It's About Time: Opportunities & Challenges for U.S. Geochronology

It's About Time: Opportunities & Challenges for U.S. Geochronology

Cover photo: The Grand Canyon, recording nearly two billion years of Earth history (photo ourtesy of Dr. Scott Chandler)

DEEP TIME is what separates geology from all other sciences. This report presents recommendations for improving how we measure time (geochronometry) and use it to understand a broad range of Earth processes (geochronology).

FRONT MATTER

Written by: T. M. Harrison, S. L. Baldwin, M. Caffee, G. E. Gehrels, B. Schoene, D. L. Shuster, and B. S. Singer

Reviews and other commentary provided by: S. A. Bowring, P. Copeland, R. L. Edwards, K. A. Farley, and K. V. Hodges

This report is drawn from the presentations and discussions held at a workshop prior to the V.M. Goldschmidt in Sacramento, California (June 7, 2014), a discussion at the 14th International Thermochronology Conference in Chamonix, France (September 9, 2014), and a Town Hall meeting at the Geological Society of America Annual Meeting in Vancouver, Canada (October 21, 2014)

This report was provided to representatives of the National Science Foundation, the U.S. Geological Survey, and the National Aeronautics and Space Administration.

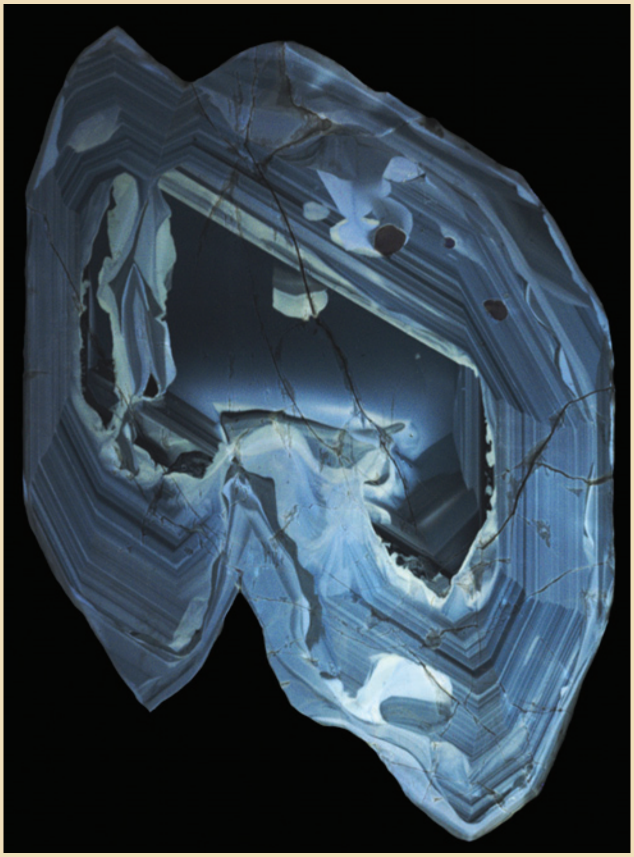
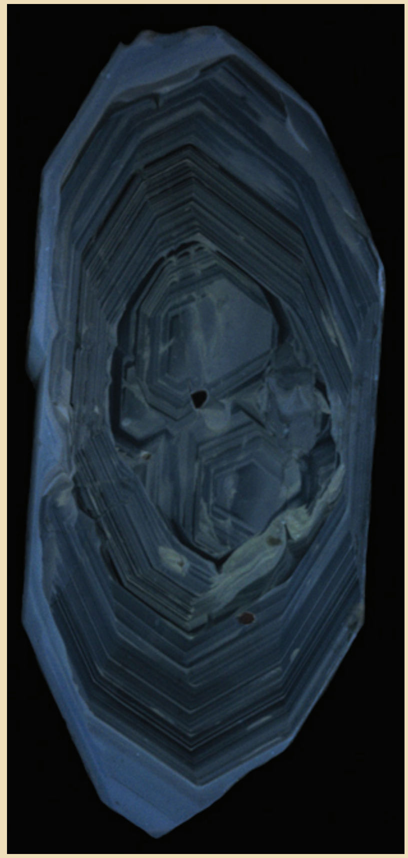
Preferred citation: T. M. Harrison, S.L. Baldwin, M. Caffee, G. E. Gehrels, B. Schoene, D. L. Shuster, and B. S. Singer (2015) It's About Time: Opportunities and Challenges for U.S. Geochronology. Institute of Geophysics and Planetary Physics Publication 6539, University of California, Los Angeles, 56 pp.

This work was supported by National Science Foundation award No. EAR-1424285

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

We thank Elizabeth Bell, Patrick Boehnke, and Margot Odlum for documenting the minutes of our various consultations, Yasmin Thomas for assistance with graphic design and layout, Kathleen Micham for helping guide publication, and Sam Bowring, Larry Edwards, Ken Farley, and Kip Hodges for commenting on the draft of this report.


GLOSSARY

AGS: NSF’s Division of Atmospheric and Geospatial Sciences

AMS: Accelerator mass spectrometry

EAR: NSF’s Division of Earth Sciences

COMPRES: Consortium for Materials Properties Research in Earth Sciences

GEO: NSF’s Geosciences Directorate

ID-TIMS: Isotope dilution-thermal ionization mass spectrometry

IF: NSF Instrumentation and Facilities program

K-Ar: Potassium-argon (and its $^{40}Ar/^{39}Ar$ variant) dating

ka: thousands of years

LA-ICPMS: Laser ablation-inductively coupled plasma mass spectrometry

Ma: Millions of years

NROES: National Research Council’s 2012 report *New Research Opportunities in the Earth Sciences*

OCE: NSF’s Division of Ocean Sciences

OSL: Optically stimulated luminescence dating

P2C2: Paleo Perspectives on Climate Change

PLR: NSF’s Division of Polar Sciences

Rb-Sr: Rubidium-strontium dating

SIMS: Secondary ion mass spectrometry

Sm-Nd: Samarium-neodymium dating

U-Pb: Uranium-lead isotopic dating

Executive Summary

Geochronology holds a pivotal position within the Earth sciences; without quantitative knowledge of absolute and relative time, no modern discipline with an historical focus could function. The 2012 report, New Research Opportunities in the Earth sciences, recognized the central role that the field plays in the geosciences and identified geochronologic instrumentation and facilities as pressing needs for fostering research and education across the Earth Sciences. This document reports the results of a yearlong consultation with consumers and producers of geochronology undertaken to understand their aspirations and the challenges the latter face as they move to develop the next generation of geochronometers.

The field of geochronology has changed dramatically over the past generation, with many today focused on dating youthful features at or near the Earth's surface. Even for those interested in deeper time or deeper Earth, the generation and publication of geochronologic data has shifted considerably, largely reflecting the growing availability of in situ methods albeit with their attendant higher uncertainties. Thus while there has never been a time when users have had greater access to geochronologic data, they remain, by and large, dissatisfied with the available style/quantity/cost/efficiency. Our exploration of this paradox suggests that a poor match of incentives to needs exists, and the view that geochronology is merely a "tool", may be largely responsible.

As geochronology expanded into emerging fields, such as those related to surficial or paleoclimate processes, it often failed to become firmly rooted within those disciplinary cultures. While routine analyses could be supported through programmatic funding, these agencies lacked the tradition of sustaining the underlying development of geochronologic protocols. For our community to truly prosper, we need to make the case across the geosciences that stewardship of geochronology is the responsibility of all disciplines that utilize its products, including the need to support innovative, high-risk research and development. In return, the geochronology community should be provided the resources needed to address the research priorities of supportive disciplines and provide enhanced user access to data.

We envision a sustained program of NSF support that links numerous single-PI labs with larger facilities to create a networked Major Multi-user Research Facility in geochronology with the goal, in ten years, of attaining:

1. ±0.01% age precision and accuracy from the Cenozoic to the Hadean (achieved by creating methods and mass analyzers of unprecedented sensitivity and resolution) to revolutionize our understanding of a broad array of Earth processes;

2. continuous temporal coverage throughout the Pleistocene – from one week to one million years – of processes key to societal security (e.g., climate change, critical zone management, volcanic hazards, paleoseismology);

3. sub-mm/year denudation rate accuracy from thermochronometers, for timescales as short as 10^3 years, to place geodetic deformation rates in context with long-term geologic trends;

4. coverage of thermal conditions ranging from the cryosphere through the brittle-ductile transition to magmic environments (i.e., -20°C to 900°C) with which to provide the 4th dimension to thermal features imaged by USArray.

These ambitions are more than simply proposing to hone a tool – they touch on the great unanswered scientific questions of our time and permit the goal of EarthScope – to understand the 4-dimensional structure of North America – to be realized. The support we require, coupled with economies of scale arising from the proposed networked facility, would result in a manifold increase in geochronologic capacity for users across the spectrum of Earth sciences.

But generating enhanced geochronologic data is only the first step. Application of geochronology requires not just knowledge of both the resolving power and limitations of the technique, but also an equivalent understanding of the underlying geophysical processes with which to predict the geochronologic observables. These interdisciplinary connections have not been adequately supported for many of the same reasons we believe geochronology has been essentially orphaned within the federal funding system. We advocate enhanced support of synergistic research that investigates and integrates the 4-D development of Earth.

THE ROLE OF GEOCHRONOLOGY IN TRANSFORMATIVE GEOLOGIC RESEARCH

Time lies at the heart of the Earth sciences; every significant advance in geochronology has produced a paradigm-shifting breakthrough in our understanding of Earth history. The earliest dates over one hundred years ago (Boltwood, 1907) immediately catapulted the discussion of the age of our planet from a few 10's of millions of years to billions. The dating of young basalts (McDougall and Tarling, 1964) permitted calibration of the geomagnetic time scale that led directly to the plate tectonic revolution. The development of high precision U-Pb zircon dating (Krogh, 1982) stimulated novel process models for the Precambrian and is now revolutionizing our understanding of magmatic timescales (Coleman et al., 2004; Schaltegger et al., 2009; Rivera et al., 2014) as well as the tempo of sediment accumulation and biologic change (e.g., Mundil et al., 2004; Shen et al., 2011; Schoene et al. 2014). The advent of in situ U-Pb dating both exposed and resolved previously unrecognized levels of complexity in zircons and revealed our only record of the Hadean (Froude et al., 1984) that is challenging the paradigm of early Earth as an arid world hostile to life. The recognition that major extinction events are coeval with the formation of large igneous provinces and asteroid impacts is changing our understanding of the processes of species change (Whiteside et al., 2007) and instructs us about the dependency of Earth's living systems on extraterrestrial inputs. The advent of ^{14}C dating (Grosse and Libby, 1946) radically altered our understanding of prehistoric human migration but, because of its ~6 kyr half-life, led to an apparent concentration of events in the 30 to 40 ka range. This pileup only relaxed to include much older ages after the development of optically stimulated luminescence dating with its much-longer age applicability (Roberts et al., 1990). These techniques and U-series dating, focused on the Pleistocene, have been essential for calibrating glacial-interglacial cycles from climate records (Cheng et al., 2009) and understanding abrupt climate change (Wang et al., 2001).

