The Environmental Background to the 2008, 2009 and 2010 Meso- and Bathypelagic Trawl Surveys of The Gully

T.J. Kenchington, N.A. Cochrane, C. Gjerdrum, B.J.W. Greenan, C. Lirette, H. Moors-Murphy and S.E. Thompson

Department of Fisheries & Oceans,
Maritimes Region.
Ocean and Ecosystem Sciences Division,
Bedford Institute of Oceanography,
PO Box 1006, Dartmouth,
Nova Scotia B2Y 4A2
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THE ENVIRONMENTAL BACKGROUND TO THE 2008, 2009 AND 2010 MESO- AND BATHYPELAGIC TRAWL SURVEYS OF THE GULLY

by

T.J. Kenchington[1]

with

N.A. Cochrane, C. Gjerdrum[2], B.J.W. Greenan,
C. Lirette, H. Moors-Murphy and S.E. Thompson

Department of Fisheries & Oceans,
Maritimes Region,
Ocean and Ecosystem Sciences Division,
Bedford Institute of Oceanography,
PO Box 1006, Dartmouth,
Nova Scotia B2Y 4A2 CANADA

[1]: Present address: Gadus Associates, 8765 Highway #7, R.R.#1 Musquodoboit Harbour, NS B0J 2L0 CANADA
[2]: Canadian Wildlife Service, Environment Canada, 45 Alderney Drive, Dartmouth, NS B2Y 2N6 CANADA

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ABSTRACT

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Three midwater-trawl surveys of the nekton and micronekton at meso- and bathypelagic depths in The Gully, a submarine canyon and Marine Protected Area immediately east of Sable Island, were conducted in August / September 2008, August 2009 and March 2010 respectively. The surveys were designed to gather data on fish, cephalopods and crustaceans but the catches also included assorted gelatinous plankton and various other species, which were all recorded. The trawling was supplemented with CTD casts, continuous acoustic recording at 38 kHz and (in 2009 only) 120 kHz, sampling with a fine-mesh Tucker Trawl in 2008, plus monitoring of marine mammals and (in 2010 only) seabirds throughout daylight hours. The resulting ancillary data were not intended to support independent studies but rather provide an environmental background to aid interpretation of the catches of the three major taxa. In this report, they are summarized and interpreted for that purpose.

RÉSUMÉ

Kenchington, T.J., N.A. Cochrane, C. Gjerdrum, C. Lirette, B.J.W. Greenan, H. Moors-Murphy and S.E. Thompson. 2014. The Environmental Background to the 2008, 2009 and 2010 Meso- and Bathypelagic Trawl Surveys of The Gully. Can. Tech. Rep. Fish. Aquat. Sci. 3114: vi+251p.

Trois relevés au chalut pélagique des espèces de necton et de micronecton des profondeurs mesopélagiques et bathypélagiques dans le Gully, un canyon sous-marin et une zone de protection marine directement à l'est de l'île de Sable, ont été menés au cours des mois d'août et de septembre 2008, d'août 2009 et de mars 2010, respectivement. Les relevés ont été conçus pour recueillir des données sur les poissons, les céphalopodes et les crustacés, mais les prises comprenaient également du plancton gélatineux assorti et diverses autres espèces, qui ont toutes été consignées. Les relevés au chalut ont été complétés à l'aide de sondes CTD, d'enregistrements acoustiques continus (38 kHz et, en 2009 seulement, 120 kHz), d'échantillonnage à l'aide d'un chalut Tucker à mailles fines en 2008, en plus de la surveillance des mammifères marins (en 2010 seulement) et des oiseaux de mer pendant les heures de clarté. Les données accessoires découlant de ces relevés ne visent pas à appuyer des études indépendantes, mais plutôt à définir le contexte environnemental pour faciliter l'interprétation des prises des trois principaux taxons. Dans le présent rapport, elles sont résumées et interprétées à cette fin.

1 GENERAL INTRODUCTION

The Gully, which cuts the edge of the continental shelf immediately east of Sable Island, is the largest submarine canyon on the eastern seaboard of North America (Figures 1 and 2). Much of it falls within a Marine Protected Area ("MPA"), designed in part to support an endangered population of northern bottlenose whales (*Hyperoodon ampullatus*). The whales are specialist predators of armhook squid (*Gonatus* spp.), which they eat at lower mesopelagic and upper bathypelagic depths (Hooker *et al.* 2001). Conservation of the bottlenose whales, and hence the success of the MPA, require maintenance of the supply of squid but the prey supporting the latter and the reasons for their concentration in The Gully remain unknown.

A research program focused on understanding the pelagic ecosystem at meso- and baythypelagic depths in The Gully, both in support of MPA management and as an example of canyon ecosystems globally, was therefore initiated. It commenced with a series of four fixed-station, depth-stratified and replicated midwater-trawl surveys of the fish, cephalopod and crustacean nekton and micronekton, which surveys were conducted from 2007 to 2010. The surveys, which used International Young Gadoid Pelagic Trawl ("IYGPT") nets (though a larger "Diamond IX" trawl was also deployed), were not expected to catch *Gonatus* spp. or other large, active squids, that can readily evade such nets. Rather, the aim was to complement on-going studies of the plankton in The Gully by developing an understanding of a (primarily planktivorous) fraction of the deep pelagic ecosystems in the canyon – a fraction that was expected to include the food supply available to the larger squid, which in turn support the bottlenose whales. The first fruits of that work are now being published (e.g. DeVaney *et al.* 2009; MacIsaac 2011; MacIsaac *et al.* 2014).

The field methodology of the four surveys has been presented in detail by Kenchington *et al.* (2009, 2014). Besides the IYGPT and Diamond IX trawling, the surveys included collection of various ancillary types of data. Some were expected to provide information on the spatially and temporally specific environmental conditions from which the trawl catches were taken, one was intended to answer a specific question, while the rest utilized the survey ships as platforms-of-opportunity for other, on-going research programs. Some of the resulting data streams, including temperature and salinity measurements as well as observations of marine mammals and birds, fed into larger data sets and will be analyzed in that context in due course, by specialists in the appropriate fields. The other data types were specific to the midwater-trawl surveys but none (excepting the trawl catches of fish, cephalopods and crustaceans themselves) yielded sufficient information to support independent studies, nor were they

intended to. Rather, they can provide a background to aid interpretation of analyses of the catch data.

For the 2007 survey, Kenchington *et al.* (2009) presented not only the field methodology but also the information on the environmental background gathered during the cruise. The equivalent information from the 2008 to 2010 surveys is presented here. It includes: CTD data on water temperatures, salinities and oxygen concentrations, sounder records of acoustic scattering layers, the catches taken by a fine-mesh Tucker trawl, plus marine-mammal and seabird observations. In addition, the IYGPT and Diamond IX catches of invertebrates other than cephalopods and crustaceans (along with the very limited catches of macroalgae), are fully reported here. The nets were not suited to sampling those "other" taxa and the limited data obtained from the surveys cannot support detailed study but they do merit being placed on record. Since the various data types had little in common, aside from being collected on the same survey cruises, they are addressed in a series of unconnected sections in this report. In preparing them, the central aim has been to describe the contents of the various datasets and particularly cross-connections amongst them, leaving the development of conclusions to later papers.

The combination of this report with those of Kenchington *et al.* (2009) and Kenchington *et al.* (2014) is intended as a reference source for future detailed studies of the trawl catches. In light of that aim, Section 2 proceeds beyond a mere summary of the CTD data collected during the three surveys by offering an account of the physical and chemical oceanography of The Gully, following an expectation that future analysts of the trawl-catch data will benefit from that summary. Since the three reports are to be used together, the details of field methodology presented by Kenchington *et al.* (2014) are not repeated here. The only data stream gathered during the surveys that is relevant to interpretation of the trawl catches but which is not considered in this trio of reports is that derived from the headline sensor packages mounted on the trawls. That will be the subject of a fourth report in due course.

This report was prepared by the senior author, with much assistance from multiple specialists in its various subject areas. He is solely responsible for Sections 1, 4 and 6. Section 5 was built on laboratory work undertaken by S.E. Thompson, while Sections 2, 3, 7 and 8 were prepared jointly with, respectively, Dr. B.J.W. Greenan, Dr. N.A. Cochrane, Dr. H. Moors-Murphy and C. Gjerdrum. C Lirette prepared most of the many maps which are an essential feature of the report. The document has been prepared for reading in digital format and many of the figures are therefore provided at high resolution, allowing readers to zoom in and examine fine details.

Throughout, it is often necessary to discuss spatial distributions of various features of the canyon's ecosystems on scales much finer than The Gully. References to latitudes and longitudes have their place but can swiftly become confusing to readers. In this report, it is sometimes possible to relate data to the trawling stations used in the survey series (Figure 3) but reference to local bathymetric features is needed also. Unfortunately, there is no agreed nomenclature for those, while the few commonly adopted names have been used in contrasting ways in the past, which appears to have sometimes led to misunderstandings. Meanwhile, perceptions of The Gully's ecosystems have too readily been constrained by the spatial extent to which that name has been applied. To avoid perpetuating such confusions, this report adopts a nomenclature that is at once new and, internally, standardized. The names used in this report are detailed in Table 1 and illustrated in Figures 1 and 4.

2 PHYSICAL AND CHEMICAL OCEANOGRAPHY

T.J. Kenchington and B.J.W. Greenan

2.1 INTRODUCTION

The ancillary data type gathered during the surveys that is of greatest importance for interpretation of the trawl catches comprises the records of temperatures, salinities and oxygen concentrations obtained from CTD casts, which provide information on physical and chemical conditions in the water column. Those data are examined in Section 2.4 below, which includes a re-interpretation of the casts made in 2007 (and previously considered by Kenchington *et al.* 2009) that is necessitated by recent revisions to understanding of the oceanography of the canyon (cf. Swart *et al.* 2011, Greenan *et al.* 2013, 2014). To provide a context for understanding the CTD data, Section 2.2 offers a brief and non-definitive summary, suited to the needs of ecologists, of the major water masses and currents which influence the waters of The Gully, including both those of the Scotian Shelf region and those of the western basin of the North Atlantic Ocean more generally. That summary is supported by a graphical representation in Figure 5. The many abbreviations used as labels for the water masses and other oceanographic features are drawn together in Table 2. That is followed, in Section 2.3, by an overview of what is known of the physical and chemical oceanography of The Gully itself. The CTD data gathered during the trawl surveys may, in time, assist in refining that understanding but Section 2.4 is confined to an interpretation of the temporally and spatially specific conditions during the fishing, placing those data in the context established by Section 2.2 and 2.3. Broader questions are not addressed here.

Studies of deep-ocean biogeography have traditionally made much use of named water masses. In the process, ecologists have tended to interpret those as discrete units that are stable over time and space, while being known and classified absolutely. In contrast, the physical oceanographers who identify the water masses are more likely to see them as convenient, and partially arbitrary, simplifications of a very complex reality. In Section 2.2, we have attempted to provide the sort of classification of water masses that will be expected by future analysts of the trawl-catch data, without denying the complexity. In Section 2.4, we have aimed both to identify which of those water masses each trawl set encountered and to show how severely over-simplified any such characterization of the waters in the canyon must be.

The initial accounts of the oceanography of The Gully, prepared in support of MPA planning (Petrie *et al.* 1998; Han *et al.* 2002; Strain and Yeats 2005), necessarily relied on then-available data, most of which was regional, rather than

Gully-specific. A field program that deployed current-meter moorings from April 2006 until August 2007, together with extensive CTD surveys at the times of both deployment and recovery of the moorings, has since allowed for a much better-founded understanding of water movements in the canyon (Swart *et al.* 2011, Greenan *et al.* 2013, 2014). On some key points, the conclusions of the earlier studies must now be set aside. Four moorings were deployed, one (mooring SG2) on the thalweg in the upper canyon, close to the northern end of the Head Station of the trawl surveys, and the other three as a section across the central canyon, passing close to the northern end of the Main Station. Of those three, the central one (SG11) was on the thalweg near the Main Station, while mooring SG10 lay almost on the line of the Wall Station and SG12 was on the western wall of the canyon (see Kenchington *et al.* 2009, 2014; Greenan *et al.* 2013, 2014).

To date, analyses of the 2006–07 data (Swart *et al.* 2011, Greenan *et al.* 2013, 2014) have been confined to near canyon-scale phenomena. While there has been some attention to along- and across-canyon spatial variation, there has not been any consideration of particular features on the scale of, for example, the Banquereau Spur or the side canyons – which is to say, the scale at which the bottlenose whales (Hooker *et al*. 2002), and presumably their prey, are aggregated. Indeed, the 2006–07 field program was not designed to address such fine-scales. The instruments on the moorings recorded data continuously but initial emphasis in analysis has been on mean currents and on tides, the latter accounting for almost all of the temporal variation around the means. Evidence for episodic events, such as might be driven by meteorological forcing or the meanderings of the slope water beyond the canyon's mouth, has not yet been examined. The 2006 and 2007 CTD surveys provided valuable spatial coverage, around the fixed points of the moorings, but were inevitably temporally constrained into two temporal "snapshots" (lacking even the multi-day coverage of the CTD casts during the trawling surveys). Some attempt has recently been made to bridge those limitations of scale and spatio-temporal coverage through high-resolution circulation modelling. Shan *et al.* (2014a, b) used a multi-nested approach of five submodels, allowing consideration of high spatial precision (100 m^2 horizontally, 4 to 100 m vertically) for the complex bathymetry of the canyon and yet spatially extensive coverage of regional forcing. Unfortunately, the model could not capture the amplification of diurnal tides deep in the canyon, which is a principal feature of the circulation in The Gully (Swart *et al.* 2011). Nor did it well capture the sharp thermo-haloclines on either side of the Cold Intermediate Layer in the uppermost part of the water column (Shan *et al*. 2014b, their Figures 5 and 6). Modelled up-canyon transport rates were very much less than those estimated from mooring data (Shan *et al.* 2014a). Given those departures from empirical evidence, the reliability of other model outputs must be uncertain. Furthermore, Shan *et al.*'s (2014a, b) presentation of those outputs, although well suited to their purposes, is of limited present utility (e.g. offering

residence times within an arbitrary rectangle, rather than within specific portions of the canyon). Hence, only limited use is made in Section 2.3 of the published accounts of the modelling, though the model itself might prove very useful in addressing particular ecological questions.

2.2 WATER MASSES OF THE SCOTIAN SLOPE

2.2.1 Surface Waters

2.2.1.1 Scotian Shelf Waters ("SSWs"): The entire Gully MPA, and most of The Gully as a whole, is usually covered by the waters of the Scotian Shelf. Those are largely derived from the Gulf of St. Lawrence outflow: the two- or three-layered Cape Breton Current. In the Gulf, four principal inputs merge to create distinctive water masses. One is a winter flow of very cold, low-salinity Labrador Shelf Water through the Strait of Belle Isle, which extends across the Gulf at depths of around 75 m. It is supplemented by coastal water, carried clockwise around Newfoundland by the inshore branch of the Labrador Current, which enters the Gulf on the Newfoundland side of the Cabot Strait. The combination of those inputs is further diluted by river flow, primarily from the St. Lawrence itself but also from other drainage basins. In winter, surface cooling maintains the low temperatures and promotes the development of a mixed layer, with low salinities (31.5 to 33‰) and very low temperatures (≈0°C), extending to depths of about 100 m. Through spring and summer, a combination of surface dilution from the spring freshet, limited vertical mixing in calm weather and solar heating creates a thin surface layer, from a few metres to 30 m deep, of very low salinity (27 to 32‰) but high temperature, especially across the Southern Gulf. The lack of vertical mixing allows the surface to warm and also leaves the deeper portion of the winter surface layer at temperatures close to freezing, in the form of a distinct Cold Intermediate Layer ("CIL") between about 50 and 100 m depth – though with broad thermoclines both above and below. When solar heating is reduced as summer turns to fall, storms stir the waters, homogenizing the surface layer and the CIL, before winter cooling and renewed inflow through the Strait of Belle Isle return the cycle to its beginning. The fourth input to the Gulf is of subsurface oceanic water that enters along the Newfoundland side of the Laurentian Channel. Some of that water is entrained into the shallower layers but most recirculates within the Channel, either inside the Gulf or before entering it. The portion which passes in through the Cabot Strait before turning back forms the deep layer of the Gulf outflow, flowing primarily below the Channel's rim depth (approximately 150 m depth). It is both warmer and more saline (4–6°C, 34.5‰) than the overlying CIL (Koutitonsky and Bugden 1991; Chassé 2001). All four of the inputs, and hence both the volume and the characteristics of the outflow from the Gulf, are subject to inter-annual and longer-period variations (*e.g.* Drinkwater and Gilbert 2004; Gilbert *et al.* 2005).

The Cape Breton Current, two-layered in winter but three-layered in summer, occupies the southern side of the Cabot Strait, including parts of the deeper water of the Laurentian Channel to depths of 300 m (Koutitonsky and Bugden 1991). Once past Scaterie Island, portions of the surface layer and the CIL (though not the warmer, deeper layer, which is absent from the basins landward of Banquereau: Han and Loder 2003) turn and head down the coast as the Nova Scotia Current or else flood across the eastern Scotian Shelf. The majority of the Gulf outflow, however, continues southeast along the Laurentian Channel, turns around the eastern tip of Banquereau and flows thence south-westwards as a shelf-break current (Han and Loder 2003). As already noted, the northern side of the Channel, below its rim depth, primarily contains subsurface oceanic water, much of which recirculates without passing through the Cabot Strait and thus joins the flow around Banquereau, whence it too feeds into the shelf-break current, where it can be joined by additional water that follows the continental slope from the flank of the Grand Banks, passing but not entering the Laurentian Channel. Meanwhile, the surface layer of the waters between Cape Breton, the Scotian Shelf and Newfoundland is subject to aperiodic, meteorologically-driven flows that can over-ride residual water movements (*e.g.* Trites *et al.* 1986). Some of the surface water south of Newfoundland (largely derived from the inshore branch of the Labrador Current) thus moves across to the Nova Scotian side and also feeds into the shelf-break flow. The net result is a strong, year-round current along the outer edge of Banquereau, which passes the mouth of The Gully and continues along the shelf break. That current carries all three layers of the modified Gulf outflow: the summer-warmed, low-salinity surface, the CIL and the more-saline, warmer water beneath (Loder *et al*. 1997, Han *et al*. 1999). Those three together are here considered the “Scotian Shelf Waters”, in the plural, or “SSWs”, though they must be seen as comprising at least two and arguably three water masses, each corresponding to one of the layers[1].

Although the SSWs are essentially continental-shelf water masses, they usually extend a considerable distance beyond the shelf break and hence southward of the mouth of The Gully. Indeed, the core of the shelf-break current generally lies over the upper slope. The outer margin of the SSWs, denoted the “shelf / slope-water boundary” (“SSB”) and approximately corresponding to the 34.5‰ surface isohaline (Smith and Petrie 1982), averages about 100 km south of the canyon’s mouth (Petrie *et al.* 2008), though its seasonal mean position is closer in

1 The lower layer of the SSWs floods the basins of the central Scotian Shelf, reaching them by passing over the saddles between the banks west of Sable Island. In that setting, the layer has been described as “Slope Water” (e.g. Han and Loder 2003). What proportion of it is derived directly from the offshore waters of shelf-break and upper-slope depths (waters here recognized as LSW, WSW and sometimes GSW), rather than the deeper layer of the SSWs carried southwest by the shelf-break current, is unclear. The latter layer is itself formed from LSW and WSW that recirculated within the Laurentian Channel, merged with LSW that followed the outer margin of the Grand Banks and crossed the Channel’s mouth. Hence, distinguishing the alternative sources of the water deep in the shelf basins is not straightforward.

summer. In winter, there is typically a 6 to 8°C difference in sea surface temperature ("SST") across the SSB but the summer warming of the SSWs' surface layer can all but eliminate that thermal distinction (Loder *et al*. 1997).

Similar processes to those which create the three-layered water mass in the Gulf of St. Lawrence act on the Scotian Shelf. Thus, the surface layer and the CIL can be homogenized by convection in winter, replenishing the CIL while eliminating the halocline across the uppermost tens of metres. Local heating and the flow of very low salinity surface water from the Gulf restore the three-layer system during the summer (Loder et al. 1997).

While the SSWs move generally south-westwards across the Scotian Shelf, there is also a tendency for weak clockwise (anticyclonic) gyres to form around each bank and hence for anticlockwise (cyclonic) gyres over the channels and basins between the banks. In practice, additional drivers operate and the partial gyres which form are not always clearly linked to bathymetry (Han and Loder 2003).

2.2.1.2 Gulf Stream Water ("GSW"): The Gulf Stream, with its very saline, very warm water, passes so far south of the Scotian Shelf that even its meanders never approach the shelf break in the vicinity of The Gully. The Stream does, however, shed warm-core rings which can move landward far enough to approach the continental slope, some GSW even reaching the coastline. Close approaches are more common to the westward of Sable Island Bank but it is likely that rings approach the canyon at rare intervals and parcels of water from them may sometimes enter it. There is no direct evidence of that having happened but Houghton and Fairbanks (2001) reported that they had detected some GSW at a station about 50 km southeast of The Gully's mouth, while Han (2004) has mapped a ring passing some 75 km south of the canyon mouth in December 1999[2].

2.2.1.3 Warm Slope Water ("WSW"): Between the SSB and the Cold Wall of the Gulf Stream lies a broad band of what is usually denoted WSW (though originally simply "Slope Water" and more recently the "Atlantic Temperate Slope Water": MERCINA Working Group 2001). It is formed by mixing of shelf and offshore waters in the vicinity of Cape Hatteras, where the Gulf Stream breaks away from the continental slope, and is further modified by inputs from warm-core rings, pinched off from Gulf Stream meanders.

From Hatteras to the Nantucket Shoals, WSW forms the surface of the "Slope Sea", which is bounded by the Gulf Stream and the shelf break, where the SSB forms a pronounced front. In that region, the WSW circulates around a partially-

[2] Swart *et al.* (2011) stated that The Gully is occasionally perturbed by Gulf Stream Rings, citing Strain and Yeats (2005). Those authors, however, did no more than state that Rings sometimes intrude onto the Shelf.

closed gyre (Csanady and Hamilton 1988). Passing south of Nantucket Shoals, the outflow from that gyre breaks away from the continent in its turn and flows generally eastward to pass around, but south of, the Tail of Grand Bank – where the WSW merges with some of the GSW to form one source of the waters of the North Atlantic Current (Clarke *et al.* 1980, Schott *et al.* 2004).

Although the seasonal mean position of the SSB, where the WSW meets the SSWs, always lies well to the southward of the mouth of The Gully, that boundary is intricately complex. Satellite SST imagery reveals an ever-changing riot of meanders, rings and filaments of WSW. While that water mass progresses generally eastwards, individual features can move in the opposite direction. In summer, bodies of WSW at the surface can reach as far as the shelf break and indeed onto the shelf. That meso-scale complexity, revealed by SST, is accompanied by fine-scale variability in the interface between the SSWs and WSW – water masses with very different temperatures and salinities but very similar densities at any given depth. Horne (1978), working some 200 km southeast of the mouth of The Gully in 1975, found interleaving of layers at about 100 m depth, with vertical scales of the order of 10 m and horizontal ones of several kilometres. Indeed, his "yo-yoing" CTD casts found detectable differences at the same depths across distances of only 500 m. He estimated the lifetime of such a layer at about 30 hours, as double diffusive processes exchanged heat and salt between the layers (Horne 1978)[3].

The WSW is a surface water mass but it extends deeper than the SSWs, reaching 300 to 400 m. WSW can thus spread under the SSWs, towards the continental slope (Gatien 1976). The extent of that penetration is also highly variable.

Off Nova Scotia, WSW is typically 10 to 13°C and 34.5 to 35.5‰ (Smith and Petrie 1982). Having formed where surface temperatures are high, the oxygen content of the WSW is relatively low.

2.2.2 Sub-Surface Waters

2.2.2.1 Labrador Sea Water ("LSW"): Two quite different water types, borne on two quite different currents, share the "Labrador" name. The very-cold, low-salinity waters of the Labrador Shelf have been introduced above. They overlie

[3] Following Gatien (1976), Horne (1978) denoted the colder, fresher water mass north of the front which he examined as "Labrador Slope Water", while reserving the term "coastal water" for the CIL and the surface layer alone. As explained below, there had been a modal change between 1960, when Gatien's (1976) data were collected, and Horne's (1978) fieldwork in 1975. By the latter date, and with the benefit of modern knowledge, LSW should not have been expected in his study area and examination of his temperature sections shows that the layering was between what are here termed WSW and the deeper, more saline, layer of the SSWs.

the shelf and shelf break, flowing south from the Arctic as the familiar Labrador Current. That is a surface current, extending only to continental-shelf depths. The LSW, in contrast, is the upper layer of the North Atlantic Deep Water ("NADW"), which in its totality fills much of the ocean basin. LSW is formed by deep convection during winter cooling of the central Labrador Sea – the overturn sometimes reaching to below 2,000 m depth, producing water with a potential temperature below 3°C (though measured temperatures at great depths are necessarily higher) and salinities around 34.84‰. The production of LSW is, however, highly variable on inter-annual and inter-decadal scales (the variations being linked to the North Atlantic Oscillation ("NAO"), though not in any simple way), with the temperature, salinity and hence density (as well as the volume) of the water produced depending on the extent of the overturn. Periods when LSW production is reduced tend to generate slightly warmer water overlying the production of earlier, colder years, the shallower layers being those that might be encountered at mesopelagic depths along the Scotian Slope. Besides that temporal variability, there are spatial differences as well, the water around the margins of the Labrador Sea tending to be warmer and saltier than that in the centre, as a remnant of the Irminger Current circles around that basin (Clarke and Gascard 1983; Lazier *et al.* 2002; Yashayaev 2007; Yashayaev *et al.* 2008). In consequence, it would be meaningless to specify the temperature and salinity characteristics, at its source, of the LSW that might reach The Gully, since precise values vary in space and time while general ranges would be broad. Besides, like the other sub-surface waters to be considered below, and more obviously with the surface waters also, downstream evolution greatly modifies those characteristics as the LSW moves towards the south and west. Forming where surface temperatures are very low, however, the oxygen content of the LSW is consistently high, relative to other water masses that it meets.

The LSW flows southward off Labrador, as part of the Sub-Polar Gyre of the Labrador and Irminger seas and also as a portion of the Deep Western Boundary Current ("DWBC") of the North Atlantic – and hence a contributor to the Meridional Overturning Circulation ("MOC"), which plays a key role in the global heat budget. Some authors have applied the "Labrador Current" label to the entire western boundary current in the Labrador Sea (including not only the familiar shelf-break current and the flow of LSW but also the southward movement of the deeper layers of NADW), while others have termed the flow of LSW the "deep Labrador Current", distinguishing it from the "traditional" Labrador Current of the continental shelf and shelf-break. To avoid confusion and following an emerging consensus amongst specialists, however, the "Labrador Current" name is here used only for the near-surface, shelf and shelf-break flow, while the movement of LSW is identified by the location and water mass concerned.

The northern flank of Grand Bank deflects the southward flow of LSW eastwards towards Flemish Cap, whence most of the water (68% by one estimate: Getzlaff

et al. 2006) recirculates within the Sub-Polar Gyre. Some, however, flows through the Flemish Pass or around the Cap, then around the Nose of Grand Bank and on to the Tail, still as a portion of the DWBC. There is a particularly swift movement of LSW at a core depth of about 1,500 m (Strama *et al.* 2004). It was formerly supposed that the water transported in the Atlantic MOC then rounded the Tail of the Bank and continued to the south-westward as a deep counter-current, more or less below the Gulf Stream – that being the DWBC of the North Atlantic. Recent research, primarily during the last decade, has led to a re-examination of that conclusion, part of a much broader re-thinking of the global MOC system (e.g. Lozier 2010, 2012). It is now known that most of the export of LSW is not along the continental margin *via* the DWBC but rather on pathways through the interior of the North Atlantic. One modelling study suggested that only a small proportion (16%) of the DWBC flow that passes 53°N below 700 m depth is ultimately exported to subtropical latitudes at all. Of that, only 60% follows the continental slope as far as the Tail of the Bank, the rest breaking away either at Flemish Cap or between there and the Tail. Of the DWBC water which does reach the Tail of the Bank between 1,200 and 2,000 m depth, only about half rounds the corner (Getzlaff *et al.* 2006). A later study using acoustically-tracked floats found that less than 10% of those released into the DWBC near the Orphan Knoll passed around Grand Bank. Only two of those floats (both released at 1,500 m depth) followed the DWBC along the Scotian Slope, while a third re-joined that pathway after moving generally westerly from the Tail of the Bank (Bower *et al.* 2011). The rest of the LSW which passes the longitude of the Tail westbound does so across a broad swath of ocean between the edge of Grand Bank and the Mid-Atlantic Ridge (Bower *et al.* 2009, 2011; Lozier 2012). Model results suggest that most water crossing a monitoring line stretching out from Georges Bank circulates within a cyclonic Northern Recirculation Gyre that occupies the volume between the Tail of the Bank and Cape Hatteras (Bower *et al.* 2009), rather than being part of a unidirectional meridional flow. That gyre should nevertheless carry water, of whatever origins, south-westerly past the mouth of The Gully.

