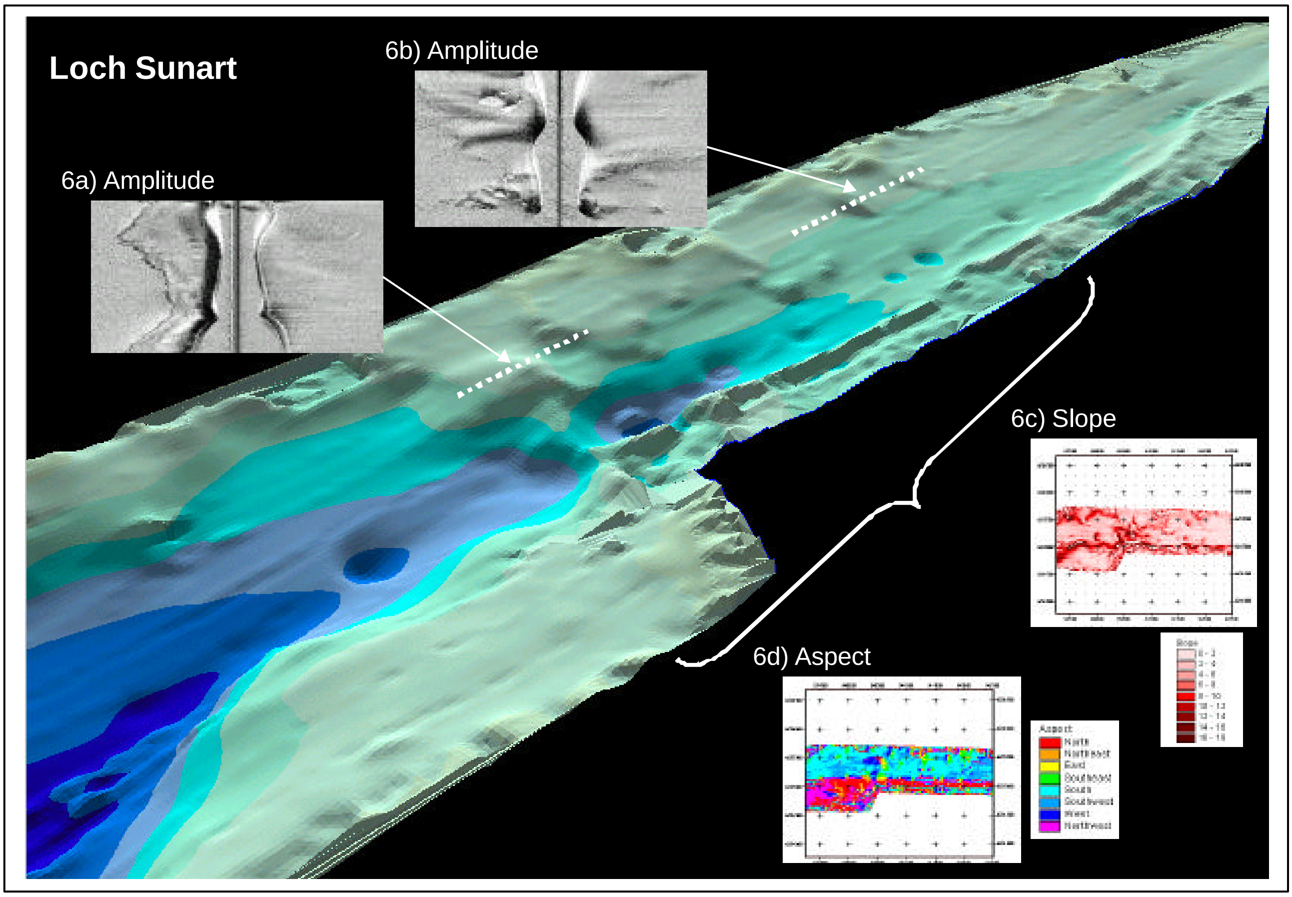
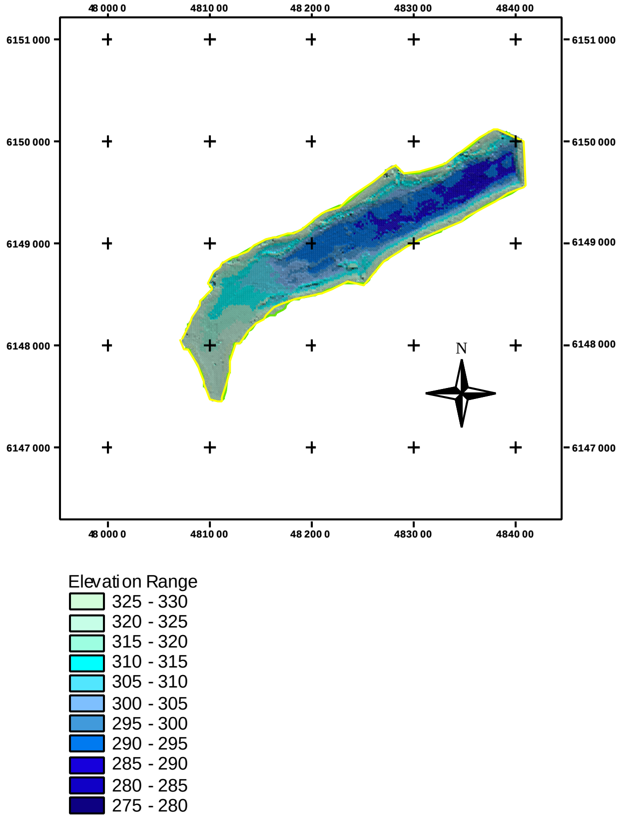


