Investigating the Relationship Between Fin and Blue Whale Locations, Zooplankton Concentrations and Hydrothermal Venting on the Juan de Fuca Ridge

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LONG-TERM GOALS

We are investigating the potential correlation between whale tracks, enhanced zooplankton concentrations and hydrothermal vents above the Juan de Fuca Ridge. Our goal is to understand the influences of globally distributed hydrothermal plumes on the trophic ecology of the deep ocean.

OBJECTIVES

We are conducting a retrospective study using existing seismic and bio-acoustical data sets from the Juan de Fuca Ridge with the following four objectives:

1. Implementing an automatic algorithm to track fin and blue whales using data from a small-scale seafloor seismic network.

2. Tracking vocalizing fin and blue whales above the Endeavour segment over a 3-year interval from 2003-2006 in order to determine whether they are preferentially found above the hydrothermal vent fields where the bio-acoustical data show that the zooplankton concentrations are higher at all depths.

3. Analyzing a total of 60 net tow samples from the Endeavour Segment from 1995 and 1996 and combining these with 119 previously analyzed net-tow samples from 1991-1994 to refine our

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14. ABSTRACT
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15. SUBJECT TERMS

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understanding of the variations of zooplankton concentrations at different depths with distance from the vent fields.

4. Using the simultaneous acoustic backscatter and net tow data to calibrate the acoustic observations so that we can make use extensive acoustic Doppler current profiler (ADCP) data sets that already exist for the region (as well as ADCP data that may be collected in the future) to estimate zooplankton concentrations.

