Chinook salmon rearing in the San Francisco Bay-Delta system: Identification of geochemical markers to determine Delta use

California Bay Delta Authority
Science Program Project #SCI-05-C179 - Dr. Lynn Ingram

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PROJECT PURPOSE

Background

The importance of the San Francisco Bay-Delta system to the native juvenile salmonid rearing is poorly understood (Fig. 1). Fish surveys in this system provide snap shots of the population as it travels down the rivers and enter and exit the Bay-Delta complex (Kjelson et al. 1982; Brandes et al. 2001; MacFarlane and Norton, 2002). But existing techniques are unable to address the most important issue, the relationship between fish residence time in the Delta and the Bay to success in later life stages, and most importantly, to becoming a successful spawner.

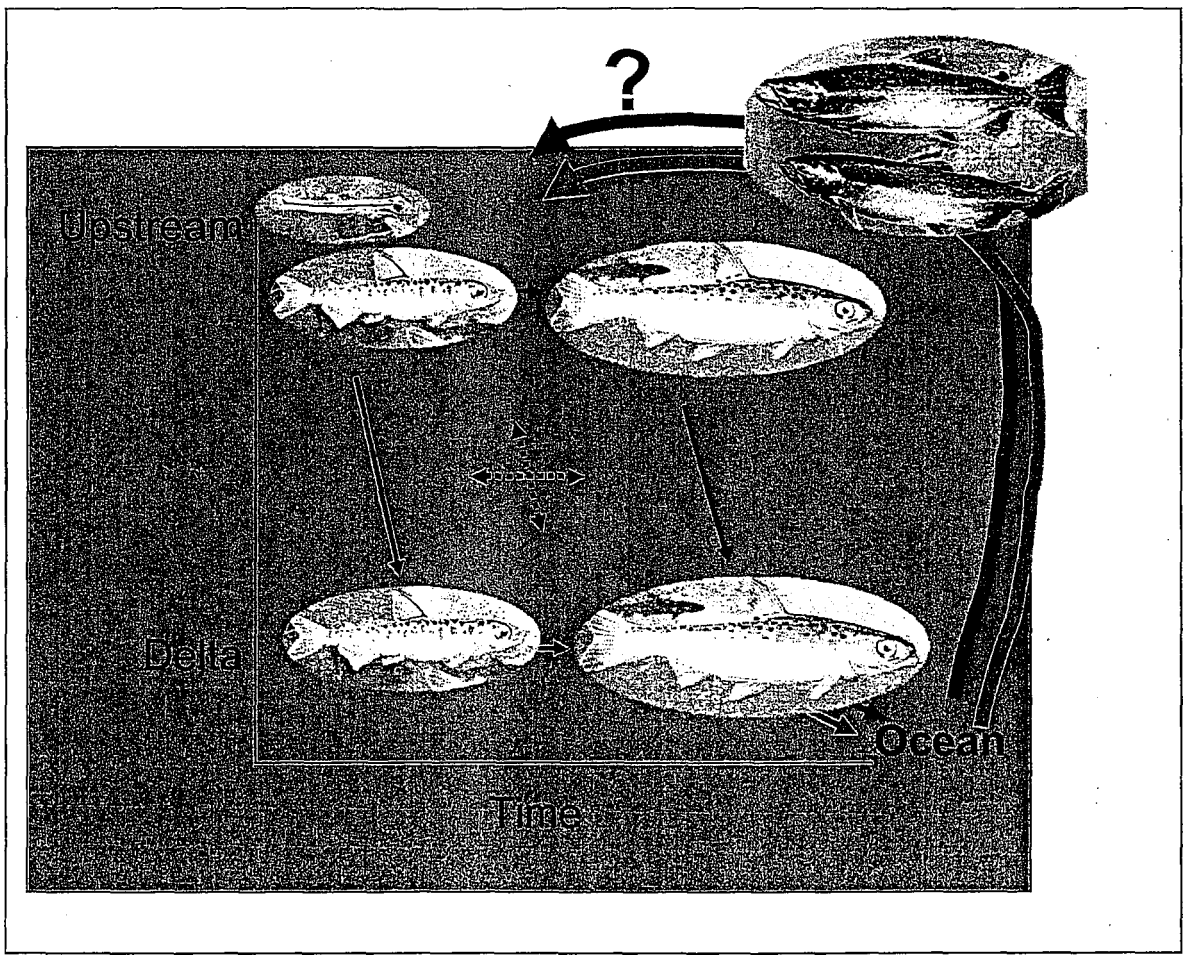

Figure 1. The central research question in this proposal is, What is the role of the Delta in salmon rearing? This figure shows a schematic representation of the continuum of rearing and outmigration possibilities for junvenile chinook salmon, and poses the question, which history is more likely to result in adults returning to spawn. The methods developed in this proposal would allow researchers to close the loop between juvenile behavior and adult spawning success.

