

**Prey Fields and Habitats of Deep Diving Odontocetes:
3D Characterization and Modeling of Beaked and Sperm Whale
Foraging Areas in the Tongue of the Ocean**

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LONG-TERM GOALS

The physical and biological characteristics of the areas inhabited by deep diving odontocetes are poorly understood. Our long term goals are: i) to measure and characterize the biomass in areas and at depths inhabited by beaked and sperm whales; ii) to measure and characterize the physics of these environments; iii) to assemble the characteristics measured (i) and (ii) into a depth integrated, 3-dimensional habitat model; the model will include other dependent and independent data, e.g., chlorophyll and depth, respectively. Our final long term goal is to then apply the habitat model produced to other geographic areas to assess their likelihood as beaked and sperm whale habitat.

OBJECTIVES

The past year has been spent analyzing data and preparing publications from the 2008 cruise, which occurred 14 September to 3 October aboard the *R/V Roger Revelle*, and collecting data concurrent with tagging of short-fin pilot whales (*Globicephala macrorhynchus*) near the Cape Hatteras shelf break. The primary scientific objective for this year's work was to compare the biological and physical environments in areas both frequently (i.e., 'hot spots') and rarely (i.e., 'cold spots') utilized by beaked whales in the Tongue of the Ocean (TOTO), particularly on the AUTEK range, Andros, Bahamas. These 'hot' and 'cold' spots were determined using data from the M3R program (DeMarzio 2006). The AUTEK range work was completed in coordination with two other programs, the Behavioral Response Study (BRS) and the Marine Mammal Monitoring (M3R) at AUTEK. The *R/V Roger Revelle* possesses specialized sampling gear that provided a unique technical capabilities, specifically the Hydrographic Doppler Sonar System (HDSS), which is a one of a kind Doppler current profiling system capable of measure current directions and velocities to ~1000 m depth. Additionally, the HDSS returns data on the biological material in the water column that causes backscatter, and these data can be compared with the Simrad EK60 scientific echosounder data, described below.

The technical objectives were: i) to place the biomass data collected in TOTO into context with the beaked whale click data and conduct the habitat modeling; ii) to integrate the physical oceanographic measurements integrated with biological sampling; iii) to compare the deep diving odontocete echolocation activity on the AUTEK range with our measurements of the biological and physical environment; and iv) compare beaked whale echolocation activity during periods when our echosounders were off vs on; and v) collect data on prey fields and physical oceanography concurrent with multi-sensor tagging of short finned pilot whales near the Cape Hatteras shelf break.

APPROACH

During the past year, we have worked in analytical as well as data collection modes. Our analyses and synthesis of the prey field and echolocation data from TOTO has resulted in the submission of a publication to the Marine Ecology Progress Series, and salient features of this paper are included as figures 1, 2 and 3 of this report. St. Laurent and his group have analyzed much of the physical data from the TOTO experiment, and their results are represented in figures 4 and 5. Finally, we recently collected EK60, ADCP and CTD data in the waters of the shelf break near Cape Hatteras, concurrent with attachment of DTAGs; those data have only been cursorily processed as we returned from the field less than two weeks ago.

The EK60 system makes measurements of the returned energy from one or more targets, which are required to obtain accurate biomass estimates from the total returned echo energy (Foote, 1980a; Foote and Traynor, 1988). The amount of backscattered energy from a single fish is the backscattering cross section or echo intensity. If echo intensity is measured on a log scale it is called target strength (TS). Target strengths are often measured during surveys (*in situ*) or predicted from trawled fish lengths using a TS-fish length regression. Target strength regression equations allow prediction of TS but require large sample sizes, measurements of fish length, and often only include one variable explicitly. For example, if the tilt distribution of a school of fish differs from the tilt distribution of the fish used to derive target strengths, a consistent difference in tilt angle could bias abundance estimates. Converting an acoustic size to a numerical size or the total returned energy to an acoustic abundance estimate relies upon appropriate target strength values for the population.