APPROACH

From 2003-2006, the W. M. Keck Foundation supported an experiment at Endeavour Segment of the Juan de Fuca Ridge (129°W, 48°N) to investigate links between geological deformation, fluid fluxes through the seafloor, and microbial productivity. As part of this effort, a remotely operated vehicle was used to deploy a network of 8 sub-bottom three-component seismometers (Figure 1) that operated from Summer 2003 to Fall 2006. The initial earthquake analysis showed that the seismic records include a very extensive data set of high-quality fin and, to a lesser extent, blue whale vocalizations. Example of fin and blue whale calls are shown in Figures 2 and 3.
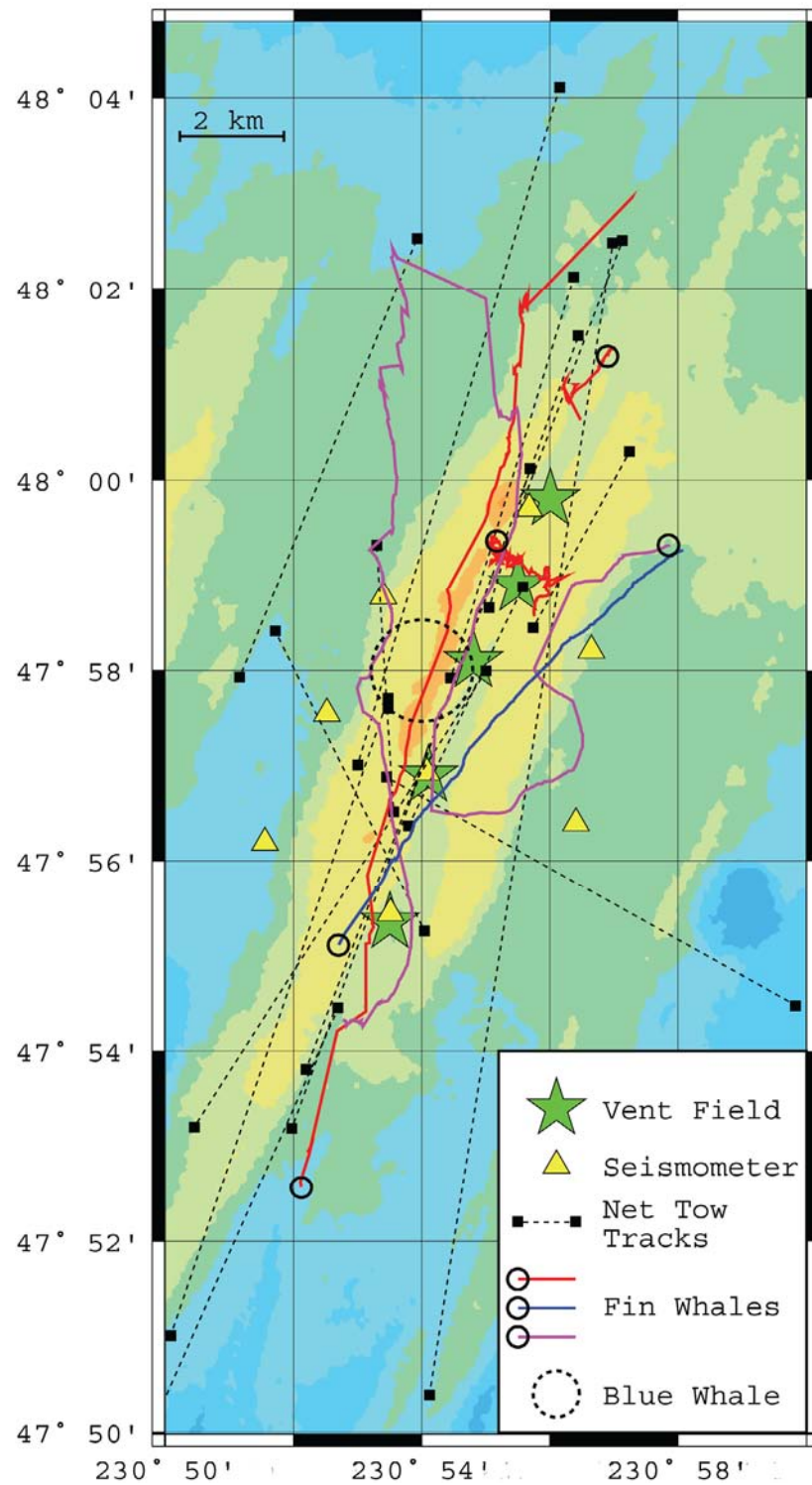
Figure 1. Bathymetric map (color changes every 100 m, blue colors at depths greater than 2500 m) showing the location of the Endeavour hydrothermal vent fields (green stars), seismometers deployed from 2003-2006 (yellow triangles), ship tracks for net tows obtained from 1991-1996. Also shown are some of the preliminary whale tracks that motivated this study
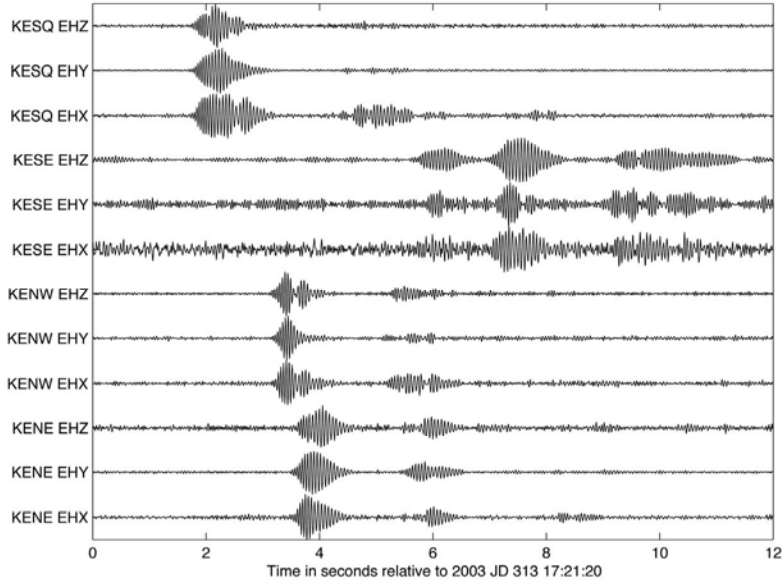
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Figure 2. Example of a fin whale vocalization recorded on four three-component seismometers (the labels EHZ, EHY and EHX indicated the vertical (Z) and horizontal channels (X and Z) of stations KESQ, KESE, KENW and KENE).   The records have been adjusted to equal maximum amplitude. The fin whale was located near the network. Note that the 1st and 2nd water column multiples are clearly visible following the direct arrival.
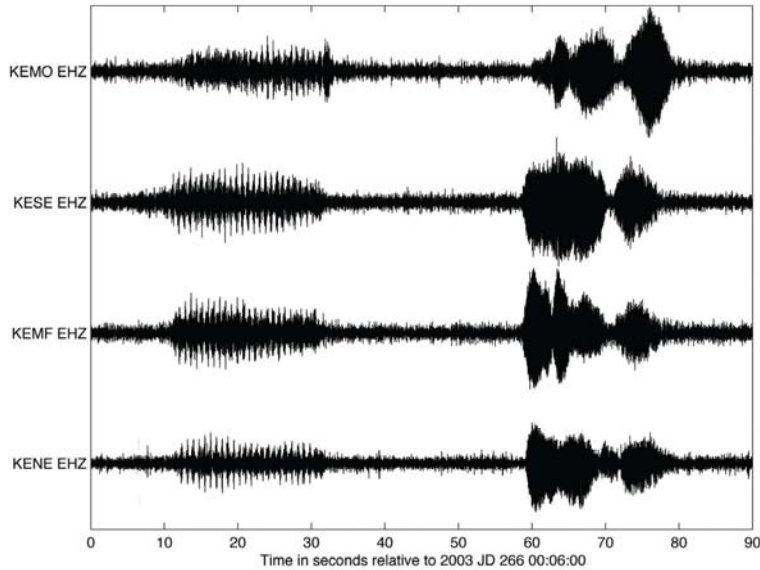

Figure 3. Examples of a blue whale vocalization recorded on the vertical channel of four stations. The "A" and "B" calls are included within the window.