In our previous work, we developed geochemical markers in otoliths to characterize the early life history of juvenile Chinook salmon in the Sacramento-San Joaquin river system (Ingram and Weber, 1999; Weber et al., 2002; Weber, 2002; Weber et al., in press). We use otoliths because they form daily bands during the juvenile life stage, which can be used to construct a chronology of an individual fish's early life (Neilson and Geen, 1982; Campana and Neilson, 1985; Carnpana, 1999). We perform micro-chemical analyses that provide approximately one-week temporal resolution in juveniles H0-micron lateral resolution) (Weber et al., 2002; Weber et al., in press). To date, we have developed geochemical tracers for Sacramento River salmon otoliths that (1) distinguish between hatchery-raised and naturally spawned salmon using sulfur isotopes (a^{34}S), (2) determine a fish's natal river of origin using strontium isotopes (^{87}Sr/^{86}Sr), and (3) can identify the timing of downstream migration from spawning grounds using carbon isotopes (5^{13}c) and (4) of ocean entry using strontium-calcium ratio (Sr/Ca). The missing piece in our work in this river system is a marker or set of markers to determine the timing and duration of use of different parts of the San Francisco Bay-Delta system (Fig. 2).

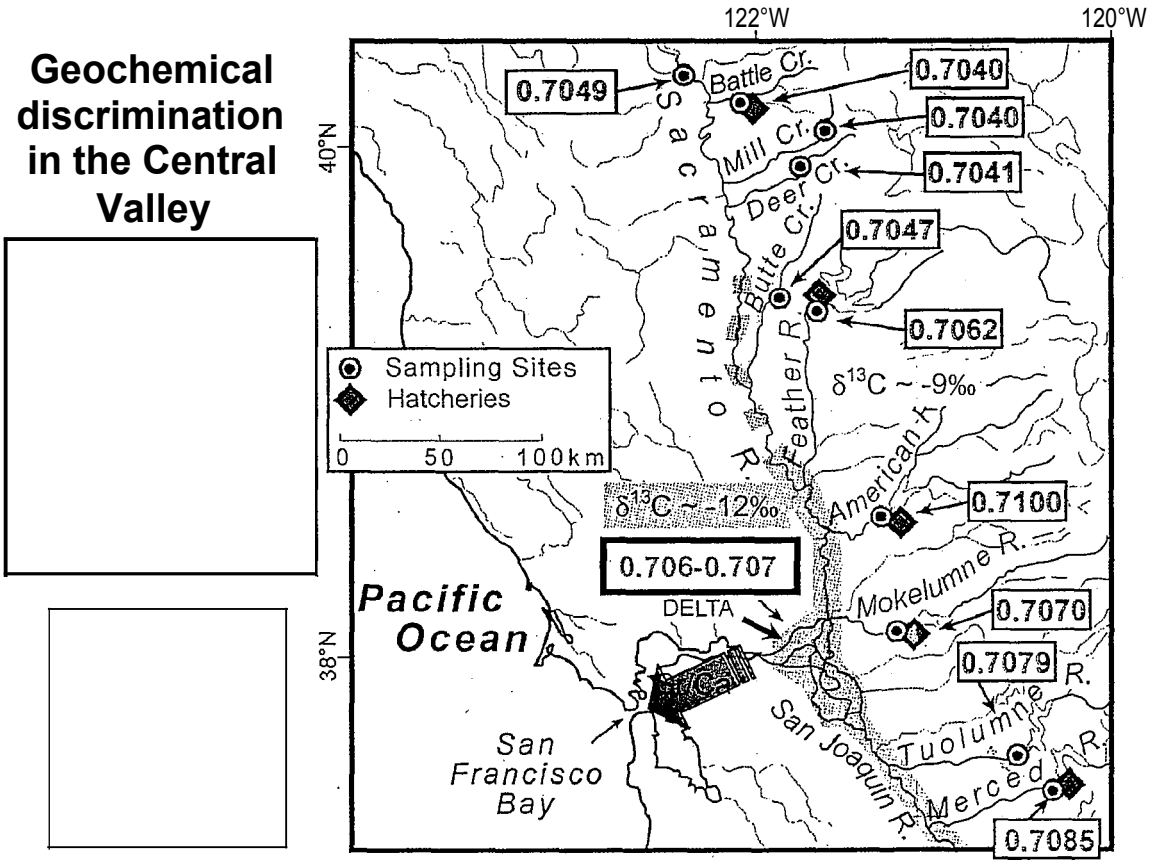

Figure 2. Map of the distribution of key geochemical markers in the Sacramento-San Joaquin river system. Sulfur isotopes (not included) can distinguish between hatchery and naturally spawned fish.