When fish echoes are too dense to be counted, target strengths are required to convert reflected echo energy to a numerical estimate. The linearity principle as defined by Foote (1983) states that the total returned energy or integrated echo can be divided by a representative backscattering cross section to estimate fish abundance. Fish lengths (L) are used in size-dependent target strength equations: $TS = \beta_1 \log L + \beta_0$ (1) where β_1 and β_0 are parameters that vary among species (Love, 1971; Foote, 1980a; Middttun, 1984). This target strength equation (1) explicitly includes length.

Spatial associations between foraging click rates, oceanography, and prey data were performed using ArcGIS 9.3 (ESRI). Although data were collected northward up to Abaco bank, the analysis was restricted to waters east of Andros Island and west of the Nassau bank in the Bahamas. All data were projected in Universal Transverse Mercator zone 18 and analyzed in 1kmx1km horizontal grid cells. This resolution was chosen to minimize data gaps between hydrophones in the tongue of the ocean while ensuring adequate resolution for fisheries acoustic and oceanographic data. Bathymetric data were obtained from the Naval Undersea Warfare Center's hydrophone locations as the acoustic data were centered on each of these features. Variograms of prey density were used to identify the key spatial scales horizontally and vertically as an input for the geostatistical analysis. To account for spatial autocorrelation in our response variables, each dataset was interpolated into a continuous surface using a universal kriging function to visually identify hotspots and coldspots. Each hydrophone location was used to sample the acoustic surface, bottom depth, and microstructure diffusivity as inputs for the models of click density as a function of prey and environment.

Dissipation:

The viscous dissipation, ε , can be thought of as the how much energy is removed from the turbulent kinetic energy (TKE) produced by turbulent mixing processes. It is determined from turbulent velocity microstructure measurements from which the vertical shear of the horizontal component, u_z , can be calculated. The molecular viscosity of water acts on the shear to dampen the TKE through the following relation,

$$\varepsilon = (15/2) * \nu * \langle u_z^2 \rangle \quad (\text{W/kg}),$$

where ν is the molecular viscosity of seawater and $\langle u_z^2 \rangle$ is the mean-square turbulent shear. The fraction, 15/2, comes from the assumption that at the microstructure level the dissipation fluctuations can be taken to be isotropic (Gregg, 1987). This means that the shear components are taken to be equal in all directions allowing for the dissipation to be measured by just one component. It has been shown that using this isotropic relation yields a good estimate of dissipation (Yamazaki 1990).

Diffusivity:

The diffusivity is the primary measurement of ocean mixing. Essentially it determines the diapycnal advection, or the mixing rate between density surfaces. This is done through the relation to the dissipation through a constant mixing efficiency parameter, Γ , and the buoyancy frequency N^2 expressed as

$$k_p = \Gamma * \varepsilon * N^{-2} \quad (\text{m}^2/\text{s})$$

where Γ is taken to be 0.2 (Osborn, 1988).

WORK COMPLETED

We have analyzed the prey field data and compared it with the click activity recorded concurrently by the AUTECH array (M3R); these analyses are contained in the submitted manuscript and summarized for this report. The physical data has also been analyzed for dissipation and shear; these results are also summarized for this report and are being prepared for publication.

During the summer of 2010 for the second major portion of this award, we worked as part of an interdisciplinary research team to tag short finned pilot whales and measure physical and biological oceanographic data at the shelf break near Cape Hatteras, NC. We tagged 8 animals with DTAGs and during these deployments we measured backscatter with 38 and 120 kHz EK60 echosounders, the current structure with a 75 kHz ADCP, and water mass characteristics with a CTD.

