

MEETING REPORT



**THE FUTURE OF THERMAL IONIZATION MASS SPECTROMETRY IN THE
EARTH SCIENCES: A REPORT FROM THE “REINVIGORATING TIMS”
WORKSHOP, NOVEMBER 5TH, 2004**

The Future of Thermal Ionization Mass Spectrometry in the Earth Sciences: A Report from the “Reinvigorating TIMS” Workshop, November 5th, 2004.

Executive Summary

To assess the future instrumentation and techniques needs in thermal ionization mass spectrometry in the earth sciences, a “Reinvigorating TIMS” Workshop was convened in Boulder, Colorado (USA) on November 5th, 2004. This workshop brought together ~35 isotope geochemists and solid source mass spectrometrists primarily from university laboratories, government facilities and the private sector in the U.S., Canada, the United Kingdom, and Germany. These scientists concluded that TIMS is and will continue to be an essential tool in the earth sciences. But there is a strong demand for a new generation of TIMS instruments, and for improved analytical techniques, that will allow higher precision isotope analyses over a wide range of sample sizes. Improved collector and ion source technologies, as well as the development of wide dispersion and high abundance sensitivity instruments, were highlighted as the areas most likely to provide the needed quality of isotope ratio determinations. Of concern is the fact that the earth science community is losing its ability to design and construct innovative TIMS instrumentation independently of the private sector, and so new instruments may only be developed as market conditions allow, and not as earth science research demands arise. To address these issues, the workshop participants proposed that the development of a TIMS Consortium, comprised of university and government researchers and their institutions involved in thermal ioniza-

tion mass spectrometry, should be seriously considered. The consortium would serve as an incubator for TIMS instrument and technique development and as a national/international voice for the needs and capabilities of the TIMS community. An *ad hoc* TIMS working group, comprised of five workshop participants, will be convened in 2005 to develop a fully realized model for the implementation of TIMS consortium that will be presented to the TIMS community as a whole, as well as to various possible funding agencies.

Introduction

Thermal ionization mass spectrometry (TIMS) has been a mainstay of isotope geosciences for fifty years and is still the method of choice for high precision isotope ratio measurements and for negative-ion isotope ratio determinations. However, increasing demands in geochronology and isotope tracer studies for even higher precision isotope ratio measurements from increasingly smaller sample sizes (subnanogram) are challenging the current capabilities of TIMS instrumentation. At the same time, rapid advances are being made in alternative methods of isotope ratio determinations, including multicollector ICP-MS, with *in situ* measuring capabilities, high ionization efficiencies and short analysis times. As a result, we are at a crossroads with regard to the isotope ratio instrumentation and a fundamental question that is being asked is whether the increasing demand for high precision isotope ratio measurements can best be met through improvements in TIMS technology, or whether efforts should be concentrated in improving alternative techniques for isotope ratio measurements.

To directly address the above issue from the perspective of earth scientists working in thermal ionization mass spectrometry, a “Reinvigorating TIMS” Workshop was convened in Boulder, Colorado (USA) on November 5th, 2004. This workshop brought together ~35 isotope geochemists and solid source mass spectrometrists primarily from university laboratories, government facilities and the private sector in the U.S., Canada, the United Kingdom, and Germany. The intent of the workshop was to assess the current state of TIMS and to debate strategies for future development and dissemination of new TIMS instrumentation and analytical techniques. The workshop was, to the best of our knowledge, the first convened in the U.S. with the sole intent of fostering a community discussion of the near and far term needs for thermal ionization mass spectrometry in the earth sciences.