The amount of LSW rounding the Tail and the extent of its further movement to the south and west are extremely variable. Such as does follow that route forms a subsurface water mass at continental-slope depths. Off Nova Scotia, just as the WSW both competes with the SSWs as a surface water body (the two meeting at the SSB) and yet also underlies the shelf waters to wash the upper slope, so the LSW competes with the WSW at upper-slope depths but also underlies the warmer water to wash the continental margin at mid-slope depths and below. Gatien (1976) denoted the LSW there as “Labrador Slope Water”, perhaps in deliberate contrast to WSW. That meaning of “LSW” is still widely used (and has been elaborated into “Labrador Subarctic Slope Water”: MERCINA Working Group 2001) but it seems an unfortunate term, as the water mass is not particularly associated with the continental slope off Labrador.

2.2.2.2 The Coupled Slope Water System: At upper-slope depths, the interaction between WSW and the colder, less-saline but oxygen-rich LSW has been described as a "coupled slope water system", in which the "maximum modal state" sees the LSW extending no further than the western flank of Grand Bank or perhaps to the Laurentian Channel, while it can reach as far as the continental slope off Maryland when in the "minimum" state (Petrie and Drinkwater 1993, Marsh *et al.* 1999, Pickart *et al.* 1999, MERCINA Working Group 2001, Greene and Pershing 2003).

Since the mid-20th Century, this system has generally been near its "maximum" (the upper Scotian Slope being washed by WSW) but there have been reversals apparently linked (though not in any simple way) with the NAO – positive values of the winter NAO Index resulting in "maximum modal states" and *vice versa* (MERCINA Working Group 2001). There was a prolonged period of the "minimum" state from 1959 until 1967 (Loder *et al.* 2001), during which a substantial wedge of LSW was found adjacent to the continental slope south of Halifax (Gatien 1976). Bugden (1991) reported a temperature of 4.5°C for the subsurface temperature maximum, around 250 m depth, at the mouth of the Laurentian Channel in 1966, which had risen to 6.1°C by 1985, with a parallel change in salinity such that the density remained steady. He ascribed the change to varying proportions of North Atlantic Central Water ("NACW") and Labrador Current waters, estimating 65% NACW in 1960 but 80% in 1976. However, given the depth of the measurements, the waters involved may have been LSW during the 1959–67 minimum and WSW thereafter. The NAO Index dropped sharply in 1996 and, after a temporal lag, LSW again advanced along the slope, entering the Gulf of Maine through the Northwest Channel in winter 1998 and eventually penetrating past the Nantucket Shoals at shelf-break depths. By the end of 1999, however, the system had returned to its "maximum" state (MERCINA Working Group 2001, Greene and Pershing 2003).

Longer-term variations in the system are not well known, though Marsh *et al.* (1999) have suggested that the major tilefish die-off of 1882, along the continental slope off the Mid-Atlantic States, may have been caused by a pronounced "minimum" event. More recently, Gilbert *et al.* (2005) examined a long-term trend in oxygen levels at the head of the Laurentian Channel, within the Lower St. Lawrence Estuary, and concluded that it was primarily driven by a changing proportion of oxygen-poor NACW (perhaps more correctly described as WSW) at the mouth of the Channel, which they estimated to have been 28% in the 1930s but 47% in the 1980–2003 period. Hence, the upper slope at the mouth of The Gully may, in former times, have usually been washed by LSW, with briefer periods of WSW, but for some decades has apparently usually seen WSW, with briefer periods of LSW.

During periods of the system's "minimum" state, LSW presumably flows south-westwards past The Gully but it cannot be assumed that the WSW of "maximum" states necessarily flows to the northeast. At the surface, where it can be observed by satellite measurements of SST, that water mass certainly progresses generally eastwards from off Nantucket Shoals to the Tail of Grand Bank but those portions of it which approach the Scotian Slope often move westwards and the same may be true at depth. Loder *et al.* (2001) modeled the flows across the Halifax Section to 500 m depth and found the water on the slope moving northeastward, except for the near-surface shelf-break current, during what they termed a "warm" period (corresponding to the "maximum" modal state), though the south-westward flow extended to below 400 m depth in the "cold" early-1960s (during the "minimum" period). In that same area south of Halifax, however, Smith and Petrie (1982) observed net eastward flow above the 500 m bathymetric contour in 1976–77 (when the system appears to have been in its "maximum" state), though there was a weak west-going current below. Further detail is available for movements at the Tail of Grand Bank. In the spring of 1972, immediately following a winter with a slightly positive NAO Index after the previous one had seen large negative values, Clarke *et al.* (1980) found evidence of westward transport around the Tail at shelf-break depths and above (the near-surface Labrador Current), at 500 to 1,000 m (marked by lower salinity and silica, indicative of LSW) and around 3,000 m (shown by lower salinity). Contemporaneous current-meter records, however, did not support such flows and actually found very slow east-going flow north of (i.e. towards the shelf break from) the 2,000 m bathymetric contour – a conflict within their data that Clarke *et al.* (1980) could not resolve but consistent with a period of moderate westward movement of LSW around the Tail having ceased shortly before the current meters were deployed. Later data, from 1993–95 and 1999–2001 (during which period only two years had sub-zero values of the NAO Index), indicated only limited southwestward flow across a section running southeast from the Tail, all of which was close to the continental slope and rise. The flow was relatively rapid close against the slope from 500 to 1,500 m depth (Schott *et al.* 2004). With yet more data, Schott *et al.* (2006) found that those flows were subject to short-period variations, though they showed no evidence of inter-decadal differences. Whether similar complexity occurs at the mouth of The Gully remains unknown.

2.2.2.3 North Atlantic Central Water ("NACW"): Iselin (1936) first illustrated (his Fig. 53) the very distinctive temperature / salinity ("T / S") curve of the upper waters of the Sargasso Sea – a portrayal repeated with more extensive data by Csanady and Hamilton (1988: their Fig. 9a). Although that curve extends across at least 4 to 20°C and 35.0 to 36.6‰, at any given temperature its salinity is tightly defined. The upper portion of the curve, above about 7°C, is composed of NACW – the immediately sub-surface water within the subtropical gyre of the North Atlantic, which occupies the depth range of the permanent thermocline. NACW is formed by sinking from the surface within the gyre of multiple mode

waters, including the “18°C Water” formed in the Sargasso Sea in winter (and sometimes termed the “Sargasso Sea Water”). The colder, denser and hence deeper portion of Iselin’s (1936) Sargasso T / S curve is, however, derived from other sources – the Antarctic Intermediate Water (which is formed in the Southern Ocean and flows northwards through the Atlantic as a salinity-minimum layer with core depths of several hundred metres) being one contributor, though much modified during its slow journey northwards, while the coldest parts of the curve are largely shaped by waters that move southwards from the Sub-Polar gyre. For want of a better label, and following Gatien (1976), the combination of the waters of the Sargasso T / S curve are here referred to simply as the “NACW”. They are oxygen-poor, either from formation at relatively high temperatures or as a result of long isolation from the atmosphere.

The cooler, deeper portions of the NACW (thus defined) can pass under the Gulf Stream, though likely carried along with its eastward and northward flow. To the north of the Cold Wall, the NACW is a sub-surface water mass, though each of its isotherms is some hundreds of metres shallower there than it is in the Sargasso. Working with data gathered in 1960 (a period of “minimum” modal state), Gatien (1976) found NACW underlying much of the WSW south of the Scotian Shelf and perhaps washing the lower continental slope off Halifax – though the NACW was then separated from the upper slope by LSW, which flooded the seabed from the shelf break down to at least 1,300 m depth. At that time, the LSW met the WSW in a complex front between 100 and 300 m depth but the LSW also partially underlay the WSW, abutting NACW at greater depths. In data from 1973 (supposedly a “maximum” period for the coupled system at upper-slope depths, with a positive NAO Index value), Gatien (1976) found a frontal surface where LSW and NACW met at 500 m depth south of Halifax[4]. Likewise, in July 1976, Smith and Petrie (1982) saw water with Sargasso-like temperature and salinity characteristics (though they regarded it as part of their “warm slope water”) on a section south of Halifax, where it extended from the shelf break southwards to the edge of a warm-core ring and from 120 m depth downwards to the seabed of the slope. Thus, it appears that bodies of NACW reach the Scotian Slope and the vicinity of The Gully at times.

If LSW were to leave the Sub-Polar Gyre via the DWBC at depths below the WSW of the coupled slope water system, then there would have to be sufficient space between the NACW and the continental margin for the LSW to flow through – which it could not do if the NACW reached the mouth of The Gully. Even if the majority of the LSW export passes much further to the east, the presence of NACW near the Scotian Slope implies that it has moved across the track of the MOC, which would be difficult to comprehend if the flow of LSW was continuous. However, in the South Atlantic the DWBC can take the form of a

[4] A front so pronounced that Gatien (1976) reported the characteristics of the water changing perceptibly during the time that she held her CTD cast stationary at depth.

migration of eddies, rather than a continuous current. While similar behaviour has yet to be confirmed for other parts of the world ocean, both theoretical and model-based arguments suggest that the MOC in the North Atlantic is driven by eddy fields (Lozier 2010). Hence, the LSW's meridional flow through the broad extent between the Scotian Slope and the Mid-Atlantic Ridge may be discontinuous, opening passage for NACW to move towards the northwest. Thus, Gatien's (1976) identification of the latter water mass close to the Scotian Slope, and even its advance to The Gully, need not be inconsistent with the undoubted existence of an MOC pathway for LSW.

2.2.2.4 North Atlantic Deep Water ("NADW"): The upper portion of the NADW, which is the LSW, has been discussed at length above. The bulk of the volume of the western half of the North Atlantic Basin is filled by the deeper layers of NADW, composed of water masses created where cold, dense Arctic water overflows the Greenland / Iceland / Scotland ridge, flowing down its southern slopes and entraining Atlantic water. One major source is the flow over an 850 m-deep saddle in the Faroe Bank Channel and hence into the eastern half of the Basin, where it contributes to the North East Atlantic Deep Water ("NEADW"). Some of that Water passes through breaks in the Mid-Atlantic Ridge, notably the Charlie Gibbs Fracture Zone, and forms much of the western basin's NADW – though with characteristics much modified from those created at the overflow (Yashayaev and Dickson 2008). Schott *et al.* (2004), who referred to NEADW west of the Mid-Atlantic Ridge as the "Gibbs Fracture Zone Water", found it washing the continental slope at the Tail of Grand Bank at depths of about 2,000 to 3,000 m. The core of the NEADW likewise met the slope in the Newfoundland Basin at about 2,500 m depth in both 1966 and 1994, despite pronounced changes in the volume of the LSW between those years (Yashayaev and Dickson 2008).

Another and deeper component of the NADW, though sometimes regarded as a distinct "North Atlantic Bottom Water", is the "Denmark Strait Overflow Water", formed in a similar way to the NEADW but between Iceland and Greenland. Schott *et al*. (2004) reported water of appropriate density to be from there washing the continental rise off the Tail of the Bank at depths below 3,000 m, where there was a flow to the south and west. Yashayaev and Dickson (2008), in contrast, placed that water mass much deeper, below 4,000 m.

The southward movement of these "overflow waters", which movement comprises the deeper portion of the Atlantic MOC, has not been as intensively studied as has that of the overlying LSW. Recent modeling has, however, indicated that much of the deep flow, like that of the LSW, moves through the interior of the North Atlantic rather than along the continental margin *via* the DWBC (Lozier *et al.* 2013).

2.2.3 Summary

Thus, the surface waters over most of The Gully most of the time are the two- or three-layered SSWs, the lower part of which extends to shelf-break depths. Its upper layers are of low salinity and the CIL is very cold but the immediate surface is warm in summer. The deep layer of the SSWs is warmer and saltier. The southern margin of that water mass, the SSB, is a highly variable front. It usually lies well south of the canyon mouth but can closely approach the shelf-break and, at rare intervals, may move even further north. South of the SSB, the surface layer is composed of warm, high-salinity WSW – except for the rare occasions when a body of GSW, pinched off from the Gulf Stream, enters the Gully vicinity.

At upper continental slope depths, of a few hundred metres, the typical water masses of The Gully are LSW and WSW, the boundary between them moving with the modal state of the coupled slope water system. Both are of very similar density but the LSW is colder, less salty and more oxygen-saturated than the WSW. At greater depths, down to perhaps 2,000 m, LSW predominates along the Scotian Slope but it shares those depths with NACW, at least sometimes. Again, the LSW is higher in oxygen than those water masses, as well as being slightly cooler and fresher than NACW of the same density and hence at the same depth. At still greater depths, and thus only in the outer canyon, southward of its mouth (and perhaps only outside the MPA), The Gully is expected to contain the deeper layers of NADW, though their presence has yet to be confirmed.

2.3 OCEANOGRAPHY OF THE GULLY

2.3.1 Seasonal Mean Circulation

The principal feature of the circulation in the Gully area is the shelf-break current, which flows across the mouth of the canyon towards the southwest, at the surface but also down to depths of at least a few hundred metres. Model outputs suggest that it is active year-round, though variable in strength, reaching 0.55 ms^{-1} in spring (Han and Loder 2003). The faster-flowing portions of that current encounter the canyon mouth in the form of the gently curving contours high on the flank of Banquereau. Whether the deeper waters which flood the sharp ridge of the Banquereau Spur also flow consistently to the southwest remains unsure but might be important to the ecosystems in The Gully: Allen and Hickey (2010) found that the radius of curvature of the isobaths at the upstream side of the mouth was one of the most important geometric parameters controlling water movements within of a model canyon and on the Spur that radius approaches zero.

It was formerly supposed that clockwise gyres around Banquereau and Sable Island combine to create an anticlockwise (cyclonic) gyre at the surface over the deep water of The Gully, particularly in fall and winter (Petrie *et al.* 1998, Han *et al.* 2002), though the field evidence for such a feature was necessarily thin – aside from a well-documented south-eastward and southward flow along the edge of Sable Island Bank (part of an irregular gyre around Sable Island). One of the major conclusions from the 2006–07 field program is that, contrary to the earlier interpretation, the surface layers (above 200 m depth) flow across The Gully (or more exactly across the canyon, since the Head Valleys Area was not included in the fieldwork) largely undisturbed by its presence below – and do so at all seasons. Over the central canyon, that flow is principally to the southwest, forming part of the shelf-break current and the general flow across the southern flanks of Banquereau and Sable Island Bank. In contrast, the mean current over the upper canyon is north-easterly (Greenan *et al.* 2013, 2014). The year-round south-westward surface flow is also seen in model outputs, which suggest that it is stronger in fall and winter than in spring and summer (Shan *et al.* 2014a). Over the central canyon, the net current transits from rim to rim in about 3 days, while the flow in the opposite direction further north takes 12 days to cross. The apparent lack of a canyon influence on the surface layer extends to its nutrients and chlorophyll, which in the top 250 m of the water column are of comparable concentrations to those over the adjacent banks (Greenan *et al.* 2014).

Before the suggestion of a surface gyre is discarded, however, it should be noted that Han and Loder (2003) discussed that proposed feature with reference to modelled transport across what they termed their “Gully section”. That had a maximum depth of less than 250 m (Han *et al.* 2002, their Figure 4; Han and Loder 2003, their Figure 13) and thus did not span the canyon, as defined here. Rather, it was a section across part of the shelf-valley system in the Head Valleys Area, the western and north-western branches of which form the connection between The Trough and the canyon. The known eastward flow above the rim of Sable Island Bank in that vicinity and the modelled westward transport occupying most of the rest of the valley (Han *et al.* 2002; Han and Loder 2003) would combine with the northeast flow across the upper canyon that was observed by Greenan *et al.* (2014) to constitute a partial cyclonic gyre. Entrainment of Trough water into the flow around Sable Island (for which there is some field evidence: Greenan *et al.* 2013: their Figure 2) would complete that gyre – though it would be one extending from upper canyon to Trough, rather than over the central canyon[5].

[5] The northward and westward flow along the eastern and northern margins of The Gully could extend from the shelf break to The Trough (paralleling the eastward and southward flow around the edge of Sable Island Bank) despite the evidence from Greenan *et al.*’s (2013, 2014) current meters. That is: The near-surface flow over the southern flank of Banquereau may curve towards the north, following the 100 or 200 m contour far to the east of the moorings in the canyon, before passing across the Head Valleys Area and into The Trough. If so, some of the north-going water east of the central canyon must turn back south-westerly to cross that feature.

Below the sea surface, the velocity of the flows across the canyon drops, reaching near-zero at rim depth (≈200 m: Shan *et al.* 2014a). The current-meter moorings provided inconclusive evidence of a subsurface cyclonic gyre around the central canyon at that depth or at least of a north-westward flow on the Banquereau side and a south-eastward one along the edge of Sable Island Bank (Greenan *et al.* 2014). Model outputs suggested similar flows, with more of a tendency towards a closed gyre over the central canyon in August than in February (Shan *et al.* 2014a). That modelling included the tracking of "particles" into and out of a layer at 200 m depth that extended across almost all of the MPA, aside from the shallows either side of the canyon[6]. In February, within a week about half of those particles were flushed away, not only from the MPA but outside of a larger "tracking domain", and were replaced from outside that domain. Much of the exchange was through the canyon mouth, with water supplied from the edge of Banquereau and flushed away to the southwest, though some export of water was northwards into the Head Valleys Area. There was much less water exchange in August, 90% of the "released particles" remaining within the tracking domain after a week and apparently a higher proportion of the flushing being northward[7]. For that same 200 m layer, e-folding times within the MPA-like study area were about a week in February and two weeks in August (Shan *et al.* 2014a).

Early modelling work suggested a substantial inflow to the central Scotian Shelf through The Gully and into The Trough, especially in the spring when the transport was estimated to reach 0.3 to 0.4 Sv, or about half the along-shore transport of the Nova Scotia Current[8]. That was suggested to be associated with topographic steering of a portion of the shelf-break current, drawing it up the eastern side of The Gully, and was further suggested to be an important mechanism for advection of water from the continental margin onto the central Scotian Shelf (Han and Loder 2003). It seems to have been perceived as a primarily near-surface current, perhaps extending to canyon rim depth, which the current-meter moorings of 2006–07 have shown does not exist over the canyon (though it might over the shoal water of Banquereau). The data from the moorings did confirm a net inflow through the central canyon but below its rim depth, an inflow extending across the full width of the canyon and downwards

[6] Shan *et al.* (2014a) referred to the rectangle within which they "released" their modelled "particles" as "Zone 1 of the Gully Marine Protected Area" but it was much larger than that Zone.

[7] Shan *et al.* (2014a) only illustrated the "particles" remaining within their tracking domain. Flushing to the north or the southwest that was swift enough for "particles" to be lost in under three days (should that have occurred) cannot be followed in their presentation of their model results. That presentation also does not provide presently-useful information on spatial variations in residence times within The Gully, since "residence" is there only considered with reference to the extent of the arbitrary tracking domain.

[8] 0.3 to 0.4 Sv was the estimate of Han and Loder (2003). Han *et al.* (2002) had offered 0.03 Sv in winter and 0.07 Sv in summer.

almost to the seabed (though with some cross-canyon and even down-canyon orientation close to the seabed: Greenan *et al.* 2014). The recent modelling also found that flow below rim depth, though it was seen as slow in winter and almost zero in summer (Shan *et al.* 2014a). The mooring data led to an estimate of a mean transport of 35,500 m^3s^{-1} (0.035 Sv) across the section in the central canyon and below 200 m depth. The two CTD surveys which accompanied deployment and recovery of the moorings found evidence of a corresponding up-canyon flow of ≈0.01 ms^{-1}, which would carry a water particle from the canyon mouth to its head in about 30 days (Greenan *et al.* 2014). The latter velocity is, however, an estimate from two temporal "snapshots", each of which would be expected to miss episodic, meteorologically driven water exchanges. Conversely, Shan *et al.*'s (2014a) modelling suggested that the transport is only 9,890 m^3s^{-1} in February and 2,357 m^3s^{-1} in August – the difference between field and model results being, as yet, unresolved.

The net flow of water up the canyon must necessarily be balanced by an equal volume upwelling past its rim depth or flowing through the shelf valleys from its head into The Trough. If the estimated 35,500 m^3s^{-1} which crossed the mooring section in the central canyon upwelled evenly between there and the canyon head, it would imply a mean upward velocity of 14 m per day (Greenan *et al.* 2014). If the bulk of the water passes through the shelf valley, the vertical velocity would be much lower, save at the canyon head itself and in the adjacent shelf valley – where a known sandwave field at about 300 m depth confirms swift water flows across the seabed.

The supply of water from the continental slope to the near-surface waters of the Scotian Shelf *via* The Gully may make a substantial contribution to regional nutrient budgets, though Greenan *et al.*'s (2014) estimate of the transport is an order of magnitude smaller than Han and Loder's (2003), while Shan *et al.*'s (2014a) estimate is much smaller still. However that may be, there is little evidence to support early suggestions that the canyon's bathymetry results in local upwelling which carries nutrients from rim depth (≈200 m), through the thermohaloclines below and above the CIL into the euphotic zone (<<50 m depth) over The Gully – thereby promoting local primary and secondary production. Indeed, the vertical profiles of nutrients in the upper 250 m of the water column over the canyon are essentially identical to those over the banks on either side. Chlorophyll levels and those of microbial plankton are likewise similar, as is the temporal pattern of the spring bloom, while satellite observations of SST show none of the cooling that should result if there was upwelling into the surface layer over the canyon. Besides, the south-westerly surface flow across the central canyon should advect any upwelled nutrients, and the phytoplankton that utilized them, away from The Gully relatively quickly (Greenan *et al.* 2013,

2014)[9], though the situation in the upper canyon may be more complex. Strain and Yeats (2005) reported a single series of observations of surface nitrate and silicate concentrations, made in mid-April 2000, which showed enhanced levels centred over the 200 m bathymetric contour in the Head Valleys Area. That could have resulted from some spatially-extensive but temporally constrained process, such as a weather event which chanced to coincide with the data collection, but it was consistent with upwelling into the valleys which reaches the surface outside Greenan *et al.*'s (2014) study area but still inside The Gully as that feature is understood here.

2.3.2 Tidal Flows

The temporal variability around the mean currents in and over the canyon is overwhelmingly dominated by tidal flows, primarily the lunar semi-diurnal, or M_2, and lunar diurnal, or K_1, tides. Modelling studies have confirmed expectations that the surface flows over the deep water of the canyon are much slower than those over the shallow banks on either side (Han *et al.* 2002; Han and Loder 2003). The mooring data, however, has shown that resonance within The Gully (at a frequency very close to that of the lunar day) serves to amplify the diurnal tides, both the K_1 and the O_1 (the solar diurnal tide), especially at great depth and towards the canyon head, though only over the thalweg. At 761 m depth on mooring SG2, in the upper canyon, the velocities of those tidal flows along the axis of the canyon reached 0.31 and 0.26 ms^{-1} respectively – the K_1 tidal excursion being as much as 8.5 km[10]. At 1,542 m depth in the central canyon, however, their velocities were only 0.19 and 0.16 ms^{-1}. There is also some indication of amplification of the semi-diurnal lunar tide (M_2), which showed a

[9] The three-day crossing time that Greenan *et al.* (2014) estimated for the central canyon should be long enough for upwelled nutrients that reached the surface over the rim on the Banquereau side (if there were such upwelling) to be taken up by phytoplankton before the water crossed the western rim of the canyon. It would not, however, be enough time for much of that phytoplankton to be consumed by herbivorous zooplankton, let alone for the latter to be eaten by vertically-migrant nekton living in The Gully. Hence, enrichment of the canyon biota through upwelling around the central canyon and the resulting promotion of primary production would be inconsistent with Greenan *et al.*'s (2014) observations.
That discontinuity between canyon circulation and canyon secondary production, on a hypothesized pathway via nutrients and primary production, should not be misunderstood as an independence of the ecosystems deep in the central canyon from those in the surface water passing by. Planktivores (primarily myctophid fishes and euphausiid krill) that spend the daylight period at depth within the canyon migrate to the surface to feed at night, then carry the energy obtained downwards at dawn. Hence, active animal migration links the surface layers and those below canyon rim depth ecologically, even though they are largely disconnected oceanographically.

[10] Greenan *et al.* (2014) did not provide a full suite of tidal excursions for all tidal constituents and all current-meter depths. They did give the excursion of the O_1 tide at 355 m depth at their mooring SG2 as 4.4 km. That is consistent with the inferred extent of up- and down-canyon movement of the interface between the distinctive patterns of acoustic backscattering in the upper and central canyon areas (see Section 3 below).

velocity exceeding 0.1 ms^{-1} at 761 m depth on mooring SG2, while the relationships between those three principal tidal constituents (K_1, O_1 and M_2) are markedly non-linear, the non-linearities emerging from analyses as the presence of overtides and compound tides such as the MK_3 (and interaction of K_1 and M_2: Swart *et al.* 2011; Greenan *et al.* 2014). The combination of all of those tidal constituents, along with the mean current and episodic flows, produced water movements past the current-meter moorings that exceeded 2 knots, or 1 ms^{-1}, at times (Shan *et al.* 2014a, b). So exceptional is the tidal regime in the canyon that Greenan *et al.* (2013) termed it "quite unique from the surrounding slope region" and also noted it as a "unique tidal response in the Gully in comparison to other submarine canyons".

The extreme velocities of those flows must have major implications for benthic ecosystems in The Gully but the flows are reciprocal and non-migratory pelagic organisms might experience little more from them than a relocation up and down the canyon on a diel cycle. The tides appear to be the principal driver of the mean up-canyon flow (Shan *et al.* 2014a) but it is that movement, and not its causes, that is of biological importance. Vertical-migrant animals which rise above the canyon rim at night have the challenge of finding the deep water again at dawn but they are then in layers which do not experience the tidal amplification. Migrant plankton that remains below rim depth might be able to use vertical shear to maintain position in the canyon, despite the mean inflow, since the tides show pronounced phase differences across depths – up to 60° phase difference for the K_1 tide (Swart *et al.* 2011). Whether any species is adapted to make such specialized use of an unusual variant of Selective Tidal Stream Transport (*sensu* Harden Jones *et al.* 1978) is unknown. The swift flows flowing over the broken bathymetry of the canyon may be of more consequence to animals in midwater by generating low-frequency sounds that propagate through the water column, providing navigational cues.

The extreme velocities also have an important physical effect of promoting mixing within the deeper portions of the water column, which emerges from analyses as very high values of vertical eddy diffusivity – the upper bound on estimates being about 20 times the level typical of the Scotian Shelf (Greenan *et al.* 2014). That mixing, rather than the supposed upwelling into the euphotic zone, may be critical to the structure of the pelagic ecosystems in The Gully.

2.3.3 Circulation Features Localized in Space or Time

While much has been learnt of water movements in and over the Gully canyon, there is still a dearth of information on small-scale variations, including ephemeral, episodic flows, spatially-localized phenomena associated with particular bathymetric features and those water movements that are localized in both space and time.