RESULTS

The most apparent acoustic feature in the tongue of the ocean was a deep scattering layer with a mean width of approximately 200 meters centered at 500 meters in depth. Mean volumetric backscatter at 500 meters was greatest at the southern edge of our study side and on the western edge of the basin ($S_{V_{\text{mean}}} = -71.03$ dB) and weakest at eastern edge of the basin ($S_{V_{\text{mean}}} = -76.3$ dB). The acoustic density of scatterers was significantly dispersed in the horizontal (x-y) dimension throughout our study area (Moran's $i = -0.02$, $p < 0.01$). This correlates with our qualitative observations that the primary scatterers were distributed in layers rather than discrete patches. In contrast, the numbers and sizes of single targets per m^2 were patchily distributed in the horizontal dimension (Moran's $i = 0.07$, 0.05 respectively, $p < 0.01$). Semi-variograms for acoustic density in the x-y dimensions corroborated these findings with no discernable sill in the variance (Figure 1). For density as a function of depth (the z-axis), semi-variograms showed a consistent sill at 200m corresponding to the mean width of the deep scattering layer (Figure 1). All acoustic and oceanographic data were subsequently binned in 200-meter increments from 0 to 1000 meters depth and in horizontal distance.

Patterns in the distribution of detected single targets were similar to overall scattering volume. Acoustically detected single targets ranged between 1-10 targets 2500 m^2 and had target strengths of -50 dB to -35dB in size. The number of targets was greatest at 200 meters in depth with just below 10 targets per 2500 m^2 (Figure 2). The largest acoustic scatterers were between 500-600 meters in depth and had mean target strengths of -35dB and the depth of these larger scatterers overlapped the bottom of the primary scattering layer. In contrast to overall backscattering density patterns, we found both the size and the number of single targets per m^2 was not significantly different along the southern and western edge of the basin compared to the northern and eastern portion of the bay ($S_{V_{\text{mean}}} = -40.7$ and -40.8 dB; mean number of targets = 1.18 and 1.16 respectively). However, without visual confirmation such as cameras or net tows, we are unable to differentiate among various scatterers including the various prey items available to beaked whales. Finally, the click activity was spatially correlated with these high Sv levels at 550 m (Figure 3).

The DMP was deployed concurrently to detect the turbulent dissipation. The dissipation and acoustic backscatter were both bin-averaged over 50 m intervals (Figure 4). Both use a logarithmic scale, with dissipation ranging from 10^{-10} to $10^{-7} \text{ W kg}^{-1}$ and acoustic backscatter from -90 to -70 db. The typical TOTO region dissipation profile displayed background levels on the order of $10^{-10} \text{ W kg}^{-1}$, with patchy elevated turbulence levels throughout the water column reaching maximum values on the order of 10^{-8} .

Over 50 % of the profiles exhibited dissipation levels greater than $10^{-9} \text{ W kg}^{-1}$ within or just outside of the deep scattering layer, of which only 3 were in excess of $10^{-8} \text{ W kg}^{-1}$.

Clovers 8 was sampled during the night hours, starting no earlier than 10:00 pm local time (Figure 4), and we found dissipation levels in excess of $10^{-9} \text{ W kg}^{-1}$ in 3 of the 6 profiles. Localized pockets of active mixing are easily apparent in the data. In particular, certain depth intervals often showed elevated levels of turbulence. For example, the central station of the Clover 8 survey showed a significant turbulent patch at between 800 m and 850 m (Figure 4). Finally, the investigation of the shear data revealed some very interesting results. Figure 5 shows a transect across the TOTO and shows an almost standing wave structure to the shear.

The scale of prey distribution was broad in the horizontal (> 6 km) but much finer in the vertical dimension (~200 m) suggesting broad-scale surveys in the Tongue of the Ocean should be sufficient for measuring DSL distribution. With respect to beaked whales, The relative foraging duration at each hydrophone was significantly related to the density of the DSL.

The 550-m depth scattering layer is aligned with a prominent shear layer. Turbulence levels are enhanced in the layer, though interestingly turbulence levels are not enhanced in the migratory scattering layer- despite examples elsewhere. Finally, while beaked whales often forage on squid in or below the deep scattering layer, the DSL density itself appears to serve as a valuable tool in predicting beaked whale distribution in the TOTO. Further analysis of temporal scale variation and examination of individual targets at broader depth bins could further elucidate the relationship between beaked whales and their prey in the Tongue of the Ocean.

Finally, our initial processing of the short-finned pilot whale shows them displaying some feeding behavior at depths where we detected layers of scatterers (Figure 6); the whales also dove to depths that did not contain dense patches or layers of prey. We have just returned from this field program, so more analyses of these data will follow soon with publication expected within the year.

