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**Papers from
the
SUMMER UNDERGRADUATE RESEARCH FELLOWSHIP
PROGRAM IN OCEANOGRAPHY**

at

**THE UNIVERSITY OF RHODE ISLAND
Graduate School of Oceanography
and
Department of Ocean Engineering**

NARRAGANSETT, RHODE ISLAND

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GSO Technical Report No. 2004-01

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SUMMER UNDERGRADUATE RESEARCH
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PREFACE

This report presents the papers written by the 13 participants in the 2003 Summer Undergraduate Research Fellowships in Oceanography (SURFO) program at the Graduate School of Oceanography (GSO), University of Rhode Island (URI). This past summer represented the 18th year in which the program has been coordinated and extended through the several disciplines in oceanography and ocean engineering at URI's Narragansett Bay Campus. The 2003 program continued excellence beyond the official duration of the program with at least one project resulting in a manuscript to be submitted for publication. In addition, five presentations were made at national meetings, including AGU and ASLO.

During the fall of 2002 advertisements were sent to physics, chemistry, biology and geology departments, including faculty advisors at a number of minority colleges.. Flyers and overheads were provided to colleagues presenting invited talks at various undergraduate institutions. The SURFO web site has continued to be updated and more useful links describing possible research programs at GSO/URI have been added. We received 74 applications for the program, and about two-thirds of these applicants used the electronic application form. This represents the third consecutive year that about two-thirds of the students have used the SURFO website to apply electronically. Thirteen students were selected for the program with a breakdown by oceanographic discipline as follows: 4 Geological, 3 Physical, 2 Chemical, 4 Biological. The gender break-down returned to a female majority (9 female, 4 male) and three participants were from under-represented groups in science.

The timeline of the 11-week program was adjusted slightly this year to provide students with an extended orientation period during the first two weeks. This orientation period began with a breakfast to welcome the new students and introduce them to the GSO campus community, and was followed by a tour of the campus and facilities. For the next 5 work days, daily background/introductory seminars were presented by graduate students from the various sub-disciplines of oceanography, including: biological oceanography, marine and atmospheric chemistry, marine geology & geophysics, physical oceanography, and ocean engineering. A cruise on the Narragansett Bay to introduce students to oceanographic tools and several team-building workshops were also held during the first two weeks. During the remainder of the program weekly seminars (on Tuesdays) on "hot topics" in oceanography were presented by a GSO faculty member or marine scientist. Topics such as "Narragansett Bay Circulation", "Life in Extreme Environments", "Kick 'Em Jenny Submarine Volcanism", and "Pollution and Aerosol Transport" were presented. On Thursdays of each week, a professional development workshop or discussion was held to round-out the students experience. Topics such as "learning/research styles", "scientific writing and effective presentations", and "hands-on modeling methods" were provided..

We continued an informal round-table meeting with several faculty members, graduate students and SURFOs to discuss how to get into graduate school and what will be expected of them. We also instituted a similar round-table format to discuss possible careers in oceanography. Our exit questionnaires revealed that students found these seminars interesting and very useful, and the exposure to a wide range of disciplines/research topics helped students identify additional areas of interest. Other undergraduates (NOT affiliated with the SURFO program) working at EPA or NOAA labs on the Bay Campus and even graduate students at GSO also attend many of these seminars.

The heart of the SURFO program is the exposure of the students to conducting authentic research in oceanography. For the 11 weeks of the summer program, each fellow worked on a research project under the supervision of a faculty mentor and a graduate student mentor. The range of research included: 1) using T-phase seismic waves to predict tsunamigenesis; 2) using rotating tables to model ocean circulation related to the formation of ocean fronts and the effect of mid-ocean ridge topography; 3) analyses of sediment geochemistry, paleomagnetism, and deeply buried microbial biomass estimates; and 4) determining the stress response of summer flounder to various hormones. In addition to preparing their

written reports, each SURFO gave a 15-minute presentation at the end of the program to summarize her/his results. The SURFOs found the report writing and oral presentation intimidating initially, but they all agreed that it was a worthwhile experience that helped them summarize and realize the scope of their summer projects. We also continued the 15-minute presentation during the fourth week of the program during which SURFO students presented the scope of their summer project.

Included in the summer events was our annual day of kayaking on the Narrow River, led by Bob Sand, to investigate the flora and fauna of an estuary. A subset of SURFOs also participated in a series of field days funded by other projects where water sampling and fish trawls were made at several locations in Narragansett Bay and Rhode Island Sound. We also continued with our tradition of having an informal noon-time barbecue each Friday for the SURFOs on the veranda at the Horn Lab. This provided the SURFOs with a taste of graduate-student life in an informal setting where they were able to meet with GSO faculty, graduate students and staff. The annual SURFOs vs ADVISORS softball game was won by the advisors, and continued the advisors undefeated streak.

One measure of success of our program is if fellows continue on with graduate studies in science and, specifically, in oceanography or ocean engineering. The exit questionnaire and follow-up conversations indicate that all 13 of the students definitely plan to continue on with graduate studies in science/engineering. Of these, 6 said they are seriously considering oceanography. Three of the students have applied to GSO for the fall 2004 semester, and three others are returning to GSO this summer to continue work on their projects. This continuation of work, however, is not funded by the SURFO program.

The participants in the 2003 SURFO program are grateful to the National Science Foundation for its support of the program through grant OCE-0243794. Jennifer Specker (IBN-0220196) and Yang Shen (OCE-9906902) contributed supplemental NSF funding for undergraduate research for Misty Garcia (JS), Lara Hinkle (JS) and Danielle Stroup (YS). The NASA Astrobiological Institute at GSO/URI (Steve D'Hondt, David Smith and Art Spivack) also provide supplemental funds for Beverly Chen and Uri Manor. The SURFO participants and I would like to thank all of those individuals at URI who contributed to the program's success including those who advised the students and who gave SURFO seminar presentations. In addition, our thanks to Rhonda Kenny and Kim Carey for their assistance in the preparation of this report as well as the administrative, financial and recruitment tasks. Finally, we would like to thank Scott Lundin who served as a graduate coordinator for the program, Friends of Oceanography for providing seminar refreshments, and Bob Sand for running the kayak trip.

Robert A. Pockalny
SURFO Site Director

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The Effect of Saxitoxin Ingestion on the Reproductive Health of *Calanus finmarchicus* after Exposure to *Alexandrium spp*

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Abstract. *Calanus finmarchicus* ingests *Alexandrium spp.* which bloom regularly throughout the spring and summer in the North Atlantic. *Alexandrium spp.* produce a saxitoxin which causes paralytic shellfish poisoning (PSP) which can cause death and sickness to humans via shellfish consumption. The Ecology of Harmful Algal Blooms (ECOHAB) project has been proposed to determine the grazing effects of *C. finmarchicus* on the bloom dynamics of *Alexandrium spp.*, as well as the physiological effects of saxitoxin ingestion on *C. finmarchicus*. As a part of the ECOHAB project, this study aimed to determine the effect of toxin concentration and exposure time on egg production, hatching and development success. Egg production, hatching and development success were measured at set time intervals (2-20days) after rearing *C. finmarchicus* on three diets: treatment 1 was 100 %*Heterocapsa* (control), treatment 2 was 50% *Alexandrium* and 50% *Heterocapsa*, and treatment 3 was 100% *Alexandrium*. Compared to treatment 1, *Alexandrium* exposure consistently lowered egg production rates in treatment 3. *Alexandrium* exposure had an effect in treatment 2; however, the effect was not consistent over time. Using variance analysis, it was determined that exposure to toxin for up to 20 days at the above concentrations had no effect on hatching success or development. It is believed that decreased egg production rates were due to the indirect effect of lower feeding rates and therefore lower body weights in animals exposed to *Alexandrium*. Since no effect of saxitoxin ingestion on hatching and development success was observed, this indicates saxitoxin does not have a direct physiological effect on eggs and nauplii to the third stage of naupliar development in *C. finmarchicus*.

1. Introduction

Alexandrium blooms occur regularly in spring and summer in the North Atlantic. Shellfish and other primary consumers such as Atlantic mackerel [Anderson et al., 1989] have the ability to bioaccumulate this toxin [International Conference on Toxic Marine Phytoplankton, 1991] and cause detrimental effects to higher trophic levels. It has been shown that saxitoxin has adverse health effects on secondary consumers such as humpback whales (*Megaptera novaeangliae*) [Anderson et al., 1989], North Atlantic Right Whales (*Eubalaena glacialis*) [Baumgartner et al., 2002], and humans. It has been observed that endangered North Atlantic Right Whales ingesting substantial amounts of PSP toxin while feeding in the lower Bay of Fundy could suffer from weakening of muscles, respiratory difficulties, decreased reproduction, and mechanical failure [Boudreau, et al., 2001]. The same effects have been seen in humpback whales along with eventual death in the case of the 14 humpback whales found dead in Cape Cod Bay [Anderson et al., 1989]. However, the effect of toxin on copepods, a primary consumer, is not known. Toxin analysis methods will determine if the toxin produced by *Alexandrium* is accumulating in zooplankton tissue. Further investigation by the ECOHAB project will then determine if this accumulation is affecting higher trophic levels. There were many goals to this project which can be

bloom dynamics and the effect of this toxin on higher trophic levels via zooplankton ingestion. This study determined the effect of saxitoxin exposure at varying concentrations for varying amounts of time on egg production, hatching and development success. Beyond these experiments, further work in this project will aid in understanding the role zooplankton grazers such as *C. finmarchicus* play in limiting or proliferating the bloom. Once understood, models will be developed to predict when and why bloom formation occurs and what manipulations will limit or proliferate the bloom. Other major objectives of the ECOHAB project include investigating the extent to which selective grazing is dependant upon the concentration of *Alexandrium* alone or on the concentration of other species of phytoplankton in the water column and mapping the distribution of zooplankton in these areas. The duration of this project is Fall of 2001 to Summer of 2004.

2. Methods

C. finmarchicus collected from the Bay of Fundy were reared on three separate treatments at a constant temperature of 8°C to maintain optimum activity and constant hatching and development periods. *C. finmarchicus* migrated between 6-12°C in the field during July 1-8, 2003. The chosen temperature of 8°C lies within this range in order to simulate field conditions in the lab. The copepods were raised for one week on substantial diets in order to acclimatize the copepods to lab conditions. Treatment concentrations (Table 1) were calculated such that all tanks remain

¹Now at University of Wisconsin, La Crosse, Wisconsin summarized by the need to better understand the biological processes that govern *Alexandrium spp.*

saturated with food for the 20-day duration of the experiment.

Food levels were measured and adjusted on a daily basis to maintain desired concentrations. After 0, 2, 6, 13, 20 days of exposure, 30 females from each tank were placed individually in 25 ml petri dishes for egg laying experiments. The females were incubated in these dishes for a period of 24 hours with eggs being extracted every eight hours to avoid cannibalism. Following the incubation, 150 eggs from each treatment were placed in the incubator for 2.5 days to determine hatching success. Once hatching success was determined the nauplii were incubated for an additional four days to determine success of development to the third naupliar/feeding stage [Cembella et al., 1998; Harris et al., 2000; Boudreau et al., 2001].

The remaining eggs and incubated females at each time increment were sampled in triplicate, flash frozen in liquid Nitrogen and sent to Dr. Allan Cembella at Institute for Marine Biosciences-National Research Council for toxin concentration analysis. Samples were collected from the stock cultures of *Alexandrium* spp. used for feeding as well as from each of the tanks to confirm that the *Alexandrium* cells maintained constant toxicity throughout the duration of the experiment.

3. Results

Egg production rates for treatment 1 remained constant, treatment 2 was variable, and treatment 3 decreased over time (Figure 1). Results from treatment

Table 1. Description of treatments to which *C. finmarchicus* was exposed to for the duration of the experiment.

Treatment	Species	Concentration (cells/ml)	Carbon (percent)
1	<i>Heterocapsa</i>	1000	100
2	<i>Alexandrium</i>	125	50
2	<i>Heterocapsa</i>	500	50
3	<i>Alexandrium</i>	250	100

Figure 1. Population egg production rate of *Calanus finmarchicus* after constant exposure to treatment 1, 2 and 3 of *Alexandrium* for varied amounts of time.

2 and 3 were determined to be statistically different from treatment 1 using a two-way ANOVA and post hoc testing (Table 2, Figure 2). Egg production rates for treatment 2 varied between 25 and 72 eggs/female, and oscillated between highs and lows over time (Table 3). There was a constant decrease in egg production rates in treatment three from 42 to 4 eggs/female.

Population reproduction frequency (PRF) is the number of females out of the females sub-sampled that produce greater than 10 eggs in a 24-hour incubation time. There was a reduction in PRF over time in both treatments 2 and 3 along with lower PRF's than the control at all points (Figure 3).

The results for hatching success indicated that all three treatments have consistent hatching successes as well as no decrease in hatching success over time (Figure 4). This was confirmed by variance analysis (Table 2). Mean percent hatching success for treatment 1 ranged between 92 and 97%. Mean percent hatching

Table 2. P-values and interference terms from the two way ANOVA on egg production rates, hatching and development success for *C. finmarchicus*.

Experiment	Independents	P-value	Interference Term
Egg Production Rate	Treatment Time	0.000 0.000	0.007
Hatching Success	Treatment Time	0.428 0.312	0.144
Development Success	Treatment Time	0.361 0.000	0.494

Treat/Time	Homogeneous Groups
2 A	A
1 A	AB
2 C	AB
1 D	AB
1 B	ABC
1 C	ABC
3 A	ABCD
2 B	BCDE
2 D	CDE
3 B	DE
3 C	E
3 D	E

A = 2 days exposure
B = 2 days exposure
C = 2 days exposure
D = 2 days exposure
1 = treatment 1
2 = treatment 2
3 = treatment 3

Figure 2. Results of post hoc testing on variance analysis of egg production rate.

Table 3. Egg production rates, Population Reproduction Frequency of *C. finmarchicus* when exposed to experimental treatments for 20 days.

Exposure (days)	Treatment	Egg Production Rate	Standard Deviation	Population Reproduction Frequency
0	None	56	42	0.87
2	1	63	45	0.93
	2	72	51	0.93
	3	42	42	0.77
6	1	59	55	0.73
	2	37	38	0.70
	3	15	23	0.48
13	1	52	61	0.83
	2	61	46	0.80
	3	6	10	0.23
20	1	61	50	0.80
	2	25	27	0.60
	3	4	11	0.17

Figure 3. Population reproduction frequency of *Calanus finmarchicus* after constant exposure to Treatment 1,2, and 3 of *Alexandrium spp.* for varied amounts of time.

success for treatment two was 92% at day two, increased, and then decreases to 79% at day 20 (Table 4). Mean percent hatching success for treatment three ranged between 83 and 94%, but followed no consistent pattern (Table 4).

Percent development success is constant for days 2-13, but at day 20 there was a decrease for all 3 treatments (Figure 5). Percent development success for treatment 1 fluctuated between 89 and 94% for days 2-13 and fell to 53% on day 20 (Table 4). A similar pattern was seen in nauplii for treatment 2; however, the fluctuation was between 77 and 95% with a final development success of 46% (Table 4). Finally, treatment three showed a slightly narrower range of 83-89% with a final development success of 53%. All of these treatments were statistically similar (Table 2). This extreme difference over time between days 2-13 and day 20 was confirmed by a post hoc test (Figure 6).

As the experiment progressed, a decrease in activity of *C. finmarchicus* was observed in treatments that were

Table 4. Hatching and development success of *Calanus finmarchicus* after varying days of exposure to toxic *Alexandrium spp.*

Exposure (days)	Treat	Hatching Success (%)	Standard Deviation (%HS)	Development Success (%)	Standard Deviation (%DS)
0	None	82	22	50	33
2	1	92	3	89	1
	2	95	3	77	20
	3	90	9	85	5
6	1	96	2	95	1
	2	95	5	97	6
	3	83	2	83	2
13	1	97	1	94	4
	2	93	2	92	3
	3	95	3	89	3
20	1	91	3	53	7
	2	79	23	46	22
	3	94	5	53	4

Figure 4. Hatching success of *C. finmarchicus* after constant exposure to Treatment 1,2, and 3 of *Alexandrium spp.* for varied amounts of time.

exposed to *Alexandrium*. Along with decreased activity, percent mortality in treatment 3 was twice that of treatments 1 and 2 (Figure 7). In treatment 2 percent mortality was more than that of treatment 1 (Figure 7).

Discussion

Alexandrium exposure significantly impacted egg production rates of *C. finmarchicus* (Figure 1). The strong decrease in egg production rates observed in treatment 3, in which *Alexandrium* was the only available food source, as well as the inconsistent pattern apparent in treatment 2 where a mixture of toxic and nontoxic is suspected to be due to an indirect effect of the toxin exposure to *C. finmarchicus*. Saxitoxin can be detected and avoided by *C. finmarchicus* (Dr. Campbell and Dr. Teegarden pers. com). Decreased food consumption in both treatments 2 and 3 would lead to decreased body weight and health which in turn can

completion of the current cruise. Also, it is possible that the inconsistent egg production rates of females in

Figure 5. Development success of *C. finmarchicus* after constant exposure to Treatment 1,2, and 3 of *Alexandrium* spp. for varied amounts of time.

Time	Homogeneous Groups
6	A
13	A
2	A
20	B

Figure 6. Results from post hoc testing for development success of *C. finmarchicus* over time.

Figure 7. Population reproduction frequency of *C. finmarchicus* after constant exposure to Treatment 1,2, and 3 of *Alexandrium* spp. for varied amounts of time.

treatment 2 could be determined by the tendency to fluctuate between both food sources. For example, females in treatment 2 consumed the most *Alexandrium* between days 1-6, the least amount between days 7-13, and more between days 14-20. The weight observations will be further confirmed by C:N analysis from before the treatment exposure began and from after 20 days of exposure at each treatment.

The PRF from day 2 decreased for all three treatments. Important to note is that the PRF in both *Alexandrium* treatments were lower than the control. This is most likely due to the decreased health of the animals. Evidence of this decreased health is most prominent in the mortality percentages (Figure 7), but is also suspected to be confirmed in the results from toxin and C:N analysis.

Exposure to *Alexandrium* spp. for up to 20 days at the specified concentrations had no effect on hatching success in any of the treatments. Since there is no decrease in percent hatching and development success, it is suspected that *Alexandrium* does not have a direct physiological effect on *C. finmarchicus*. Despite decreased weight and continuous toxin exposure in treatments 2 and 3, the eggs produced by the females were healthy and hatched and developed normally in relationship to the control group. However, there is a remarkably sharp decrease in percent development success in all three treatments at day 20. The cause of this is unknown at this time, but is clear from statistical testing that *Alexandrium* is not the cause. Further investigation is needed. There are a few hypotheses to explain these results: the toxin was not passed from the mother to the egg, the toxin passed to nauplii has been manipulated/mutated to a less toxic form, the development process detoxifies the toxin, the amount of toxin present per egg is not sufficient to change the physiology of the nauplii so they developed normally since they were no longer in the presence of high levels of *Alexandrium*. After toxin analysis the following factors will be known: how toxic the females in each treatment became with time, and how much of this toxin was passed to their eggs. Toxin and C:N analysis will assist in discounting or supporting the above hypotheses.

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Estimation of biomass in deeply buried sediments using adenosine 5'-triphosphate (ATP) assay

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Abstract. Currently, it is estimated that the total amount of the cellular carbon of prokaryotes is ~ 350 to 550 Pg (1 Pg = 10^{15} g), which is equivalent to 60 to 100 % of the estimated total plant biomass on Earth. The majority of prokaryotic biomass is thought to inhabit marine sediments. This estimate is based on direct cell counts, but this method does not distinguish living cells from dead cells. Therefore, an alternate method is desirable because biomass is defined as the total amount of living organisms. We quantified adenosine 5'-triphosphate (ATP) using the luciferin-luciferase reaction to estimate the amount of biomass. Because all living cells contain ATP and it is degraded after cell death, this method does provide a distinction between living and dead organisms. Sediment samples were collected on the Peru Trench (Ocean Drilling Program Leg 201, sites 1230 and 1231) using the drill ship *JOIDES Resolution*. Our estimates range from 7,500 to 110,000 cells/g, which is around two orders of magnitude lower than the estimates from acridine orange direct counts (AODC). This result suggests that current estimates of biomass in deeply buried marine sediments may be too high.

1. Introduction

Prokaryotic biomass is an important component of the total biomass on Earth. Recently, it has been suggested that the majority of the prokaryotic biomass is found in deeply buried ocean sediments [Whitman et al. 1998]. These estimates are based on direct cell counts using the DNA-fluorochrome Acridine Orange [Parkes et al. 2000]. However, there are two problems with direct cell counts: (i) the total amount of sample that can be viewed is small due to the limited depth of focus at high magnification. (ii) It has been shown that both live and dead cells can be stained with DNA fluorochromes [Zweifel and Hagström, 1995]. This is not fitting with the definition of biomass. Therefore, ATP quantification assay is a more accurate method to estimate the total amount of biomass because ATP degrades quickly upon death and this assay provides an independent estimate of biomass from staining.

2. Environmental Setting

Ocean Drilling Program (ODP) Leg 201 site 1230 A ($9^{\circ} 6.7525'S$; $80^{\circ} 35.0100'W$) is located on the lower slope of the Peru Trench [D'Hondt, Jørgensen and Miller et al. 2003]. The water depth above the sediments is 5086 m. This site is in the upwelling zone and therefore highly biologically productive. The depth distribution of subsurface bacterial populations in Parkes et al. [2000] showed that there is high biological productivity at Peru Margin. We quantified the ATP from this site and Leg 201 site 1231 B ($12^{\circ} 1.2640'S$; $81^{\circ} 54.2393'W$) to observe the contrast because site 1231 B is in the deep Peru Trench (maximum water depth is 4813 m) underlying very low biological productivity waters. The two sites are shown in Figure 1.

3. Materials and Methods

3.1. Materials

The cores were collected using the advanced hydraulic piston corer (APC). Whole round cores were cut and immediately kept frozen at $-80^{\circ}C$. There are three main steps in this quantification assay: subsampling, extraction, and assay. The ATP from the sediments was extracted by the extraction mixture developed by Webster et al [1984] and Egeberg [2000]. The extraction mixture contains 0.67M phosphoric acid, 2M urea, 20% DMSO, and 1.6 mg adenosine. Beside the extraction buffer, a strong acidic cation exchanger resin (Biorad AG 50W-X12) and luciferin-luciferase are used. All the tools are flamed and all glassware was soaked in 0.1 M HCl for 24 hours, rinsed with deionized

Figure 1. Map showing all the sites in Leg 201 of Ocean Drilling Program (ODP) including sites 1230 and 1231.

¹Now at Washington University, Saint Louis, Missouri

water, and then dried at high temperature as described in Egeberg [2000]. All disposable microcentrifuge tubes and luminometer cuvettes are autoclaved beforehand. All steps of this experiment are conducted with gloves.

3.2. Subsampling, Extraction, and Assay Procedures

3.2.1 Subsampling Procedures

The sediment cores are originally stored at -80°C to stop the ATP in the cells from degrading. The outer edges of the sediment cores are contaminated by drilling fluid (i.e., surface sea water), so the outer edges (around 2 cm) are cut away by means of a metal saw and a chisel to obtain clean inner cores. All the tools used in this step are flamed beforehand and this step is performed in the laminar flow hood to prevent bacterial contamination. The mini-cores are kept in pre-weighed centrifuge tubes and stored at -20°C to prevent the ATP in the cells from degrading.

3.2.2 Extraction Procedures

Around 2 to 5 grams of the subcore are homogenized with 5 ml of the extraction mixture by a homogenizer. The centrifuge tubes are placed in an ultrasonic water bath for 2 minutes, and then an additional 3 ml of extraction buffer are added. The tubes are covered but unsealed for 5 minutes to allow degassing. The tubes are shaken by a Burrell wrist-action shaker at $200\text{ shakes min}^{-1}$ for 30 minutes. They are kept in a slush ice-water mixture while shaking to maintain at around $0 - 4^{\circ}\text{C}$. Then the tubes are centrifuged at 4°C at 3400 rpm for 35 minutes. Five ml of the supernatant from each centrifuge tube are transferred to a sterile culture tube followed by the addition of 500 mg of the strong acidic cation exchanger resin (Biorad AG 50W-X12) into each tube. The tubes are shaken in a bucket of ice by an orbital shaker. The solution from each tube is then transferred to a new sterile culture tube. A subsample is titrated with 1 M NaOH to adjust pH of the solution to 8.2. The neutralized solution is then stored at 4°C . A little bit of precipitation is observed after the neutralization step; therefore, the samples are centrifuged before ATP measurements. Only the supernatants of the centrifuged samples are used for ATP measurements because the precipitation interferes with and lowers the luciferase activity.

3.2.3 ATP Measurements.

The amount of ATP is measured by using *Photinus pyralis* (firefly) luciferin-luciferase reaction. The amount of light emitted by the reaction is directly proportional to the amount of ATP in the sediment samples. The total cell abundance is calculated assuming $4 \times 10^{-17}\text{ g ATP per bacterium}$ assuming the mean ratio of carbon to ATP is 250 and there is $10^{-14}\text{ g C cell}^{-1}$ [Egeberg, 2000]. There are two advantages of ATP quantification assay: (i) a more accurate amount of living prokaryotic organisms can be measured without including any dead cell population, and (ii) it provides an independent estimate of biomass in deeply buried sediments. All reagents, cuvettes, and the luminometer used in this step were purchased from Turner

Biosystems. The ATP measurements protocol provided by Turner Biosystems is used. For every new bottle of luciferin-luciferase mixture, a blank analysis and a standard analysis are done to correct for the difference in the activity of the luciferase from different bottles. In the blank analysis, 50 μl of deionized water, 50 μl of ATP releasing reagent, and 50 μl of ATP HEPES buffer are added. Then 100 μl of luciferin-luciferase reagent is injected by a constant-rate liquid-tight and gas-tight syringe (Hamilton). In the standard analysis, everything is the same as the blank analysis except 50 μl of ATP working standard mixture is used instead of 50 μl of ATP HEPES buffer. In the sample analysis, 50 μl of ATP releasing reagent and 50 μl of the extracted sample are allowed to stand for 15 seconds before the ATP HEPES buffer is added. After that, 100 μl of luciferin-luciferase reagent is injected to the solution. The concentration of ATP in the cuvette is calculated by the following equation:

$$\text{ATP}_{\text{sample}} = ((R_u - R_b)/(R_s - R_b))(\text{ATP}_{\text{standard}}) \quad (1)$$

Where:

R_u – relative light units from sample

R_b – relative light units from blank

R_s – relative light units from standards

Cell abundance is then calculated by assuming that an average of $4 \times 10^{-17}\text{ g ATP per bacterium}$.