It might be expected that there should be strong, meteorologically driven flows along The Gully, similar to those observed in other canyons (e.g. Kinsella *et al.* 1987). West of Sable Island, the edge of the Scotian Shelf has a series of broad saddles, reaching 200 m depth, between the Western, Emerald, La Have, Baccaro and Browns banks. Meteorological forcing drives water from the upper continental slope (primarily WSW, LSW or the deep layer of the SSWs) over those saddles and into the deep basins of the central Scotian Shelf (Petrie 1983). The edge of the eastern Scotian Shelf, in contrast, forms an almost-unbroken "mountain wall", rising from below 4000 m depth to about 100 m, and extending some 400 km from Western Bank to the Laurentian Channel. The sole break in that wall is The Gully, including the combination of the canyon and the shelf-valleys communicating with The Trough. When atmospheric cyclonic depressions move off the mainland and across the Scotian Shelf, the pressure differential should drive some 10 km^3 of water onto the eastern Shelf and a not-inconsiderable fraction of that might be expected to pass through the narrow confines of the canyon. Whether it does so remains unsure, however. Shan *et al.* (2014a) found that the wind had little effect on modelled circulation. In a separate application of their model, using time-specific data, Tropical Storm *Alberto* (of June 2006) had only a rather limited effect on water movements in the canyon (Shan *et al.* 2014b). Similarly, Greenan *et al.* (2014) found that almost all of the temporal variability in their current-meter data was tidal, leaving little as episodic movements. That little has not yet, however, been examined to see whether it contains rare but strong flows.

The interactions of the tides with canyon bathymetry can generate internal waves and such waves, even the breaking of such waves, have been reported from the edge of Banquereau, adjacent to The Gully and at water depths around 100 m (Sandstrom and Elliott 2002). Kenchington *et al.* (2009) noted wave-like patterns in echograms suggestive of internal waves generated by tidal flow over the canyon walls, while Kenchington *et al.* (2014) have reported unusual behaviour of their midwater trawl, hinting at waves in the thermohalocline beneath the CIL during March 2010. Similar features may be common in The Gully, though localized in space and time. If so, no research program suited to their description has yet been undertaken.

2.3.4 Water Characteristics

During the 2006 and 2007 CTD surveys, most of the canyon was filled with water of 4 to 9°C and 34.3 to 35.0 ‰, which Greenan *et al.* (2014) interpreted as LSW. The deep water in the upper canyon was, however, detectably cooler and less saline than that near the canyon mouth. Below some 400 m depth, the cooling and freshening appeared approximately linear along the canyon's axis. At depths from 100 to 350 m, there was a layer of WSW (9–13°C, 34.7–35.6 ‰),

identifiable by its low oxygen concentration (Greenan *et al.* 2014), while the uppermost 100 m of the water column comprised the SSWs. The isopycnals, or density surfaces, below rim depth were relatively flat, both across and along the canyon (Greenan *et al.* 2014).

Between January 2007 and the recovery of the moorings early in August, there was an intrusion of colder, less-saline water into the canyon at about 290 m depth. (One CTD cast in the upper canyon recorded about 5.5°C and 34.5‰, suggestive of LSW.) Its up-canyon progress between the moorings on the thalweg showed a flow of 0.02 ms^{-1}, consistent with the average derived from current-meter data (Greenan *et al.* 2014). Irregularities in the observed temperature and salinity profiles (Greenan *et al.* 2014, their Figure 5) suggest that that was not the only temporal variation in the water which entered the Gully's mouth at depths of 200 to 400 m and then moved along the canyon axis.

2.4 OCEANOGRAPHIC CONDITIONS DURING THE TRAWL SURVEYS

2.4.1 September 2007

The oceanographic conditions during the September 2007 survey have been described in detail by Kenchington *et al.* (2009), who provided temperature, salinity, density and oxygen-concentration profiles, plus T / S plots, for all of the CTD casts made. However, the developing understanding of The Gully's waters, outlined above, necessitates two major revisions of their conclusions. Firstly, Kenchington *et al.* (2009) identified the water in The Gully between the subsurface temperature maximum (at ≈8°C and ≈150 m depth[11]) and the greatest depths reached by the CTD as being LSW of approximately 4 to 8°C and 35‰ salinity. That accorded with Greenan *et al.*'s (2014) interpretation of data from CTD casts made a month earlier, though those authors might have seen the 8°C upper bound as indicative of WSW rather than LSW. In contrast, the data from the 2009 and 2010 surveys shows that the waters of the central canyon and the canyon mouth, below the subsurface maximum, had NACW-like temperature and salinity characteristics. Re-examination of Kenchington *et al.*'s (2009) data, in light of that observation, shows that (below the subsurface temperature maximum) most of them also resemble the colder, denser end of the Sargasso Sea T / S curve identified by Iselin (1936) and by Csanady and Hamilton (1988) – the extreme development of the CIL in 2007 (Petrie *et al.* 2008) having excluded the upper, warmer portions of that water mass and so prevented its recognition. Of the T / S plots for the CTD casts made in September 2007 (Kenchington *et al.* 2009), only the ones on the Head Station lacked any indication of NACW-like water. Measured oxygen concentrations at

[11] Depths read from the CTD data streams, from all four surveys, are here presented as being in metres, though the records are actually in decibars. The resulting error, about 1%, is of no biological significance.

depths below a few hundred metres were rather less than 5 ml.l^{-1} (Kenchington *et al.* 2009), which is lower than expected for LSW in the area south of the Scotian Shelf (cf. Clarke *et al.* 1980) but higher than expected for what is here termed NACW (e.g. Csanady and Hamilton 1988). However, the measurements relied on the factory calibration of the sensor mounted on the CTD and hence their absolute values cannot be relied upon. Thus, those measurements cannot aid in identifying the source of the deeper waters in the canyon during September 2007.

Where Greenan *et al.* (2014) had found water at 400 m depth in the upper canyon to be ≈5°C and not much more than 34.7‰, Kenchington *et al.* (2009) found 5.25°C and 34.85‰ – characteristics more similar to those that Greenan *et al.* (2014) had found about six weeks earlier in the central canyon and the canyon mouth. Given the estimated 30 days for an up-canyon transit by water below rim depth (Greenan *et al.* 2014), the changes in temperature and salinity are not surprising but they do point to a change in the characteristics of the water at depth at the canyon mouth.

In May of that same year, the Atlantic Zone Off-Shelf Monitoring Program had found water with NACW-like temperature and salinity characteristics on its Extended Halifax Line (a line of routine monitoring stations which runs down the continental slope and rise from the shelf break southeast of Halifax and ≈250 km west of The Gully), though it was mostly far southward of the continental slope. Only below 1,000 m depth did it approach the continental margin, the upper slope being washed by LSW[12]. Thus, it appears that both water masses were present in the general vicinity of The Gully.

The second change to the previously-presented interpretations concerns two CTD casts made on the Head Station which provided evidence of major water movement at depth in the upper canyon, coinciding in time with a minor wind event. Kenchington *et al.* (2009) interpreted the movement as episodic and perhaps meteorologically driven. That remains possible but the discovery of resonant tidal amplification in the same part of the canyon, added to the very limited episodic water movement recorded by the current meters (Swart *et al.* 2011; Greenan *et al.* 2014), suggests that the displacement of isotherms noted by Kenchington *et al.* (2009) may have been the result of tidal flow towards the obstruction of the shallowing at the canyon head.

Otherwise, the observations made in September 2007 (Kenchington *et al.* 2009) were generally in accord with the emerging understanding of The Gully offered by Greenan *et al.* (2014) and others. Where the two CTD surveys undertaken by

[12] Sections illustrating the monitoring data are available from: http://www.bio.gc.ca/science/monitoring-monitorage/azomp-pmzao/slope-pente/conditions-eng.php

the latter found generally horizontal isopycnals (though in 2006 they were somewhat deeper in the central canyon than at the mouth or in the upper canyon), Kenchington *et al.* (2009) noted that, in September 2007, the isotherms below the subsurface temperature maximum generally sloped upwards towards the canyon head. Re-examination of the data shows that, once averaged within stations, the isopycnals above 600 m depth ($\sigma^t \leq 27.7$) on the Deep Station were a few metres shallower than they were on the Offshore Station, while those below 600 m were tens or hundreds of metres deeper. Within the canyon, the shallower isopycnals (approximately those at 200 to 400 m depth, $27.4 < \sigma^t < 27.6$) rose a few metres between the Deep and Main stations but those at greater depth were depressed by some tens of metres (the anomalous Set 40 of the 2007 survey being excluded from the Main Station means, though it showed the same trends more strongly). Of the two CTD casts made on the Head Station, Set 47, which found the isotherms at similar depths to those they had on the Main Station, showed the shallower isopycnals depressed tens of metres relative to the Deep Station, while those below were depressed hundreds of metres. Set 80 found offsets of isopycnal depths that were similar in magnitude but reversed in direction.

2.4.2 August-September 2008

In 2008, the regional oceanographic conditions were notably less anomalous than they had been the previous year, though the volume of the CIL was not much reduced from its exceptional level, while 2008 remained colder than normal on the eastern Scotian Shelf (Petrie *et al.* 2009). Winter nutrient levels were higher than normal but the summer concentrations were low – at the Atlantic Zone Monitoring Program (AZMP) Halifax Line Station 2, the lowest since regular monitoring began in 1999. On the AZMP Louisbourg Line (which runs southeast from Cape Breton and intersects the shelf break ≈70 km east of The Gully), the spring concentrations were the highest yet observed, though those in fall were rather low when compared to past records for that season. Meanwhile, the spring phytoplankton bloom in 2008 came later and was of shorter duration and lesser magnitude than normal. Zooplankton biomass concentrations on the Louisbourg Line were normal in spring and fall, yet those of *Calanus finmarchicus* specifically were low in spring but exceptionally high in the fall, especially immediately north of Banquereau (Harrison *et al.* 2009). In June and on the Extended Halifax Line, water with NACW-like characteristics flooded the continental slope from depths of several hundred metres down to below 2,000, though there was a body of LSW reaching down to 1,000 m depth some 75 km south of the shelf break[13]. Otherwise, while no single year can be said to be “typical”, oceanographic conditions around The Gully were generally “normal” in 2008.

[13] Sections illustrating the monitoring data are available from: http://www.bio.gc.ca/science/monitoring-monitorage/azomp-pmzao/slope-pente/conditions-eng.php

AVHRR (Advanced Very High Resolution Radiometer) satellite imagery from the period of the survey that year shows that the Gulf Stream lay far to the south of the shelf break, its nearest approach to The Gully being some 200 km from the canyon mouth. The SSB was not much closer, though SST in and around The Gully appeared to be in the 15 to 20°C range, depending on the image examined (Figure 6).

The pressure sensor on the CTD taken on the 2008 survey proved to be defective and no data accurate enough for oceanographic analyses were obtained. However, it was possible to reconstruct parts of the data from five casts, two made on the Deep Station and three on the Main Station, with sufficient certainty to be indicative for biological purposes (Kenchington *et al.* 2014). Those showed the surface water to be around 18°C, with a mixed layer less than 10 m deep overlying a very pronounced thermocline. The latter led to the core of the CIL, lying at about 50 m depth, with a narrow band of minimum temperatures around 5 to 5.5 C – unlike the broad, cold CIL seen in 2007. In 2008, the subsurface maximum was around 120 to 180 m depth and 8 to 8.5°C. In contrast to what had been seen in 2007, there was considerable irregularity in the temperature profile below that depth and down to 300 or 400 m, though at greater depths the profiles smoothed and reached (or headed towards) the expected ≈4°C at 1,000 m. The accompanying salinity data were, unfortunately, untrustworthy. On the three sets which gave useable data, surface salinity was between 31 and 31.3‰ (typical of the surface layer seen in 2007). Below, there was a pronounced halocline that contained some narrow bands of near-stasis, which tended to lie above the core of the CIL – meaning that temperatures varied markedly where salinity did not. Four of the casts showed the deep water to be close to 33.5‰, while Set 10 (made on the Deep Station) suggested that it was nearer to 34.5‰, both of which contrasted with the 35‰ seen in 2007 and again in 2009 and 2010 (see below). Given that pronounced disagreement, the 2008 data cannot be given much credence, which is disappointing since the lower salinity suggests an intrusion of LSW into the canyon replacing the NACW-like water seen during the other surveys. The data also suggested some variability in salinity between about 200 and 400 m depth which, coupled with the irregular temperatures seen at those depths, indicated intrusions of slightly warmer and more saline layers, though still within the range characteristic of LSW.

Besides the reliance on the factory calibration of the CTD's oxygen sensor, which casts doubt on the absolute values of the resulting data, variability in the sensor's output did not inspire confidence in relative values either. Nevertheless, the data do show a broad oxygen minimum at or below the depth of the subsurface temperature maximum on every cast for which data could be reconstructed. The minimum was variously estimated at 2.25 to 5.2 $ml.l^{-1}$ – that range indicating the general unreliability. With a single exception, measured concentrations at the

bottom of the casts were between approximately 6 and 7 ml.l^{-1}, "spiking" in the data preventing more precise specification of the range, while surface concentrations were considerably higher (recorded at anywhere from 5 to 12 ml.l^{-1}). The maximum concentration detected by each cast lay above the depth of the CIL, rather than coinciding with it, as had been seen in 2007. While too much should not be demanded of the 2008 data, not least because of to the lack of *in situ* calibrations, when compared with the values the previous year, the higher measured oxygen levels in 2008 do hint at possible replacement of NACW with oxygen-rich LSW at great depths, while the oxygen minimum at about 200 m suggests the presence of some WSW there.

2.4.3 August 2009

2.4.3.1 Regional and Annual Overview: Environmental conditions across the Scotian Shelf during 2009 were broadly normal, many routinely-measured variables being very close to their long-term averages. Seabed temperature anomalies on the banks around The Gully in July, for example, lay between -1° and +1°C, average anomalies across NAFO Divisions 4Vs and 4W being +0.2° and +0.1°C respectively – though the anomalies in The Trough and along the Scotian Slope exceeded 1°C. The volume of the CIL, after being much higher than the long-term mean in 2007 and 2008, dropped to somewhat below that level. Greater deviations from the norm were seen in the volume of ice on the Shelf in the spring, which was high, and in winter nutrient inventories at about 200 to 300 m depths, which were generally higher than in past years, though that trend was not particularly evident on the Louisbourg Line. The spring phytoplankton bloom at the Halifax-2 station was stronger than normal (peaking at 670 mg.m^{-2}, rather than the average 470), thus reversing the anomaly seen in 2008. Zooplankton concentrations across the eastern Scotian Shelf were higher than normal in spring, with the key *Calanus finmarchicus* being the highest on record, but were low by July and unremarkable in the fall (Petrie and Pettipas 2010; Hebert *et al.* 2011; Johnson *et al.* 2012). On the Extended Halifax Line in May, the waters immediately adjacent to the continental slope above 2,000 m depth were NACW-like, aside from a thin layer of LSW centred at about 500 m[14]. Hence, regionally and seasonally, 2009 (like 2008) can be regarded as a rather "typical" year, within the extreme variability characteristic of the Scotian Shelf, at least where surface and near-surface waters are concerned – routine monitoring not extending to the depths of The Gully's floor.

2.4.3.2 Interpretation of CTD Data: At finer scales of time and space, however, during the period of the 2009 survey the waters around The Gully were exceptionally atypical – with features that generated even more complexity in the

[14] Sections illustrating the monitoring data are available from: http://www.bio.gc.ca/science/monitoring-monitorage/azomp-pmzao/slope-pente/conditions-eng.php

waters of the canyon than was seen on other surveys. The distinctive physical feature at that time was a tongue of WSW, with SST above 22°C, which was pressed against the continental slope in the vicinity of the canyon mouth, the surface front of the SSB lying almost at the shelf break. That body of WSW was evident in the satellite imagery (Figure 7) and produced temperatures at the ship's cooling-water intakes that were too warm for the main engine, while the front was once visible, lying across the Deep Station and marked by floating *Sargassum* (Kenchington *et al.* 2014)[15].

A total of 23 CTD casts were made during the survey. The oxygen sensor produced data that were at times suspect, because of spiking in the output signal, but the temperature and salinity data from at least one leg (down or up) of each cast were deemed satisfactory for oceanographic analysis – though it was often only one of the legs and even then surface data were missing for a few casts (Kenchington *et al.* 2014). To facilitate understanding of the mass of data obtained, a diagrammatic summary interpretation is provided in Figure 8, while the temperature, salinity, density and oxygen-concentration depth profiles for each cast are presented in Figure 9 and T / S plots in Figure 10.

On its upcast, the sole CTD cast on the Slope Station (Set 2) showed a very thin layer of SSWs (22.7°C and 33.9‰) at the surface, overlying an equally thin layer of WSW (23.3°C and 34.9‰) at 9 m depth. Beneath those were, in sequence, two layers of different variants of WSW (one 14.4–16.1°C, 35.3–35.6‰ at 30–52 m, the other with a core at 74 m, 11.2°C and 34.9‰), then NACW-like water or perhaps particularly-saline WSW (13.0–13.7°C, 35.4–35.6‰) from 88 to 144 m. From 230 m downwards, the water consistently had the T / S characteristics of NACW, as that water mass is defined above, its temperature gradually dropping with increasing depth from a maximum of about 9°C. The data from the downcast appear unreliable.

Seven casts were made on the Deep Station. Being in the immediate vicinity of the SSB, they revealed exceptional spatio-temporal complexity in the top 300 m of the water column. Below that, the water consistently resembled NACW. Two of those casts (Sets 7 and 14) were made near the south-eastern end of the Deep Station on 14 and 15 August respectively. The upcast of Set 7 found a warm layer of 23.2°C and 34.9‰ salinity at the surface and extending to 29 m depth. Beneath, there was a sharp thermohalocline, representing the frontal surface under the tongue of WSW. Temperature dropped 4.3°C and salinity rose 0.9‰ across a depth difference of 5 m, below which was a long thermocline, leading from 19.0°C at 34 m depth to 8.9°C (and 35.0‰) at 280 m. The downcast of that Set did not produce data from the surface but its differences from the upcast at intermediate depths illustrated the magnitude of the spatial variability. It too found

[15] While that drift line was very prominent, there were patches of *Sargassum* further to the northwest, showing that the surface front was not simply linear.

a sharp thermohalocline (6.4°C and 0.4‰ salinity change with just 3 m change in depth) but below 200 m. Beneath was a relatively homogeneous layer (17.0–16.9°C, 35.5–36.1‰ – resembling a warm variant of NACW[16]) extending from 211 to 251 m depth, then another sharp thermohalocline leading to a different body of NACW-like water of 9.7°C and 35.1‰ at 255 m. From there, temperature slowly declined with increasing depth. At 1,000 m, the water was 4.2°C and 34.95‰ salinity. Only a day later and in almost the same place, Set 14 found a different surface layer, composed of the uppermost portion of the SSWs. The upcast recorded 22.1°C and 33.0‰ extending to just 5 m depth. Beneath it, between 16 and 19 m depth, was a thin lens of WSW (23.2 to 23.5°C, 34.8 to 35.2‰), immediately below which was the NACW-like water. The downcast again failed to yield data from near-surface depths but, if its data are to be trusted, it did record the bottom of the SSWs layer at much greater depth, finding 21.9°C and 32.7‰ at 104 to 108 m depth. It also found a homogeneous layer of warm NACW, of 15.0 and 35.8‰, extending from 119 to 189 m, which was not seen by the upcast. Evidently, almost all of the WSW had been advected away from that end of the Deep Station during the 24 hours between the times of the two sets.

Of the two casts made near the middle of the Deep Station, Set 8 found the WSW (23.3°C and 34.9 or 35.0‰) at the surface. The upcast recorded it extending to 22 m depth but the downcast (which produced no data from the top 9 m of the water column) traced that layer to 51 m. Beneath, the downcast found a layer of 15.6 to 15.7°C and 35.1 to 35.2‰ water at 81 to 101 m – probably a subsurface portion of WSW. It was bounded by thinner layers of colder and fresher water. Inspection of the T / S plot suggests that those were horizontal intrusions from the CIL, the main body of which lay further north. The upcast found no such clear pattern but rather a confusion of layers blending into one another – most or all of them variants of WSW. On the downcast, the upper edge of the NACW-like water was best marked by a sharp increase in density at 171 m depth. The temperature immediately below was 10.8°C and the salinity 35.1‰. That density boundary was less marked on the upcast but 35.0‰ water was reached at 196 m depth and 10.1°C. Set 15, like the near-contemporaneous Set 14 a few kilometres away, found a surface layer of SSWs, which on the downcast was 8 m deep and of 21.9°C and 32.7‰ (6 m, 22.5°C and 33.2‰ on the upcast). That overlay a body of WSW of 23.3 to 23.4°C and 35.0 to 35.1‰, extending from 12 to 62 m on the downcast (12–20 m, 23.6–23.9°C and 34.8–35.1‰, on the upcast). At greater depths, the data from Set 15 rather resembled the pattern seen in the upcast of Set 8.

[16] That particular layer was warm enough to have perhaps originated as near-surface water in the Sargasso. It may have entered the WSW through the breakdown of a Gulf Stream ring. While of little oceanographic interest, such a movement could transport warm-water species, confounding biogeographic studies.

Sets 9, 16 and 21 were CTD casts made near the north-western end of the Deep Station on 14, 15 and 16 August respectively. They showed even less homogeneity among casts, and perhaps increased complexity within each profile, than was seen further to the southeast. Each of the three showed a very warm surface or near-surface layer, usually delimited by a sharp thermohalocline. On its downcast, Set 9 found such a layer from 3 m (the minimum depth of recording) to 100 m but its characteristics were varied (22.8 to 23.3°C and 34.2 to 35.1‰ , with warmer, saltier water deeper). The upcast found a 3 m deep layer of 21.5°C water (no salinity data available due to an instrument failure) overlying 23.0°C water (of 34.3 to 34.4‰) at 7 to 16 m depth and 23.5 to 23.6°C (35.0 to 35.2‰) at 21 to 26 m, all being variants of WSW. Beneath them lay the CIL. On the downcast, that had its core at 180 m, 6.7°C and 32.9‰ but the upcast found a core of 6.3°C and 33.0‰ at 58 m depth – the thermohalocline between that and the overlying, warmer water seeing temperature change by 10°C in 6 m. Both legs of the cast saw the CIL grade into a subsurface temperature maximum which coincided with the top of the NACW-like water at 185 m, 10.6°C and 35.1‰ on the downcast, 175 m, 11.0°C and 35.1‰ on the upcast. Set 16 recorded a different surface water of 20.9°C and 35.3‰, extending to 24 m depth, on its downcast but the upcast saw typical surface WSW (23.2 to 23.8°C and 34.9 to 35.1‰) at 13 to 17 m depth with a variant of SSWs (19.8°C and 31.5‰ at 3 m, possibly even less saline at the surface) above. Next below, the downcast found twin CIL cores at 110 m, 8.7°C and 34.3‰ and at 207 m, 6.9°C and 34.4‰, separated by what appears to have been a layer of mixed CIL and NACW. The upcast encountered WSW between 28 and 46 m depth (14.2 to 16.8°C and 34.5 to 35.0‰) and then the twin-cored CIL (cores at 63 m 7.3°C and 33.6‰, 148 m 6.2°C and 34.2‰). The subsurface temperature maximum, which was also the top of the NACW-like water, was at 222 m, 9.8°C and 35.0‰ on the upcast. The upcast of Set 21 found a relatively cool, low-salinity (19.5°C and 31.0‰) surface layer overlying water more typical of the upper SSWs (22.3°C and 33.5‰) at 5 m depth – the characteristics of the extreme surface presumably being products of local cooling and rainfall. Below was a broad band with WSW- or NACW-like characteristics, with salinities of up to 35.5‰, but it was layered, rather than homogeneous. That graded into the typical, deep NACW-like water at about 180 m depth but without any very clear distinction between those layers.

In contrast to what was recorded on the Deep Station, the five CTD casts made on the Main Station (Sets 23, 24, 36, 42 and 47) produced data much more typical of what would be expected of The Gully, with a very thin, warm but low salinity mixed layer of surface SSWs overlying a weak CIL, a subsurface temperature maximum and then the NACW-like mass filling the canyon. Four of those sets were made near the southern end of the Station during 16 to 20 August. On its downcast, Set 23 found a mixed layer (20.1°C and 31.2‰) only 4 m deep, with the core of the CIL at 37 m, 3.2°C and 32.7‰ (46 m, 3.5°C and 32.8‰ on the upcast). The subsurface maximum was at 158 m (upcast) or 161 m

(downcast), 9.9°C and 35.1‰. Set 36 did not obtain surface data but the downcast recorded what appears to have been the bottom of a mixed layer (20.2°C and 31.0‰) from 44 to 47 m depth, whereas the upcast found a cooler layer, 10.5 to 13.4°C and 33.8 to 33.9‰ between 30 and 45 m depth. Those contrasting measurements were taken less than 4 km apart relative to the seabed and considerably closer relative to the surface water, in which the ship was drifting. Both legs of the cast found the CIL to be poorly developed, while the subsurface temperature maximum was at 145 m, 9.8°C and 34.9‰ on the downcast and 141 m, 10.5°C and 35.0‰ on the upcast. The upcast of Set 42 found a 7 m mixed layer of SSWs (20.0 to 20.1°C and 30.9‰), a CIL core at 86 m, 7.7°C and 34.1‰, and the subsurface temperature maximum at 130 m, 10.6°C and 35.0‰. Set 47 similarly only gathered surface data on its upcast, which found a mixed layer 8 m deep of 20.1 to 20.2°C and 31.0‰. The CIL was centred at 87 m, 8.0°C and 34.1‰, while the subsurface maximum was at 135 m, 10.6°C and 35.0‰).

Set 24 was located near the centre of the Main Station. Both legs of the cast found the same surface mixed layer seen by Set 23 (20.0 to 20.1°C and 31.2 to 31.4‰ – salinity data only available from below 10 m depth) but it extended to 12 or 13 m depth. In contrast to the profile some 6 km to the southeast and a few hours earlier, however, on the Set 24 downcast the thermohalocline beneath the surface layer was stepped, with a homogeneous layer of 13.1 to 13.3°C and 33.7‰ extending from 28 to 65 m depth. The core of the CIL was at 105 m, 6.7°C and 34.2‰ and overlay a subsurface temperature maximum at 187 m, 9.1°C and 35.0‰. The upcast, in contrast, missed the homogeneous 13°C layer but found a broad CIL, containing complex layering. Its core was at 152 m, 7.2°C and 34.5‰, while the subsurface maximum was at 194 m, 8.9°C and 34.9‰. During that Set, the ship drifted less than 4 km, beginning over the canyon thalweg and ending over the eastern wall, with some 600 m of water under her keel.

Most of those Main Station CTD casts found the NACW-like water below the subsurface temperature maximum to be very homogeneous in salinity, with temperature dropping gradually with increasing depth. Set 42, however, recorded colder, less saline water between 216 and 282 m depth, with a core at 7.2°C and 34.7‰. One day later, Set 47 found the same thing at 208 to 228 m (core at 7.5°C, 34.8‰). Somewhat further north, Set 24 detected that layer with its core at 229 m, 7.2°C and 34.8‰, the homogeneous NACW only beginning at 240 m depth (7.9°C and 35.0‰). That layer appears to have been an intrusion of LSW-like water from the upper canyon, balancing an up-canyon intrusion of NACW-like water (the presence of which was revealed by the CTD casts made on the Head Station: see below). The data from Sets 15 and 21, re-examined in light of the recognition of this apparent movement of LSW, hint that it may have reached the Deep Station.