This partial history doesn't so much trumpet past achievements as illustrates the bellwether role that geochronology holds in the Earth sciences and demonstrates how hardware and methodological improvements led to applications not envisaged by previous generations. Whether by increased precision, being able to observe at heretofore unattainable lengthscales, capitalizing on previously unused systems, or increasing efficiency to generate larger data sets, advances in geochronometry have always challenged orthodoxy. While the relationship between the provision of highly resolved time and transformative Earth Science research is clear, the serendipitous nature of the most momentous breakthroughs in Earth Science (e.g., plate tectonics) tempers the specifics of our prognostications (see Grand Challenges sidebar). The clearest motivation to provide enhanced resources for chronologic innovation is the near certainty of fundamental discovery. Thus the justification for the next generation geochronometer is akin to that for a particle accelerator with ten times greater energy or a telescope with ten times bettter resolution – create it and breakthrough science awaits. If innovation is the peak of the geochronological pyramid, the base is the capacity to provide age constraints for the myriad investigations now reliant on these methods. As shown on Figure 1, this base consists of a broad array of research areas in Earth science, and includes nearly all fields in geoscience that have immediate societal impacts.

But geochronology (establishing timescales, rates, physical mechanisms, etc.) is more than geochronometry (i.e., the measurement tool). It requires integration with geology, geophysics, and geochemistry using theoretical and numerical modeling techniques and the creation and transfer of knowledge between disciplines and researchers with diverse skill sets and expertise. For example, understanding the interactive processes manifested in Earth's topography across spatial and temporal scales requires a coordinated collaboration among scientists with a shared vision of Earth as a system, and resources to allow them to work together across subdisciplines ranging from field studies to laboratory research to computational geophysics. Geochronologic data is used as input for numerical models to study linkages between mantle dynamics, plate tectonics, surface processes, and climate. Thermochronologic data provides constraints on the spatial and temporal controls on the rates of exhumation and rock uplift that, when coupled with thermokinematic and climate models, can then be used to determine the temporal development of landscapes as a function of tectonic uplift, climate, and erosional processes. Improvements in modeling capabilities of Earth system dynamics will only be possible by integrating chronometric data to more realistically simulate complex processes on all spatial and temporal scales. We note that development of mantle flow models coupled to plate tectonic and surface erosion models informed by geochronology is identified as a grand challenge by the Earth surface processes community (Merritts et al., 2010). Geochronology was cited in other recent National Academy reports as key to understanding earthquake cyclicity (Jordan et al., 2003) and climate change (Montañez et al., 2011, Lay et al., 2012), and to address the great unresolved questions in Earth science (DePaolo et al., 2008; Lay et al., 2012).

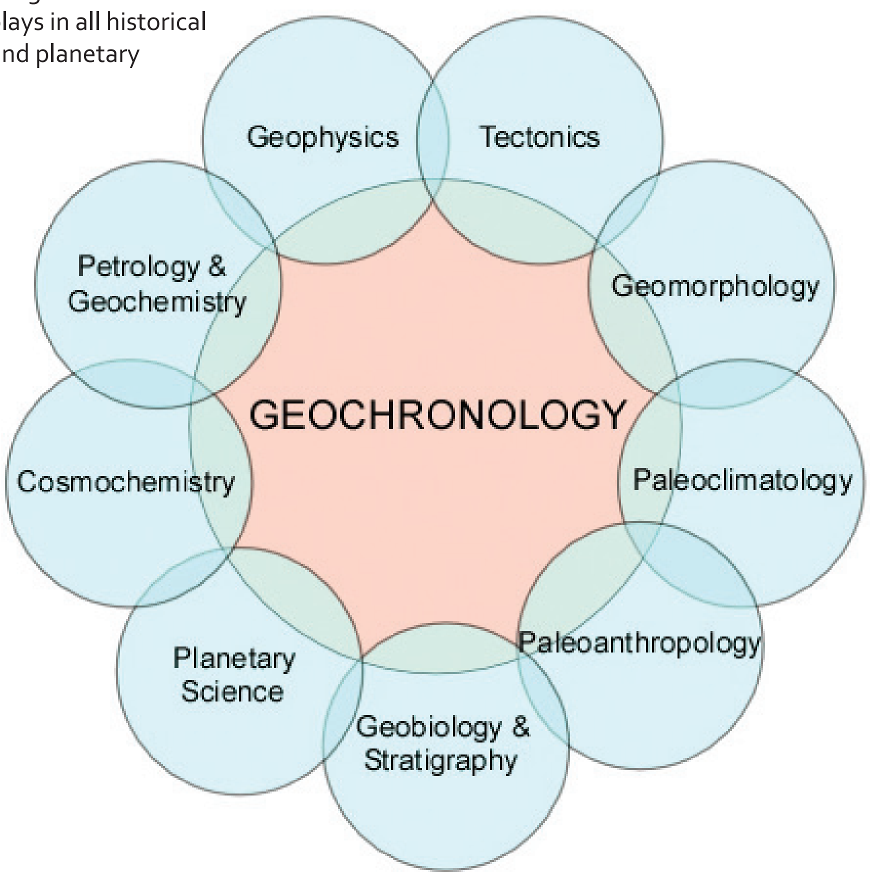
SUSTAINING TRANSFORMATIVE GEOCHRONOLOGIC RESEARCH

Through much of the late 20th century, geochronologic innovation and application in the United States was supported by federal programs representing many of the disciplines shown in Figure 1. The funding paradigm, accepted by both researchers and federal agencies, was that innovations in instruments and methods should be supported by programs that would most benefit from the development of new chronometers or from enhanced precision/accuracy, improved spatial resolution, and generation of more data. Because geochronology has expanded beyond its original goals, this linkage is no longer clear. Proposal success rates have declined while new research areas (e.g., paleoclimate) have become significant consumers of geochronologic information with little contribution to its infrastructure.

Thus it is the pivotal position that geochronology occupies within Earth science research that may be impeding its growth. While all of the surrounding disciplines shown in Figure 1 are explicitly identified for programmatic support by one or more federal science agencies, geochronology is not. Geochronology is continuously evolving to meet the myriad demands for new methodologies whose development may not fit neatly into any one existing program. A new relationship is called for that invites the broad spectrum of Earth science disciplines to share the responsibility for the well-being of geochronology. In turn, our community needs to be motivated to address the research priorities of supportive disciplines and provide enhanced user access to data.

Given the central role of geochronology in the historical geosciences (Fig. 1), it was entirely appropriate that the National Research Council's 2012 report, New Research Opportunities in the Earth Sciences (NROES; Lay et al., 2012) identified geochronology instrumentation and facilities as a pressing need which could foster research and education across a host of Earth Sciences programs.

Figure 1
Venn diagram illustrating the central role that geochronology plays in all historical aspects of the Earth and planetary sciences.



NROES REPORT AND FOLLOW-UP ACTIVITIES

The NROES report (see sidebar, right) recognized an urgent need to "enhance the community's capacity to produce high-quality dates". It offered a range of possible solutions, from the creation of national centers that would act as service facilities for one or more geochronologic methods to enhanced support for single-PI labs to better serve community needs. There was considerable emphasis in the report for any future system to support technical advances as well as to generate geochronologic information.

In order to facilitate the NROES recommendations on geochronology instrumentation and facility development, a community-led group arose with Mark Harrison (UCLA) as chair. Members, who range across most geochronologic disciplines and career stage, are (see Appendix I for biosketches):

Geochronology Steering Committee

Mark Harrison (UCLA, Chair)	K-Ar and SIMS U-Pb geochronology
Suzanne Baldwin (Syracuse University)	K-Ar and fission track geochronology
Marc Caffee (Purdue University)	cosmogenic radionuclide geochronology
George Gehrels (University of Arizona)	LA-ICPMS U-Pb geochronology
Blair Schoene (Princeton University)	ID-TIMS U-Pb geochronology
David Shuster (UC Berkeley)	(U-Th)/He geochronology
Brad Singer (University of Wisconsin-Madison)	K-Ar geochronology

The committee established goals of:

1. disseminating the NROES recommendations to the broader Earth Science community, and especially to researchers who use or generate geochronologic information.

2. gathering responses from geochronologists and users of geochronology regarding the NROES recommendations.

3. learning of other challenges and opportunities in regard to geochronology.

4. formulating a response and set of recommendations.

It was agreed that exchange with the broader research communities should occur both through a questionnaire-based survey and direct consultation with the producer and consumer communities. Our announcement specifically invited early career researchers, graduate students, and those from groups underrepresented in science to participate.

Activities of the steering committee included:

1. Compiling a list of 243 researchers who "produce" geochronologic data using ^{14}C, $^{40}Ar/^{39}Ar$, cosmogenic radionuclides (CRN), fission track, Lu-Hf, Rb-Sr, Re-Os, optically stimulated luminescence (OSL), Sm-Nd, (U+Th)/He, U-Th-Pb, and U-series chronometers.

2. Posting (on-line) and compiling results from a survey, shared with all 243 researchers, with questions concerning (see http://sims.epss.ucla.edu/usg-survey.docx for details):

   a) the role of geochronology in transformative geologic research

   b) current and needed support for single-PI labs versus centralized facilities

   c) development of synergies between disciplines

   d) how to support geochronologic innovation

   e) the need for improved decay constants

3. Hosting a one-day workshop at the 2014 Goldschmidt meeting (see Appendix II and http://sims.epss.ucla.edu/usg-Goldschmidt-minutes.docx).

4. Hosting a discussion at the14th International Conference on Thermochronology (see Appendix II and http://sims.epss.ucla.edu/usg-Thermo2014-minutes.docx).

5. Hosting a Town Hall discussion at the 2014 GSA Annual Meeting in Vancouver (see see Appendix II and http://sims.epss.ucla.edu/usg-GSA-townhall-minutes.docx).

This reports summarizes our findings and presents six recommendations that would enable the broader community to make the best use of geochronological facilities to enhance research in Earth sciences. We hope that the document stimulates discussion within the geochronological community so that we might more clearly prioritize our goals.

new research opportunities in the earth sciences

In response to a charge from NSF's Division of Earth Sciences (EAR) to identify next generation research opportunities, the National Research Council oversaw publication of the 2012 NROES report (Lay et al., 2012). Part of the project purview was to identify the instrumentation and facility support needed to realize their recommended scientific goals and to suggest ways to integrate the training of the next generation of Earth scientists into facility capitalization and geochronology figured prominently. The NROES committee felt that the community of end users were underserved by the traditional model by which geochronologic research is largely conducted in single principal investigator (PI) laboratories. They observed that *"One way forward is for EAR to entertain proposals that seek funding for major new facilities capable of meeting these challenges…We can envision creating one or more national geochronology centers that would require capitalization and operating costs that exceed the capacity of existing NSF-EAR programs, including the Major Research Instrumentation (MRI) program. Alternatively, single PI laboratories or networks of such laboratories could potentially fulfill the same objectives but would require substantially more support and more commitment to serving community needs than if implemented through current EAR programs"*.

The NROES recommendation reads:

"EAR should explore new mechanisms for geochronology laboratories that will service the geochronology requirements of the broad suite of research opportunities while sustaining technical advances in methodologies. The approaches may involve coordination of multiple facilities and investment in service facilities and may differ for distinct geochronology systems."

The NROES report identified six principles that could guide NSF supported facilities toward greater access and productivity:

1. The best science outcomes occur when strong intellectual engagement exists between the investigators who make the measurements and those who use them. This extends all the way from the inception of a project, through sampling strategy and sample selection, to the collection and interpretation of results. The committee believes that a simple analysis-for-hire scheme is unlikely to yield results of consistent high quality.

2. It will be useful to identify mechanisms that will encourage broad community access to the facilities.

3. It would be useful if facilities were encouraged or required to routinely demonstrate that the quality of their results meet the standard expected by the community they serve. Such a demonstration would eliminate any questions regarding the integrity of ages produced.

4. The education of investigators, especially students and post-docs, is an essential goal of these facilities. The education of geochronologists and that of users of geochronology are equally important. Intellectual isolation of measurements from applications is best avoided.

5. A component of the support given to facilities could be used to innovate new or better methods.

6. Traditional single-PI laboratories doing high quality, innovative research will remain essential to the vitality of the field.