4. Results and Discussion

Four assumptions have been made in this experiment: (i) all cells contain ATP; (ii) ATP quickly degrades upon cell death; (iii) average bacterium contains $4 \times 10^{-17}\text{ g of ATP}$; and (iv) the method is robust over various sediment types and cell concentrations. To examine whether the third assumption is appropriate, the calculation of ATP concentration in cells with different size is done in Table 1. The number of ATP molecules in the biggest assumed cell size is enough to produce energy for normal metabolic activities. A standard curve is plotted to act as a calibration curve because the concentration of ions and the components of the sediments are different and the luciferase is sensitive to these factors. It is plotted by adding different amount of ATP standard solution with the same amount of deionized water, ATP releasing reagent, and luciferin-

Table 1. Different amount of ATP concentration and number of ATP molecules in the cell corresponding to different cell size. We assumed that average amount of ATP per bacterium is $4 \times 10^{-17}\text{ g}$. The ATP concentration decreases with increasing cell size.

Cell Size (mm)	ATP Concentration (mol/L)	ATP Molecules in the Cell
0.5	3.830	2.31×10^{24}
1.0	0.479	2.88×10^{23}
1.5	0.142	8.55×10^{22}
2.0	0.060	3.61×10^{22}

Figure 2. Standard curve calculated by assaying different concentration of ATP standard solution with the same amount of luciferin-luciferase mixture.

luciferase solution (Figure 2). The R^2 value for the graph is 0.9967.

There are three curves on the graph for the sediment profile of site 1230 (Figure 3). The AODC analyses were done on board. It is on average two orders of magnitude higher than the total amount of cells calculated by ATP measurements. This suggests that AODC is overestimating the amount of living cells underneath the seafloor. The number of dividing cells was also counted on board. The number of dividing cells is a good indicator of cell growth and therefore shows that those cells are metabolically active. It should be lower than total cell counts because the M phase only occupies a portion of time of the cell cycle. In the graph of site 1230 (Figure 3), most of the data of the number of dividing cells is around one order of magnitude higher than the number of cells calculated from ATP measurements, but some of them are the same (at 65.5 mbsf) and some of them, especially in the deeper part of the sediments, are lower than ATP measurements (at 232.55 mbsf, 244.54 mbsf, and 257.7 mbsf). In the graph for the sediment profile of site 1231 (Figure 4), the amount of cells calculated from ATP measurements is generally three orders of magnitude lower than the total cell counts by AODC and is around two fold lower than the amount of dividing cells.

We were expecting that the curve of ATP measurements should be in between the curve of total amount of cells and the curve of number of dividing cells; however, this is not the case. It is not clear why the number of dividing cells is mostly higher than the ATP measurements.

The average viable cell counts in open seawater range from 700,000 cells/ml to 1,000,000 cells/ml. In Leg 164, site 994, the cell counts range from 1×10^8 to 1×10^9 cells/ml of sediments. However, our results in site 1230 range from 7,500 to 110,000 cells/ml; this is a lot lower than what has been shown before and provides us a completely new view on life abundance in deeply buried sediments.

5. Conclusion

There are two implications for this experiment: (i) prokaryotic biomass is much lower than current estimates, and (ii) cell-specific activities are more consistent with those observed from other systems. It is not clear why the number of dividing cells is higher than the total amount of cells calculated from ATP quantification, so we need more replicates to confirm our results. In the future, more precise tools to conduct these assays are required and a more appropriate ATP

Figure 3. Sediment profile of site 1230. There are three curves on this graph: Total cell abundance estimated by ATP (open circles), acridine orange direct counts method (open squares), and number of dividing cells (open triangles).

Figure 4. Sediment profile of site 1231. There are three curves on this graph: Total cells abundance estimated by ATP (open circles), acridine orange direct counts method (open squares), and number of dividing cells (open triangles).

per cell conversion factor for the prokaryotic cells in deeply buried sediments has to be determined.

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The Effects of Topography on the North Atlantic Current

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Abstract An experiment by Bower et al., 2002, found that floats released into the North Atlantic Current had a tendency to cross the Mid-Atlantic Ridge at fracture zones especially the Charlie-Gibbs and the Faraday fracture zones. This result led to the idea that topography has an effect on the path of currents. Using a rotating table and various models of fracture zones, we found that topography has a great effect on the route of the current. But more interestingly, it is more than the mere breaks in the ridge that attracts the current; it is whether or not there is a constant f/h path and friction that determines how well the fracture zone will work as a path.

1. Introduction

The warm waters of the North Atlantic Current travel up the eastern coast of the United States across the North Atlantic towards Europe and Iceland. In the midst of its travels, the North Atlantic Current must intersect the Mid-Atlantic Ridge. A study by Bower et al [2002] found that subsurface floats released into the North Atlantic Current had a tendency to cross the Mid-Atlantic ridge at fracture zones. The two fracture zones with the most float traffic were the Charlie Gibbs and the Faraday Fracture Zones [Bower et. al., 2002]. These finding were very interesting and led us to ask why would the North Atlantic Current prefer to cross at fracture zones? How does topography affect the North Atlantic Current? And does the North Atlantic Current split to cross the Mid-Atlantic Current at the Charlie Gibbs and Faraday Fracture Zones?

2. Experimentation

To explore these questions, we performed laboratory experiments on a rotating table with a circular tank, one meter diameter and forty-five centimeters tall, placed on the table. In one of its three 120° pie shaped sections a source was placed on the left or west wall of the tank and a sink on the right or east wall of the (Figure 1). A pump drove the water through the source and sink at a rate of 2.41 ml/sec. The table was filled with six centimeters of water and then spun at $\omega=1.64$ radians/second or 3.28 seconds/rotation. At this rotation rate, the Ekman layer, $d=\sqrt{\nu/2\omega}$ where ν is the viscosity, approximately one millimeter thick. When the table is spinning, the water surface takes on a parabolic shape with the water at the center, or north, of the tank measuring four centimeters in depth and the water at the outside, or south, side of the tank measuring eight centimeters. In each run of the experiment, the pump was turned on and the table was allowed to spin up for forty-five minutes so that a steady flow pattern could be established in the rotating system. A blue dye made of water and food coloring was then added to the water through a pair of valves to make the current visible. The dye was made with as little food coloring as possible so that the density of the dye was roughly the same as the

Figure 1 An aerial view of the tank.

water to keep it from stratifying.

The experiment consisted of four parts. The first part was a control study, to create a simple zonal flow. After the water had reached solid body rotation, the zonal flow was established and dye was injected. We allowed the current to develop without any interference.

The second stage of the experiment involved towing a ridge across the tank from south to north (from the outside wall towards the apex of the tank). We made two ridges; one 3cm high x 9cm long and 1.5mm wide and the other 3cm x 12cm. The two different sizes were used to see if the size of the ridge affected the current. For each run we first bring the table to equilibrium rotation then turn on the dye and waited until the dye marks the zonal flow across the tank before we would start to pull the ridge across. Because the motor pulling the ridge could not be geared down enough, we had to position the ridge in steps and let the current reestablish itself by waiting a few minutes. We took pictures roughly every thirty seconds to a minute depending on the run.

For the third and forth parts of the experiment we used stationary ridges that went the entire way across the tank from north to south. The ridges were forty-five centimeters long, two centimeters high at the north end and four centimeters high at the south end. These ridges were cut at an angle so that the top of the ridge was

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roughly at half depth throughout the tank since the water takes on a parabolic shape while spinning. We made three different ridges. One had two equal sized fracture zones. A second had three equal sized fracture zones. The third had a short, wide fracture zone on the south side and a tall, thin fracture zone on the north side (Figure 2). We also cut the middle fracture zone on the ridge with the three equal fracture zones so that was open. For another variation we built a ramp up to the short wide fracture zone. We varied the position of the sink to see how or if it affected the current. Again the tank was allowed to spin for 45 minutes, the dye was turned on and a picture was taken every one-and-a-half minutes.

3. Results

The first experiment was the control experiment. The current followed a constant radius or "latitude" line, on both the source and the sink were located (Figure 3). The current was much more defined at the sink rather than at the source. That information travels from the east to the west, or sink to source. The dye took a little more than fifteen minutes to cross the tank given a current flow rate of 2.41 ml/sec, neglecting diffusion of the dye.

Figure 2 Diagrams of stationary ridges.

Figure 3 The zonal flow going from the source (right) to the sink (left).

We observed several runs with both sizes of the towed ridge and observed similar results. With the towed ridges, there were very interesting results. Originally we started the ridge against the outside wall perpendicular to the current's path. But this proved to be a problem when the "zonal" current headed straight for the ridge. We could not begin with the position of the ridge inside the current because the experiment could not start from the control situation of a zonal flow. After trial and error we found that we had to rest the ridge along the outside wall parallel to the zonal current and pull it out with the motor once the zonal current was established.

As we pulled the ridge, the current reacted to the ridge in four different ways. First when the ridge was a quarter to a third of the way into the current, the current would bend around the north end, or top, of the ridge (Figure 4a). Once the ridge was in the center of the current, the current would intersect the center of the ridge, then bend and go around both ends of the ridge, with a stronger current on the south side of the ridge (Figure 4b). And finally as the ridge exited the boundary of the zonal flow, the current flowed around only the south corner or bottom of the ridge (Figure 4c).

One of the most curious results happened when the ridge was completely out of the current. Once we had finished pulling the ridge through the current, we pulled the ridge half way between the current and the center of the tank to see if and how the current would reestablish itself. The current did indeed reestablish its zonal flow, but the interesting part is that two or three "fingers" of current would break off of the main zonal flow and head straight for the center of the ridge (Figure 4d). This was quite interesting and not anticipated at all.

The third experiment had quite interesting results. We had three different stationary ridges, each ridge have a different amount and sizes of fracture zones, and positioned the sink in four different places along the eastern wall. Even though we used different ridges and had different positions of the sink that spanned most of the eastern wall, our results were all quite similar. In each case, three small currents leave the source and head towards the ridge. The fingers would head dead center between two fracture zones. None of the current branches headed straight for a fracture zone. Usually, one of the three branches was along the outside wall of the tank (Figure 5). Although there must be a flow of water across the ridge because of the pressure gradient created by the source and the sink, we did not observe any of the dyes water crossing the ridge. It appears that water crossed the ridge either by "leaking" via the viscous Ekman layer over the top or at the end of the ridge where the ridge met the outer wall of the tank. In this case only a smaller blue dyed water column would get over, making it appear as if no dyed water made it.

During the fourth set of experiments, we attempted to get the current to cross the ridge at the fracture zones. Our first attempt was to build a small ramp of modeling clay on the west side of the ridge. We intended that the ramp create as close a constant f/h path as possible. We built the ramp up to the short wide fracture zone on the ridge with the tall thin and short wide fracture zones.

Figure 4 The progression of the towed ridge in the current. a) The ridge is entering the current from the south and the current bends around the north corner to get around. b) The ridge is in the middle of the flow and the current goes around both ends, mainly the southern end. c) The ridge has exited the current and the zonal flow is reestablished. d) The ridge is completely out of the newly reformed zonal flow and "fingers" of current break off and head for the ridge.

Figure 5 The stationary fracture zone with three equal sized fracture zones marked by the black boxes.

Figure 6 The current goes through the middle, but out fracture zone marked by the white box and the other two regular fracture zones marked by black boxes.

The current climbed up the ramp and a small stream of blue dye crossed the ridge at the fracture zone. But again we had the branches of current that would go to the center of the two fracture zones and then make its way to the ramp.

For our second attempt we cut out the bottom of the middle fracture zone from the ridge with the three equal sized fracture zones. Again, we observed the same three current fingers as in the previous experiments. In this case, however, the finger that was just south of the open fracture zone hit the wall, traveled north along the wall, bent around the corner, went south to a point more south than where it intersected the ridge on the opposite side, and continued to the sink (Figure 6).

We made a second gently sloping ramp on both sides of the ridge to minimize the change in f/h throughout the tank. On this second attempt with the ramp, the current went up the ramp on the west side, following the path of constant height, or as close to it as possible, through the fracture zone and down the east side of the ramp, also following the path of constant height (Figure 7).

4. Discussion

The results of the experiments were quite interesting. We originally thought that the interaction between the

Figure 7 The stationary fracture zone with the white box marking the tall slender fracture zone and the ramp going up to the short fat fracture zone. The black line shows the path of the current.

ridge and current could simply be explained with Kelvin and planetary waves. We realized while analyzing the data that the explanation for the behavior of the current is found with Taylor columns and the conservation of potential vorticity. Although we could not explain the current in the experiments from solely planetary and Kelvin waves, they were present at one time. We assumed that because the table is spun for some time before the experiment is run, it should be viewed as a steady state problem.

The Taylor-Proudman Theorem states that when a fluid is rotating, it moves in columns that are parallel to the axis of rotation. This water column moves as a solid body that can not go over obstacles or change length. The column as a whole goes around obstacles or needs a gently sloping ramp or friction to get over it. This explains why the current would not go past the stationary ridge. The current could not even go over the small piece of ridge that was under the fracture zone because it involves a change in depth. The small section of ridge under the fracture zone was as big of a blockade as the larger section of the ridge because a fluid column would have abruptly to change its length and would be unable to conserve potential vorticity.

Potential vorticity is defined as $(f+\zeta)/h$ where f is the planetary vorticity from the rotating tank, ζ is the relative vorticity that the current creates to conserve the potential vorticity, and h is the height of the water. The tank is at constant f , which is evident because of the parabolic shape of the water, so the only things that can change are h and ζ . When the current has to travel to a lesser height to get across the ridge, it must add a negative vorticity to keep potential vorticity conserved, and visa versa. The vorticity adjustment, ζ , that the current makes to conserve potential vorticity has two parts. There is the shear vorticity and the curvature vorticity. Another part of the changing ζ is friction [Pond 1983]. This is how the flow across a blocking ridge might be explained, but more detailed experimentation needs to be done to get a better look at the shear and curvature vorticities at turning points around the ridge, perhaps with the Particle Imaging Velocimetry (PIV) system.

We could not get the current to cross the ridge without the fracture zone going completely to the bottom, or having a ramp, which leads to another complication to our problem, stratification versus non-stratification. If the water is stratified, the bottom layer of water will feel the fracture zone, and not be able to cross its barrier while the top layer will not feel the fracture zone and is free to cross anywhere. The entire column of non-stratified water feels the fracture zone, but is unable to cross it due to the Taylor-Proudman Theorem. Since the water in our experiment was non-stratified, our current felt the steps, or partial ridges and therefore could not cross them. There are now two issues: one, what happens in the tank and two what are the oceanographic connections. In the tank we suspect that frictional effects become important, perhaps through the Ekman layer. With respect to why the floats crossed the Mid-Atlantic Ridge at the fracture zones is that the warm stratified North Atlantic Current is leaning against the cold non-stratified Labrador Sea water. Since the Labrador Sea water is non-stratified, it is confined to the path provided by the fracture zones. The Labrador Sea water guides the North Atlantic Current to the fracture zones. The bottom layer of the North Atlantic Current feels the fracture zone but can not go through it while the top layer is free to go through where ever it chooses. The Labrador Sea water could guide the floats in the upper layer of the North Atlantic across the fracture zones [Bower, 2002].

Although the experiments gave different results from what we expected, they were very informative. Currents are indeed guided towards fracture zones. It is the makeup of the fracture zone, the presence or absence of stratified water and its shape that determines whether it presents a significant opening in the ridge. We also have questions concerning how the flow satisfies the pressure gradient across the ridge for the homogeneous or non-stratified case. We hope to conduct more experiments to get a more quantitative picture of the current and the water around it.

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Measurements of Vertical Mixing in Narragansett Bay From a Towed Instrument

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Abstract. Measurements of vertical turbulent mixing and currents were made using a towed instrument and a 600-kHz ADCP in the mouth of the Narragansett Bay. A wide range of sensors, including temperature, pressure, and microconductivity sensors, were mounted on an Acrobat, a depth-programmable winged structure, and towed over the full tidal cycle on July 18, 2003. Data were collected from across the mouth at depths of 0m to 25m at a constant speed of 5.5 knots. Microscale conductivity fluctuations were used to determine temperature variance dissipation rates (χ_T), which in turn was used to calculate eddy diffusivities (K_T) along the transect. The eddy diffusivities are examined in conjunction with temperature, salinity and density (σ_T) profiles of each section in order to identify vertical turbulent mixing regions and characterize them. Two main mixing regions appear in the mouth of Narragansett Bay, one near Beavertail Point, the other near Brenton Reef.

1. Introduction

A limiting factor in the study and modeling of estuarine environments has traditionally been a relatively poor understanding of fine-scale vertical turbulent mixing. The dynamics of Narragansett Bay is an example of this situation. Kincaid et al. [2003] point out that while numerous physical, chemical, and biological processes have been the focus of study in the Bay, the dynamics are still not well understood. Despite various studies of estuarine dynamics cited in Peters [1997], it is clear that vertical mixing remains one of the topics most in need of further research. Peters and Bokhorst [2001] point out that there are very few field measurements of vertical mixing in estuarine environments.

The ability to model hydrographic behavior of estuaries is particularly limited by the inability to resolve small-scale mixing events. As a result, the better understanding of turbulent mixing events in estuarine environments such as the Narragansett Bay will aid in better hydrographic models. More accurate models will help provide a better understanding of ecological and biological dynamics in the Bay and similar estuarine areas.

Coastal areas are statistically more likely to support humans. Gross and Gross [1972] quote coastal areas as being home to almost 60 percent of the world's population, including many of the largest, fastest growing cities in the world. The ecological relevance of studying dynamics is clear; a better understanding of nutrient fluxes helps interpretations of bacteria and algal behavior. The distribution and dispersion of wastewaters is also an especially important question near human habitats. In modeling the dynamics of estuaries vertical turbulent flux must be parameterized using eddy diffusivity,

$$F_H = -K_T \frac{\partial \bar{T}}{\partial z} \quad (1)$$

While vertical temperature gradients are relatively easy to measure, eddy diffusivities must be parameterized using models guided by observations, such as those taken in this experiment. One of the goals of this project is to characterize eddy diffusivities at the mouth of Narragansett Bay over a tidal cycle.

The thermal inertia of thermistors prevents direct measurement of microscale temperature microstructure. Temperature microstructure is key in finding eddy diffusivities so a way around the problem of thermal inertia was found. Microscale measurements were made using a fast response conductivity probe with the knowledge that conductivity gradients can be mapped to temperature variance dissipation rates, an intermediary to eddy diffusivities [Washburn et al., 1996].

The role of this descriptive paper is to analyze data on vertical mixing and corresponding hydrography of a well-mixed estuary, Narragansett Bay. To this end, we will compare results of our data to results of Peters [1997] and Kincaid et al. [2003] as well as make any relevant observations of our own. After a brief explanation of the data collection methods we will present observations on the data followed by a summary and comparison to previous data.

2. Experimental Description

The data presented in this paper were collected between 11:00 and 21:00 UTC of July 18 of 2003, three days before neap tide. The microstructure profiler used was the TOMASI (manufactured by RGL Consulting), based on the towed instrument of Wolk and Lueck [2001] and carried aboard an undulating vehicle (Acrobat). The Acrobat was towed 80 meters behind the ship using faired Vectran cable that transmitted the data from the Acrobat to the ship along eight conducting wires. The boat traveled at a constant 5.5 knots and the Acrobat oscillated with a period of roughly two minutes. The Acrobat sampled continuously from the surface to 5 meters above the bottom in water ranging in depth from 15 to 30 meters. The transect was 5.75 kilometers long and lay along the $71^\circ 26.5'$ N line of latitude,

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Figure 1. Bathymetric chart of Narragansett Bay showing the location of the surveyed transect.

approximately 750 meters south of Beavertail Point at the mouth of Narragansett Bay (Figure 1). The Acrobat carried two thermistors, two shear sensors, two pressure sensors, an accelerometer, a SeaBird SBE7 microconductivity sensor, a SeaBird SBE3 temperature sensor, a SeaBird SBE4 conductivity sensor, a fluorometer, a transmissometer, and a dissolved oxygen sensor. There was also a 600-kHz Acoustic Doppler Current Profiler (ADCP) mounted on the boat. Only data from the SeaBird sensors, pressure sensors, and the ADCP are dealt with in this paper.

The SeaBird temperature and conductivity signals (sampled at 32 Hz) were transformed to real units using calibrations supplied by Seabird Inc. Microconductivity from the SBE7 (sampled at 1024 Hz) was calculated by calibrating it against the SBE4 sensor. Data from the ship's GPS were logged allowing the construction of temperature, salinity, and density (σ_T) sections across the Bay mouth. Washburn et al. [1996] presented a method for estimation of the rate of temperature gradient variance dissipation (χ_T) from conductivity measurements:

$$\chi_T = 2 * \kappa_T \left(\overline{(\partial T' / \partial x)^2} + \overline{(\partial T' / \partial y)^2} + \overline{(\partial T' / \partial z)^2} \right), \quad (2)$$

Assuming that fluctuations in the temperature variation dissipation rate are isotropic, this can be approximated by:

$$\chi_T = 6 * \kappa_T \overline{(\partial T' / \partial z)^2}, \quad (3)$$

where K_T is the molecular diffusivity for heat. Due to time constraints we calculated the arithmetic variance over one second rather than by integrating the temperature variance spectrum. This approach does not take instrument noise into account, but it does provide a good working data set. Calculations of eddy diffusivity, K_T , were made using the Osborn-Cox model for diapycnal heat flux [Gregg, 1987],

$$K_T = \frac{\chi_T}{2 \left(\partial \bar{T} / \partial z \right)^2} \left[m^2 s^{-1} \right]. \quad (4)$$

3. Observations

The darker line at the bottom of each plot represents the ocean floor and the thinner oscillating line (when present) represents the undulating track of the Acrobat. To provide geographic reference, the “bump” at 2.5 km relative distance is the end of Beavertail Point and marks the separation between the East and West Passage. However, there seem to be three distinct regions along the transect; the first is the West Passage, second is the portion of the East Passage that lies between the Beavertail bump and the second visible bump at 4.25 relative km, and the third region is the East Passage, east of the second bathymetric bump. For simplicity these regions will be referred to as regions 1-3, respectively (seen in Figure 3). Predicted high tide was at 16:05 UTC and predicted low tides were at 9:26 and 21:44 UTC.

3.1. Current Profile

The current profile through the course of the tidal cycle exhibits the behavior described by Kincaid et al. [2003]. In general, the flood current was strongest and occurred earlier deep in the East Passage and the ebb tide was surface intensified. Also observed by Kincaid et al. [2003] is a westward flow from the Brenton Reef area. In our observations this was most noticeable during flood tide. At the time of predicted high tide a relatively strong northwest flow drew water into the Bay at the east end of region 3, an interesting observation reflected in the data mentioned in later sections.

There are a few noteworthy events in the current data set. The first is that the ebb tide seems to continue in the west side of the East Passage (region 2) well into the predicted flood tide. Figure 2a, illustrating this feature, was taken two and a half hours after the predicted low tide. Figure 2b illustrates a feature that is reflected in other data sets in this paper; an intrusion of offshore waters, beginning at the peak of flood tide enters region 3, as can be seen in the strong westward component of the water velocities in this region. Both figures are clearly from flood tide as is seen in the strong, deep region 3 flow northward. Tidal flow at the other end of the spectrum, near the end of ebb tide, also shows certain identifiable characteristics. Figure 2c shows the strong southward flow of water on the surface, coming from both the East Passage (regions 2 and 3) and the West Passage (region 1) in distinct flows. The strong outflow from the East Passage creates strong vertical shear suggesting that this region might be a location of high turbulent mixing. Another interesting thing about this last figure is the strong divergence of east-west velocities between regions 2 and 3. This suggests the presence of a corresponding convergence in the southward ebb flow in this region.

Figure 2. Series of ADCP sections along the mouth of Narragansett Bay at a) mid-flood, b) close to predicted high tide, and c) close to predicted low tide. The top of each figure shows north-south flow direction with positive values representing northward (into the page) flow. Similarly, the bottom of each figure shows the east-west flow component with positive representing eastward flow.

3.2. Temperature, Salinity, and σ_T

Figures 3 and 4 show the temperature, salinity, and density (shown as σ_T) cross-sections of the Bay at the farthest ebb and at high tide. The ebb tide figure is from the end of our data collection and marks the observation closest to low tide made on our trip. The diagonally stratified density structure that is characteristic of estuarine dynamics is clearly visible in Figure 3. The temperature and salinity profile denote a strong, warm water outflow near the surface during ebb tide in region 1. This figure corresponds to Figure 2c, suggesting that the strong, warm outflow seen in the temperature and salinity profiles may be due to greater advection to the location than the away from it, not necessarily intensity of flow.

The warm, fresh water occurrence found at Beavertail Point appears to be present at high tide and throughout the tidal cycle. Figure 4, however, shows what appears to be a warm, salty intrusion at the surface in region 3. This intrusion appears during flood tide (it is noticeable as the strong westward flow in Figure 2b) and disappears during ebb, lasting for at least four hours. This intrusion generates a well-defined pycnocline in region 2 at a depth of about twelve meters.

To compare this intrusion to “normal” conditions we plotted temperature versus salinity graphs for the data sets of Figure 3 and Figure 4 (Figures 5a and 5b respectively). The “normal” graph, seen in Figure 5a is what would be expected in a situation with two water masses; a colder, saltier mass mixing with a warmer, fresher, water mass. This scenario depicts the mouth of the Bay because the East Passage has colder, saltier water than the West Passage. Figure 5b on the other hand seems to have three water masses, the two previously mentioned plus a third, warm, salty mass that is found in the eastern part of the East Passage, mostly near the surface. This T-S diagram, like Figure 2b, reflects the findings of Kincaid et al. [2003] that there seems to be an intermediary mixing region in the Brenton Reef area.

In mid-flood the temperature, salinity and density profiles, seen in Figure 6, are also intriguing. Region 1 of the figure has vertical isopycnals suggesting that vertical mixing may be intense there. Also noticeable is the surface pocket of warmer fresher water in region 2 that corresponds to the continuation of ebb tide near Beavertail Point seen in Figure 2a. The wide isopycnals in region 2 below the halocline are also suggestive of mixing events (especially with the horizontal shear set up in that region in Figure 2a).

3.3. Eddy Diffusivity (K_T)

Figures 7a, b and c are log plots of the eddy diffusivities calculated for the data sets corresponding to Figures 2a, b, and c, respectively. The eddy diffusivities were all in the range of values ($10^{-6} \text{ m}^2/\text{s} - 10^{-2} \text{ m}^2/\text{s}$) found by Peters and Bokhorst [2001] for the Hudson estuary. The mid-flood eddy diffusivities found in Figure 7a are highest in regions 1 and 2, close to Beavertail Point. This feature is found throughout the

Figure 3. Temperature, salinity, and density (shown σ_T) section from late in the ebb flow. The darker line represents the bottom while the lighter, dotted line shows the undulating track of the Acrobat. The three distinct regions are clearly pointed out in this figure.

tidal cycle except in the sections closest to high tide (about an hour before and after) and seen again in Figure 7c. The interaction between waters from the East and West Passages are probably responsible for this. Also the noticeable change in bathymetry probably plays a role in this mixing region.