In comparison to that extreme complexity in the central canyon and around its mouth, the CTD casts at the Head Station provided a relatively simple picture. Sets 51, 49 and 50 formed a transect along the length of the Station from north to south, closely spaced in time. Set 48, made on the GULD 3 AZMP station, extended that transect onto the western wall of the canyon, abreast the south end of the trawling station, while Set 59 repeated Set 50 after a delay of some 20 hours, though it was located somewhat west of the canyon thalweg (Figure 11). The downcast of Set 51 found a surface mixed layer, 10 m deep, of SSWs (18.8–18.9°C and 31.0‰). Beneath that was a thermo-halocline to 20 m depth and then a thermocline leading to the core of the CIL at 50 m, 3.2°C and 32.9‰. The subsurface temperature maximum was at 151 m, 10.0°C and 34.8‰. However, rather than the homogeneous NACW-like water seen further south, the deeper water was less saline (34.9‰ at 700 m) and apparently composed of LSW, while there was an intrusion of warmer, more-saline water with its core at 222 m, 9.3°C and 35.0‰ – probably a portion of the NACW-like water that dominated further down the canyon. Set 49 showed an almost identical profile, though the core of the CIL was at 73 m, 3.7°C and 33.0‰, while the subsurface maximum had all but disappeared, its role taken over by the intrusion of putative NACW, with its core at 181 m, 9.7°C and 35.0‰. Set 50 offered a marked contrast. The downcast found the mixed layer of SSWs, of 19.4°C and 30.8‰, to be 8 m deep. Below was a homogeneous layer (15.8°C and 32.1‰) extending from 20 to 45 m depth and then a very sharp thermohalocline from 70 m, 14.7°C and 32.9‰ to the core of the CIL at 72 m, 4.8°C and 33.3‰. The subsurface temperature maximum, once again composed of an intrusion of what appears to have been NACW, lay at 185 m, 9.1°C and 34.9‰, with less-saline LSW-like water below. The upcast provided no data from above 26 m depth. It recorded the lowest few metres of a thermocline and then a homogeneous layer of 10.0°C and 33.7‰ between 30 and 37 m depth. Below that was a gradual thermohalocline to the core of the CIL at 62 m, 4.3°C and 33.1‰. The subsurface temperature maximum was, however, very similar to that seen on the downcast (186 m, 8.8°C and 34.8‰). By the following afternoon, much of that structure had broken down. Set 59 recorded the SSWs at 5 m depth as 19.4°C and 30.8‰ but beneath there was a rather steady thermohalocline leading to a weak CIL with its core at 95 m and 7.1 C. The subsurface temperature maximum was at 136 m, 9.0°C and 34.7‰ but there was a salinity maximum at 167 m, 8.9°C and 34.8‰ which represented what was left of the apparent NACW intrusion. Over the canyon wall, Set 48 was limited to a maximum depth of 448 m. Rather than resembling the adjacent Set 50, its profile was more similar to that recorded the following day by Set 59, though Set 48 revealed the same intrusion of putative NACW seen by Set 50 (with its core at 183 m, 9.3°C and 34.9‰).

As expected, below the subsurface temperature maximum, the water column was far more homogeneous than it was at lesser depths. Any spatial pattern in

the subtle variations, among CTD casts, in that volume was confused by temporal change – most isotherms and isopycnals becoming progressively shallower between Sets 49, 50 and 51 (Figure 11), perhaps as a consequence of tidal flow towards the obstacle of the canyon head (though the data from Set 59 do not fit that pattern). Set 48 found 6.3°C at its 448 m deepest extent, which temperature was only recorded by the other four sets above 380 m. That depression over the canyon wall was reflected by most shallower isotherms and isopycnals, though they may have been affected more by temporal than spatial variation. Most notably, there was a temperature inversion at about 400 m, marked by the 6.5°C isotherm, and even the density at 448 m was 0.0141 $g.l^{-1}$ lower than at 437 m on the downcast of Set 48 (and 0.0166 $g.l^{-1}$ lower than at 434 m on the upcast). Together, those suggest that downwelling was occurring on the western wall of the canyon at the time, the flow extending perhaps 100 m above the seabed and carrying water 50 m or more deeper than it would have been over the thalweg.

While crossing the Banquereau Spur on 17 August, an unusual pattern of acoustic backscattering, suggestive of large-scale vertical water movement, was observed on the vessels echosounder (see Section 3 below) and it was decided to suspend trawling operations while investigating that feature, using a combination of acoustic transects and three CTD casts. Sets 28, 29 and 30 were all completed within six hours and 8.5 km of one another: Set 28 was made over a seabed depth of 1700 m southeast of the spine of Banquereau Spur, Set 30 made immediately southeast of that ridge, and Set 29 over the thalweg northwest of the Spur (Figure 12). The area around the canyon mouth, between the Deep and Main stations, also saw two other casts made at much the same time: Set 22 over the canyon thalweg near the south-western tip of the spur on 16 August and Set 37 on AZMP station GULD4, also over the thalweg but about 2 km further north, on 18 August (Kenchington *et al.* 2014). Four of those casts yielded data from the surface, where they recorded a very thin (1 to 7 m deep) layer of SSWs (18.9–20.6°C and 31.0–31.4‰). That overlay an equally thin band of WSW (3 to 4 m thick, centred at 11 to 14 m depth; 22.7–23.6°C and 33.6–35.1‰), Set 30 additionally recording a second such layer at 16 to 19 m depth, 20.3 to 21.0°C and 35.0‰. The presence in the records from Sets 30 and 37 of that near-surface WSW, the same water that was seen to slide beneath the immediate surface on the Deep Station (forming the line of *Sargassum*), shows that small amounts of it penetrated into the central canyon, north of the Banquereau Spur and almost to the southern end of the Main Station, though WSW was not detected on that Station itself.

Beneath those near-surface waters, the downcast of Set 28 (which recorded no data from the surface) showed a complex of layers likely comprising both WSW and NACW (12.0–13.7°C, 35.3–35.6‰), with its upper bound at less than 68 m depth and its lower merging into NACW-like water at 190 m. The upcast revealed

a similar pattern, though the layering was seen from 34 to 157 m depth. The downcast of Set 30 found some of that same complex (13.0–13.9°C, 35.2–35.4‰) at 77 to 100 m depth, though there was an intrusion below it (at around 105 m depth) by a layer that had an admixture of CIL water. The upcast, which reached the surface some 4 km northeast of the start of the downcast, found only traces of that water as thin layers, notably one at 75 to 79 m. The CIL itself lay above it, with a core depth of 69 m (8.1°C, 34.0‰) on the downcast and 56 m (7.9°C, 33.9‰) on the upcast. The considerable temperature change between the CIL and the over-lying surface WSW took the form of a gradual thermohalocline. Set 29 found none of the layered complex of WSW and apparent NACW, just the CIL with a sharp thermohalocline above and a more gradual one below leading into the cooler NACW-like water. On the downcast, the core of the CIL was at 33 m and 5.1°C, while the least salinity was 32.2‰ at 22 m depth. The upcast found the core of the CIL at 49 m, 3.3°C and 32.6‰.

Set 22 found WSW extending down to 86 m depth (from the least depth at which data were obtained: 58 m). Beneath was a very sharp thermocline, with temperatures falling 5.2°C in 2 m, and then the core of the CIL at 88 m and 8.9°C. A gradual thermo-halocline led from there to the top of the NACW-like water around 130 m depth and 10.5°C. The upcast found cooler WSW below the surface variant of that water mass but the sharp thermocline beneath was centred on 40 m depth and saw temperatures drop 7°C in as many metres. The core of the CIL was at 45 m, 7.1°C and 33.5‰. Beneath that again was a broad band of cool layers and a subsurface temperature maximum of 10.5°C and 35.0‰ at 133 m. By the time that the downcast of Set 37 was made nearby, the cooler WSW had been displaced, aside from a gentle thermocline beneath the surface variety which appeared to represent mixing between those two warm waters. Immediately beneath was a very sharp thermo-halocline at 25 m, which saw temperatures and salinities drop 9.3°C and 1.7‰ respectively with 2 m change in depth. The underlying CIL had its core at 49 m and 3.7°C, while the NACW-like water was reached at 190 m and 9.7°C.

Below their subsurface temperature maxima, each of those five Sets showed that the water column was filled with apparent NACW, though some casts showed hints of an intrusion of a less saline layer. Sets 28 and 29, made either side of the spine of the Banquereau Spur, recorded temperatures and densities throughout their water columns which closely resembled those found the previous day over nearby portions of the thalweg, by Sets 21 and 23 respectively (Figure 12)[17]. In contrast, Set 30, made almost directly over the Spur's ridge,

[17] Figure 11 illustrates the temperature and salinity data gathered around the Banquereau Spur on 16 and 17 August. Two further CTD casts were made in that general area on 18 August: Set 36 very close to where Set 23 had been made two days earlier and Set 37 ≈2 km north of the location of Set 22. In each case, the water column below the subsurface temperature maximum was almost unchanged. Most isotherms and isopycnals had moved deeper (though some had

detected pronounced elevations of both isotherms and isopycnals – some of those close to the seabed being lifted more than 100 m compared to their depths further southeast and northwest. Thus, while the appearance of large-scale vertical displacement of water suggested by the acoustic records (see Section 3 below) was misleading, it does seem that local flows interacted with the seabed of the Spur to generate some upward motion. Whether that is a normal feature of the oceanography of The Gully, whether it was driven by the movement of the tongue of WSW across the mouth of the canyon, or whether it had some other transient origin remains unknown.

Along the canyon thalweg, from the southeastern end of the Deep Station to the northern extent of the Head Station, the isotherms and isopycnals beneath the subsurface temperature maximum showed local variation in depth, some perhaps temporal rather than spatial, but no clear overall pattern (Figure 13). There was a general upward slope along the length of the Deep Station, probably associated with the presence of the overlying tongue of WSW, which continued around the Banquereau Spur at depths of less than 500 m. From the south end of the Main Station to the north end of the Head Station, however, there was little discernable trend in isotherm or isopycnal depth, despite considerable set-to-set variation.

Figure 13 contrasts with previous results from The Gully. In their CTD data, collected in April 2006 and August 2007, Greenan *et al.* (2014) saw a near-linear up-canyon trend towards cooler, less saline water below 400 m depth – a trend that would appear as an up-canyon elevation of isotherms (and a matching depression of isohalines). The isopycnals, in contrast, were near-horizontal along the length of the canyon, though somewhat depressed in the central canyon relative to their depths in the upper canyon and around the canyon mouth. Greenan *et al.* (2014) examined the possibility that the trend resulted from an "estuarine-like" exchange of heat and salt between the cold, low-salinity CIL and the deep water within the canyon, enhanced by the very high vertical eddy diffusivity resulting from tidal amplification. The CTD data from the 2007 trawl survey found a general elevation of the isotherms below the subsurface temperature maximum from the Deep to Head stations, though the pattern was broken by two anomalous CTD casts, which apparently illustrated temporal change (Kenchington *et al.* 2009). The isopycnals did not show the elevation but did display the temporal change (see above). When interpreting their data, Kenchington *et al.* (2009) assumed that temperature was a conserved property of the water below rim depth in the canyon and hence a marker of layers within that water – the elevation of the isotherms indicating a deep inflow at the canyon

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shallowed) but almost all by less than 50 m and some by very much less. On Set 36, only the 4.8 and 5.0°C isotherms (≈600 m depth) had moved further, the former deepening by 74 m. On Set 37, the deepest isotherms and isopycnals, below ≈1000 m, had moved downwards by as much as 84 m.

mouth and an export of water at much shallower depths around the upper canyon, rather than by progressing mixing along the length of the canyon. Greenan *et al.* (2014) have since shown that an inflow was normal during the 16 months that their current meters were deployed, though that does not preclude mixing also being important. The general parallelism between isotherms and isopycnals (and hence also of isohalines) along the canyon thalweg in August 2009 (Figure 13) does, however, cast doubt on the magnitude of progressive along-canyon mixing, at least at the time of that survey. Unravelling the contrasts among the different sets of CTD data from the canyon will require a dedicated study and cannot be attempted here. Suffice to say that the pattern observed in August 2009 differed from that in April 2006 and August-September 2007.

It has been noted above that, below the subsurface temperature maximum, the temperature and salinity properties of the water on the Main Station (hence in the central canyon) were NACW-like, whereas those on the Head Station (in the upper canyon) were LSW-like. That distinction is not apparent in the along-canyon isotherms and isopycnals (Figure 13). The reasons for that apparent conflict remain unsure, though it may result from nothing more than the distinction between NACW-like and LSW-like waters being so subtle that they emerge from T / S plots but not from isotherms along a transect.

The performance of the oxygen sensor on the CTD during the 2009 survey was erratic, while the measured concentrations appeared generally biased downwards, and only limited trust can be placed in some of the output data (Figure 9). At the Head and Main Stations, the pattern that the sensor revealed was relatively simple: In the mixed layer of surface SSWs, measured concentrations were 4.1 to 4.5 $ml.l^{-1}$, while there was a maximum of 4.6 to 5.2 $ml.l^{-1}$ between 15 and 25 m depth. Below that, oxygen levels dropped away to a minimum (measured as 2.5 to 2.8 $ml.l^{-1}$) usually at and below the depth of the subsurface temperature maximum. On Set 51, the minimum corresponded to the intrusion of more saline water, supporting its tentative identification as NACW. Set 48, in contrast, found a deeper minimum at around 300 m depth. That was also the cast which produced indications of downwelling over the canyon wall in its temperature and salinity data (see above). Beneath the oxygen minimum, there was a gradual increase to a measured concentration of 3.0 to 3.2 $ml.l^{-1}$ at the bottom of the casts, where the data could be trusted at all. During Sets 36, 42 and 47 on the Main Station, the layer of slightly colder and less saline water that appeared within the supposed NACW at depths a little greater than 200m (see above) was particularly well marked as being relatively oxygen-rich (measured as 2.9 to 3.0 $ml.l^{-1}$.). The richness, though not the measured concentration, is in accord with expectations for LSW. In terms of ecological effects, even 2.5 $ml.l^{-1}$ of oxygen (equivalent to 112 $mmol.m^{-3}$) is above the levels usually deemed to constitute hypoxia (e.g. Gilbert *et al.* 2005). There is no

reason to suppose that any of the nekton in The Gully was exposed to significant oxygen stress.

On the Deep Station and around the Banquereau Spur, the surface WSW was recorded with oxygen concentrations anywhere from 3.9 to 4.9 $ml.l^{-1}$, though whether that was real variation in the water or resulted from the unreliable sensor is unclear. There was usually a subsurface oxygen maximum at a few tens of metres depth, which typically fell in the WSW and could show measured concentrations as high as 6.6 $ml.l^{-1}$, though 4.5 to 5.0 $ml.l^{-1}$ was more normal. The oxygen minimum was typically measured as 2.2 to 2.5 $ml.l^{-1}$, though it was recorded as low as 2.0 and as high as 2.7 $ml.l^{-1}$ (3.5 $ml.l^{-1}$ over the Spur), while its depth lay anywhere from 232 to 319m. It was almost invariably slightly deeper than the subsurface temperature maximum. Below that minimum, on all casts from which the data can be trusted at all, measured oxygen concentrations invariably increased progressively, reaching 3.0 (Sets 8 and 9), 3.4 (Set 15) or 3.5 (Set 16) $ml.l^{-1}$ at depth on the Deep Station. Whether the latter difference among sets represented movement of more highly oxygenated water across the Station or, alternatively, resulted from defects in the sensor is unclear, though all of the values were so low as to suggest a downward bias in the measurements. (Over the Banquereau Spur, values of 3.7 $ml.l^{-1}$ and 4.3 $ml.l^{-1}$ were recorded at depth on Sets 30 and 22 respectively. Those are suspected to have been instrument errors.) Where the immediate surface layer was derived from surface SSWs, it was recorded as having oxygen concentrations between 3.4 and 5.6 $ml.l^{-1}$, sometimes with the sea surface showing 0.9 $ml.l^{-1}$ higher than the base of the mixed layer.

The oxygen data from Set 2, the sole CTD cast on the Slope Station, do not merit consideration here.

2.4.3.3 Summary: From the perspective of analysts of the trawl catches, perhaps the most important point amidst the mass of information derived from the 2009 CTD casts is the presence of a tongue of WSW immediately outside the mouth of the canyon. While that was a thin layer, it can be expected to have advected individuals of southern species of epipelagics and diel-migrant mesopelagics (transported at night) to the mouth of The Gully. The presence of that surface water mass, pressing the SSB almost to the shelf break, temporarily disturbed the usual pattern seen over the canyon of the SSWs at the surface, overlying a subsurface temperature maximum and then a body of deep water, either LSW or NACW.

The second obvious lesson is that the water layers above the subsurface maximum were extremely complex, with marked spatio-temporal variability across scales of a few kilometres or a day, especially around the canyon mouth. The warm, uppermost layer of the SSWs extended to the SSB, usually covering

the Deep and Slope stations but briefly pushed off most of the Deep Station by the tongue of WSW. The CIL (which was nowhere as prominent as it had been in 2007) did not reach as far south but was recorded at the north-western end of the Station, immediately outside the canyon mouth. Further complicating the picture, an intrusion of WSW entered the canyon and reached almost to the Main Station, while thin layers of the CIL and the upper SSWs penetrated some kilometres into the volume otherwise occupied by WSW. Even that does not capture the full complexity, however. Each nominal water mass, as is expected, contained water of varied characteristics, bodies of which were apparently moving past each other with considerable vertical sheer, thus adding temporal variability to the vertical structure and sometimes creating extremely abrupt thermohaloclines as disparate waters moved over and under one another. It might be supposed that the momentum of the moving tongue of WSW interacted with the steep bathymetry of The Gully to enhance that complexity but there is no direct evidence of its causes, while Horne (1978) reported generally similar complexity in the same SSB when it was much further from the continental slope.

Below the subsurface temperature maximum, the predominant water mass had the characteristics of what is here termed the NACW, though it might more accurately be described as the cooler portion of the Sargasso Sea T / S curve identified by Iselin (1936) and by Csanady and Hamilton (1988). That was the same water type seen in the central canyon and around the canyon mouth (below the subsurface maximum) in September 2007. In both years, however, the upper canyon (or at least the Head Station) was filled with LSW-like water, as it had been during the CTD surveys of April 2006 and August 2007 (Greenan *et al.* 2014). Hence, the along-canyon gradients in temperature and salinity noted by Greenan *et al.* (2014) persisted through September 2007 and August 2009. As will be shown below, they were also seen in March 2010, though they may not have been present in August–September 2008.

Three other features merit note here. One is the thin intrusion of apparent NACW that reached north to the Head Station, balanced by a similar flow of LSW southwards across the Main Station and perhaps as far as the canyon mouth. The second is the evidence of downwelling against the canyon wall near the Head Station and specifically on AZMP station GULD3. Primary productivity is enhanced by upwelling into the euphotic zone but secondary and tertiary productivity in a canyon may be enhanced by downwelling of continental-shelf water, bearing plankton and detritus from relatively-rich neritic depths. If the downwelling is persistent, it might be important to The Gully's ecosystems. It might also mean that the GULD3 monitoring station is unrepresentative of the canyon. Finally, the Slope Station was selected as an analogue of the Main Station, on the open continental shelf rather than within the confines of the canyon (Kenchington *et al.* 2014). During this 2009 survey, however, it had

overlying water layers which resembled those seen on the Deep Station and, as regards its pelagic ecosystem, may be more comparable to that.

2.4.4 March 2010

2.4.4.1 Regional and Annual Overview: Where 2008 and 2009 had been rather "typical" years for the Scotian Shelf, 2010 was not, though the midwater trawl survey that year was conducted in the spring and hence the biota that were captured had not been affected by much that was to follow. Globally, 2010 was the warmest year on record to that date. The NAO reached a record low. The spring ice volume on the Scotian Shelf was not significantly different from the lowest on record. Annual water temperature anomalies for the various monitoring sites around the Scotian Shelf were all positive (+0.9°C for SST on the eastern Scotian Shelf), while a composite index reached the fourth warmest of a 41-year record. The stratification index was the third highest in a 64-year record. Sable Island air temperatures showed positive anomalies in every month of the year, with March being one of the highest (Hebert *et al.* 2011). The spring phytoplankton bloom began early: At the Halifax-2 Station, it peaked on 9 March, whereas early April is normal. It was rather weak (320 $mg.m^{-2}$ at its peak) and, at that station, was the shortest on record – though the latter may have been a very local feature, the AZMP bi-weekly sampling being significantly impacted by mesoscale variability (Greenan *et al.* 2008). Satellite data showed the shift in timing to be widespread, with the bloom peaking on the eastern Scotian Shelf during the second half of March (i.e. while the trawl survey was in progress), with surface chlorophyll concentrations over The Gully near double their normal levels for that period. In contrast, the spring zooplankton concentrations were normal, despite the aberrant availability of phytoplankton. Later in the year, there were unusual features in the zooplankton community composition on the Halifax-2 Station but, even if those were not local (as they seem to have been), they came too late to affect the survey. The same can be said of the concentration of *Calanus finmarchicus* on the eastern Scotian Shelf, which was second only to its record level the previous year (Johnson *et al.* 2012). On the Extended Halifax Line in May, and thus two months after the trawl survey, the water adjacent to the continental slope between 1,000 and 2,000 m depth had salinities and oxygen-concentrations characteristic of NACW. Unfortunately, data from the vicinity of the upper slope are not available[18].

Unfortunately, few of the routinely monitored, regional indices relate to winter conditions and thus little can be said of the state of the environment that influenced the nekton in The Gully in March – even the early phytoplankton bloom being too late to have much effect, until after the survey, on the predators

[18]Sections illustrating the monitoring data are available from: http://www.bio.gc.ca/science/monitoring-monitorage/azomp-pmzao/slope-pente/conditions-eng.php

of the herbivorous plankton. The warm air temperatures recorded on Sable Island were also evident over the canyon, where the survey enjoyed remarkably calm, pleasant weather (Kenchington *et al.* 2014), which will have affected stratification at the sea surface.

2.4.4.2 Interpretation of CTD Data: During the survey, there were Gulf Stream eddies, with SST around 20°C, passing less than 300 km south of The Gully. WSW, at about 12°C, was less than 100 km from the canyon mouth. The SST over The Gully was, however, only a few degrees above freezing (Figure 14).

Thirteen CTD casts were made during the cruise (Figures 15 and 16), the instrument functioning effectively throughout (Kenchington *et al.* 2014), except that examination of the data calls into question the calibration of the oxygen sensor. As was to be expected during the season when the CIL is replenished through surface cooling, the data revealed a simpler picture than was seen during the summer surveys, though the exceptionally calm weather sometimes allowed a distinct surface layer to appear. With such simplicity, only the downcasts of each set are considered here.

Two casts were made at the Head Station (Sets 27 and 41), with another (Set 42) at the nearby GULD3 AZMP station. They found almost no mixed layer at the surface, both temperature and salinity increasing downwards, while oxygen concentrations fell, except that Set 42 showed local warming of the top 25m of the water column and Set 27 found that the surface oxygen concentration was slightly reduced. Surface conditions were 1.9 to 2.4°C, 32.2 to 32.5‰ and, as measured, 7.7 to 8.5 $ml.l^{-1}$. A continuous thermohalocline extended to the subsurface temperature maximum at 183 to 190m depth (7.3–10.6°C, 34.4–35.1‰), while the recorded oxygen concentrations dropped away to 4.9–5.3 $ml.l^{-1}$, though the rate of change with depth was rather less steep over the uppermost 50 to 100 m (meaning down to the summer depth of the CIL) than below. As seen in summer, the oxygen concentrations continued to decline to minima a little below the depth of the temperature maximum, though in March the measured concentration remained above 4 $ml.l^{-1}$ on each Set.

Below the subsurface temperature maximum, there was the same indication of layering seen in some CTD casts in the summer but at greater depths the LSW-like water took the form seen on the Head Station the previous August, with salinities below 35.‰ and temperatures dropping away towards 4°C. There was some tendency towards reduced salinity around 400 m depth. The isotherms within the apparent LSW did not show such clear evidence of downwelling against the canyon wall as they did the previous summer, partly because of some complex layering within that water mass, but the 6.3 and 6.5°C isotherms were unambiguously deeper, by 33 and 88 m, respectively, on Set 42 than on Set 41. The 5.5°C isotherm, in contrast, was 9 m shallower over the wall. The

isopycnals were generally deep than on Set 27 but only by 10 to 35 m. There was a temperature inversion between 213 m (6.41°C) and 252 m (7.34°C) over the canyon wall, though whether that had been caused by water flows interacting with the seabed or represented layering within the water of the upper canyon which only chanced to lie over the wall is unclear.

The three CTD profiles from the Main Station (Sets 15, 26 and 34) were comparable to those recorded further up the canyon, though the surface mixed layer was much better developed, reaching to some tens of metres deep. Surface conditions were 2.5 to 2.9°C, 32.6 to 32.8‰ and, as measured, 7.7 to 7.8 $ml.l^{-1}$ – a noticeably greater temperature and salinity than around the Head Station. The thermohalocline led to a subsurface temperature maximum at 158 to 209m depth, where the water was 10.3 to 12.1°C and 35.2 to 35.4‰, the higher temperatures and salinities being indicative of NACW. Measured oxygen concentrations dropped away to 3.8–7.23 $ml.l^{-1}$ (with one interesting example of layering on Set 15 revealed by oxygen concentration when it was not apparent in temperature or salinity). The oxygen minima were again at greater depths than the temperature maxima, though the measured concentration was always above 3.5 $ml.l^{-1}$. The underlying water was of the familiar NACW-like form, except that oxygen concentrations recorded at depth exceeded 6 $ml.l^{-1}$, which would suggest LSW if the sensor's calibration could be trusted.

Two casts were made on the Deep Station (Sets 19 and 47). The profiles revealed were much as those on the Main Station, though neither found a true mixed layer at the surface. Set 19 detected something of the reduced-oxygen layer around the depth of the CIL that was prominent in Set 15. The immediate surface water was at 2.5 or 3.0°C, 32.6 or 32.7‰ and, as measured, 7.6 or 7.8 $ml.l^{-1}$, while the subsurface temperature maximum lay at 166 or 170 m depth, 9.3 or 12.0°C, 35.0 or 35.3‰ and 4.1 or 5.8 $ml.l^{-1}$ – values almost identical to those seen on the Main Station. The recorded oxygen minima were again above 3.5 $ml.l^{-1}$. The slight reduction in the salinity seen at mid-depths at the Head Station, which was arguably present at the Main Station, did not extend to the Deep Station. Sets 19 and 47 found salinities of consistently 35.0‰, indicative of NACW, below the subsurface temperature maximum, though measured oxygen concentrations approached 6 $ml.l^{-1}$ at depth.

Three additional CTD casts were made on a transect across the canyon mouth at stations previously adopted by other programs: Set 20 at AZMP station GULD4 and Sets 48 and 49 east and west of the mouth at Greenan *et al.*'s (2013, 2014) Stations SG23 and SG28. Given the limited differences between the profiles recorded on the Main and Deep Stations, it is not surprising that those three casts were again similar, though Set 49 showed no mixed layer at the surface at all, while Set 20 had a pronounced one – likely a matter of local temporal change. Set 48 found 1.8°C water at the immediate surface, with 0.9°C at 35 m

and a halocline extending from the surface downwards. The other Sets did not reveal such extreme cold. All three casts detected the reduced-oxygen layer near CIL depth but it was weakly developed, while Set 20 in particular showed some unusual layering around 300m depth.

The single cast made to the westward on the Slope Station (Set 1) was also consistent with the pattern seen in and near The Gully, though it showed much better development of a mixed layer about 40 m deep – likely a temporal difference resulting from wind-driven mixing before the period of unseasonable calm experienced during the survey.

Set 58, the only CTD cast made on the Offshore Station, was the marked exception to this impression of general spatial homogeneity. It showed a mixed layer 13m deep at 8.4 to 8.6°C, 34.2‰ and, as measured, 6.9 $ml.l^{-1}$ – very substantially warmer and more saline than had been seen over The Gully. That is suspected to have been a tongue of WSW that had cooled at the surface. Beneath, there was a strong thermohalocline leading to a layer from 49 to 75 m depth that was almost consistently 12.4°C, 35.4 or 35.5‰ and 4.1 to 5.6 $ml.l^{-1}$. Over the next hundred metres, temperature and salinity were almost steady (maxima 12.7°C at 172 m depth and 35.6‰ at 188 m) but oxygen concentrations spiked upwards to a recorded maximum of 7.4 $ml.l^{-1}$ at 157m depth). From their appearance in the T / S plot, those appear to have been bodies of NACW. Below the subsurface temperature maximum, the water followed the expectations for the temperature and salinity of NACW, reaching 4.2°C and 35.0‰ by the bottom of the cast at 1185 m, except for an intrusion of colder less saline water between 520 and 710 m depth, with its core at 4.2°C and 34.83‰ – suggestive of LSW. Oxygen concentration showed the expected minimum beneath the subsurface temperature maximum (recorded as 3.6 $ml.l^{-1}$ at 306 m) but then increased downwards to a new maximum (reaching a measured 6.9 $ml.l^{-1}$ at 623 m) corresponding to the temperature and salinity minimum (as expected of LSW), before settling down to 6.3 or 6.4 $ml.l^{-1}$ from 755 to 1060 m depth. It then dropped away again to 6.0 $ml.l^{-1}$ at the bottom of the cast. While those depth variations in concentration corresponded to interpretations built on the temperature and salinity data, the measured values were high throughout, again implying a calibration failure.