Here, we propose to focus our effort on developing geochemical markers to determine the timing and duration of Delta and Bay use. We will focus on Delta use because the tole of the Delta in salmonid rearing is a major question in Central Valley ecosystem and water management, and because we expect the salinity gradient to provide a ready reference for migration from Chipps Island to the Golden Gate. But we will include samples collected between the Delta and the ocean to provide a complete picture of the geochemical markers in the system. To the extent possible, we will identify geochemical markers that identify sub-regions of the Delta.

We are in a strong position to take on this problem. Prof. Ingram and Dr. Weber have extensive experience in the Sacramento-San Joaquin river system, including six years working on otolith chemistry. We have an archive of hundreds of samples from the Bay and Delta collected by the U.S. Fish and Wildlife Service, the California Department of Fish and Game and ourselves. We have otolith microchemistry data from outmigrating juveniles and returned adults that point towards specific geochemical markers in otoliths as strong candidates for distinguishing Delta and Bay use from other periods of the salmonid life cycle. We have access to the analytical equipment we need at the University of California, Berkeley (UCB), Lawrence Livermore National Laboratory (LLNL), and the University of California Davis. And we have a reliable and experienced staff member, Corey Phillis, in the Ingram Laboratory at the University of California, Berkeley, to take on the project under the joint direction of Prof. Ingram and Dr. Weber.

We are very excited about this work because of its potential to expand our understanding of salmonid habitat use. We would be particularly interested to use these markers to study how year-to-year environmental variations (such as ENSO) affect Delta and Bay use. We have in hand a set of adult otoliths to which we are already applying our techniques to understand spawning sources, and with which we could study Delta and Bay use on an interannual basis. While this question of interannual variability is larger than can be addressed in this study, the tools that we would develop would help to address such questions, and therefore would be a major contribution to the toolkit of researchers and managers in this system.

PROJECT DESCRIPTION

Otoliths are calcium carbonate concretions in the inner ear of bony fish. They accrete with discernable daily increments in juvenile chinook salmon (Neilson and Geen, 1982; Campana and Neilson, 1985). The chemistry of these increments can be directly related to the chemistry of the water the fish were living in and/or the food they were eating at the time that the increments were deposited (Campana, 1999). The goal of this project is to identify the chemical markers that can be used to constrain Delta use in the Sacramento-San Joaquin river system that can be measured in otolith growth increments using microanalytical techniques. This project will cover two years. In the first year, we will do broad surveying to identify promising Bay and Delta markers. In the second year, we will focus on promising markers to establish their reliability to uniquely identify Delta and/or Bay residence.

Our approach is to do directed surveying of the spatial distribution of geochemical markers in the Delta and Bay. For samples, we will primarily rely on our archive of juvenile chinook salmon. We will receive additional fish samples from Delta monitoring and complement these samples with our own field sampling for water and prey items for their period of outmigration. For this project, we will prioritize geochemical markers that study based on (1) our knowledge of what can be detected in otoliths, (2) our knowledge of geochemical drivers, such as regional geology, nutrient cycling, and the hydrologic cycle, and (3) our extensive previous work in the Sacramento-San Joaquin river system.

Step 1 is to constrain departure from the Delta. We will use otolith Sr/Ca as the reference for departure from the Delta because it is relatively easy to measure and it is directly related to the salinity of the water the fish is residing in at the time of otolith $CaCO_3$ deposition (Fig. 3). The salinity gradient between the Delta and the ocean results in an increase in the Sr/Ca ratio, as indicated in Figure 2. The change in Sr/Ca with salinity will be examined using our collection of juvenile chinook salmon collected at Chipps Island by the U.S. Fish and Wildlife Service, and by the California Department of Fish and Game at various locations in the Bay. Period of increasing Sr/Ca would to the first order define the period of Bay residence. Changes in otolith Sr/Ca ratio during freshwater residence are smaller and are not likely to be useful for distinguishing Delta residence from river residence.