Current State of TIMS

The longevity of TIMS as an essential tool in the isotope geosciences stems from several fundamental, but unique, aspects of this analytical technique. Most significant is that TIMS utilizes thermalized ions for isotope ratio determinations, and such ions, by definition, are characterized by a narrow energy spread. This narrow energy spread allows for the use of a single magnetic sector as an efficient mass separation device, at high transmission efficiencies (>90%) and with the use of multiple simultaneous collectors (analog and digital). In addition, while elemental ionization efficiencies for ion emitters used in TIMS (e.g. Si gel, salts) could be improved (currently 0.001 to 10%, see below), for some elements, such as Nd, the efficiencies are not much less than that obtained from high temperature plasma ion sources. Another TIMS advan-

tage is that it involves the discrete loading of purified samples on individual emitter substrates (typically a metal ribbon) and so represents a “clean” method that minimizes contamination from the mass spectrometer source, an important consideration when dealing with radioactive sample material and very small sample sizes. The mass spectra produced by thermal ionization are simple and consist mainly of elemental ions and oxides. Although isobaric interferences are minimized by chemical separations prior to introduction of a sample to the mass spectrometer, in many cases, remnants of these interferences can be minimized due to the differing volatilities of the interfering and the analyte elements in the source of the mass spectrometer. Mass fractionation produced during thermal ionization can be modeled using nonradiogenic isotope pairs or double spike techniques and efforts to improve the accuracy of these models are currently being made.

All of the above capabilities lead to high external reproducibilities on isotope ratio measurements (< 10ppm) for a number of elements, even with sample sizes of <10 ng. In addition, for some measurements not limited by sample size, such as $^{142}\text{Nd}/^{144}\text{Nd}$ determinations, precisions of 2 ppm appear to be possible. Therefore, despite competition from other techniques for elemental isotope ratios determinations, workshop participants were adamant in their support of TIMS as an essential analytical tool in the earth sciences. For example, TIMS is the only technique available that generates the highly precise and accurate Pb isotope ratio measurements on < 50 picogram samples required for high resolution geochronology. Osmium and tungsten isotopic measurements are dependent on TIMS because of its superior sensitivity for these elements (as negative ions). TIMS is the technique of choice in the development of the latest U-series iso-

tope techniques (Ra, Pa). For elements efficiently ionized in TIMS ion sources (Sr, Nd), TIMS is used when limited sample material is available but high precision isotope ratios are still required, such as in studies of meteorite and lunar material or in living tissue samples.

New instrumental techniques, in particular multicollector ICP-MS, certainly provide an advantage over TIMS in ease and rapidity of isotope analyses, but still cannot match TIMS in terms of accuracy of isotope ratio determination, especially for small samples. In fact, TIMS measurements continue to provide external validation of isotope ratio determinations for many elements obtained by multicollector-ICPMS. The two instrumental methods should be viewed as complementary, rather than competing techniques.

Future Development of TIMS techniques

Because the inherent advantages of TIMS for high precision/high accuracy elemental isotope ratio measurement are unlikely to be supplanted in the near future by any alternative technique, the issue then becomes one of identifying desirable future improvements in TIMS instrumentation and associated analytical techniques.

High quality solid-source mass spectrometers are currently available from two commercial manufacturers; GV Instruments (IsoProbe-T) and ThermoFinnigan (Triton). Despite the remarkable capabilities of these instruments they do not yet provide the level of accuracy desired for many elements of geologic interest, particularly for subnanogram sample sizes. Even a two fold increase in the precision currently possible through TIMS for such elements as Nd, Sr and Ca (~5 ppm for Nd and Sr; 20ppm for Ca) would open a variety of new avenues of research in,

for example, seawater isotopic evolution and terrestrial ^{142}Nd studies. *In situ*, physical micro-sampling, of rocks and minerals also demands high precision isotopic measurements for subnanogram sample sizes. All of these drivers require improvements in basic TIMS technologies.

In discussing how to best meet these new demands for increased TIMS capabilities, the workshop attendees identified collector and ion emitter technology as the prominent areas in which short term improvements could be achieved

Detectors: For low intensity ion beams ($<10^{-13}$ amps), typically measured through multiplier techniques, a major area of concern is in continuous-dynode secondary electron multiplier (SEM) (cf. *Channeltron*®) technology. To enable higher precision isotope measurements, these devices require improved output linearity, gain stability, and longevity over a wide signal range. By comparison, discrete dynode secondary electron multipliers (and Daly-type conversion dynode-photomultiplier variants) are much more reliable, although some workshop participants noted a lack of uniform quality in commercially available SEMs of this type. The physical size of discrete dynode electron multipliers also precludes their use at unit mass spacing for current commercially-utilized focal plane geometries.

