Photosynthesis as a Possible Source of Gas Bubbles in Shallow Sandy Coastal Sediments

D.V. Holliday
Graduate School of Oceanography
University of Rhode Island
(deceased)

C.F. Greenlaw
302 Tailwind Drive
Seguin, TX 78155
phone: (830) 372-3239 fax: (401) 874-6240 e-mail: cgreenlaw@xetexracing.com

David Thistle
Department of Earth, Ocean, and Atmospheric Sciences
Florida State University
Tallahassee, FL 32306-4320
phone: (850) 644-4089 fax: (850) 644-2581 e-mail: dthistle@fsu.edu

Jan E.B. Rines
University of Rhode Island, Graduate School of Oceanography
South Ferry Road
Narragansett, RI 02882-1197
Phone: (401) 874-6691 fax: (401) 874-6240 e-mail: jrines@gso.uri.edu

Award Number N00014-09-10491

LONG-TERM GOALS

Our long-term interests involve the possibility that biological activity can influence acoustic scattering at the water column-seabed interface and the propagation of sound in and over a sandy substrate in a shallow-water, coastal, marine environment. Evidence from laboratory studies on sand collected from the surf zone clearly demonstrates that gas bubbles can be formed when photosynthesis by benthic microalgae causes pore water to become supersaturated with oxygen.

OBJECTIVES

The goal of this work was to determine whether this phenomenon occurred in the coastal ocean. Our near-term objective was to determine whether photosynthesis produces conditions that lead to the formation of oxygen bubbles in the top few millimeters of shallow sandy coastal sediments and, if it did, how such bubbles change the acoustic reflectivity of the seabed.

APPROACH

In the laboratory, natural sand from a beach in Panama City, FL, was observed to scatter broadband sound in different amounts as a function of time of day (Figure 1).

