Effects of Sediment Microfabric on Benthic Optical Properties

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LONG-TERM GOALS

The overall goal of this project is to examine how inorganic factors, such as differences in sediment character or packing, contribute to the reflectance, scattering, and fluorescence of incident light at the seabed in coastal environments. Of particular interest is the degree to which the water column light field is sensitive to inorganic changes in bottom type, and whether such changes can be described in simple mathematical models. Ultimately, my intention is to apply this work to the identification of seabed sediment characteristics utilizing remote sensing platforms, such as hyperspectral satellite and airborne imagery. My secondary goal is to improve fiber-optic technology for standard use as probes to measure sediment parameters.

OBJECTIVES

Four hypotheses form the heart of my CoBOP objectives. They are 1) that the microfabric of grains at the sediment surface and to a depth of light penetration (~5 mm in well-sorted sands) has a strong impact on sediment reflectance and the in-sediment light field; 2) that the fluorescence of carbonate mineral grains is virtually universal in carbonate settings, and therefore, has a significant effect on sediment reflectance, while carbonate and other biogenic grains compose a smaller percentage of siliciclastic sediments and has an inconsequential impact on the overall benthic light signal; 3) that siliciclastic mineral fluorescence is present in 5-10% of the mineral grains in siliciclastic environments and is a useful tool for sediment provenance; and 4) that inorganic variations in grain size and composition are the first-order control on sediment reflectance and the in-sediment light field in bare sediments not covered by a significant algal mat or biofilm. In the latter areas, organic absorbance at specific wavelengths is a major contributor.

APPROACH

My approach for solving the four objectives outlined above has been two-fold. Objectives #1 and #4 have involved the development of a fiber-optic microprobe system that can be used to profile scalar irradiance from the sediment surface to the limit of light penetration in undisturbed sediment cores. The success of this methodology has yielded spectral information (350-1100 nm) from a variety of sediment settings. Core preservation methodologies have permitted preservation of original fabric for later impregnation and thin-sectioning to give quantitative information about inorganic properties of the sediments that are inducing changes in the light field. The methodology has also allowed for manipulation experiments to determine the relative impact of inorganic and organic sediment

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parameters. Core work is now transitioning into direct seabed measurements with the development of new in situ probe technology by this study. Objectives #2 and #3 have been approached by using a microspectrofluorometer built into an epi-fluorescence microscope to generate and measure the spectral properties of sediments on a single-grain level. This has been supplemented by the use of a Fluoromax spectrophotometer to examine whole-sediment properties.

WORK COMPLETED

Field studies have been completed in league with other CoBOP PI's to Lee Stocking Island (LSI), Bahamas and Monterey Bay. LSI studies were conducted in May 1998, January 1999, and May, 1999, January 2000, May 2000, and April 2001. Monterey studies were conducted in April 1998, October 1998, and April 1999. Fiber-optic microprobe in-sediment light profiles have now been collected at all major sub-environments at each CoBOP field site in the two areas. Seasonal differences have also been measured at several of the key localities. All the 1998-2000 profile data has been submitted to the web-accessible CoBOP database.

Core material has been impregnated and over 100 thin-sections generated for cores analyzed by fiber-optic microprobe. Computer imaging software is being used to reduce information from each thin-section about downcore variations in porosity, grain size, shape factors, etc. Representative grain samples have also been collected and isolated for fluorescence studies at each of the major sub-environments at Monterey and LSI. Samples were also collected from representative beaches and nearby coastal environments to track source functions for the fluorescent particles. A suite of particle end members was analyzed by Fluoromax spectrofluorometer to determine the range of fluorescence observable at LSI. Detailed studies of the site grain fluorescence are ongoing with the newly upgraded epi-fluorescence microscope to do rapid spectral response fluorescence imaging with the addition of an Ocean Optics S2000 spectrophotometer.

In Year 4, a new planar fiber-optic probe was developed and tested at Lee Stocking that permits overhead core insertion in cores and can be deployed on the seafloor directly. This probe has greatly simplified and improved the measurements of light profiles and shows great promise as a tool for measuring a variety of sediment parameter *in situ*. This probe was utilized in the April 2001 field study to conduct an extensive study of mat vs. bare sediment areas and to analyze cores for diel changes in light penetration due to microbiota migration. The new probe development has given opportunities for in situ work and for measuring in three different ways: 1) an overhead light source to measure the sediment euphotic zone, 2) a self-illuminated fiber probe that allows examination of sediment fabric below the euphotic zone, and 3) a filtered self-illuminated (excitation) probe that permits measuring the intensity of biological fluorescence profiles in the sediment. The new self-illuminated design is also a valuable probe for micron-scale measurements of sediment bulk properties in a variety of sediment types.

RESULTS

In this final year of the project (unless an additional year is funded—under consideration), our results to date are summarized below.