Ion beams corresponding to 10^{-12} to 10^{-13} A are particularly problematic for precise isotope measurements because these intensities lie between the values best suited to SEMs and to Faraday-type collectors. Faraday collectors would be the preferred method for analyzing ion beams in this range, but only if a highly linear, low-noise 10^{12} or 10^{13} ohm resistor were available. In any event, current TIMS instruments would benefit from having selectable input resistors for the Faraday collectors, and more expedient methods of switching ion beams between ion

multipliers and Faraday collectors. This is viewed as an absolute high priority and both TIMS manufacturers are working to provide these capabilities.

A longer term option for fundamental improvement of TIMS detector systems was presented at the workshop by Gary Hieftje (Indiana University). His research group has been recently involved in developing a Faraday cup-based multiple detector array (“focal plane camera”; Knight et al., 2002). In the focal plane camera, multiple Faraday cups (current version contains 128 detector channels) are each connected to a capacitive transimpedance amplifier, allowing simultaneous ion beam measurements over a dynamic range of eight orders of magnitude. The use of such arrays in a thermal ionization mass spectrometer is possible but has not yet been implemented. Workshop participants considered this work to represent a groundbreaking advance in detector technology that should be actively supported by the earth science community. However, it should be emphasized that the majority of the participants in the workshop were unaware that this work was being done, illustrating the need for more cross-disciplinary discussions.

Thermal Ion Emitters: Improvement in the characteristics of thermal ion emitters used in TIMS has been a long neglected area of research, but given the generally low (usually <10% and often <1%) ionization efficiencies for many elements, this could prove a fruitful area for research and development, given that precision in isotope ratio determinations is ultimately limited by the number of ions counted during a particular measurement. Over the past ten years, what research in this regard that has taken place has been largely restricted to the development of thermal ioni-

zation cavities (TIC; Wayne et al., 2002) and in efforts to determine the mechanism of ion formation from liquid glass ion emitters (Kessinger and Delmore, 2002), the latter being the method of choice for Pb isotopic measurements. Neither of the above research activities has yet led to new, high ionization efficiency, thermal ionization sources for TIMS. However, the work by Delmore and coworkers provides the theoretical basis needed for efforts to use electrochemical techniques in liquid glasses under high vacuum (low fO_2) to increase the efficiency of liquid glass ion emitters, potentially with the ability to better control the magnitude of mass fractionation in emitted ions.

Over the longer term there was some support at the workshop for the development of larger format instruments with greater mass dispersion and higher abundance sensitivity than possible in currently available commercial instruments. In this regard, Tony Appelhans and James Delmore (Idaho National Engineering and Environmental Laboratory) described a prototype wide dispersion multiple collector instrument that may provide an alternative to simply scaling up existing TIMS designs (Appelhans et al., 2005). This instrument employs an electrostatic dispersion lens, in tandem with a conventional magnetic sector. This combination reduces ion beam divergence while increasing dispersion between ion beams. The dispersion is sufficiently high that simultaneous measurements can be made of high mass isotopes ($A=238$ to 244) using normal size, discrete dynode multipliers. This instrument could lead to new and unforeseen scientific opportunities, although some workshop participants felt that answers to some compelling scientific questions would be needed before the development of a high dispersion instrument could be justified within the earth science community.

Where are advances in TIMS instrumentation taking place?

Historically, advances in TIMS technology were driven by academic researchers, among them scientists like A. Nier, G. Wasserburg and L. Brown. However over the past twenty years, developments in TIMS have come largely from the private sector, and in general conference participants have found the companies somewhat responsive to the needs to the earth science community. However, issues regarding the proprietary nature of instrument design, the lack of open-source software, the high engineering costs to potential return ratios, and potential future problems if companies should either lack competitors or simply cease to develop TIMS instrumentation, puts the TIMS community at some risk.