IMPACT/APPLICATIONS

The scientific impact of our accomplishments are likely to be significant because as far as we are aware, no field program has ever combined intensive sampling of biological and physical data in the known prey fields of a marine mammal, or any marine megavertebate for that matter. The results reported clearly demonstrate some relationship between physical and biological parameters in areas where beaked whales prefer to forage and those they do not frequent. .

RELATED PROJECTS

We have worked with M3R to share the click data from the areas where we were working, and, importantly, full audio data from the time period surrounding our work on the range to assess any potential effects our echosounders may have had on the whales. A Master's student at Duke is currently analyzing these data for her degree, which will be completed by May 2011.

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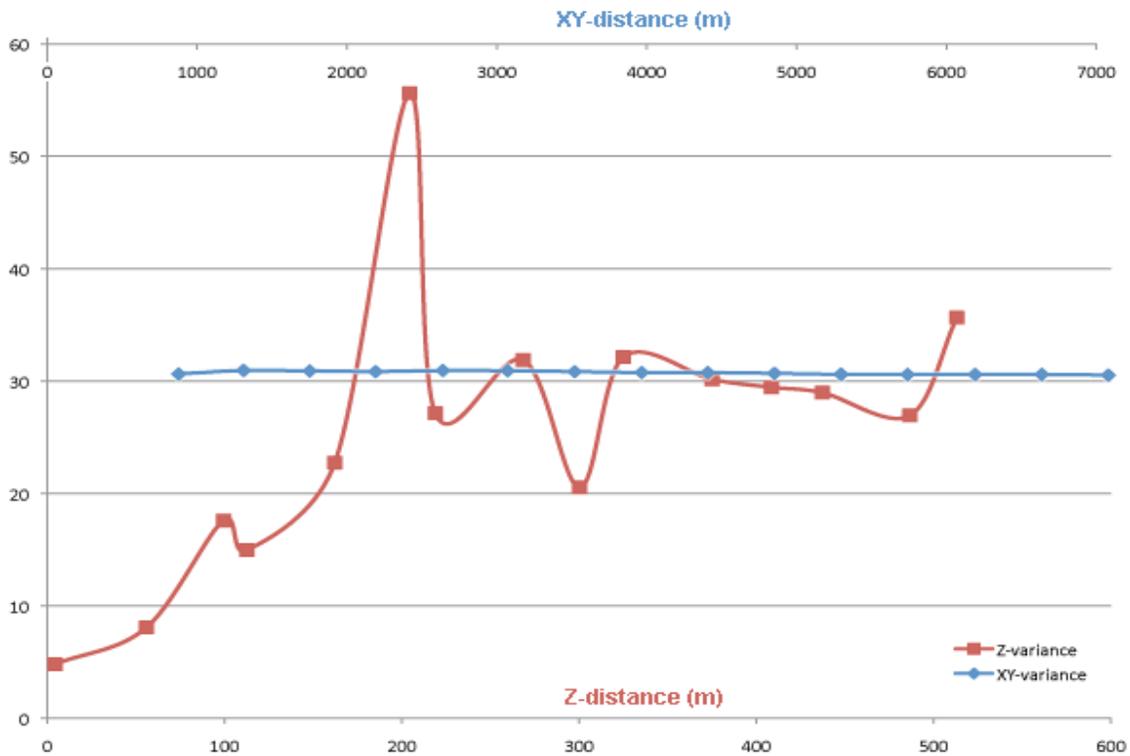


Figure 1 – Semivariograms of acoustic backscatter with vertical (depth) and horizontal distances (x,y). Lag distance is on the x-axis with semivariance on the y-axis. The plot shows a large peak in semivariance at 200m in the vertical indicating patch size, with no discernible sill in the horizontal.