Figure 7b shows the strong mixing effect of the intrusion commented on earlier in the observations section. This suggests that the waters from the intrusion are different enough in direction and composition to be conducive to mixing. As this figure comes from the close to the height of high tide the lull near the bottom

Figure 4. Temperature, salinity, and density (shown σ_T) section from predicted high tide.

in the Beavertail mixing region can be seen marked by values that are some of the lowest of the entire data set.

4. Discussion

This paper presents a preliminary look at a comprehensive data set that covers hydrographic variability over a summer tidal cycle. One of the goals of this study was to characterize turbulent mixing and corresponding hydrographic conditions. Here we present key observations pertaining to our data set.

Figure 5. Temperature versus salinity plots for sections from a) late in the ebb flow and b) predicted high tide, during the warm, salty intrusion. The darker points represent water found farther West.

4.1. Brenton Reef Intrusion

One of the most interesting features found in this first look at the data is the warm salty intrusion that occurs around high tide (seen in Figure 4). The ADCP data tells us that the water is moving from the southeast, which is directly coming from the Brenton Reef area. Kincaid et al. [2003] present a model in which the Brenton Reef area serves as an intermediate mixing region for Rhode Island Sound water heading into the Bay. Our data supports this model and demonstrates that the mixed waters of Brenton Reef are injected into the East Passage and mixed there (as seen in Figure 7b).

Figure 6. Temperature, salinity, and density (shown σ_T) section from mid-flood.

4.2. Beavertail Point Mixing Region

The other most interesting feature described in our data was the semi-permanent mixing region on Beavertail Point. The behavior of the East Passage waters seems to be such that there is a nearly constant outflow to the southwest on the surface of the western side of the East Passage (along Beavertail). This flow runs against the flood tide and exaggerates the ebb tide in that region, possibly providing shear that generates turbulence seen in the mixing events around Beavertail Point. The exaggerated outflow during ebb is seen in the east-west velocity divergence of Figure 2c.

Figure 7. Log plots of eddy diffusivity (K_T) for sections from a) mid-flood, b) close to predicted high tide, and c) close to predicted low tide. Darker regions represent regions of more intense mixing.

4.3. Bottom Layer and Halocline Mixing

Similar to the conditions of estuarine dynamics in the Hudson River studied by Peters [1996], our data showed weak stratification in the bottom layer. However, the bottom layer did not reinforce Peters' result of having the strongest eddy diffusivities during flood tide. In fact, diffusivities in the bottom layer reached a minimum of the entire data set during flood (as seen in Figure 7b). In response to Peters' findings that mixing was weak in the halocline, there seemed to be little if any correlation between the strength of the mixing events and the established haloclines.

5. Summary

The Acrobat towed microstructure profiler and boat-mounted ADCP helped generate a comprehensive data set for the study of turbulent vertical mixing in the Narragansett Bay. The data that was processed was done quickly and roughly to allow for quicker analysis. In the future, the temperature variance series will be compared to Batchelor curves to find the turbulent kinetic energy dissipation as described in Luketina and Imberger [2001]. More importantly, there will be more filtering of the data to remove instrument noise to allow for better accuracy.

While the eddy diffusivity values are rough estimates at this stage there were still interesting features to be described in the Bay area. Mixing regions were found at Beavertail Point and near Brenton Reef. The Brenton Reef mixing event was particularly interesting because it supports the model proposed by Kincaid et al. [2003]. Brenton Reef appears to act as an intermediate mixing area in the process of Rhode Island Sound-Narragansett Bay exchange.

The data only loosely supported Peters' work [Peters, 1997] although with improvements in the data processing methodology there may be more of a connection. Also, further data in the Bay in different stages of the spring-neap cycle could provide useful insight into the effects of tidal amplitude on the mixing.

In general, the Acrobat and ADCP profiling of the Narragansett Bay have provided a wealth of data and information about the dynamics of the Bay. Further study of the Bay area with similar data collection techniques will surely result in an improvement in the understanding of vertical turbulent mixing in estuarine environments. In fact, even a further analysis of this data set will help us on this path.

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The Effect of Exogenous Cortisol and RU 486 on Cortisol Concentrations and Glucocorticoid Receptors in Summer Flounder, *Paralichthys dentatus*

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Abstract. The glucocorticoid hormone cortisol is secreted in response to stress and has been shown to be a salt water-adapting hormone in fish. To explore the effect of exogenous cortisol, cortisol concentrations and the glucocorticoid receptor (GR) were analyzed in juvenile summer flounder, *Paralichthys dentatus*. Summer flounder were placed in water containing 20 μ M cortisol, 0.12 μ M RU 486 (cortisol antagonist), a combination of both hormones, or water with vehicle, controls. Whole body cortisol concentration was measured using radioimmunoassay. Immunocytochemistry was used to compare expression of the GR in the stomach, intestine, and gills along with expression of the Na⁺/K⁺ATPase in the gills across treatments. Five days after treatment, the groups treated with RU 486 showed an increase in whole body cortisol concentration compared to the control group most likely due to suppression of the negative feedback loop on the cortisol axis. Expression of the GR was decreased in all treatment groups compared to the control group in the intestine and stomach, but not in the gills, while Na⁺/K⁺ATPase activity was unaffected by any treatment. Localization of the receptor in the stomach, intestine, and gills further evidences a direct action of cortisol on the major osmoregulatory organs. The present study also adds to the understanding of cortisol and the stress response in marine teleosts.

1. Introduction

Cortisol is a steroid hormone secreted in response to stress, and regulates salt and water balance in fish. The glucocorticoid receptor binds cortisol and mediates cortisol's osmoregulatory functions in tilapia [Dean *et al.*, 2003]. This is further evidenced by an increase in glucocorticoid receptor concentration in Atlantic salmon prior to smolting in preparation for the seasonal increase in cortisol concentration [Shrimpton and McCormick, 2003].

RU 486 has a strong affinity for the glucocorticoid receptor and suppresses the effects of cortisol. RU 486 has been used as a cortisol antagonist previously and shown to block the action of cortisol on the intestine in Atlantic salmon [Veillette *et al.*, 1995].

The present study aims to find the effect of exogenous cortisol on the regulation of its receptor and the effect on cortisol concentrations after blocking the receptor in a marine teleost. To do this, juvenile summer flounder were administered exogenous cortisol and/or RU 486, and protein and gene expression of the glucocorticoid receptor and cortisol concentrations were studied. Long-term observations are necessary to characterize and understand the solar influence on various phenomena.

2. Material and Methods

2.1. Fish Maintenance and Treatment

Juvenile summer flounder were obtained from the summer flounder hatchery at the University of Rhode Island Narragansett Bay Campus. One hundred fish with an average weight of 0.542 g with a standard error of 0.03 and average length of 41.13mm with a

standard error of 0.755 were distributed equally among 4, five-gallon tanks. Temperature was kept at ~20° C, and fish were fed 10 mm pellets every day. Four treatments were administered: (1) Cortisol dissolved in dimethylsulfoxide (DMSO, 0.073 g/ml), at a final concentration of 20 μ M in seawater plus phosphate buffered saline (PBS); (2) RU 486 dissolved in DMSO (50 mg/ml), mixed in acetic acid (1:10), and added to PBS (1:100) to reach a concentration of 0.12 μ M in seawater plus DMSO; (3) RU 486 and cortisol at the same concentrations as above; (4) control, DMSO and PBS. Half water changes were conducted every day and hormones were replaced. The experiment duration was six days.

Prior to sampling, fish were anesthetized with MS222 (200 mg/L and buffered in 400 mg sodium phosphate/L), then weighed and measured. Gills, intestine, and stomach were excised and placed in RNA later for Northern blot analysis in 6 fish per treatment and stored at -20° C. Three fish per treatment were fixed in 10% neutral buffered formalin and 12 juveniles were placed in test tubes and stored at -20° C.

2.2. Immunocytochemistry

2.2.1. Glucocorticoid Receptor

Fixed juveniles were embedded in paraffin and sectioned at 5 μ m. Sections were attached to precoated polylysine slides. Sections were deparaffinized and rehydrated, then incubated in 0.3% H₂O₂ in water for 30 min followed by a 20 min incubation in normal blocking serum diluted in PBS (15:1000). Slides were incubated in the primary antibody, rabbit anti-glucocorticoid receptor diluted in PBS (1:1000) overnight at 4° C. This antisera has been successfully used previously by Carruth *et al.* [2000]. Thirty minute incubations each with anti-rabbit biotinylated secondary antibody (Vector) 5:1000 in PBS and avidin-biotin horseradish

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peroxidase (Vector, Elite ABC kit). Five-minute washes in PBS were done after every incubation excluding the normal blocking serum. Incubations took place in a humid chamber at room temperature, unless otherwise noted. Slides were developed using Sigma diaminobenzidine tablet kit in ddH₂O for 5 min, dehydrated, and covered.

2.2.2. Na⁺/K⁺ATPase

Staining for the Na⁺/K⁺ATPase followed the same procedure as above with a few exceptions. Prior to conducting immunocytochemistry on sections of each treatment, varying dilutions of the primary antibody, mouse anti-Na⁺/K⁺ATPase in PBS, were tested to determine optimal concentration for incubation. Slides were incubated with 7, 0.7, 0.07, 0.007 µg/ml or no antibody (control) for 2 hours at 4°C. The effectiveness of the antiserum has been shown previously by Schreiber and Specker [2000]. The secondary antibody was anti-mouse biotinylated secondary antibody (Vector) in PBS (5:1000). Treatment sections followed the same procedure used above with a primary antibody dilution of 0.07 µg/ml.

2.2.3. Radioimmunoassay

Juveniles stored at -20° C were thawed and cut into small pieces, then homogenized in 3 ml of PBS using a polytrone. Samples were centrifuged (3400 rpm, 4° C) and 1 ml of the supernatant was taken and 10 µl of radioactive

cortisol was added. Samples were incubated for 30 min. followed by the addition of 3 ml of ether. Vortexed samples were placed in a methanol cold bath until the lower aqueous layer was frozen. The ether layer was decanted off and steps were repeated with the aqueous layer. Samples were left two nights to evaporate and then reconstituted with 500 µl of standard diluent. Extraction efficiencies were calculated using 50 µl of reconstituted sample. The following was added to each tube: 200 µl of sample, standard, or standard diluent; 150 µl of radioactive cortisol in PBS (~13,000 CPM's); 100 µl of cortisol antibody in standard diluent (1:100) or 100 µl of standard diluent. Samples were incubated for 2 hours at room temperature then immersed in ice for 5 min. This was followed by addition of 400 µl of PBS or Dextran coated charcoal, vortexing, and incubating and centrifuging (3000 rpm) for 20 and 15 min, respectively, at 4°C. Radioactivity was measured using 500 µl of sample in 5 ml of BioSafe II scintillation cocktail and counted in a scintillation counter.

2.2. Northern Blot

Total RNA was extracted using RNAwiz and quantified spectrophotometrically. Due to low concentration of RNA in samples, repelleting and concentrating of the samples was done following the Ambion protocol. Ambion NorthernMax-Gly was followed for gel electrophoresis

Figure 1. Glucocorticoid receptor immunoreactivity (arrow) in the fundic region of the juvenile summer flounder stomach. Note the striking decrease in staining intensity in hormone treated groups: a) control; b) cortisol (20µM); c) RU 486 (0.12µM); d) RU 486 + cortisol. Stomach was observed using a light microscope at 200x magnification.

Figure 2. Glucocorticoid receptor immunoreactivity (arrow) in the intestine of the juvenile summer flounder. Note the striking decrease in staining in hormone treated groups: a) control; b) cortisol (20 μ M); c) RU 486 (0.12 μ M); d) RU 486 + cortisol. Intestine was observed using a light microscope at 200x magnification.

Figure 3. Glucocorticoid receptor immunoreactivity in the chloride cells (arrow) in the gills of juvenile summer flounder. Note the increase in staining in the group treated with cortisol compared to the control group: a) control; b) cortisol (20 μ M); c) RU 486 (0.12 μ M); d) RU 486 + cortisol. Gills were observed using a light microscope at 200x magnification.

using a glyoxal based gel. As a size marker, an RNA ladder was run parallel to the samples. RNA was then transferred to a BrightStar™-Plus positively charged nylon membrane and cross-linked by heating in an oven at 90°C for 15 min. The DNA oligonucleotide probe (42 b.p.) for flounder glucocorticoid receptor was labeled using the Ambion BrightStar™ Psoralen-Biotin nonisotopic labeling kit. The membrane was hybridized with the probe overnight at 42°C. The membrane was exposed to film 45 min after washes were complete. However, after rehybridization and exposure of the membrane to the film for 45 min after washes were completed, exposure for 90 min one day after end of hybridization, and for 4 hours three days after incubation, no visible bands could be seen except for the RNA size markers.

2.3. Statistical Analysis

Data from the radioimmunoassay was analyzed with SPSS statistical software and verified with the JUMP statistical package. A one-way Analysis of Variance (ANOVA) was used with log-transformed, whole-body cortisol concentration (ng/g) as the dependent factor and treatment group as the factor. Tukey's honestly significant post hoc test was used with 3 degrees of freedom and significance level set at $p=0.05$.

3. Results

3.1. Immunocytochemistry

The glucocorticoid receptor was located in the major osmoregulatory organs, the gills, stomach and intestine. The effects of cortisol, RU 486, and RU 486 + cortisol, on intensity of staining for the GR in these organs and the intensity of staining for the Na^+/K^+ ATPase in the gills were compared to control juveniles. The most intense staining for the GR was localized predominantly in the stomach and intestine epithelium, and no specific staining was found in the connective tissue in the control group. Cortisol and RU486 altered GR staining in the fundic region of the stomach and the intestine (Figs. 1 and 2). Nuclear staining was seen in the control and cortisol group, while the majority of the staining was cytoplasmic in the groups treated with RU 486. Staining intensity decreased overall in the three variable groups.

Staining for the receptor in the gills was most specifically localized in the chloride cell, at the junction between the primary and secondary filaments in the control group (Fig 3). In all groups, staining occurred in the chloride cells. Comparing the sections of tissue taken from the middle of the filament, the cortisol-treated group had more intense staining and more stained cells when compared to the control group. The groups treated with RU 486 had staining similar to the control group.

Sections incubated with serial dilutions of the primary antiserum for the Na^+/K^+ ATPase were analyzed for specificity of binding and amount of background staining in the gills. The control group showed no staining except in the cartilage of the gills giving

Figure 4. Serial dilutions of primary antiserum for the Na^+/K^+ ATPase. Immunoreactivity in the chloride cells (arrow) in the gills of juvenile summer flounder. Note the slight increase in background staining as the concentration of antiserum increased. Gills were observed using a light microscope at 400x magnification.

Figure 5. Na^+/K^+ ATPase immunoreactivity in the chloride cells (arrow) in the gills of juvenile summer flounder: a) control; b) cortisol (20 μM); c) RU 486 (0.12 μM); d) RU 486 + cortisol. Gills were observed using a light microscope at 200x magnification. Counter stained with Hematoxylin and Eosin.

Figure 6. Whole body cortisol concentrations (ng/g) for each treatment group. Groups with different letters are statistically different: control; cortisol (20 μM); RU 486 (0.12 μM); RU 486 + cortisol.

evidence for its specificity for the Na^+/K^+ ATPase. Background staining increased slightly as the concentration of antiserum increased, but binding in all groups was very specific and localized in the chloride cells (Fig. 4).

The Na^+/K^+ ATPase was localized in the chloride cells similar to the glucocorticoid receptor. There was no effect on expression of the Na^+/K^+ ATPase by cortisol, RU 486, or the two combined (Fig. 5). There was no staining in the stomach or intestine for the Na^+/K^+ ATPase.

3.2. Radioimmunoassay

Whole body cortisol concentrations were obtained from the radioimmunoassay for six juveniles per treatment. Cortisol concentrations were elevated in all the treatment groups (Fig. 6). Statistical analysis on log transformed cortisol concentrations yielded a significant difference between control fish and RU 486-treated fish, as well as the RU 486/cortisol-treated juveniles at the $p=0.05$ significance level. The RU486/cortisol treatment also had significantly higher cortisol levels compared to the cortisol treatment.

3. Discussion

RU 486 has been shown to elevate plasma cortisol levels in Atlantic salmon [Veillette *et al.*, 1994].

Similar results were found in this study in which juvenile summer flounder treated with RU 486 showed elevated whole body cortisol levels. Furthermore, these groups also showed a decrease in expression of the glucocorticoid receptor in the stomach and intestine of the flounder.

There was an increase in whole body cortisol concentration in RU 486 and the RU 486/cortisol treated juveniles compared to control juveniles. This is most likely due to inhibition of negative feedback on the pituitary-interrenal axis [Veillette *et al.*, 1994].

Immunocytochemical reaction showed localization of the glucocorticoid receptor in the gill chloride cells, indicated by similar Na⁺/K⁺ATPase immunoreactivity, of summer flounder as previously shown in chum salmon fry [Uchida *et al.*, 1998], indicating that cortisol is involved in osmoregulation in summer flounder. Furthermore, expression of the receptor in the stomach and intestine implicates those organs in the regulation by cortisol of salt and water balance, as well as other functions. Previously it has been shown that glucocorticoid protein expression decreased in the liver of rainbow trout treated with cortisol [Vijayan *et al.*, 2003]. In this study, juveniles with significantly increased cortisol concentrations (RU 486 and RU 486/cortisol) compared to the controls showed a decrease in GR expression in the stomach and intestine. Although not significant, cortisol treated juveniles had an elevated average cortisol level compared to the control group and also a decrease in glucocorticoid receptor expression. This suggests that increased cortisol concentration down-regulates the glucocorticoid receptor in the stomach and intestine of juvenile summer flounder. This is, however, speculative because the exact effect of RU 486 combined with an elevated cortisol concentration needs to be further studied.

Interestingly, in both the stomach and intestine nuclear staining was strikingly higher in the groups that were not administered RU 486. Because cortisol is a steroid hormone, it binds to the GR and translocates to the nucleus to affect physiological changes. In groups treated with RU 486, the unbound receptor would not translocate to the nucleus, resulting in the little to no nuclear staining observed. This further supports the antagonistic action of RU 486.

Downregulation of the GR receptor did not occur in the gills. Rather, there was an increase in expression in the cortisol treated juveniles. This effect of cortisol treatment has been shown in the freshwater tilapia *Oreochromis mossambicus* [Dean *et al.*, 2003]. Although the groups treated with RU 486 did have a significant increase in cortisol concentrations, no effect was observed on receptor immunoreactivity in the gills, suggesting that RU 486 was blocking some effects of elevated cortisol in the gills. Furthermore, cortisol had been found to increase Na⁺/K⁺ATPase density in the gills of freshwater tilapia *Oreochromis mossambicus* [Dang *et al.*, 2000], but the

present study did not indicate any effect of increased cortisol concentration on Na⁺/K⁺ATPase immunoreactivity. The results may imply species-specific differences between freshwater and seawater fish in their response to increased levels of cortisol. However, there are also implications of tissue specific responses to RU 486 and increased cortisol concentrations. Further work needs to be done to learn about the competition between RU 486 and high cortisol concentration for the glucocorticoid receptor.

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^{226}Ra Distributions in the Chukchi-Beaufort Sea

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Abstract. Recent signs of a potential warming of the Arctic from a rise in greenhouse gas emissions has lead to the need for understanding decadal changes in this polar regime. The shelf-slope regime of the Chukchi Sea has the highest water column production in the Arctic Ocean [Springer et al. 1996]. Biogenic particulate matter represents a sink for atmospheric CO_2 , and the exchange of this material between the shelf and basin are an important mechanism for modeling the fate of carbon. As part of the Shelf-Basin Interaction (SBI) Phase II Study, a suite of radiochemical tracers (^{234}Th , ^{228}Th , ^{234}U , ^{210}Pb , ^{226}Ra) are being used to determine the fate and transport of particulate organic carbon from the water column to the sediments. This study specifically focuses on determination of ^{226}Ra activities in 25 discrete samples collected in the Chukchi-Beaufort Sea shelf-slope waters and Canada Basin. Seawater samples ranging between 10-20 liters were analyzed by the radon emanation technique. These ^{226}Ra activity data will be interpreted by comparison with distributions of salinity, temperature and dissolved silicate. Additionally, ^{226}Ra data will be combined with ongoing studies of ^{210}Pb in the water column. Disequilibrium between ^{210}Pb and ^{226}Ra in the water column due to preferential scavenging of ^{210}Pb by marine particles can be used as a proxy tracer of particulate carbon export. These water column ^{210}Pb - ^{226}Ra distributions will be ultimately combined with sediment data to constrain the export of organic carbon from the shelf regime of the Chukchi Sea to the deep interior Arctic.

1. Introduction

The physical characteristics of the Arctic Ocean include wide continental shelves accounting for 36% of the ocean's surface area [Moore and Smith, 1986] with seasonal ice cover over the shelves. In this polar regime productivity is limited by light during much of the year and the removal rate of biochemically active particles is slow due to long residence time of water on the shelves. The production of particulate organic carbon through the process of photosynthesis will increase in the spring as less ice cover increases the amount of surface area that is exposed to the atmosphere. This results in a larger portion of the ocean being a sink for carbon dioxide, an important component in biochemical processes.

In the Western Arctic there is a pronounced halocline. The upper halocline contains mainly Pacific water that has a low salinity that enters through the Bering Strait. Atlantic water makes up the lower halocline and flows in through the eastern part of Fram Strait and circulates over the Barents, Kara and Laptev Seas before providing a supply to the shelves. The halocline prevents mixing with surface waters. There is vertical mixing between the dense surface and deeper waters every fall and winter as the water cools and forms ice. A highly concentrated brine solution is excluded into the surface water and makes it more dense allowing it to sink.

In the open ocean there exists a linear relationship between ^{226}Ra ($t_{1/2} = 1620$ years) and dissolved silicate (SiO_2). Organisms utilize dissolved silicate as a nutrient to produce silicate tests. Along with the uptake of silicate, ^{226}Ra , a trace element is incorporated by

organisms and subsequently remineralized at depth, resulting in a ratio that maintains a linear correlation. ^{226}Ra is a radionuclide naturally found as a stably dissolved isotope in water and produced from the decay of ^{238}U . ^{226}Ra is the parent of ^{210}Pb ($t_{1/2} = 22$ years), a particle-reactive radiochemical isotope. Disequilibrium between the activity ratio of $^{210}\text{Pb}/^{226}\text{Ra}$ results from differences in isotope properties and through the preferential scavenging of ^{210}Pb .

Radionuclide tracer measurements together with temperature, salinity and silicate distributions, help to constrain our understanding of the hydrography of the Western Arctic. The Shelf-Basin Interaction (SBI) Phase II Study (May 5- June 15, 2002, July 17-August 26, 2002) incorporated interdisciplinary research projects to understand the fate of carbon in this regime. To estimate the exchange of materials between the shelf and inner Canadian Basin radiochemical tracers (^{234}Th , ^{228}Th , ^{234}U , ^{210}Pb) are being measured to estimate the

Figure 1. Station location and cruise track of the USCGC Healy. [Final Cruise Report]

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Figure 2. Area enlarged in the box from above in Figure 1. Stations are represented as West Hanna Shoal (WHS), East Hanna Shoal (EHS) and Barrow Canyon (BC). The box represents the stations where silicate, salinity and temperature were measured.

exchange of materials in the shelf-slope areas of the Chukchi-Beaufort Sea. Figure 1 shows the cruise track during the SBI Phase II Study on the *USCGC Healy*. Vertical profiles were collected for ^{226}Ra measurements in Barrow Canyon (BC) stations and in two stations in the East Hanna Shoal (EHS) shown in Figure 2. Silicate measurements were made at these stations and in the West Hanna Shoal (WHS).

2. Methods

Seawater samples for ^{226}Ra analysis were collected in 6x30 liter Niskin bottles and stored in 20-liter plastic containers. ^{226}Ra was extracted from 25 samples containing 10-20 liters of seawater. Each sample was passed through a column with MnO_2 -coated acrylic fiber at a flow rate of 0.43 Lmin^{-1} . Six samples were sequentially filtered through two MnO_2 -coated acrylic fibers to evaluate collection efficiency.

^{226}Ra was leached from the fiber in bottles containing 500 mL of 1.5 N hydrochloric acid and analyzed by the radon emanation method [Mathieu et al.1988]. Salinity, temperature and silicate were collected from CTD casts. Silicate was measured using a Technicon Autoanalyzer II ODF modified 6 channel. ^{226}Ra activities, silicate and depth are given in Table 1.

3. Results

The temperature profile in Figure 3 from Barrow Canyon shows a thermocline in the range of 150-450 meters. The lower thermocline water corresponds to warmer water of the Atlantic as seen in the water range of 450-3000 meters. The temperature range of this water is between -0.5 to 0.5°C . The influence of colder Pacific water over the shelf composes the upper thermocline and is observed between 0-150 meters with a temperature range of -1.75 to -0.5°C .

Table 1. Sampling locations. Latitude, longitude, water depth, silicate and ^{226}Ra activity at Barrow Canyon (BC) and East Hanna Shoal (EHS).

Station	Lat. (N)	Long. (W)	Depth (m)	Silicate ($\mu\text{mol/L}$)	^{226}Ra (dpm/100L)
(HLY-02-01)					
EHS6-17	72.87	-158.55	430	8.91	2.332
EHS6-17	72.87	-158.55	250	9.45	5.502
EHS6-17	72.87	-158.55	125	34.96	10.826
EHS6-17	72.87	-158.55	25	6.55	4.427
BC2A-24	71.82	-155.72	80	29.84	10.911
BC2A-24	71.82	-155.72	60	24.47	8.585
BC2A-24	71.82	-155.72	40	16.41	6.508
BC2A-24	71.82	-155.72	20	10.97	7.883
BC4-31	71.93	-154.85	300	9.68	2.661
BC5-32	72.11	-154.49	300	10.98	4.7491
BC5-32	72.11	-154.49	50	16.86	4.271
BC5-32	72.11	-154.49	20	16.99	8.26
BC5-32	72.11	-154.49	10	11.08	3.5561
BC7-34	72.56	-154.58	900	7.48	3.4867
BC7-34	72.56	-154.58	225	16.21	7.1972
BC7-34	72.56	-154.58	60	19.61	4.4136
BC3-37	71.65	-155.76	150	44.49	5.6466
BC3-37	71.65	-155.76	20	17.16	7.3087
(HLY-02-03)					
EHS-11	73.42	-157.40	2900	4.9724	7.66
EHS-11	73.42	-157.40	1500	5.4788	10.12
EHS-11	73.42	-157.40	900	7.39	-2.85
EHS-11	73.42	-157.40	600	4.5461	6.99
EHS-11	73.42	-157.40	250	5.0696	10.76
EHS-11	73.42	-157.40	75	10.183	19.36

Figure 3. Depth versus temperature plot from all Barrow Canyon stations.