At the same time, the capabilities for TIMS instrument design and development outside of the private sector have significantly diminished over the past 20 years. Many U.S. universities now lack facilities for instrument design and construction, and earth scientists may not have either the expertise or the resources to pursue instrument development. Instrument development and design remains a part of the mission of several U.S. National Laboratories (including INL, PNNL), although the long-term prospects for continued funding of these facilities are unclear. Other government facilities, including the Los Alamos National Laboratory and the U.S. Geological Survey, no longer support instrument development facilities. No private U.S. research institution, including the Carnegie Institution of Washington, is involved in TIMS instrumentation development.

A similar picture exists in Canada and the UK, according to workshop participants. The UK does support a National Isotope Geology Laboratory (NIGL), through the Natural Environ-

ment Research Council of the British Geologic Survey, but the mandate of this organization is to provide isotopic analysis and training, largely to the UK academic community. Research into new analytical techniques, but not TIMS instrument development, occurs at NIGL.

Summary

The primary conclusion reached from the Reinivigorating TIMS workshop was that TIMS is and will continue to be an essential tool in the earth sciences. But there is a strong demand both for a new generation of instruments, and for improved analytical techniques, in order to allow higher precision isotope analyses particularly for subnanogram sample sizes. Improved collector technology and ion source technologies, as well as the development of wide dispersion and high abundance sensitivity instruments, were highlighted as the areas most likely to provide the needed quality of isotope ratio determinations.

Some of these advances are likely to take place within the private sector. There is no question that commercial instrument manufacturers (currently GV Instruments and ThermoFinnigan) have played the key role in providing new TIMS analytical capabilities to the geoscience community over the past twenty years. Further development of the Triton (ThermoFinnigan) and Isoprobe-T (GV Instruments) should obviously be left to their respective companies. But neither company can hope to survive financially without providing a diversified portfolio of instruments, and developments in TIMS instrumentation that do not obviously serve as broad a spectrum of the user community as possible cannot be pursued. As a result, production of large format TIMS instruments, development of innovative TIMS designs (such as the wide dispersion instrument

designed at INL), and the implementation of new collector designs will not necessarily be undertaken by commercial entities. Community efforts to foster such innovations independently of, or in partnership with, the private sector need to be more rigorously pursued.

Analytical technique development, including ion-source technology advances, have been and should continue to be undertaken largely by the TIMS user community, in both university and government laboratories. However, it has become increasingly difficult for individual TIMS laboratories in the U.S. to make such development work a first priority. Largely because of financial concerns, many such labs turn to grants and contracts that largely involve existing techniques and instrument capabilities, given the fact that such activities are perceived to be more easily funded. This issue is compounded by the fact that many U.S. Universities cannot afford to fund the professional technical personnel required for these laboratories. Technician funds available through federal agencies are highly limited and many existing laboratories cannot compete for these funds because of restrictions imposed by a given funding agency.

Aside from professional research associates, graduate students are another pool that could be tapped in university settings to stimulate advances in TIMS instrumentation and analytical techniques. Unfortunately few U.S. geoscience graduate students have sufficient training in the technical aspects of mass spectroscopy (ion optics, electronics, material science, etc.) to design and implement such advances. The generation of earth scientists that grew up designing and building mass spectrometers have already, or will soon, retire, leaving a major void.

The above concerns distill to the following: TIMS instrumentation and analytical techniques need to advance in the face of new demands within the earth science community, but the

earth science community in the U.S. has essentially lost its ability to independently advance TIMS instrumentation and is instead largely dependent on the private sector to provide new instrument capabilities. While the isotope geoscience community has been well served by the private sector in the past, it may be unwise to relinquish all expertise in TIMS instrument development to commercial interests. Disadvantages include the issue of the proprietary nature of instrument designs and instrument software, as well as the issue that high risk, low profit, advances in instrumentation are unlikely to be pursued by the commercial manufacturers. There is also the obvious concern that in the future, the market may not be large enough to support continued commercial interest in TIMS.