FINDINGS AND RECOMMENDATIONS

Stewardship of U.S. Geochronology

Geochronology is the science of establishing and interpreting a quantitative time framework for geological processes, primarily using radioactive decay, ingrowth, or decay products. From a handful of US-based practitioners 60 years ago, we have grown to a community of several hundred who, together with international colleagues, produced as many dates in the past decade as were generated in the previous 100 years of the discipline. To the extent that bibliometrics might be a useful proxy to gain insight into changing trends in the field, we offer a few selected observations.

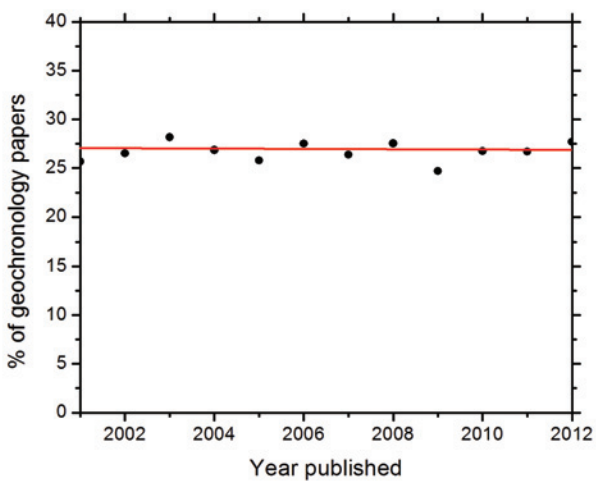


Figure 2
Percentage of papers in Geochemistry & Geophysics journals (e.g., n = 8206 in 2012) that include geochronologic information. (from Web of Science).

Since 2001, the Web of Science has indexed papers according to 177 subject categories, including two Earth sciences disciplines: Geochemistry & Geophysics and Geology. In 2012, there were 8206 papers in the Geochemistry & Geophysics category and 2314 in Geology, up overall by more than 75% from a decade ago. For papers in the Geochemistry & Geophysics category, the proportion of those papers that explicitly depend on the reporting of geochronologic data has been essentially constant at about 27% over the past 12 years (Fig. 2). This demonstrates the remarkable reliance of publication-worthy Earth science research on geochronology.

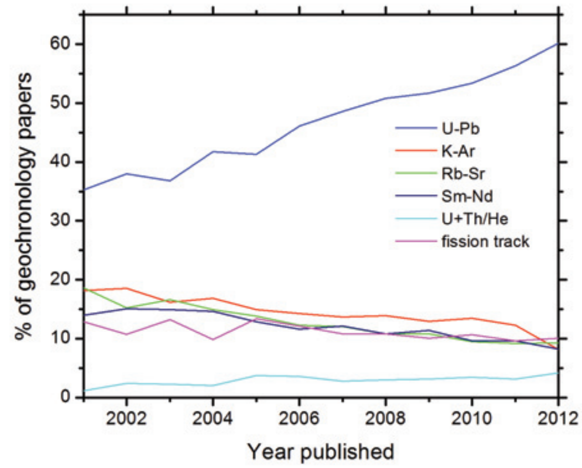


Figure 3
From 2001 to 2012, as the number of Geochemistry and Geophysics papers increased by 76%, U-Pb rose from 35% to 60% of the total in the Geochemistry & Geophysics category, implying that reporting of most other methods is declining. (Web of Science).

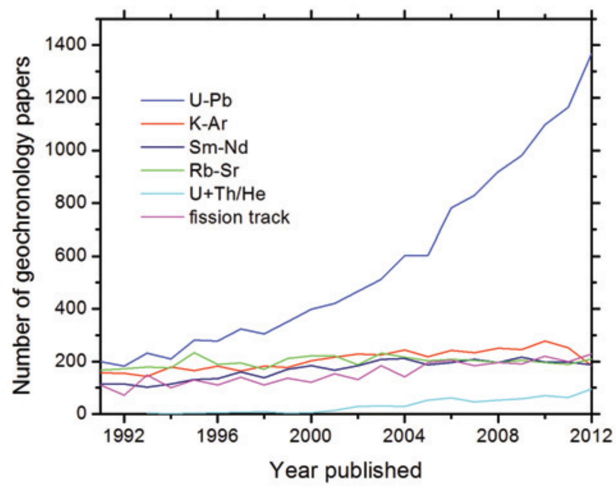


Figure 4
Plot of the number of geochronology papers published from 1991 to 2012 as identified in the ISI Web of Science database by Topic (i.e., method name appearing in the title, abstract or keywords).

An interesting trend is revealed from an analysis of the methods that were used in each of the publications that include geochronologic information. As shown on Figure 3, U-Pb increased dramatically between 2001 and 2012, whereas most other chronometers decreased in relative proportion. As shown in Figure 4, this growth of U-Pb relative to other chronometers dates back to at least the early 1990's.

Why the dramatic increase of U-Pb geochronology relative to other methods? Throughout the 1970s, U-Pb zircon dating became seen as the premier geochronometer for studying crustal history due to its refractory nature and enrichment in U and Th relative to daughter product Pb (Hanchar and Hoskin, 2003). Early-on, the sole method for determining U-Pb zircon ages was by bulk analysis of multi-grain aggregates using isotope-dilution, thermal ionization mass spectrometry (ID-TIMS). With the advent in the 1980's of multicollector mass spectrometers, well-calibrated spikes using ^{233}U and $^{202,205}Pb$, Teflon for low-blank dissolution, and chemical abrasion to remove disturbed portions of grains, ID-TIMS is now able to determine ages with a precision of ~0.05%, although the accuracy of ages is limited to ~0.1% by uncertainties in the U decay constants (Schoene, 2014). Virtually all other chronometers, and the Geologic Time Scale, are calibrated relative to ID-TIMS ages of zircon, and are accordingly limited to ≥0.1% accuracy because of aforementioned

A modern clean laboratory of the kind used to extract trace U and Pb isotopes from rocks and minerals (courtesy of Dr. Blair Schoene).

uncertainties in U decay constants and interpretive complications due to the capacity of zircon to reside in magmas for up to half a million years prior to eruption (Reid et al., 1997).

During the 1980's, secondary ion mass spectrometers (SIMS; aka ion microprobe) became available, enabling U-Pb ages to be determined with micron-scale horizontal resolution and nano-scale vertical resolution, albeit with precisions limited by counting statistics and determination of inter-element sensitivities. This enabled analysis of very small portions of crystals and provided a means of testing the prevailing interpretive model that assumed closed system behavior of the analyzed aggregate (Froude et al., 1984) and for determining the growth history of complex crystals (Ireland and Williams, 2003).

During the 2000's, laser ablation-inductively coupled plasma mass spectrometry (LA-ICPMS) arose, with the ability to generate U-Pb dates very efficiently. With a throughput of several dates per minute, LA-ICPMS techniques are ideal for studies of detrital minerals, where large amounts of data may be required (e.g., Pullen et al., 2014).

The increase in the number of studies relying on U-Pb geochronology (Figs. 3 and 4) can accordingly be attributed to development of instruments and analytical methods that are optimized for accuracy (e.g., ID-TIMS for Phanerozoic time scale calibration), spatial resolution (e.g., SIMS for unraveling complex magmatic/metamorphic histories), and cost effectiveness (e.g., LA-ICPMS for detrital mineral studies).

By means of comparison, the ^{40}Ar/^{39}Ar dating community experienced a rather different history. Between 1980 and 1990, a significant number of U.S.-based facilities were introduced at institutions without a tradition of expertise in geochronology. This explosion of interest corresponded to the rise of the sub-discipline of thermochronology of which the ^{40}Ar/^{39}Ar approach was one of the leading methods. Twenty-five years later, relatively few new facilities have since been established, several have folded, and most new mass spectrometers are being commissioned by those very same, now quite senior, scientists who drove that early growth. After a prolonged period beginning in the mid-1980s in which instruments and methods remained static, the recent introduction of high-sensitivity multi-collector rare gas mass spectrometers

has dramatically improved attainable temporal precision and efficiency (Singer et al., 2014). However, in the absence of a new generation of practitioners, this renaissance could prove short lived.

During this time, other chronometers, including (U-Th)/He, cosmogenic radionuclides, and U-series dating came into their own and publications reporting such data are on the upswing (e.g., (U-Th)/He, Fig. 3). The rapid growth of these chronometers is largely due to their capacity to better understand processes operating at lower temperatures and on shorter time scales than the traditional methods. U-series expanded in the 1990s following mass spectrometric developments (Edwards et al., 1987) and is now further accelerating due to continuing analytical improvements (Cheng et al., 2013) and expanding applications. Notable among the applications are a new generation of climate records from cave depositis and efforts to better calibrate the ^{14}C timescale. Given the growing emphasis on studies of the Earth's critical zone, the role of these chronometers will certainly increase in the future.

Noble gas mass spectrometry laboratory at the New Mexico Bureau of Mines (courtesy of Dr. Matt Heizler).

Realizing ±0.01% age precision and accuracy across Earth history

The consensus among isotope geochemists throughout the 1990s was that not one of them had yet demonstrated isotope ratio precision (e.g., of Nd) better than ±50 ppm, but precisions of some isotopic systems as low as ±1 ppm are now being reported (e.g., Steele et al., 2011; Craddock et al., 2014; McLeod et al., 2014; Kohl et al., 2015). This order-of-magnitude or greater improvement dramatically altered our perception of early Earth (through short timescale radioactivities such as ^{142}Nd and ^{182}Hf) and introduced new stable isotope proxies that weren't viable at lower precision (for example, clumped isotopes in the carbonate system would be entirely useless without better than ±50 ppm precision; Petrizzo et al., 2014). However, this enhanced capability has not translated into equivalent gains in geochronologic age precision. Why? The answer reflects the nature of radioactive decay that is generally to transmute the parent isotope into a different chemical species (e.g., ^{87}Rb→^{87}Sr), thus putting as much emphasis on determining the precision of inter-element ratios (e.g., ^{87}Rb/^{86}Sr) as isotopic (e.g., ^{87}Sr/^{86}Sr). The absolute age uncertainty versus time relationship over the last 500 million years shows that even the best currently attainable precision and accuracy grow into an uncertainty greater than half a million years during the Phanerozoic – a span of time equal to nearly one quarter of the Pleistocene epoch. If we are to understand the nature of species variation and climate change across the Paleozoic at anything comparable to our knowledge of the Cenozoic, then we require an order of magnitude improvement in geochronologic precision and accuracy. The good news is that there is no physical impediment to realizing this. There are enough atoms of radiogenic Pb in the outer few microns of a Paleozoic zircon grown moments before eruption to permit ±0.01% precision and accuracy in the U-Pb system. All we need is the will and resources to synthesize and calibrate the spikes, enhance ionization efficiencies (see below), exploit existing microscale sampling methods, and improve our knowledge of the relevant decay constants correspondingly (see Decay Constant sidebar).

Timescale calibration at the next level

The most important unresolved problems include: When did life arise on Earth? When did plate tectonics initiate? How did the biosphere and lithosphere coevolve? Although we can debate which of these or others constitutes our greatest scientific challenge, what the resolution of all these problems share in common is a need for the new kinds of geochronologic capability described above. To understand how the planet became habitable, the rates at which life evolved, and the causality and interconnection between Earth subsystems and climate variability, we will need to better utilize the sedimentary record as well as better understand the processes by which our mineral geochronometers form and how their radiometric clocks tick. We are already seeing on the horizon a level of integration of geochronology with bio- and chemostratigraphy that could lead to absolute calibration of paleoclimate proxy records and sea-level changes at better than the ±1% level for portions of the Cenozoic. This would enhance our ability to establish causality in earth changes, such as large igneous province events, climate change and mass extinctions. To do this we will need improved knowledge of decay constants, zircon crystallization behavior and uranium isotopic fractionation in Nature. With this knowledge, we can test our supposition that an astrochronologically calibrated time scale can provide a near-term path to linking absolute time and biologic change throughout the Cenozoic at an unprecedented level.