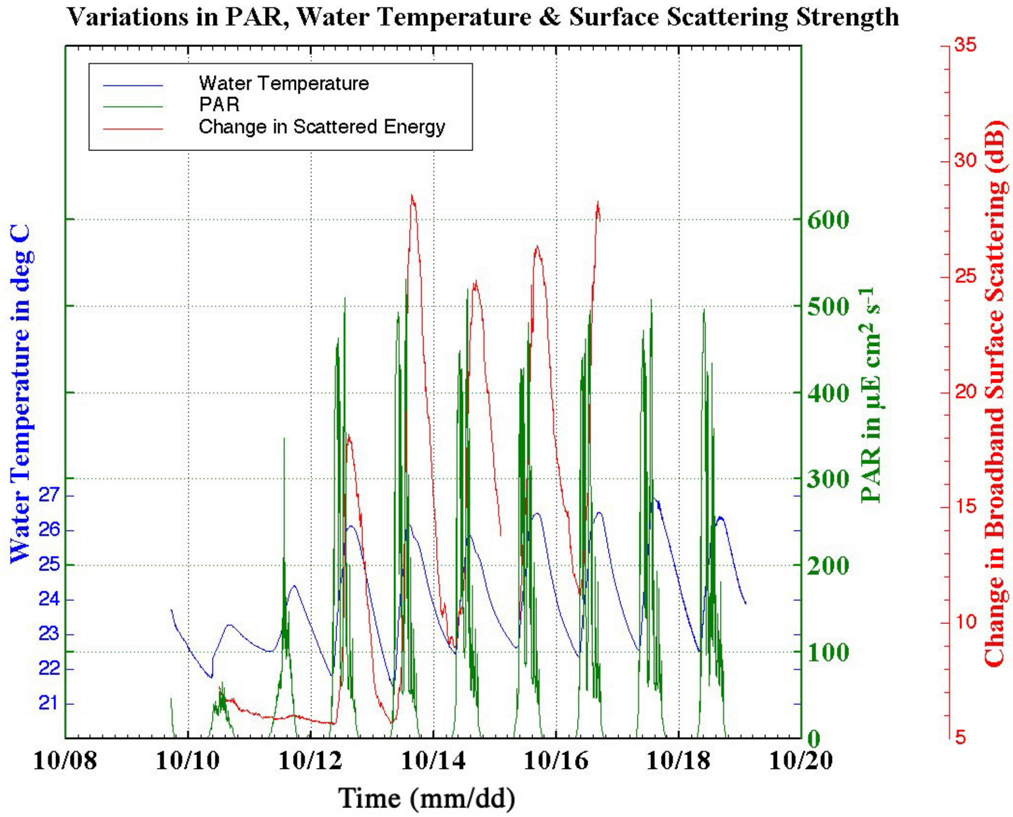

Figure 1: Diel variations in the broadband (100 kHz to 900 kHz) acoustical scattering from a bed of sand (red), the water temperature (blue), and photosynthetically active radiation (green) as measured in a laboratory aquarium exposed to natural sunlight via a neutral density film over a glass window. The resulting light levels simulated a depth of ca. 20 m. The changes in water temperature were determined to be too small to have caused the increases in scattering. The sand was from a beach in Panama City, FL. A 30 dB change in scattering is equivalent to an increase in back-scattered intensity of 1000 times.

The variations in scattered sound were synchronized with, but lagged, diel changes in light levels incident on the bed of sand. Bubbles were seen on the surface of the sand during periods of high scattering. This observation strongly suggested that photosynthesis created sufficient oxygen to cause supersaturation in the spaces between the sand grains. Supersaturation eventually led to the formation of small bubbles that then migrated to the sediment-water interface, coalescing during and after the migration to form larger bubbles that were visible to the naked eye. The acoustic scattering from the bubbles then caused increases in the broadband scattering from the bed of sand as more bubbles were formed and those present grew in size during the day. In the absence of sunlight, the bubble numbers and sizes were reduced, either by release of the bubbles when their growth or buoyancy exceeded the forces keeping them in place on the sand surface or by reabsorption of the gas into the water after oxygen production slowed and finally ceased during the dark hours. For additional details regarding the laboratory experiment, see Holliday *et al.* (2004) and Holliday (2009).

Our objective was to determine whether the phenomenon observed in the laboratory also occurred in the sea. We developed equipment that allowed us to obtain backscattering data from the seabed and to examine the records for the temporal changes that would be expected should the production of oxygen be sufficient to produce bubbles. We also developed equipment (i.e., a time-lapse, underwater camera) to investigate other possibilities (e.g., biological roughening).

Initially we chose a site at a 5-m deep site on the north Florida shelf in the Gulf of Mexico (29° 52.169' N, 84° 26.428' W) because Thistle had worked there previously (Teasdale, Vopel, and Thistle, 2004). The seabed was well-sorted, unconsolidated, medium sand. Storms occasionally caused sediment resuspension and ripple fields. In order to get unambiguous answers about the source of any observed change in scattering, we also deployed a time-lapse camera to record conditions in the field of view of the acoustic sensor to allow us to separate macroscale physical changes in the bottom topography from biological processes other than bubble production that lead to changes in the acoustic reflectivity. We also collected sediment samples from the upper few mm of sand to identify the dominant taxa of benthic microalgae present.

Although benthic diatoms were present in abundance previously, we found that they were in much lower abundance during our project, presumably because the water during spring 2010 was much less clear. After several deployments gave mixed results, we began working in St. Joe Bay, FL, at a 1-m deep site where the water was clear and benthic diatoms were abundant.

Charles Greenlaw prepared and bench tested the acoustic (Figure 2) instrumentation for this research project. David Thistle from Florida State University (FSU) provided ancillary sensors, tested the equipment in the field, and collected samples for Jan Rines (Graduate School of Oceanography / University of Rhode Island = GSO/URI) to identify the benthic microalgae in the samples. Following the untimely death of Dr. D.V. Holliday, the remaining team members shared the responsibility of analyzing data and preparing presentations and publications.

Figure 2: The Sand Scan acoustic sensor consists of a broadband acoustic transducer, a small green cylinder shown here on a movable arm at the upper left of the instrument. The white pressure case contains the electronics necessary to transmit a sequence of 200-microsecond pulses at several discrete frequencies between ca 0.22 and 0.335 MHz, receive the echoes from a small area on the seabed, and store digital representations of the received bottom reverberation waveforms. The black cylinder contains batteries. For scale, the tiles on the lab floor were 1 foot on each side. A later version of this instrument added a datalogger to extend the deployment duration to up to two weeks, and loggers for light, temperature, salinity, and oxygen concentration.