1. *Inorganic Effects on the Sediment Euphotic Zone* Fiber-optic microprobe work has, for the first time, mapped the nature of the sediment euphotic zone in undisturbed natural marine sediments. These results are valuable to overall CoBOP goals because downwelling light at the seafloor that is not

reflected from the sediment surface, enters the sediment, may be absorbed or scattered, and in the case of the scattered fraction, may return, in part, to the water column. Our work has shown that the general downcore light penetration profile can be modelled in most settings as an exponential decay with increasing penetration depth with increasing wavelength (in the range from long UV to short IR wavelengths—350 to 850 nm). The first-order control on reflection, absorbance, and scattering characteristics of the sediment is the inorganic character of the medium. Our work at Lee Stocking Island (carbonate sands and muds), Monterey Bay (siliciclastic sands), and some siliciclastic muds from a variety of sites in CA, TX, and LA has shown there is considerable variation in the downcore light field (depth of penetration, downcore boundaries in light levels) between sites. The largest effect is a function of porosity differences related to changing grain size and packing. In the absence of major changes in porosity in the upper 1-2 cm of the sediment column, the downcore light field in sandy sediments is relatively insensitive to changes in grain size and shape. In muddy sediments, downcore porosity increase due to compaction is usually significant in the upper cm, and leads to a strong site-to-site variability in depth of penetration. Microfabric layering in the sediments may also produce sharp changes in light penetration, equivalent to the production of acoustic reflectors with the penetration of sound. These optical interfaces are found most often in sands (which are generally near spherical) when there is a compositional layering of mineral grains of a different color, such as heavy minerals sorted by density. In muds, microfabric effects are observed where there is a difference in packing of the platy clay mineral and mica grains. In general, when a cardhouse structure exists, such as is present when rapid deposition takes place as flocs or bioturbation is mixing particle orientations, light penetration exceeds layers where the cardhouse structure has been collapsed (deposition under strong BBL flows) and platy grains are aligned. A final effect is the difference between carbonate and siliciclastic sands. In general, the depth of penetration in carbonate sands exceeds siliciclastics. This effect is a function of the white, opaque nature of carbonate grains, which favors reflectance off the grain surface, increasing scattering in the sediment euphotic zone and enhancing the number of downwelling photons available. Siliciclastic sands are most often dominated by quartz, in the form of transparent to translucent grains more likely to absorb photons than scatter them.

2. Bioeffects on the Sediment Euphotic Zone Our work has discovered that the presence of microfauna and associated exopolymer secretions (EPS) in the sediment euphotic zone is an important second-order effect on the light field at depth. In particular, the effect of biological mats produces a 20-80% increase in the depth of light penetration compared to bare sediments at the same site due to increased grain spacing (and possibly forward scattering) with growth of the mat. At many carbonate (LSI) sites, the strong downwelling light signal at the shallow seafloor (due to high water clarity) results in such a large biological effect of absorbance by CDOM, biofilms, and benthic organisms (diatoms, etc.) that it overwhelms first-order variations induced by inorganic differences in the sediment, particularly at wavelengths where major pigment absorb light (most notably the 670 nm chl-α line). This can be seen both in the increased porosity induced by surface mats and films and in the resulting profiles in cores where the biological component has been removed for comparison with the pre-treated light field. In addition, the PI and other CoBOP PI's (Decho, Reid, Wheatcroft, Voss) conducted a set of laboratory experiments in Miami in April 2001 to test the addition of EPS and other substances to quantify their effect on light penetration and other parameters. Presence of biofilm-like EPS substances increased depth of light penetration up to 50%, supporting the field observations at LSI. High-levels of detrital accumulation of particulate organic matter were observed in some sandy (Norman's grapestone site) and muddy sites (Norman's pond) at LSI. These areas displayed the thickest sediment euphotic zone observed (up to 5 cm). This is primarily a function of the high porosities produced by the organic accumulation. Monterey siliciclastic sites, with reduced microfaunal levels, generally shows less of a bioeffect on the in-sediment light field. An exception was areas of high diatom abundance, where a porosity increase similar (but reduced) to LSI sites was observed.

A second area of bioeffect studies was an attempt to determine whether diel migration of diatoms produced a measureable change in depth of light penetration, and hence, on seafloor reflectivity. Limited diel studies of sediment cores in May 2000 incubated for 24-48 hr in outdoor seawater tanks at LSI seemed to indicate that light penetration id vary diurnally in sediments collected with a well-established benthic diatom mat. However, a more extensive dataset (7 sites and monitoring up to 4 days) collected in April 2001, with refutes these early results and supports the results of CoBOP PI Brand that diel variability in sediments has little or no effect on bottom reflectance or fluorescence.

3. Fluorescence Properties of Carbonate Sands Epi-fluorescence microscope measurements of single carbonate grains from LSI have been conducted in order to examine the nature, and controls on variability, of the broadband fluorescence inherent in marine carbonate grains. This work was done in concert with CoBOP PI's Burdige and Mazel. The results on a wide range of carbonate grain types show this broadband fluorescence has some variability in intensity and wavelength depending on the type of secreting organism (coral vs. mollusc vs. echinoderm, etc.) but the major emission signature is related. Changing the mixture of grain types does produce slight variability in whole-sediment emission signatures. The fluorescence is also long-lasting, as we observed it in Pleistocene-age eolianites from LSI. However, studies of single grain types (such as ooids) from multiple sub-environments at LSI have shown no variability that can be traced to deposition environment or shallow diagenesis in the sediments. These datasets, in concert with those of Burdige and Mazel suggests that the signal is probably a result of humic organic matter trapped in the crystal matrix at the time of precipitation, and hence, is a function of marine water chemistry rather than sedimentology.