Getting more from less

Despite all the remarkable advances in geochronology over the past 40 years resulting from innovations such as multicollection, synthetic multiple isotope spikes, or in situ analysis (e.g., SIMS and LA-ICPMS), our ability to translate a daughter atom in a sample into a detected ion has remained at the percent level or so. This means that a roughly two-order-of-magnitude increase in signal strength can be achieved before we approach the physical limit set by counting statistics. While there are a variety of ways to enhance yields, such as the use of cavity ion sources (Burger et al., 2009), possibly the most promising tool is broad spectrum lasers of sufficient power to ionize all neutral species. Radical new design approaches to mass analysis of such increased signals are emerging, including trapped ion cyclotron resonance (Savory et al., 2011), time-of-flight (TOF) mass spectrometry (Stephan et al., 2014), and multi-turn TOF sputtered neutral mass spectrometers capable of turning bench top instruments into spectrometers with mass resolutions in excess of 100,000 and effective flight paths of several kilometers (Ebata et al., 2013). Innovations such as these hold great promise in geochronology but have been largely developed in the cosmochemical sector that has been traditionally more supportive of fundamental developments in mass analysis than their more earthly-focused colleagues. At first glance, this appears to make sense in that cosmochemists are classically atom-limited (e.g., small mass sample return missions, interplanetary dust particles (IDPs), stardust, etc.). However, this may be more a matter of perception than truth as there are no more radiogenic atoms in the outer few microns of a zircon than there are in an IDP – and our ambition is to determine ages to ±0.01% precision and accuracy. To truly reach the fundamental limits of geochronological signals, we will need to look past the seeming macroscopic nature of our samples to the truly microscopic domains that hold the temporal information we need and pursue transcendental approaches to detecting every daughter atom present in a sample.

Who are geochronologists?

As the field expanded into disciplines requiring novel methods embodying very different challenges, geochronologists became increasingly diverse. While most of us continue to use mass spectrometers, others have never touched one. Some are frustrated by the low accuracy with which decay constants are known while others would not be significantly impacted by tenfold improvements to their measurement. Costs to establish geochronological facilities – from fission track dating to large accelerator mass spectrometers – range over a factor of a hundred. While there is no simple profile of the 'average geochronologist', we do appear to share several traits and realities in common. The most salient feature is that virtually every geochronologist operates within a disciplinary home. This in part echoes intellectual heritage, but more and more it reflects a calculated decision regarding reliable funding support. This need is driven by the fact that there is simply no federal science program whose core mission is to sustain geochronology infrastructure/innovation. The reasons for this are partly historical and partly due to the necessity of the field to expand into new disciplines needing to constrain timing and rates.

As a generality, the core discipline of geochronology grew out of geochemical studies of the crust and mantle and for decades was supported by EAR programs (such as Petrology & Geochemistry, Tectonics). As redirected science priorities began to drive funding towards surficial and critical zone problems, many geochronologists were quick to adapt and find ways to provide absolute ages using challenging materials and at considerably shorter timescales than those traditionally utilized. While these disciplines greatly appreciated the power that these methods brought to their interests, they lacked the tradition of supporting the underlying development of geochronological protocols and our community was probably insufficiently aggressive about making the case to support and maintain the essential infrastructure. Simultaneously, and understandably, the Petrology & Geochemistry program began to reduce support for the development of analytical tools that focused on lower temperature processes. Regardless of the cause, there is a strong sense in the community that the level of funding available from NSF to support geochronology has declined. So ironically, as the demand for geochronology increases, the apparent availability of funds to support that work is decreasing.

By way of example, consider a seismologist interested in utilizing geophysical methodologies – honed through crustal and mantle studies – to understand glacial transport. The relevant program synopsis[1] focuses on the medium (i.e., solid Earth), signals (e.g., seismic wave propagation), and goals (e.g., Earth's thermal structure) appropriate to the program without ruling out nontraditional applications, such as our example. However, the equivalent synopsis for Petrology and Geochemistry specifically limits its solicitation to "high temperature" igneous and metamorphic processes. What happens between the processes of rock formation at depth and their disintegration as they approach the surface has in some respects been orphaned in the current EAR system. If only to drive this point home, it is sobering to note that of the 48 synopses of active funding opportunities listed in the EAR portfolio[2], tectonics is called out seven times, sustainability and critical zone ten times each, and climate thirty-two times, but geochronology is mentioned only once (in Track 2 of Sedimentary Geology and Paleobiology). We appear to be akin to the air we breathe; absolutely essential, but largely taken for granted[3].

---

1 http://www.nsf.gov/pubs/2012/nsf12598/nsf12598.htm
2 http://www.nsf.gov/funding/pgm_list.jsp?org=EAR
3 We note that in NSF's September 2013 report to Congress, the GEO Directorate emphasized "Unraveling the Earth's history…Earth's 4-D geodynamic, plate tectonic, landscape, climatic, biotic, and hominid evolution". Despite its central role in all of these, geochronology was not mentioned under "Tools of the trade"

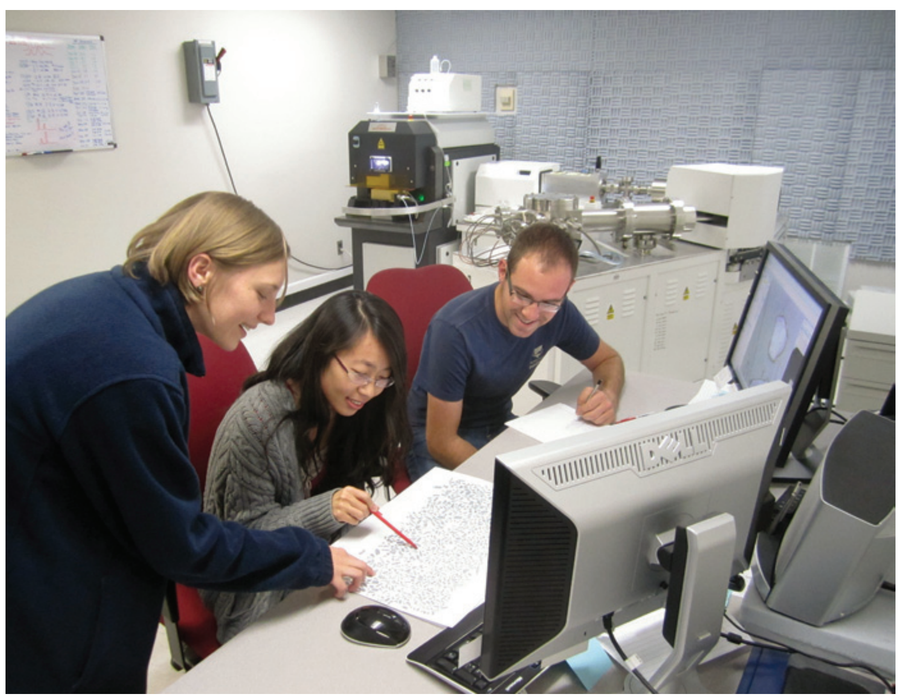
earthtime

Geochronology is the science of putting absolute time to geologic phenomena whose context is either unknown or known only in relative time. That said, all absolute dates are relative to an artifact or physical constant, whether it be a natural mineral standard, a tracer solution, or a decay constant. In order to correlate timing or rates using dates generated in different labs or using different techniques they must be directly comparable with no systematic biases. Achieving this requires transparency in sample collection and preparation techniques, data acquisition and reduction, and reporting of dates to the community – a goal that has not always been met. If lab X produces an $^{40}Ar/^{39}Ar$ date for the Permian-Triassic boundary of 252.3±0.3 Ma, is this different or the same as a date from lab Y that reports a U-Pb date of 252.6±0.1 Ma? Or are two U-Pb dates that differ slightly beyond reported uncertainties actually different? The answers to questions such as these are requisite if we're to truly understand the causes and consequences of biotic change, rates and mechanisms of plate tectonics and deformation, or climate change.

With this goal in mind, the EARTHTIME initiative was launched early this millennium with the goal of building a geologic timescale that is comparable across labs and dating methods at the 0.1% level. $^{40}Ar/^{39}Ar$ and U-Pb geochronologists teamed with stratigraphers and paleontologists and quickly realized that each discipline was far from where they needed to be in terms of interlaboratory agreement on standard and sample ages, best practice protocols, and data reporting and archiving, and that the only way to change this was to work together with a common goal. Ten years on, what began as an NSF-funded grant to a small number of PIs has become a paradigm shift in the way we do geochronology internationally. EARTHTIME has inspired similar funded efforts in Europe and China. Interlaboratory bias in ID-TIMS U-Pb geochronology has largely been reduced from 0.5-1% to the ±0.1% level through shared knowledge and standard solutions, a better understanding of the minerals we're dating, and common data reduction platforms. Ongoing efforts at intercalibrating the U-Pb and $^{40}Ar/^{39}Ar$ systems through multi-sample comparisons and constraints from astrochronology suggest the need for refinements to decay constants. These activities are leading towards not only more precise ages for geologic time boundaries, but also a greater ability to correlate changes in the biologic and environmental records in both terrestrial and marine sections, explore potential diachroneity in first and last appearances of index fossils, and compare the timing of impacts and volcanism with biologic turnovers. As a result, the demand for high-precision dates from the geologic community has increased as the necessity of high accuracy time constraints is further realized. As the EARTHTIME collaboration enters its second decade, our access to absolute time across geochronometers will continue to grow.

To be clear, the fault for this state of play rests largely with the geochronology community – we have failed to promulgate a compelling narrative that enlists support across the geosciences. The reason for this may be the very nature of our product which does not lend itself to community organization in the same way that geophysicists have been able to rally around programs such as IRIS, UNAVCO, or EarthScope, that utilize standardized instrumentation to acquire ultimately open source data that most practitioners could equally well parse. In contrast, geochronological dates are individually 'handmade' by integrating isotopic and/or geochemical data with knowledge of instrument performance (see point 2 in National Center sidebar), field relations, degree of preservation, overall geological context, and often conflicting interpretive models. This point is driven home by the contrasting challenges of finding an international standard for reporting seismological vs. geochronological data. However, efforts such as EARTHTIME and EarthCube have shown that when matters of broad relevance and mutual benefit arise, the geochronology community can be highly cooperative and funding agencies, both here and abroad (i.e, Europe, China), responsive.

For the geochronology community to truly prosper, we need to not only continue and expand these community-based efforts but make the case across the geosciences that stewardship of geochronology is the responsibility of all disciplines that utilize its products, including the need to support innovative, potentially high-risk R&D. We were unable to procure the data needed to assess the overall flow of EAR funding to geochronology but can report a broad perception among geochronologists that EAR support for developmental work has declined. Whether true or not, if the majority of geochronologists are not submitting potentially transformative developmental proposals to EAR due to a sense of indifference on the part of the system, then the status quo is masking an unvirtuous cycle. Thus it is timely to break down real or perceived barriers to supporting geochronology in the form of a GEO Directorate initiative that spreads responsibility for the well-being of our field across the disciplines that draw primary benefit from quantitative dating methods.