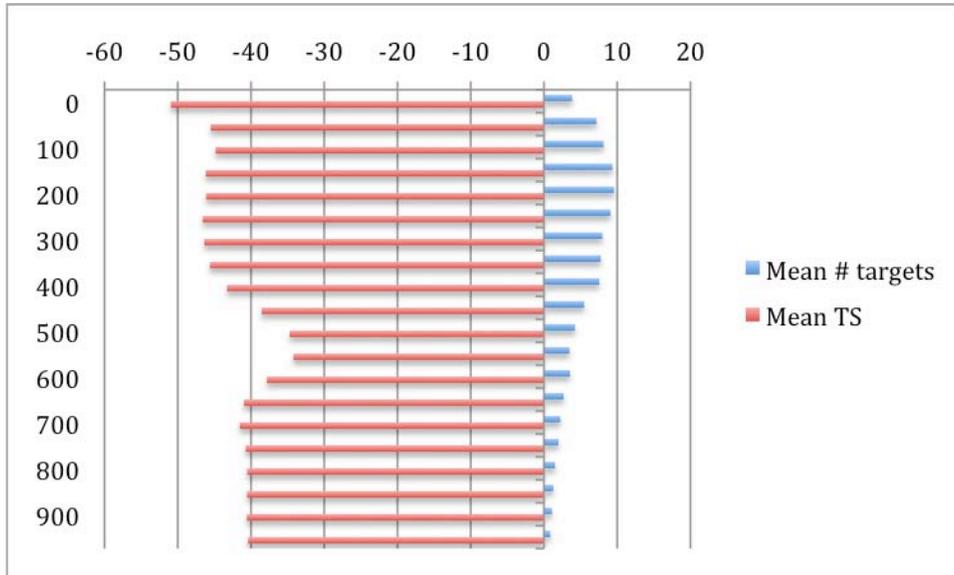


Figure 2 – The mean number of targets, target size, and mean scattering volume with depth for the entire study area. There was a peak in 9 targets / m² at 200-250m, a peak in target size of -35dB at 550-600m, and a peak in mean scattering volume at 500m.