Recommendations

Establishment of a TIMS Consortium

Given the above concerns, the workshop participants agreed that there was now a need to shift aspects of how the TIMS community interacts among its members, with funding entities, and the private sector. In the past there has been immense value in terms of scientific vigor and innovation to the current U.S. paradigm in which individual TIMS oriented scientists have worked more or less independently from one another. But while there was no call to replace this system with, say, a National TIMS Center, there was still a recognition by the workshop participants that there may be advantages to a community effort designed to promote advances in TIMS instrumentation and to foster education and outreach in thermal ionization mass spectrometry. These advantages have not been tapped. As a result, the workshop participants agreed that the

development of TIMS Consortium should be seriously considered, with the consortium being composed of scientists and their home institutions interested in the future development of TIMS instrumentation and analytical techniques,

The main functions of a TIMS consortium would be to serve as an incubator for TIMS instrument and technique development and to serve as an effective national/international voice for the needs and capabilities of the TIMS community. The former may consist of the TIMS consortium organizing periodic workshops and technical meetings, along with short courses, or other educational tools (e.g. web pages), in the technical aspects of mass spectrometry geared specifically for the geoscience community (particularly geoscience graduate students). The latter may be accomplished through the production of “position papers” or through direct lobbying with funding and other agencies. A consortium may also provide a mechanism for developing mutually beneficial partnerships between TIMS users, the private sector, and funding agencies. Forging new relationships between researchers in disciplines not traditionally allied, such as the earth sciences and analytical chemistry, should be a high priority.

A TIMS consortium could also serve as a community resource. It may provide a mechanism of matching TIMS laboratories with researchers requiring isotopic analyses, a service that might reduce sample turn-around times, by distributing the backlog of isotopic analyses over a larger set of laboratories. The consortium could provide information on what laboratories have underutilized older instruments that could be moved to institutions wanting a basic TIMS setup. A TIMS consortium might also oversee the production, maintenance and distribution of carefully calibrated enriched isotope spikes, concentration and isotope composition standards, and high

ionization efficiency emitter substances. Any efforts along these lines would be coordinated with other relevant groups (eg. EARTHTIME). A coordinated, community effort to produce such materials would help to improve data quality among various laboratories and reduce the amount of time in any given lab spent on generating spike, normal, and standard solutions.

A TIMS Working Group

Fully assessing the need for and the potential mandate of a TIMS Consortium requires more time and energy than could be devoted to the issue during the Reinvigorating TIMS workshop. As a result, the workshop participants recommended the creation of an *ad hoc* TIMS working group, comprised of five or six workshop participants that would develop over the course of 2005 a more fully realized model for a TIMS consortium. The working group will initially consist of Lang Farmer (University of Colorado), Sam Bowring (MIT), Gary Hieftje (Indiana University), Tony Appelhans (Idaho National Laboratory) and Brian Marshall (U. S. Geological Survey). This group will work to define those TIMS activities that would benefit from a cooperative approach, and create a possible framework for the TIMS consortium. Funds required for working group meeting(s) and site visits are available from funds remaining from in the Reinvigorating TIMS Workshop grant from NSF-EAR (Instrument and Facilities). The working group will plan to provide an initial recommendation on a TIMS Consortium to the TIMS community and to NSF by the end of summer 2005.

References Cited

- Appelhans, A. D., Delmore, J. E., and J. Olson, 2005, Wide dispersion multiple collector isotope ratio mass spectrometer: *Int. J. Mass Spectrom.*, v. 241, p. 1-9.
- Kessinger, G. F., and J. E. Delmore, 2002, High temperature chemistry of molten glass ion emitters: *Int. J. Mass Spectrom.*, v. 213, p. 63-80.
- Knight, A. K., Sperline, R. P., Hieftje, G. M., Young, E., Barinaga, C. J., Koppenall, D. W., and M. B. Denton, 2002, The development of a micro-Faraday array for ion detection: *Int. J. Mass Spectrom.*, v. 215, p. 131-139.
- Wayne, D. M., Hang, W., McDaniel D. K., Fields, R. E., Rios, E. and V. Majidi, 2002, The thermal ionization cavity (TIC) source: elucidation of possible mechanisms for enhanced ionization efficiency: *Int. J. Mass Spectrom.*, v. 216, p. 41-57.

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