1 STEWARDSHIP OF GEOCHRONOLOGY

We recommend that an interconnecting, GEO-wide network of funding opportunities be implemented that solicit geochronological solutions to outstanding disciplinary and interdisciplinary questions across EAR, P2C2, AGS, OCE and PLR. Expansion of stewardship of geochronology across all geosciences disciplines that utilize its products should include responsibility for support of potentially high-risk instrumentation and technique development as well as enhanced capacity that meets the needs of users of geochronology.

Support of single-PI labs vs. centralized facilities

The NROES report discussed the creation of one or more national geochronology centers at a level implicitly beyond the capacity of existing EAR programs, but did not address the set of national geochronology facilities currently supported by EARs Instrumentation and Facilities program[4]. Our workshops provided a rare opportunity for direct feedback from the producer community to NSF and their IF-supported facilities. During these discussions, representatives of several of the NSF/IF geochronology facilities addressed the strengths and weaknesses of the current system and explored possible consequences of creating a national center for geochronology on a larger scale. The subsequent discussion focused on the potential shortcomings of such a facility (see National Center sidebar) and addressed how single-PI laboratories, combined with existing multi-user facilities functioning with a coordinated network, could serve community needs. On balance, while the current 'free market' approach has not produced the optimal capacity for producing data that users demand, geochronologists agree that initiatives that are too strongly consumer driven could restrict the kind and style of needed capabilities and potentially limit innovation relative to providing access to conventional methodologies. This is especially true if centralized facilities are to be housed in research universities, where tenure and promotion processes reward innovation over community service. Although a centralized national facility for most geochronology methods may help to meet end-user demands, it runs counter to the current single-PI model, including the small number of multi-user geochronology facilities already supported and operating at capacity. We heard opinions that the UK's NERC Isotope Geosciences Laboratory (NIGL) functions well both in serving the community and developing new analytical protocols. While appropriate for a small nation, we sense that the U.S. geochronology community views a centralized facility such as NIGL as impractical for this country where it might result in unequal geographic opportunities for training the next generation of scientists. Whether it would trigger or stifle innovation would largely depend on the center's reward structure but, absent a clear mandate to develop the next generation of methods and instrumentation, the tempting metrics of productivity alone would likely drive institutional culture.

Ironically, the views just expressed contrast sharply with the early history of U.S. geochronology which was strongly influenced by national centers. During the 1960s and 70s, isotope geology assets of the U.S. Geological Survey served as both a national center of excellence and regionally distributed (Reston, Denver, Menlo Park) facilities. At its peak, USGS geochronologists were among the most distinguished on the planet[5], responsible for many of the breakthrough discoveries of that era (Cox et al., 1964; Tatsumoto, 1970; Zartman and Doe, 1981), and an obvious cohort to host the 1978 International Conference on Geochronology, Cosmochronology and Isotope Geology (Zartman, 1978). Following a dramatic reduction in force in the mid-1990s, that curiosity driven research atmosphere was replaced by a mission support ethic and innovation - at least of the kind associated with the citations in the previous sentence - was greatly attenuated. It's difficult to know what role the USGS disengagement from basic geochronologic research played in defining the current status of the field but we're unaware of any explicit response by NSF-EAR at the time. In any case, university-based scientists picked up the mantle and have become the principal drivers of change in U.S. geochronology.

Given that large-scale facilities in support of geochronology (e.g., large-radius SIMS, AMS) are now dominantly based at academic institutions, it is fair to say that they are beyond the level that any individual university can afford to support. Inevitably, they require a different relationship to federal support than typical for most single-PI laboratories. The current EAR-IF model is that, in exchange for a facility subsidy covering approximately half of directs costs, the supported facility provides broad user access, community outreach, and leadership in applications development as judged through 3-4 year proposal renewal applications. It stands to reason that smaller-scale facilities that derive technical support from EAR funds should also bear external user access obligations proportional to the NSF contribution to overall operational cost. However, regardless of facility scale, we recommend that a balance between external user utilization and PI innovation be struck that grows the community of users while encouraging methodological advances.

4 http://www.nsf.gov/geo/ear/if/facil.jsp

5 Geochronology's only two National Medal of Science winners spent their formative careers outside the university environment at the U.S. Geological Survey (G. Brent Dalrymple) and Carnegie Institution of Washington (George Wetherill).

enhancing productivity

We recognized four potentially limiting elements to productivity:

1) instrument access,

2) sample preparation,

3) the education of users, and

4) community access to data.

Most geochronology producers agree that their productivity is principally limited by a lack technical support personnel rather than instrumental capacity. In the current financial climate, such support is increasingly difficult to secure from home institutions or funding agencies due to reduced investments by state governments in their universities and the prohibition on requiring matching funds for NSF technical support. Out of necessity, a common response is to undertake contract geochronologic analyses for industry. In many such cases there is little gain to research as most analyses thusly conducted remain unpublished and there is rarely any educational benefit to either party because of IP restrictions. This creates a nonvirtuous cycle in which producer's job satisfaction erodes as their geochronology consumer colleagues frustration mounts as their data takes longer to be generated.

For many geochronologic methods, the rate-controlling step is in preparing samples for analysis. For some techniques this centers on extracting mineral separates from rock samples, whereas for others this involves dissolution and chemical extraction. In both cases, the procedures could well be undertaken at researcher's home institutions rather than at the geochronology facility. In many cases this could be accomplished with a minimal investment and training.

Most geochronology labs lack the expertise to take full advantage of new information technologies that would enable more efficient operation (e.g., automation), better training (e.g., data visualizations), and broader dissemination of information (e.g., data archiving). Updating existing or outdated software that have served the community for years (e.g., Isoplot, which is run on platform no longer maintained by Microsoft) should be done as part of lab intercalibration experiments and with the goal of transparency in data reduction and interpretation. Given that many Earth science disciplines require large data sets, and that geochronologic information is one of the underpinnings of EarthCube, our community has an urgent need to continue developing enhanced expertise with cyberinfrastructure. Current initiatives such as the Geochron database (www.geochron.org), sponsored by EarthChem, are examples of movement in this direction. Expanding these efforts and integrating them into EarthCube will be critical for users of geochronologic data who wish to capitalize on the broadening applications and resolving power of geochronology in the Earth sciences.

We found general agreement that the principal limitation on the availability of many geochronology techniques is inadequate support for human resources to realize the full capacity of existing facilities to meet end user demand. A closely related perception is that the potential of some prior NSF funding is not yet fully realized due to inadequate support for sample preparation and instrumentation maintenance.

We strongly believe that the best way to ensure a diverse supply of competent practitioners is to maintain a 'sufficient' base of single-PI-operated labs and multi-user facilities. For example, the expansion of large-radius SIMS labs has been limited as much by the relatively few specialists being turned out by the handful of facilities globally as by the steep entry costs. The present 'sellers market' in $^{40}Ar/^{39}Ar$ dating appears to reflect changes in research emphasis in only a few labs globally (i.e., the field is still below threshold that ensures a steady supply of well-trained scientists with a spectrum of experience and interests). Further concentration of these activities in a central facility is likely to be detrimental to a balanced, intellectually diverse, and innovative community.

Thus an immediate need is to network single-PI labs and multi-user facilities to create a connected community with complementary expertise spanning the methods in demand across the geosciences (Fig. 1) for traditional and novel geochronologic data. One way forward is to increase support to single-PI laboratories across many geochronologic methods, perhaps tripling the number of IF-sponsored facilities. In this model, PI-led laboratories become "nodes" on the facility network in which no two pursue identical research programs. End-users would be encouraged to pursue their projects in the lab node where expertise and methods most closely match their aims. Ongoing collaborations, or geographic proximity, may also lead to end-user projects being pursued in particular parts of the network. Economies of scale are expected to arise. An oversight group, perhaps similar to the IRIS consortium (for seismology) or COMPRES (for material properties), could be established to coordinate the activities of this network.

Another possible model is exemplified by NASA's Astrobiology and Solar System Exploration Research networks that support nodes that are themselves multi-institutional consortia. These nodes are chosen to have differing but complementary scientific research themes, but have overlap with regard to methods. So, for example, two different nodes may have strong and active programs in the chronology of planetary impacts on the assumption that multiple labs working on truly outstanding problems are more likely than a single lab (with a single perspective) to achieve success.
By building such networks up from several single-PI and multi-user laboratories, the NSF can capitalize on many successful investments already made to increase the capacity to serve end-user demand with relatively modest outlays. The impact of such a network will be greatest if it allows integration of datasets from multiple chronometers, as well as provides opportunities for innovations with various methods and instruments that are employed to address the spectrum of problems that can be tackled by each chronometer. The proposed oversight board could serve to help end-users find and communicate with the laboratory "nodes" best equipped to address particular projects. An elected board could represent the interests of U.S.-based geochronologists in establishing funding priorities in a more representative fashion than does, for example, our volunteer committee.

The operation of a coordinated network of facilities would also be strengthened through a well-organized set of educational activities. These activities would be best designed to promote the training of students and post-docs who come from any geoscience discipline or background (e.g., paleontology, stratigraphy, tectonics, etc.) in the theory, analysis, applications, and importantly the limitations, of geochronologic methodology. Workshops held annually by the PIs in the facilities themselves that include a component of 'hands-on' training and work with isotopic data sets, coupled with rotation of these workshops among the various facilities within the distributed network, would promote coordination as well as a common sense of purpose among the laboratory/PI nodes.

a national center for geochronology?

Our consultation suggests that establishing a national center for geochronology is problematic due to the operational realities of geochronology and the issues that they raise for such a model:

1. Geochronologists agree that every date generated requires some level of interpretation. Geochronologic systems are complex, with unconstrained variables that can compromise both the determination and significance of a date. For example, a U-Pb zircon date from a granite may record the crystallization age of a single magma, the age of a slightly older (co-mingled) magma, the age of igneous country rock from which the magma was generated, the age of detrital components in metasedimentary country rock (formed far from the site of emplacement), the time of pluton metamorphism, or the date may have no geologic significance if it experienced radiogenic Pb loss. Fortunately, methods can be modified or complemented by other analyses that can help resolve these complexities. It is accordingly essential for the producer and the user of the date to work together to ensure that appropriate methods are used and that the age information is appropriately interpreted. This is unlike other geochemical techniques, for example whole-rock geochemistry, where interaction between the analyst and the user of the information is less important.

2. Most mass spectrometers currently used to generate geochronologic data are essentially unique, with hardware and software that are tuned for a particular type of measurement and analytical protocol. This is because (a) each isotope system requires a different instrument design, (b) each type of instrument is available from multiple manufacturers who use proprietary technologies, and (c) manufacturers traditionally work with researchers to optimize each instrument for a specific protocol. The geochronological community should be, and is (see EARTHTIME sidebar), moving towards standardizing these protocols but there are today, in effect, over a hundred different mass specs in the US used for geochronology.

3. As with the instruments we use, each geochronologist is essentially unique in terms of interests and expertise. For example, K-Ar geochronologists tend to focus on young igneous systems, the thermal history of older orogenic belts, detrital minerals, or planetary processes. It is beneficial for researchers who are interested in acquiring information in one of these areas to establish collaborations with a geochronologist who has similar interests and expertise.

4. Most of the important innovations in geochronology have come from the need to solve a particular geologic problem. In most cases, they are identified in collaboration with non-geochronologist researchers, and it is this fertile collaboration between them and geochronologists (see Fig. 1) that has led to many of the transformative breakthroughs in Earth science.

5. Geochronologic information is most powerful when combined with data from other disciplines. As shown in Figure 1, this complementary information comes from many different disciplines, which requires collaborations with researchers across the spectrum of Earth sciences.

The national facility model for geochronology is problematic because the best science is done when a researcher teams with a geochronologist who shares similar interests and has instruments and methods that are optimized for the critical measurements. It is difficult to imagine how a centralized facility would be able to provide this breadth of expertise, instrumentation, and methods for even a single technique, let alone for all different geochronologic methods.

