An example of how the text file of your article should be formatted. Please include continuous line numbers

The font style and size is not important. Full instructions for presentation and style can be found at:

http://www.geolsoc.org.uk/author_instructions

Note: please submit your text as an editable file, not a PDF.

Coincident swath acoustic backscatter and bathymetry for the interpretation of shallow-water sediment composition and processes

Barbara Glynn[1], Colin Brown[2*] & Shane Rooney[1, 3]

[1]*Research School of Earth Sciences, The Australian National University, Canberra, ACT 0200, Australia*

[2]*Department of Earth and Ocean Sciences, National University of Ireland, Galway*

[3]*Present address: Department of Earth Science, University of Oxford, Parks Road, Oxford Ox1 3PR, UK*

**Corresponding author (e-mail: colin.brown@nuigalway.ie)*

Abstract: Two surveys from the west of Ireland demonstrate how the combination of high-resolution, geo-referenced, spatially coincident, swath acoustic bathymetric and backscatter data is effective for understanding underwater geological processes and assisting the design of environmental monitoring programmes. One case study corroborates terrestrial observations of Quaternary glacial cycles around Clew Bay by identifying seabed morphology that is consistent with a glacial advance from east to west, followed by deglaciation and a subsequent re-advance to the NW during the Last Glacial Maximum.

Supplementary material: [description of material] is available at https://doi.org/xxxx'. [GSL will assign the doi and url unless you already have one]

Over the last decade, there have been significant advances in remote sensing technology for mapping the seabed, based upon the reflection of swath acoustic waves from a water-sediment interface. Some swath sonars can simultaneously collect data on the strength of the returned echo (backscatter) and on detailed bathymetry; these data have been used *inter alia* to interpret seabed geology, understand surficial sediment processes (Coxon 2001*a*, *b*; Müller *et al.* 2007), identify geotechnical hazards and sub-seabed gas seeps (Orange *et al*. 2002), assess environmental impacts, and classify benthic habitats (Fig. 1).

We show that interferometric swath sonars (see Fig. 3) that acquire geo-referenced, spatially coincident, swath acoustic bathymetric and backscatter data are well-suited and cost effective for mapping shallow underwater environments. We outline data acquisition and processing methods and demonstrate the effectiveness of a combined interpretation of backscatter and bathymetric data by referring to case studies in two locations on the west coast of Ireland. The landscape in each location is dominated by glacial processes but each offers different and significant scientific problems. Clew Bay, an embayment open to the Atlantic Ocean, is in a region with a history of studies of Quaternary geology on land. Acoustic remote sensing of the seabed in Clew Bay provides the first opportunity to map the distribution of the submarine sediment associated with Last Glacial Maximum (LGM) or late Devensian glaciation (23–13 ^{14}C ka BP). Lough Corrib, a freshwater lake that drains into Galway Bay, is a region where environmental concerns require an understanding of the hydrogeology of pollution.

Geological setting

The geology of the two areas is summarized in Figure 1. Previous hydrographic data are restricted to depths at points, acquired using a lead-line sounding technique and line-of-sight triangulation, and a categorization of sediment type (e.g. mud, sand, rock). The surveys described in this paper obtain 100% coverage of swath acoustic data over specific areas of interest (Table 1). They include sediment grab samples that allow calibration of sediment type with acoustic backscatter (Table 2).

Lough Corrib is the largest of the western Irish lakes (Figs 2–4). Its northern basin (the focus of this study) has a maximum depth of *c.* 50 m. To the north and the west, numerous rivers provide river-borne sediments into the basin; to the east is flat peat bog and farmland with few streams. The lake is managed as a recreational fisheries resource, supports a commercial eel fishery and is an important tourist attraction for the region. However, over the last few decades, changes in farming practices around the lake have generated concerns about its vulnerability to eutrophication (Alvisi & Dinelli 2002; Cannaby 2005). Elsewhere, studies of lake sediments have provided information on the distribution of aquatic benthos (Denny & Danforth 2002) and natural and anthropological influences on the evolution of lakes (Juracek 1997; Geen 1999). The spatial distribution and composition of sediments in Lough Corrib inferred from high-resolution swath acoustic data are therefore essential for the design of integrated environmental monitoring programmes.