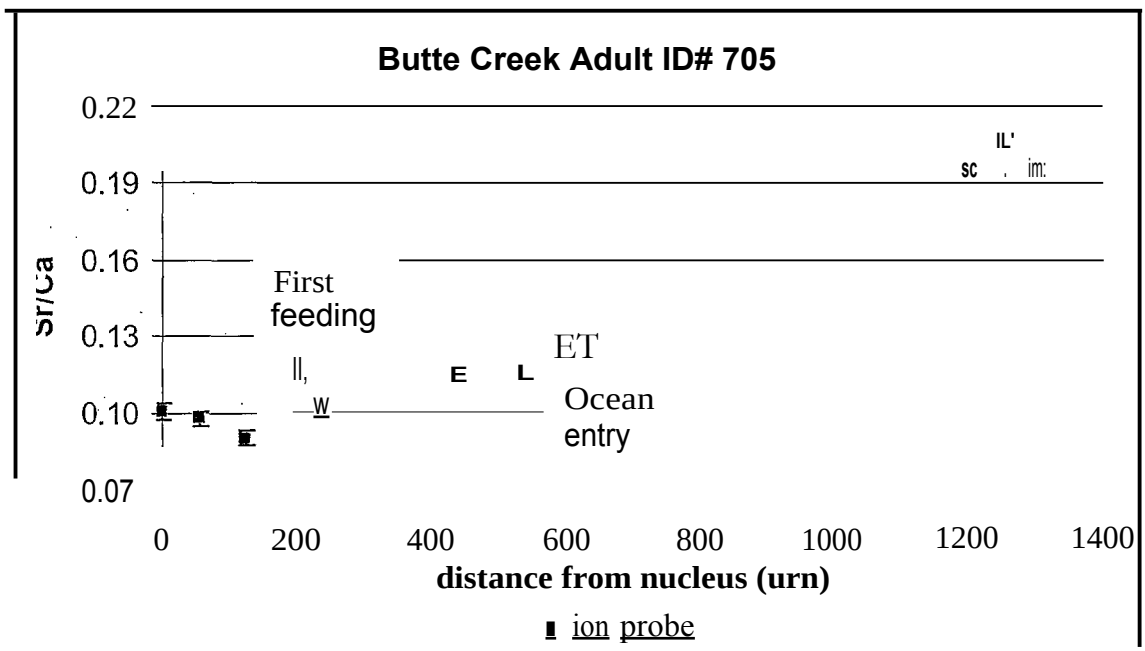

Figure 3. Otolith Sr/Ca profile in the otolith of an adult chinook salmon showing ocean entry. Based on this easily measured parameter, departure from the Delta can be constrained. The data are presented as ion ratios. Error bars are 2 standard errors.

With Sr/Ca to constrain departure from the. Delta, theoretically only one additional marker-a Delta entry marker-is necessary to constrain Delta residence. Conbeptually, this marker could take various foiuis:. a positive marker (present in the

Delta and not in the river), a negative marker (the opposite), or a combination. On the Bay and ocean side, the otolith could reflect the same signal as in the river or the Delta, or could have a third level. Figure 4 presents two examples of hypothetical marker that would constrain Delta residence. In this example, Marker 2 would be sufficient by itself to constrain Delta residence, but such a remarkable marker is highly unlikely in the Delta, and therefore it is important to have Sr/Ca as a reference. Environmental complexities may necessitate the identification of more than two markers to provide sufficient discrimination power to determine duration of Delta residence.

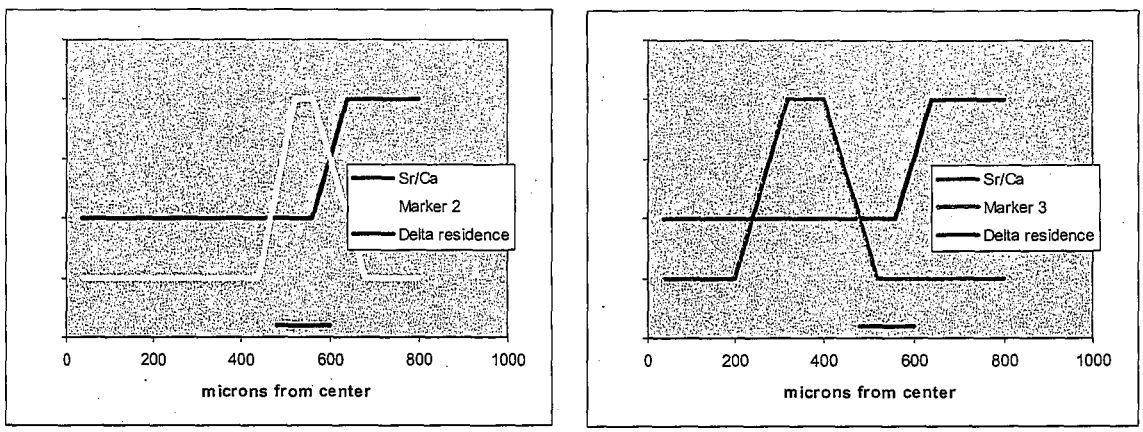

Figure 4. Conceptual model: Profiles of otolith Sr/Ca and a hypothetical markers that would constrain Delta residence. The otolith chemistry profiles on the left represent a positive marker, and on right is a negative marker. Temporal duration of Delta residence would be determined by band counting.