Previous work on the Juan de Fuca Ridge has demonstrated that the fin whales can be tracked to distances of up to 20 km from a seafloor network by incorporating direct arrivals and the 1st, 2nd and 3rd multiples (Figure 4) in the analysis [*McDonald et al.*, 1995; *McDonald and Fox*, 1999]. Our approach

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to automatically tracking whales is to adapt a MATLAB algorithm that we first developed to automatically locate earthquakes [*Weekly et al.*, 2007]. First, we use the ratio of short-term and long-term running RMS averages on the vertical channels of the OBSs, to identify triggers and categorize them as possible whale calls if their spectra are dominated by energy near 20 Hz (local and regional earthquakes tend to have most of their energy below 10 Hz). Second, we find potentially locatable whale calls by finding groups of nearly coincident whale triggers on multiple OBSs. Third, we pick the whale call arrivals and locate them by modeling the arrival times of the direct arrival and water path multiples. To pick the whale arrivals, we calculate an envelope function and pick the arrival at the time where half the energy of the arrival comes before and half afterwards. To locate the fin whales we apply a grid search method using travel times calculated with the ocean acoustical ray-tracing software RAY [*Bowlin et al.*, 1992] to find the location that minimizes the misfit to the other arrival times.
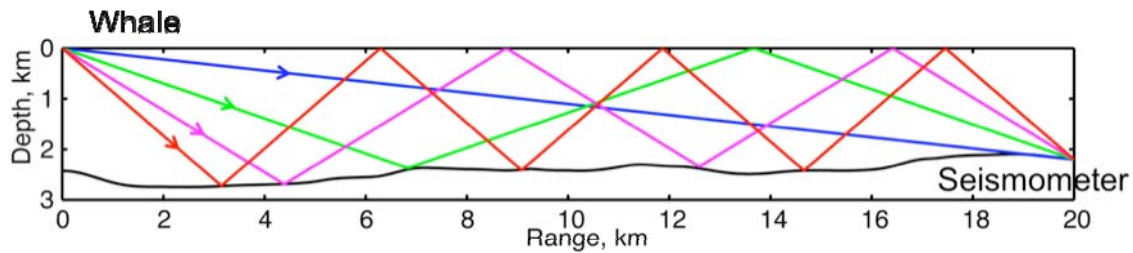

Figure 4. Examples of ray paths between a whale and a seafloor seismometer at 20 km showing the direct (blue), 1st multiple (green), 2nd multiple (purple) and 3rd multiple (red).

In the early to mid-1990s, Richard Thomson and Brenda Burd at the Institute of Ocean Sciences in Sidney, BC conducted annual summer cruises to the Endeavour to collect surface to bottom temperature, salinity, light attenuation and acoustic backscatter intensity measurements that were coupled with a series of plankton net tows. The towed instrument package was designed such that biomass could be sampled at six distinct depths or depth ranges. The locations of net tows are shown in Figures 1 and 5. A total of 119 mixed faunal zooplankton net samples collected between 1991-1994 have been previously analyzed and show an enhanced zooplankton concentrations at all depths above the hydrothermal vent fields in comparison to stations 10 to 50 km off-axis [*Burd and Thomson*, 1994; 1995]. At depth, the zooplankton were concentrated in a 100-m-thick layer of increased acoustic backscatter near the top of the hydrothermal plume at 1.9 km depth [*Burd et al.*, 1992; *Thomson et al.*, 1991a], leading to the inference that the zooplankton were taking advantage of the chemosynthetic bacteria, fine grained particulates and other nutrients carried by these plumes while avoiding the highest concentrations of chemicals in the plume cores. Zooplankton biomasses in the normal near surface scattering layers (< 400 m) were elevated but highly variable [*Burd and Thomson*, 1994]. Community analysis revealed that the deep faunal assemblages above the vents (but not elsewhere) where infiltrated by shallow faunal species including a large number of filter feeding copepods and their predators [*Burd and Thomson*, 1994; 1995]. This suggests that shallow zooplankton migrate vertically between the upper ocean and the hydrothermal plume [*Burd and Thomson*, 1994].
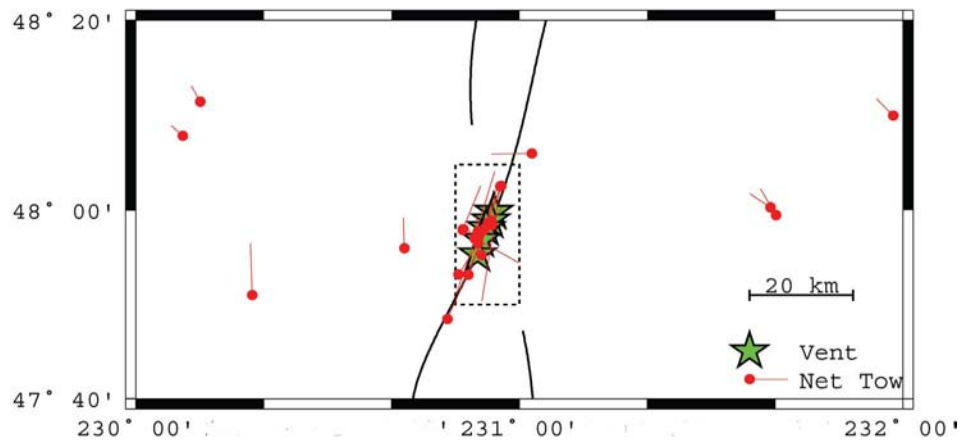
Figure 5. Regional map showing the location of the Endeavour vent fields (green stars), ship tracks for net tows in 1991-1996 (red line with a red circle at the start of the track), the location of the spreading ridge axis (solid line) and the area covered by Figure 1 (dashed line).

We are analyzing an additional 60 net samples that were collected from the area in 1995-1996. For each net sample we know the depth, location and time, and we are in the process of identifying major zooplankton and fish species and determining length, gender, stage of development, and dry/wet biomass. The expanded zooplankton data set can be used to refine our understanding of variations in zooplankton concentrations with distance from the hydrothermal vent fields. We will compare variations in near surface zooplankton concentrations with spatial variations in the incidence of vocalizing whales.