Data acquisition and processing

The swath acoustic surveys were conducted with a hull-mounted Submetrix 2000 Series interferometric sonar (Fig. 4; Sanei *et al.* 2001; Wilson *et al.* 2007), a phase discrimination system operating at a centre frequency of 234 kHz. The system acquires geo-referenced bathymetry and backscatter data simultaneously along a swath at right angles to the direction of the vessel. It is sufficiently compact and easy to use that it can be deployed on any covered vessel with the capacity to take a skipper and one technical person.

$$\omega = \mathrm{atan}\left(\frac{a_y^b}{a_x^b}\right) \tag{1}$$

$$\vartheta = \mathrm{atan}\left(\frac{a_x^b \cos\omega + a_y^b \sin\omega}{-a_z^b}\right) = \mathrm{atan}\,\frac{\sqrt{(a_x^b)^2 + (a_y^b)^2}}{-a_z^b} \tag{2}$$

Tidal variations in Clew Bay were predicted every 10 minutes using Admiralty TOTAL tide software (Fig. 3). During the Lough Corrib survey, a decrease in the water level of 0.5 m over two weeks was measured at three tidal gauges. The swath bathymetry data were corrected for tidal and water level variations, water sound velocity, vessel motion and acoustic sensor-GPS offset. These were reduced to the Malin Head Datum and horizontal locations were transformed into UTM Zone 29N coordinates for Clew Bay and the Irish National Grid for Lough Corrib. The horizontal resolution of the data is 2 m but, in order to manipulate a dataset of manageable size, these data were gridded with a cell size of 5 m. The gridded data were then filtered to reduce long-wavelength noise associated with inaccurate removal of tidal variations along and between survey lines.

Sediment samples. Sediment samples were collected using a 0.1 m^2 Van Veen grab at 11 geo-referenced sites prior to the Clew Bay acoustic survey. These were analysed for grain size using conventional sieve techniques. Samples in Lough Corrib were acquired with a Jenkinson corer consisting of a Perspex tube (diameter 75 mm) pushed into the sediments with a piston. These were analysed for organic content and redox profile and were scanned for 46 elements with an inductively coupled mass spectrometer (Keane, pers. comm. 2006).

List style

Lists take up more space than normal text and their use should be carefully considered. Where they offer great enhancement of the argument, they should be laid out thus (with a tab after the number/letter):

(a) they should begin with a colon;
(b) each item in the list should be only one phrase;
(c) the items should be numbered or lettered;
(d) the number/letter should be enclosed in parentheses;
(e) the phrases should end with a semi-colon;

(f) the only full stop should be at the end of the list.

Where the listed items comprise more than one sentence, they should not start with a colon. Numbered paragraphs may be more appropriate in such cases.

Conclusions

A combination of bathymetric and backscatter data, interpretation techniques based on terrain attributes (e.g. bathymetric position index) and classification of sediment types based on backscatter data has been more effective than interpretations of individual data sets for understanding geomorphology and sedimentology in Clew Bay or Lough Corrib.

The following people ensured the completion of this paper: Kieran McCarthy, Ian O'Connor, Bridget Keane, Mike Williams, Margaret Wilson, Fiona Grant, Eve Daly, Paul Ryan, Tracy Vallier and Saidbh Baxter, Niall O'Boyle of the *Inishoo*, David Luskin and Tony Youlton of the *Corrib Queen* and Tom Hiller of GeoAcoustics. The Submetrix system and Barbara Glynn's funding was acquired through the Higher Education Authority Programme for Research in Third Level Institutes, Cycle 2. We thank Richard England and an anonymous reviewer for their comments.

References

Alvisi, F. & Dinelli, E. 2002. Evolution of sediment composition of the coastal Lake San Puoto (Latium, Italy) in the last two centuries. *Journal of Limnology*, **61,** 15–26.

Brinkhurst, R. O. 1974. *The Benthos of Lakes.* McMillan, New York.

Cannaby, H. 2005. *The physical limnology of Lough Corrib.* PhD thesis, National University of Ireland, Galway.

Coxon, P. 2001*a*. Cenozoic: Tertiary and Quaternary (Until 10,000 years Before Present). *In*: Holland, C.H. (ed.) *The Geology of Ireland.* Dunedin Academic Press, Edinburgh, 387–428.

Coxon, P. 2001*b*. *The Quaternary History of Clare Island, New Survey of Clare Island, volume 2: Geology*. Royal Irish Academy, Dublin.