We have identified a number of promising markers that could be used in combination with Sr/Ca to constrain Delta residence. The most promising ones are isotopic ratios, which are expressed in delta notation (e.g., for carbon isotopic composition, $5'^{3}C = [(^{13}C/^{12}C)_{unknown}/(^{13}C/^{12}C)_{reference} - 1] \times 1000$, in units of permil). We have previously noted changes in sulfur ($6^{34}S$), carbon ($6^{13}C$) and oxygen ($6^{18}0$) isotopic compositions of otolith bands associated signatures related to the Delta and Bay, but we have not had the resources to focus on this region to map the changes as are necessary for this work. For example, the data in Figure 5 indicates that otolith $8^{34}5$ may be useful for constraining Delta residence. The data are for two adult chinook salmon, one of which is hatchery-raised and other of which was naturally-spawned. Because of the differences in the life history of the two fish, the otolith $6^{34}5$ values diverge after first feeding. What is of interest for this project is the fact that the signatures reconverge just before ocean entry. The value at which they reconverge is potentially a Delta signature. Otolith $6^{34}S$ is determined by the nutrient source at the time that the otolith increments are deposited (Weber et. al. 2002). We have similarly intriguing data for otolith $5^{13}C$ and $8^{18}0$. Figure 6 shows how otolith$8^{34}S$ and otolith $8^{13}C$ could be used in combination with Sr/Ca to potentially constrain Dela residence.

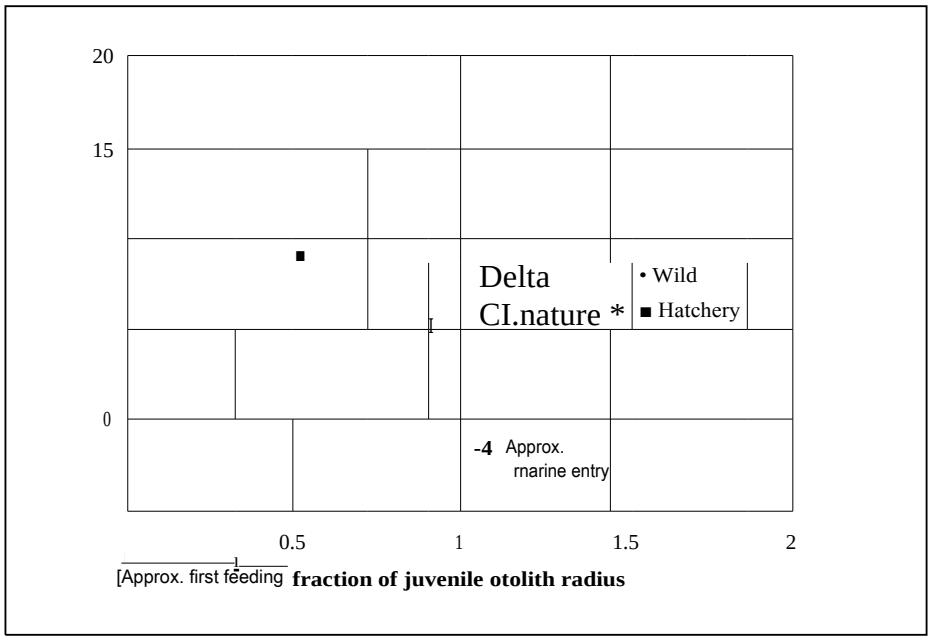

Figure 5. Otolith $6^{34}S$ for two adult chinook salmon, showing potential Delta $\delta^{34}S$ signature.

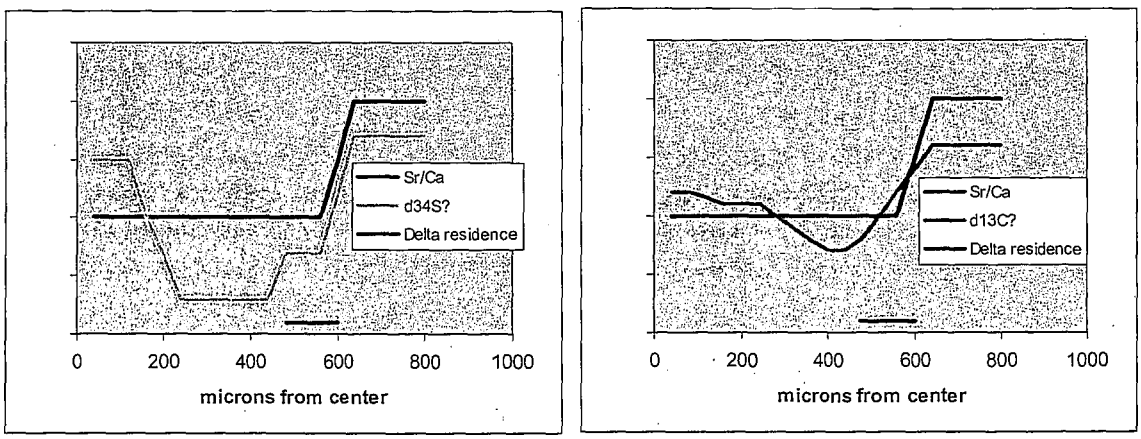

Figure 6. Potential otolith chemical profiles that would constrain Delta residence, based on data in hand. $S^{34}S$ and $S^{13}C$ would be studied under CalFed funding.