RECOMMENDATION

2

SUPPORT OF SINGLE-PI LABS VS. CENTRALIZED FACILITIES

We recommend that the US geochronology community establish a coordinated network of complementary laboratories that span the most widely employed chronometers. This network would act as a springboard for innovation, educate users of geochronologic data, and provide the geochronologic information needed by the broader NSF-supported user community. Included in the network would be larger laboratories, for example the existing NSF-IF supported multi-user facilities, as well as single-PI labs that are committed to provide geochronologic data for other researchers. Contingent on additional resources, the network would be coordinated by a committee of geochronologists and disciplinary experts who (1) monitor activities of member labs for quality control and productivity, (2) direct researchers to appropriate labs to establish collaborations, (3) facilitate studies that utilize several different chronometers, (4) assist with development of new and emerging labs, (5) coordinate intercalibration experiments, and (6) drive community outreach efforts and other initiatives. The governing board of COMPRES may be an example of how this "Geochronology Network Oversight Board" would function. We further recommended that NSF explore ways to provide block technician funds to single-PI laboratories by tying support to hosting external users, as documented in the Broader Impacts section of proposals. NSF should increase priority consideration for acquisition of geochronologic sample preparation equipment in those cases where an on-going link between preparation facility and geochronologic analysis can be made. We recommend that NSF provide support for developing enhanced expertise in cyberinfrastructure for geochronologists.

Support of geochronologic innovation

While highlighting the need to expand capacity for the established geochronologic methods, the NROES report also emphasized the importance of maintaining support for innovative, exploratory work that may be best conducted in single PI laboratories. This raises the key question of how geochronologic innovation has arisen and what support structures are needed to ensure its continuation. However, the past may be a poor model for the future and, possibly, the present as well.

New geochronologic methods have arisen spontaneously and at other times were motivated by specific applications. In cases where novel hardware is required for advancement, our ~60 year history shows that there has been no single path to commissioning new generation instrumentation. The post-war development of modern geochronology was essentially a by-product of a nuclear physics culture focused on deterring nation-state aggression. Development of the first digitally-controlled, thermal ionization mass spectrometer resulted from a national effort in planetary R&D, ultimately also fed by the cold war. The development of the high-resolution, high-sensitivity ion microprobe was carried out by a block-grant supported research institution in a nation 1/15th our size with the first such instrument in this country funded through a private gift. The race to perfect multi-collection TIMS from the mid-80s to mid-90s was largely driven by intense competition among multiple manufacturers. Inductively-coupled plasma mass spectrometry arose from an adaptation of instrumentation developed in a different discipline. Although the very diversity of these origins might at first glance seem a strength, the landscape that produced these revolutions is starkly different today. The cold war and space race are long gone. Block-grant funded research organizations are virtually extinct. Previously available sources of private philanthropy now appear less responsive to geochronology. The geochemical mass spectrometer industry has been consolidated into relatively few competitors. All these changes, coupled with a widespread decline in local capability to build scientific instrumentation, have significantly limited the potential for hardware innovation.

Given these changes, we suspect that looking to the past offers little in the way of guidance for the path forward. The one benefit it may offer is an opportunity to judge how well U.S. geochronologists have used opportunities to demonstrate leadership over the past 30 years or so. In that period, certain nations have dominated the development of specific dating schemes; fission track dating and SIMS U-Pb in Australia and OSL in Denmark readily come to mind. U.S.-based scientists have demonstrated considerable leadership in refining the $^{40}Ar/^{39}Ar$, U+Th/He, and ID-TIMS U-Pb dating methods, albeit using mass spectrometers of mostly German or British origin. The growth of mass spectrometer-based U-series dating was essentially an American innovation (e.g., Edwards et al., 1987; Bard et al., 1990) but perhaps our greatest achievement has been the conception and implementation of a range of terrestrial cosmogenic radionuclide (CRN) chronometers and tracers, including ^{10}Be (Brown et al., 1981), ^{36}Cl (Nishiizumi et al., 1984), ^{26}Al (Lal and Arnold, 1985), and ^{3}He (Kurz, 1986). On balance, U.S. geochronologists have held their own on the global stage but in our view not markedly outperformed their international colleagues relative to resource availability.

The reduced opportunities for support of innovation is nested within a broader national trend of level federal support of research and development following years of growth. This is perhaps most clearly seen in the biomedical research community which experienced a period of explosive growth through the millennium change, but is now barely coping under level funding (Alberts et al., 2014). This enlarged community would require near geometric funding growth just to retain the same standard of care that the community enjoyed 30 years ago when total federal outlays for non-defense R&D were half as much in constant dollars as today. Under level funding, the fabric of biomedical research culture is starting to fray – an unintended consequence of what was once seen as an enviable growth spurt. To a lesser but still significant degree, growth of the geosciences over this period has today put tremendous stress on the operation of relatively numerous single-PI labs; too few dollars for what could historically, but mistakenly, be seen as too many facilities. While sustaining these operations in their present form reduces the amount of support for costly, high risk, but potentially game-changing innovation, reducing their number in the face of rising consumer demand could produce a domino effect of decreased productivity across the geosciences. Furthermore, adapting the size of the community to sustainable growth risks a generation without the capacity for transformative change. Increased funding alone to support the now central role of geochronology across the Earth sciences is only part of the answer. Our community needs to expand internal cooperation in order to wring out the substantial capacity for producing dates that exists in latent form but cannot presently be accessed due to local financial constraints (e.g., lack of technical support; see Enhanced Productivity sidebar). Our view is that the networked facility initiative emphasized in the previous section (Recommendation 2) is an important component to creating efficiencies that could free up financial support for high-risk innovation. EAR's Instrumentation and Facilities program currently provides about $1.4M in annual support for multi-user geochronological facilities for which a national need has been identified. The four current facilities (Purdue Rare Isotope Measurement Laboratory, UCLA National Ion Microprobe Facility, and University of Arizona LaserChron Center, Woods Hole Northeast Ion Microprobe Facility) represent either quasi-unique instrumentation of a scale outside the realm of single-PI's (e.g., PRIME) or a focused commitment on the part of the facility to provide cost-effective user access to consumers of geochronology (e.g., LaserChron). Present funding precludes expansion of this program and accountability of each facility to the community is left largely to the multi-year grant renewal process and internally appointed advisory groups. This status quo is a barrier to the ambition of younger scientists whose ideas about future directions in geochronology cannot be presently be entertained due to funding limitations. To provide a greater degree of grassroots input into the process, this quartet and the proposed tripling of new facilities needed to realize the Grand Challenges (see sidebar) should be brought together under an umbrella organization (e.g., the "Geochronology Network") as a Major Multi-user Research Facility that more directly links them with the community at large and coordinates training of the next generation of geochronologists, who will not only need to understand instruments and applications but will require enhanced expertise with IT to improve software and for data management/mining, than those who have come before.

3 SUPPORT OF GEOCHRONOLOGIC INNOVATION

We recommend that the EAR Instrumentation and Facilities program provide enhanced support for development and long-term maintenance of a networked geochronological Major Multi-User Research Facility from which to drive the next generation of geochronology and satisfy user demand. Emphasis should be on improving methodological precision, accuracy, spatial resolution, efficiency, and productivity. In some cases, this may require IF to support multi-million dollar requests from large research universities without a contribution from Major Research Instrumentation given the severe limitations on the number of MRI proposals that can be submitted from one institution.

One of the highest priority goals of the geochronology community is to further increase the precision and accuracy of dating biostratigraphically controlled horizons.

Improved knowledge of decay constants

Accurate and precise knowledge of decay constants (λ) are cornerstones for calibrating a fully integrated geologic timescale and for building increasingly complex 4-D models for Earth systems that require utilization of multiple geochronometers. The existing convention for geochronologic decay constants (Steiger and Jäger, 1977) has remained unmodified for nearly four decades. Geochronologists have recognized the shortcomings of this convention and undertaken evaluations (e.g., Begemann et al., 2001; Schön et al., 2004), re-measurements (Rotenburg et al., 2013; Kossert et al., 2013), and recalibrations (Scherer et al., 2001; Mattinson, 2010) over the past 20 years. While these efforts have increased awareness among geochronologists and some users of geochronologic data about the difficulties of, and protocols for, comparing data from different decay schemes, it has also resulted in a literature in which multiple values are being used for a given λ or interlaboratory standard. The non-expert may have difficulty distilling this information, leading to confusion among those who simply need a date to, for example, establish a stratigraphic correlation.

A joint IUPAC and IUGS task group[6] was appointed to recommend a new set of working values for the most utilized decay constants in the geosciences. The task is a difficult one, however, given that many of these values are currently the subject of ongoing investigation and any recommended value could become obsolete shortly after recommendation. At our pre-Goldschmidt workshop, we heard a report from Paul Renne (Berkeley Geochronology Center) on task group activities and several members of our committee attended a workshop he co-organized the following day to discuss the status of decay constants in the geosciences. The IUPAC-IUGS task group made one formal recommendation regarding the definition of a year as a derived unit of time (Holden et al., 2011) but a community consensus did not emerge (e.g., Biever, 2011; Christie-Blick, 2012). It was clear from both Sacramento workshops that the community as a whole feels the best approach to determining more precise and accurate decay constants may differ between different decay schemes; some may benefit most from new first-principal measurements while others may be best refined through intercalibration experiments on geologic materials. In all cases, more data is better and community input is critical given the dynamic nature of the field.

Opinions expressed at our workshop revealed a libertarian streak among U.S. geochronologists in this regard. Said one: "The concept of a central authority for decay constants is strange…today it's important to use the best values and indicate which one you're using in a particular paper". Boehnke and Harrison (2014) proposed an alternate approach along the lines of that used by the nuclear physics community to update the properties of elementary particles. The Particle Data Group (2012) is a community collaboration that regularly examines published measurements, combines them through meta-analysis, and proposes a community consensus. The rise of similar (and potentially competing) international groups evaluating published decay constant measurements and emphasizing community input and experimental design would not only provide a mechanism for on-going assessment but, perhaps as important, create a culture that expects continuous improvement to these foundational parameters.

Our pre-workshop survey found that although all participants felt that updated values of λ were necessary, opinions were mixed regarding the relative priority of these measurements. This likely reflects the fact that certain decay schemes require improvements to λ in order capitalize on increased analytical precision (such that decay constant uncertainty limits the science) whereas for other types of geochronology, analytical uncertainties are larger than the precision at which λ is known. This interpretation is supported by the consensus at the decay constant workshop that the level of precision and accuracy of existing values is insufficient for high-precision (i.e., better than ±0.1% accuracy) geochronological studies aimed at geologic time scale calibration, assessing correlation versus causality between mass extinctions and their drivers, determining the rates of biologic and climate change, and development of a highly resolved geologic timescale into the Precambrian.