WORK COMPLETED

We modified the SandScan acoustic sensor to provide the capability of echo ranging over a slant range of 1.7 m. The range resolution is now *ca*. 15 cm, depending on the speed of sound near the seabed. The sensor sequentially transmits 200-microsecond pulses at seven discrete frequencies between 0.220 and 0.335 MHz, which spans much of the range of frequencies that produced large scattering strength changes in the laboratory experiment. Sufficient battery power and memory were installed to allow recording of a complete data set of 24 pings per frequency every 20 min for about two weeks.

SandScan outputs raw echo-amplitude samples in digital format to the associated acoustic data logger. These amplitudes were downloaded and processed post-deployment. Normal processing included estimating the mean bottom backscattering echo in each range bin and correcting each channel for system response. The expectation was that the bottom backscattering echoes would show some temporal correlation with incident light as measured by light sensors on SandScan.

SandScan was deployed at our first site on five occasions in 2010. Two deployments (March and August) resulted in no data due to equipment failures. Two deployments (April and June) netted ten days of bottom-scattering data. On the August deployment, we obtained acoustic data, but the light meter's data logger failed, so no photosynthetically active irradiation (PAR) data were recorded. The results of the 2010 deployments have been previously reported. Although these data showed variability over time – sometimes fairly dramatic variability – there was no clear diel signal at all. At this site, the water was quite turbid, and ripple fields were observed in the sand. Very few benthic microalgae were observed and migrating sand dollars likely caused bioturbation. We concluded that both biotic and abiotic factors made it impossible for us to have detected oxygen bubbles if they occurred.

Two final deployments were made in July and November of 2011 in St. Joe Bay, FL. The risk of loss due to theft at this shallow site was weighed against the potential benefits of the clear water, and, since the grant was ending, we elected to risk the equipment.

In contrast to the ambiguous 2010 results, data from July 2011 revealed a very clear diel change in the acoustic backscattering from the bottom, which was in synchrony with the incident irradiance! Figure 3 displays the mean backscattered bottom echoes, corrected for system gains, at the seven frequencies of the SandScan compared with the logged incident irradiance. It is evident from these data that there was a marked change in bottom backscattering strength over a diel cycle of as much as 20 dB (a change in backscattered intensity of 100 X). These results were just as strong as those obtained in the laboratory – a remarkable result!

The same data can be plotted as backscattering spectra versus time (Figure 4). This view emphasizes the relatively flat spectrum of the backscattering, which is characteristic of backscattering from bubbles at frequencies above the fundamental bubble resonance.

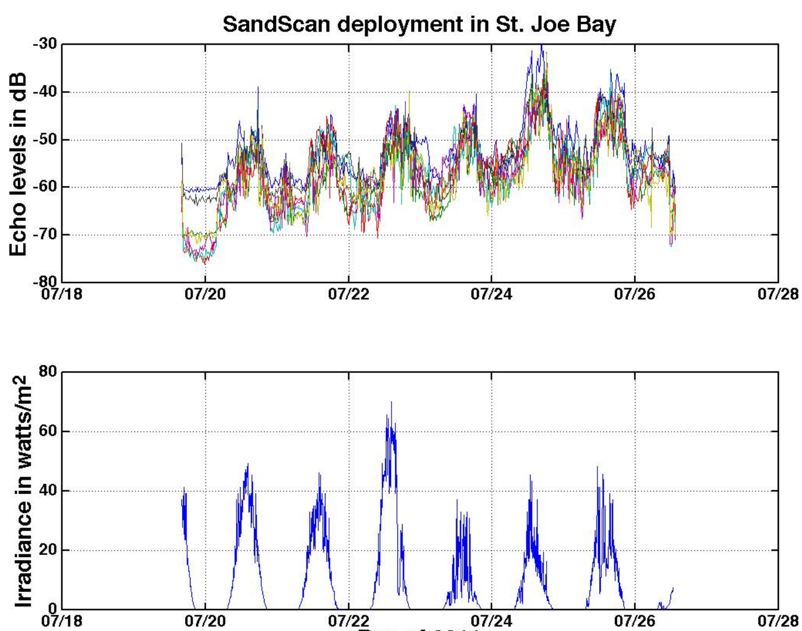

Figure 3. St. Joe Bay, July 2011. Plot of averaged bottom echo intensity (upper) at seven frequencies from 220 - 335 kHz versus time. Irradiance data recorded at the same site are shown in the bottom plot. The acoustic data show strong diel variations that are clearly associated with the irradiance. Note the increase in minimum (daytime) echo intensities over time.