We will also examine other markers that could provide constraint on this problem. We will measure the Sr isotopic ratio ($^{87}Sr/^{86}Sr$) in a limited number of otoliths to make a more complete assessment of the value of this marker in the Delta. Our previous work suggested that this marker would be of limited usefulness for the Delta because the Delta $^{87}Sr/^{86}Sr$ ratio is very similar to the $^{87}Sr/^{86}Sr$ ratios in the Feather, Mokeluxnne, and lower Sacramento and San Joaquin rivers (Fig. 2). Furtheiiiiore, Delta $^{87}Sr/^{86}Sr$ ratios can have large temporal variations. However, with recent instrumental advances (Ramos et al.

2004) and with the importance of the $^{87}Sr/^{8}6Sr$ ratio to the overall geochemical mapping of the Sacramento-San Joaquin river system (Ingram and Weber 1999; Weber 2002), it is important to include this marker in this study. We will also examine trace elements that may be related to Delta circulation, including Ba and Mn, and contaminants associated with the Delta and Bay, such as Hg and Se. The work on Hg and Se is speculative, but if successful, these would be ground breaking measurements, not only for our work, but also for contaminant work in the Bay and Delta..

We will analyze samples collected from throughout the Delta to develop a database of the geographic distribution of geochemical markers. This study will be based on our archive samples, and selective new sampling in the Delta. The primary samples for this study will be CWT juvenile chinook salmon released near and in the Delta and recaptured as part of the USFWS Delta monitoring (>300 samples). These samples include CWT juvenile chinook salmon released in the lower Sacramento River and recaptured at the same location in the lower Sacramento River (-30 samples) and in the Delta (-20 samples) in 1999. The release-recapture samples will allow us to relate otolith chemistry just upstream of the Delta to otolith chemistry in the Delta to constrain movement from the mainstem into the Delta. These samples also have the distinct benefit of providing good control on the duration that the fish were in the lower Sacramento. We will then sample from our archive of samples to test our results. We will primarily use fish for which we not only know when and where the fish were captured, but also when and where they were released.

Out-migration from the Delta will be constrained using juvenile chinook salmon collected in the San Francisco Bay by the California Department of Fish and Game, which we have in our archive (-70). We also have food item and water samples from the lower Sacramento River, the Delta, and the Bay, which we will analyze for further comparison of geochemical signatures between sites.

In addition to the archival samples, water and prey samples will be collected in March, April and May of the first year of the grant. These samples will be related to juvenile chinook salmon collected in the Delta and Bay by the USFWS and DFG in field monitoring of that year.

The primary approach to surveying the geochemical markers will be to make microanalyses of the outer increments of otoliths. In the case of $S^{34}S$, however, we will focus on analyzing prey items because this is a simpler and cheaper method. Inferences from the $8^{34}5$ analyses of prey will be confirmed by making otolith $6^{34}S$ measurements. Water sample $5^{18}0$ and water DIC $6^{13}C$ will be used to confirm otolith measurements. Water trace element data Will also be used in a similar fashion, although the link between water chemistry and otolith chemistry is not as direct as in the case of the stable isotopes.

Plan of Work

All sample preparation will be carried out at UCB. Otoliths will be analyzed for carbon and oxygen isotopic composition, and for trace element composition. Food items will be analyzed for sulfur isotopic composition. Water samples will be analyzed for carbon and oxygen isotopic composition, and trace element composition. Initial Sr/Ca characterization of the otoliths will be performed by electron microprobe at LLNL. Further in situ trace element analyses of otoliths, with the exception of Se, will be performed at UCD using the new laser sampling system coupled to the quadrapole ICP-MS. Selenium analyses will performed at LLNL by secondary ion mass spectrometry because of the high sensitivity of that instrument for elements such as Se that preferentially produce negative ions. For most of the isotopic analyses; otolith samples will be microsampled at UCB using Prof. Ingram's micromill and then analyzed using her isotope ratio mass spectrometer. Limited S, C and 0 isotopic analyses will be performed at LLNL by secondary ion mass spectrometry to confirm other work. Water and food item isotopic analyses will also be performed in Prof. Ingram's lab. Water trace element chemistry will be carried out at UCD by quadrapole ICP-MS. Otolith Sr isotope data will be collected with the UCD laser sampling system coupled to the multicollector ICP-MS. The data will be compared to our database of geochemical signatures for the Sacramento-San Joaquin river system, and to the marine signatures, to determine discrimination power.