Denny, J. F. & Danforth, W. W. 2002. USGS shallow water mapping surveys using an interferometric sonar system. *In: Multibeam Echosounding – The Total Inshore Solution? Overcoming the shallow water challenge.* Hydrographic Society of the United Kingdom, 1–9.

Geen, M. 1999. Applications of interferometric swath bathymetry. *Sea Technology*, June, 25–30.

Juracek, K. E. 1997. A*nalysis of bottom sediment to estimate nonpoint-source phosphorus loads for 1981-96 in Hillsdale Lake, NE Kansas.* US Geological Survey, Water-Resources Investigations Report, **97-4235**.

Müller, R. D., Eagles, S., Hogarth, P. & Hughes, M. 2007. Automated textural image analysis of seabed backscatter mosaics: a comparison of four methodologies. *In:* Greene, G. & Todd, B. (eds) *Marine Benthic Habitat Mapping. Mapping the Seafloor for Habitat Characterization*. Geological Society of Canada Special Papers, **47**, 43–62.

Sanei, H., Goodarzi, F. & Van-Der Flier-Keller, E. 2001. Historical variation of elements with respect to different geochemical fractions in recent sediments from Pigeon Lake, Alberta, Canada. *Journal of Environmental Monitoring*, https://doi.org/10.1039/b006819p

Wilson, M. F. J., O'Connell, B., Brown, C., Guinan, J. C. & Grehan, A. J. 2007. Multi-scale terrain analysis of multibeam bathymetry data for habitat mapping on the continental slope. *Marine Geodesy*, **30**, 3–35.

Figure captions

Fig. 1. Location and geological setting of Clew Bay and Lough Corrib on the west coast of Ireland. Inset shows Ireland and the UK on the eastern margin of the Atlantic Ocean. G, Galway.

Fig. 2. (**a**) Location map of Clew Bay and generalized geology of the surrounding area. The survey area is shown between Clare Island and Achillbeg Island at the southern tip of Achill Island. ABF, Achillbeg Fault; LF, Leck Fault; EF, Emlagh Fault. (**b**) The distribution of glacial landforms, principal directions of ice flow, moraine ridge and possible ice limits of the Glenavy Stadial (Last Glacial Maximum) in Clew Bay (after Alvisi & Dinelli 2002). Coloured inset is area of study.

Fig. 3. (**a**) Shaded relief bathymetry data gridded at 5m and illuminated from the NE. 1: Inferred unconformable geological contact between Carboniferous sandstones and older rocks. (**b**) Detailed bathymetry around Clare Island's palaeo-coastline. (**c**) Detailed bathymetry around Achillbeg Island's palaeo-coastline. (**d**) Detailed bathymetry showing submerged drumlin and surface depressions in the east of the survey area.

Fig. 4. Map of bathymetric position index for the Clew Bay survey. Positive values (indicating a cell elevation higher than its neighbours) are white, negative values are black. The locations of the eleven sediment samples are marked. The location of the end moraine is indicated.

Table 1. *Percentages of sediment type in eleven grab samples from Clew Bay*

	Late Early Miocene*	**Middle Miocene†**	**Late Miocene**	**Pliocene–Recent**
vs	15 000 km^3	36 000 km^3‡	40 000 km^3	38 000 km^3
a	46 200 km^2 §	46 200 km^2	46 200 km^2	46 200 km^2
$\mathbf{a}_1$	9000 km^2	6000 km^2	2000 km^2	1000 km^2
$\mathbf{a}_2$	minor to 13 600 km^2?	minor to 5500 km^2?	1000 km^2¶	0 km^2
$\mathbf{a}_3$	4600 km^2	4600 km^2	0 km^2	0 km^2
d	0.91	0.91	0.89	0.86
$\boldsymbol{v_{rw}}$	10 000 km^3	6000 km^3	2000 km^3	0 km^3

Table legends must be under the table, preceding table footnotes.
*First table footnote
†Second table footnote
‡Third table footnote
§ Fourth table footnote
¶ Fifth table footnote

Table 2. *An example of a second table*

Spanned heading		**Column 3**
Column 1*	**Column 2†**	
Abc	Def	Ghi
Heading within the table		
Jkl	Mno	Pqr
Stu	Vwx	Yza
Bcd	Efg	Hij

*First table footnote
†Second table footnote