4. Siiliciclastic Sand Fluorescence Epi-fluorescence microscope measurements of single siliciclastic grains from Monterey Bay determined that approximately 2-10% of the sand grains exhibited fluorescence. This fluorescence is mineral-specific and narrowband and is an inorganic response to cation contaminants in the mineral structure. Although this property was determined to have a minimal effect on the total sediment fluorescence compared to biological sources of fluorescence, it presented a new avenue of research into sand transport vectors. Traditionally, heavy mineral analysis has been utilized to determine sand provenance—a procedure that is laboratory intensive, slow, and uses toxic chemicals to separate out the sand fraction. These procedures also do not indicate provenance of the most common siliciclastic minerals (quartz and feldspars). We collected sands from beaches around Monterey Bay and obtained box core samples from the submerged bay zone from the USGS Coastal and Marine lab in Menlo Park in an attempt to ascertain whether fluorescence can be used to determine the source of sand grains in Monterey Bay (and elsewhere). Results showed the technique has great promise. A number of fluorescing grain types were found associated with small beach and offshore areas associated with an individual riverine sand source to the bay. These trends mirror earlier work by investigators using heavy mineral analysis. In addition, several types of fluorescing quartz were observed, potentially providing a valuable method for determining quartz provenance. The results of this pilot study are in publication to be available as a method for other sedimentological and sediment transport researchers.

IMPACT/APPLICATION

As mentioned before, our fiber-optic microprobe work on sediment light fields is the first done on undisturbed marine sediments. It has shown that in-sediment light fields can be easily modeled as a exponential decay downcore. This can be readily added to existing models of benthic optical properties (e.g., Hydrolight). This work also demonstrates that fiber-optic analysis of the seafloor holds great promise as a method to remotely and inexpensively examine variations induced by inorganic or organic properties of marine sediments. The impact of this work raises the possibility of identifying sub-seafloor features solely from the reflectance spectra, given that our microprobe work has also shown that depth of penetration of light is predictable dependent on wavelength (longer wavelengths penetrate further). In addition, this probe design can be used for rapid assessment of sediment properties in the seabed and for suspended sediment concentrations.

The carbonate grain fluorescence work to date has shown that it is the source of the apparent green background light visible in scans with laser line scanning systems at LSI. In siliciclastic sediment (Monterey), the mineral- and site-specific nature of fluorescence holds great promise as an indicator of sediment transport vectors in sandy sediments in lieu of more expensive, toxic, and time-consuming analyses such as heavy mineral work..

TRANSITIONS

I am investigating the use of fiber-optic microprobes as measurement of sediment bulk properties in near-seabed and seabed environments. The new *in situ* probe can measure bulk properties over enormous concentration ranges. This holds promise for developing a rapid seabed assessment probe for the navy. To pursue this avenue, a proposal has been funded by ONR Geology and Geophysics for the new Mine Burial initiative. This experiment will allow testing of the probes for this purpose in league with other sediment assessment techniques (e.g., cone penetrometers, shear vane, electrical resistivity probes). In addition, a Navy DURIP was funded (with CoBOP PI Wheatcroft) in Summer 2002 that will permit construction of the prototype fully submersible and internally logging fiber-optic microprobe system suitable for deployment on bottom tripods or ROV's and AUV's.

RELATED PROJECTS

Continuing collaborations continue on the following projects:

1 – David Burdige (ODU), Charlie Mazel (PSICORP) and I are conducting a series of experiments on Lee Stocking Island carbonate grains to determine the organic (humic) substances that are present in the crystalline structure and whether they are the origin of the widespread broadband and week fluorescence noted in CoBOP studies of the area.

2 – I am working with the CoBOP sediment group (P. Reid, U. Miami, L. Brand, U. Miami, R. Wheatcroft (Oregon State), David Burdige (ODU), Fred Dobbs (ODU) and Alan Decho (U. South Carolina) in coordinating our sediment sampling of inorganic and organic parameters at the LSI and Monterey sites to determine the relative importance of our individual measurements in the benthic light signal. These measurements are being interfaced with reflectance measurements at the sites being made by C. Mazel (PSICORP), P. Reid (U. Miami), and Ken Voss (U. Miami).

3 – I am interacting with C. Stevens and L. Brand (U. Miami), P. Reid (U. Miami), and C. Mazel (PSICORP) in an effort to relate my measurements of in sediment light profiles to spectral reflectance data at the LSI sites to devise methodologies for deconvolving reflectance data to give information about the biological or inorganic changes occurring below the sediment surface. Diel measurements are mainly with Brand.

PUBLICATIONS

Five manuscripts *in press* or *in review*. Three conference presentations.