6 www.iupac.org/nc/home/projects/; project number 2006-016-1-200

better uranium decay constants

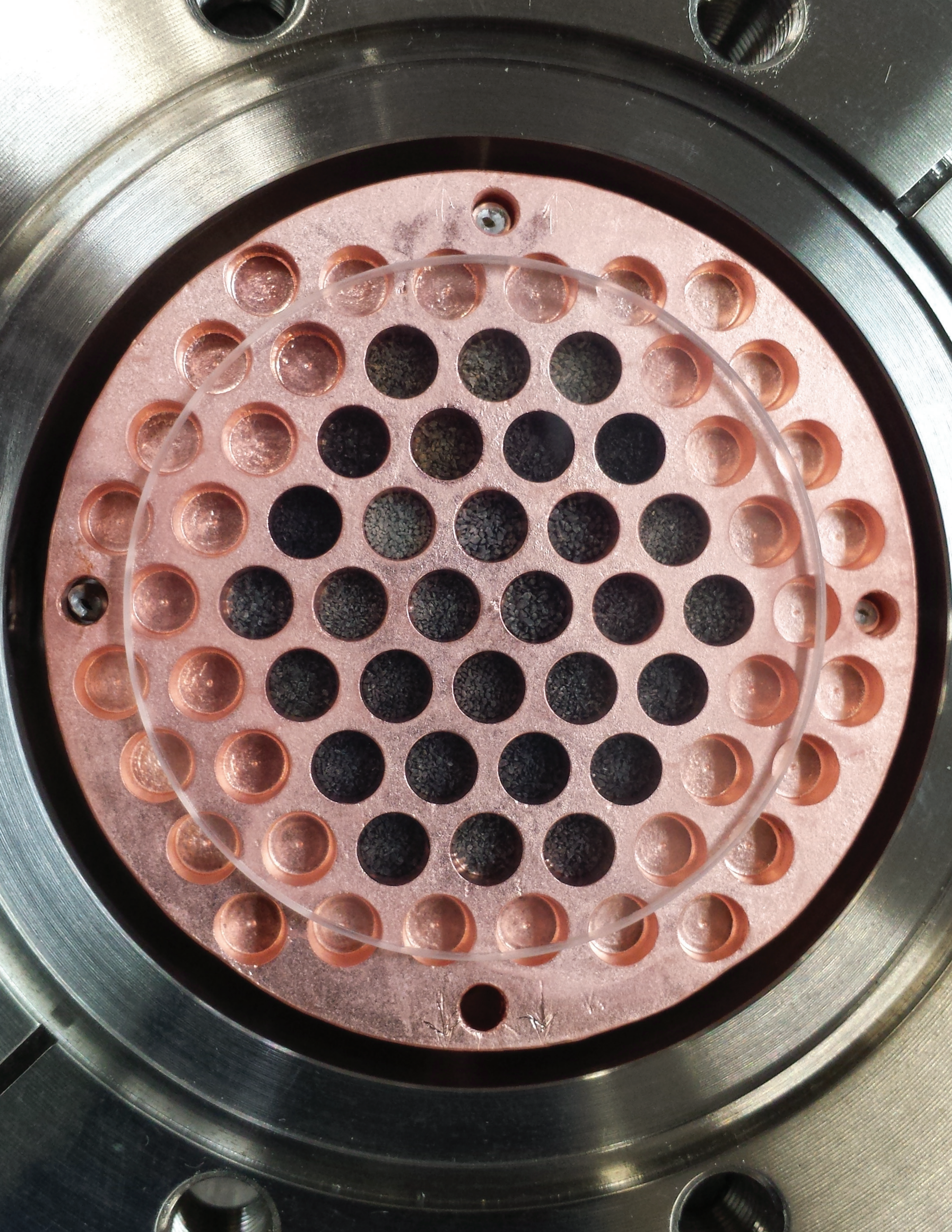
Improved knowledge of decay constants (λ) can be obtained either through direct measurements (e.g., α-counting or ingrowth experiments) or intercalibrations (e.g., Renne et al., 2010; Selby et al., 2007). The latter are carried out by comparing dates derived using one of the U isotope decay constants with another decay scheme, either on the same mineral or samples expected to have become closed systems simultaneously. The choice of λ_{238} or λ_{235} as benchmarks derives from the precision with which these values have been determined (±0.1%; Jaffey et al., 1971) and because their internal accuracy can be tested through mutual intercalibration (Mattinson, 2000; Schoene et al., 2006). Although the ratio of λ_{238} and λ_{235} can be determined with high precision, their accuracy is entirely dependent on the single, reliable published value (Schoene et al., 2006; Mattinson et al., 2010; Boehnke and Harrison, 2014). The most widely used values for the decay constants of ^{176}Lu, ^{187}Re, ^{232}Th, ^{40}K, and ^{238}U spontaneous fission are calibrated against the α–decay of $^{238,235}U$. In essence, the accuracy with which we understand geologic time, and thus Earth history, is dependent on the accuracy for which we know λ_{238} and λ_{235}. An argument can be made for immediate new measurements of $\lambda_{238,235}$ in that many are adopting a Cenozoic timescale based on the assumption of orbital forcing of cyclic stratigraphic sections and not radioisotopic dates (see Astrochronology sidebar). Some of these model timescales are tested with geochronology but many are not. Increasingly sophisticated solutions to orbital parameters (Laskar, 1999, 2011) can be evaluated, and potentially improved, by intercalibration with geochronology but only if accurate decay constants are known. Recent experiments carried out under the auspices of EARTHTIME resulted in a protocol by which U-Pb ID-TIMS dates are fully traceable to first principles calibrations (Condon et al., 2014; McLean et al., 2014), but again, the accuracy of even fully-traceable dates is limited by the value used for λ_{238}. During our workshop, Dr. Ian Hutcheon (Lawrence Livermore National Laboratory) spoke to the feasibility of re-measuring λ_{238} and λ_{235} using α-counting on their existing equipment. It was stressed that while the apparatus, isotopically pure U, and knowledge still exist at LLNL (and other national labs), they may not for long. Dr. Dan Condon (British Geological Survey) expressed interest in cost-sharing such measurements. We see determination of better values of $\lambda_{238,235}$ (and λ_{234} for U-series dating) as overdue and absolutely key to realizing our ambitious agenda (see Grand Challenges sidebar).

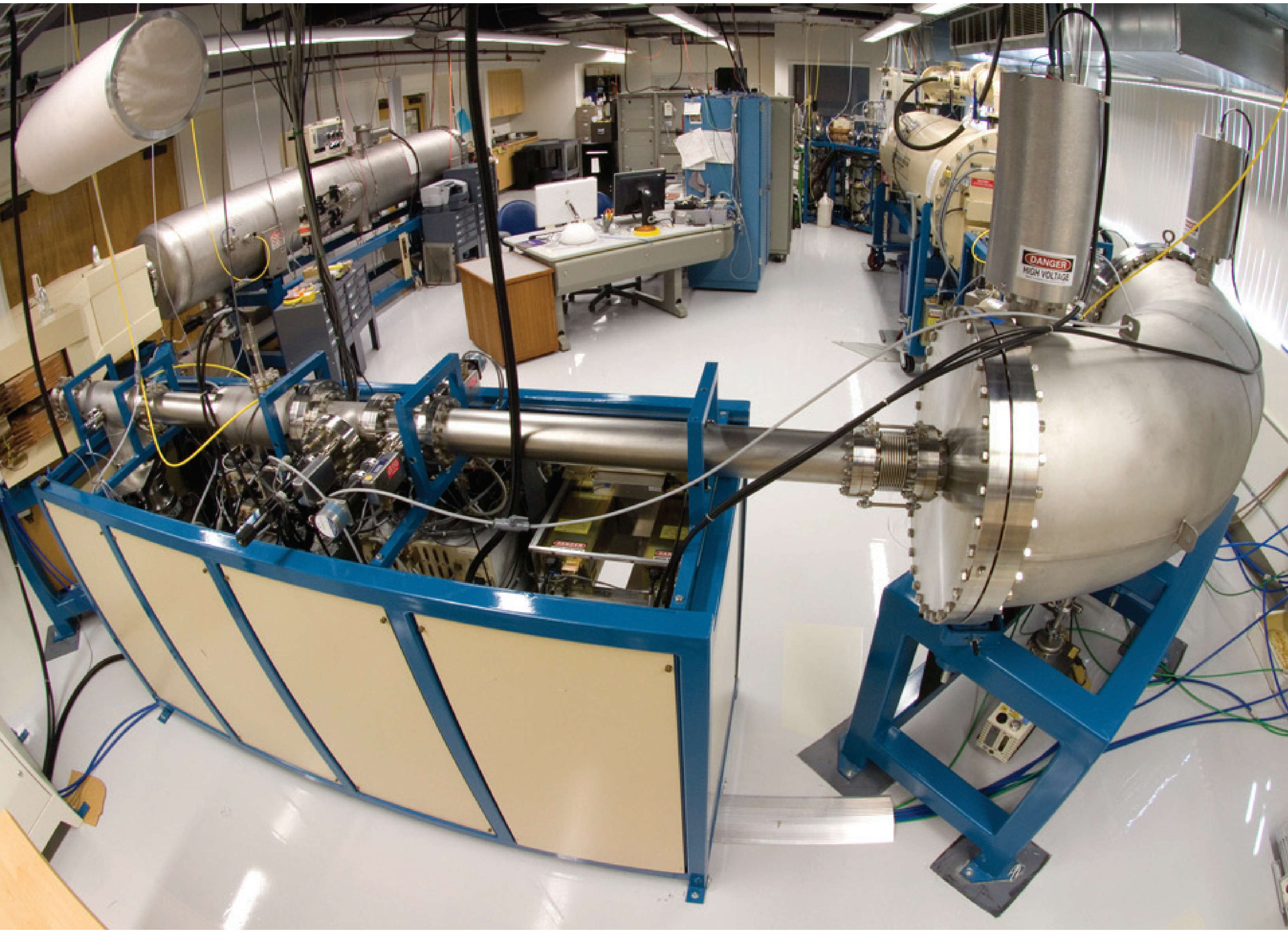
RECOMMENDATION

4 Improved knowledge of decay constants

Efforts to determine decay constants of improved accuracy and precision, including new counting and accumulation measurements, should be a continuing process and supported with high priority by all federal funding agencies (e.g., NSF, NASA, DOE) with a mandate for examining deep time. These efforts could be coordinated under the aegis of the Major Multi-user Research Facility, as proposed in Recommendation 3. Formation of a community-based geochronology data group (or groups) to evaluate the status of λ, related physical constants, and laboratory intercalibrations is warranted and timely.

A copper tray used to isolate mineral and rock samples during laser fusion for $^{40}Ar/^{39}Ar$ analysis (courtesy of Dr. Brad Singer).





The MegaSIMS instrument, featuring a 1.4 MeV accelerator coupled to an ion microprobe source, is being developed for in situ U-series dating (courtesy of Dr. Kevin McKeegan).

high-precision geochronology & astrochronology

SIDEBAR

The past decade has seen significant advances in the precision of U-Pb and $^{40}Ar/^{39}Ar$ geochronology which provide the backbone of the Phanerozoic time scale. Major achievements have included the reduction of inter-laboratory bias with new U-Pb tracer solutions, the development of chemical abrasion methods to address the problem of lead-loss (U-Pb), improvements in the calibration of $^{40}Ar/^{39}Ar$ monitor minerals, and instrumental advances that greatly reduce analytical uncertainties (Schmitz and Kuiper, 2013). In tandem, astrochronology has emerged as a potential tool for enhancing the accuracy and precision of high-resolution time scales, especially through ash-poor intervals that cannot be directly dated with radioisotopic methods (Hinnov, 2014).

Astrochronology utilizes the geologic record of climate oscillations – those ascribed to periodic changes in the Earth's orbit and rotation ('Milankovitch cycles') – to measure the passage of time from rhythmic layers in strata (Hinnov and Hilgen, 2012). During the past 25 years, advancements have stemmed from improvements to astronomic models, the acquisition of high-quality paleoclimate records and their integration with bio-chemo-magneto-lithostratigraphy and radioisotopic data, and the development of statistical methodologies to assemble and evaluate cyclostratigraphic records (Hinnov, 2014).