The data we have collected on zooplankton distribution and biomass in the water column overlying Endeavour Ridge are well suited to acoustic calibration of net samples. The ADCP was mounted just below a 330 μm mesh, 1-m^2 opening/closing multiple-net apparatus which was towed obliquely through the water column [*Burd and Thomson*, 1993; 1994]. This configuration produced acoustic and faunal data which were concurrent in both time and space. The attitude sensors and three-dimensional current measuring capabilities of the ADCP allowed us to determine the flow volume through the nets with only 2 to 3% error [*Burd and Thomson*, 1993], and thus, obtain accurate volume-adjusted estimates of the contribution of each acoustic ensemble to the total zooplankton biomass. A close regressional relationship between the biomass and acoustic backscatter (for the specified scattering cross-sectional model) means that profile acoustic data can be used to map three-dimensional distributions of biomass in the vicinity of the ridge without the need for expensive and labor intensive net sampling tows.

WORK COMPLETED

1. *Implementing an automatic algorithm to whales.* William Wilcock has completed the development of an automated tracking algorithm for fin whales using the approach described above. The method was validated against locations determined with manually picked direct arrivals by undergraduate student Elizabeth McHugh. The automatic locations method and some initial results were presented at the Spring 2009 meeting of the ASA [*Wilcock et al.*, 2009]. He has also applied the double difference method [*Waldhauser and Ellsworth*, 2000] to the whale location problem.

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2. *Tracking vocalizing fin and blue whales above the Endeavour segments.* Graduate student Dax Soule has applied the first two steps of the automatic detection and location method to the full 3-year data set to generate a histogram of fin whale calls as a function of time. He has applied the third step to a full year of data, a process that has to date yielded 116 fin whale tracks. These results will be presented at the 2009 meeting of the Society for Marine Mammology [*Soule et al.*, 2009]. He is in the process of completing the fin whale call locations for the remaining two years of data and will incorporate blue whales into the analysis.

3. *Analyzing net tow sample.* The analysis of the 1995 and 1996 macro-faunal data is being undertaken by Val Macdonald (M.Sc.), president of Biologica Environmental Services Ltd., under subcontract to the Institute of Ocean Sciences. There is a major shortage of taxonomists in the world and Biologica Environmental Services has a significant backlog of work. Nevertheless, the analysis is well underway and should be completed by the end of October, 2009.

4. *Calibrate the acoustic observations with net tow data.* Because the analysis of net two data from 1995-1996 has been delayed, Richard Thomson has worked with Dr. Brenda Burd to analyze the 119 tow samples from 1991, 92, 93 and 94.

RESULTS

The seismic network recorded ~400,000 fin whale calls that were of sufficiently high amplitude to trigger at least 3 stations. The distribution of fin whale calls is strongly seasonal (Figure 6) with very few calls in the summer and almost daily call sequences in the winter. There appears to be a significant decrease in the number of calls between 2003-4 and subsequent years.
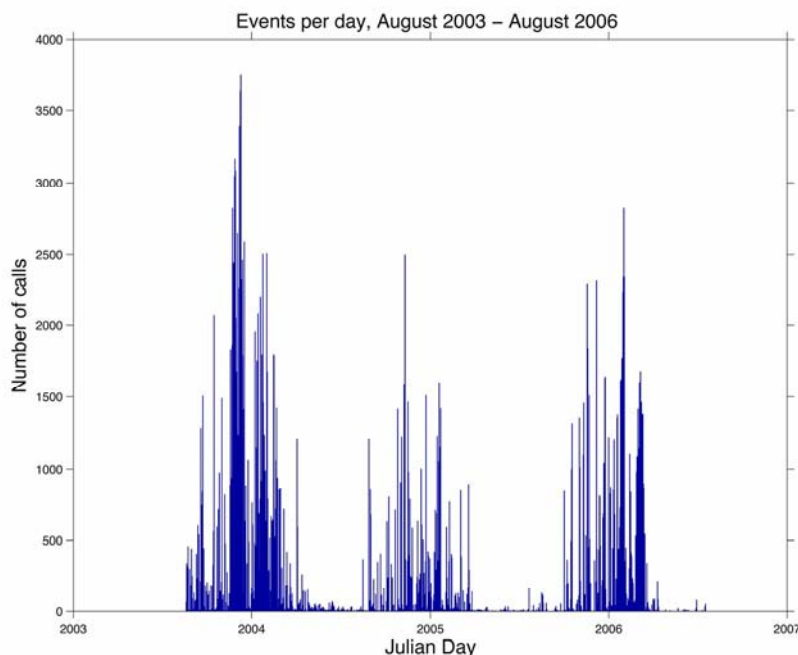

Figure 6. Histogram of the number of fin whale calls
per day detected by the Endeavour seismic network.

The automatic location algorithm typically works well for fin whales located up to about 10-15 km outside the network and is able to generate solutions that fit the observed arrivals quite well (Figure 7). At larger ranges, the signal to noise of the arrivals is smaller and the method often generates alternate locations in which there is one additional water path multiple for each arrival in one solutions – the ambiguity can often be resolved by careful inspection. We are investigating whether the use of relative arrival amplitudes can resolve such ambiguities automatically.