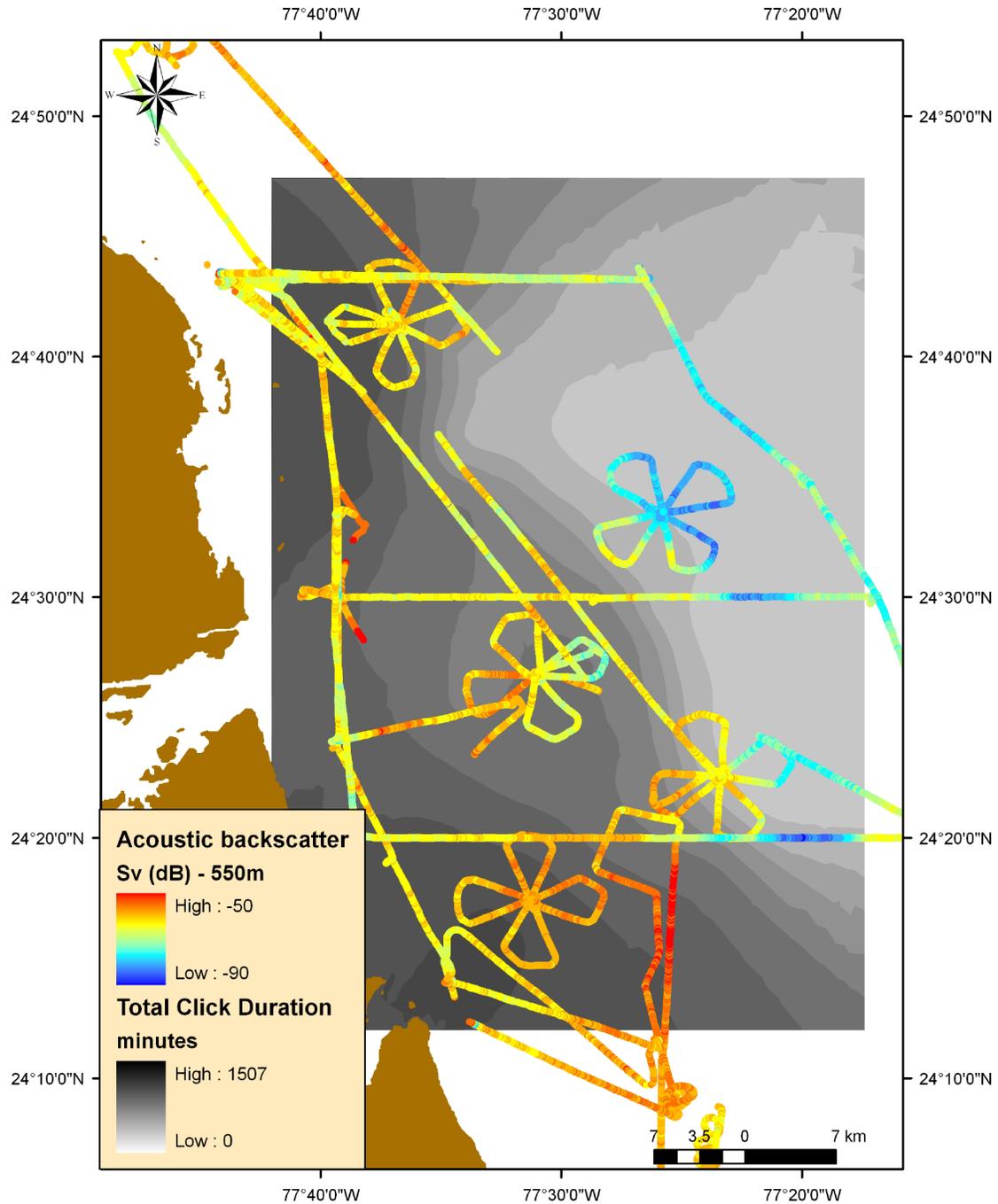


Figure 3. Interpolated relative foraging density (click duration) in grey (generated from the AUTECH hydrophone array) and acoustic backscatter at 550 meters as blue to red points. The western and southwestern areas of the study area had higher foraging effort and greater mean scattering volume.