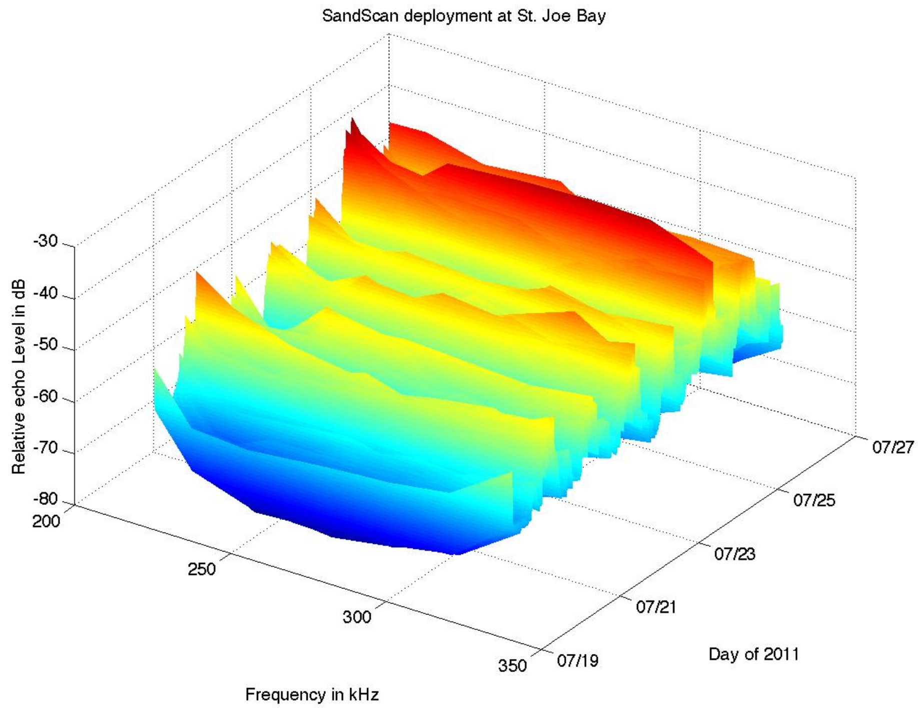

Figure 4. St. Joe Bay, July 2011. Bottom backscattering echo intensity versus frequency and time. Higher backscattering is shown in warm colors (reds) and lower backscattering shown in cool colors (blue). Echo data have been corrected for system gains.

Sand samples were collected at the deployment site on 27 July and sent on dry ice to Rhode Island, where they were thawed and qualitatively examined. Some sand samples were noticeably pink. When examined on the microscope, a variety of pennate diatoms and both blue-green and red cyanobacteria were observed (Figure 5). Some cells were loose, indicating that they had been living interstitially, whereas others were attached to the surface of sand grains. In spite of having been frozen and thawed, the cells appeared highly pigmented, thus should have been capable of very active photosynthesis.