The halocline is observed in the range of 50-200 meters in Figure 4. Upper halocline water contains Pacific water and river water, which has a lower salinity than more dense Atlantic water. Atlantic water makes up the lower halocline water. The salinity of upper halocline water ranges from 31-32 ppt and lower halocline water ranges from 34-35 ppt.

Figure 4. Depth versus salinity from data at Barrow Canyon stations.

3.1 ^{226}Ra and dissolved silicate

Measured ^{226}Ra activities at Barrow Canyon were plotted against silicate measurements collected from the same depths and compared with published data. ^{226}Ra -silicate data has been reported for two regions of the Arctic Ocean. Measurements were made of ^{226}Ra from water collected in the Arctic Ocean Section [Smith et al. 2003] from the Western Arctic with ranges from 6-14 dpm/100L. The transect extends between the Mededeylev Ridge of the Canadian Basin to the Lomonosov Ridge in the Eurasian Basin. Data for the Eastern Arctic at four stations between Lomonosov Ridge and the Nansen Basin were reported by Rutgers Van der Loeff et al. 1995. The ^{226}Ra activities at these stations were determined through a correlation made between salinity and silicate in Moore and Smith [1986].

$$\text{Ra (dpm/m}^3\text{)} = (105 + 1.0 \times \text{Si(umol/L)}) \times \text{salinity}/35(1)$$

This equation is used to calculate ^{226}Ra activities for Barrow Canyon stations from corresponding silicate and salinity data.

The relationship between measured ^{226}Ra activity and silicate data from SBI II Study is apparent in Figures 5 and 6. SBI represents measurements from five BC stations and two EHS stations using ^{222}Rn emanation. The range of ^{226}Ra activity was 2.33-10.9 dpm/100L with most of the data ranging between 4-7 dpm/100L. Silicate measurements are in the range of 6.55-34.9 umol/L. Kadko [2003] measured ^{226}Ra using gamma spectroscopy. Kadko's data was taken from EHS and WHS and measurements show high silicate data with a range of (3.72-38.39 umol/L) with low range ^{226}Ra activities. For Kadko's data, the range for ^{226}Ra was between 4.33-28 dpm/100L where the majority of data was between 5-9 dpm/100L.

Figure 5. ^{226}Ra -silicate correlations from data measured at Barrow Canyon and East Hanna Shoal stations in the Chukchi-Beaufort through SBI II Study. Literature data was taken from Smith et al. [2003], Rutgers Van der Loeff et al. [1995] and the Moore and Smith [1986] correlation.

Figure 6. Comparison of data at Barrow Canyon with unpublished data from Kadko during SBI HLY-02-01

3.2 Contour Maps of ^{226}Ra distribution in the Chukchi-Beaufort Sea.

Figure 7 are section views of depth versus ^{226}Ra activity for the observed and modeled data. The observed data at Barrow Canyon indicate water below 900 meters was not taken for measurement in Figure 7. Using the ^{226}Ra -silicate correlation from the observed distribution at Barrow Canyon and East Hanna Shoal the missing data is filled in Figure 7 using the observed equation.

$$y = 2.1322 + .26735x \quad (2)$$

Figure 7. Observed and modeled distribution of ^{226}Ra and silicate a) observed ^{226}Ra distribution at five stations at Barrow Canyon., modeled ^{226}Ra distribution at b) Barrow Canyon, c) West Hanna Shoal, d) East Hanna Shoal. Silicate distributions for all Barrow Canyon stations.

The slope is used to model three ^{226}Ra distributions in Figure 7.

The ^{226}Ra activity in Figure 7 range between 3-10 dpm/100L. The activity decreases away from the coast. The continental shelf (0-200 m) has a high activity of 7-10 dpm/100L. In surface waters of the same depth away from the coast the activities range between 5-6 dpm/100L. Activities in depths of 200-700m range between 4-6.5 dpm/100L and the activity between 700-900m is in the range of 3-4 dpm/100L.

Figure 7 observes a high ^{226}Ra activity of 9-11 dpm/100L along shelf waters and decreasing activity off the shelf. Surface water (0-250 m) demonstrate intermediate activities of 4-7 dpm/100L and deeper water (250-1500 m) are in the range of 2-4 dpm/100L. Figure 7 shows the shelf and surface water (0-250 m) away from the coast as having the highest activity of 4-6 dpm/100L. Water depths of 250-1500 m observe activities of 2-4 dpm/100L.

Figure 7 is a section view of silicate distribution for all of Barrow Canyon stations. Higher silicate values are found in the shelf regime with measurements in the range of 28-40 umol/L with intermediate measurements in the surface waters (0-250 m) off the coast in the range of 15-25 umol/L. Below 250 meters the silicate measurements range between 5-15 umol/L.

4. Discussion

High ^{226}Ra activity is observed on the shelves and lower range ^{226}Ra activity is modeled in deeper water at BC, EHS and WHS in the Western Arctic. Colder waters and lower salinity data on the shelves compare with high range ^{226}Ra activities and high range silicate measurements. This is consistent with the expectation that Pacific Ocean water and rivers carry cold, low salinity water and high concentration of nutrients to the shelves. Warm water with a high salt content, a lower range ^{226}Ra activity, and low silicate measurements in the deeper water is expected of Atlantic water inflow. A low range ^{226}Ra activity is expected in the open deep water from little inflow of ^{226}Ra from rivers and the water is not in contact with sediment pore water.

The measurements of ^{226}Ra activity at Barrow Canyon stations and Kadko data from EHS and WHS represented in Figure 6 are 3-5 dpm/100L lower than reported data for Western and Eastern Arctic including the Moore and Smith correlation [Moore and Smith, 1986]. The slope correlation for BC and EHS are similar with linear relationships from Figure 5 of reported data. The linear correlation of data from Kadko [2003] shows a less positive slope. The ^{226}Ra -silicate relationship for BC and EHS show a related slope to reported data in Figure 5 and compare with lower range ^{226}Ra activities to Kadko data in Figure 6.

It would be expected from reported data from the Western and Eastern Arctic that the ^{226}Ra measurements from BC and EHS would fall in the range of 7-13 dpm/100L. Western and Eastern Arctic data range between 7-11 dpm/100L, while data points of ^{226}Ra

activity calculated from Moore and Smith [1986] for all BC stations are 3-4 dpm/100L higher in the range of 10-14 dpm/100L. It is not clear why BC and EHS activity data for ^{226}Ra are in a lower range of 2.33-10.9 dpm/100L or why the Kadko data to be is lower in the range of 4.33-9 dpm/100L. One possible reason for the low ^{226}Ra activity may be due to seasonal variations in Arctic river discharges. Differences in the inflow of ^{226}Ra from rivers create a non-steady state distribution of ^{226}Ra over the shelves.

5. Conclusion

The ^{226}Ra -silicate relationship of the measured values in the Chukchi-Beaufort Sea at the Barrow Canyon stations and unpublished Kadko [2003] data show a similarity in ^{226}Ra activity. The ^{226}Ra activity measurements are lower compared to reported data sets. The ^{226}Ra distributions at WHS and EHS will be used along with ongoing particulate ^{210}Pb measurements for these stations to constrain the knowledge of the scavenging of organic particulates to evaluate the amount of carbon being drawn into the deep interior Arctic.

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Cortisol Levels and Glucocorticoid Receptor Expression in Summer Flounder (*Paralichthys dentatus*) Subjected to Osmotic Stress

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Abstract. The present study was designed to monitor the effect of an osmotic stress on whole body cortisol levels and glucocorticoid receptor (GR) expression in a marine teleost. In the present study, juvenile summer flounder were exposed to seawater concentrations that consisted of a control, 30 ppt (bay water), an estuarine environment, 5 ppt (parts per thousand), and an extreme saline environment, 50 ppt. Whole body cortisol levels were measured using radioimmunoassay techniques, immunocytochemistry was used to locate the GR protein and Na⁺/K⁺-ATPase enzyme, and northern blot analyses were used in an attempt to semi-quantify expression of the GR. Northern blot results are still being processed. Cortisol levels were significantly higher in flounder exposed to 50 ppt salinity as compared to flounder exposed to 30 ppt ($P < 0.05$). Immunoreactivity of the GR was observed in gills, stomach, and intestine of juvenile summer flounder. Immunoreactivity for the Na⁺/K⁺-ATPase was observed in gill chloride cells. Immunoreactivity of the GR and Na⁺/K⁺-ATPase in gills, as well as immunoreactivity of the GR in the stomach and intestine, implicate cortisol in ion regulation in summer flounder. However, observations made in the stomach and intestine of flounder exposed to 5 ppt salinity may indicate that cortisol is not the low salinity-adapting hormone in summer flounder

1. Introduction

Osmoregulation is an important physiological process by which fish regulate their ionic content. In the face of different or varying external environments, osmoregulation is the process that maintains salt and water balance. In marine fish, the primary osmoregulatory organs include the gills, stomach, and intestine; in addition, within these organs reside specific enzymes that partake in ion exchange. In juvenile and adult marine teleosts, chloride cells in the gills secrete excess Na⁺ and Cl⁻ ions from the body fluids [Hiroi et al., 1998]. A key enzyme in the exchange of these ions is the Na⁺/K⁺-ATPase in gill chloride cells [Hiroi et al., 1998].

In teleosts, cortisol is considered to be an important hormone involved in salinity tolerance and the regulation of these enzymes [Uchida et al., 1998]. Cortisol is commonly referred to as the stress and/or salinity-adapting hormone in fish. The action of cortisol on osmoregulatory organs is mediated by its receptor, the glucocorticoid receptor (GR) [Uchida et al., 1998]. Cortisol, a steroid hormone, binds to the GR in cell cytoplasm and translocates to the nucleus-there regulating gene expression for the GR.

The summer flounder (*Paralichthys dentatus*) is a marine teleost, and like all euryhaline fish it can tolerate a wide range of salinity. Often during the metamorphosis of summer flounder, the transition from

bilateral larvae to asymmetric settled juvenile is accompanied by a move from an oceanic (30 ppt) to an estuarine (5 ppt) environment [Schreiber and Specker, 1999]. After metamorphosis flounder seasonally move into estuarine environments to feed. Salinity tolerance tests previously performed on juvenile summer flounder revealed high survival at 5, 30, 45, and 50 ppt salinity [Schreiber and Specker, 1999].

The present study was designed to monitor the effect of an osmotic stress on whole body cortisol levels and glucocorticoid receptor expression in a marine teleost. In this experiment, juvenile summer flounder were exposed to seawater concentrations that consisted of a control, 30 ppt (bay water), an estuarine environment, 5 ppt, and an extreme saline environment, 50 ppt. Since summer flounder naturally expose themselves to a range of salinities, extreme environments were specifically chosen in an effort to induce a stress response.

Localization of the glucocorticoid receptor as well as the Na⁺/K⁺-ATPase was performed immunocytochemically. The primary antiserum to human GR that was used in detection of flounder GR was polyclonal rabbit anti-human. This antibody has been proven effective in GR detection in the brain of kokanee salmon [Carruth et al., 2000]. The primary antiserum used in detection of the Na⁺/K⁺-ATPase was mouse anti-chicken. Immunocytochemical studies performed with this antibody have confirmed its effectiveness in localization of the Na⁺/K⁺-ATPase in summer flounder [Schreiber and Specker, 2000].

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2. Materials and Methods

2.1 Fish Maintenance and Treatments

All juvenile summer flounder were obtained from the summer flounder hatchery at the University of Rhode Island Narragansett Bay Campus. Juvenile summer flounder were transferred to 5-gallon tanks where they were subjected to an acute osmotic stress. Twenty-four summer flounder were introduced to a 5, 30, or 50 ppt seawater treatment. The 30 ppt control treatment was Narragansett Bay water. Extreme environments were prepared as follows: Narragansett Bay water was diluted with ddH₂O to a concentration of 5 ppt; Narragansett Bay water was concentrated with instant ocean to 50 ppt. Summer flounder were exposed to their respective treatments for 6 days. Temperature was maintained at ~20°C. Fish were feed 10 mm pellets up to a day prior to sampling. Half water changes were performed daily and salinity was measured using a light refractometer (Zeiss).

At the time of sampling, flounder were anesthetized in MS222 (200 mg/L and buffered in 400 mg sodium phosphate/L). Flounder were pre-weighed and measured. Mean lengths of juvenile summer flounder exposed to 5, 30, and 50 ppt seawater were 28.04 mm, 29.30 mm, and 28.44 mm, respectively. Mean weights were 0.1922 g, 0.1876 g, and .1817 g, respectively. Twelve summer flounder from each treatment were set aside and stored at -20°C. Three summer flounder from each treatment were fixed in neutral buffered formalin (10%). Gill, stomach, and intestinal tissues were dissected out of summer flounder and stored at -20°C in RNA later.

2.2 Cortisol Radioimmunoassay

Whole body cortisol concentrations were measured from juvenile summer flounder stored at -20°C. Juveniles were homogenized in 1 ml of phosphate buffered saline (PBS) using a polytron. Samples were centrifuged at 3400 rpm for 15 minutes at 4°C. Sample supernatants (500 µl) were spiked with 10 µl of radiolabelled (³H) cortisol and incubated at room temp for 30 minutes. Spiked samples were combined with 1.5 ml of ether, agitated for 15 minutes, and chilled in a methanol cold bath. Unfrozen aqueous layers were decanted and saved. This ether extraction was performed twice. Ether was evaporated overnight. The following day, dried samples were reconstituted with 500 µl of standard diluent and vortexed briefly. Duplicate samples were incubated overnight at 4°C and consisted of 200 µl of unknown sample 150 µl of radiolabelled cortisol in PBS (~13,000 cpm's), and 100 µl of cortisol antibody in standard dilluent (1:150 dilution). Dextran coated charcoal (400 µl) was added to sample tubes. Tubes were vortexed briefly and centrifuged at 3000 rpm for 15 minutes at 4°C. Samples (500 µl) were combined with 5 ml of Biosafe II scintillation cocktail and counts per minute were obtained from a scintillation counter.

2.3 Immunocytochemistry

Juveniles fixed in neutral buffered formalin (10%) were routinely embedded in paraffin, sectioned at 5 µm, and attached to polylysine coated slides. Slides were deparaffinized, hydrated, and incubated in 0.3% H₂O₂ in

Figure 1. Na⁺/K⁺-ATPase immunoreactivity in gills of juvenile summer flounder treated with mouse anti-chicken antiserum. Dilutions of antiserum were tested for specific staining of the Na⁺/K⁺-ATPase with little background. Tenfold dilutions ranging between 7.0 and 0.007 mg/ml were applied to slides and incubated for 2 hrs at room temp. Observations were made using a light microscope at 400x magnification.

water for 30 min. For localization of the glucocorticoid receptor the following reagents were applied to slides and incubated in a humidity chamber: normal rabbit serum in PBS (15:1000) for 20 min; anti-rabbit glucocorticoid receptor 1:1000 in PBS at 4°C overnight; anti-rabbit biotinylated secondary antibody (Vector) 5:1000 in PBS for 30 min; avidin-biotin horseradish peroxidase (Vector, ABC kit) according to manufacturer instructions. All incubations were performed at room temperature, unless specified otherwise. After all incubations, slides were washed in PBS for 5 minutes with the exception of the incubation with normal rabbit serum. Finally, slides were developed using Sigma diaminobenzidine in ddH₂O for 5 minutes, dehydrated, and mounted.

Immunocytochemical analysis for the Na⁺/K⁺ ATPase in gill chloride cells was performed following the procedure above with some modifications. Prior to conducting immunocytochemistry on sections, various dilutions of primary antibody were tested to determine the best concentration for incubation. Slides were incubated in 7.0 µg/ml, 0.7 µg/ml, 0.07 µg/ml, 0.007 µg/ml or no antibody (control) for 2 hrs at 4°C (Figure 1). For the localization of the Na⁺/K⁺ ATPase, anti-mouse Na⁺/K⁺ ATPase antibody (0.07 µg/ml) was applied to slides and incubated at room temp for 2 hrs. Following immunocytochemical staining, slides were counterstained with hematoxylin and eosin.

2.4 Northern Blot Analysis

At the time of analysis tissue samples were frozen and ground in liquid nitrogen. RNA was extracted from tissue using RNA wiz and quantified spectrophotometrically. RNA was electrophoresed on a glyoxal-based gel aside a RNA ladder and blotted onto a BrightStar™-Plus positively charged nylon membrane following Northern Max™-Gly protocol (Ambion). RNA was cross-linked by heating in 90°C oven for 15 minutes. Hybridization was performed following BrightStar™-Psoalen-Biotin protocol (Ambion) with a few modifications. Hybridization took place at 42°

Figure 2. Survival of juvenile summer flounder adapted to 5, 30, and 50 ppt saltwater. Each treatment group consisted of 24 to tank. N = 1 tank per treatment. Duration of treatment was 6 days. Survival of fish adapted 50 ppt saltwater indicates that this treatment is an osmotic stress.

C overnight with a biotinylated 42 b.p. oligonucleotide probe for flounder GR, sequence 5'-CCA GTT TTG ACT GGC GTT CTC CTC CCT CTT GAC GAT GGC TTT -3'. Results are still being processed.

2.5 Statistical Analysis

Radioimmunoassay data was log-transformed and computed into means ± SEM. One-way analysis of variance (ANOVA) was applied to determine whether there was a significant difference ($P < 0.05$) between the three treatment groups. When the difference was significant, comparisons for all pairs were performed using Tukey's honestly significant post hoc test. Statistical analyses were performed using SPSS statistical software.

3. Results

3.1 Survival

In an effort to determine the strength of each treatment as an osmotic stress, survival was plotted against time. Throughout the 6-day treatment period, daily recordings were made noting deaths in each salinity treatment (Figure 2). The survival of juvenile summer flounder was most notably affected by 50 ppt salinity.

3.2 Cortisol Radioimmunoassay

Mean whole body cortisol concentrations in juvenile summer flounder subjected to 5, 30, and 50 ppt salinity were 1.28, 0.44, and 4.66 ng/g, respectively. Cortisol levels in flounder exposed to 50 ppt salinity were significantly greater than those in flounder exposed to 30 ppt (Figure 3). Statistical tests confirmed a significant difference ($P < 0.05$). Cortisol levels in fish exposed to 5 ppt salinity were not significantly different from those in fish exposed to 30 ppt.

Figure 3. Mean whole body cortisol concentrations in summer flounder exposed to 5, 30, and 50 ppt saltwater. Groups with the same letter are not statistically different.

3.3 Localization of the GR in Osmotic Tissue

Expression of the glucocorticoid receptor was evident in osmotic tissues (gills, stomach, and intestine) in summer flounder sampled from all three salinity treatments, as evidenced by immunoreactivity with anti-glucocorticoid receptor antisera (Figures 4-6). Immunoreactivity for the GR in osmotic tissues, as well as the Na^+/K^+ in Gills, from flounder exposed to 5 and 50 ppt salinity was compared to that from control (30 ppt) flounder.

Figure 4 shows localization of the GR in gills. Immunoreactivity was greater in gills and chloride cells of flounder exposed to 5 ppt than 30 ppt salinity (Figure 4). No difference in immunoreactivity in gills and gill chloride cells was observed for flounder exposed to 50 ppt when compared to control. The relative amount of chloride cells appeared to be the same across all three treatments.

Figure 5 shows localization of the Na^+/K^+ -ATPase in

gill chloride cells. Immunoreactivity was observed to be greater in chloride cells in gill sections of flounder exposed to 5 ppt salinity than 30 ppt; however, fewer chloride cells were expressed in the gills of 5 ppt treated flounder. Immunoreactivity of the Na^+/K^+ -ATPase was comparatively the same in gill chloride cells of flounder exposed to 50 ppt salinity and 30 ppt.

Figure 6 shows GR localization in the fundic stomach of juvenile summer flounder. Nuclear staining of the GR was observed in epithelial cells and cells surrounding the gastric glands in flounder exposed to 30 salinity. Fewer nuclei in epithelial cells and no nuclei in cells surrounding the gastric glands were immunoreactive in flounder exposed to 50 ppt salinity. Although some nuclear immunoreactive cells were evident in stomach of flounder exposed to 5 ppt, the majority of the immunoreactivity was cytoplasmic.

Figure 7 shows GR localization at the basal side of columnar epithelial cells in the intestine of summer

Figure 4. Glucocorticoid receptor immunoreactivity in gills of juvenile summer flounder adapted to 5, 30, and 50 ppt saltwater. Immunoreactivity shows localization of the GR in gill chloride cells (arrow). Sections were analyzed under a light microscope at 200x magnification.

Figure 5. Glucocorticoid receptor immunoreactivity in stomach of juvenile summer flounder adapted to 5, 30, and 50 ppt saltwater. Nuclear staining is evident in epithelial cells of the fundic region (arrow). Sections were analyzed under a light microscope at 200x magnification.

flounder from all three treatments. Intense nuclear staining and little cytoplasmic staining was observed in intestine of flounder exposed to 30 ppt salinity. Immunoreactivity of the GR was predominantly nuclear in flounder exposed to 50 ppt salinity. Fewer immunoreactive nuclei were observed in 50 ppt treated fish than control. Immunoreactivity in flounder exposed to 5 ppt was mainly cytoplasmic with little evidence of nuclear staining.

4. Discussion

The most important finding from this study is the localization of the glucocorticoid receptor in three major osmoregulatory organs: the gills, stomach, and intestine of summer flounder. Specifically, in the gills, immunoreactivity for the GR and the Na^+/K^+ -ATPase was observed at the site of gill chloride cells. This observation is in agreement with results obtained for chum salmon fry, in which immunocytochemical reactivity for the glucocorticoid receptor was identified

in Na^+/K^+ -ATPase rich gill chloride cells [Uchida et al, 1998]. Previous studies on summer flounder have implicated the Na^+/K^+ -ATPase as the main enzyme involved in the exchange of ions across the gills [Schreiber and Specker 1999]. Na^+/K^+ -ATPase is regulated by cortisol in fish [McCormick, 1995]. Identification of the GR in chloride cells of summer flounder provides evidence for a direct action of cortisol on the gills.

The increase in whole body cortisol concentration in summer flounder exposed to 5 and 50 ppt salinity mirrors increases often observed when flounder undergo metamorphosis and move from oceanic to estuarine environments [de Jesus et al., 1993]. Thus a change in the level of cortisol is likely adaptive for changes in environmental salinity. The immunoreactivity of the GR observed in the present study in flounder exposed to 5 ppt may however contradict previous beliefs. Immunoreactivity of the GR, although high in gill chloride cells, was mainly cytoplasmic in the stomach and intestine of flounder exposed to 5 ppt salinity,

Figure 6. Glucocorticoid receptor immunoreactivity in intestine of juvenile summer flounder adapted to 5, 30, and 50 ppt saltwater. Intense nuclear staining is evident at the basal side of columnar epithelial cells (arrow). Sections were analyzed under a light microscope at 200x magnification.

Figure 7. Na^+/K^+ -ATPase immunoreactivity in gills of juvenile summer flounder adapted to 5, 30, and 50 ppt saltwater. Immunoreactivity shows localization of the Na^+/K^+ -ATPase in gill chloride cells (arrow). Sections were analyzed under a light microscope at 200x magnification.

when the opposite was true in flounder exposed to 50 ppt. Very little immunoreactivity in the nuclei was observed in flounder exposed to 5 ppt. It may be that cortisol is in fact the salinity-adapting hormone as observed previously, but not the low salinity adapting hormone. This however is speculative and would need to be investigated further.

In this study, a more intense immunoreactivity for the GR as well as the Na^+/K^+ -ATPase in the gills was observed in flounder exposed to 5 ppt salinity as compared to 30 and 50 ppt. Previous studies have reported the opposite. Uchida et al. [1998,] observed a greater GR staining density in chum salmon fry adapted to seawater than those adapted to freshwater. In addition, in the present study, flounder exposed to 50 ppt were overall less immunoreactive than flounder exposed to 30ppt salinity; however, the flounder exposed to 50 ppt exhibited significantly greater whole body cortisol levels than those exposed to 30 ppt. These results are similar to those obtained for chum salmon fry in which fish treated with exogenous cortisol exhibited a lower immunoreactivity of the GR [Uchida et al., 1998]. It may be possible that these raised cortisol levels are signaling a down regulation of the GR and would account for few numbers and low staining intensity.

Immunoreactivity of the GR, accompanied by raised cortisol levels in flounder exposed to 5 and 50 ppt salinity imply that a biological response to the sudden change in environment was occurring. The incidence of this response was most likely to signal a change in osmoregulatory capacity in an effort to adapt to the new salinity. However, in the case of flounder exposed to 50 ppt salinity the decreased immunoreactivity of the GR in the stomach and intestine (as compared to flounder exposed to 30 ppt), the observed down regulation of the GR may be a homeostatic mechanism in response to elevated cortisol.

The observation that juvenile summer flounder transferred to 50 ppt salinity had low survival contradicts those results of Schreiber and Specker [1999], where juvenile summer flounder exposed to 50 ppt salinity exhibited 100% survival. Osmotic stress may have contributed to the survival ability of juvenile summer flounder in the extreme salinity treatment (50 ppt).

Juvenile summer flounder exposed to extreme saline environments exhibited raised cortisol levels implicating a stress response was taking place. Immunoreactivity of

the GR and Na^+/K^+ -ATPase in gills, as well as immunoreactivity of the GR in the stomach and intestine implicate cortisol in ion regulation in summer flounder. However, observations made in the stomach and intestine of flounder exposed to 5 ppt salinity may indicate that cortisol is not the low salinity-adapting hormone in summer flounder. Further information would need to be gathered in order to support these ideas.

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Mapping of the Crater of the Submarine Arc Volcano, Kick'em Jenny, in the Lesser Antilles Volcanic Arc.

