Workshop Report

SSRL Workshop on STXM and X-ray Nanoprobe Capabilities and Needs in the Environmental, Geological, and Biomedical Sciences

Scanning transmission x-ray microscopy (STXM) has emerged as an important technique for chemical imaging and spectromicroscopy on the <100 nm spatial scale in the environmental, geological, and biomedical sciences. Much has transpired technologically and scientifically in the 20-plus year interval that zone-plate STXM technology has been in development. Yet, STXM/nanoprobe facilities are few in number, beam time remains exceedingly tight, and numerous scientific, technical, and infrastructure challenges continue to present significant barriers to the widespread use of these techniques in these three areas of science.

These challenges as well as new research opportunities were examined at a workshop on STXM and X-ray Nanoprobe Capabilities and Needs for Environmental, Geological, and Biomedical Sciences, held on July 9-10, 2007 at Stanford University. Specific goals of the workshop were to: (a) comprehensively assess current and planned scanning x-ray microscope facilities in North America and Europe for environmental, geological and biomedical sciences, (b) to define/forecast scientific opportunities and grand challenges in these fields that can be addressed by STXM, and (c) to discuss STXM beam line optics and end-station hardware. Environmental, geological, and biomedical sciences share important instrumentation requirements, particularly in the area of imaging and spectroscopy at the sub-micron scale, including the need to perform x-ray absorption spectroscopic analyses, to characterize inorganic and organic nanoparticles, to spatially resolve membranes and other cellular structures, and to perform measurements on dilute hydrated samples. The workshop was co-organized by SSRL staff scientists John Bargar, Serena DeBeer George, Hendrik Ohldag, and Stanford Professor Gordon Brown. The workshop brought together 43 leading environmental, geological, and biomedical scientists and STXM instrument designers from across North America and Europe. Financial support for the workshop was provided by the U.S. Department of Energy, Offices of Basic Energy Science and of Biological and Environmental Research.

The first day of the workshop focused on scientific research and STXM optics. The keynote talk, presented by Harald Ade, reviewed the history, state of the art, and projected future possibilities for STXM. This was followed by a series of scientific talks that included x-ray imaging of cells, the impact of microbial metabolism on elemental cycling in soils, and the biogeochemical fate of halogens. The morning session concluded with a discussion on the future of zone plates and beam line design considerations for microscopy. In the afternoon session, the scientific talks ranged from micro-XANES of soil colloids to imaging dynamic events in cell biology to new opportunities for applications of STXM to problems in archeometry. The day ended with attendees dividing into three working groups, one on biomedical sciences, one on geological and environmental sciences, and one on instrumentation. The first two groups were asked to identify the most important scientific drivers or grand challenges in their subject areas and the instrumentation needed to address these issues. The third group focused on instrumentation challenges and possible technological solutions. On the second day of the workshop, representatives from US, Canadian, and European nanoprobe facilities presented facility overviews of their STXM end stations, their current capabilities, and user statistics. To conclude the workshop, the working groups reconvened and presented summaries of their findings.

The geological-environmental sciences working group addressed technical needs associated with studies of biogeochemical processes that control the compositions and chemical dynamics of soils, natural waters, and the atmosphere (*e.g.*, cycling of nutrients and trace metals, mineral and aerosol transformations, fate and migration of contaminants). Important scientific impact areas identified by this working group included soil biogeochemistry, environmental microbiology, marine biogeochemistry, the physical chemistry of water in confined spaces, and atmospheric colloid chemistry. For example, one grand challenge for which STXM is foreseen to provide significant contributions is identifying the physical and chemical factors that control the reactivity of soil aggregates. Other grand challenges foreseen as important STXM impact areas include characterizing the biogeochemical reactions that microbes promote at their interfaces with mineral surfaces; characterizing the composition, speciation, and distribution of organic carbon in atmospheric aerosols; characterizing the composition, sources, and digenetic mechanisms of organic carbon in marine sediments; and characterizing the molecular and electronic structure of water at interfaces and in nanopores.

The biomedical working group identified several key areas where x-ray nanoprobe capabilities could make a major scientific impact. Many important questions in biology and biomedical research could be addressed by using trace element localization on the nanometer scale. These include understanding the mechanism of metal homeostasis in cells, as well as understanding drug transport, metabolism, and localization. These methods could also be used to obtain insight into pathogenesis and diagnostics of metal-related diseases, such as Wilson’s, Menkes diseases, Alzheimer’s, and Friedreich’s ataxia. Processes of biomineralization including calcification, arterial plaque formation, and pathologic mineralization would also benefit greatly from the ability to monitor these biomineralization products with high spatial resolution.