The depths of the isotherms and isopycnals beneath the subsurface temperature maximum generally decreased up-canyon from the Offshore Station to the Head Station (Figure 17) – the isotherms often being more steeply inclined which indicates that the isohalines tended to deeped up-canyon. That was in accord with the slope of the isotherms seen in September 2007 (Kenchington *et al.* 2009) and with the cooling and freshening in April 2006 and August 2007 noted by Greenan *et al.* (2014), though it contrasted with the absence of such a gradient in August 2009. It is to be expected that broad patterns were disturbed

by short-period temporal variability, especially over the outer canyon where varied waters pass the canyon mouth, and in the upper canyon, where the amplified tides meet the obstruction of the canyon head. Set 47, in particular, found all but the deepest isopycnals to be anomalously shallow. Within that limitation, it appears that the deepest isotherms (e.g. 4.2°C at >1100 m) were almost horizontal, as were isopycnals as shallow as ≈650 m. Otherwise, the along-canyon gradients were generally greater at lesser depths and seem to have increased towards the canyon head (Figure 17).

Across the outer canyon and at depths between the subsurface temperature maximum (≈160 m) and about 350 m, the data suggest pronounced elevation of both isotherms and isopycnals over the thalweg, compared to their depths on stations over the continental slope to the northeast and southwest (Stations SG23 and SG28 of Greenan *et al.* 2013). Deeper in the water column, the isotherms and isopycnals over the thalweg were depressed relative to those to the south-westward (Figure 18). Those patterns were, however, dependent on the anomalous Set 47 and thus seem likely to have been products of varied waters passing along the continental slope.

2.4.5 Water Masses Trawled

The extreme complexity and variability of the waters in The Gully, as revealed by the CTD casts, means that the water masses fished by a particular trawl set cannot be well described using data from casts made hours or days, or just a few kilometers, from the trawl track. Meanwhile, the differences between the characteristics of the various waters are so fine that their identification requires data on salinity and, preferably, oxygen concentration, in addition to temperature. Yet the instrumentation on the headropes of the trawls did not include CTDs but only temperature-depth recorders and only in 2009 and 2010 did those include a instrument of adequate precision – a Seabird SBE39 (Kenchington *et al.* 2009, 2014). Nevertheless, consideration of the catch data requires some understanding of the water masses from which the animals were taken and hence some summary must be offered here:

- In 2007, every set passed through both the surface layer of the SSWs and the CIL. They may all have also encountered some of the lower layer of that complex. All sets, other than those made on the Head Station, entered, and all that went below 250 m depth primarily fished, the water mass that is here identified as NACW-like. The Head Station sets similarly entered, and those which went below 250 m mostly fished, LSW-like water.
- The data from the 2008 survey are inadequate but it is likely that every trawl set passed through all three layers of the SSWs (certainly the surface layer and the CIL). Some may have encountered WSW but those

which went below 250 m mostly fished a water mass which seems to have resembled LSW, though that identification is highly uncertain.

- In 2009, every set passed through the surface layer of the SSWs and the CIL, though some sets made on the Deep Station will have seen very little of those. All sets made on the Deep and Slope stations passed through WSW. Apart from those made on the Head Station, every set entered the putative NACW. Sets with maximum depths of 750 or 1,250 m primarily fished that water mass but those on the Main Station also encountered some of the LSW-like water otherwise found on the Head Station. For sets made on the latter, the roles of NACW-like and LSW-like waters were reversed.

  The ships used during the midwater trawl surveys did not carry sufficient wire on their hydrographic winches to place a CTD as deep as 1,500 m. It remains possible that the sets made to 1,750 m passed through the NACW-like water and into a deeper and denser form of LSW. The two very deep tows, Sets 38 and 43, may even have entered NEADW as the second of those reached 2,379 m depth. The headline sensor then recorded a minimum temperature of 3.21°C and recorded 3.47 and 3.45°C when passing 2,000m depth on its way down and up. However, monitoring data from the extended Halifax Line (west of The Gully) in May 2009 shows the markedly lower salinities and higher oxygen concentrations, indicative of NEADW or perhaps Denmark Strait Overflow Water, only below 3,000 m depth[19].

- In 2010, every set except the one made on the Offshore Station passed through the SSWs, Set 59 encountering WSW instead. Apart from those made on the Head Station, every set entered the putative NACW. Sets with maximum depths of 750 or 1,250 m primarily fished that water mass, though the one set made on the Offshore Station may also have encountered some LSW. As in 2009, the sets which passed 1,500 m depth may have entered a deeper layer of LSW, beyond reach of the CTD casts. The Head Station sets differed only in fishing LSW-like water, rather than the putative NACW.

Some of those water-mass differences are likely of great ecological or biogeographic significance. The presence of the CIL, for example, seems likely to affect the animals which migrate through it at dusk and dawn, while inspection of the catches taken on the Deep Station in 2009 strongly suggested that the tongue of WSW had brought a great increase in species richness to the mouth of The Gully. In contrast, the distinctions between what appear to have been LSW and NACW may be irrelevant to the biota within them. The differences in

[19] Sections illustrating those data are available from: http://www.bio.gc.ca/science/monitoring-monitorage/azomp-pmzao/slope-pente/conditions-eng.php

temperature and salinity are far too small to have direct biological significance and even the oxygen concentrations may have little relevance. It should not need to be said that the presences of those water masses in the canyon does not mean that The Gully is ecologically part of the Sargasso or Labrador seas. Downstream evolution is sufficient to change the characteristics of each water mass considerably between its formation and its arrival on the Scotian Slope. In the case of the NACW, the isotherms in the canyon lie hundreds of metres closer to the surface than they do in the Sargasso Sea, meaning that a species which seeks to maintain a given depth by day will experience much lower temperatures in The Gully. More important, mesopelagic ecosystems are dependent on epipelagic production, with the diel migrants rising into the surface layers to feed at night. Not only the productivity but the species composition and physical conditions of the waters above the canyon are very different from those in either the Sargasso or the Labrador Sea.

3 ACOUSTIC SCATTERING LAYERS

T.J. Kenchington and N.A. Cochrane

3.1 INTRODUCTION

Throughout each of the four surveys in The Gully, the ship's 38 kHz scientific sounder was operated almost continuously, usually recording acoustic backscattering to depths of 1,000 m. In 2009, a sounder additionally operated at 120 kHz. Records of the detected echoes comprised a mixture of printed hardcopy and digital data capture, with extensive unrecorded periods during some surveys (Kenchington *et al.* 2009, 2014).

Kenchington *et al.* (2009) examined the paper records from the 2007 survey in detail, finding extreme small-scale spatial variation, both horizontally and vertically. There existed multiple scattering layers which, particularly inside the canyon, often showed a "wavy" appearance on the sounder records – though that resulted more from spatial than temporal variations in depth. In some cases, the "waves" appeared to be associated with water flowing over bathymetric features. Some epipelagic schools and near-surface scattering layers were seen. Diel vertical migration of the deep scattering layer was only observed on the Offshore Station and but once north of the canyon mouth, near the southern end of the Main Station. It extended between the surface and depths of about 300 m. The migrants were thought to be primarily myctophids and (from the composition of the trawl catches) presumably mostly *Benthosema glaciale*.

The principal scattering layer, however, was non-migratory, broad and diffuse. It was found from approximately 350 to 750 m depth, and its volume backscattering strength, or S_V, was generally not much greater than the -75 dB threshold set for the recording of received echoes. That layer included a particularly intense patch of backscattering at 400 to 500 m depth near the Banquereau Spur. From there, its intensity fell off rapidly along the length of the Deep Station. Northwards, the scatterers extended up the central canyon past the Main and Wall stations but the levels of backscattering then declined rapidly. There was little sign of the deep, non-migratory layer in the upper canyon and, such as was observed there, was mostly over the canyon walls. Kenchington *et al.* (2009) reviewed other reports of a similar 38 kHz scattering layer over wider reaches of the North Atlantic, suggesting that the Gully non-migratory layer could be a manifestation of a more widespread phenomenon. In The Gully, it was not a result of echoes off temperature structures in the water column, which was homogeneous at the depths in question, yet the only non-migratory organisms taken by the IYGPT which might have been responsible for this backscattering layer were fish of the genus *Cyclothone* – a possibility taken up in Section 5 of the present report. A

final feature of the 2007 records was “flecks” that were suggested to be records of the vocalizations of whales at approximately 38 kHz (Kenchington *et al.* 2009).

In this section, those various observations are extended through examination of the sounder records from the 2008, 2009 and 2010 surveys, except that consideration of the “flecks” is deferred to the next Section of this report.

3.2 ANALYTICAL APPROACH

Subsequent to each survey, the echograms printed in real time were scanned into electronic images. For the 2008 survey (and as had been done for the 2007 data), ArcView files were prepared from the ship’s navigational records, showing the cruise track subdivided into time periods corresponding to each printed echogram page, with track segments hyperlinked to the scanned images. It was thus possible to identify either the locations of features identified on an echogram or else to examine the echo traces corresponding to a particular location. Those identifications were subject to uncertainty because the paper records were only time-stamped at the start of each page. The sounder was intended to be operated with a fixed ping-interval of 4 s but, sometimes either through human intervention or automated processes, it was re-set to intervals that varied with water depth, thus introducing an uncertainty of up to several minutes in the timing of specific pings. Depending on ship speed, each minute of uncertainty in timing could correspond to as much as 300 m of uncertainty in position.

The 2008 survey also generated digital records of backscattering in *.HAC* format. The ship’s navigation data were merged into those files, which were subsequently examined using *CH2* software (Simard *et al.* 2000). That provided a direct readout of position, depth and S_V for any selected pixel in the echogram. The positions read from *CH2* were considered with reference to the ArcView maps of the ship’s track. During the 2009 and 2010 surveys, acoustic data were primarily or exclusively captured digitally and examined using *CH2*. Their interpretation was aided by maps, prepared in ArcView, showing the ship’s track with positions identified at 15-minute intervals.

Publication-quality images of selected portions of the digitally-captured echograms were prepared using custom software developed at BIO. In addition to single-frequency echograms (showing backscattering at either 38 or 120 kHz), two-channel colour overlay echograms were prepared from some portions of the data from the 2009 survey. The overlays show 38 kHz backscattering in red and 120 kHz in cyan, potentially assisting interpretation of the data as described by Cochrane *et al.* (1991, 2000).

3.3 RESULTS

3.3.1 August / September 2008

During the 2008 survey, 105 pages of echograms were printed and 145 hours of digital records of acoustic data were gathered. They showed the same general pattern as was observed in 2007, with an epipelagic scattering layer, a strong diel-migratory layer (rising at dusk from about 300 m depth to the near-surface layer and descending again at dawn), and a diffuse non-migratory layer starting below about 350 or 400 m and extending to approximately 700 m (see Figure 19 for examples). There was, however, much less of the complex multiple layering that had been observed with the same sounder in 2007 as well as much less of the small-scale spatial variability that appeared on the echograms as "wavy" layering. The reduced spatial complexity does not appear to have been related to tidal conditions as the period that the ship worked in The Gully in 2007 spanned from immediately before spring tides (12 September at Point Tupper) almost to the following neaps (20 September) – a portion of the tidal cycle which closely corresponded to the timing of the 2008 survey (Kenchington *et al.* 2009, 2014).

During the 2008 survey, the epipelagic layer was often well-developed, particularly in the vicinity of the Head Station. It was sometimes seen above 10 m depth at night but at around 25 m by day. It probably represented backscattering by saury, *Scomberesox saurus*, which were much more plentiful around the ship at night in 2008 than in 2007 (and were caught in larger, if still small, numbers by the IYGPT). *S. saurus* is known to spend daylight at depths of a few tens of metres, while rising to (or above) the surface at night (Sauskan and Semenov 1969; Dudnik *et al.* 1981). In addition, during the 2008 survey, some discrete epipelagic schools were recorded at about 75 m depth. They could not be identified.

Diel migration of mesopelagic scatterers was frequently observed and, unlike in 2007, was evident within the central canyon. The scatterers were observed to begin moving upwards after 1900[20], accelerating their ascent at 2130 to 2200, reaching 50 m depth about 2300 (around 30 minutes after sunset) and continuing on to about 20 m by 0000. The subsequent descent from there sometimes began at about 0600, accelerated downwards around 0800 to 0830 (i.e. about an hour before sunrise) and slowed again, while passing 300 m depth, around 1100 or 1200, though the scatterers sometimes did not settle at their maximum depth (below 350 m) until nearly 1400 (see Figure 19 for an example). That timing was similar to what was seen in 2007, though in clock times the dawn migration commenced earlier and that at dusk later, as was expected from the different times of sunrise and sunset with the survey starting in late August rather than one week into September. Whether or not the observed within-survey variations

[20] Following the practice of Kenchington *et al.* (2009, 2014), all clock times presented in this report are in UTC (synonymous with GMT).

in migratory timing were related to cloud cover, moon phase or some other factor has not been investigated.

One notable difference relative to the 2007 survey was a southward distributional shift in the deep, non-migratory scatterers. The dense mass observed over the Banquereau Spur extended southwards across the Deep Station and north to the southern end of Main Station, though its greatest density remained immediately south of the crest of the Spur.

Early in the survey (approximately though to the end of August), those deep, non-migratory scatterers were largely south of 43° 53'N (the latitude of the southern end of the Wall Station), the intensities of both the migrant and the non-migrant backscattering dropping away sharply by the mid-points of the Main and Wall stations. As in 2007, both were essentially absent north of 44°N. On 3 September, however, dense backscattering at depth extended to 43° 57'N (near the northern end of the Wall Station), at least along the eastern side of the canyon, and traces extended to the southern end of the Head Station. The following day, the migrant scatterers appeared rather thin north of 43° 53'N, though that may have been because the ship then operated over the thalweg, rather than along the canyon wall. The deep non-migrants remained further north than observed at the start of the survey and on 6 September they were relatively dense as far north as the end of the Wall Station at 43° 56'N.

3.3.2 August 2009

During the 2009 survey, digital capture of acoustic data (at both 38 and 120 kHz) successfully commenced at 1335 on 17 August and continued until the ship left The Gully – a total of 103 hours[21]. In addition, 21 different "screen shots" of the sounder's monitor were printed in hard-copy before the problems with digital data capture were resolved and a further seven printed subsequently – some of the images overlapping in time. All printed images captured 38 kHz backscatter, many extending to depths greater than the 1,000 m limit of the digital recording.

The recorded scattering layers were complex and some were different from anything seen in 2007 and 2008. During the period of digital data capture, there appeared to be three distinct spatial areas, each characterized by its own distinctive pattern of echoes: the upper canyon, the central canyon and the outer canyon in the vicinity of the Deep Station. The transition between the first two areas was abrupt. Between the Main and Deep stations, however, the acoustic records showed a region of complex change centred over the Banquereau Spur

[21] The time data in the digital acoustic files (in *.HAC* format) from the 2009 survey are for Time Zone Z-1 and thus show times one hour later those recorded in other data sets for the same events. Those times have been corrected in this report and should be similarly corrected by any future users of the data.

and that area merits separate treatment. Finally, one exceptional phenomenon was observed around the Spur on 14 August but was recorded only on paper and then incompletely.

3.3.2.1 Upper Canyon: C.C.G.S. *Needler* was in the vicinity of the Head Station from approximately 1630 on 20 August until leaving The Gully around 2000 the following day. During that period, the most prominent backscatter feature at 38 kHz was a diffuse cloud of weak echoes (S_V typically -65 to -75 dB) which extended from about 400 to 600 m depth all the way to the canyon floor – or at least to the maximum 1,000 m depth of data capture where the canyon was deeper. Besides lying somewhat deeper than the non-migratory layers seen further south in 2007 and 2008, that cloud was remarkably homogeneous, with very little spatial variation (see Figure 20 for an example). The primary exception to the homogeneity emerged on the one occasion that the ship drifted up the large feeder canyon that enters the main canyon from the north, near the northern end of the Head Station. Then, the scattering began to thin while the ship was still over the main canyon thalweg, around 2110 on 20 August, and faded away as *Needler* proceeded north. The scattering reappeared as the ship returned to the main canyon.

Later in the recording period at the Head Station, diffuse layering was observed at depths as shallow as 300 m, resembling what was seen on the Main and Deep stations during the 2007 and 2008 surveys. Whether those more-structured echoes came from the same kind of scatterers as the deeper, homogenous mass seen the previous day remains unclear.

A second feature seen around the Head Station was a well-defined migratory layer, probably composed of krill (likely *Meganyctiphanes norvegica* – the dominant species in the IYGPT catches) since it was prominent in the 120 kHz records but weak or absent in those from the 38 kHz channel. By day, this layer was centred at about 200 or 250 m depth but it began to rise around 2200 on 20 August (approximately an hour before sunset), passing 100 m depth at about 2300 and reaching 25 m depth a half-hour later (Figure 21). The downward dawn migration of that layer was not well recorded but was in progress long before 1000, or an hour after sunrise, by which time the layer had already descended to 180 m depth. It reached 250 m around 1130. While much of that migratory layer produced only weak echoes, there were portions that reached S_V levels of about -50 dB at 120 kHz, perhaps indicative of krill swarms.

Finally, in the uppermost 200 m or more of the water column around the Head Station, the acoustic records showed thin layers of backscattering, some of which were likely echoes off the sharp thermoclines above and below the Cold Intermediate Layer, while others may have represented epipelagic schools. The latter backscattered sound at both frequencies, with 120 kHz S_V levels

sometimes surpassing -40 dB, though considerably less at 38 kHz. Around 1400 on 20 August, they were seen at about 65 to 75 m depth, with a particular concentration over the canyon wall. The following morning, from about 0930 to 1000, they were observed at about 40 m. The same schools may have risen to only a few metres beneath the ship at night when, in one instance, very intense scattering was observed at that depth on both sounder frequencies.

Needler did not follow the canyon thalweg between the Main and Head stations, hence the southward extent of this pattern of backscattering was not definitively recorded. The ship did, however, cross the thalweg once at about 43° 58'N (half way between the Head and Wall stations) and the scattering there was very similar to that seen in the upper canyon. Examination of echograms from other crossings of the canyon suggested that the transition to the form of scattering seen on the Main Station occurred around 43° 55' N – the latitude of the northern end of the Wall Station and nearly as far up the canyon as the deep, non-migratory scattering layer was observed to extend in 2007 and 2008.

3.3.2.2 Central Canyon: Digital recording of echoes from the vicinity of the Main and Wall stations began around 1500 on 17 August and continued intermittently (broken by periods spent further southeast) until 1630 on the 20th. Throughout the daylight portions of that time, complex layering (much of it diffuse) was observed below 200 m depth on both frequencies (see Figure 22 for an example). At 38 kHz, that scattering extended to 1,000 m, or to the canyon walls where they were shallower, though the lower parts tended to take the form of the amorphous cloud seen at the Head Station, rather than displaying discrete layering. Otherwise, the observed appearance of the backscatter was not notably different from what was seen in 2007 or 2008 in the same area. Maximal S_V values were around -60 dB. On some occasions when checked, the sounder's monitor revealed diffuse clouds of scattering below the 1,000 m limit of digital data collection and extending to the canyon floor. At 120 kHz, this scattering extended to the limit of detection at 400 to 500 m depth established by the sounder noise floor.

During daylight, the shallowest of those deep layers, around 250 or 300 m depth, was often much more prominent in the 120 kHz records and either weak or undetectable at 38 kHz (not seen in Figure 22, which presents a nocturnal example). That was presumably continuous with the similar layer seen in the upper canyon and likewise probably composed of krill. That layer was sometimes broken into discrete lumps, perhaps representing swarms of the animals, and at other times was almost unbroken but contained much denser areas. In contrast to that uppermost deep layer, some of those below showed clearly on both frequencies. As seen during previous surveys, those layers were spatially variable but did not show much temporal change when the ship was drifting slowly.

The shallower portions of this complex of layers was once observed to migrate upwards at dusk. On the evening of 17 August, the supposed krill layer ascended from 200 to 70 m through the period 2220 to 2315, after which the ship left the canyon. A separate layer, seen at both 38 and 120 kHz rose from 325 to 200 m during the same period. There is a hint in the echograms of a 200 to 400 m layer moving down as the shallower ones ascended (Figure 23) but that may have been a spatial change. No other such upward movement was observed while the ship was in the vicinity of the Main Station but, at night, layers were sometimes detected by both frequencies at 25 m depth and (more often at 120 kHz only) in the top 20 m of the water column.

There was little indication of any variation in the intensity of backscattering along the length of the Main Station but there was some reduction when the ship ran along the canyon thalweg immediately north of there, as the pattern of echoes changed towards that typical of the Head Station. Backscatter intensities over the Wall Station appeared generally less than those over the adjacent thalweg, in contrast to what had been seen in 2007 (Kenchington *et al.* 2009). At one point, the ship strayed east of the Wall Station and, over the 700 m bathymetric contour, there was relatively dense scattering at 38 kHz from 400 to 500 m depth but very little else to be seen in the water column. Much the same was observed north of the Wall Station on another occasion, over bottom depths of 500 to 700 m.

The pattern of epipelagic backscattering seen in the upper canyon, a combination of weak layers (perhaps echoes off thermoclines) and discrete schools, extended across the Main Station.

3.3.2.3 Outer Canyon: The pattern of backscattering seen on the Deep Station was dominated by multiple scattering layers between 300 and 800 m depth, which were both more intense (S_V reaching -55 dB) and better defined than those seen on the Main Station (see Figure 24 for an example). As was seen further up the canyon, in daylight the shallowest of those deep layers (≈300 m depth) was only prominent at 120 kHz. Usually, there was very little 38 kHz energy returned from depths greater than 1,000 m but one echogram detected layering down to 1,500 m. There was also the typical scattering from epipelagic depths (though even weaker than was recorded further up the canyon), while the migrant echoes (detected at both frequencies) were centred around 25 m depth at night. One curious feature was that the deep non-migrant layers were persistently shallower, by 200 or 250 m, at the north-western end of the Deep Station than at its south-eastern limit. Each layer appeared to curve upwards as it approached the Banquereau Spur. The limited data from beyond the south-eastern end of the Deep Station suggested that the layers were horizontal there, rather than being depressed further.

On the evening of 18 August, the upward migration was only incompletely observed because of high levels of ship noise. The following day, however, three discrete migratory layers were noted at 38 kHz, with the upper two also appearing weakly at 120 kHz. The upper layers were at 250 and 300 m respectively at 2120, rising to 200 and 250 m by 2200, when the deeper layer became evident at 400 m. The three layers had merged by 0000, when their upper limit reached the surface while the lower was at about 100 m. Throughout the night, there persisted a scattering layer, observed at both frequencies, in the uppermost 50 m of the water column (see Figure 25).

3.3.2.4 Banquereau Spur: The distinctive characteristics of the transition zone centred on the Banquereau Spur were not seen early in the survey, though only a few echograms were printed then and the digital data-capture system was not working. Hence, the pattern of backscattering is poorly known. At about 1800 on 16 August, the ship followed the canyon thalweg around the Spur. The multiple scattering layers that were later seen only on the Deep Station were then detected to the west of the Spur and approaching the Main Station. Other echograms showed such layers near the southern end of that Station on 14 August, while there was a mass of scatterers over the Spur, much as seen in 2007 and 2008, that same day.

When the ship crossed the Spur at 0600 on 17 August, however, a new pattern of backscattering was evident (and an echogram was printed). That pattern remained unchanged in any fundamental way until 0230 on the 20th, when *Needler* made her last pass across the Spur during the survey. It was stable in space as well as time – the pattern of echoes changing little regardless of where along its length the Spur was crossed. Throughout those three days, the well-defined, multiple, non-migratory scattering layers of the Deep Station, which rose to lesser depths as the Spur was approached, showed exceptional “wavy” development near that feature – giving a (misleading) appearance of large-scale “turbulence” in the water column. Meanwhile, the diffuse scattering seen on the Main Station rose to shallower depths as it approached the Spur, as though to meet the layers on the other side, and the water column directly over the ridge was full of scatterers from some 300 m depth downwards to the seabed (see Figure 26 for an example). The echo records sometimes gave a (false) impression of water and scatterers “spilling” down the south-eastern side of the Spur. The boundary between the diffuse scattering typical of the Main Station and the layering of the Deep Station was sometimes inclined so as to hint at an outflow from the central canyon across the Spur and sometimes in the opposite direction. The apparent “turbulence” in the scattering layers was usually (though not invariably) more marked when the ship crossed the crest of the Spur closer to Banquereau, and hence where the ridge was shallower, than when the ship passed further to the southwest.

On 17 August, acoustic transects were run around the Spur and three CTD casts were made near it (see Section 2 above), though a combination of ship drift and the steep slopes precluded precisely-targeted data collection. The acoustic records served to confirm that the pattern of backscattering was spatially extensive (confirming impressions from the multiple crossings of the Spur at longer intervals) and temporally persistent – the appearance of "turbulence" in the scattering layers being a matter of spatial (rather than temporal) variability, as with the "waviness" of other backscattering observed in The Gully. The CTD data, however, showed that the impression given by the echograms of large-scale vertical displacement of water was misleading: The isotherms had only limited differences in depth across the Spur (see Section 2 above) and hence the patterns observed acoustically, which presumably reflect biological distributions, were non-conformal to the physical structure of the water column.

The echograms printed on 14 August, and referred to above, were intended to capture a record of another and most curious feature observed around dawn that day and at no other time (Figure 27). On that day, *Needler* ran to the northwest, crossing the crest of the Spur at about 0920, where it was about 650 m deep. During the approach to the crest, a strong, concentrated scattering layer was observed at 38 kHz (though barely detected at 120 kHz), rising as the ship proceeded. At 0840, it was at about 750 m depth. By 0900, it faded away as it reached 100 m depth, where the bottom depth was a little more than 1,000 m. As the ship crossed the crest of the Spur, she turned southwest and by 0940 the scattering layer re-appeared at a depth of 200 m, where the seabed was again a little below 1,000 m. As the ship approached the canyon thalweg, proceeding diagonally across the north-western face of the Spur, the layer descended and thickened, forming dense bodies of scatterers at 800 to 900 m over the thalweg. Around 1050, the ship turned to the southeast to cross the Spur again, though near its outer end. As the seabed rose under the sounder, the scattering layer did also. Once the ship crossed the crest of the Spur, the layer descended again, levelling off at nearly 800 m depth when the ship crossed a minor side canyon, then descending once more. The layer dropped below 1,000 m (and so off the printed echogram) before the ship reached the thalweg outside the spur.

The nature of the scatterers which formed that layer is entirely unknown. Whatever they were, they appeared to maintain a near-constant "altitude" (above the seabed) of some 800 to 1,000 m, achieved their maximum densities at 750 to 1,000 m or more below the sea surface but reached to 100 or 200 m depth at low densities, the scattering fading away as the seabed rose and the layer rose with it. While that layer was only recorded along the lengths of the three transects, it appears to have been a three-dimensional feature, surrounding and overlying the Banquereau spur. Nothing similar has been observed during any of the other surveys of this series.

3.3.2.5 Continental Slope: The sole acoustic record from the Slope Station was a single screen shot covering the period 1934 to 2023 on 13 August. Intended to show seabed depth (which was between 1500 and 1750 m) in connection with IYGPT trawling, that echogram revealed only thin, but well-defined, scattering layers at depths between 250 and 700 m. However, as the ship steamed towards the Deep Station and crossed a shallower portion of the continental slope, dense bottom-associated scattering began to appear, sometimes filling the minor canyons between ridges running down the slope (Figure 28). That scattering was recorded from above 400 m depth down to 1,000 m but never rose more than 100 m above the crests of adjacent ridges. Since the transit between the Slope Station and The Gully was made at night, some near-surface backscattering was also observed.

3.3.3 March 2010

The pattern of acoustic backscattering observed in March 2010, while noticeably different from that seen during the summer surveys, still had marked similarities, despite the difference in season and the consequent differences in physical conditions near the surface. In particular, the diffuse scattering below about 400 m depth was present in the canyon during the March survey (see Figure 29 for an example). Where that scattering was well developed, associated S_V levels were typically only -60 to -75 dB.