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Abstract. A survey of Kick'em Jenny, a submarine volcano north of Grenada, was conducted in March 2003 using a SEABEAM mapping system. An unmanned submersible (ROV) that was employed in the crater of Kick'em Jenny recorded approximately 22 hours of video footage, which was subsequently used in this study to make qualitative observations of the crater's geologic formations. Observations were made of crater floor characteristics such as slope, color, type and other features (i.e., hydrothermal vents, lava flows, pyroclastic deposits, fish), at a minimum of 30-second intervals. These observations were then used to create a geologic map of the crater. A bathymetric map created with the SEABEAM data served as a base map on which observations were plotted spatially using correlated time codes and ROV navigational data. These plotted observations were then mapped using ArcGIS. Mapping of Kick'em Jenny crater was conducted on the scale of tens of meters, a higher resolution than used in previous submarine volcano mapping projects. Three separate crater regions, the crater rim, main crater floor, and the inner crater on the west of the main crater floor, were distinguished through the mapping. Notably, hydrothermal venting was isolated to the inner crater, which may be the location of recent volcanic activity. The rim and the main crater floor displayed different features, including a thick orange-red mat on the main floor, and large blocky outcrops on the rim. Comparisons between the crater of Kick'em Jenny and other mapped submarine volcanoes and craters will enhance our understanding of submarine volcanic processes.

1. Introduction

Submarine arc volcanoes are an important part of active island arc systems, though they are not well understood. The formations found in these volcanoes, including volcanoclastic sequences (Wright, 1996) and hydrothermal mineralization, are indicative of the past and current types of eruptive processes and activity taking place. It is also understood that shallow submarine volcanoes, such as Kick'em Jenny, present hazards to surrounding populations due to explosive styles of volcanic activity that take place at depths less than several hundred meters (Kokelaar, 1986).

A detailed geologic map of a submarine arc volcano can help us to better understand the volcanic processes that take place in this geologic setting, and summit depth. By pinpointing locations of rock structures and other features in the volcano, we can more effectively determine the eruptive processes that take place in a submarine arc volcano. To date, only a small number of submarine arc volcanoes have been studied in detail (i.e. Wright, 1996).

In March of 2003, a cruise using a SEABEAM mapping system, conducted a survey of the Kick'em Jenny volcano. An unmanned submersible (ROV) took three dives in the crater of the volcano, capturing video footage of the crater floor and rim. In this paper we will use ROV observations coupled with a high resolution

map of Kick'em Jenny crater to create a detailed geologic map.

2. Geologic Background

Kick'em Jenny (KEJ) is a submarine volcano located 7.5 km north of Grenada in the Lesser Antilles volcanic arc. Previous studies have laid a foundation for the detailed study of the eruptive processes, structure, and magmatic system of Kick'em Jenny. (Sigurdsson and Shepherd, 1974; Shepherd and Robson, 1967; Devine and Sigurdsson, 1995; Smith and Shepherd, 1996). First discovered in 1939 during an eruption, KEJ has since erupted 12 times, most recently in 2001. Of these eruptions, three have broken the surface of the water, and the most recent of these events took place in 1990. KEJ is the most active volcano in the West Indies. Currently at its summit, KEJ is approximately 180 meters below the surface of the water. The cone itself is growing within a westward opening horseshoe shaped scarp, similar to the one seen on Mt. St. Helens after a massive failure on its flanks took place at the beginning of the May 18, 1980 eruption.

The crater of KEJ can be divided into three morphologically different regions. (Figure 1a) The first is the crater rim, which is topographically higher than the rest of the crater, and does not completely circle the crater. A gap in the rim of the crater is present in the north. The crater summit is located on the west side of

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Figure 1. Bathymetric map of Kick'em Jenny crater, ranging from -61.64° to -61.6355° longitude and 12.2985° to 12.303° N latitude. a. Regions of different morphologies: 1) the crater rim; 2) the inner crater; and 3) the flat crater floor. b. Survey coverage.

the crater rim. The second region is a depression in the north of the crater, located in the northwest of the crater floor, called the inner crater in this paper. This inner crater is the deepest part of KEJ crater. Finally, the third region is the remaining flat crater floor area south and east of the inner crater.

The summit, located on the crater rim, is approximately 180 meters in depth, while the deepest point in the inner crater is approximately 265 m deep. The main floor of the crater is about 240-245 meters in depth. The crater is approximately 320 meters in diameter.

Rock types at Kick'em Jenny range from olivine basalts to andesites (Sigurdsson and Shepherd, 1974), though the volcanics are considered unusual. Amphibole megacrysts in basalts are present in great abundances. These megacrysts have been attributed to

high volatile content or to the assimilation of xenocrysts from crustal rocks (Devine and Sigurdsson, 1995). In the crater of the Kick'em Jenny, outcrops with jointing, as well as ash and lapilli have been found.

3. Methodology

3.1. Video Observations

Videos taken with an ROV were viewed in order to make qualitative observations of the floor of the crater of Kick'em Jenny. Three dives were made in the crater (dives 2, 3, and 6 of the 2003 ROV survey, Figure 1b) which amounted to approximately 22 hours of total video footage. In addition to the video camera, the ROV was also equipped with push cores, a suction pump, a robotic arm, and a transponder for location.

Observations made from the ROV tapes were logged with times based on videotape time codes, and then converted to GMT times. Video observations were made on the basis of changes in feature identification (discussed in section 3.4, Feature Identification), and either every 30 seconds, or in an ad hoc fashion, as determined by ROV operations at any point in a dive, or the clarity of the image.

3.2 Navigation

A transponder onboard the ROV provided the ROV's positions relative to the cruise vessel during dive operations. Every two seconds, a position for the ROV was recorded, and converted into UTM's. These positions were then converted into latitude, longitude decimal degrees for incorporation into the GIS map.

3.3 Crater Map

Using SEABEAM data from the survey conducted in March 2003, a high-resolution bathymetric map was created in SURFER (Figure 1). The data were gridded at ten meters, and subsequently filtered using a low-pass filter feature in SURFER, and plotted using a contour plot. The contour interval seen in all map figures is five meters. This high-resolution bathymetric map was imported into ArcGIS, and assigned spatial coordinates to serve as a base map for the detailed geologic map.

3.4 Feature Identification

Qualitative observations of the crater's geologic and other features included bottom type, bottom color, bottom slope, hydrothermal vents, and biological organisms, (Figure 2 and Table 1). Observations were made when the bottom type, color, or slope changed relative to the previous location, or, if bottom type had not changed, when approximately 30 seconds had passed during ROV movement. Features were also observed in the same fashion.

3.4.1. Type. Types were identified on the basis of relative size, location (relative to a slope), and overall appearance (e.g. presence of jointing). "Sediments" differed from ash in color only (gray v. beige), and talus was observed on the basis of the shape of the rock

Figure 2. Examples of observed features: a: Orange bacterial mat and gray ash/lapilli; b: fish; c: fissures and shimmering water with a hard packed organic mat; d: nearly vertical outcrop with thin organic cover.

Table 1. Observed Bottom Types

Category	Observed Bottom
Type	ash, lapilli, block, talus, breccia, hard packed organic material, bacterial/organic mat, dykes/lava, sediments
Color	red, orange, white, white patches, gray, dark gray, black, beige, brown, orange-beige, mottled
Slope	Flat, gentle, moderate, steep, cliff, hummocky, irregular, mounds, pits
Hydrothermal Features	Fissures, hydrothermal vents, gas bubbles, shimmering water
Biological Features	Fish, sharks, swimming shrimp, shrimp, worm, coral
Other Features	Crusted layers, man made objects, ridges, ledges, sedimentary ripples, gravity flow chutes, debris flows

(round v. angular), as well as proximity to the base of a slope.

3.4.2. Color. Colors were marked in hues relative to one another. Light quality on the bottom was at times lacking, which created some difficulties in determining the exact color of the bottom material. The full list of colors observed is listed in Table 1. Warm colors, such as reds and oranges may be lumped together as similar colors due to lighting difference during ROV operations. Also, gray and dark gray may be grouped in a similar color category. White was fairly clear throughout the videotape, and was easily observed, especially when juxtaposed with grays.

3.4.3. Slope. Slope identification posed a few difficulties, as ROV tilt information, was not readily available during the observation process. Flat and gentle slopes may appear very similar to each other in the videotape depending on the tilt of the ROV. However, cliffs and very steep slopes (nearly vertical or greater than $\sim 60^\circ$) were distinguishable from the flat and gentle slopes. Mounds were in general quite smooth in appearance and on the scale of a meter to a few meters in size. Pits were identified as large bowls in the bottom with steep sides.

3.4.4. Hydrothermal Features. Hydrothermal vents and fissures were indicated by either gas bubbles in the water column, or by shimmering water escaping from the crater floor. Fissures were observed as narrow openings on the crater floor where either gas bubbles or shimmering water was being released, while hydrothermal vents were observed as features and points that exhibited either shimmering water or bubbling from the crater floor.

3.4.5. Biological Features. Fish, shrimp, and coral were among the biological organisms observed in the crater. A distinction was made between largely immobile shrimp and what appeared to be swimming shrimp in order to locate these occurrences on the GIS map. Spiral corals, sharks, worms, and fish ranging from large to very small were also observed.

3.4.6. Other Features. Other features viewed in the videos, including ridges and ledges were also observed and identified.

3.5 Integration of observations with GIS map

All observations, as previously mentioned, were entered in a database as time codes taken from videotape footage. These time codes were converted into decimal degree coordinates by linking time codes for each dive with corresponding coordinates determined using the ROV navigation data. The coordinates for each kind of observation (e.g. ash, fish, fissures) were then placed in “x, y” form tables and imported into ArcGIS. Each set of observations was plotted spatially as separate layers over the previously created base map. Related layers (e.g., types, slopes) were then grouped for easy navigation through the GIS map.

4. Results

Each group (e.g., type) was best viewed in small sections with one layer or a few layers on at a time. With all data points turned on, interpretation is extremely difficult, if not impossible. In this section, we break into some main categories of interest (Figure 2).

4.1 Hydrothermal Vents

Hydrothermal vents in the Kick'em Jenny crater are found exclusively in the inner crater of the volcano. No other hydrothermal activity was observed outside of this region. There are two major fissure locations centered near 12.3013°N latitude, -61.6380° longitude, and near 12.3010°N latitude, -61.6375° longitude (Figure 3). Fissures were generally noted by an outpouring of shimmering water, as previously mentioned. Though shimmering water was at times found at vents not labeled as fissures, gas bubbles were generally not seen escaping from fissures.

Such tight clustering of vents and fissures within the inner crater likely represents the active vent site for recent volcanic activity.

4.2 Biological

Not only was hydrothermal venting restricted to the inner crater region, but shrimp were also limited to the inner crater region of the Kick'em Jenny crater (Figure 4). Many shrimp were found scattered or piled among hydrothermal vents, while others were found in locations where venting was not visible. Fish, large and small, for the most part avoided the inner crater region and the hydrothermal vents (Figure 4). Fish observations were most common along the crater rim, and on the flat crater floor region on the east side of the crater. Only two sharks observations were made in the not observed again in the crater. Given the locations of the fish relative to the hydrothermal activity, it is possible that the vents are emitting toxins that these fish cannot tolerate, which leaves shrimp to be found in large quantities in the inner crater.

Figure 3. Close-up of the inner crater region. Left: Hydrothermal vents (white) and fissures (black). Right: Gas bubbles (black) and shimmering water (white).

Figure 4. Fish (black) are seen along the rim and crater floor, while shrimp (gray) and hydrothermal vents (white) are seen in the inner crater. crater, both were hovering near the inner crater, and one venturing in the inner crater. One fish was also seen in the inner crater, this type of fish was unique, and was

Along one of the fissures, shrimp were not visible, and shimmering water was the most obvious feature. Given this information, it is possible that these fissures are either not providing proper nutrients for shrimp to feed on, or are located in areas with currents that make habitation unfavorable.

Corals were viewed only on the most shallow areas along the crater rim.

4.3 Bottom Types

A majority of the crater floor is covered in an orange-red bacterial mat that varies in thickness and texture depending on location within the crater (Figure 5). In the flat, main crater floor region, the mat appeared thick and bright in the video; occasionally dark gray talus blocks disrupted the orange-red colored floor. In the inner crater the orange-red bacterial mat was much more patchy than on the flat floor region. Along the rim, however, the bacterial mat was not visible, but an organic material was seen in the form of a sparse and curly covering on the rock faces, usually white in color. Throughout the crater, the bacterial mat often obstructed the view of other bottom types, making identification difficult at times.

Among the obstructed types, ash and lapilli were often found somewhat covered by the bacterial mat. Most ash and lapilli was identified in the inner crater, and some patches were visible on the flat floor of the crater. Blocks were at times seen broken and scattered along the crater floor, and along the rim. The rim consisted of mostly blocky and dome features, not seen on the crater floor. Hydrothermal vents were found among breccias with ash and lapilli also surrounding them.

Lava flows and outcrops of possible dykes were observed across the inner crater, and at points along the crater rim, though the number of observed locations is too few to draw conclusions.

4.4 Slope

Through the crater, a great deal of variability in bottom slope was observed (Figure 6). This was especially apparent in the inner crater region, where cliffs were observed in areas where the bathymetric map indicated a somewhat gentle slope. In the inner crater, both steep and gentle slopes were observed. Cliffs were also seen along the crater rim, as was expected given the bathymetric map's contours.

Besides cliff faces, hummocky bottoms were observed in the flat crater floor area in the east, and also in the inner crater. The inner crater was also the site of most mounds seen—observed near fissure areas—and pits, which were located only in the inner crater near major venting areas centered around 12.3014°N latitude, -61.6377° longitude (Figure 6).

4.5 Color

Though color may at times be difficult to determine in the underwater environment due to the poor quality and location of the light source, color may prove an

Figure 5. Dots indicate the orange-red bacterial mat in KEJ crater.

Figure 6. Distribution of cliffs (black dots), hummocky surfaces (white dots), mounds (light gray triangles), and pits (black circles).

excellent indicator for specific features. For example, when the color white was found in patches along the floor, the ROV was either near a hydrothermal vent field, or gas bubbles and a hydrothermal vent accompanied that color patch. The red and orange bacterial mats were found all across the floor of the crater. Most of the gray color in the form of sediment was found in the inner crater in patches (Figure 7).

4.6 Topographic

Potential debris flows were observed in the ROV videotapes. Debris flows were identified on the basis of topography (location relative to a slope, hummocks) as

well as rock type present relative to dissimilar adjacent bottom types. One of these potential flows was found centered around 12.3010°N latitude, -61.6377° longitude. This possible flow is found just west of a fissure center, and also in a lower topographic region.

5. Discussion

The ROV observations in Kick'em Jenny's crater reveal a series of distinct geologic environments. The small inner crater is perhaps the most interesting owing to the great diversity of geologic and biologic features. Unlike the rim and the flat floor of the main crater, the inner crater is the only area with visible hydrothermal activity. The inner crater is also the only site where shrimp, either swimming or sedentary, have been observed. Also limited to the inner crater are pits and one likely debris flow. Ash and lapilli in the inner crater are also visible due to the patchy nature of the bacterial mat. Mounds are seen around fissure sites, which may indicate the material below the surface of the inner crater has undergone some expansion. The presence of shrimp and the lack of fish around hydrothermal vents and fissures may indicate that toxins intolerable to fish, and either tolerable or intolerable, yet not sensed by shrimp, are present in the water. If the masses of sedentary shrimp are in fact alive, the lack of fish in the inner crater would provide for an ideal living environment for these animals.

Fish found along the crater rim and main crater floor are of a range in size from approximately one half-foot to more than a few feet in length. Their presence in these areas of the crater is not unexpected, however, their absence from the inner crater is noteworthy. The rim appears to invite large fish, and is also home to corals, worms, and small, white organic rock coverings. The blocks and steep slopes of the crater rim may provide an area of upwelling of nutrient-rich water from currents entering the gap in the crater rim. This may explain the relative abundance of corals, fish and other forms of life in this area.

The main crater floor is largely covered in a flat, orange-red bacterial mat, which is occasionally disrupted by rock fall from the rim. In this location, the thickest and least disturbed orange-red bacterial mat was observed, though ash and lapilli were occasionally visible through the mat. All blocks seen along the floor of the crater were angular; no pillow lavas were observed in the Kick'em Jenny crater. This, in conjunction with the great abundance of ash and lapilli on the crater floor, would indicate that the latest dominant style of volcanism was explosive in nature.

The complex geologic structure present in the inner crater and the abundant hydrothermal activity strongly suggest that the inner crater is the active vent area at Kick'em Jenny, and that the inner crater region is likely the site of the last eruption.

6. Conclusions

ROV observations at the crater of Kick'em Jenny have provided a foundation for the construction of a

high-resolution map of a variety of geological and biological features. An important find is that hydrothermal activity is restricted to the inner crater region of the Kick'em Jenny crater. Ash and lapilli are generally found in the inner crater and are observed through patches of the thick bacterial mat covering the main crater floor. Biological features, including fish and shrimp were observed in separate regions of the crater. These organisms demonstrate an important link to the hydrothermal venting at Kick'em Jenny. The shrimp were restricted to the inner crater region, while nearly all fish were observed outside of this geologically active region. Mounds and lava flow/dyke outcrops found near hydrothermal vents further point to the likelihood that the location of the latest eruptive activity took place in the inner crater, and will likely take place in the inner crater in the future.

Further work on this map will add push core and grab sample information taken in the crater to the map, as well as attempt to map distinct geologic unit contacts. Future work will also look at furthering our understanding of bottom slope and bottom type relationships across the crater that are not evident when looking at a bathymetric map of the study area.

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Figure 7. Orange-red (gray), gray (black), and white (white) color distribution in KEJ crater.

Evolution of Laboratory Generated, Velocity-Shear Fronts

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Abstract. This paper discusses an experimental technique used to produce and observe laboratory-generated, constant forcing, velocity-shear fronts. We also provide arguments for the use of particle imaging velocimetry (PIV) in quantifying slow liquid flows. The experiments were performed in a 1m in diameter, cylindrical tank, atop a rotating table. The flow was visualized through the use of a PIV system. Fronts were produced through use of a “front generator”, consisting of an inner disk encircled by flat outer ring. To produce the velocity shear, the inner disk was made to rotate relative to the outer ring. Data shows that these shear fronts are subject to continuous change, never reaching a true steady state. They are subject to either continual collapse and rebuild, or are discontinuous and circulate around the frontal area.

1. Introduction

A prominent feature the oceans are fronts, which may be defined as a boundary at which the background gradient is much less than that across the boundary. Studies of the subtropical convergence zone (STCZ) have indicated that it is an area of great frontal activity. Satellite-generated sea surface temperature data seems to suggest that frontogenesis in this region be on a time scale of about one month. (Cornillon, Shan 2000 yet unpublished). A desire to better understand the processes responsible for frontogenesis is the motivation for the following work. We turn to the lab to better understand the processes behind front formation. I wish to emphasize that we are not attempting to recreate ocean fronts, we are only attempting to produce them in the lab, and if successful, study their evolution and behavior. Work on this project has been the focus of summer interns for the last three years. Preliminary work included designing a dye injection system to observe the fluid behavior (Buffington and Cornillon, 2001), and then to obtain vector fields from this dye injection system (Dionne and Cornillon, 2002). Using this dye injection system, rotating table, and front generator (consisting of an rotating inner disk and outer ring fixed to the table) it was suggested that spin-up of the inner disk results in a flip of the azimuthal velocity component at 100s after disk rotation begins. At this same time lateral shear was found to peak about 1cm on either of the inner disk (Dionne and Cornillon, 2002). There was concern that the injection of dye effected the fluid motion and also that a dye system would not give the detail need to understand front formation. This year we have implemented a Particle Image Velocimetry system (PIV) to solve these problems. In what follows, I will show evidence of PIV's ability to quantify slow flow fluids, and illustrate some of the characteristics of frontal formation.

2. Set-up

An effective method for studying fluids is to use a

rotating table. The rotating table we used is controlled via an external control panel adjustable to 0.001rad/sec and having a rotational speed stability of $\pm 0.01\%$ between 0.2-10rad/sec. Fixed to the table, extending 227cm above its surface is a rigid, external superstructure. Inside the superstructure, sitting on the table, is a cylindrical tank 1m in diameter by 46cm tall with a clear plastic lid (note the lid is not in contact with the fluid). Inside the tank sits our front generator. This consists of a circular sheet of plastic 1m in diameter. A 50cm disk in its center is cut allowing it to rotate freely. While the exterior ring is fixed to the table, a 90V DC motor, whose speed was varied by a Permanent Magnet DC Gearmotor Speed Control, drives the inner disk. Connection is made with the outer world through 20 gold slip rings in the base of the table and various wireless communications.

The new addition to the set-up this year has been a PIV system. This system consists of a dual cavity, Nd:YAG pulse laser, two CCD cameras (two are need for 3D imaging) and a computer. The computer and laser control box are mounted underneath the table rotating with it and the cameras are mounted on optical tracks running up and down the height of the superstructure. The laser is mounted vertically off the side of the tank on tracks allowing it to move both vertically and horizontally. This set-up allows for a wide range of versatility while remaining very stable. A mirrored elbow reflects the laser pulse 90° horizontally into the tank. A beam diverger attached to the end of the elbow then diverges the laser pulses into sheets of light. These sheets of light are then reflected off seed particles in the fluid. The CCD cameras capture the light reflected off the seed particles. The computer triggers the camera shutter so that it picks up only one pulse of light at a time. Our system is capable of up to eight separate images per second. That is four 2D vector fields or two 3D vector fields each second. Each images is 1376x1040 pixels. The imaging rate of the system is limited by the speed at which the camera is able to transfer data to the computer. However, the camera is able to store one image while taking another. This allows for two images to have time separations of only a few microseconds. These specifications are for running the cameras in double-frame double-exposure

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mode, which we chose to use because it allows us to evaluate the images with a cross-correlation method to derive our vector fields. Our system was purchased through LaVision and runs Davis software.

For the runs presented here, the rotation rate of the table was 1.611rad/sec. The fluid was water, and at rest had a depth of 4cm above the front generator. When the inner disk was activated it had a rotation rate of .0087rad/sec with respect to the table. Both were rotated in the counter-clockwise sense. These numbers give us a Rossby radius of deformation (R_d) of 19.4cm, five times larger than our water depth, meaning we have approximately a vertically rigid fluid. The Rossby number (R_o , using a safe approximation of $L=r$) gives us a value of $0.0054 \ll 1$ so we can ignore advective terms and are dealing with a geostrophic flow. Finally, the Ekman number (E_k) is $1.55 \times 10^{-5} \ll 1$ so that frictional forces are of little importance except during spin-up.

3. Methods

The PIV system provided the initial cross-correlation software to produce our vector fields. This software was also used to do an initial filtering of the data. This was accomplished through a median filter, which looked at a 3×3 gridded region and removed and replaced the center value if it was not within three standard deviations of its eight neighbors. Further filtering was done using a Matlab filter program (this extent of

filtering may not have been needed but was a first attempt to achieve an optimal method) and another Matlab program was used to decompose the velocity into radial, azimuthal, and vertical components, as a function of time, and to average these components in time and plot them against radial position.

4. Tank Spin-up

The key features seen in Figure 1 are the exponential decay of azimuthal velocity, as well as an exponential “mirror image” for the radial velocity. Note as well that the radial velocity is negative (inward), except for the first few seconds, which qualitatively makes sense if we think of the Ekman layer pumping outward in the small Ekman layer at the bottom of the tank with a return flow inward higher up in the fluid. Another important feature is the linearity of the radially averaged azimuthal velocity versus radial distance. A crude best-fit line reveals that the slope is about 1.8 (after appropriate conversions). Since $v=r\omega$, v/r should equal the rotation rate of the table which is 1.611rad/sec. This is within a 12% error.

Consider again the exponential behavior of the azimuthal velocity, the tank was initially at rest for some time, roughly 15s (while images were being taken) and the tank takes a few seconds to go from 0 to 1.611rad/sec. To take this into account, we omitted the first 20s when fitting a curve to the exponential. This

Figure 1. Tank spin-up velocity data: top, azimuthal; middle, radial; bottom, vertical. The different colors indicate radial distance (red about 27cm, black about 20.5cm). On the right we have the temporally averaged components of velocity versus radial distance. The vertical red line indicates the boundary between the inner disk and outer ring. Note that positive azimuthal velocity is counter-clockwise, positive radial velocity is outward, and positive vertical velocity is up.

Figure 2. Same as Fig. 1 but for inner disk velocity spin-up data

gives us a result of $v = 0.4473e^{-0.0215t}$ m/sec. At $t=0$ this should be close to our table rotation rate. We obtain a rate of 1.78 rad/sec very near to the actual 1.611 rad/sec. Finally, a first estimate of the time required for the tank to spin-up is $E^{-(1/2)}\Omega^{-1}$ (Greenspan, 1969) where E is the Ekman number and Ω is the rotation rate of the table. This gives us a spin-up time of 158s, remembering to take into account the 20s of rest before the tank spin-up, we see that this estimate is in good agreement with our experimental results. These are crude estimates, but we can see that the PIV system give us results consistent with theory, lending credence to PIV's ability to quantify slow-flow fluids.

5. Spin-up and Steady State of Inner Disk

In this experiment we focus in on a 9x9cm region centered on the boundary between the inner disk and outer ring. The cameras are focused 2cm up from the front generator and are using 3D imaging. The sampling rate is one 3D image per 1.25s, and the time between two consecutive images is 90 milliseconds. The tank was spun-up at 7:50pm; at 12:30am the next day the inner disk was spun-up, and then at 10:40am steady state images were taken. Several features jump out immediately (Figure 2). Looking at the azimuthal velocity versus time graph, we see that the shear (difference in velocity from red to black) seems to have distinct minima. At the same time as the shear minima occur, we also see a spike in vertical velocity. This

corresponds to upwelling in the region just outside the inner disk.

Again, we see the same trends as we did for that of the spin-up case (Figure 3). Looking at the regions of least shear, we see that they seem to occur on a time scale of about 50s. That is, to go from a time of high shear to low shear takes about 50s and then back to a time of high shear in another 50s. This time scale corresponds to about 13 rotations. To further emphasize the relation between low shear and up-welling outside the inner disk, consider Figure 4 in which we see a strong correlation between low shear and vertical velocity outside the disk (blue), but none between low shear and vertical velocity inside the disk. This leads us to two possibilities: either the front (or a hole in the front) is moving into and out of the viewing area or the front is collapsing and rebuilding. To determine which possibility is correct, we must look at a wider viewing area. At this time, we do not have a lens of sufficiently wide angle to view the entire tank, or a 3D calibration plate large enough to calibrate the entire tank, but we can get a 2D picture of most of the tank. Experiments have been run but the data have not yet been processed. In either case, we can look more closely at the mechanism behind these oscillations.

The azimuthal velocity gradient decreases during the time 550-605s (Figure 5). During this same time period the radial velocity near the inner disk edge and farther out slightly increases, also the vertical velocity outside the inner disk doubles. Then during 605-700s, the

Figure 3. Same as Figure 1, but for steady-state data

Figure 4. Vertical velocity plotted with azimuthal shear (velocity difference between 27.0 and 20.5 cm radius).