Instrumenta requirements to address forefront scientific problems that were communicated to the instrumentation working group were as follows: the energy range of greatest importance to enviro-/geo-/biomedical sciences was found to be from 200 to at least 14,000 eV because it provides access to the C, N, O, P, S, and Cl K-edges as well as the K- and/or L-edges of important metals and metalloids. Extending the energy range up to ~19,000 eV would provide access to the environmentally important actinide L-edges. For all of the identified scientific frontiers to be accessible, future enviro-/geo-/biomedical sciences STXM systems will need to provide many capabilities that yet have not been fully realized, but that are within reach. For example, a spatial resolution of *ca* 10 nm would address existing forefront scientific questions, although higher spatial resolution will be needed for many future problems. The need to perform XANES and EXAFS spectroscopy (*i.e.*, scan range of several hundred eV), particularly in the energy range >5 keV, was found to be universally important to the participants. Fluorescence-yield detection will be necessary to improve analysis/detection limits for elements in dilute and wet samples. The sample stage would require rapid raster scanning and rotation to allow reasonably fast tomography over regions of *ca*. 10 μm in each dimension, while maintaining the sample at controlled (often cryogenic) temperatures or in a controlled ambient environment that allows triggering of a biological reaction and monitoring the response (kinetic microscopy). Overall, most of these requirements were found to be currently achievable. The greatest challenge at this point remains the ability to measure K-edge spectra in the 200 – 2000 eV range (*e.g.,* C, O, S) and in the >3,000 eV range (*e.g.*, first-row transition metal K-edges) within the span of a single day. This capability was judged to be crucial to maintain sample integrity while obtaining the desired scientific data and is currently not available at any existing instrument. To be able to cover such a large energy range, it will likely be necessary to design two complementary microscopes at adjacent beam lines, one optimized for the soft x-ray energy region and another for the hard energy region. In combination with high precision fiducialized sample holders, this would allow for rapid sample transfer from one instrument to another (*e.g.*, from low to high energy STXM instruments or to a transmission electron microscope) and rapid location of the same spot within 20 nm.

Presently, access to spectromicroscopy facilities is constrained by a serious shortage of beam time and facilities. There are 11 STXM facilities worldwide, with 3 more facilities under construction. Existing microscopes are oversubscribed by factors of 2-3. The arguments in favor of building more instruments are compelling and motivated by strong scientific driving forces in the environmental, geological and biomedical sciences.

All speakers who presented talks at the workshop were (in order of occurrence): Day 1: H. Ade (NCSU), S. Myneni (Princeton), C. Larabell (UCSF), K. Benzerara (CNRS and Institut de Physique du Globe de Paris), W. Yun (Xradia inc.), J. Thieme (U. Goettingen), L. Finney (ANL), T. Schäfer (INE Karlsruhe), P. Lay (U. Sydney), G. Chiari (Getty Conservation Inst.), Jianghong Rao (Stanford), and Day 2: T. Tyliszczak (ALS), J. Susini (ESRF), J. Thieme, B. Lai (APS), I. McNulty (APS), M. Obst (CLS), R. Fink (U. Erlangen-Nuremberg), and H. Ohldag (SSRL). Geological-environmental sciences working group participants were: D. Shuh (LBNL, working group leader), J. Bargar (SSRL), S. Bone (Berkeley), B. Bostick (Dartmouth), J. Brandes (Skidaway Inst. Oceanography), Gordon Brown (Stanford), G. Chiari (Getty Conservation Inst.), P. Dobson (DOE-BES Geosciences), S. Fendorf (Stanford), S. Gleber (U. Goettingen), S. Myneni (Princeton), A. Nilsson (SSRL), T. Schäfer (FZR Karlsrühe), J. Susini (ESRF), A. Tabazedeh (Stanford), and J. Zachara (PNNL). Biomedical sciences working group participants were: R.A. Scott (U. Georgia, working group leader). K. Benzerara (CNRS and Institut de Physique du Globe de Paris), B. Constantz (Stanford), S. DeBeer George (SSRL), D. Domaille (Berkeley), L. Finney (ANL), W. Gu (UCSF), B. Hedman (SSRL), B. Lai (APS), C. Larabell (UCSF), Peter Lay (U. Sydney), Z. Liu (SSRL), A. Mehta (SSRL), P. Pianetta (SSRL), J. Rao (Stanford), Instrumentation working group participants were: M. Rowen (SSRL, working group leader), H. Ade (NCSU), D. Attwood (CXRO, LBNL), I. McNulty (APS), M. Obst (CLS), H. Ogasawara (SSRL), H. Ohldag (SSRL), J. Stöhr (SSRL), J. Thieme (U Goettingen, BESSY), R. Fink (U. Erlangen-Nuremberg), T. Tyliszczak (ALS), T. Warwick (ALS), and W. Yun (XRADIA). The complete agenda for the workshop is available at http://wwwssrl.slac.stanford.edu/conferences/workshops/stxm2007/index.php. We thank all speakers and participants for making this workshop a strong success!

John Bargar, SSRL
Gordon Brown, Stanford University
Serena DeBeer George, SSRL
Hendrik Ohldag, SSRL

Figure 1. Group photograph of workshop participants: back row (from left) S. Myneni, P. Pianetta, G. Chiari, M. Rowen, T. Schäfer, M. Obst, D. Shuh, S. Bone, D. Domaille, B. Hedman, Z. Lu; 3rd row: S. Fendorf, I. Lindau, H. Ade, G. Brown, Jr., T. Tyliszczak, R. Fink, J. Susini, K. Benzerara, J. Zachara; 2nd row: H. Ohldag, P. Dobson, A. Tabazedeh, H. Ogasawara, B. Lai, J. Brandes, S. Gleber, J. Thieme, B. Constantz; Front row: S. DeBeer George, A. Mehta, W. Yun, C. Larabell, B. Bostick, R. Scott, J. Bargar, L. Finney, P. Lay.