The whale tracks (Figure 8-9) are comprised of sequences of calls that are about 20 s apart and which can last from an hour or two to over 24 hours and can include gaps in the calling of up to several hours. Some of the tracks are quite complex with whales often doubling back on themselves and others are quite simple. We are in the process of determining if there is a seasonal net directionality to tracks and looking for diurnal patterns in calling or track characteristics.

The double-difference technique [*Waldhauser and Ellsworth*, 2000] is a relatively new technique in seismology which allows cross-correlated signals to be located relative to each other with great accuracy. Figure 10 shows two examples of its application to fin whales. Within the network (Figure 10, right) the method is able to resolve a consistent spacing of 40 m between adjacent calls that are 20 s apart indicating that the whale was swimming at 2 m/s or 7 km/hr.
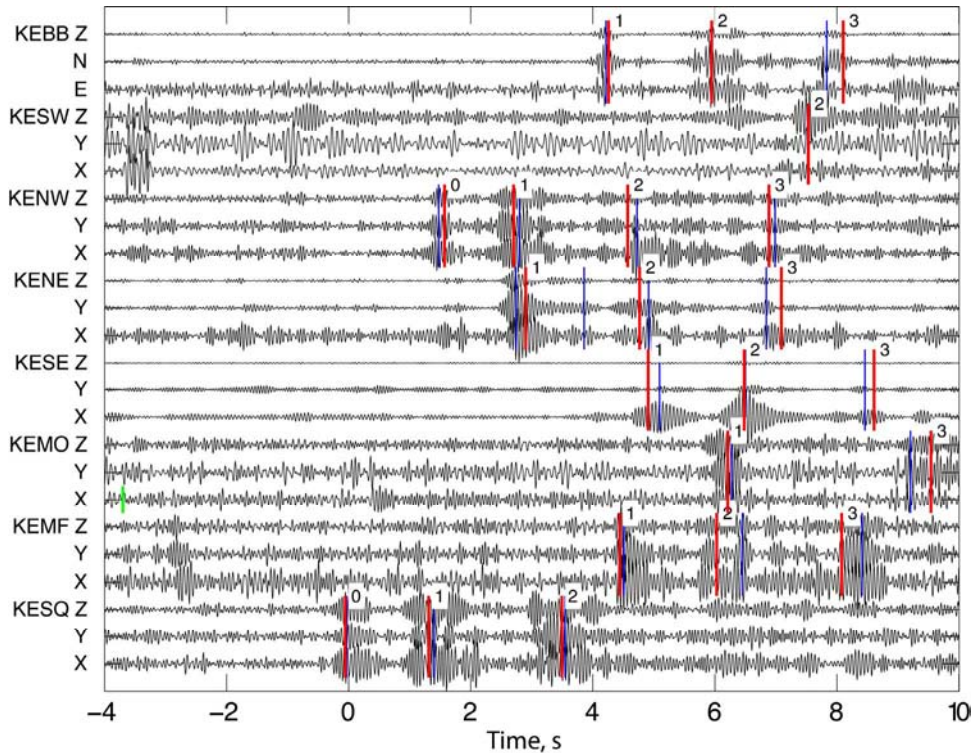