The most prominent differences from the summer observations were in the near-surface layers. During March 2010, there was no evidence anywhere in the echograms of the schools of epipelagic fish seen in summer. There were extensive and complex bands of faint layering in the upper 200 m of the water column, some of which may represent echoes off thermoclines rather than from marine life. Those bands reflected the degree of spatial variability inferred from the CTD data (see Figure 30 for an example). On the Head Station, one (or sometimes two) of those bands was both more intense and more consistent than was seen elsewhere. It took the form of a (sometimes broken) narrow layer, usually between 125 and 200 m below the surface – though seen once as shallow as 25 m and once as deep as 260 m. There was no sign of any diel pattern in its depth.

An upward migration of mesopelagic scatterers at dusk was seen on a number of occasions. On 15 March, with the ship over the continental slope, west of The Gully, it began at 2145 at 250 m depth, passed 100 m about 40 minutes later but then stopped while still some 60 m below the surface. On the 17th and in the vicinity of the Banquereau Spur, two discrete layers began moving upwards from 200 and 350 m respectively at 2200 (Figure 31) – that is immediately before the time of sunset and thus later, relative to the Sun, than the migrations observed in

summer. After some 40 minutes, they levelled off at about 70 m depth (i.e. below the cold surface layer, rather than at or very close to the surface, as was seen in summer). Similar upward movement was seen over the thalweg north of the Main Station on 19 and 20 March. On the latter day, there was also a very weak trace of upward movement to the surface between 2200 and 2300. On the 21st, the observation was of a scattering layer which rose slowly from 275 m depth at 1930 and more swiftly after 2140, as the vessel passed from the Deep Station across the Banquereau Spur. The migrants began to settle at 75 to 100 m depth around 2235, though others joined that layer through to 2255 – or perhaps passed right through it and continued rising, as a further migration up to 25 m depth was recorded from 2300 to 2315 (Figure 32). Next day, the ship was on the Deep Station when the upper bound of the scattering layer began to lift from 300 m depth around 1820, passing 260 m at 2010, 215 at 2100 and reaching 70 m around 2235 (by which time the ship had passed over the tip of the Banquereau Spur), at which depth a layer again formed. On the 23rd, in the vicinity of the Spur and the south end of Main Station, the upward movement from 250 m began around 1935 and passed 160 m at 2140. Those latter movements conformed with the summer observations in their timing relative to the Sun.

On 17 March, with the ship well outside the canyon mouth, the dawn migration was observed leaving 150 m depth at 0930 (about 40 minutes before sunrise), one portion of it reaching 400 m by 1020 but most levelling off at 250 m by 1115 (Figure 31). The following day, when southeast of the Deep Station, it was a descent from approximately 150 m to around 275 m in the period 0920 to 1000. On the 20th and in the vicinity of the Main Station, however, the descending migration began near the surface around 0845. No further example of a pronounced downward migration was observed until the 23rd, when the ship was far south of the canyon mouth. In that case, the movement commenced at 80 m depth around 0920, passing 250 m before 1230.

The diffuse non-migratory scattering layers below about 400 m depth that were observed during the summer surveys were present in March 2010. They once again extended up the canyon beyond the north end of the Main Station but not as far as the south end of the Head Station. During the March survey, there were thirteen opportunities to estimate the northernmost extent of those layers, when the ship crossed the canyon between 1800 on 17 March and 1300 on the 25th. Those estimates of maximum latitude for the fully-developed feature all lay between 43° 53'N and 43° 59'N – a range of only 11 km. On 19 March, the ship steamed down the canyon thalweg from near the canyon head (at 2015) to the Banquereau Spur (at 2245) completing a continuous acoustic transect (Figure 33). Traces of the non-migratory scattering appeared at 44° 02'N, which was almost as far to the north as they were observed during any point in the survey, but the layers' full development began sharply at 43° 58'N. Thus, the

layer appears to have an abrupt limit, which (during the survey) was variably located though that variation was narrowly confined – and confined close to the point where the corresponding limit was observed during August 2009. That point was also in the general vicinity not only of where the same transition between the backscatter patterns of the upper and central canyon areas lay in 2007 and 2008 (albeit not so well defined then) but also of the apparent interface between NACW-like and LSW-like water masses during the 2009 and 2010 surveys (see Section 2 above). These deep, non-migratory scatterers have not been identified but they cannot be caught by either the IYGPT, the Diamond IX or the Tucker trawl (see Section 5 below), arguing against their being smaller nekton, while the diffuse nature of the backscattering suggests that they are not large fish, capable of out-swimming the nets. If they are planktonic, as therefore appears likely, then the latitudinal constancy of the northern limit to their distribution argues for a physical control on water movements, linked to the bathymetry of the canyon.

Aside from a few thin traces, the sole exception to that limit on the northward extent of the non-migratory backscattering came on the one occasion (about 0300 on 25 March) that the ship passed the mouth of the large feeder canyon at 44° 05' N 59° 04' W. A small but dense patch of scattering between 290 and 400 m depth was observed there, with weaker echoes received from greater depths. It cannot be known whether or not that patch was composed of similar scatterers to those further south.

The narrow band of scatterers noted above as seen in the vicinity of the Head Station and usually above 200 m depth generally had a southern limit near the diffuse non-migratory layer's northern end. During some crossings of the canyon, however, the narrow band, although thin, could be traced rising above the diffuse layer.

In March 2010, there was little sign of any association between the deep, non-migratory scattering layer and the canyon walls, while the concentration over the Banquereau Spur that was so prominent during the summer surveys was rarely seen. Instead, in March there seemed to be more of the non-migratory scattering to the southwest of the canyon's mouth as well as dense patches of the same far to the east and south of the Deep Station. There was also a tendency for relatively-dense scattering to be seen within the canyon immediately west of the Banquereau Spur, and hence southwest of the Main Station.

When the Spur was crossed farther away from Banquereau, and thus at points where its crest was deeper, there was little sign during the March survey of its influencing the overlying scattering. However, at 0355 on 22 March it was crossed at a crest depth of 420 m, while at 2050 on the 24th it was crossed at 415 m. On both occasions, there was a mass of spur-associated scatterers, though it is not possible to say whether some of that scattering came from

bentho-pelagic forms or all from pelagic species aggregated near the seabed (Figure 34).

3.4 SUMMARY

One feature of the backscattering in The Gully that is evident from the entire collection of acoustic records is its intense local variability. That is particularly manifest as horizontal spatial variability, but also appears as temporal variations and as variations with depth, the latter shown by the layering of scatterers even where there was little vertical change in water temperature or density. While that is only an observation of acoustic backscattering at (primarily) 38 kHz, it implies a high degree of spatial variability in the pelagic biota and hence in the structure of the ecosystems in the canyon.

The horizontal spatial distribution of backscattering suggested a strong link to bathymetry at two particular locations: over the Banquereau Spur and near the bend in the canyon thalweg between the central and upper canyon areas. While those linkages have been observed as connections between the seabed and acoustic backscattering, it can be inferred that it is the non-migratory scattering organisms that are affected. As Kenchington *et al.* (2009) noted and as confirmed by the IYGPT, Diamond IX and Tucker trawl catches of the later surveys (see Section 5 below), there is no known nekton in the canyon that could represent the majority of the non-migratory scatterers. While those have yet to be identified, if they are planktonic the linkage between bathymetry and scattering would seem to be mediated through water movements. Should that prove to be so, then the two bathymetric features would be expected to shape all aspects of the pelagic ecosystems in The Gully, from plankton to whales.

The uppermost backscattering was probably caused by epipelagic animals, some forming schools and others in layers. Those tended to undergo diel vertical migrations and were generally more prominent in the upper canyon. They were absent in March 2010. There were also prominent mesopelagic diel migrants. They formed up to three discrete layers and sometimes appeared to occur in dense swarms, likely of krill. In March, few of those migrants rose into the cold, surface layer. Beneath the subsurface temperature maximum, and generally below about 400 m depth though reaching 200 m during the 2009 survey, diffuse, non-migratory backscattering was a consistent feature across all four surveys, from north of the Main Station to the southeastern end of the Deep Station or beyond – though for much of the 2009 survey, the backscattering on the Main Station was anomalously homogeneous. The non-migratory scatterers only rarely penetrated towards the southern end of the Head Station, though a different form of deep, non-migratory scattering was seen in the latter area in August 2009. Tentative identifications of some of the scatterers have been offered but others, notably the deep, non-migratory types, remain unknown.

4 ACOUSTIC "FLECKS"

T.J. Kenchington

4.1 INTRODUCTION

As noted in the previous Section, some of the echograms printed during the 2007 survey showed a scatter of curious and distinctive "flecks" , each apparently corresponding to a burst of acoustic energy lasting about 60 ms, with rather even intensity throughout each burst (Kenchington *et al.* 2009)[22]. Those "flecks" might readily have been dismissed as an unusual form of interference, derived from some source on board the research vessel, except that on three occasions they were arranged on the echograms in the form of parabolas, two apex downwards and one apex upwards, set amongst other similar "flecks" that were not so regularly arranged (Figure 35). Inspection of each of the three parabolas suggests that some energy source produced a series of bursts at gradually-varying intervals close to three times the ping interval of the sounder – the "inter-burst intervals" either starting slightly greater than three times the ping interval and reducing, over a minute or two, to rather less than that standard or else the reverse (though the possibility that it was the sounder's ping interval that changed, while the "inter-burst interval" remained steady, cannot be eliminated). Unfortunately, the hard-copy recording of echograms used in 2007 did not provide for logging of ping intervals but, at the times that the parabolas were recorded, the sounder was tracing the seabed at approximately 1,000 m depth – meaning a minimum ping interval greater than 1.3 s and hence an "inter-burst interval" of at least 4 s. The sounder was often manually set to a 4 s ping interval and so the "inter-burst interval" could have been as long as 12 s.

Bursts of acoustic energy at regular intervals suggest some deliberate human agency, whether the sounder on a passing ship, a distant seismic survey or something else. However, no such cause can explain the simultaneous occurrence of regularly-spaced "flecks" and similar but irregularly timed ones, as seen on the echograms. The combination might more plausibly be accidentally generated by mechanical means but it would be highly improbable for any acoustic source external to the sounder to show, on three occasions, the observed close association between bursts of energy and the ping interval of the sounder. That hints at a causal relationship. While transient generation within the sounder itself of some interference linked to the pings cannot be dismissed, the linkage to three times the ping interval and the lack of more parabolic traces would both be surprising if the cause was internal to the instrument. Rather, the

[22] The duration of the burst of energy corresponding to the "flecks" seen in 2007 was misreported by Kenchington *et al.* (2009). Re-examination of the echograms from that survey indicates that the duration was similar to that seen in 2009, which has been measured at ≈60 ms.

observed “flecks” suggest multiple similar sources, emitting bursts of energy that in combination appear haphazardly timed while, on three occasions, one of those sources deliberately adjusted its generation of sound to match the rhythm of the sounder’s pings. That apparent deliberation implies an intelligent response, possibly human but maybe cetacean.

Kenchington *et al.* (2009) indeed suggested that the “flecks” observed in 2007 might be records of the vocalizations of whales at frequencies of approximately 38 kHz – the active-acoustic echosounder system having functioned as an inadequate form of passive-acoustic recorder. To further investigate that hypothesis, the echograms from the three subsequent surveys were examined for the presence of similar “flecks” and the characteristics of those observed were noted.

4.2 AUGUST / SEPTEMBER 2008

In contrast to each of the other surveys, no “flecks” were noted on the 2008 echograms. Since those were generated by the same sounder, installed on CCGS *Templeman*, as had produced the 2007 records, the inter-annual difference in the data does not appear to have been an artifact of the instrumentation.

4.3 AUGUST 2009

“Flecks” of the form seen in 2007, each such mark on the echograms corresponding to a burst of acoustic energy with a click duration of about 60 ms and with rather even intensity through that period, were recorded during the 2009 survey at both 38 and 120 kHz. Some “flecks” were recorded simultaneously and with similar intensities on both frequencies but others appeared on only one or were very weak on the other. A scatter of such “flecks” was recorded on a number of occasions while the ship was operating over the upper canyon, while they were common but not universal when over the central canyon. “Flecks” were usually few and weak in digital records from the vicinity of the Deep Station but a printed echogram which captured the end of Set 26 recorded many of them near the south-eastern limit of that Station.

When the digital records were examined at high magnification, additional “flecks” that were undetectable in printed echograms became apparent. It was then evident that many (though not all) of them were arranged in regular patterns across the echograms, suggesting that the source or sources had closely regulated repetition rates. The clearest example, recorded over the upper canyon on 21 August 2009, is presented as Figure 36. That illustration includes 26 identifiable “flecks”. Excluding a very faint one that falls outside the sequence, those delimit 24 “inter-fleck intervals”, each extending from the beginning of one

detected “fleck” to the beginning of the next. Eleven of those intervals had measured durations of 10.84±0.04 s, while the others were 55.75±0.13 s, 65.5±1.40 s or, in one case, 133.27 s in duration, suggesting that only every fifth, sixth or twelfth burst of acoustic energy had generated a detectable “fleck” – perhaps in part a result of aliasing between the “inter-burst” interval of the source and the pulse rate of the sounder. Thus, whatever it may have been, it appears that a single source was emitting 60 ms bursts of acoustic energy at ≈11 s intervals.

The circuitry of the Simrad EK-series echosounders used during the four surveys effectively filters out interference at frequencies other than that at which the sounder transmits. Hence, the sound sources seem to have emitted some energy at both ≈38 and ≈120 kHz, implying a broad-band source. However, the “flecks” were usually only noticeable when the energy was detected more than a second after the sounder had transmitted its most recent pulse and hence when the received energy was considerably amplified by the instrument’s Time Variable Gain (TVG). It follows that the received energy levels were very low. If a broad-band source emitted with high intensity relatively close to the ship’s transducer, sufficient energy for amplified detection might have been received at the sounders’ nominal frequencies, even though the peak intensity of the emitted sound was at a very different frequency.

4.4 MARCH 2010

“Flecks” broadly similar to those seen during the 2007 and 2009 surveys were detected again in March 2010 but they were much more variable in form. The ≈60 ms “flecks” with energy evenly distributed throughout, as recorded during the earlier surveys, will here be designated “Type I”. As seen in 2010, the intensity within each such “fleck” was often less constant than it had appeared in previous years, the variability sometimes suggesting “stuttering” (Figure 37a, c). That difference may simply have been an artifact of a more sensitive transducer and sounder, better able to detect and digitally capture variations in energy levels. “Type II flecks” were of similar duration to “Type I” but with markedly uneven energy distribution. Some showed their greatest intensity near the start of each fleck, others near the middle (Figure 37b) and yet others near the end (Figure 37c). Whether the difference in between “Type I” and “Type II flecks” was anything more than individual variation is unknown. “Type III flecks” were shorter, ≈20 to 30 ms, with their energy concentrated near the middle of the burst (Figure 37c), while “Type IV” appeared weak but had their energy rather evenly spread over 150 to 250 ms (Figure 37b, d). Distinctive “Type V flecks” were recorded just once, when the ship paused over the canyon wall (seabed depth *circa* 300 m) well north of the Head Station, from 0800 to 0920 on 21 March. Those corresponded to an energy burst of about 40 ms duration, with maximum intensity at the beginning and a swift fading away. One selected example

reached its maximum intensity in 0.5 ms, sustained that for about 1 ms and fell away to very low intensity within 20 ms of the start, though energy levels above background were detected by the sounder for twice that duration (Figure 37e, f).

Whether the five “Types” were really discrete or graded into one another cannot be determined without quantitative analysis, which has not been attempted. Each “Type” was typically recorded in an aggregation of similar ”flecks”, usually though not always somewhat separated in time from examples of other “Types”. That argues for some real difference. The “Types” could, however, differ from one another and yet all be products of the same general type of source.

When the ship was operating over the outer canyon during the 2010 survey, “flecks” were recorded in discrete groups without much apparent geographic pattern. Over the central canyon, and particularly over the upper canyon, “flecks” were sometimes so numerous as to resemble interference (e.g. Figure 37d).

4.5 ECHOGRAM “FLECKS” AND CETACEAN VOCALIZATIONS

Seen in isolation, any of these “flecks” (and particularly “Type IV”) could readily be dismissed as interference, probably generated on board the research trawler as a consequence of transient activities. However, “Type I flecks” were seen on the echograms produced by the sounders fitted on three different ships, though not on one of the two surveys made aboard CCGS *Templeman*. A ship-board source might be expected to be specific to one ship and to emit sound during every cruise of that ship. The parabolic arrangements of “flecks” observed in 2007 hint at a deliberate response to the sounder’s pings, either human or cetacean, as argued above. Finally each “Type” of “fleck” tended to be recorded from characteristic parts of the canyon, rather than bearing any apparent relationship to particular ship-board activities, which is more consistent with a biological source than with some engineering deficiency.

High-frequency whale vocalizations (with energy at 38 or 120 kHz) are, however, primarily used as hunting sonar. Their click durations and inter-click intervals are very much shorter than the observed “fleck” durations and “inter-fleck intervals”. The hunting clicks of northern bottlenose whales, for example, each last about 0.3 to 0.5 ms (Hooker and Whitehead 2002) or more than an order of magnitude less than even the shortest of the “flecks”. Such brief clicks would not be detectable in the output of a sounder set to record echoes across a 1,000 m depth range, as in these surveys.

The only animal known to create sounds with approximately the observed characteristics of the “flecks” is the sperm whale. Amongst their other vocalizations, adult males of that species produce “slow clicks”, also called “clangs”, with inter-click intervals of several seconds, which are thought to be

used for communication. While the ≈11 s "inter-fleck interval" observed on 21 August 2009 was approximately twice the norm for sperm whale "slow clicks", inter-click intervals of near that length have been reported. However, consistent with their communication function, "slow clicks" are low frequency vocalizations, with most of their energy below 5 kHz. Each "slow click" comprises a brief but intense burst of energy, which then dies away over a few milliseconds (Oliveira *et al.* 2013). Thus, only the "Type V flecks" recorded on 21 March 2010 resembled sperm whale "slow clicks" and, if that is what they were, then the individual or individuals emitting them would have had to be relatively close to the ship for their clicks to be detected at 38 kHz. No sperm whale was observed at the time those "flecks" were recorded, though one had been seen the previous day and the passive-acoustic recorder deployed during the survey (Kenchington *et al.* 2014) detected the species' distinctive clicks on a number of occasions, including the morning of 21 March.

If the other "Types" are records of whale vocalizations, then each "fleck" might not represent a single click but rather a train of clicks, merged together by a sounder not designed to record such brief bursts of energy – a possibility that might explain the appearance of "stuttering" within some "Type I flecks". What species might be responsible for such click trains remains unclear. No cetacean is known to generate click trains at regular inter-train intervals, in the way that some source created "flecks" at ≈11 s intervals on 21 August 2009. Indeed, the linkage between the "flecks" and cetaceans of any kind can only be a speculative interpretation of the data. The identifications of the sound emitters remain unknown.

5 TUCKER TRAWL CATCHES

T.J. Kenchington and S.E. Thompson

5.1 INTRODUCTION

The deep, non-migratory acoustic scattering layer was prominent in the 38 kHz echosounder records from the 2007 survey (Kenchington *et al.* 2009), as it was in those from the following three surveys (see Section 3 above). Potential scatterers have not, however, been evident in the IYGPT catches. All of the species taken by that net have been either of low abundance, migratory, lacking in a swimbladder or other strongly sound-reflective structure, or some combination of those characteristics. Kenchington *et al.* (2009) could only suggest the gonostomatid fish of the genus *Cyclothone* as potential agents of the observed deep, non-migratory acoustic backscattering – and then only if they had functional, gas-filled swimbladders of an appropriate size (about 0.5 mm at 400 m depth) for resonance with 38 kHz sound.

During the 2008 survey, a Tucker trawl (5.2 m^2 mouth area, 2.1 mm mesh) was therefore deployed on ten sets, in an attempt to discover potential sound scatterers in a size fraction of the pelagic community smaller than that efficiently sampled by the IYGPT (Kenchington *et al.* 2014). Specifically, the Tucker trawl was intended to sample the *Cyclothone* spp., which were thought to mostly escape through the meshes of the larger net.

The Tucker trawl was deployed in open mode only, following V profiles. Further details of the sets made have been provided by Kenchington *et al.* (2014).

5.2 LABORATORY AND ANALYTICAL METHODS

The Tucker trawl catches were only briefly examined at sea. Samples, predominantly of *Benthosema glaciale*, were removed from each catch and frozen for stable-isotopes analysis, while samples of krill (100 g per sample) were taken from the catches of three of the sets for contaminants analysis. The residue of the catch was fixed in formalin in bulk.

On shore, those bulk catches were rough-sorted into a half-dozen recognizable categories. The volume of small crustaceans was measured and the numbers of individuals in each of the other categories were counted. The numbers of specimens of *B. glaciale* extracted were added to the counts of animals found in the bulk catches. Subsequently, each individual of the genus *Cyclothone* was identified to its species, or as close to that ideal as damage would permit, and measured (standard length to nearest millimetre, following fixation).

The filtered volume for each set was estimated as the mouth area of the net multiplied by an assumed length of each tow calculated from the straight-line distance between the ship's position when the Tucker trawl entered the water, the net depth and ship's position when the gear reached its maximum depth, and the ship's position again when the net left the water. Thus calculated, the volumes under-estimate true filtered volume (and so over-estimate the densities of the organisms caught) by ignoring curvature in the ship's track, the steeper descent of the net as it fell astern of the ship and irregularities in the depth profiles. However, they over-estimate the true volume by assuming that the mouth of the net lies perpendicular to the direction of travel, when it is actually designed to be somewhat oblique, and by ignoring any displacement of water flow resulting from the restriction of the mesh of the net. Additionally, densities of some organisms are under-estimated by ignoring active net avoidance. Larger but unknown errors are likely to have arisen from water flows at the depths fished, since the calculations assume that the water is static relative to the seabed. The overall effects of those errors are unknown but the resulting estimates of densities of organisms are thought to be adequate for judging whether or not the species caught are major contributors to the observed acoustic scattering, which was the purpose of the Tucker trawling.

Similar estimates were made of the filtered volumes within the non-migratory scattering layer noted by Kenchington *et al.* (2009) and observed again during the surveys reported here (see Section 3 above). They were prepared in the same way as the estimates of total volumes filtered, except for substituting the ship's positions when the net passed 400 m depth on the downward and upward legs of the tow for the start and end positions of the set, while deducting that 400 m from the maximum depths reached by the Tucker gear.

No echo-sounder data were successfully recorded during the early part of the 2008 survey, which encompassed Sets 3 and 4, made with the Tucker Trawl (Kenchington *et al.* 2014). The sounder record corresponding to Set 24 was so broken that layers cannot be clearly seen, though it is certain that there was considerable scattering. The portions of the digital acoustic records corresponding to the time that each of the other seven Tucker trawl sets was in the water were extracted from the digital files and a point marked on each corresponding to the maximum depth achieved by the Tucker trawl and the time that that depth was observed. An approximate route of the net through the scattering layers was then estimated by linking straight lines between the plotted point and the sea surface at each of the times of starting and ending the set (see example in Figure 38) – though the Tucker tow profiles did not follow straight-sided V's, while the net necessarily lagged behind the ship during each tow. Since the non-migratory scattering layer was generally diffuse, the resulting error

should not greatly affect the impression of scattering at the depths and locations fished by the net.

5.3 RESULTS AND DISCUSSION

Ten sets were made with the Tucker trawl during the 2008 survey, most being targeted on the non-migratory scattering layer (Table 3). None of the catches was large and most of what was taken comprised either myctophids, which are expected to be migratory and hence cannot account for the non-migratory scattering layer, or else a mixture of chaetognaths, copepods, euphausids and other small crustaceans, none of which would scatter much acoustic energy at 38 kHz. The catches also contained scattered fragments of shells which appeared to be from holoplanktonic heteropod molluscs.

The only component of the Tucker-trawl catches which might plausibly account for the non-migratory layer was *Cyclothone* spp., 402 of which were taken – about one per 230 m^3 of water filtered below 400 m depth. 173 of them proved to be *C. microdon*, 3 were *C. pseudopallida* and a further 121 were members of one or the other of those two species. Each of the remaining 105, though too damaged for specific identification, was consistent with being either *C. microdon* or *C. pseudopallida*, though they could also have been other species in the genus. That intrageneric species composition was not unexpected: *C. microdon* has been reported as the principal species of *Cyclothone* found north of the Warm Slope Water in the northwest Atlantic, while *C. pseudopallida* is one of the few other species known from Atlantic Canadian waters (McKelvie and Haedrich 1985; Scott and Scott 1988). Subsequent to this work on the Tucker Trawl catches, examination of samples taken from the IYGPT and Diamond IX catches from The Gully has also found predominantly *C. microdon* with a small admixture of *C. pseudopallida* (unpublished data).

Standard lengths of the *Cyclothone* spp. specimens taken varied between 14 and 57 mm, with most being between 20 and 30 mm (Figure 39). While some sets took too few individuals for meaningful comparisons of length frequencies to be made, there were no apparent among-sets differences in size composition.

Given the rather moderate catches, the only *Cyclothone* spp. which could contribute more than negligibly to the observed acoustic backscattering would be those with functional, gas-filled swimbladders of a size to resonate with 38 kHz sound – meaning about 0.5 mm at 400 m. The fish do have such bladders as postlarvae but, later in life, they become fat-invested and would not return much acoustic energy. Some species of *Cyclothone* retain gas-filled bladders into adulthood, *C. braueri* in particular having such a bladder until it reaches lengths of about 35 mm, but *C. microdon* is the deepest-living of the temperate-latitude species in the genus and is generally supposed to fill its bladder with fat at a

much smaller size (Marshall 1962). Thus, unless the Tucker Trawl was unexpectedly inefficient at catching juvenile *Cyclothone* spp., there appear to have been too few with gas-filled bladders to account for the observed backscattering.

Moreover, the numbers caught did not well accord with the distribution of acoustic backscattering. The seven sets for which corresponding acoustic data are available each took between two and 55 individuals of *Cyclothone* spp. The relative magnitudes of three of those seven catches were consistent with the densities of the observed scattering layers on the relevant tows: Set 16 passed through a rich migratory layer but barely entered the upper edge of the non-migratory layer and only took two *Cyclothone* spp. Set 40, in contrast, saw very heavy non-migratory scattering and took 55 individuals. Set 42 passed through moderate scattering and took 49 *Cyclothone* spp. The other four sets, however, did not show such congruence: Set 26 passed through rather light scattering but caught 45 *Cyclothone* spp., Set 33 encountered heavy scattering but took only 16 individuals of the genus, Set 34 did not go deep but did pass through a moderate non-migratory layer and yet only took 2 *Cyclothone* spp., while Set 35 took 26 after passing through moderately-heavy non-migratory layers.

Kenchington *et al.* (2009) suggested that the IYGPT catches taken in The Gully in 2007 did not include any plausible candidate to be the non-migratory 38 kHz scatterers, other than perhaps *Cyclothone* spp., which are under-sampled by that net. Experience during the 2008 to 2010 surveys (unpublished data) -would extend that conclusion across years and to the Diamond IX net. The Tucker trawl catches, however, suggest that *Cyclothone* spp. are not the principal scatterers, while they do not offer any plausible alternatives. Thus, whatever the scatterers may be, they do not appear vulnerable to net capture with mesh sizes between those of the Tucker and those of the Diamond IX.

6 IYGPT AND DIAMOND IX CATCHES OF "OTHER" TAXA

T.J. Kenchington

6.1 INTRODUCTION

The IYGPT and Diamond IX trawling was the core of the survey program (Kenchington *et al.* 2009, 2014), those nets being suited to catching most of the fish, cephalopods and larger crustaceans of the midwater nekton and micronekton at meso- and bathypelagic depths – the exceptions being the largest and most active of the fish and squids, which could evade the gear, as well as the smallest, which could pass through the meshes. The catches of those three major taxa are not addressed here as they will be published elsewhere (e.g. MacIsaac *et al.* 2014). The trawls also took incidental catches of other animals, plus a very few plants. They were not suited to quantitative sampling of those organisms but the data obtained nevertheless have some interest, pending more appropriate field studies, and are fully reported here.