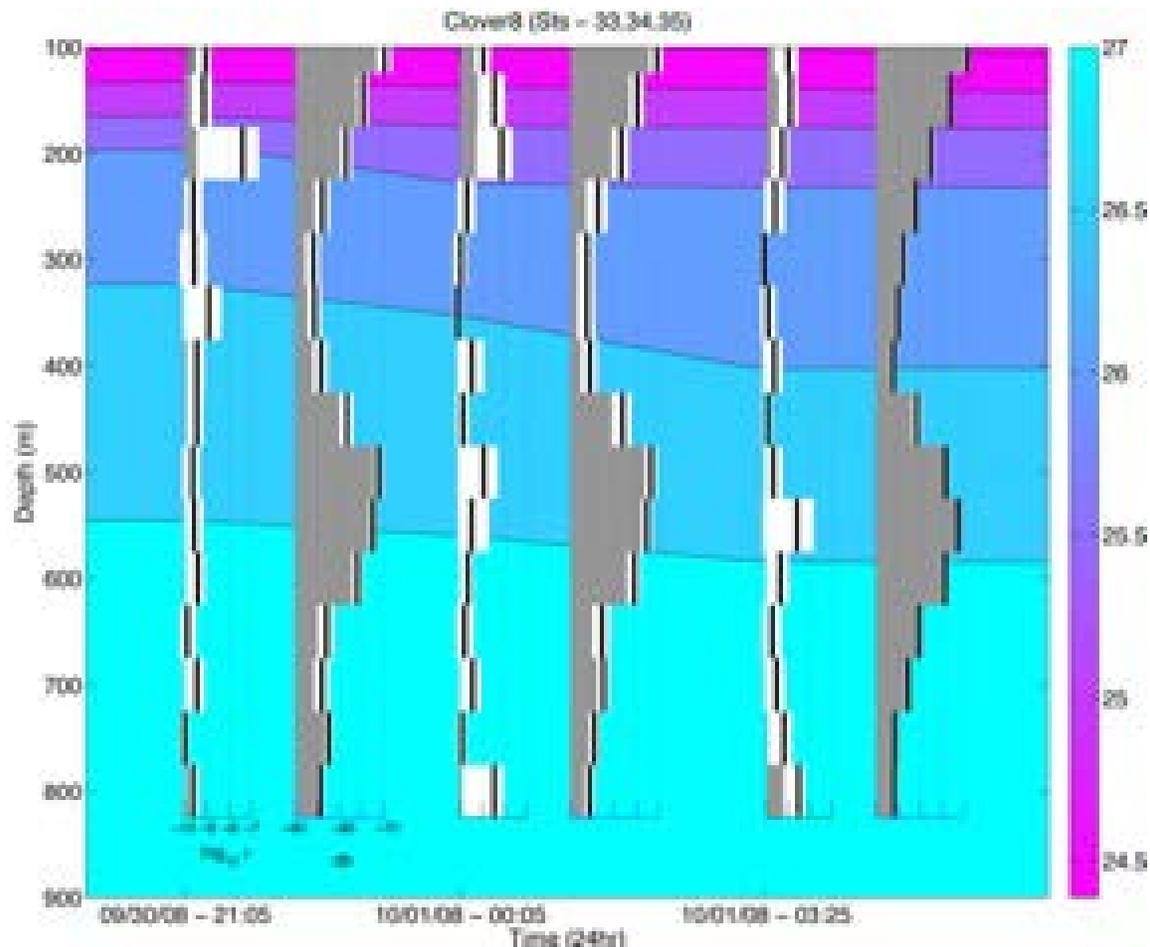


Figure 4. Plot of the Clover 8 survey comparing the dissipation data to the acoustic backscatter data with density contours in the background. The profile to the left is the dissipation profile with the acoustic profile to the right in each pair of profiles. The data is estimated over 50 m depth intervals with the bold vertical line being the mean values and the white area the 95 % confidence interval. A logarithmic axis is used for the dissipation data plotted about a reference level of $\varepsilon = 1 \times 10^{-10} \text{ W kg}^{-1}$, corresponding to the background dissipation level. The acoustic data are plotted with a reference level of -90 db.