Figure 7. Example of a seismogram for a fin whale call located several kilometers outside the seismic network. Blue lines show the picked times and red lines the predicted times for the grid search location. Numbers indicate the number of surface (or bottom) bounces along the path.
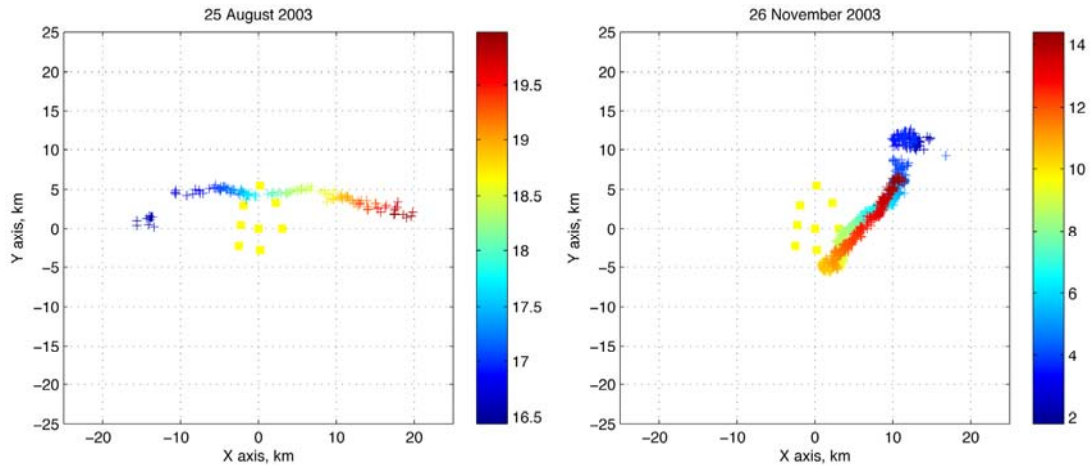
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Figure 8. Examples of individual whale tracks for two days color coded by time (hour of day) with cold colors at the start of the track and warm colors at the end. The origin of the plot coincides with the center of the network and the y-axis for the plot is aligned with the mid-ocean ridge axis. The seismic stations are shown by yellow squares. Note that in the right hand plot the whale reverses course.
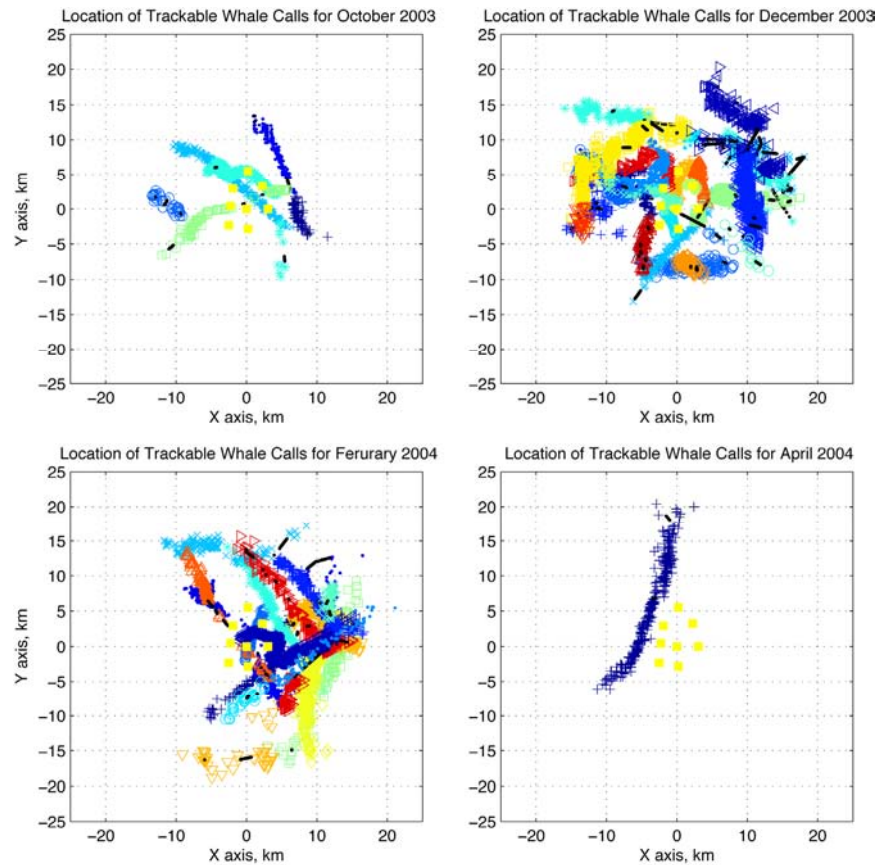

Figure 9. Composite plot of all monthly fin whale tracks for October 2003, December 2003, February 2004 and April 2004. Each track has a different color and black lines are used to connect portions of the tracks where there is a break in calling and the whales position is interpolated.
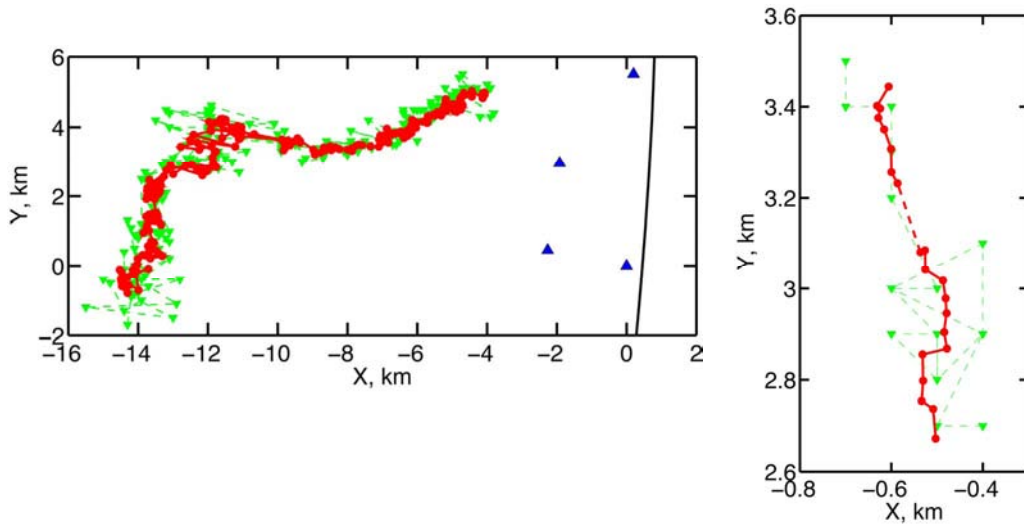
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Figure 10. Examples of fin whale tracks determined by the automatic algorithm (green) and those determined using the double-difference method (red). On the left hand plot seismometers are shown by blue triangles and the ridge axis by a black line. The right hand plot is within the network but the area covered is too small to include any seismometers. The double-difference method dramatically reduces the scatter of locations. Within the network it resolves calls that are 30-40 m apart with relative errors of about 10 m.