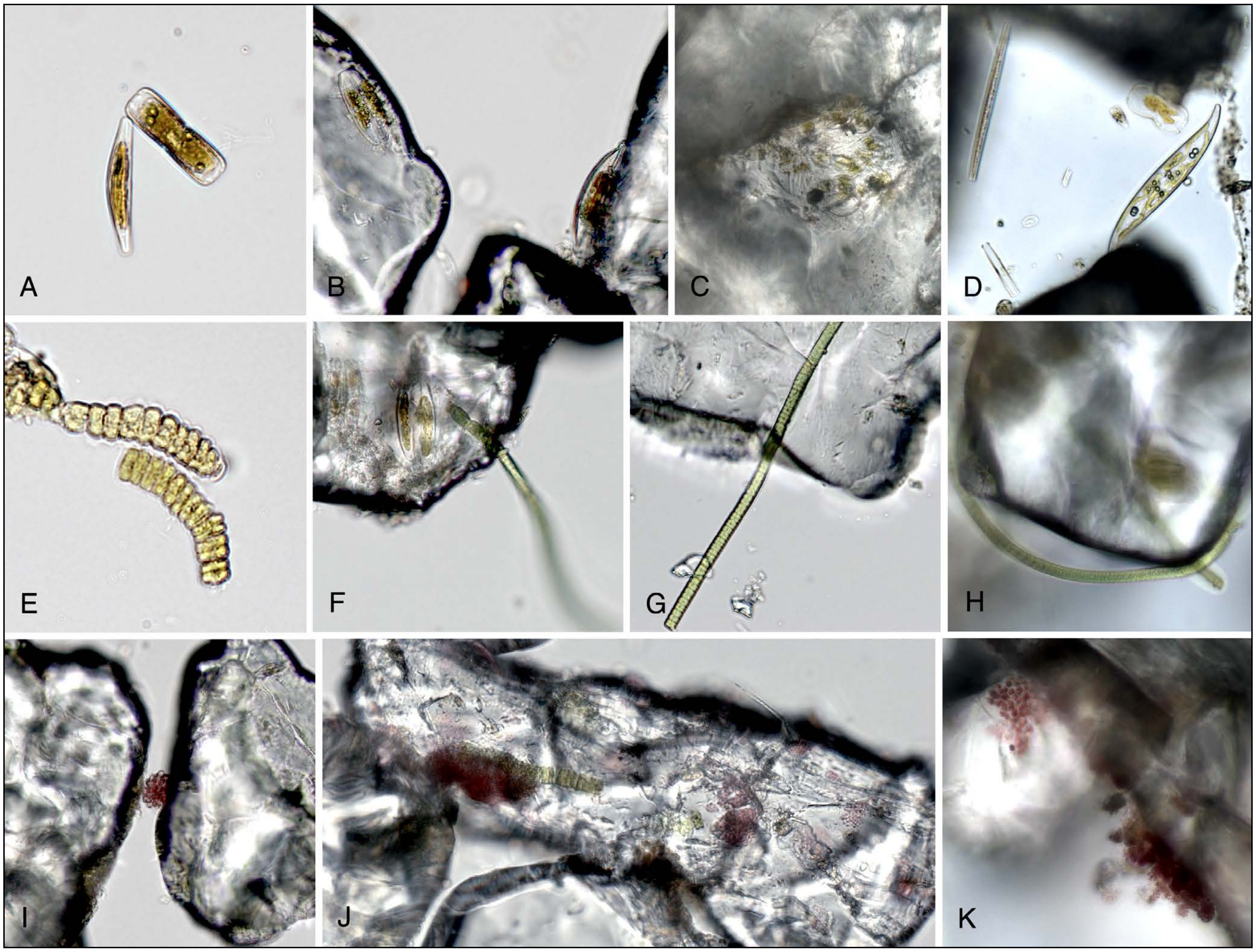

Figure 5. Photomicrographs of sand samples and benthic microalgae collected from the deployment site in St. Joe Bay on 27 July 2011. These brightfield images depict a variety of pennate diatoms and cyanobacteria. A, D, free living, interstitial pennate diatoms. B, C, diatoms attached to the surface of sand grains. E, interstitial cyanobacterial colony. F-H, filamentous cyanobacteria. I-K, clusters of red, coccoid cells, which we believe to be cyanobacteria, attached to sand grains.

We replicated this experiment in November, 2011. This deployment produced similar, although weaker results (Figure 6). Again, photosynthetically active microalgal cells were present (Figure 7). During both 2011 deployments, a diverse microalgal community was present.