6.2 GELATINOUS PLANKTON

The IYGPT is not expected to be an efficient gear for collecting gelatinous species, which were almost certainly grossly under-represented in the catches, many breaking up on contact with the meshes and being lost without reaching the codend. Indeed, various gelatinous species will have had very different catchabilities in the trawl, meaning that even their relative abundances are poorly indicated by the catch data. The limited indications provided by the IYGPT catches do, however, offer an insight into the pelagic ecosystem in The Gully.

Despite the expected low catchabilities, the summed recorded weights of gelatinous plankton totalled 366 kg over the three surveys (compared to >200 kg during the 2007 survey alone: Kenchington *et al.* 2009), exceeding the totals of either fish or crustaceans – though because of the high water content of the gelatinous species, the amounts of carbon and energy that the catches represent are probably far less than those contained in fish or crustacean flesh taken by the trawls. Which group comprises for the greatest density of carbon and energy in the watercolumn within The Gully remains unknown.

More than 60% of the gelatinous biomass that was caught by the IYGPT comprised the deep-living scyphozoans *Atolla* spp., which were present in the catch of most sets (aborted tows excepted), including those made on the Slope Station. One specimen was identified by DNA barcoding as *A. wyvillei* but other species of the genus may have been present in the catches. They were absent from sets made above 250 m in daylight (save for four small catches which may

have represented contamination from previous sets) and from eight made above that depth at night (usually at the Main and Head stations but once on the Deep Station). Otherwise, it was only missed by one deeper IYGPT: Set 30 of the March 2010 survey, which was made on the Head Station. Catches in the sets made to 750 m on the Main Station averaged 3.27 kg per set, *Atolla* spp. being the principal gelatinous taxon in the catches there in biomass terms. The average catch in the sets made to 1,250 m on that Station was slightly lower (3.06 kg), indicating that this genus largely lives above 750 m depth in The Gully, while its presence in shallow night tows, but not those made in daylight, demonstrates migratory behaviour and a nocturnal upper depth limit somewhat above 250 m. Night catches in sets made to 750 m were notably higher than those taken by day (averaging 4.0 versus 2.5 kg), though the effect was less evident in the deeper sets. There was considerable inter-annual variability (average catches of sets made to 750 m on the Main Station being 3.5 kg in 2008, 1.7 kg in 2009, 9.3 kg in March 2010). Those results were driven, in part, by a single exceptional catch of 10.6 kg taken by Set 24 of the March 2010 survey but the same trends were evident even if that one data point was suppressed.

A further 28% of the gelatinous biomass in the IYGPT catches was composed of the scyphozoan *Periphylla periphylla*. It was even closer to being ubiquitous than *Atolla* spp., being absent only from four sets made above 250 m in daylight, four similarly-shallow sets made at night and the same number of deeper sets – three of them made on the Head Station in March 2010. *P. periphylla* had a very similar temporal and depth distribution on the Main Station to that of *Atolla* spp., though its biomass in the catches was lower (average 2.1 kg in sets made to 750 m). Considerably greater catches were taken above 750 m at night than by day (2.6 *versus* 1.7 kg per set) but the difference was much less in the catches of sets that went to 1,250 m (average 1.6 kg at night, 1.2 kg by day), suggesting diel migration across 750 m depth. Inter-annual and seasonal variation was, however, small, the per-survey averages in sets made to 750 m on the Main Station being 2.7, 2.3 and 2.8 kg respectively. *Atolla* spp. and *Periphylla periphylla* were also present in the catches from each of the six sets made with the Diamond IX net (their catches totalling 23 kg and 22 kg respectively).

Atolla spp. and *Periphylla periphylla* are both abundant and widespread at deep mesopelagic depths around continental margins and in some parts of open ocean. They were respectively the first and third most abundant cnidarians in RMT catches from two stations in the Scotia Sea portion of the Southern Ocean (Piatkowski *et al.* 1994). Biomass densities recorded in that area were much higher those seen in The Gully: 11 $g.m^{-2}$ summed across the upper 1,000 m of the water column for *P. periphylla* at each station and 10 $g.m^{-2}$ for *A. wyvillei* at one of them, though some of the difference is likely in part attributable to the relative efficiencies of the nets. In the Scotia Sea, both species were found from a 200–300 m depth stratum to the deepest one fished (800–1,000 m), with

P. periphylla being particularly abundant between 400 and 800 m (Piatkowski *et al.* 1994). In and near the Monterey Canyon, Osborn *et al.* (2007) found *Atolla* spp. (*A. wyvillei* and *A. vanhoeffeni*) and *P. periphylla* to be the first and second of three abundant large scyphozoans at mesopelagic depths, based on video imagery from ROV dives. During daylight hours, *Atolla* spp. were seen from 200 m depth down to the 1,000 m maximum of most dives but primarily between 400 and 600 m. *P. periphylla* was seen from 400 m downwards, with a lesser peak in frequency at similar depths to those preferred by *Atolla* spp. (Osborn *et al.* 2007), consistent with observations in The Gully. Lucas and Reed (2010) captured specimens of both species using a manned submersible in the Gulf of Mexico, west of peninsula Florida, and off Cape Hatteras. In the former region, *P. periphylla* comprised 40% of their catches, whereas *A. wyvillei* constituted only 8%. Off Cape Hatteras, the diversity of gelatinous plankton was higher and the two species together comprised less than a quarter of the catch. They were taken at depths of 400 to 900 m, though at considerably higher temperatures than their conspecifics were found in The Gully: 5.5 to 6.8°C (Lucas and Reed 2010), rather than about 4°C. Both species have also been recorded in Oceanographer Canyon (on the southern edge of Georges Bank), along with *A. vanhoeffeni*. There, one *A. wyvillei* was taken at 500 to 625 m depth and three *P. periphylla* were recorded from above 850 m (Pagès *et al.* 2006). Finally, Moore *et al.* (2004) reported 26 *Atolla* spp. and one *P. periphylla* from trawl catches taken over Bear Seamount.

P. periphylla occurs in exceptional densities in some Norwegian fjords – 80 individuals m^{-2} and up to >1 m^{-3} in one study, though the great majority of those were small (under 60 mm coronal diameter) and likely young-of-the-year (Youngbluth and Båmstedt 2001). Their location in enclosed waters has allowed detailed study, though the results may not be applicable to open-sea populations. In Lurefjorden, small *P. periphylla* show diel migration, being centred at about 100 m depth at night but 200 to 300 m by day, the water at both depths being around 6°C and 33‰. They feed on chaetognaths and small crustaceans, including copepods and ostracods, while cruising or lying as ambush predators. They are preyed upon in their turn by parasitic hyperiid amphipods and pycnogonids (Youngbluth and Båmstedt 2001). In European waters, *A. wyvillei* typically reaches reproductive maturity at diameters about 50 to 60 mm (Russell 1959). Many, perhaps most, of those taken in the IYGPT in The Gully were larger and hence it may be inferred that the species reproduces in the canyon.

Of the remaining 12% of gelatinous biomass in the IYGPT catches, 3.6 kg (nearly 1% of the whole) comprised a single individual of a third deep-living scyphozoan: *Stygiomedusa* cf. *gigantea*. The specimen was taken by Set 58 of the 2009 survey, which reached 750 m depth on the Head Station in daylight. Two further specimens of that species, each chocolate-brown in colour, were taken on the Main Station by the Diamond IX during the March 2010 survey. One, caught by

Set 54, weighed 11.6 kg and the other, of 17.3 kg, was taken by Set 55. *S. gigantea* must, however, be considerably more abundant in The Gully than those few catches suggest: The species has well-developed oral arms (suggesting feeding on small crustaceans, large gelatinous plankton or even detritus: Benfield and Graham 2010), which can reach several metres in length but which break up on contact with nets. When picking the net after many sets, skeins of brown tissue were seen caught on the meshes but were not recognized as fragments of such *S. gigantea* arms until the very end of the surveys reported here.

Stygiomedusa gigantea is a large but rarely seen, meso- and bathypelagic scyphozoan, previously known from only 118 specimens or other observations worldwide (Benfield and Graham 2010). It has most often been recorded in the Southern Ocean and there have only been eight prior reports from the North Atlantic: two from the Bay of Biscay, one each from the Mid-Atlantic Ridge area and the Denmark Strait, one (an unpublished observation by cameras on an ROV) from the Newfoundland offshore oil fields and three from off New England (Benfield and Graham 2010). While its presence in The Gully was thus no surprise, taking the bells of three individuals and the oral arms of an undetermined additional number was exceptional – though not unique, Piatkowski *et al.* (1994) having taken four specimens with just 20 tows (each comparable in filtered volume to the IYGPT sets in The Gully) in the Southern Ocean. The mean depth of those Atlantic records for which data are available was about 920 m (Benfield and Graham 2010) or broadly comparable with the limited data available from The Gully.

The IYGPT catches also included a number of familiar, shallow-dwelling scyphomedusae, likely taken as the trawl was hauled through near-surface layers. In 2009, but no other year, there was a substantial catch (2.0 kg, summed across six sets) of *Aurelia* sp., well-known in coastal waters, which was almost entirely confined to the Head Station but was taken by five of the six sets completed there. At the same time, there were lesser catches of the equally familiar *Cyanea capillata* but that was confined to the Wall, Main and Deep stations. A single, small specimen of that species was taken on the Head Station during March 2010. Finally, fragments of gelatinous material taken by one set on the Main Station in March 2010 were identified by DNA barcoding as *Pelagia noctiluca* – usually a warm-water form[23].

A further 6.6% of the weight of gelatinous material caught by the IYGPT was composed of ctenophores. The bulk of that catch was the familiar *Pleurobranchia*

[23] While the DNA sequenced was undoubtedly that of *P. noctiluca*, experience with other samples has shown a potential for mistakes in sample management between tissue collection and barcode generation. Some doubt about the presence of *P. noctiluca* in The Gully in March 2010 must remain.

pileus, or a very similar species. Aside from one catch of 18 g taken on the Head Station in 2009, it was only recorded in March 2010. It was then caught on the Deep and Main stations but in much larger quantities, up to 13.8 kg in a single set, on the Head Station, where the ctenophores were likely swarming in surface waters. Throughout the three surveys, small numbers were taken of another type of ctenophore that resembled the familiar *Beroe* spp. but was likely a deep-living species.

The remaining gelatinous catch taken by the IYGPT included members of perhaps six other, unidentified scyphozoan species. The total catch of those from the three surveys (IYGPT and Diamond IX catches combined) amounted to only 6.7 kg, while the 2010 survey yielded a further 3 kg of unidentified gelatinous material.

Of greater ecological interest than those latter species, there were traces of a number of siphonophores. The extreme fragility of members of that Order of the Hydrozoa suggests that even very small catches in an IYGPT may indicate a high abundance in The Gully. The mostly widely recorded form was noted in the catches of 21 IYGPT sets (plus one made with the Diamond IX) after first being observed in quantity half way through the 2009 survey (including being taken by 11 of the 12 IYGPT sets which fished below 750 m in March 2010). Those included sets made on all stations, except the rarely-fished Slope Station, but no sets confined to the top 250 m of the water column. Relatively large catches (up to 648 g per set of retained material) were, however, limited to sets which fished below 750 m on the Deep Station, with two exceptions. One was a catch made on the Main Station and the other, with 300 g retained, from Set 40 of the March 2010 survey, which reached 750 m depth on the Head Station. That form has been identified by DNA barcoding as the physonect *Stephanomia amphytrides*[24].

[24] Two (morphologically very different) gelatinous "types" were recognized at sea as "Scyphozoa 7A" and "7B". Based on their repeated co-occurrence in the catches, it has been assumed that they were different parts of the same siphonophore – apparently detached nectophores and the denuded stem of the nectosome and / or siphosome, respectively. The DNA sequences for barcode identification were derived from "7A", which is the type confirmed as *S. amphytrides*, since no amplification was achieved from samples of "7B". A third recognizable "type" (labelled "Siphonophore Sp. 1" at sea) was represented in the catches by the single, semi-intact specimen mentioned in the main text. It has been identified (with high confidence) as *S. amphytridis* by Dr. Phil Pugh, based on photographs of the fresh material. The weights quoted in the text are totals of the aggregate of all three "types", the greater portion likely being "7B".

The status of *Stephanomia amphytridis* Lesueur & Petit, 1807 has become rather confused. Mapstone (2004) provided a re-description of the species, based on a specimen from the Flores Sea, and moved it into the genus *Halistemma*. In an appendix to a paper on a different genus, however, Pugh (2006) re-identified Mapstone's (2004) specimen as *Halistemma (Stephanomia) foliacea* (Quoy & Gaimard, 1833) – a conclusion which Mapstone (2009) has accepted. Pugh (2006) also noted a number of reports of a different species, which he linked to the name *Stephanomia amphytridis* Lesueur & Petit, 1807, including a recent molecular phylogenetic study by Dunn *et al.* (2005). The material from The Gully has been identified to that

Another specimen, sufficiently intact to be recognized as a siphonophore while at sea (Figure 40), was taken by Set 50 of the 2010 survey, which reached 1750 m depth on the Deep Station. It has been identified by Dr. Phil Pugh, from photographs of the fresh material, as *S. amphytridis*.

That is not a well-known species and, by current taxonomy, it has no congeners from which inferences might be drawn. Pugh and Gasca (2009) categorized it as mesopelagic (750–850 m depth) and tropical to temperate in the Atlantic, Indian and Pacific oceans but also as rare. However, Hamilton (2006) reported a genetic identification of supposed microorganism tissue, taken from the North Water Polynya in Baffin Bay, that proved to be this species, establishing its presence in the Arctic. Meanwhile, both Dunn *et al.* (2005) and Cartwright *et al.* (2008) used DNA from a specimen which had been taken by a submersible at 800 m depth in Oceanographer Canyon, on the southern edge of Georges Bank. Hence, the species' occurrence in The Gully is not surprising. The apparent interannual variation in its presence may be more notable, though the mode of recording of the gelatinous plankton adopted during the Gully surveys prevents certainty of its complete absence in 2008, before the "type" was recognized as distinct.

A single catch, taken by Set 8 of the March 2010 survey (which fished to 750 m on the Main Station), included material designated at sea as types "13A" and "13B". The latter was identified by DNA barcoding as *Erenna* sp., a fish-eating physonect siphonophore. A "stem" from that same catch (Figure 41)[25] was identified by Dr. Phil Pugh, from photographs of the fresh material, as another piece of *Erenna* sp. – presumably the same individual. Three species of *Erenna* are currently recognized, all being known from the North Atlantic. In that ocean, *E. richardi* has mostly been found south of 35°N and at depths greater than 1,000 m. *E. laciniata* has been recorded from the vicinity of the Bahamas, as *E. cornuta* has from near Bermuda (Pugh 2001). They are notable for generating long-wavelength (orange-red) bioluminescence, apparently as a lure (Haddock *et*

S. amphytridis of Dunn *et al.* (2005) and Pugh (2006). It is currently the only valid, described species in the genus *Stephanomia* (Mapstone 2014).

Stephanomia and *Halistemma* were long been placed in the Agalmatidae, of the Suborder Physonectae, but that was treated as something a "catch-all" family for physonect siphonophores which do not fit elsewhere. Dunn *et al.* (2005) concluded that there is a monophyletic core group within the family, which they termed the Agalmatidae *sensu stricto*. That core contains *Halistemma* but the *Stephanomia* of their *S. amphytridis* falls outside it – a conclusion that has been supported by more recent work by Cartwright *et al.* (2008) and Ortman *et al.* (2010), though the latter named the species of present concern "*Halistemma amphitridis*". Pugh (2006) excluded *Stephanomia* (meaning his *S. amphytridis*) and some other genera from the Agalmatidae but provided no other family for them. Mapstone (2009) explicitly left *S. amphytridis* in the Agalmatidae, though outside the Agalmatidae *sensu stricto*. She has since listed *Stephanomia* as an "unascribed genus" amongst the dioecious Physonectae (Mapstone 2014).

[25] Misleadingly labelled at sea as a "Urochordate?".

al. 2005). That implies a prey type with eyes sensitive to red light, which would be an unusual characteristic for a deep-living fish, though Haddock *et al.* (2005) noted that the eyes of *Cyclothone* spp. have yet to be studied. *Erenna* spp. may be a specialist predator of that abundant genus.

The catches from Sets 38 and 39 of the 2009 survey (respectively made to 1600 m on the Deep Station and to 1250 m on the Main Station) each included siphonophore "stems" (Figure 41)[26], over 0.5 m long and weighing 18 and 21 g respectively. Those may both have been taken Set 38, if the second specimen was hung up in the net and not recovered from the codend until after Set 39. A further unidentified fragment taken over the continental slope, by Set 2 of the 2010 survey, resembled those others. The first of the two specimens from 2009 differed from the *Erenna* sp. stem from 2010 but neither it nor the two later ones has yet been identified to species. Six small specimens taken by five sets of the 2010 survey, each of which reached at least 1,250 m on either the Main, Deep or Offshore stations (IYGPT Sets 11, 14 and 21, plus Diamond IX Sets 54 and 59) appeared generally similar to one another[27]. The first of them was retained and is another siphonophore stem.

In addition, the catches frequently included firm, transparent gelatinous bodies that were vaguely "bullet-shaped". Those were not identified at sea nor separately recorded and hence no samples were retained. However, post-survey study has suggested that they may have been the anterior nectophores of diphyomorph calycophoran siphonophores (hence neither *Stephanomia* sp. nor *Erenna* sp.) or rather the robust portions of those bodies which survived contact with the trawl.

Finally, salps were almost ubiquitous in the IYGPT catches and a few additional ones were taken by one set of the Diamond IX net. Some of the specimens were intact, live individuals of the Family Salpidae but many were "barrels" created by the hyperiid amphipod *Phronima sedentaria*. That species is known to excavate its barrels from both salps and pyrosomes, the origin of a particular barrel being impossible to determine without close examination under a microscope – which was not attempted at sea. Hence, the catch records list the salps and excavated pyrosomes only as Class Thaliacea, though 84 g of intact *Pyrosoma* sp. were separately recorded in March 2010. Less than 0.75 kg of the salp / pyrosome combination was recovered from all three surveys combined.

The remnants of gelatinous plankton which were retained in the IYGPT cannot provide a foundation for a description of that component of the deep pelagic ecosystem in The Gully but they are enough to suggest that the "jellies" are likely very important to trophic pathways in the mesopelagic and upper bathypelagic

[26] Misleadingly labelled at sea as "Hemichordates".
[27] Each of the six misleadingly labelled at sea as a "Hemichordate".

zones within the canyon – as they are generally in deep pelagic environments (Robinson 2004). The principal species present are those which might have been anticipated, though *Stygiomedusa gigantea* and *Stephanomia amphytridis* appear enexpectedly prominent in the community. The overall gelatinous biomass may be relatively high, though not to match what has been seen in some Norwegian fjords. Without directly comparable data from other areas, however, it is not possible to determine whether the magnitude of the catches in The Gully were a result of the sampling protocols or the density of the organisms. One firm conclusion can be drawn: A thorough understanding of the Gully ecosystem will require targeted study of the deep gelatinous plankton, using appropriate sampling and recording methodology. That was never among the aims of the surveys reported here.

6.3 OTHER INVERTEBRATES

As was seen in 2007 (Kenchington *et al.* 2009), once the cephalopods, crustaceans and gelatinous species were excluded, most of the few other invertebrates taken by the trawls were (probably ubiquitous) giant chaetognaths. While they were clearly abundant, the total recorded IYGPT catch of them (after the losses to low catchability and the frequent difficulty of extracting them from amongst the gelatinous plankton) totalled only 0.17 kg over the three surveys. They were also almost the only non-gelatinous "other" invertebrates taken by the Diamond IX net, though very few chaetognaths were extracted from the catches of that gear – perhaps a deficiency of sorting.

Pteropods, some of them identified as *Clione* sp., were taken in many IYGPT sets, though the total recorded catch amounted to only 16 g. Two small gastropod molluscs were taken on the Deep Station during the 2009 survey. One was identified as the holoplanktonic heteropod *Carinaria* sp. and the other as the closely related *Atlanta* sp. Two further catches, one each from the Deep and Main stations, were recorded at sea only as "Gastropoda". In the laboratory ashore, the former was found to contain both pteropod and heteropod material[28]. As noted in Section 5 above, fragments of shells which appeared to be from such heteropods were found in the Tucker trawl catches in 2008. Two unidentified nudibranchs were taken in 2009, both by sets made to 250 m on the Main Station. The IYGPT also took two very small mussels, of the family Mytilidae, but it seems probable that those had been growing on the hull of the research trawler and were dislodged while the net was close astern of the ship.

Finally, during 2008 and 2009, four sets made to 1,250 or 1,750 m on the Main or Deep stations took small (about 0.5 g each) pelagic nemerteans, apparently just

[28] Kenchington *et al.* (2009) reported a single gastropod taken by the IYGPT during the 2007 survey and suggested that it might have been a benthic snail swept away from the canyon wall by swift tidal currents. It seems more likely that it was a planktonic heteropod.

one per set, which were identified as *Nectonemertes* sp. – one of those specimens being further identified, by DNA barcoding, as *N. mirabilis*. Three more were taken in a 750 m set on the Head Station. They can be compared with the much larger nemertean caught in 2007 (Kenchington *et al.* 2009), which has since been identified as *Dinonemertes* sp[29]. No nemerteans were seen during the March 2010 survey.

6.4 MACROALGAE

Fragments of the planktonic macroalgae *Sargassum* spp. were taken by the IYGPT on the Main and Deep stations during the 2009 survey, when there was Warm Slope Water across the mouth of the canyon. It was recorded amongst the catches of nine sets. Besides the pieces found in the net, other *Sargassum* spp. was seen floating at the surface, as noted in Section 2 above.

[29] With the identification of that 2007 specimen, it may be noted that Moore *et al.* (2004) reported the capture of two *Dinonemertes investigatoris* over Bear Seamount.

7 MARINE MAMMALS

T.J. Kenchington and H. Moors-Murphy

7.1 INTRODUCTION

During the 2007 survey, marine mammals were recorded when seen, most often by the ship's officers, but no dedicated mammal observer was carried. On the 2008, 2009 and 2010 surveys, in contrast, a specialist marine mammal observer maintained a watch throughout daylight hours (Kenchington *et al.* 2009, 2014). The data obtained have been added to the cetacean sightings database maintained by Fisheries and Oceans Maritimes Region. They are but a small supplement to the extensive collection of observations from The Gully made by the Whitehead laboratory at Dalhousie University since 1986, which are also included in the same database. In due course, the sightings made during the four trawl surveys will contribute to analyses of that broader body of data. They are summarized here only in support of time-specific comparisons with the trawl catches and other data from the surveys – emphasis being given to observations of northern bottlenose whales since the surveys were originally conceived as a study of the ecosystem that supports the prey of that species.

7.2 AUGUST / SEPTEMBER 2008

Forty-six marine mammal encounters, each involving a sighting of one or more individuals at the surface over The Gully, were recorded between 30 August and 5 September 2008, during 101 hours of observation effort (Table 4). The estimated numbers of mammals present during the encounters summed to 267, though it is not always possible to count the cetaceans in a group with complete certainty and the same individuals may sometimes have been recorded during more than one encounter.

Northern bottlenose whales were the most commonly sighted species, with 25 recorded encounters and up to an estimated 15 individuals being present at any one time (mean estimated group size: 3.0 individuals). While their documented distribution will have been affected by the location of the ship and its trawling activities, they were observed from 43° 48.0'N, immediately north of the Deep Station, to 43° 59.0'N (between the Main and Head Stations), though they were most abundant between the Main Station and the canyon mouth[30]. Indeed, 15 of the encounters and 51 of the 76 recorded sightings lay within the rectangle

[30] This summary of the distribution of the encounters excludes one sighting of a lone individual that was recorded with an erroneous position – a position that the ship did not pass through. It has not been possible to resolve that error within the preparation of this Report.

43° 49.1' to 43° 51.2'N, 58° 52.6' to 58° 56.2'W – an area of just 3.9 by 4.8 km located immediately west of the Banquereau Spur. Even within that limited area, they were concentrated over the eastern wall of the canyon, meaning the western slope of the Spur, rather than over the thalweg or the western wall (Figure 42).

Other cetacean species recorded included long-finned pilot whales (*Globicephala melas*), short-beaked common dolphins (*Delphinus delphis*), Atlantic white-side dolphins (*Lagenorhynchus acutus*) and various baleen whales, including at least some fin whales (*Balaenoptera physalus*), all of which species are well known over the Gully in summer (Whitehead *et al.* 1998; Whitehead 2013). Indeed, the first three have been the species most commonly observed during dedicated cetacean surveys over the canyon, aside from the northern bottlenose whales and sperm whales (*Physeter macrocephalus*) that the surveys were directed towards (Whitehead 2013).

7.3 AUGUST 2009

Between 14 and 21 August 2009, 64 marine mammal encounters, involving an estimated 252 individuals, were recorded during 99 hours of observation over The Gully (Table 5). Sightings of northern bottlenose whales were scarcer than the previous year, with only 13 encounters, involving an estimated 55 individuals, in all and no more than eight seen at any one time (mean estimated group size: 4.2 individuals). That inter-annual difference can be explained in part by more frequent fog in 2009 (44 of 99 hours of observation effort, compared to 16 of 101 hours in 2008). All of those sightings were within the rectangle 43° 49.1' to 43° 54.7'N, 58° 50.7' to 58° 59.1'W (an area 10.4 by 11.2 km in size) – which includes the area where the bulk of the northern bottlenose whales were sighted during the 2008 survey[31]. Indeed, 23 of the 55 individuals were recorded within the smaller rectangle that saw 51 of 76 sightings the previous year, though in 2009 the sightings there tended to be over the thalweg, rather than the slope of the Spur (Figure 42).

Other cetacean species recorded during the survey included long-finned pilot whales, one group of unidentified beaked whales (likely *Mesoplodon* sp.), one group of *Kogia* sp. (probably *K. sima*, the dwarf sperm whale, but possibly *K. breviceps*, the pygmy sperm whale), numerous unidentified dolphins and various baleen whales, including at least some humpback (*Megaptera novaeangliae*), minke (*Balaenoptera acutorostrata*) and fin whales. Whichever species they may have been, the *Kogia* sp. were a new record for the Gully MPA, though a few stranded individuals have been reported from Sable Island in the past (Whitehead *et al.* 1998). *Mesoplodon* sp. were formerly only rarely recorded

[31] As for the 2008 data, this summary of the distribution of the encounters excludes one that was recorded with an erroneous position. It was an encounter with four individuals.

over The Gully but the numbers of *M. bidens* observed above the canyon have increased rapidly in recent decades (Hooker and Baird 1999; Whitehead 2013). Their presence in 2009 was unsurprising. Minkes, although generally considered a species of shallower waters, have been recorded over The Gully in the past, while humpbacks are regularly sighted there (Whitehead *et al.* 1998; Whitehead 2013).

7.4 MARCH 2010

Forty-nine encounters with mammals (involving an estimated 167 individuals) were recorded within the MPA during 99 hours of observations between 16 and 26 March 2010, while two further encounters and 17 individuals were recorded in the vicinity of the Offshore Station (Table 6). Thirty-four of those encounters, all of them within the MPA, were with northern bottlenose whales, an estimated 80 individual sightings being recorded (though some may have been repeat sightings of the same individuals). Those northern bottlenose whales were, however, scattered, with no more than five seen together at any one time (mean estimated group size: 2.4 individuals). They were observed from 43° 44.2'N (west of the Deep Station) to 43° 57.2'N, close to the northern limit of records in 2008, and were rather more widespread than during the summer surveys, only 23 of the encounters and 56 of the individuals being recorded within the rectangle that enclosed all of the encounters in 2009 (Figure 42).

Other cetacean species recorded included two groups of long-finned pilot whales, one adult male killer whale (*Orcinus orca*), one sperm whale, numerous unidentified dolphins and a few baleen whales, including at least two sightings of humpback near the Offshore Station, which may have been of the same individual. The killer whale was the first of its species to be formally recorded in the Gully MPA, though halibut fishermen had recently reported sightings and one was taken from the canyon area by whalers in 1964 (Whitehead *et al.* 1998). Sperm whales are regularly seen over the head of The Gully in summer and have been inferred to be present all year, based on both records of strandings on Sable Island (Whitehead *et al.* 1998) and acoustic records of their vocalizations (Moors 2012). During the survey, there were also two recorded sightings of grey seals (*Halichoerus grypus*) in the vicinity of the upper canyon.