We anticipate making 400 C and 0 isotope analyses on otoliths by IRMS (both 5^{13}C and 5^{18}0 data are produce with each analysis). This will include at least 20% replicates for quality control. The outer layers of -150 otoliths will be analyzed by this method, and an additional 25 to 50 will be subsampled over the entire period of otolith growth to provide isotopic profiles. Three hundred S isotope analyses of prey items and gut contents will be made by IRMS. This will include gut contents and tissue samples from approximately one-third of the fish sampled for otoliths (-150 samples) and field samples (-100). Duplicate samples will be, made for -20%. One hundred and fifty samples will be analyzed for water C and 0 isotopes by IRMS. This will include -75 for $6^{18}0$ and -75 for DIC 6^{13}C. All water samples collected for this study will be analyzed for trace elements (150). Approximately three runs per sample will be necessary to allow for dilutions (50 hours). In situ trace element analyses will be performed on all otoliths. The 100 hours allows for experimental work on Hg in otoliths. Selected otoliths will be analyzed for ^{87}Sr/^{86}Sr (90 hours). The analytical time allotted for these measurements allows for calibration. We have a unique set of ^{87}Sr/8^{6}Sr standards for these measurements, which will insure quality control. Electron probe Sr/Ca analyses at LLNL will be performed on all otoliths, as necessary. The exploratory Se otolith analyses by secondary ion mass spectrometry at LLNL will be performed during two days; additional work will be performed if shown to be promising. In situ otolith stable isotope analyses by secondary ion mass spectrometry at LLNL will be performed on a "as needed" basis. There will be no cost for the analytical work at LLNL.

Task Table: Task summary, schedule, and list of deliverables

task ID	task name	start month	end month	personnel involved	description	deliverables
1.1	Field Sampling	1	22.5	Phillis, Corey C. *Work-Study Student	Collect water samples and juvenile chinook prey items in the Sacramento River, San Joaquin River, Delta, and San Francisco Bay Estuary for trace element and stable isotope analyses. Samples will be collected in late winter and early spring. Performed by UC Berkeley.	Provide samples necessary to perform a river-to-bay overview of potential geochemical markers to be used in otolith analyses.
2.1	Water Sample Preparation	1	22.5	Phillis, Corey C.	Prepare water samples for trace element and isotopic analysis. Water samples must be filtered for trace element and oxygen isotopic analyses. Performed by UC Berkeley.	Water samples prepped and ready for analysis.
2.2	Water Sample Analysis (C and O isotopes by IRMS)	1	22.5	Phillis, Corey C.	Analyze water samples for Oxygen isotopes using Isotope Ratio Mass spectrometry (IRMS) Performed by UC Berkeley.	Water Carbon and Oxygen isotopic composition of study site for potential use as geochemical markers.

2.4	Water Sample Analysis (trace element composition by ICP-MS)	1	22.5	Phillis, Corey C.	Analyze trace element composition of water samples using ICP-MS. Performed by UC Berkeley.	Water trace element composition of study site for potential use as geochemical markers.
3.1	Prey Item/Gut Content Sample Preparation	1	25	Phillis, Corey C.	Take juvenile chinook salmon gut contents for sulfur isotopic composition analysis, Prepare collected prey items for sulfur isotopic composition analysis by doing lipid extraction and weighing out samples in tin cups for analysis. Performed by UC Berkeley	Juvenile chinook salmon prey item and gut content samples prepped and ready for sulfur isotopic composition analysis.
3.2	Prey Item/Gut Content Sample Analysis (by IRMS)	1	25	Phillis, Corey C.	Analyze juvenile chinook salmon prey items and gut content for sulfur isotopic composition using IRMS. Performed by UC Berkeley.	Sulfur isotopic composition of junvenile chinook salmon prey items.
4.1	Otolith Sample Preparation	1	27.5	Phillis, C. *Work-Study Student	Remove, clean, mount and section otoliths for in situ analysis and micromilling. Performed by UC Berkeley.	Prepared otoliths for analysis.
4.4	In Situ Otolith Trace Element Analysis (by LA-ICP-MS)	1	27.5	Phillis, Corey C.	Analyze otoliths for trace elements. Performed by UC	Otolith trace element data.