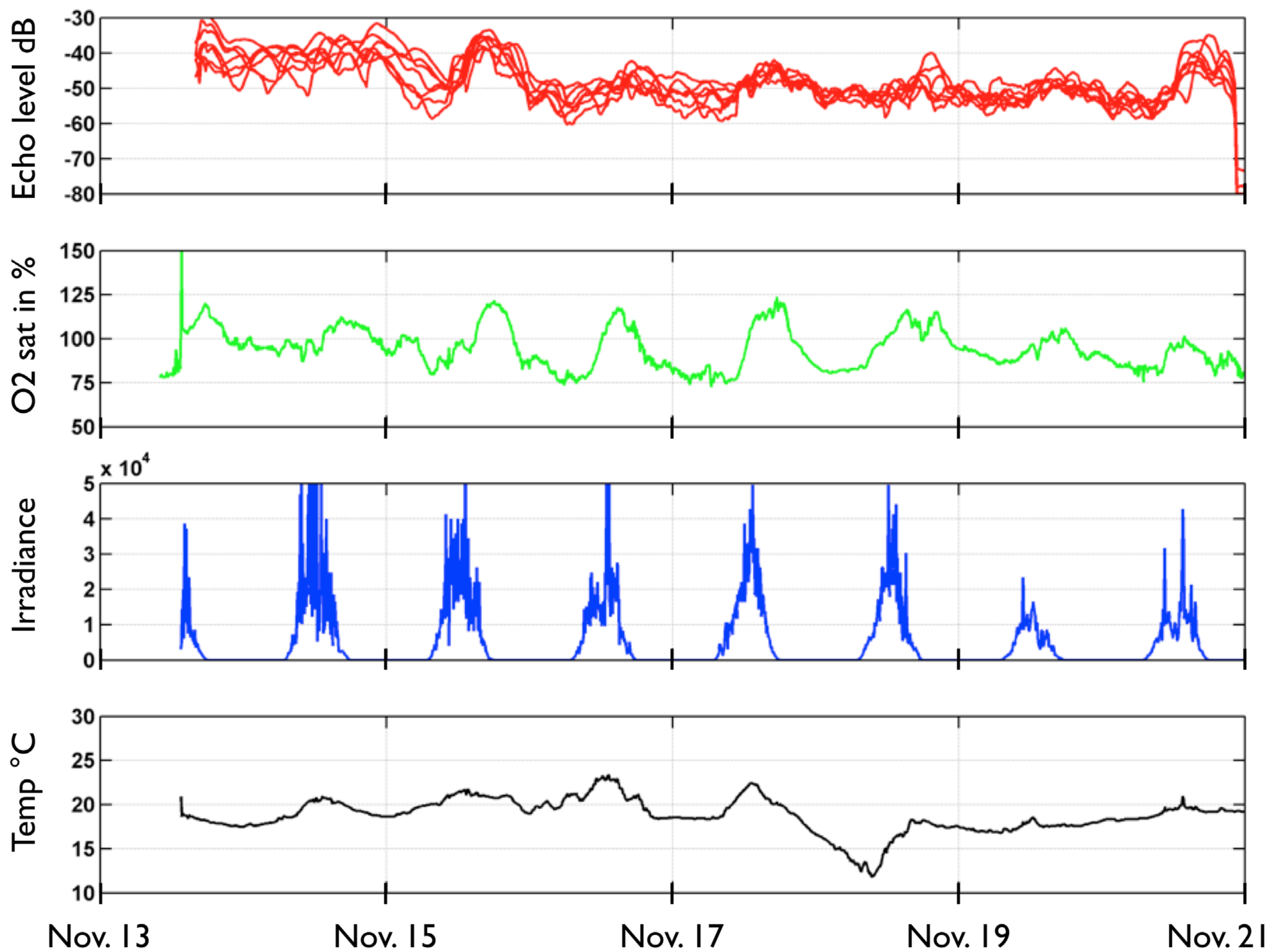

Figure 6. Data from the November 13 to 21, 2011 deployment in St. Joe Bay. The four panels depict acoustical backscatter at 7 frequencies, percent oxygen saturation, irradiance, and water temperature. Diel variation in backscatter and oxygen saturation is synchronized with, but slightly lags the irradiance signal. This pattern is to be expected, as it takes time for enough photosynthesis to take place to generate sufficient oxygen for bubble formation. A decrease in water temperature on November 18 followed by two days of lower light levels suggests passage of a meteorological front, which is reflected in the oxygen and backscatter data.