Figure. 5. Azimuthal (top), radial (middle) and vertical (bottom) velocities as function of radial distance at these times (550, 606, 700s). Also the mean of these three profiles. We see the components of velocity plotted against their radial distance, at different times throughout one of these oscillations (an actual movie the event is more useful). The inner disk edge is marked with a vertical line.

azimuthal velocity gradient reappears. This is accompanied by an increase in radial velocity inside the inner disk and a great decrease in vertical velocity outside the inner disk as well as a few centimeters inside the inner disk.

According to previous observations (Dionne and Cornillon, 2002), 100s into spin-up of the inner disk a flip of the azimuthal velocity component occurs and lateral shear peaks about 1cm on either side of the inner/outer disk boundary. This is consistent with our data. Flips in azimuthal velocity occur just after regions of low shear, and these events also have large lateral shear. The use of the PIV, however, gives us a much more detailed picture of what is going on as well as allowing us to lengthen our observational time scale.

6. Problems/Solutions

1. The main problem we faced (all three years) is that the seam between the inner disk and outer ring is a place where fluid from underneath the front generator is able to upwell. Since the front generator sits up a little off the bottom of the tank to allow room for the drive mechanism. The first attempt to stop this upwelling was to place two plastic sheets 1mm in thickness over the entire bottom. One sheet would be a disk and the other

a ring, like the front generator. The outer ring would slightly overlap the inner disk and thus cover the seam. This, however, lead to some unwanted topography. The data I have presented here is subject to this topography. A second attempt was to plug this seam with grease. This worked with minimal success (data still being processed) but it is not an entirely satisfactory solution. The grease seeps out of the seam reflecting laser light and obscuring the images, also small gaps in the grease can form destroying its effectiveness. The best solution, which we could not accomplish due to time constraints, is to revamp our front generator, as shown in Figure 6. The Teflon is to reduce friction. A more easily implemented version would be achieved by placing another thinner ring and inner disk on top of the existing one, but with the seam offset. The reason we did not do this is again was due to a lack of time. The greatest difficulty in manufacturing these parts is the precision to which the seam cut must be made.

2. The inner disk drive mechanism should be improved. The present pulley-and-chain system is too fragile, and requires frequent attention. I recommend a direct drive shaft.

3. Light reflection from the top of the front generator was initially a problem in using the PIV system. This problem was overcome by painting the top surface of

Figure 6. Present (upper) and proposed (lower) designs for the front generator inner/outer disk boundary

both the inner disk and outer ring black.

Conclusions

We have demonstrated PIV's ability to quantify slow liquid flows by looking at the well-known tank spin-up problem. Nevertheless, I am a novice PIV operator, and have only scratched the surface of the system's potential. We have also shown that velocity shear fronts can easily be generated in the lab. The evolution of

these fronts is indeed a dynamic one. On the time scale we observed, they may never settle to an actual steady state. Whether these fronts collapse and rebuild or circulate around the tank is under investigation at this time. We do know, however, that the velocity shear decreases on a time scale of 50s or 13 revolutions. Accompanying this decrease, fluid near to and outside the inner disk ceases its inward flow becoming fairly stable in the radial direction, and there is large upwelling outside the inner disk. On the same time scale the velocity shear then reforms, accompanied by the formation of an outward flow inside the disk and a large cut off in the amount of upwelling near to and outside the inner disk.

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An Improved Numerical Model For Determining Chemical Reaction Rates

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Abstract. A robust numerical procedure for biogeochemical interpretation and analysis of measured concentration profiles has been developed by Berg et al.¹ The model utilizes an approximation of Fick's Second Law to find constant reaction rates in equally spaced/sized ranges of depth (a.k.a. 'zones'). This method works well for profiles several centimeters deep, where the resolution and complexity of behavior is uniform throughout the profile. However, it is limiting when attempting to analyze profiles several hundred meters in depth, in which case a model that can adjust accordingly to changes in sampling resolution and profile complexity would be more useful/accurate. Therefore, the concepts of the old model have been used and modified to make a new model that allows differently spaced and sized zones throughout the profile. It is evident that this approach is flexible enough to handle the complexity of profiles in marine sediments several hundred meters below the ocean floor. The program was written in MATLAB, which enables the user to analyze the profiles with a higher degree of accuracy in a fraction of the time (several hours vs. several minutes), due to MATLAB's matrix calculating abilities, providing a new useful tool for analyzing concentration profiles.

1. Introduction

In the following section, the use of the model is briefly discussed, and the methods used by Berg and the new model are outlined along with the alterations made to the previous method.

There are several oxidation reactions that are indicators of biological activity in the ocean sediments. By gaining an understanding of the vertical variation in the rates of these various reactions and their relationships (or lack thereof), it is possible to get an idea of the dynamics of the coexistence of the various microbes living in these deep-sea sediments. The Ocean Drilling Program (ODP) and its predecessor, the Deep Sea Drilling Project (DSDP) have collected sediment samples from over 1,000 open-ocean and near-shore sites. Amongst many other measurements, the pore water concentrations of chemicals used in known metabolic reactions of deep-sea-sediment dwelling microbes have been measured, as well as the porosity, formation factor, and temperature of the sediment, thereby allotting us with the necessary information to calculate the rates of various chemical reactions, including those used in microbial metabolism.

In steady-state conditions, the equation that accounts for diffusivity and formation factor along with chemical concentrations for calculating the reaction rate is:

$$(1) \quad \frac{d}{dx} \left(\frac{D}{ff} \cdot \frac{dC}{dx} \right) = -R$$

Here C is the concentration of the chemical, D is the diffusivity of the porewater, ff is the formation factor of the sediment, x is the depth, and R is the reaction rate. Since only a finite number of measurements can be taken, equation (1) must be replaced with a numerical

solution approximation. In this model, a control volume approach is used, as was done in the Berg et al. (1998) model.

Equation (1) becomes:

$$(2) \quad \frac{\left(\frac{D}{ff} \cdot \frac{dC}{dx} \right)_{j+1/2} - \left(\frac{D}{ff} \cdot \frac{dC}{dx} \right)_{j-1/2}}{\Delta x_j} = -R_j$$

Here j is the control volume length, where all of the terms in the equation are assumed to be constant over that length. The program was written such that on the average there will be ten control volumes between every measured data point, and all of the control volumes will have equal sizes. One could also allow either the user of the program or even the program itself to find the optimum size of the control volume for various sections of the profile being evaluated, thereby increasing the overall flexibility and accuracy/resolution of the model.

Equation (2) can be expressed as two separate terms as follows:

$$(3a,b) \quad \begin{aligned} \left(\frac{D}{ff} \cdot \frac{dC}{dx} \right)_{j-1/2} &= \frac{2D_j \cdot D_{j-1}}{ff_{j-1} \cdot \Delta x_{j-1} \cdot D_j + ff_j \cdot \Delta x_j \cdot D_{j-1}} \cdot (C_j - C_{j-1}) = AA_j \cdot \Delta x \cdot (C_j - C_{j-1}) \\ \left(\frac{D}{ff} \cdot \frac{dC}{dx} \right)_{j+1/2} &= \frac{2D_j \cdot D_{j+1}}{ff_j \cdot \Delta x_j \cdot D_{j+1} + ff_{j+1} \cdot \Delta x_{j+1} \cdot D_j} \cdot (C_{j+1} - C_j) = CC_j \cdot \Delta x \cdot (C_{j+1} - C_j) \end{aligned}$$

Note that Δx is the same at j , $j+1$, and $j-1$.

These two terms can then be combined and expressed in a tri-diagonal matrix as such:

$$(4) \quad AA_j C_{j-1} + BB_j C_j + CC_j C_{j+1} = -R_j$$

Here AA is the first term in the right hand side of equation (3a) divided by Δx , CC is the same term from equation (3b) divided by Δx , BB is the negative of the sum of the aforementioned terms divided by Δx , R is the reaction rate. At $j=0$ and $j=n+1$, where n is the length of the profile, boundary conditions are imposed.

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Here the known concentrations and fluxes are assigned at the top and bottom of the profile such that

$$(5a) R_0 = R_0 - CC_1C_1$$

$$(5b) R_n = R_n - AA_{n+1}C_n$$

$$(5c) C_0 = C(m)_1$$

$$(5d) C_{n+2} = C(m)_{n+2}$$

($C(m)$ is the measured concentration)

Theoretically one could calculate the reaction rate (the forward solution) directly using equation (4), however this will give a scattered profile with leaps between positive and negative values at every measurement point (Fig. 1). It would be more desirable to have ranges of depths, or zones, that have constant reaction rates to explain the measured data, and it is this idea that both the current method and the Berg et al. (1998) model employs (Fig. 2). First the model attempts to find a single constant reaction rate for the entire profile that will best describe the measured data. Then the profile is divided into two zones, and the best constant reaction rate to fit the measured data for each zone is found, and the process is repeated until the maximum number of zones has been reached. In every case, the zones are all equally spaced/sized in the Berg model, and there is a maximum of 12 zones allowed. This probably worked well for profiles that were only several centimeters deep, where the samples taken were most likely uniform, and not very complex. When analyzing profiles several hundred meters deep, the Berg model is not flexible enough to capture their varying behaviors for the following reasons:

1. Since the maximum number of zones is 12, the smallest range of depth the model could achieve for a 400-meter profile is 33.333 meters. Some of these profiles have varying reaction rates within 12 meters, in which case the model fails to capture the behavior within these ranges. Some profiles that would be worth analyzing are over a kilometer deep. A greater number of maximum zones would be necessary to accomplish this task.
2. 400+ meter profiles often have varying resolutions ranging from 10 to 50 measured data points every fifty meters. A minimum of three points are required to calculate a reaction rate, however there should be at least four data points in order to ensure a fit that appropriately matches the data. Therefore some ranges of depth would require more/smaller zones, while in others it would only be appropriate to have one large zone. Therefore, profiles with varying sample resolution cannot be analyzed using equally spaced/sized zones. It is necessary to allow for unequally spaced/sized zones to match the resolution of the concentration measurements at various depths.
3. Regardless of the complexity of the sample resolution, the complexity of the reaction rates (or concentrations, depending on how one looks at it) throughout the profiles usually cannot be described by equally spaced/sized zones. Some reaction rates persist over ranges of depths less than 2 meters,

Figure 1. Typical profile of reaction rates as a function of depth in a deep-sea drill core (left) and the associated reaction rates calculated using simple forward solution.

Figure 2. Conceptual view of the Berg et al (1998) method that separates the chemical concentration profile into equally sized sections with constant reaction rates.

while another reaction rate in the same profile will persist over a range of 100+ meters. While the Berg model does combine zones with similar reaction rates, it would be inefficient to divide certain ranges of depths into many zones only to combine them later. In these cases, it would be more appropriate to use differently sized/spaced zones.

4. The Berg model usually requires several hours to analyze a profile with a reasonable degree of accuracy (the less accurate the parameters, the less time it takes). This makes it extremely difficult to work with. The possibility of greatly decreasing the calculation time is certainly worth investigating/pursuing.

2. Methods

In the new model these problems have all been addressed and resolved. By allowing the user to define “intervals” of depths (sections of the overall profile) that are analyzed one at a time, it is possible to employ Berg’s method while having differently spaced and

Figure 3. Conceptual view of the method used in this paper that separates the chemical concentration profile into variably sized sections with constant reaction rates.

sized zones throughout the overall profile (Fig. 3). For example, if there is complex behavior in the first fifty meters of the profile, and the rest of the profile is relatively simple, the user would be able to define an interval for the first 50 meters, and furthermore decide the maximum number of zones to be used within that interval (i.e. 10, making each zone 5 meters long), and define another interval for 50 to 400 meters, and pick a different maximum number of zones for the second interval (i.e. 7, making each zone 50 meters long). The program will estimate the maximum number of zones using the number of data points within each interval, but the user will still be able to ultimately decide what the maximum number will be. The user is given a plot of the concentration data vs. depth to use when deciding the ideal lengths each interval, and how many zones to use within each interval. The methods of finding the reaction rates that best fit the data are as follows:

1. Guess a reaction rate (the default is '0', since in general the reaction rate could be negative or positive).
2. Calculate the concentration using a tri-diagonal matrix built from equation (4). That is, instead of directly calculating the reaction rate, we are guessing a reaction rate and calculating the concentration (the inverse solution).
3. Calculate the sum-of-squared-errors (SSE) of the calculated concentrations vs. measured concentrations using the following equation:

$$(6) \quad SSE = \sum_{i=1}^M (Cm_i - Cc_i)^2,$$

4. Find the reaction rate that minimizes the SSE using the Downhill Simplex Method (Nelder and Mead 1965). One could use different minimization algorithms and the current model is constructed to easily facilitate this. The algorithm terminates if/when the change in successive calculated errors is

less than or equal to the mean value of the concentration data divided by 10^7 .

5. Repeat the process for higher and higher number of zones.
6. Once the maximum number of zones has been calculated, find the minimum number of zones that gives the best fit using statistical F-testing. A minimum p-value of 0.01 is set as the maximum limit.
7. See if any of the zones can be combined. Sometimes neighboring zones have similar reaction rates, and it would be more reasonable to combine the two zones into one zone.
8. Repeat F-testing for the new set of profiles.

2. Results

In this section, we compare results generated using the Berg model approach (Fig. 4) and using the new user-defined interval approach (Fig. 5). The actual Berg model code was not available, which used some sort of unit conversion when calculating the error, making a direct comparison with the new model's errors impossible/meaningless. Therefore it is necessary to simply use the *approach* of the Berg model (a maximum of 12 equally spaced zones) to analyze the profile, and compare that with the new model's results when using user-defined intervals. It is also of course necessary to alert the reader about the difference between the two. The Berg model probably does not have exactly the same parameter settings (i.e. when to decide that the SSE is low enough to discontinue searching for a better fit), so it would be incorrect to say that these are the errors that the Berg model finds, only that these are the errors that the *approach* accomplishes given the parameters used. The plots will be shown along with the SSE values for each plot (494.23 vs. 704.5).

Sometimes the process of finding the best fit requires over 3000 iterations, in which case calculation efficiency is crucial. While access was not granted to the actual code written by Berg et al., it seems that they did not use MATLAB to write it, since they did mention that the Thomas algorithm was used in the calculations with the tri-diagonal matrix. MATLAB is much more efficient since it can calculate any number of equations in a single step if they are defined as a matrix, whereas all programming languages require such calculations to be performed in loops. If the depth of the profile is over 400 meters, it is feasible that the final matrix used in the calculations will be greater than 4000x4000. This means there could be about 12 million calculations per interval, and there are of course repeated assignments performed at each iteration that add to the total calculation time. We believe this is why the MATLAB code is capable of doing in less than 10 minutes what the Berg model requires more than 4 hours to do. Furthermore, we found the use of the Thomas algorithm unnecessary. When the fact that more accurate interpretations are possible with this new model is considered (in addition to its more efficient operation), it becomes clear that there have been notable advances made with this model.

Figure 4. Example of reactions rates calculated with the Berg et al (1998) method.

Most of the reduced Mn below the sea floor is oxidized within the first few meters into the sediment, if not before, thus the pore water Mn concentration (oxidized Mn is insoluble) is rapidly decreased. Within a few meters Mn is reduced by microbes that utilize the substance in metabolic reactions, thereby returning it to the pore water. At site 1226 of the ODP Leg 201 (D'Hondt et al. 2003) this all happens within about 9 meters. The length of the entire profile is approximately 420 meters long. A constant reaction rate for a minimum of 35 meters (as prescribed by the limit of a maximum of 12 zones in the Berg model) cannot capture the true behavior of the profile. However, if the user defines an interval between 0 and 12 meters, the maximum number of zones allowed by the number of data points within that range is only 4, but they are small enough to truly capture the complex behavior of extreme consumption (removal from the pore water) followed by extreme production (addition to the pore water) of Mn. At 12 meters below the sea floor (mbsf) there is a significantly high downward flux, followed by a long period of nearly zero Mn concentration in the pore water until about 250 meters, at which point the concentration builds up to another peak and trough echoing the initial behavior at the top of the profile but over a much larger depth interval. This would be another section in need of a separate interval since the complexity significantly changes, as does the sample resolution. Thus, separate intervals are defined for 0-12, 12-250, and 250-417 meters. The errors and profiles are shown in figures 4 and 5 for both the old Berg model and the new version, respectively. It should be noted, however, that it is not only the actual error in the fit that is relevant, but the ability to give a profile with appropriate reaction rates – this is where the difference between the two approaches is emphasized.

3. Future Explorations

While the user-defined intervals modification does increase the flexibility and accuracy of the Berg method, it is a subjective process, in which the user is allowed to

Figure 5. Example of reactions rates calculated using the method developed in this paper.

manipulate the profiles to a degree. While this is desirable in certain situations, it would also be appropriate and easier in many situations to have a more objective method for choosing intervals. If the program could be revised such that it would find the optimal size and location of the intervals based on the complexity and resolution of the concentration data throughout the profile, it would save the user much time and effort, as well as provide an objective analysis of the profile. The program would have to look at a combination of factors to make a truly efficient and optimal decision. Relatively high changes in gradients over more than a negligible fraction of the total number of data points is one way the program could easily and quickly detect changes in the reaction rate, as long as the noise in the data is not too extreme. Where the gradient changes significantly could be a good location for interval boundaries. Local minima and maxima along the major curve would be a good midpoint for each interval (imagine one peak per interval, where a single reaction rate or zone could possibly be found to fit the parabola). However, the density of data points would also have to be considered, since the zones would need to have at least four data points within them in order to get a truly reliable fit from the error calculations. Changes in sample density over a pre-defined minimum fraction of the profile could be easily and quickly found. Somehow accounting for both of these factors would enable the program to permit automatic interval selection if one desires.

Another useful addition to the model would be an option for the generation of Monte Carlo uncertainties on the reaction rates. Random noise could be imposed upon the data in the sample profile by using MATLAB's random number generator normalized to plus or minus 1/10 of the magnitude of the mean value of the data. The process could be repeated however many times the user wishes, resetting the random noise each iteration of the Monte Carlo simulation. It is necessary for the program to be set such that the same number of zones is used for the final reaction rate profile – obviously a higher number of zones would be

more accurate in most cases, and would therefore be more useful in this particular operation. Once all of the iterations are complete, a plot of the reaction rates calculated without the random noise with the same number of zones could be made with the standard deviation of all the reaction rates plotted as error bars. It would also be useful to calculate the mean value of the standard deviation of the entire system

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The Dispersion of a Mantle Plume Beneath a Mid-Ocean Ridge-Transform Corner

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Abstract. Observational and experimental studies support the theory that tectonic processes at mid-ocean spreading ridges interact with plumes of hot material rising from depth in the earth's mantle. The dispersion of thermally buoyant mantle plumes near mid ocean ridges is thought to be influenced by plate driven mantle flow and the presence of a sloping rheological boundary layer at the base of the lithosphere. It is still unclear as to how, or if, transform offsets in mid-ocean ridges effect the dispersion of plume material. We examine the essential physical aspects of the case of a plume source centered beneath one corner of a ridge-transform system through laboratory experiments in a fluid with temperature dependent viscosity. We incorporate diverging shear driven flow at the surface of the fluid, an upper boundary layer induced by surface cooling, and plume style upwelling due to a focused heat source at the fluid's base. Results show that transport of plume material in the vicinity of a ridge-transform offset is distinct from that which arises in the case of a ridge without any offset. This is due both to differences in rheological boundary layer morphology and the pattern of plate driven upwelling associated with the presence of a transform boundary. The transform offset deflects rising plume heads, and at slow spreading rates and weak to medium plume strengths blocks flow of plume material to the plume-distant ridge.

1. Introduction

Two major modes of flow transport heat and mass in the earth's mantle: plate driven convection and buoyancy driven convection (plumes). Plate driven convection occurs as moving lithospheric plates are viscously coupled to the underlying asthenosphere resulting in sheet like upwelling at mid-ocean ridges and downwelling in subduction zones. Bouyancy driven convection occurs as hot material rises from depth in the mantle because it is less dense than that which overlays it. The bouyant material rises in a characteristic "plume" shape with a round leading head fed by a trailing conduit (Figure 1). These two modes of flow interact most dramatically where plumes rise and disperse in the vicinity of mid-ocean spreading ridges. Surface observations of geochemistry [Schilling, 1991], gravity and topography/bathymetry [Ito and Lin 1995] as well as 3D seismic tomography [Wolfe *et al.*, 1997] have been used to identify and quantify plume-ridge interaction. Since direct observation of mantle flow is not feasible we rely upon numerical [Kincaid *et al.*, 1996] and laboratory models [Kincaid *et al.*, 1995] to help develop and constrain theories on the mechanics of plume-ridge interactions. One of the many questions that remain to be answered in this area of study is: how do transform offsets in spreading ridges affect plume dispersion? We explore this question through 3D laboratory modeling of the rise of a thermally buoyant plume beneath a ridge-transform intersection with a sloping rheological boundary layer.

The dispersion of a chemically buoyant plume beneath a spreading ridge was modeled experimentally

by Feighner and Richards [1995], illuminating the effect of plate driven flow on plume dispersion. They found plumes initially spread in a radial manner when

Figure 1. A time series of photos showing the rising of a thermal plume in the fluid tank used for experiments.

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they near a spreading surface, but reach a steady state along ridge (waist) width of dispersion as plume material is swept away by plate motion faster then it can be supplied by the plume conduit. This waist width was found to be inversely proportional to plate velocity, and increased perpendicular to the ridge resulting in a bow tie shaped dispersion pattern in plan view.

Since the earth's mantle has a temperature dependent viscosity and is cooled from the top it develops a rheological boundary layer (RBL), also known as lithosphere, of colder more viscous material near the surface. This layer thins near spreading ridges, where upwelling of warmer deeper mantle material occurs to take the place of material swept away with the plates, and thickens in the ridge perpendicular direction as the spreading material cools. It has been suggested that the RBL can influence plume dispersion by causing buoyant plume material to be deflected up the sloping RBL towards the ridge, a theory supported by geochemical anomalies [Schilling 1985]. Kincaid et al. [1995] incorporated a RBL into their experimental investigation of a plume rising off-axis of a spreading ridge. By modeling mantle flow in a fluid with temperature dependent viscosity (enriched sucrose solution) they were able to form a sloping RBL through surface and create a thermally buoyant plume using a disk shaped resistance heater at the base of the fluid. The temperature dependence of the fluid's viscosity is described by:

$$\mu = e^{\left(\frac{1888}{T+93.3} - 11.48\right)} \quad (1)$$

where μ is viscosity in Pascal-seconds, and T is temperature in degrees Celsius [Olsen and Kincaid 1991]. Results of this study suggested that the presence of a sloping RBL aids in the dispersion of an off-axis plume towards a ridge, but for high plume temperatures thermal erosion of overlying lithosphere forms a pocket in the RBL, which inhibits ridgeward flow.

The presence of a transform boundary connecting two spreading ridges has the potential to effect both the style of plate driven flow as well as the morphology of the lithosphere and thus can also effect plume dispersion. Magde et al. [1996] used numerical and laboratory models to explore the relationship between buoyant and plate driven upwelling beneath a segmented spreading center with no RBL. Their results show for flow plate driven flow the along ridge zone of maximum upwelling cuts across the inside corners of ridge-transform intersections, passing through the middle of the transform. Since there is no spreading occurring at a transform boundary there is little upwelling and therefore less heat advected from depth in the mantle. This results in a lithosphere that is cooler and thicker along the transform than along the ridges. It has been suggested that such a structure could act as a barrier to along axis flow of plume material (Figure 2) [Viso, 2003]. In 3D models of on-axis plume dispersion along a ridge-transform-ridge system, considering variable transform lengths, Georgen and Lin [in press] finds transforms to reduce and deflect along-axis flux of

plume material. Their study shows this effect to be more pronounced for greater transform lengths. Experimental work done by Viso modeling the dispersion of an on-axis plume beneath a ridge with a transform offset uses very similar methods to Kincaid [1995] to create plate driven flow, a sloping RBL and a thermally buoyant plume. Those results suggest that at slow plate rates with no RBL transform offsets can act as dams. In addition Viso [2003] suggests that thermal RBLs can limit along axis flow as rising plume heads erode into the lithosphere creating a pocket that elongates perpendicular to the ridge with spreading, and channels plume material (Figure 3).

Our work attempts to better understand the effect of a transform on plume dispersion by modeling the rise of a

Figure 2. A view from below of lithospheric plates at a segmented spreading ridge. Plume material rising below the plates and spreading along axis may be dammed by thicker lithosphere at the transform boundary.

Figure 3. View at two times of a plume dispersing under a spreading ridge with a rheological boundary layer. A rising plume head erodes a pocket into the cold plates of viscous fluid near the surface. Spreading pulls the plates apart the pocket is elongated in the ridge perpendicular direction and acts to channel flow of plume material.

plume directly beneath a ridge transform intersection. The Ontong Java and Manihiki Plateaus (now in the western Pacific) were formed in the middle Cretaceous by extensive volcanism, with likely major climatic consequences *Tarduno et al.* [1991]. It has been suggested that plume activity was responsible for these events, and that a segmented spreading ridge in the vicinity of the present day Nova-Canton Trough may have influenced plume dispersion [Larson, 1997]. A better understanding of the dynamics of plume-ridge dispersion including transform offsets can help to constrain theories on the sequence of events that formed these plateaus and influenced major plate boundary reorganizations. Additionally such knowledge contributes to a better understanding contemporary plume-ridge interactions such as the dispersion of the Galapagos plume located ~170km south of a ridge transform corner [Ito and Lin 1995].

2. Methods

2.1. Setup

Plume-ridge interactions were modeled in a tank measuring 96x72 cm and filled with enriched sucrose solution to a depth which varied between 14.5 to 16.5 cm. Plate driven flow was simulated by dragging sheets of mylar across the top of the fluid in the geometry of two spreading ridges separated by a 5.5 cm transform. Two pairs of mylar rolls (one for each ridge) were held above the tank by a support structure, threaded down through metal bars along the ridge axis, laid across the surface of the fluid, and fed back up through heated scraper bars to remove excess fluid and finally to take-up reels on either end of the tank (Figure 4). The take-up reels were driven by a high torque DC motor with a gear reducer that allowed the speed of spreading to be adjusted. The temperature dependence of the fluid's viscosity is shown by equation (1). A thermally buoyant plume was formed by heating the fluid above a disk shaped resistance heater 7.5 cm in diameter placed at the bottom of the tank beneath one of the ridge-transform corners. The temperature of the heater is adjusted for different plume strengths by varying the voltage across it. A rheological boundary layer was formed at the top of the fluid by cooling the surface with frozen carbon dioxide (dry ice) held 1cm above the mylar surface near the ridge.