Monthly compilations of tracks (Figure 9) and a preliminary call density plot for 2003-4 (Figure 11) shows higher densities near the network as would be expected given the greater sensitivity at short ranges but it is not yet clear whether the whales have an affinity for the ridge. Additional analysis in progress will add tracks for 2004-6 and more tracks for whales between 10 and 20 km from the network.
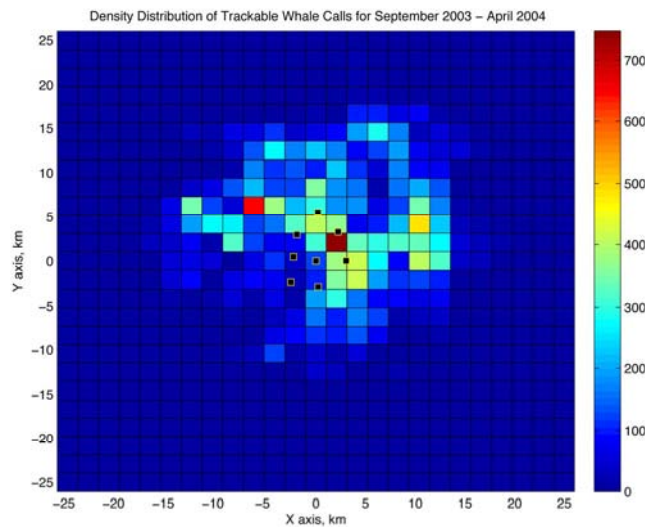

Figure 11. Plot showing the density of whale calls for 2003-4. The color scale shows the number of whale calls located in each 2 x 2 km box during the year. The center of the network is at the origin of the plot and the y-axis is aligned with the ridge axis.

The 119 individual biological net samples for the summers of 1991-1994 were obtained with a towed CTD/ADCP/Tucker trawl system (Figure 12; [*Burd and Thomson*, 1993]). Samples cover the full 2200 m depth range but are focused in the lower portion of the depth range. During each net tow, the downward-looking RDI acoustic Doppler current profiler (ADCP) recorded values of the ensemble-averaged acoustic target strength every 30 s for each of four transducer beams. Although backscatter intensity varies with species and animal orientation, the 153 kHz ADCP typically "sees" animals with length scales $L > 1$ cm. The backscatter intensity is a relative measure of the number of macrozooplankton within a given volume of water.
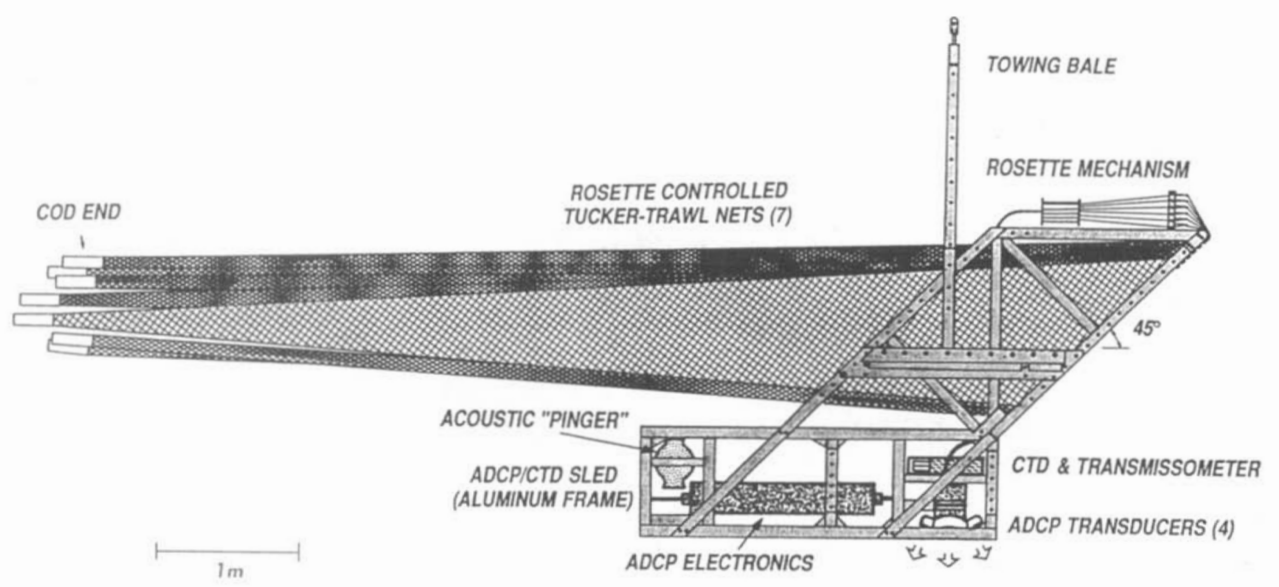

Figure 12. Side view of the net frame and CTD/ADCP package used for oblique tows. During deployment the towing bale is normally at an angle of 37° from vertical when the frame is upright. The net mouth rests at an angle of 45° to horizontal when the device is level (from Burd and Thomson, 1993).