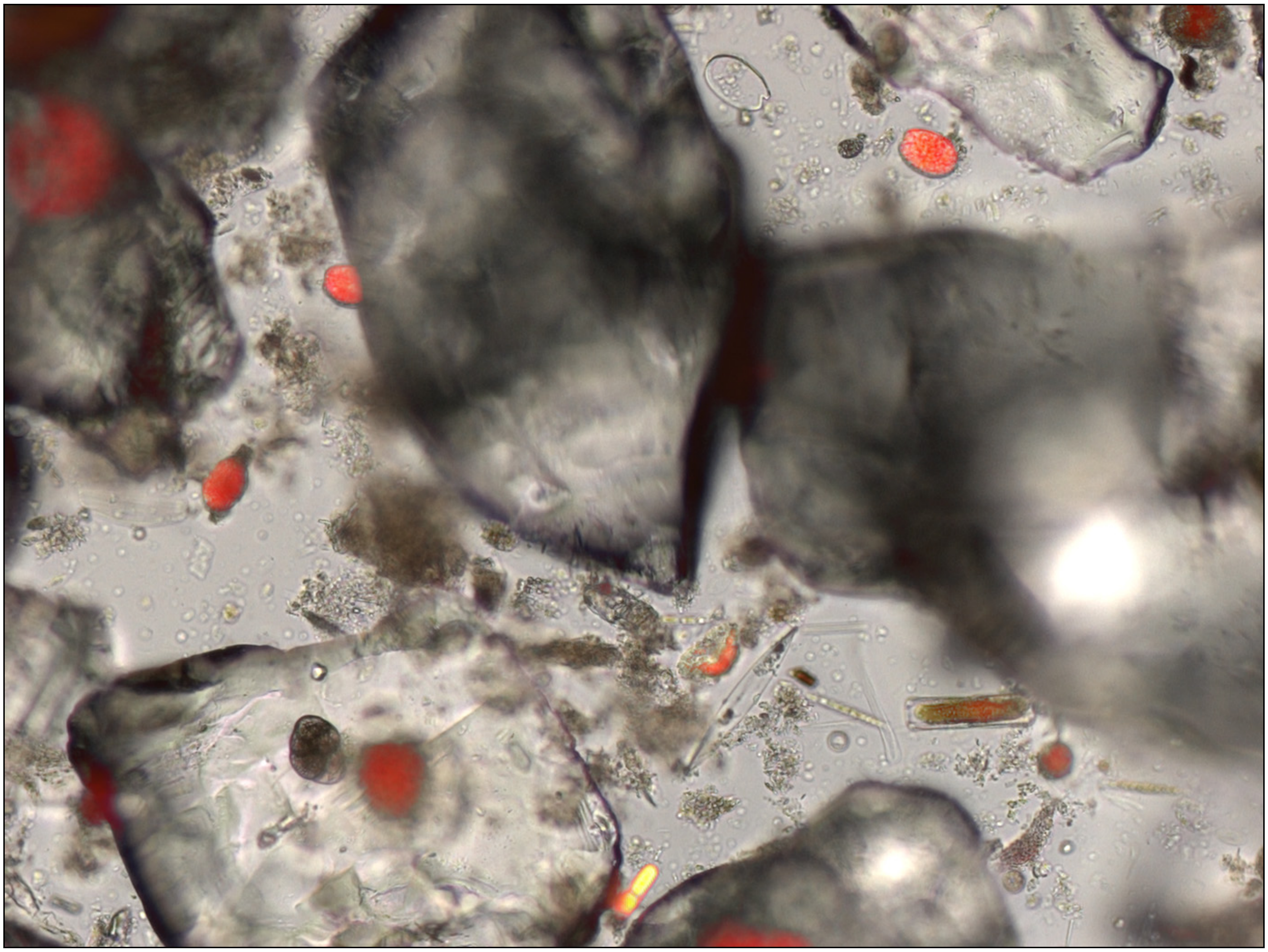

Figure 7. Photomicrograph of a frozen then thawed sample of sand and microalgae from the November, 2011, deployment. The image is a composite of a brightfield photograph, which shows the sand grains and microalgal cells, and an epifluorescent image, which depicts the autofluorescence of photosynthetic pigments. Red chlorophyll fluorescence is characteristic of all photosynthetic organisms. Yellow-orange phycoerythrin fluorescence in this case is from cyanobacteria.