2.2. Procedure

Experiments began by cooling the surface. A vertical thermocouple array with 1cm sampling intervals monitored temperature with depth in the upper fluid near where the ridge met the tank wall. When the temperature at 2.5cm depth read between 6 and 9 C a sufficient viscosity contrast was reached between the upper and ambient fluid and the mylar spreading was initiated. The spreading was run for about fifteen minutes allowing for the ridge temperatures to reach a steady state, at which point the plume heater was turned on. Dispersion of the heated plume fluid along the ridge-transform system was monitored by a series of

Figure 4. The experimental setup.

Figure 5. The geometry of the segmented ridge used in the experiments is shown in plan view. Thermocouples are evenly spaced at 3cm intervals running from 0 to 8 along the first ridge, 9 is placed halfway along the transform, and 10 to 14 are spaced along the second ridge.

fourteen J-type thermocouples mounted along the ridge-transform system at 3cm intervals and sunk to 1.5cm depth in the fluid. Nine thermocouples were mounted along the near-plume ridge, one in the center of the transform, and four along the far-plume ridge (Figure 5). Temperature readings were logged at 30-second intervals by computer automated sampling from before the plume heater was turned on until after along ridge temperatures reached a steady state.

2.3. Scaling

Scaling of tank experiments to the mantle was accomplished using the dimensionless Rayleigh and Peclet numbers. The Peclet number (Pe) is the ratio of advection terms to thermal diffusion terms:

$$Pe = \frac{\text{advection}}{\text{diffusion}} = \frac{U_p D}{\kappa} \quad (2)$$

where U_p is plate velocity, D is depth of convecting fluid, and κ is thermal diffusivity. We equate the Peclet number for the tank and the mantle to scale plate velocity and distances. The Rayleigh number (Ra) is the ratio of the terms for buoyant forces to viscous forces:

$$Ra = \frac{\text{buoyancy}}{\text{viscosity}} = \frac{g \rho \alpha \Delta T}{\kappa \mu} D^3 \quad (3)$$

where g is acceleration due to gravity, ρ is fluid density, α is coefficient of thermal expansion, ΔT is the temperature difference between heated plume material and the ambient fluid, D is depth of the convecting fluid, κ is thermal diffusivity, and μ is dynamic viscosity. We

Table 1. Parameters for tank and working fluid and mantle values from scaling

Parameter	Tank Value	Mantle Value
Thermal Expansivity (α) ($^{\circ}\text{C}^{-1}$)	4.6×10^{-4}	2×10^{-5}
Density (ρ) (kg/m ³)	1422	3700
Thermal Diffusivity (κ) (m ² /s)	1×10^{-7}	1.4×10^{-6}
Depth (m)	0.145 - 0.165	6×10^5
Transform Length (m)	0.055	2×10^5 - 2.28×10^5

equate the Rayleigh number for the tank and the mantle to scale temperature differences and distances (Table 1). For scaling we take the tank fluid depth to represent the entire 600km of upper mantle. Our transform offset scales to between 200 and 228 km (scaled length depends on the fluid depth in the tank).

3. Data

Along axis temperature data was collected for nine experiments varying plate rate and plume strength (Table 2). Four experiments were conducted as controls without surface cooling. The laboratory is maintained at approximately 20°C and measurements made along the ridge are of absolute temperature. Temperature data presented is from along ridge measurements of temperature logged after the plume rises and readings reached a steady state. The data is presented as temperature anomaly with respect to the steady state average ridge temperatures attained before the plume heater is turned on.

4. Results

4.1. Experiments without a RBL

Figure 6 shows the steady state temperature anomalies measured in experiments 1 through 4 where there was no dry ice applied to cool the surface and thus no RBL formed. Experiments 1 through 4 all had medium strength (60 V) plumes. Experiment 1 was run with no plate driven flow and thermocouple (TC) #8 was the first to experience a temperature anomaly, followed by TC 7 and TC 9. The generally symmetric form of the steady state anomaly observed in experiment 1 suggests a radial pattern of dispersion. Experiments 2 through 4 had slow (.36 cm/min), medium (1.4 cm/min) and fast (4.38 cm/min) plate velocities respectively. The resulting steady state temperature anomalies from these runs show an inverse relationship between along axis dispersion of warm plume material and plate velocity. For experiments 2 and 3 TC 7 was the first to record a temperature anomaly and for experiment 2, TC 7 shows the highest steady state anomaly. In experiment 4 no plume head formed in the fluid and, TC 9 was the first

Table 2. Experimental parameters for each run

Expt	Cooling	Mylar Speed (cm/min)	Scaled Plate Speed (cm/yr)	Plume Voltage (V)	Fluid Depth (cm)
1	No	0	0	60	16.5
2	No	0.36	0.52	60	16.5
3	No	1.4	2.02	60	16.5
4	No	4.38	6.14	60	16.0
5	Yes	0.36	0.52	50	16.5
6	Yes	0.36	0.46	60	14.5
7	Yes	0.30	0.43	70	16.5
8	Yes	1.6	2.31	60	16.5
9	Yes	0.3 - 4.0	0.41 - 5.8	60	15.8

to record a temperature anomaly. TC's 9 and 10 were the only ones to experience a steady state anomaly in this case.

4.2. Experiments with a RBL

4.2.1. Variable plume strengths, slow spreading.

Figure 7 shows the steady state temperature anomalies that resulted from experiments 5 through 7. These were conducted with a slow plate rate (between .3 and .36 cm/min), surface cooling and variable plume strengths (50V, 60V, and 70V respectively). Also plotted on Figure 7 is the temperature anomaly from experiment 5, measured after spreading had initiated and temperatures reached a steady state, but before the plume heater was turned on. This effect is due strictly to the combination of plate driven flow and surface cooling, and should be similar for experiments 6 and 7 (since cooling and plate rate were identical for all three runs). In all three experiments TC 7 is the first to detect a temperature excess from the surfacing plume head. Experiment 6 shows the narrowest along ridge anomaly followed by experiments 5 and then 7. These results suggest that along axis dispersion is not simply inversely proportional to plate rate when a RBL is involved. In experiments 5 and 6 the initial cold, high viscosity material in the plane of the transform is warmed and eroded more as plume strength is increased. In experiment 7 evidence of the initial cold anomaly is completely absent from the final steady state temperature. Experiment 7 is unique in that it provides the only result in this group where a significant positive temperature anomaly occurs along the plume-distant ridge.

4.2.2. Variable spreading rate, medium plume strength.

Figure 8 shows the steady state anomalies that resulted from experiments 6, 8 and 9. These were conducted with a medium strength (60 V) plume, surface cooling and variable plate velocities. Experiments 6 and 8 had slow (.3 cm/min) and medium (1.6 cm/min) plate velocities respectively. Experiment 9 began with a slow plate velocity (.3 cm/min) which was maintained until a plume head was visually observed to begin rising, at which point the plate velocity was increased to a fast rate (4 cm/min). This was done to allow the development of a plume head, which would otherwise not occur at the fast spreading

Figure 6. Steady state temperature anomalies for experiments conducted with no surface cooling, medium strength (60V) plume, and variable plate rates.

Figure 7. Steady state temperature anomalies for experiments conducted with surface cooling, slow spreading (.3 cm/min) and variable plume strength. The initial cold anomaly measured in experiment 5 is also plotted to show the effect of different plume strengths on RBL temperature structure.

Figure 8. Steady state temperature anomalies for experiments conducted with surface cooling, medium plume strength (60V) and variable spreading rates.

rate (eg. experiment 4). In experiments 6 and 8 TC # 7 is the first to be affected by the presence of the plume while in experiment 9 TC #'s 7-10 are all affected nearly simultaneously. In experiments 8 and 9 a positive steady state temperature anomaly is observed on the far ridge.

5. Discussion

5.1. Experiments without a RBL

The temperature anomaly for experiment 1 (no spreading, no cooling) agrees with the dispersion pattern expected for a plume rising, without the influence of plate driven flow or a RBL, until it impacts the air fluid interface at which point it flattens and spreads radially. The decrease in along axis dispersion from experiments 1 through 4 supports *Fieghner and Richards' [1995]* result of waist width varying inversely with spreading rate. As plate rates increase, plume material is swept away faster in the ridge perpendicular direction and has less time to spread radially along axis. The results of experiments 2 through 4 where TC's other than #8 detect the plume's excess heat first suggest that the leading plume material (the plume head in 2 and 3) is being deflected laterally by plate driven flow rather than rising straight up. A shift in the location of the anomaly towards the transform occurs as plate rate is increased in experiments 1 through 4. This may represent deflection of plume material towards the transform by a strengthened zone of maximum upwelling (shown by *Magde et al. [1996]* to cut through the transform) at faster plate rates. Dispersion of plume material results in positive temperature anomalies on the far ridge, as well as the near ridge, at all spreading rates for experiments with no RBL. For a medium strength plume, at slow to medium spreading rates, plate driven flow initially deflects the plume head towards the near plume ridge; however, the pattern of flow alone is insufficient to prevent dispersion of plume material past the transform.

5.2. Experiments with a RBL

5.2.1. Variable plume strengths, slow spreading. In slow spreading experiments 5 through 7, TC 7 is the first to record excess plume temperature, and also shows the largest positive steady-state anomaly. This suggests that the plume is deflected by the flow geometry as shown in experiment 2 (and possibly also by the thicker RBL under the transform) towards the channel of thin lithosphere which occurs under the near ridge. In experiment 5 the weak (50V) plume has less thermal buoyancy and less excess heat to expend in eroding the cold fluid beneath the transform and so is deflected strongly towards the near ridge where it causes the most observed temperature anomaly (Figure 9a, b). In experiment 6 the medium (60V) plume erodes more of the cold fluid under the transform as it is deflected towards the near ridge. Along ridge dispersion is inhibited, because higher excess temperature erodes a more pronounced pocket into the lithosphere above TC 7. Thus flow is channeled preferentially in the axis

Figure 9. Vertical cross sections through the lithosphere/ asthenosphere (taken from A to B in Figure showing the dispersion of plume material. (a) shows the initial shape of the cold lithosphere before it interacts with the rising plume. (b) shows the dispersion of a weak plume which is heavily deflected by the lithosphere, then channeled along the near ridge. (c) shows the dispersion of a medium strength plume which is deflected by the lithosphere, but significantly alters it as well. The plume burns a pocket when it reaches the near ridge which channels its flow. (d) shows the dispersion of a strong plume which experiences the least deflection, and is responsible for the most alteration to the overlying lithosphere.

perpendicular direction, preventing further along ridge dispersion (Figure 9c). The results of experiments 5 and 6 show along axis dispersion to decrease with increasing plate rate in the presence of and RBL, and are in agreement with the channeling effect proposed by *Viso* [2003]. The failure of plume material to cross the transform in experiments 5 and 6 supports the results of *Georgen and Lin* [in press] that suggest transforms limit along ridge flow at slow plate rates. In experiment 7 the strong (70V) plume is larger and has a greater temperature excess and thus, although it is initially deflected towards the near ridge, it erodes a large dome shape into the RBL as its head nears the surface. The cold sink is completely eroded, allowing plume conduit material to disperse widely in both directions (Figure 9d).

5.2.2. Variable spreading rates, medium strength plume. In experiments 6 and 8 (slow and medium plate rate) the plume head is still deflected towards the near ridge as described above. Such a deflection is not observed in experiment 9 (fast plate rate). Enhanced transport of excess plume temperature towards the far ridge occurs in experiments 8 and 9. This is logical since at faster spreading rates the RBL is thinner and so any damming effect should be less pronounced. In experiment 9 plume material appears to be transported more to the far ridge than the near ridge, whereas in experiment 8 plume material seems to be split between the two ridges. This may be due to deflection towards the far ridge as a result of a strengthening of the zone of upwelling that cuts across the transform boundary at faster plate rates as suggested by the results of experiment 4.

6. Conclusions

The results of our laboratory modeling of plume-ridge interactions with a segmented ridge and RBL suggest that there is an effect on plume dispersion due to the presence of a transform offset. Part of this effect is due strictly to plate driven flow. For slow plate rates and weak to medium plume strengths the transform offset acts as an impenetrable barrier, preventing dispersion along the far ridge. For these cases the presence of an RBL also served to narrow along ridge dispersion by a ridge perpendicular channeling effect. For slow spreading and a strong plume the greater buoyancy and erosive capacity of the strong plume head diminishes the transform barrier effect. The influence of the transform effect on dispersion is strongly affected by changes in plate velocity due to changes in RBL geometry and rate of plate driven flow. Additionally, transport of plume material across a transform is possible and even encouraged at high spreading rates.

These results suggest that transport of plume material along segmented ridges is feasible, as is being considered in the case of the formation of the Ontong Java and Manihiki Plateaus. Along axis transport may be more probable at fast spreading rates or with a strong plume.

The deflection of and erosion by the plume head as it rises beneath the ridge-transform corner has been an

important factor in these results. In nature, plumes are not often observed to rise directly under transforms, but more often beneath spreading centers or off-axis. Thus, there may be some important differences in dispersion patterns and it is important to continue with further work to characterize the dynamics of on and off axis plumes.

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Sedimentary Evidence of Environmental Change in Somes Sound, Mount Desert Island, Maine

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Abstract. Somes Sound, a deep, narrow inlet cutting through Mount Desert Island (Maine, USA), is the only fjord-type estuary on the eastern seaboard of North America. Its unique morphology and its location near Acadia National Park make it an exciting focus of geologic research. This paper presents preliminary findings from physical and chemical analyses of short (approximately 1m) sediment piston cores taken from Somes Sound in the summer of 2003. Cores are dated using results from analyses of organic geochemistry and natural remnant magnetism, and interpreted using results from organic and trace metal geochemistry, loss on ignition and total organic carbon, and magnetic susceptibility and density. Results demonstrate that these sediments have been deposited relatively recently, within the past two centuries, at an average rate of approximately .3cm/yr. The sediments are relatively unpolluted, with trace metal and organic values near or below established values of effects-range-low (ERL). Nevertheless, trends in metal concentrations seem to reveal the evolution of the Somes Sound area from a small industrial region in the nineteenth century to its present-day status as a protected, recreational area.

1. Introduction

Somes Sound, a deep, narrow inlet cutting through Mount Desert Island, Maine, is the only fjord-type estuary on the eastern seaboard of North America (Figure 1). The unique geomorphology, along with its location on Mount Desert Island in Acadia National Park, make it an exciting focus of geologic research. However, surprisingly little research has been conducted on the Sound. Pettigrew et al (1997) have studied mixing and circulation in the sound, Doering and Roman (1994) have investigated nutrient levels and inputs, and Folger et al (1972) have provided a general review of surface sediments and water circulation in the sound. No one, however, has performed a detailed analysis of subsurface sediments in Somes Sound and the environmental record that they preserve. In this study, sediment cores taken from Somes Sound are used to explore two main questions regarding the history of the sound. First what do the sediments reveal about the sound's post-glacial evolution? Do they demonstrate a progression from a proglacial lacustrine environment to a marine estuarine environment over time? If so, can we date these changes? Second, what do the sediments reveal about the area's more recent anthropogenic history? Somes Sound is relatively undeveloped, and is in a protected, National Park area; can we see evidence of industry and development in the sediments? Can we see evidence of pollution, and if so, how bad is it?

To answer these questions, we have used a variety of laboratory techniques analyzing physical and chemical properties of Somes Sound cores. This paper presents preliminary results and conclusions based on data from analyses of natural remnant magnetism, organic geochemistry, trace metal geochemistry, grain size, loss on ignition, and total organic carbon performed on two

short piston cores taken from the sound during the summer of 2003.

2. Site Background

2.1. Glacial History of Somes Sound

Geomorphologically, Somes Sound is characterized as a fjord: it is relatively long (8km) and narrow (1km at its widest point) and has a steep rising shoreline, deep holes (up to 50 m), and a shallow sill at its southern end (10m) where it opens into the Gulf of Maine. Fjords are glacial features, created as a glacier advances through a

Figure 1. Somes Sound, Mount Desert Island, ME (from Folger et al, 1972)

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v-shaped valley and carves it into a u-shaped valley. As the glacier retreats, relative sea level initially drops due to isostatic rebound, and then rises again due to the input of meltwater into the ocean. Meltwater may also collect behind the glacier's terminal moraine, forming a proglacial lake. Ultimately, however, this lake is inundated when rising marine waters surpass the height of the moraine. The submerged moraine is known as a sill.

Somes Sound is a product of Pleistocene glaciation and subsequent Holocene warming, and we expect that it developed in a series of stages similar to that described above. A Maine sea level curve by Barnhardt et al (1995) demonstrates that inundation of the 10m sill in Somes Sound occurred approximately six thousand years ago (Figure 2). However, site specific evidence of inundation from the Sound's sediments would provide more accurate insight into the post-glacial evolution of the sound.

2.2. Development History of Somes Sound

Mount Desert Island was first settled by English colonists following their victory in the French and Indian war. Somesville, the first village on the island, was founded in 1761 on Somes Harbor, located in the northwest corner of the Sound. Although now a National Historic District, during the 19th century, Somesville was home to small but bustling industries including a varnish factory, lumber mill, grist mill, woolen mill, dye shop, tannery, lathe and shingle mills, a cobbler shop, a blacksmith shop, and five shipyards. In 1881, Hall Quarry opened south of Somesville, on the western margin of the Sound. The quarry mined Somes Sound pink granite, which was loaded onto large schooners and used in the constructions of many well-known state and national government buildings. Mining, lumbering, farming, shipbuilding, and fishing all persisted as major occupations throughout the island during the nineteenth century.

By the end of the nineteenth century, however, industries on Mount Desert Island, like industries throughout Maine, began to decline. On Mount Desert Island, a new industry was taking over: tourism. The island rivaled Newport, RI, in its appeal to wealthy vacationers, and these tourists played an important role in the creation of the nation's first national park. In 1916, 6000-acre Sier de Monts National Monument was established on the island. By 1929, the park had grown to over 35,000 acres, and was renamed Acadia. The decline of industries and the increasing emphasis upon the preservation of the island has left the Somes Sound area relatively undeveloped to this day (Table 1).

3. Methods

3.1. Field Collection

Sediment samples were taken from Somes Sound on June 25-26, 2003 using a modified pontoon boat. Six sites were surveyed (Figure 3): (1) near the mouth of Richardson Brook, called SS1 (depth= 15'; N 44°21.481' W 068°18.442'); (2) in Somes Harbor, called SS2

Figure 2. Maine sea level curve. Rising marine waters would have inundated Somes Sound's 10m deep sill approximately 6ka. (from Barnhardt et al, 1995)

DATE	EVENT
1999	Island Explorer propane bus system reduces car traffic
1977-1997	Car traffic doubles to Mount Desert Island
1947	Major fire burns half the island
1929	35,000-acre park is renamed Acadia
1916	6000-acre Sier de Monts National Monument is established on the island
late 1800s	Tourism increases to Mount Desert Island as industries decline
1881	Opening of Hall Quarry
1800s	Somesville has small industries, including woolens mill, dye shop, varnish factor, tannery, et al
1761	Founding of Someville, first town on Mount Desert Island, on Somes Harbor

Table 1. Important events in the development of Somes Sound and Mount Desert Island.

(depth= 22'; N 44°21.602' W 068°19.619'); (3) near Hall Quarry, called SS3 (depth= 150'; N 44°20.058' W 068°18.442'); (4) near St Sauveur Mt, called SS4 (depth=150'; N 44°18.715' W 068°18.717'); (5) in Southwest Harbor, called SS5 (depth= 30'; N 44°16.394' W 068°18.858'); and (6) in Northeast Harbor, called

Figure 3. Sampling Sites. Black Dots represent the 6 sites surveyed. Grab samples were taken from all site except SS4. Short cores were taken from Richardson Brook (SS1), Somes Harbor (SS2) and Hall Quarry (SS3). Long cores were taken from SS2 and SS3.

SS6 (depth= 26'; N 44°17.710' W 068°16.883'). A Van Veen grab sampler was used to take surface samples from all stations except SS4 (this site was too coarse grained). The top two centimeters of the surface grab samples were subsampled in the field. Cores were taken using modified piston corers and polycarbonate core tubes. Three short piston cores (10.5 cm diameter) were taken from three sites: Richardson Brook (core length 97cm), Somes Harbor (94cm), and Hall Quarry (104cm). Long piston cores (7.5 cm diameter) were taken from Somes Harbor (core length 276.5cm) and Hall Quarry (422.5cm). The cores were transported back to the University of Rhode Island Graduate School of Oceanography's Narragansett Bay Campus, where they were stored in a walk-in refrigerator. This summer's SURFO research focused on analysis of the short piston cores from Somes Harbor and Hall Quarry.

3.2 Laboratory Analysis

3.2.1. Magnetism. Both short piston cores were split, imaged, and measured for various physical properties. Imaging was performed using a camera mounted on a GEOTEK ® multi-sensing core logger. Volume magnetic susceptibility (K) was measured at 1cm

intervals using a Bartington Instruments MS2EI high-resolution surface scanning point sensor mounted on a GEOTEK ® multi-sensing core logger. Density was measured using gamma measurements taken on the GEOTEK. The cores were then u-channelled and analyzed for natural remnant magnetism (NRM) on a 2G cryogenic magnetometer, where they were measured at 1cm intervals for inclination, declination, and intensity. Demag cleaning was performed using an AF system.

3.2.2 Grain Size The Hall Quarry short piston core was subsampled at 8cm intervals and analyzed for grain size on an Elzone particle size analyzer.

3.2.3 Organics The Somes Harbor core was subsampled and tested for organic contaminants (PAHs, PCBs, DDTs) at the following intervals: 0-2, 4-6, 8-10, 20-22, 32-34, and 44-46cm. The Hall Quarry core was subsampled and tested for organics at the following intervals: 4-6, 8-10, 14-16, 20-22cm. Organic analysis was performed on a GCMS by the Quinn lab at the URI/GSO campus. Further sampling intervals are pending analysis.

3.2.4 Trace Metals The Hall Quarry core was subsampled at 2cm intervals to a depth of 60cm and analyzed for the following trace metals: Pb, Cr, Cu, Cd, Ni. All of the samples were prepared for analysis using a total digestion. Freeze dried sediment was digested with concentrated hydrochloric, nitric, and hydrofluoric acids, neutralized after 48 hours with boric acid, and brought to volume with hydrochloric acid. The samples were analyzed using a graphite furnace atomic absorption spectrometer.

3.2.5 Loss on Ignition/ Total Organic Carbon The Hall Quarry core was subsampled at 4cm intervals to a depth of 60cm, and 8cm intervals for the rest of the core, for loss on ignition (LOI) and total organic carbon (TOC). LOI was calculated using measurements from a 24 hour (100°C) dewatering step followed by a one hour ignition step (550°C). Carbon content was calculated from LOI data. These methods are described by Dean (1974).

4. Results

4.1. Visual observations.

The upper 43 cm of the Somes Harbor core is banded tan and dark brown silt, with some plant debris scattered throughout. There is a marked color change from darker to lighter colored sediment at 43 cm. Below this depth there is approximately 10cm of medium brown/gray silt with some sand, small (2-4mm) shell debris, and wood pieces approximately 2cm in length. Below 53 cm is a 20cm layer of coarse and unsorted silt, medium to coarse sand and gravel, and several pebbles approximately 3 cm in diameter. The bottom 20 cm is medium brown/tan silt with medium to fine sand.

The Hall Quarry core displays 1cm-wide bands of dark gray, medium gray, and tan silt to a depth of 45 cm. Below 45 cm, banding is mainly dark gray-green and medium gray, with small (1mm) shells scattered throughout.

Figure 4. Physical and magnetic properties from a) Hall Quarry and b) Somes Harbor cores.

Figure 5. Grain size distribution in Hall Quarry core.

4.2. Physical Properties.

4.2.1 Magnetics Results from physical analyses of the Somes Harbor and Hall Quarry short piston cores are shown in Figure 4. NRM inclination data for the upper halves of the Somes Harbor and Hall Quarry cores show similar series of peaks and troughs. Declination data is not as easily correlated between the two sites. Similarly, susceptibility and density data do not correlate easily between the two sites. In the Somes Harbor core, peaks in density and susceptibility approximately 50cm down the core correlate with coarse grained (gravel and pebbles up to 3 cm) material observed in the core.

4.2.2 Grain size Results from grain size measurements are shown in Figure 5. In the Hall Quarry core, grain size data demonstrates a consistently high percentage of silt throughout the core until the bottom 20 cm, when silt percentage drops and clay percentages increase.

4.3. Chemical Properties.

4.3.1. Organics Results from organic analyses of the Somes Harbor and Hall Quarry short piston cores are shown in Figure 6. The data set for Hall Quarry organics is incomplete. However, with the exception of the 8cm PCB point at Hall Quarry, those points that are currently available for Hall Quarry correlate well with the data points from Somes Harbor. The Somes Harbor data for all three organics show an initial increase in organic content downcore, followed by an abrupt decrease. At Somes Harbor, PAHs decrease quickly below 32 cm while PCBs and DDT decrease rapidly below 20 cm. In both cores, PAH and PCB concentrations fall well below the effects range low (ERL) values described by Long et al (1995) (PAH=4022; PCB=22.7). The peak DDT values for both cores fall slightly above the ERL (DDT=1.58) but well below the ERM (DDT=180).

4.3.2. Trace Metals Results from trace metal analysis of the Hall Quarry core are shown in Figure 7. Lead and chromium demonstrate similar curves, with higher values present deeper in the core, an up-core decrease in metal concentration beginning at 20 cm, and then an increasing concentration beginning at 10 cm. Copper holds at a relatively stable concentration with the exception of spikes of higher concentration at 10 and 16cm. Cadmium has a brief peak in concentration at 40cm, but otherwise remains relatively stable. Similarly, nickel remains stable with the exception of two short spikes of minimum concentration at 6 and 56cm, and a peak concentration at 34cm. All five metals are found in concentration near or below their ERL values, and, with the exception of nickel, well below their ERM values. (ERL/ERM: Cr=81/370; Pb= 46.7/218; Cu= 34/270; Cd= 1.2/9.6; Ni= 20.9/ 51.6).

4.3.3. LOI/ TOC Results from analysis of loss on ignition and total organic carbon in the Hall Quarry core are shown in Figure 8. Values for percent water, percent organic, and percent carbon are relatively stable throughout the core, with the exception of a brief decrease in percent water at 44 cm, and brief peaks in percent organic and percent carbon at 12 cm.

Figure 6. Properties from a) Hall Quarry and b) Some Harbor cores.