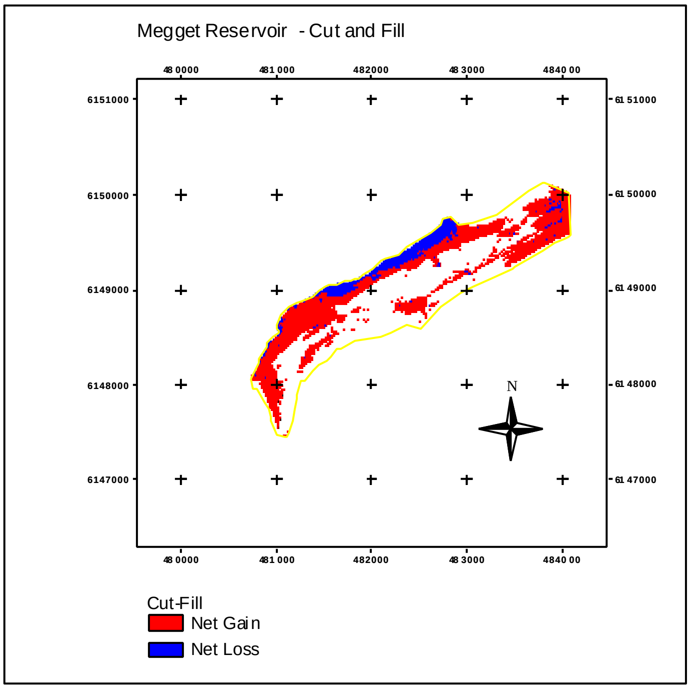
Figure 5


Loch Sunart - Bathymetry and Geology
334000
336000
338000
340000
342000
344000
346000
6290000
6288000
6286000
6284000
6282000
Ice limit
Geology
Porphyritic granodiorite
Pelite
Psammite
Tonalitic granodiorite
Elevation Range
-10 - 0
-20 - -10
-30 - -20
-40 - -30
-50 - -30
-60 - -50
-70 - -60
-80 - -70
-90 - -80
-100 - -90
-120 - -100
N


Loch Sunart
6a) Amplitude
6b) Amplitude
6c) Slope
6d) Aspect

Megget Reservoir - Bathymetry




Megget Reservoir - Cut and Fill
480000
481000
482000
483000
484000
6151000
6150000
6149000
6148000
6147000
N
Cut-Fill
Net Gain
Net Loss