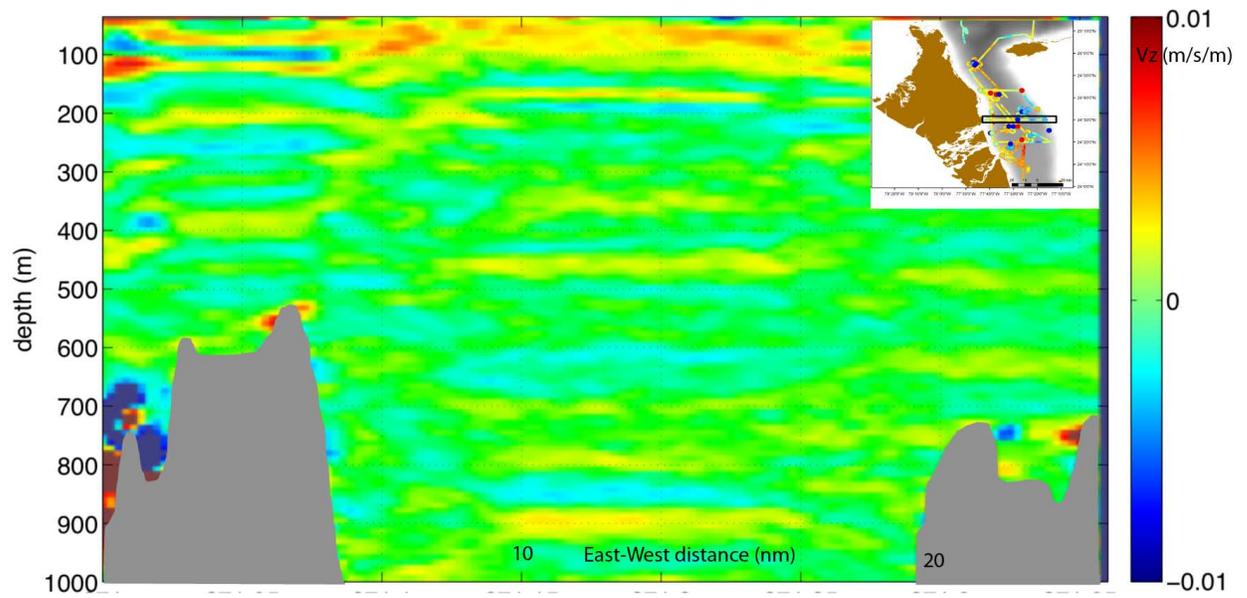


Figure 5. *Shear in the water column generated by using the HDSS ADCP system on the R/V Roger Revelle. The transect represented in the data corresponds to an east-west line across the middle of the TOTO (inset).*

Pilot whale dive record and sampling prey distribution

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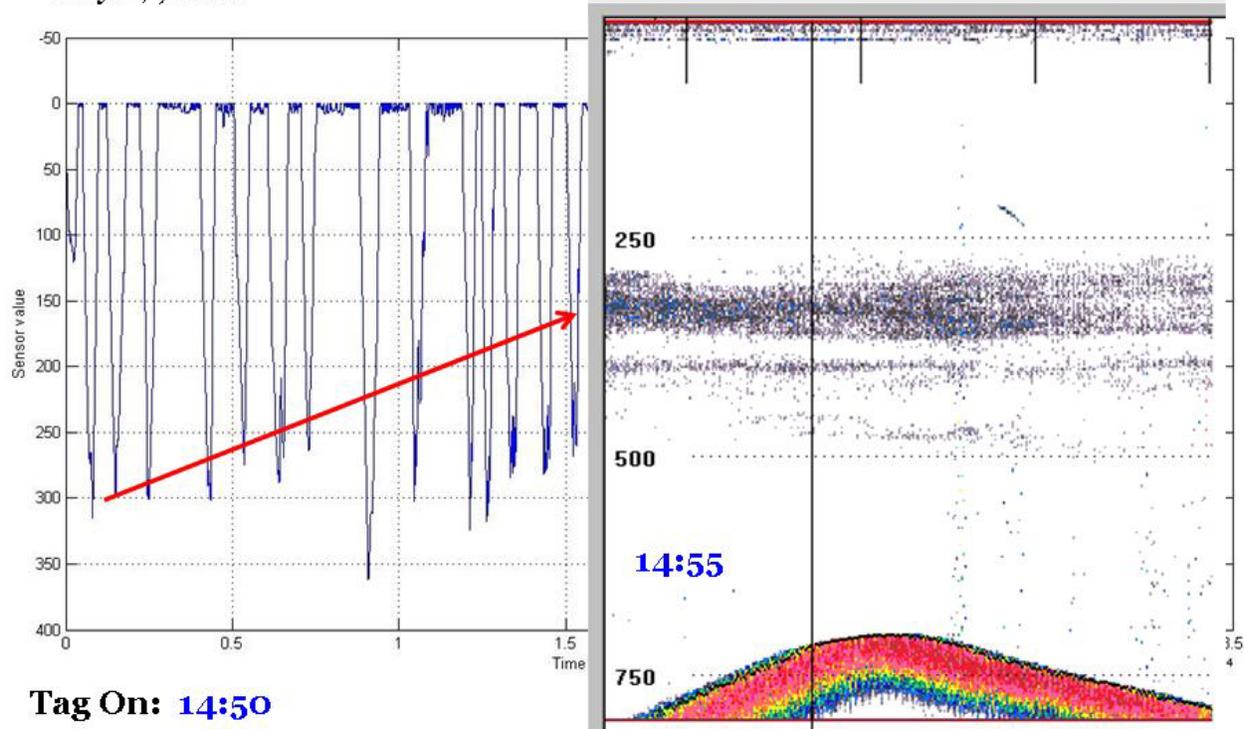


Figure 6. Time-depth records (left) for a diving short-finned pilot whale carrying a DTAG, and water column backscatter (right) generated by the 38 kHz EK60 system aboard the research vessel following the tagged whale at ~500 m. Note the dense layer of prey located at the depth to which the whale is diving; also interesting is the large apparently single target at just less than 250 m depth.