5. Discussion

5.1. Constructing an Age Model

An interpretation of the environmental history of Somes Sound requires an accurate age model by which we can gauge the approximate age of the sediment at any given depth within the core. Although radioisotope dating is the favored means of producing reliable age models, the procedure is lengthy, and we unfortunately did not have time for it within the context of this summer's research. In the absence of isotope data, we attempted to construct an age model using alternative means. **5.1.1. NRM.** A second method of correlating core depth with age is the use of natural remnant magnetism. NRM records changes in the orientation of the earth's magnetic pole over time, and cores of unknown age can be compared to standard reference curves that plot NRM against radiocarbon ages. Unfortunately, our NRM data from the Hall Quarry and Some Harbor cores demonstrate no obvious correlation with the Northeast Regional age models developed by King and Peck (2001) (Figure 9). However, the notable correlation between peaks and troughs in the inclination curves of both cores demonstrates 1) that our NRM data is robust, and 2) that dates derived from one core may be translated to the other (Figure 10).

5.1.2. Organics. We can derive a few key dates from the organics data for Some Harbor. PAHs, PCBs, and DDT are predominantly anthropogenic contaminants: PAHs are found in only very minimal concentrations in the natural background environment, and PCBs and

Figure 7. Trace Metals at Hall Quarry. Vertical lines represent ERL values for each metal (Cr= 81; Pb= 46.7; Cu= 34; Cd= 1.2; Ni= 20.9).

Figure 8. Results from analysis of loss on ignition and total organic carbon in the Hall Quarry core.

Figure 9. Northeast Regional age models developed by King and Peck (2001).

Figure 10. Correlation of peaks and troughs in the inclination curves for Hall Quarry and Somes Harbor (Table 2). Slight offsets in depths of peaks indicates that Somes Harbor has a slightly faster deposition rate.

Date	Organic Indicator	Somes Harbor Depth	Hall Quarry Depth
Post-1972	DDT's banned	32 cm	29 cm
Post-1939	DDT's used	20 cm	15 cm
Post-1880	PAH's prevalent	8 cm	7 cm

Table 2. Dating with Organics. Hall Quarry depth derived using NRM correlations (Figure 10).

DDT are man-made compounds that are not found in the natural environment. PAHs became prevalent during the industrial revolution of the late 19th century, and the sudden increase of PAHs above 32 cm in the Somes Harbor core may be reasonably estimated to be after 1880. PCBs were not used until 1929 and DDT was not used until 1939. The appearance of both of these compounds at and above 20 cm allows us to assign this depth a date of no earlier than 1939. Finally, we know that DDT was used in Acadia National Park during the 1950s and 60s (Connery, personal comm), and was then banned throughout the United States in 1972. The absence of DDT at and above 8 cm allows us to reasonably estimate that this depth is no older than 1972. With these three dates - 1880, 1939, and 1972 - we can assign a rough age model to the Somes Harbor core. We can then correlate this model to the Hall Quarry core using NRM correlations (Figure 10).

The dates explain our inability to correlate with NE regional reference curves: the sediments in our cores have been deposited very recently and relatively rapidly (approximately .3cm/yr), and the reference curves do not have sufficient resolution to allow correlation with cores only 200 years old. Such young cores, in turn, can provide no information about post-glacial evolution of Somes Sound, but can provide detailed information regarding the sound's anthropogenic history.

5.2 Anthropogenic History

Concentrations of trace metals and organics at or near ERL values provide no significant threat to environmental health. Somes Sound is relatively unpolluted, a finding that is expected due to its relatively undeveloped nature and its proximity to a National Park. A few small shipbuilding businesses are virtually the only industries currently operating on the sound, and these are well regulated by environmental rules regarding contaminant prevention (Williams, personal comm).

However, the lack of severity of contaminants in Somes Sound does not mean that the trends seen in the trace metal curves are not significant. The consistency of the grain size data demonstrates that changes in trace metal concentrations are not due to lithology. The sources of metal input must therefore have changed over time. The higher values of lead and chromium downcore may correlate with the activities of small Somesville industries and Hall Quarry during the nineteenth century (Table 1). The decline of these metal concentrations beginning around 20 cm (approximately the 1920's) seems to demonstrate the decline of these

industries that occurred during the early twentieth century as well as the growing emphasis upon tourism and the establishment of the national park at that time. The increase in these metals beginning at 10 cm (approximately the late 60s) may indicate that rapidly increasing car traffic to the island in the last 30 years may have locally counteracted the effect of the Clean Air Act in phasing out lead gasoline. The spikes in copper and nickel in recent years are more difficult to explain. The copper spike may be related to the opening of small boatbuilding companies (which may use copper-based antifouling paints) just prior to Clean Water Act of such businesses. This hypothesis, however, is at best a tenuous one; the fact that only one data point defines the brief spike in copper may indicate that this is an anomalous (although valid) data point.

A second noteworthy spike in our data is that seen in organic and carbon contents at approximately 12 cm. This brief influx in carbon may reflect the fire of 1947, which burned half of Mount Desert Island. However, smear slides at and around this depth failed to demonstrate concrete evidence of fire (for example, an abundance of charcoal.)

6. Conclusions

Preliminary data from two short piston cores taken in Somes Sound demonstrate 1) Recent sediments have been deposited in the sound at a relatively fast rate of approximately .3 cm/yr. As a result, a short core of approximately a meter in depth represents at best only a few centuries of sedimentary record. This record is insufficient to provide information regarding the sound's post-glacial evolution; in fact, at the current average sedimentation rate, a core approximately 18m long would be required to reach the age of inundation of the fjord. Obtaining such a core is beyond the current technology used at URI/GSO and, for that matter, at all but a small number of research institutions. 2) The short cores described in this study reveal Somes Sound to be, as expected, a relatively unpolluted region. Trace metal and organics data do demonstrate, however, that Somes Sound has experienced greater industry in past centuries than it does today.

Further study of Somes Sound will utilize ^{210}Pb and pollen dating in order to construct a stronger age model for our cores. Further study will also include analysis of trace metals further down the Hall Quarry core, as well as throughout the Somes Harbor core. The results from the two different locations may then be compared with each other, and with cores taken from other national park areas, such as Cape Cod National Seashores. Such a comparison may reveal differences in contaminant

inputs to protected areas varying in proximity to more developed regions.

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Analyzing Tsunamigenesis Using Relationships between Seismic Moment and Spectral Strength

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Abstract. Several methods have been proposed for using earthquake seismic waves to study tsunami generation. Today, P and S waves are used for tsunami warning. This method has proven ineffective. It has been suggested that T-phases generated by earthquakes can be analyzed for key parameters that may lead to better tsunami warnings, though T-wave research on tsunamis to date has been inconclusive due to insufficient data. In this study, we analyze T-waves generated by earthquakes located near the coast of Japan and surrounding islands, and recorded by SOFAR channel hydrophones near the equatorial East Pacific Rise. Our data shows a lack of correlation between T-phase spectral strength and seismic moments. In general, tsunamigenic earthquakes from these same source locations have lower T-phase spectral strengths than nontsunamigenic earthquakes of similar seismic moments. These findings suggest that future research on T waves is necessary to improve the reliability of tsunami warnings.

1. Introduction and Background

Tsunamis are destructive natural disasters that cause major destruction to the shoreline and to communities near the shoreline. Therefore, tsunami warnings are crucial to protect shorelines from devastation. To date, however, tsunami warnings are very inaccurate with false warnings given over 50% of all cases. False warnings are given as a result of the inability to accumulate a sufficient amount of usable data, due the inaccuracies involved in quantifying P- and S-waves, to analyze the differences between tsunamigenic and nontsunamigenic earthquakes. Today, only bottom-moored hydrophone stations have been used for earthquake data analysis.

Another usable source of data exists, however, from SOFAR (SOund Fixing and Ranging) hydrophones. When an earthquake occurs, there are three main types of waves that emanate from an earthquake: primary (P), secondary (S), and tertiary (T) waves. P- and S-waves are body waves that travel through the solid Earth at a much faster speed than the T-waves. Currently, primary and secondary waves are used to predict tsunamis. Though P- and S-waves have proven inaccurate for tsunami warning, one of the current key parameters in examining whether an earthquake is tsunamigenic or not is determined from the amplitude of the secondary wave. This key parameter, seismic moment, is the amount of work an earthquake performs.

Though both primary and secondary waves travel much faster than the tertiary (T-) wave, primary and secondary waves have proved inaccurate for the issuing of tsunami warnings. Ewing et al. (1950) first proposed analyzing the T-wave for predicting tsunamigenesis. The T-phase can be propagated from an earthquake, through the oceanic column into the SOFAR channel. The low-velocity SOFAR channel, which lies between 600-1200 m below the sea, has the ability to propagate energy released from an

earthquake over long distances to hydrophones, where data can be obtained and analyzed. The propagation of the T-wave from an earthquake, to the SOFAR channel, and then to a hydrophone for data accumulation is shown in Figure 1.

The correlation between T (tertiary)-phase and tsunami warning has been a matter of debate since first proposed by Ewing et al. (1950). The primary argument was that the generation of both tertiary and tsunami waves was favored by the strong coupling between the seismic source and the ocean column, which Ewing et al. (1950) contributed to the extreme shallowness of the source. Today, studies have shown earthquakes at any depth produce T-waves, and the generation of any far-field tsunamis is only moderately dependent on the bathymetry.

Figure 1: T-waves can travel through the ocean column into the SOFAR channel, where the energy can then be propagated to hydrophones thousands of kilometers away.

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Table 1. All three sets, with origin times, location, depth, body wave magnitude (M_b), secondary wave magnitude (M_s), seismic moment (M_0), and tsunamigenesis, are shown.

Earthquake Set	Origin Date (yr/mo/day)	Origin Time (hr mm ss.dec)	Coordinates		Depth (km)	m_b	M_s	M_0 (dyne-cm)	Tsunamigenic
			Lat(N)	Lon(E)					
Set 1	96/09/05	23 42 06.15	21.90	121.50	20	6.4	6.6	1.91E+26	No
	96/10/18	10 50 20.86	30.57	131.09	10	6.0	6.6	1.00E+26	Yes
	96/10/19	14 44 40.79	31.81	132.12	33	6.3	6.6	1.43E+26	Yes
	98/05/03	23 30 21.91	22.31	125.31	33	6.4	7.3	1.83E+27	Yes
	98/11/19	15 39 19.10	22.60	125.78	10	5.8	6.0	3.27E+25	No
	99/09/20	17 47 18.49	23.77	120.98	33	6.5	7.7	3.38E+27	No
	99/09/20	18 03 44.29	23.57	121.30	33	NA	NA	NA	No
	99/09/20	18 16 18.51	23.76	121.25	33	NA	NA	NA	No
	99/09/20	21 46 42.87	23.39	120.96	33	5.8	6.5	4.83E+25	No
	99/09/25	23 52 48.66	23.74	121.16	17	6.2	6.4	6.01E+25	No
	00/07/01	07 01 55.58	34.22	139.13	10	6.0	6.1	1.79E+25	Yes
	00/07/08	18 57 44.47	34.05	139.13	10	5.9	5.6	6.85E+24	No
	00/07/16	03 21 45.53	20.25	122.04	33	6.1	6.3	4.38E+25	No
	00/07/30	12 25 45.57	33.90	139.38	10	6.0	6.5	6.05E+25	No
	01/12/18	04 02 58.28	23.95	122.73	14	6.3	7.3	2.08E+26	Yes
	02/03/26	03 45 48.70	23.35	124.09	33	5.8	6.6	5.24E+25	Yes
	02/03/31	06 52 50.49	24.28	122.18	32	6.4	7.4	5.45E+26	Yes
Set 2	96/08/02	12 55 29.30	-10.77	161.45	33	6.2	7.1	2.85E+26	No
	97/04/21	12 02 26.43	-12.58	166.68	33	6.4	7.9	4.39E+27	Yes
	99/08/22	12 40 45.96	-16.12	168.04	33	6.3	6.2	7.72E+25	No
	99/11/26	13 21 15.57	-16.42	168.21	33	6.4	7.3	1.67E+27	Yes
	99/12/29	13 29 19.62	-10.86	165.35	33	5.6	6.8	2.33E+26	No
	00/08/03	01 09 38.98	-12.04	166.45	33	5.7	6.5	8.86E+25	No
	00/10/04	16 58 44.31	-15.42	166.91	23	6.1	6.9	3.02E+26	No
	02/01/02	17 22 48.76	-17.60	167.86	21	6.3	7.5	7.72E+26	Yes
	02/01/03	10 17 36.30	-17.66	168.00	10	5.8	6.4	9.91E+25	No
	02/06/17	21 26 22.92	-12.59	166.38	33	6.0	6.7	1.41E+26	No
	02/09/24	23 01 28.67	-10.65	161.21	19	5.7	6.5	3.68E+25	No
Set 3	96/16/41	10 07 36.65	1.20	120.25	33	6.0	6.4	8.40E+25	No
	96/07/22	14 19 35.77	1.00	120.45	33	6.0	6.9	3.61E+26	No
	96/09/20	04 10 27.68	9.46	126.33	33	5.8	6.4	7.51E+25	No
	96/09/20	04 11 04.55	9.45	126.33	33	5.9	0.0	1.00E+26	No
	97/03/11	19 22 00.13	7.45	127.65	10	6.3	6.7	2.23E+26	No
	97/08/29	08 14 09.97	-3.56	144.36	22	5.8	6.8	7.50E+25	No
	97/11/25	12 14 33.63	1.24	122.54	24	6.1	6.8	4.13E+26	No
	98/02/19	14 14 51.19	-4.48	129.08	33	6.1	6.4	6.84E+25	No
	98/07/17	08 49 13.28	-2.96	141.93	10	5.8	7.1	3.67E+26	Yes
	98/07/29	18 00 29.99	-2.69	138.90	33	5.9	6.7	1.21E+26	No
	98/10/28	16 25 03.84	0.84	125.97	33	6.2	6.2	6.75E+25	No
	98/11/29	14 10 31.96	-2.04	124.89	33	6.5	7.7	4.48E+27	Yes
	98/12/06	00 47 13.45	1.25	126.20	33	6.3	6.2	8.54E+25	No
	99/03/04	08 52 01.90	5.40	121.94	33	6.4	6.5	4.92E+26	No
	00/05/04	04 21 16.21	1.11	123.57	26	6.7	7.5	2.44E+27	Yes
	00/08/28	15 05 47.91	-4.11	127.39	16	6.5	6.8	1.73E+26	No
	00/08/28	19 29 24.57	-4.16	127.31	33	6.0	0.0	4.59E+25	No
	01/01/01	06 57 04.17	6.90	126.90	33	6.4	7.2	1.73E+27	No
	01/01/01	08 54 31.58	6.63	126.90	33	5.4	6.0	1.84E+26	No
	01/02/24	07 23 48.73	1.27	126.25	35	6.6	7.0	4.48E+26	No
	01/03/19	05 52 15.89	-4.03	128.02	33	6.0	6.5	6.52E+25	No
	01/09/11	14 56 50.92	-0.58	133.13	33	5.8	6.4	6.62E+25	No
	01/10/19	03 28 44.46	-4.10	123.91	33	6.3	7.3	1.86E+27	No
	02/01/10	11 14 56.93	-3.21	142.43	11	6.0	6.6	1.43E+26	No
	02/03/05	21 16 09.13	6.03	124.25	31	6.3	7.2	1.94E+27	Yes
	02/09/08	18 44 23.71	-3.30	142.95	13	6.5	7.8	2.94E+27	Yes
	02/10/10	10 50 20.57	-1.76	134.30	10	6.5	7.7	2.59E+27	Yes
	02/10/10	12 28 25.80	-1.51	133.97	10	NA	NA	NA	No

Recent studies on the correlation between seismic moment and spectral strength have been performed by Hiyoshi et al. (1992) and Okal et al. (2003). Hiyoshi et al. (1992) concluded that a correlation exists between seismic moment and spectral strength, mean spectral density.

Also, tsunamigenic earthquakes have larger T-phase spectral strength and seismic moment than nontsunamigenic earthquakes of similar source parameters (Hiyoshi et al., 1992). Okal et al. (2003) disagree and show a correlation between seismic moment and spectral strength, total power density, but note that tsunamigenic earthquakes have smaller seismic moment and spectral strength than nontsunamigenic earthquakes of comparable magnitude. Okal et al. (2003) propose a new definition of a “tsunami earthquake”, an earthquake characterized by a smaller magnitude produces a larger tsunami than to be expected. Though “tsunami earthquakes” are rare, this type of earthquake is characterized by a deficient T-phase of 1.5-2.5 orders of magnitude less than a nontsunamigenic earthquake of comparable source parameters.

In our study, only SOFAR hydrophones were used in the investigation of the relationship between spectral

strength and seismic moment. In the past, SOFAR hydrophones have not been used because the signals were “clipped” (i.e. the hydrophones were too sensitive and became saturated by the amount of energy the earthquake produced). In efforts to find all available resources to predict tsunamis, SOFAR channel hydrophones were used. While small data sets were produced, the SOFAR channel still provides accurate information that in the future, could help predict tsunamis and improve tsunami warning.

2. Data

Earthquakes were chosen based on magnitude (6.5–10) and depth (0 and 40 km). The earthquakes were gathered from three databases of the USGS National Earthquake Information Center, Harvard CMT, and the NOAA Acoustic Monitoring database. Earthquake information, such as time, magnitude, depth, and source location, was obtained from the USGS National Earthquake Information Center (NEIC). Data for the magnitudes of both primary and secondary waves, as well as the seismic moment, were obtained from the Harvard CMT database. Finally, seismograms were obtained from the NOAA Acoustic Monitoring database

Figure 2. All East Pacific Rise (EPR) Hydrophones are located near the coast of Central America. The three rectangular sets are shown above.

for analysis of T-phase duration and spectra. All data accumulated from these databases are shown in Table 1.

Data were obtained from SOFAR channel hydrophones located along the East Pacific Rise (EPR) from June 1, 1996 to December 31, 2002. Three rectangular source locations, located near Japan and the surrounding islands, were chosen to keep similar source parameters, such as bathymetry and travel path dependence to the SOFAR channel. All hydrophones, as well as the locations of the three rectangular sets and tsunamigenic earthquakes can be found in Figure 2.

3. Methods

The primary objectives of research were to analyze the correlation between seismic moment and T-phase spectral strength, as well as the differences in these two key parameters between tsunamigenic and nontsunamigenic earthquakes. Spectral strength is found from cut T-phase duration seismograms. Hiyoshi et al (1992) cut a one-minute interval for T-phase duration, thirty seconds before and thirty seconds after the main earthquake shock. Though a one-minute duration provides a constant window of time, this study analyzed the total T-phase duration and estimated an appropriate cut to provide for a more accurate result of the T-phase energy. The seismograms were cut for total duration, and then analyzed by a Matlab program (Appendix A). The Matlab program was designed to produce a spectrum of power spectra density vs. frequency. The spectrum was integrated for the calculation of the total power (T-phase energy flux) and the average power using another Matlab program (Appendix B). An example of a cut seismogram and the spectrum over all frequencies is shown in Figure 3. The total power (T-phase energy flux) and average power results correlated against seismic moment are shown for all three rectangular locations in Figure 4.

Figure 4: An example of a cut seismogram of a nontsunamigenic earthquake located within Set #3 and the Power Spectrum Density vs. Frequency in Hz

4. Observations

Set #1 produced eight usable tsunamigenic and seven usable nontsunamigenic earthquakes for analyses. The tsunamis within this set produced run-up between a range of 4 cm to 1.1 m. Graphs showing total power vs. seismic moment and average power vs. seismic moment were produced, with no clear correlations. This set also had three clipped earthquake events (2 nontsunami, 1 tsunami), and this clipping may have resulted in an

underestimate of the energy released. Overall, tsunamigenic earthquakes appear to have higher seismic moments and lower spectral strengths compared to the nontsunamigenic earthquakes of comparable magnitude.

Earthquakes located within set #2 produced three usable tsunamigenic and five usable nontsunamigenic events. The tsunamis produced in this set had a range of 10 cm to 15 m in run-up. Again, graphs showing total power vs. seismic moment and average power vs. seismic moment were constructed. Though a much smaller data set was used, no clear correlation was found. Again, tsunamigenic earthquakes appear to have larger seismic moments and smaller spectral strength than nontsunamigenic earthquakes with similar magnitude. Many of the earthquake events within this set had no identifiable T-phase or the T-phase was too clipped for analysis.

Events located within set #3, the largest rectangular set, produced three tsunamigenic and twelve nontsunamigenic earthquakes. Tsunamis within this set were 1.5 cm to 15 m in run-up, causing major destruction to the shore. Graphs of total power vs. seismic moment and average power vs. seismic moment were constructed, and still, no correlation could be found. Also, tsunamigenic earthquakes appear to have larger seismic moments and smaller spectral strengths than nontsunamigenic earthquakes of similar parameters. Four earthquake events were clipped, three being nontsunamigenic events, providing an underestimate of energy release.

In sets two and three, there existed one clipped tsunamigenic earthquake anomaly. This earthquake had both large seismic moment and large spectral strength. No information is available for the tsunamigenic anomaly occurring in set two, but the tsunamigenic event in set three was a large M_s 7.1 earthquake that occurred near the coast of Papua New Guinea. Three tsunami waves were released that devastated shore villages. The tsunami run-up was felt in New Zealand as well as Japan.

5. Discussion: Problems and Future Research

SOFAR channel hydrophones were too sensitive in some cases to fully record the amount of T-phase energy released from an earthquake, and therefore these earthquakes were not examined in this study. This sensitivity limits the amount of conclusive data that exists, so larger data sets need to be obtained for future research. Also, the effect the travel path of T-phase energy to the hydrophone has to be analyzed because of the direct effect the path has on the amount of energy that makes it through the SOFAR channel and eventually to the hydrophone. Island chains could block some of the earthquake travel paths resulting in an underestimate of the total T-phase energy. Another problem that future research needs to explore is the T-phase duration. Hiyoshi et al. (1992) used a one-minute window, thirty seconds before and thirty seconds after the main shock to quantify T-phase duration, while methodology used in this paper gave an estimate of the

total T-phase duration in every earthquake event. An underestimate of the total T-phase duration would provide a lower estimate of T-phase energy, and vice-versa for an overestimate of the T-phase duration. Lastly, source mechanism of tsunami-generating earthquakes needs to be explored. Earthquakes of all types of fault mechanisms are not the only method of producing a tsunami. Landslides, and even meteor impacts, have resulted in tsunamis, and the energy released from the T-phase recorded from these events needs to be accumulated and analyzed.

6. Conclusion

There may exist a correlation between seismic moment and the total T-phase energy flux. When clipped earthquakes are ignored, tsunamigenic earthquakes appear in all three sets to have lower T-phase energy flux and higher seismic moment than nontsunamigenic earthquakes of similar magnitude.

Hiyoshi et al. (1992) conclusions, using data from bottom-moored hydrophones, do not apply with the data used in this research. Though Hiyoshi et al. (1992) showed a positive correlation between seismic moment and spectral strength, the data set used in this research does not prove that the same correlation exists. Also, Hiyoshi et al. (1992) showed that tsunamigenic earthquakes had larger spectral strength and seismic moment than nontsunamigenic earthquakes of similar magnitude. In fact, there is an indication that Okal et al. (2003) results may be correct, for all tsunamigenic earthquakes and not just for "tsunami earthquakes". Okal et al. (2003) identifies "tsunami earthquakes" as T-phase deficient, and of lower spectral strength and seismic moments, but also shows this deficiency is in direct result of slow rupture velocities. Further study of earthquakes of lower magnitude, such that would be comparable to Okal's definition of a "tsunami earthquake", may be able to prove Okal et al. (2003) conclusions correct.

This study shows that SOFAR channel hydrophones provide another source of earthquake T-phase data, and could add to the advancement of tsunami warnings. In the future, T-phase duration, seismic moment, and spectral strength need to be further analyzed and more modifications need to be made to seismic analysis to finally put to rest the fifty year old controversy about the correlation between T-phase generation and tsunamigenesis.

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Appendix A: Matlab Program for obtaining the graph of Power Spectrum Density (Spectral Strength) vs. Frequency, as well as showing cut seismogram

```

echo off
global trace tt
global kstnm baz
global nzyear nzjday nzhour nzmin nzsec nzmsec
global B
trace = []; tt=[];kstnm=[];
nzyear=[];nzjday=[];nzhour[];nzmin=[];nzsec=[];
nzmsec=[];
B=[];
read_sac)1,'/d2/epr/set3/97.241.10/junk1.sac')
figure(1)
clf
subplot('position',[0.3 0.65 0.4 0.3])
plot(tt-tt(1),trace)
hold on
xlabel('time, s')
ylabel('counts')

subplot('position',[0.3 0.15 0.4 0.3])
[Pss,F]=pwelch(trace,200,256);
plot(F,Pxx(:1))
hold on
xlabel('Frequency, Hz')
ylabel('Power Spectrum Density')

[nr nc]=size(trace);
dt=tt(2)-tt(1);

%Numerical recipes, pp.384
tpower=0;
for i=1:nr
tpower=tpower+trace(i)*trace(i)*dt;
end
tpower
apower = tpower/nr

```

Appendix B: Matlab program to produce plots of total power and average power vs. seismic moment

```

%
clear

%load tsunami1.dat
%load nontsunami1.dat

load tsunami.dat
load nontsunami.dat

%load tsunami2.dat
%load nontsunami2.dat

t=tsunami;
nt=nontsunami;

figure(1)
clf
subplot('position',[0.2 0.3 0.5 0.4])

[nr nc]=size(t);
for i=1:nr
    if t(i,4) == -1
        loglog(t(i,3),t(i,2),'g+')
        hold on
    end
    if t(i,4) == 1
        loglog(t(i,3),t(i,2),'r+')
        hold on
        loglog(t(i,3),t(i,5),'rs')
        hold on
    end
end

[nr nc]=size(nt);
for i=1:nr
    if nt(i,4) == -1
        loglog(nt(i,3),nt(i,2),'go')
        hold on
    end
    if nt(i,4) == 1
        loglog(nt(i,3),nt(i,2),'ko')
        hold on
        loglog(nt(i,3),nt(i,2),'k*')
        hold on
    end
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%average
e T phase energy flux
figure(2)
clf
subplot('position',[0.2 0.3 0.5 0.4])
[nr nc]=size(t);
for i=1:nr
    if t(i,4) == -1
        loglog(t(i,3),t(i,5),'g+')
        hold on
    end
    if t(i,4) == 1
        loglog(t(i,3),t(i,5),'r+')
        hold on
        loglog(t(i,3),t(i,5),'rs')
        hold on
    end
end

[nr nc]=size(nt);
for i=1:nr
    if nt(i,4) == -1
        loglog(nt(i,3),nt(i,5),'go')
        hold on
    end
    if nt(i,4) == 1
        loglog(nt(i,3),nt(i,5),'ko')
        hold on
        loglog(nt(i,3),nt(i,5),'k*')
        hold on
    end
end
end

```

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