CONCLUSIONS

Our evidence clearly supports the hypothesis that supersaturating photosynthesis by benthic microalgae results in the formation of oxygen bubbles in and on the seabed. Large (up to 100X) diel variations in backscattered bottom intensity imply that this phenomenon can interfere with Naval sensors. For example, 20 dB fluctuations over a 12-hour period dictate that temporal and spatial scales of variation can be confounded during seafloor mapping exercises. We can expect that the degree of bubble formation (and resultant acoustical signal) by supersaturating photosynthesis of microalgae will vary depending on the species-specific composition of the microalgal community, variations in insolation, season, sediment type, perturbation factors, and geological/geographic variation. The next logical step in this work would be to undertake a preliminary geographic and seasonal survey to further understand the nature of this phenomenon from both a biological and sensor-related perspective.

IMPACT/APPLICATIONS

This research has implications for understanding:

1) the stimuli cuing emergence of large numbers of sound-reflecting animals from the seabed into the water column
2) the role of bubbles in scouring surficial sediments,
3) the performance of naval sensors used to detect objects on, in, or near the seabed,
4) the characteristics of acoustic communications channels in shallow water,
5) the development of mathematical models for seafloor sound scattering,
6) and, the limitations and benefits of acoustic methods now being proposed and used for classifying, describing, and mapping benthic habitats in the littoral zones of many coastal nations.

The magnitude of the change in bottom backscattering strengths observed in our clear-water experiments was so dramatic that the potential impact for shallow-water acoustics in the mid-frequency range (from <100 kHz to 500 kHz or more) is huge. Our study was limited to two locations – one turbid and one clear – with somewhat similar sandy bottoms. Both were protected bays with modest wave activity. The ubiquity of benthic phytoplankton in temperate sandy bays leads us to surmise that similar results would be obtained in similar situations. This presumption could be easily tested with portable systems similar to our SandScan.

Reflection of sound at the sediment-water interface implies reduction of sound penetration into the sediment. It is possible – even likely – that lower-frequency systems designed to penetrate the seafloor to detect buried objects could see reduced performance in places where benthic algae are producing oxygen bubbles. Of note is the observation that the night-time levels of bottom backscattering strengths were higher than the initial measurements obtained when the instrument was first deployed on disturbed sediment, suggesting that not all bubbles are resorbed at night and thus, that the presence of gas-producing algae alters the bottom acoustic characteristics both day and night.

REFERENCES

Holliday, D.V., C.F. Greenlaw, J. E. B. Rines, and D. Thistle. 2004. Diel variations in acoustical scattering from a sandy seabed. Proceedings of the 2004 ICES Annual Science Conference, Vigo, Spain. ICES CM 2004/T:01, p. 23 (A). (Full paper on the Conference CD ROM; available on request).

Holliday, D.V. Technology for Evaluating Marine Ecosystems in the Early 21st Century. 2009. Chapter 17 in *The Future of Fisheries Science in North America*, Beamish, Richard J. and Rothschild, Brian J. (Eds.), Springer-Verlag Fish & Fisheries Series, Vol. 31: 293-311, doi:10.1093/icesjms/fsp127.

Teasdale, M., K. Vopel, and D. Thistle. 2004. The timing of benthic copepod emergence. Limnology and Oceanography 49: 884-889.

PUBLICATIONS

Holliday, D.V. Technology for Evaluating Marine Ecosystems in the Early 21st Century. Chapter 17 in *The Future of Fisheries Science in North America*, Beamish, Richard J. and Rothschild, Brian J., Eds. Springer-Verlag Fish & Fisheries Series, Vol. 31: 293-311, doi:10.1093/icesjms/fsp127. [published, refereed.]

Holliday, D.V., P.L. Donaghay, C.F. Greenlaw, J.M. Napp, and J.M. Sullivan. 2009. High-frequency acoustics and bio-optics in ecosystems research. ICES Journal of Marine Science 66: 974-980, doi:10.1093/icesjms/fsp127. [published, refereed.]

Holliday, D.V., C.F Greenlaw and P.L. Donaghay. 2010. Acoustic scattering in the coastal ocean at Monterey Bay, CA USA: Fine-scale vertical structures, Continental Shelf Research 30: 81-103. [published, refereed.]