7.5 SPATIAL DISTRIBUTIONS

Detailed studies of the distribution of northern bottlenose whales in The Gully have been undertaken using data from dedicated cetacean surveys aboard small sailing vessels, primarily in July and August. Hooker *et al*. (2002) found that most observations of that species were confined to a rather short portion of the canyon. In five of eight years, the northern limit of the area of concentration lay between 43° 54'N (at the north end of the Main Station of the trawl surveys) and 44° 00'N, though in three of those years there were reasonable numbers

immediately north of 44°N (and thus at the south end of the Head Station). In the remaining three years of the study, the limit was further south, between 43° 51' and 43° 54'N (which range encompasses the length of the Main Station). In 1989–93, the southern limit of the concentration was between 43° 48' and 43° 51'N, meaning immediately west of the Banquereau Spur. From 1994 to 1998, however, it was further north, in the vicinity of the Main Station (Hooker *et al.* 2002). In short, when observed at the surface over The Gully in summer, northern bottlenose whales are primarily animals of what is here termed the central canyon, though sightings of them are often largely confined to one part of that already-limited area.

In late August and early September of 2008 and 2009, the latitudinal limits of the species (as observed from the survey trawlers) were at 43° 48' and 43° 59'N, though most of the encounters were between 43° 49' and 43° 53'N, meaning that the whales were about as far to the southward as Hooker *et al.* (2002) ever found them. Since the 2007 survey had found the whales most often on the Main and Wall stations later in September (Kenchington *et al.* 2009), the southerly distribution appears to be the consequence of inter-annual, rather than seasonal, variation. Viewed at a coarser scale, the observations of all three summer surveys reinforce conclusions from the previous cetacean surveys, showing that most northern bottlenose whale sightings are made over the central canyon. It may be particularly notable that high densities of this species have rarely been observed in summer over the upper canyon, north of the 43° 53' to 43° 59'N belt where the pattern of deep, non-migratory acoustic backscattering changes from the form typical of the Main Station to that seen on the Head Station (see Section 3 above).

The sole sperm whale observed in 2010, one of only two identified during the four surveys, was recorded in the vicinity of the Deep Station. (The other record of that species was of one sighted on the Main Station in 2007: Kenchington *et al.* 2009.) The lack of additional observations was unexpected as Whitehead *et al.* (1992) often recorded sperm whales over the upper canyon[32]. The contrast in sperm-whale sighting rates between the cetacean and trawl surveys could be attributed to a number of causes, including differences the survey approach and methods, differences in the research platform (e.g. active avoidance of the much noisier trawlers), possible differences in sighting conditions or an actual difference in the number of sperm whales present. The true cause of the contrast is likely to remain unknown. Whitehead *et al.* (1992) found sperm whales throughout The Gully, wherever seabed depths were greater than 200 m, but they were most frequent north of 43° 55'N – essentially the same latitude which

[32] It is unclear from Whitehead *et al.*'s (1992) published account whether the sperm whales were only frequent in the canyon or whether they were also regularly seen in what is here termed the Head Valleys Area.

marks both the northern limit of abundant northern bottlenose whales and the transition in deep acoustic backscattering.

The northern bottlenose whales in The Gully are thought to feed primarily on *Gonatus* spp. at depths between 500 and 1,500 m (Hooker *et al.* 2001). Their observed distribution over the canyon presumably reflects that of the availability (not necessarily the distribution) of the squid at meso- and bathypelagic depths. Globally, sperm whale diets are quite varied, though dominated by cephalopods, and hence the prey species eaten in The Gully cannot be known without site-specific studies. However, the partitioning of space between the two whale species implies a parallel partitioning of food resources (Whitehead *et al.* 1992) and hence that the sperm whales in the canyon do not focus their hunting on *Gonatus* spp. Rather, they apparently concentrate on some other prey, which is presumably more readily available in the upper canyon than elsewhere in The Gully. What factors might limit the density of *Gonatus* spp. in the upper canyon or make them less available to whale predation there (and which might have the opposite effect on the chosen prey of the sperm whales) are unknown. However, the coincidence in the latitudinal limits of the whales, by implication their prey and also the deep, non-migratory scatterers hints at a major difference between the structures of the deep pelagic ecosystems in the central and upper canyons. It has been argued above that the location of the boundary observed in the acoustic backscattering is determined by the bathymetry of the canyon and its effects on water movements. If so, the ecological consequences of that interaction appear to propagate upwards to the highest trophic level.

8 SEABIRD OBSERVATIONS

T.J. Kenchington and C. Gjerdrum

Systematic seabird observations were only made during the 2010 survey, when they followed the standard protocol of the Eastern Canada Seabirds at Sea program (Gjerdrum *et al.* 2012; Kenchington *et al.* 2014). Through that entire cruise, 14 to 27 March, 1,245 birds of at least 13 species and five families were recorded within the 300 m-wide transect along 909 km of ocean track. Of those birds, 1,078 were seen within the Gully MPA (Table 7). The spatial distribution of the records was influenced by the amount of daylight time that CCGS *Teleost* spent in different places, most of which was within the MPA. That area, however, also produced the highest recorded densities (Figure 43), especially of murres (mostly thick-billed murres, *Uria lomvia*) and dovekies (*Alle alle*). Each of those two species was seen throughout The Gully but particularly from the Banquereau Spur northwards to about the mid-point of the Main Station (Figure 44).

No comparable data from The Gully in March of other years exist but most of the 13 recorded species have long been known to occur on the eastern Scotian Shelf and southern Grand Bank during the first quarter of the year (e.g. Brown *et al.* 1975), though the storm-petrel, gannet and tern would not normally be seen before April or May. The local concentration of murres and dovekies immediately inside the mouth of the canyon is more notable, not least because that is the area where northern bottlenose whale sightings were concentrated in August and September of earlier years (see Section 7 above). It is also the area that had distinctive non-migratory acoustic backscattering at mesopelagic depths (see Section 3 above).

Whereas the whales dive to depths of several hundred metres to feed, dovekie dives only extend to a maximum of 30 m or so and are often much shallower – at least on their summer feeding grounds in the Arctic (Falk *et al.* 2000; Brown *et al.* 2012). There, they consume primarily large calanoid copepods, particularly *Calanus glacialis* and *C. finmarchicus*. Their winter diet is known from only one study but that found them primarily eating euphausiid krill and the hyperiid *Themisto* spp., the former being more important in weight terms. A sample (primarily of juvenile birds) collected from Placentia Bay, Newfoundland in March 2011 had eatied exclusively the euphausiid *Thysanoessa raschii*, the hyperiids *Themisto gaudichaudii*, *T. abyssorum* and *T. libellula*, plus a small amount of *Calanus* spp. (Rosing-Asvid *et al.* 2013). Those are smaller animals than can be efficiently caught with an IYGPT net but *T. gaudichaudii* and *T. libellula* were taken in large numbers on the Main Station both in summer: (MacIsaac *et al.* 2014) and in March (unpublished data) nonetheless. Those catches also included mixed collections of smaller krill, which have not been identified to

species. Thus, there was no shortage of food for the dovekies recorded in and above the canyon.

Thick-billed murres dive deeper than their smaller relatives, sometimes exceeding 100 m but more typically reaching a few tens of metres. In one study in the Bering Sea, Takahashi *et al.* (2008) found that at night they only made very shallow dives, to a maximum of 5 m depth. It is unclear whether they ceased feeding then or, conversely, found all they could eat very close to the surface. Information on their winter diets is available from Newfoundland coastal waters, where there is a hunt for human food. During the season, the birds move southwards, ahead of the advancing ice, thus confounding seasonal and spatial diet variations. During the winters of the mid-1980s, Elliot *et al.* (1990) found that thick-billed murres along the shores of southern Labrador and northeast Newfoundland in November and December ate mostly fish. From January to March, and from Bonavista to the Burin, they ate primarily crustaceans. Their prey species were likely those locally available within the birds' diving depths. The fish consumed were primarily capelin (*Mallotus villosus*), Arctic cod (*Boreogadus saida*), sandlance (*Ammodytes* spp.) and small juveniles of Atlantic cod (*Gadus morhua*), though the species composition varied across time and space. Invertebrate consumption was dominated by small euphausiids (*Thysanoessa* sp.), though one sample taken on the south coast in February had been eating mostly *Themisto gaudichaudii*. Of particular note here, a minority of birds in the northernmost (and hence earliest) samples contained the beaks of *Gonatus* spp. (the only species of squid eaten: Elliot *et al.* 1990). A further study ten years later found a similar diet of primarily Arctic and Atlantic cod, capelin, euphausiids and hyperiids, though that did not greatly change from October to March. Interestingly, 55 of 237 non-empty stomachs (a few of them from specimens of common murre, *Uria aalge*) contained the remains of *Gonatus* spp., though perhaps only their beaks (Rowe *et al.* 2000). Elliot *et al.* (1990) cautioned that their data were confined to the diets of individuals overwintering in coastal waters and that murres concentrated along the shelf break might have different prey available. Nevertheless, it seems likely that the birds over The Gully in March 2010 were competing with the dovekies for small euphausiids and hyperiids and perhaps also feeding on diel-migrant fishes, likely myctophids. However, the migrant deep-scattering layer recorded by the echosounder seems not to have risen above several tens of metres depth at night, remaining below the Cold Intermediate Layer (see Section 3 above), and hence few fish may have been available to the murres.

It is also possible that one or both species of birds was preying on newly-hatched *Gonatus* spp. Adult female *Gonatus* spp. are thought to brood their egg masses until hatching and their own deaths (Bjørke *et al.* 1997; Arkhipkin and Bjørke 1999), presumably at depths of several hundred metres or more – though larval release has not been observed and brooding females only very rarely. The timing

of the hatch varies among regions but it occurs in spring south of Iceland (Lu and Clarke 1975; Kristensen 1983, 1984). Three large, spent females were taken in the trawls during the March 2010 survey (unpublished data), implying that larval release was in progress in The Gully at that time, though it may have been either the beginning or the end of the season. The young squid emerge as paralarvae of about 3 mm pen length ("PL") and ascend to the surface, likely to feed on the abundant zooplankton there. They are themselves planktonic, probably distributed through the upper 50 m of the water column, until achieving juvenile morphology, and sufficient motility to be classed as micronekton, at about 15 mm PL. They either descend to depth or become much harder to catch in plankton nets at about 50 mm PL (Kristensen 1983, 1984; Arkhipkin and Bjørke 1999). The Newfoundland murres in Elliot *et al.*'s (1990) and Rowe *et al.*'s (2000) samples presumably ate *Gonatus* spp. of either the paralarva or near-surface, early-juvenile stages, the former authors suggesting that the squid they observed had been 20 to 50 mm length.

The combination of a widespread distribution of scattered northern bottlenose whales (see Section 7 above), the few specimens of spent female *Gonatus* spp. taken by the trawls, and a known predator of young *Gonatus* spp. distributed above where the whales feed, probably primarily on late-juvenile and adult *Gonatus* spp. (Hooker *et al.* 2001), in summer is suggestive. It is consistent with the March 2010 survey falling near the end of the squids' hatching season, the consequent deaths of the adult females terminating a period of rich feeding for the whales, while the ascent of the paralarvae to the surface created a new feeding opportunity for the murres, approximately a kilometre above. Without samples of the birds' stomach contents, however, that must remain an untested hypothesis.

Whatever they were eating, both the murres and the dovekies were concentrated over the canyon mouth and the southern portion of the central canyon, despite being confined to a surface layer (many tens of metres above rim depth) which is itself little influenced by the presence of deep water beneath (Greenan *et al.* 2014). Thus, the bathymetry at mesopelagic depths evidently shaped the distribution of the birds at the surface, despite the absence of much physical influence – the medium of the control presumably being the active vertical migrations of animals between the waters below rim depth and those at the top of the water column. Whether diel or seasonal-ontogenetic migrations were the more important remains unknown.

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TABLES

Table 1 : Names of Selected Bathymetric Features
These names and their definitions are those used in the present report. They are not offered for general use. Within these definitions, cross references to names defined elsewhere in this table are italicized.

Feature	Definition and Explanation
Banquereau Spur	A mountain spur, some 2,000 m high, formed by the intersection of the steep eastern wall of the *canyon*, where it meanders towards its *mouth*, and the continental slope (Figures 4E, 4F). The upper end of the Spur has long been called the *Southwest Prong* of Banquereau. While that name has been used for the feature as a whole (e.g. Kenchington 2010; Kenchington *et al.* 2014), it poorly represents such a mighty ridge – one which appears critical to the ecology of The Gully (and which lies on its eastern, not western, side). The name "Banquereau Spur" is here adopted as a more-suitable alternative. That term has previously been used, informally, by Kenchington *et al.* (2009, 2014). The Spur lies entirely within the MPA.
Canyon	A combination of the Gully thalweg, from where it crosses the 400 m bathymetric contour (at the *canyon head*) to as far down the continental rise as that thalweg can be discerned (at a depth greatly exceeding 3,000 m), together with the slopes and side canyons descending to that thalweg. Those slopes and the heads of the various thalwegs can generally be delimited by the 400 m contour, which serves to mark the upper limit of the steep walls around most of The Gully. Some of the side canyons have distinctively steep slopes, characteristic of canyon morphology, that reach to as shallow as 100 m depth, while similar gradients extend above the 400 m contour in some other parts of *The Gully*. Those areas are here considered to be parts of the canyon.

Feature	Definition and Explanation
	North of the *canyon mouth*, the canyon's rim depth (in the oceanographic sense, affecting water movements) is much shallower than the 400 m limit invoked here. Delimitation by that lesser depth would, however, place wide areas of the flanks of Banquereau and Sable Island Bank inside the "canyon" and would require arbitrary lines to distinguish the canyon-proper from the shelf valleys in the *head valleys area*. The canyon is here subdivided into three portions: the *upper canyon*, *central canyon* and *outer canyon*. Much of the canyon, thus defined, lies outside (southeast of) the *canyon mouth*, where other authors would place its southern limit. From the *canyon head* to the *mouth* and beyond, the canyon (as here understood) lies entirely within the MPA but its deepest part is outside that Area.
Canyon Head	For much of its length, the canyon thalweg dips towards the south at ≈2° (Fader and Strang 2002). Between 800 and 1,000 m depth and between 500 and 600 m it is steeper, averaging ≈4°. That relatively swift shallowing constitutes the head of the canyon but it encompasses some 10 km of the the thalweg. For greater precision, the "canyon head" is here considered to be where the thalweg cuts the 400 m bathymetric contour, which closely approximates to the limit of canyon morphology. Thus defined, the head lies close to the mouth of the westernmost of the three major side canyons which join the main canyon along its uppermost reach (Figure 4C). The canyon head lies within the MPA. Swart *et al.* (2011) defined the canyon head similarly but placed it where the thalweg is about 700 m deep (close to the mouth of the major side canyon that enters the main canyon from the north). That was well suited to their particular focus but there is no general reason to place the "head" in that location.

Feature	Definition and Explanation
Canyon Mouth	That portion of the *canyon* where it cuts the shelf break. In practice, the mouth is shaped by the *Banquereau Spur*, which prevents a simple definition in terms of a single section across the *canyon*. The thalweg passes the mouth at about 43° 52'N and at a depth of approximately 2,000 m (Figures 4E, 4F). The Canyon Mouth is entirely within the MPA.
Central Canyon	Portion of the *canyon* (including its side canyons) between the southern limit of the *upper canyon* (at the pronounced curve in the thalweg around 43° 59'N) and the *canyon mouth* (approximately 43° 50'N :Figure 4D). That area contained the Main and Wall stations of the trawl surveys (Kenchington *et al.* 2009, 2014), as well as oceanographic moorings SG10, SG11 and SG12 of Greenan *et al.* (2013). The Central Canyon is entirely within the MPA.
The Gully	The combination of the *canyon*, the *head valleys area* and such of the flanks of Banquereau and Sable Island Bank, below 200 m depth, as border the *canyon*. As understood here, much of The Gully is outside the MPA, while parts of Zone 3 of the MPA lie outside The Gully. The Gully is often referred to as the “Sable Gully”, which is one of two names used by fishermen (the other being the “Sable Island Gully”), for whom a number of other features of the Scotian Shelf have equal claim to being <u>the</u> gully, including the channel between Browns Bank and Cape Sable (the “Inside Gully”) and the Northeast Channel (Kenchington and Halliday 1994). Despite that usage, the name “The Gully” was adopted with its present meaning by the then-Canadian Permanent Committee on Geographical Names (now the Geographical Names Board of Canada) in 1968. It was taken as the name of the MPA when that was established in 2004 and hence that style has been adopted here.

Feature	Definition and Explanation
Head Valleys Area	A large area of mixed depths (100–400 m) lying north of the Gully *canyon*, between Banquereau and Sable Island Bank (Figure 4B). The principal features of that area are the three branches of a shelf-valley system and the ridges between them. The westerly and northwesterly valley branches are the principal connections between *The Trough* and the *canyon*. Multibeam bathymetric data shows that it contains an extensive sandwave field straddling the 300 m bathymetric contour, indicative of water movement through the valley. Fader and Strang (2002) noted a "large megaflute" in the same vicinity. Most of this Area is outside the MPA and all is external to the *canyon*, though the Head Valleys Area is here considered to be part of *The Gully*. It approximates to what Strain and Yeats (2005) denoted as the "Inner Gully" but has, in the past, been designated as "The Trough" (e.g. Fenton 1998). Fader and Strang (2002) termed the sandwave field "The Gully head".
Outer Canyon	Portion of the *canyon* (including its side canyons) south of the *canyon mouth* (Figure 4G). That area contained the Deep Station of the trawl surveys (Kenchington *et al.* 2009, 2014). Much of the Outer Canyon is outside the MPA.
Rim Depth	In discussions of water movements within *The Gully*, its rim depth is taken as ≈200 m, following Greenan *et al.* (2014) and Shan *et al.* (2014a, b). That contrasts with the typical (though not invariable) ≈400 m depth of the upper limit of the distinctive, steep-walled canyon bathymetry. The latter is here used to bound the definition of the *canyon*.
Southwest Prong	Southernmost extremity of Banquereau, projecting southwards at a depth of about 300 m, and its deeper extension as a ridge between the canyon thalweg and the continental slope (Figures 4E,

Feature	Definition and Explanation
	4F). That feature was known to the early halibut fishermen, who fished the ridge to depths of a few hundred metres from the 1870s, and the "Southwest Prong" name is found in 19th Century sources (e.g. Collins and Rathbun 1887). It is, however, a misnomer for the overall feature, which is here named the *Banquereau Spur*, "Southwest Prong" being retained as the name for the uppermost portion of the ridge only. Some modern fishermen prefer the variant name "Southwest Peak".
The Trough	An extensive, shallow (mostly 100–200 m depth) depression in the eastern Scotian Shelf between Banquereau, Middle and Sable Island banks, lying generally north of Sable Island (Figure 1). The Trough is entirely outside the MPA and is here considered to be external to *The Gully*, though the connection between them is expected to be ecologically important to both.
Upper Canyon	Portion of the *canyon* (including its side canyons) between the *canyon head* and the pronounced curve in the thalweg around 43° 59'N (Figure 4C). That area, which appears to be ecologically distinct from the parts of the *canyon* further south (the *central canyon* and *outer canyon*), contained both the Head Station of the trawl surveys (Kenchington *et al.* 2009, 2014) and oceanographic mooring SG2 of Greenan *et al.* (2013). The Upper Canyon is entirely within the MPA.

The Canadian Geographical Names Data Base contains only two formally recognized names from the general area of present concern. One is "The Gully". The other, "DesBarre Spur", is the name of a south-easterly extension of the East Bar of Sable Island, which lies at depths of 20 to 40 m. Its eastern end adjoins the head of the major feeder canyon that enters the main canyon at 44° 59'N. The DesBarre Spur has no relationship to what is here termed the "Banquereau Spur".

The name "Southwest Prong" is listed in the Geographical Names Data Base but with reference to a shoal near 44°40'N 63°05'W – approximately 4 km southwest of Cape Jeddore, on the mainland coast of Nova Scotia. The Southwest Prong recognized in this report is an entirely different feature located at about 43°53'N 58°50'W.

Table 2 : Abbreviations used in this report when describing water masses

CIL	Cold Intermediate Layer (part of the SSWs)
DWBC	Deep Western Boundary Current
GSW	Gulf Stream Water
LSW	Labrador Sea Water, sometimes termed Labrador Slope Water (part of the NADW)
MOC	Meridional Overturning Circulation
NACW	North Atlantic Central Water. Also used for the combination of waters that contribute to the distinctive temperature / salinity curve found in the Sargasso Sea.
NADW	North Atlantic Deep Water
NAO	North Atlantic Oscillation (a meteorological, rather than oceanographic, phenomenon)
NEADW	North East Atlantic Deep Water (part of the NADW)
SSB	Shelf / Slope-Water Boundary (front between SSW and WSW)
SST	Sea Surface Temperature
SSWs	Scotian Shelf Waters. Used in the plural as an aggregate of the warm summer surface layer, the CIL and the warmer, more saline lower layer.
WSW	Warm Slope Water

Table 3 : Summary of Tucker Trawl Catches and Filtered Volumes
Catches, other than those of small crustaceans, are counts of individuals

Set	**3**	**4**	**16**	**24**	**26**	**33**	**34**	**35**	**40**	**42**
Total filtered volume (m^3)	18300	21600	24500	18400	18000	16100	17500	17600	13300	12500
Volume filtered below 400 m depth (m^3)	10300	10800	5600	11100	10900	9500	5800	10500	10300	9200
Small crustaceans	200 ml	250 ml	270 ml +100 g	70 ml	140 ml	160 ml	130 ml +100 g	140 ml +100 g	180 ml	250 ml
Larger decapods	10	11	2	18	8	10	6	25	26	9
Chaetognaths	153	124	29	28	76	49	9	20	20	81
***Cyclothone* spp.**	80	72	2	55	45	16	2	26	55	49
Small myctophids	7	4	30	0	0	25	25	26	29	8
Larger myctophids	12	27	31	3	2	18	20	31	12	7
Other and unidentified fish	4	5	9	3	1	7	6	5	2	4
Unidentified fish pieces	6	5	8	7	2	3	1	3	8	10

Table 4 : Summary of 2008 Marine Mammal Sightings in the Gully
Species identifications are as recorded at sea, some being uncertain. The numbers given are the total counts of sightings for the species, station (including the surrounding area) and day, sometimes combining the counts from multiple encounters. Hence, it is possible that smaller numbers of individuals were present and were repeatedly sighted. The number of discrete encounters is also provided. (Mammals sighted *en route* to and from the Gully are not listed here.)

Date	Nearest Station	Species	Numbers	Encounters
30 Aug	Deep	Bottlenose whale	8	3
31 Aug	Deep	Pilot whale	2	1
		Fin whale	1	1
1 Sept	Deep	Bottlenose whale	4	1
	Main	Bottlenose whale	10	5
		Pilot whale	32	2
2 Sept	Main	Bottlenose whale	2	1
		Unknown	1	1
	Head	Bottlenose whale	1	1
		Pilot whale	16	3
		White-sided dolphin	10	1
		Sei or Fin whale	1	1
3 Sept	Head	Pilot whale	8	1
		Fin whale	2	2
	Main	Bottlenose whale	10	5
		Pilot whale	12	1
		Unknown baleen whale	1	1
		Common dolphin	20	1
4 Sept	Main	Bottlenose whale	17	5
		White-sided dolphin	15	1
		Common dolphin	60	3
		Unknown dolphin	10	1
	Head	Bottlenose whale	1	1
5 Sept	Main	Bottlenose whale	23	3

Table 5 : Summary of 2009 Marine Mammal Sightings in the Gully
Species identifications are as recorded at sea, some being uncertain. The numbers given are the total counts of sightings for the species, station (including the surrounding area) and day, sometimes combining the counts from multiple encounters. Hence, it is possible that smaller numbers of individuals were present and were repeatedly sighted. The number of discrete encounters is also provided. (Mammals sighted *en route* to and from the Gully are not listed here.)

Date	Nearest Station	Species	Numbers	Encounters
14 Aug	Deep	Bottlenose whale	4	1
		Humpback whale	2	1
15 Aug	Deep	Pilot whale	4	1
		Minke whale	2	2
		Unknown baleen whale	1	1
		Unknown whale	1	1
16 Aug	Main or Wall	Bottlenose whale	9	3
		Unknown baleen whale	1	1
		Unknown whale	2	2
17 Aug	Main or Wall	Bottlenose whale	29	6
		Beaked whale, *Mesoplodon* sp.	8	1
		Pilot whale	10	2
		Unknown dolphin	25	1
		Humpback whale	3	1
		Unknown baleen whale	2	2
		Unknown whale	2	2
18 Aug	Main or Wall	Bottlenose whale	3	1
		Pilot whale	9	2
		Humpback whale	2	2
		Unknown baleen whale	5	5
		Unknown whale	4	1
	Deep	Pilot whale	9	2
		Unknown dolphin	10	1
19 Aug	Main or Wall	Bottlenose whale	10	2
		Pilot whale	34	5
		Dwarf or Pygmy sperm	8	1

		whale, *Kogia* sp.		
		Humpback whale	5	2
		Unknown baleen whale	2	2
20 Aug	Main or Wall	Unknown dolphin	2	1
		Humpback whale	3	1
		Unknown baleen whale	1	1
	Head	Pilot whale	4	1
		Unknown baleen whale	8	1
21 Aug	Head	Pilot whale	20	1
		Fin whale	3	2
		Humpback whale	4	1
		Unknown baleen whale	1	1

Table 6 : Summary of 2010 Marine Mammal Sightings in The Gully
Species identifications are as recorded at sea, some being uncertain. The numbers given are the total counts of sightings for the species, station (including the surrounding area) and day, sometimes combining the counts from multiple encounters. Hence, it is possible that smaller numbers of individuals were present and were repeatedly sighted. The number of discrete encounters is also provided. (Mammals sighted *en route* to and from the Gully are not listed here.)

Date	Nearest Station	Species	Numbers	Encounters
16 Mar	Main	Bottlenose whale	6	3
17 Mar	Main	Bottlenose whale	28	11
18 Mar	Head	Pilot whale	10	1
19 Mar	Main	Bottlenose whale	3	1
	Head	Unknown baleen whale	2	2
		Killer whale	1	1
		Unknown dolphin	50	2
		Grey seal	1	1
20 Mar	Main	Bottlenose whale	21	5
		Sperm whale	1	1
		Unknown dolphins	10	1
21 Mar	Main	Bottlenose whale	11	6
		Unknown dolphin	3	1
	Deep	Bottlenose whale	2	2
		Unknown whale	2	1
22 Mar	Deep	Bottlenose whale	4	2
23 Mar	Deep	Unknown dolphin	5	1
24 Mar	Main	Bottlenose whale	5	4
25 Mar	Offshore	Pilot whale	15	1
		Humpback whale	2	2
26 Mar	Head	Pilot whale	1	1
		Grey seal	1	1

Table 7 : Summary of Marine Birds Recorded During 2010 Survey

Family	Species	Number recorded in Gully MPA	Number recorded elsewhere
Procellariidae	Northern fulmar *Fulmarus glacialis*	39	26
Hydrobatidae	Leach's storm-petrel *Oceanodroma leucorhoa*	1	0
Sulidae	Northern gannet *Morus bassanus*	3	1
Laridae	Herring gull *Larus argentatus*	40	6
	Great black-backed gull *L. marinus*	28	5
	Glaucous gull *L. hyperboreus*	4	2
	Iceland gull *L. glaucoides*	6	1
	Unknown gull *Larus* spp.	13	1
	Black-legged kittiwake *Rissa trydactyla*	28	11
	Unknown tern *Sterna* spp.	0	1
Alcidae	Dovekie *Alle alle*	433	45
	Thick-billed murre *Uria lomvia*	329	54
	Common murre *U. aalge*	0	3
	Unknown murre *Uria* spp.	144	20
	Black guillemot *Cepphus grylle*	0	1