Following Thomson *et al.* [1991b], we standardized our acoustic data for inter-tow comparisons by subtracting the depth-averaged background value of the target strength for each of the four beams to yield a target strength anomaly, TS_k'. By making reasonable assumptions about the relationship between the effective length scale of the scatterers and the instantaneous net biomass m_k, a relationship can be derived relating the total biomass of the tow, M, to the target strength anomaly.

$$m_k = c_2 v_k \left(10^{(TS_k'/10)}\right)^{1/p+q} = c_2 v_k (F_k)^{1/(p+q)} \qquad (1)$$

$$\log M = \log c_2 + \log\left\{\sum_{k=1}^{K} v_k [10^{(TS_k'/10)}]^{1/(p+q)}\right\} \qquad (2)$$

where v_k is the volume of water passing through the net for each ensemble, and c_2, p and q are constants. We use linear regressional analyses of equation (2) to determine which value of $(p+q)$ maximizes the goodness of fit (r^2 value) of the regression. Using an iterative process, the highest variance explained by this analysis was for $p+q \sim 5.55$, which is comparable to the value of 5 suggested by dimensional arguments. The regression of total net biomass, M, against the modeled

target strength (weighted by the water volume passing through the net for each acoustic ensemble) is presented in Figure 13 and accounts for 88% of the variance in the data (adjusted r^2).
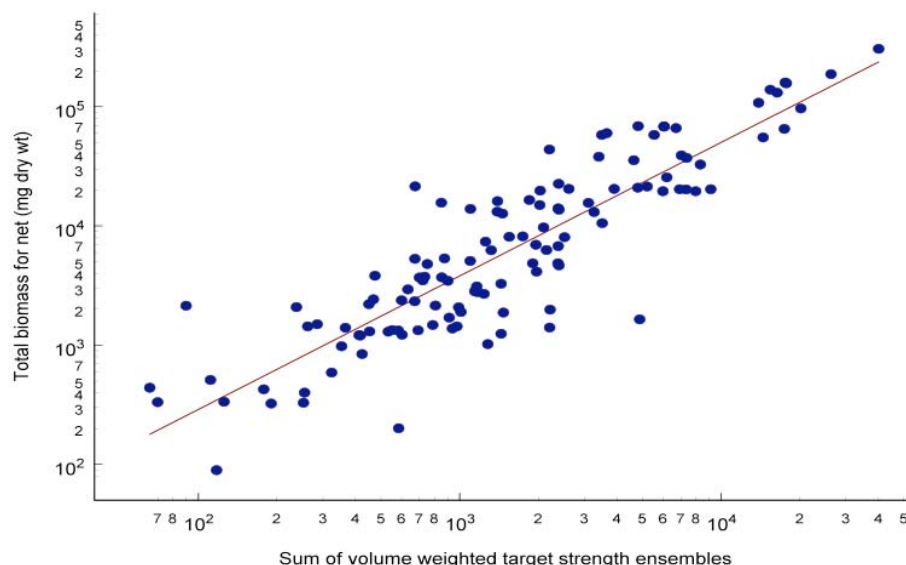

Figure 13. Linear regression of total biomass per net versus sum of volume-weighted target strength over all acoustic ensembles per net based on Model 2 (eqn. 7). Data are plotted on a log-log scale.

We are now analyzing an additional 60 net samples collected in 1995 and 1996. Once the analysis of these biological samples is complete, they will be incorporated in the revised regressional analysis. The results will enable us to use our extensive series of ADCP backscatter data from Endeavour Ridge – collected from the late 1990s to early 2000s – to examine temporal changes in zooplankton biomass in the venting region as a function of depth in the lower 500 m of the water column. The initial focus will be on seasonal and inter-annual variations and possible linkages to hydrothermal activity within the Axial Valley.

IMPACT/APPLICATIONS

We will develop an automatic whale-tracking algorithm that can be applied to other seafloor seismic networks. There is considerable interest and controversy surrounding the effect of academic seismic surveys and some Navy exercises on marine mammals. William Wilcock has suggested to NSF program managers that the US Ocean Bottom Seismometer Instrument Pool (OBSIP) include a subset of instruments that are capable of recording marine mammals at frequencies of up to at least 1000 Hz (enough to record most baleen whale vocalizations).

If our final analysis confirms a close regression relationship between biomass and acoustic backscatter, we will have developed a method to reliably extrapolate limited net tow data to images of the 3-D distribution of biomass. If our study demonstrates a correlation between whale tracks, enhanced zooplankton concentrations and hydrothermal vents it will have implications for our understanding of the global influences of hydrothermal vents on the trophic ecology of the ocean [*Gisiner et al.*, 2009].

The Endeavour segment will be a node on the NEPTUNE Canada regional cabled observatory. In summer 2010 the Endeavour node will be populated with a seafloor seismic network and water column experiments that will monitor deep macrozooplankton concentrations. These experiments could be augmented by deploying shallow moorings equipped with ADCPs to monitor acoustic backscatter intensity in the upper water column. Year round acoustic backscatter and whale monitoring would allow for correlations between individual whale tracks and zooplankton concentrations.

RELATED PROJECTS

The W.M Keck Foundation provided $5M to a group led by John Delaney at the University of Washington to develop prototype observatory experiments to monitor the linkages between seismic deformation, seafloor venting and microbial productivity. William Wilcock was the lead-PI for the seismic component of this project which funded the deployment and operation of the Endeavour seismic network from 2003-6.

NEPTUNE Canada is installing a regional-scale cabled observatory in the NE Pacific Ocean that will become operational in Fall 2009. The observatory includes a node at the Endeavour that will be instrumented in 2010. Rick Thomson at the Institute for Ocean Sciences is the lead PI for a regional circulation experiment that will provide high resolution, near real-time records of current velocity, water properties (salinity and temperature), and macrozooplankton concentrations within the axial valley of the Endeavour segment of Juan de Fuca Ridge.   William Wilcock is a co-PI on a seismic experiment that will occupy five of the sites developed by the Keck experiment (enough to track whales).

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