					jBerkeley.	
4.6	In Situ Oto li th Isotopic Analysis (by SIMS)	1	27.5	Weber, Peter K., PhD. Phillis, Corey C.	Analysis of selected samples for confirmation of IRMS data. Performed by LLNL.	High spatial resolution otolith isotopic data to confirm IRMS data.
4.5	Otolith Sr. Isotopic Analysis (by LA-ICP-MS)	1	27.5	Phillis, C orey C.	Analyze otolith Sr isotopic composition. P er f orme d by Berkeley.	Otolith Sr isotope data.
4.3	Otolith Isotopic Microanalysis (by Micromill IRMS)	1	27 5	Phillis, Corey C.	Analayze otolith C and 0 isotopes spatially in otolith by micromilling for IRMS. Performed by UC Berkeley.	Otolith C and 0 isotopic data.
5.1	Data Analysis and Presentation of Results	1	30	Weber, Peter K., PhD, Phillis, Corey C.	Analyze, integrate, and interpret data from the project. Performed by UC Berkeley.	Scientific publication(s) and project report.
4.2	In Situ Otolith Sr/Ca Analysis (by electron microprobe)	1	22.5	Weber, Peter K., PhD.• Phillis, Corey C.	Characterization of otolith Sr/Ca ratio. Performed by LLNL.	High resolution otolith Sr/Ca ratio data to characterize the rise in this ratio with exposure to. higher salinity water.

DELIVERABLES

We will produce the following data:

- Otolith Sr/Ca by electron microprobe
  Otolith Sr, Ba, Mn, Hg and other by LA-ICP-MS
- Otolith Se by secondary ion mass spectrometry
- Otolith C and 0 isotopes sampled by micromill for isotope ratio mass spectrometry (IRMS)

Otolith S, C and 0 isotopic composition for selected samples by secondary ion mass spectrometry
Otolith Sr isotope composition by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS)
Food item S isotopes by IRMS
Water C and 0 isotopes by IRMS
Water trace element composition by ICP-MS

General deliverables involving all tasks:

- Presentations at conferences including the CALFED Science Conference.
- Semi-annual reports will be submitted every 6 months following the project start date;
- Final report will be submitted 30 months from the project start date.
- Draft manuscript will be substituted for a project closure summary report and submitted 30 months from the project start date.
- Final manuscripts will be submitted after publication..

We will also produce a report on geochemical markers for determining residence in the Delta and Bay, including all data generated under this grant. The report will relate the geochemical data for the Delta and Bay to the rivers in the Sacramento-San Joaquin system and the ocean. The report will assess the ability to distinguish Bay and Delta residence from residence elsewhere. The work under this grant will also be the basis for peer-reviewed publications.

PERMITTING

Peiinits are not needed because proponents are not the ones collecting the samples. They will be receiving samples from U.S. Fish and Wildlife Service and other sources that will be collecting the samples for their own purposes, under their own permits.

PROJECT **JUSTIFICATION**

This research is relevant to the goals of managing the freshwater fishery, mitigating habitat loss and contamination, and managing and planning ecosystem restoration. The identification of geochemical markers specific to the Delta would provide managers with a new tool to monitor and understand Delta use by salmonids. The information that could be gained by this new method would be more comprehensive than could be gained by previous methods, because it would allow Delta and Bay use to be placed within the context of the entire life history of a spawning fish. This information would be useful to management decisions ranging from water management to restoration efforts. This method would also likely be transferable to other species that migrate in and out of the Delta, such as striped bass, smelt, and splittail.

BUDGET

The budget covers 80% of the salary and benefits for one staff member (Corey Phillis) for 30 months (the other 20% will be covered by an independent funding source) and

100% salary and benefits for one part-time work-study student. The budget also covers sample analyses at UCB and UCD. Analyses will be perfoimed at LLNL without charge to the project.

QUALIFICATIONS

Prof. Ingram is an expert in geochemical markers in the San Francisco Bay Estuary. She has worked in the Estuary for 14 years. Dr. Weber is an expert in otolith geochemistry and microchemical analysis. He has worked in the Sacramento-San Joaquin river system for six years. Corey Phillis has a B.S. in Marine Biology and previously did salmon population work for NMFS in Santa Cruz, as well as work for three different graduate students' research projects. For the last 19 months he has been a staff researcher at UC Berkeley in charge of the field work, sample collection, sample preparation, microanalysis, and statistical analysis of data necessary to Dr. Weber's otolith geochemistry analyses.

SELECTION PANEL REQUIRED MODIFICATIONS

The Selection Panel wanted to ensure that this project team incorporate salmonid biologists so that new techniques developed here can be finely-tuned to management needs and incorporated into management applications. The proponents will meet this requirement by working with the salmonid management community through the Interagency Ecological Program satellite project work team on salmonid rearing in the Delta, chaired by Joe Miyamoto. Proponents have attended meetings, presented findings, and discussed needs with managers. Proponents are also working with Pat Brandes of the U.S. Fish and Wildlife Service, who has supplied samples from throughout the Delta. For this project, proponents will intensify their work with the Interagency Ecological Program satellite project work team on salmonid rearing in the Delta and the U.S. Fish and Wildlife Service.