To fully understand the processes that drive mass extinction events, climate/ocean reorganizations, and to assess rates of paleoenvironmental and paleobiologic change, we need high-precision temporal resolution of the stratigraphic record. Linking astrochronology and radioisotopic dating provides complementary data that allows for testing internal consistency among the chronometers and offers the promise of establishing accurate and continuous multimillion year time scales (Davydov et al., 2010; Meyers et al., 2012; Sageman et al., 2014). Astronomical calibrations currently under scrutiny include efforts to reconcile $^{40}Ar/^{39}Ar$ and U-Pb results (Kuiper et al., 2008; Costentino et al., 2013) and evaluating the U-Pb zircon system in young rocks. The setting of many tephra deposits dated by Wotzlaw et al. (2014) in a well-studied Miocene basin in Italy offers the possibility to explore in parallel the uncertainties associated with both the astrochronologic age model and the U-Pb zircon data set, particularly the effects of hiatuses in sedimentation, prolonged pre-eruption crystallization of zircon, and intermediate daughter product (^{230}Th) disequilibrium in zircon. Astrochronology of marine sediments has been used to calibrate the geologic time scale for most of the Cenozoic where it could provide temporal resolution at the 20 kyr scale of a precession cycle. Astrochronology anchored using high-precision radioisotopic dates is also being used to provide chronological resolution of Mesozoic and Paleozoic strata spanning tens of millions of years of deposition at the scale of ~100 kyr and 405 kyr eccentricity cycles. Concerns that radioisotopically-anchored astrochronology requires an unattainable ideality in both geochronometers and sedimentary recording and preservation remain to be reconciled by further experiment and testing.

Fostering synergies between disciplines

We have emphasized that modern Earth science research is fundamentally interdisciplinary (Fig. 1). Understanding Earth's 4-D (i.e., spatial and temporal) evolution requires linking mantle dynamics to plate tectonics, surface processes and climate. Addressing grand challenges in our understanding of Earth's geodynamic development is arguably impossible without input from geochronology. However, the interpretation of geochronometric data requires integration of observations from multidisciplinary interfaces such as geochemistry, geophysics, petrology, structural geology, and tectonics. Only after isotopic ages have been obtained (e.g., age of hot spot tracks), can rates of geologic processes (e.g., plate motions) be determined. Once rates are known then how the Earth has evolved can be assessed. If our ultimate goal is to understand geologic processes, Earth history, and why the Earth changes over time, geochronology is at the very heart of this research.

Since geochronology provides the observables that constrain geologic timescales, applications of geochronology require detailed knowledge of both the resolving power and the theoretical and analytical limitations of each technique. Similarly, such applications require knowledge of the geophysical theories and numerical methods used to predict the geochronologic observables as well as their limitations. Importantly, it is the questions that arise from advances in Earth science sub-disciplines that necessitate and justify the basic research and development of entirely new geochronologic techniques. But of course, such developments will facilitate new questions; advances between disciplines occur in conjunction with one another.

Because virtually every sub-discipline of Earth science requires geochronology, it is important that NSF funding facilitates and appropriately supports interdisciplinary research that incorporates both applications of geochronology and basic research on its innovations/advances. Currently, the appropriate NSF programs to support interdisciplinary geochronologic research are not always evident. Furthermore, high-risk research involving innovative applications of geochronology in conjunction with the analysis of other data types and/or numerical modeling (e.g., structural geology, basin analysis, paleoclimatic data, seismic data, tectonics, geodynamics, geomorphology) may be viewed as beyond the scope of a given core program.

5 Fostering synergies between disciplines

We recommend development of a GEO-wide Earth Evolution program that promotes synergistic research across the four Divisions that investigates Earth's 4-D (i.e., spatial and temporal) development, including processes that link mantle dynamics to plate tectonics, surface processes and climate. Integration with EarthCube is an obvious opportunity for this program.

It's about time: Fulfilling the promise of EarthScope

EarthScope is a visionary NSF program to "explore the 4-dimensional structure of North America to gain fundamental insight into how the Earth operates"[7]. Its goal "is to enable and encourage scientists to study the Earth in creative new ways, allow innovative ideas to thrive, and ultimately provide new insights into the past, present, and future of the planet we live on"[8]. Since its inception in 2002, the program has focused almost exclusively on revealing the present seismic structure of, and deformation rates within, our continent. Geochronology figured prominently in early EarthScope discussion documents[9] and in the acquisition and facility construction proposal to NSF[10] (for example, the Scientific Needs and Opportunities section notes the need for "Analytical improvements in geochronology that provide both higher precision and application to a wider age range of events"). Although monetary "credits" to support project related geochronological data gathering (GeoEarthScope[11]) were provided to several dating facilities, implementation of that relatively small program is widely seen as ineffective.

By any measure, EarthScope has been spectacularly successful in revealing the 3-dimensional structure of North America. But as the USArray winds down in this second decade of EarthScope, it is timely to look ahead and identify priorities that will fulfill the remaining goals of the initiative. If we are to truly understand the 4-dimensional structure of North America and make confident predictions about the future arising from knowledge of the past, a new generation of dating investigations arising from novel and refined geochronometers is essential. However, the recommendations of the EarthScope 2010-2020 Science Plan ("Unlocking the Secrets of the North American Continent")[12] make no mention of geochronology.

Meeting the vision embodied in our Grand Challenges will require an effort on the order of a Major Multi-user Research Facility to achieve. We estimate that support of a connected community of twenty to thirty single-PI labs and a dozen larger multi-user facilities together with acquisition costs would require $8-10M/yr over ten years.

7 http://www.earthscope.org/information/funding
8 http://www.earthscope.org/information/about
9 http://www.earthscope.org/assets/uploads/pages/es_wksp_mar2002.pdf
10 http://www.earthscope.org/assets/uploads/pages/es_parts_I-IV_lo_1.25.pdf
11 www.earthchem.org/sites/earthchem.org/files/GeoES_Geochron_Report_Final.pdf
12 http://www.earthscope.org/information/publications/science-plan/

6 Achieving EarthScope's promise through a Major Multi-user Research Facility in geochronology

Given the central role of geochronology in realizing EarthScope's goal of understanding the 4-dimensional evolution of the North American continent, we recommend creation of a Major Multi-user Research Facility in geochronology.

Appendix I: Steering Committee Biosketches

Professor Mark Harrison (University of California, Los Angeles; Chair) pioneered $^{40}Ar/^{39}Ar$ thermochronology and introduced a new generation ion microprobe for geochronologic research. His research has been recognized through awards such as NSF's Presidential Young Investigator Award, GSA's Day Medal, Fellowship in the Australian Academy of Sciences, and Membership in the U.S. National Academy of Sciences. His publications have accumulated > 31,000 citations (h = 93). Prof. Harrison served in senior administrative positions including Director of the Australian National University's Research School of Earth Sciences and UCLA's Institute of Geophysics and Planetary Physics. A signature activity has been his open lab policy through which more than 300 scientists have utilized his geochronologic facilities.

Professor Suzanne Baldwin (Syracuse University) utilizes multiple geochronologic methods to investigate how the Earth has evolved over geologic time. Her current research is aimed at understanding lithospheric plate boundary processes, and noble gases in planetary materials. The analytical techniques she uses reveal the age and conditions (e.g., depth, temperature) in which minerals and rocks form and are exhumed to the surface. She directs the Syracuse University Noble Gas Isotopic Research Laboratory where noble gases are extracted from minerals to reveal their thermal histories. Her research is funded by the National Science Foundation and NASA.

Professor Marc Caffee (Purdue University) is the director of the Purdue University Accelerator Mass Spectrometer (AMS) Facility (PRIME Lab). This facility provides measurements of cosmogenic nuclides to the geoscience community and has been an NSF multi-user facility for about two decades. His research goals are to: 1) develop new AMS techniques and improve the precision of applicability of existing techniques; 2) better understand the underlying physics behind the production of cosmic-ray produced nuclides; and 3) use cosmogenic nuclides to investigate geologic processes on Earth, the moon, and in meteorites. He was a co-PI on the CRONUS-Earth Project, a project aimed at improving the availability and robustness of cosmogenic nuclide techniques.

Professor George Gehrels (University of Arizona) specializes in the application of U-Pb geochronology to solving tectonic, petrologic, and geochemical problems in the Earth Sciences. His work has been honored through awards such as the Day Medal of the Geological Society of America. He directs the Arizona LaserChron Center (www.laserchron.org), which has operated as a NSF multi-user facility since 2005. The ALC utilizes Laser Ablation–ICP Mass Spectrometry to conduct U-Pb geochronologic, Hf isotopic, and trace element geochemical measurements on accessory phases such as zircon, titanite, apatite, baddeleyite, and monazite. Gehrels is one of the organizers of the "International Working Group on LA-ICP-MS U-Th-Pb Geochronology" and the new NSF initiative to bring geochronology into EarthCube.

Assistant Professor Blair Schoene (Princeton University) specializes in the application of high-precision U-Pb geochronology and thermochronology to problems in petrology, tectonics, and Earth history, in addition to method development focused on increasing precision and accuracy in U-Pb dates and data interpretation. He was a member of the ID-TIMS isotope geology labs at MIT (PhD, 2006) and the University of Geneva prior to joining the faculty in Geosciences at Princeton in 2009 and building the radiogenic isotope laboratory, opened in 2011. He was a long-time participant in the EARTHTIME initiative, which guided the high-precision geochronology community in interlaboratory and intermethod calibration, standard development, and decay constant refinement.

Associate Professor David Shuster (UC Berkeley) is primarily focused on understanding processes that occur at or near terrestrial, martian and lunar surfaces. His research involves laboratory-based geochemical observations and the development of analytical techniques and modeling tools to address these questions. Much of this work utilizes the relatively simple physical behavior of He, Ne, Ar and Xe to constrain timescales, rates and temperatures associated with orogenic and planetary processes and chemical weathering. Recently he has engaged in quantifying properties such as the diffusion kinetics, production rates and open system behavior of cosmogenic radionuclides. He pioneered $^{4}He/^{3}He$ thermochronometry during his Ph.D. research at Caltech and was awarded AGU's Macelwane Medal.

Professor Brad Singer (University of Wisconsin-Madison) uses high-precision geochronology to resolve fundamental problems in three areas: (1) linking the evolution of subduction zone volcanoes to current states of activity and unrest, (2) the history of Earth's magnetic field and geodynamo, and (3) chronostratigraphy and evolution of sedimentary basins. He participated in the EARTHTIME initiative since its inception and is active in geologic time scale calibration. Singer established a target prep lab for ^{10}Be and ^{26}Al surface exposure dating and has helped refine the Quaternary glacial history of southern South America. He enjoys bringing the geochronology to the benefit of others and his $^{40}Ar/^{39}Ar$ laboratory is utilized by many external researchers and students to address volcanic, igneous, tectonic, and sedimentary processes.

Appendix II: Questionnaire, Workshop, Discussion and Town Hall

The steering committee supported four different opportunities to hear from the US geochronological community in 2014, including an on-line questionnaire distributed to 243 researchers, a full-day workshop at the Goldschmidt Conference (Sacramento, June 7), a discussion at the 14th International Conference on Thermochronology (Chamonix, September 9), and a Town Hall Meeting at the Annual Meeting of the Geological Society of America (Vancouver, B.C., October 21). By linking our proposed meetings to conferences that our target communities normally attend, it was hoped to leverage their participation at an incremental cost.

The central aims of the questionnaire and meetings were to (1) enumerate the aspirational goals of geochronologists, (2) identify barriers to realizing those goals and the resources needed to overcome them, and (3) build understanding of the geochronologic needs of those outside the producer community and develop a plan to address them.

Questionnaire: The steering committee compiled a list of U.S.-based geochronologists, eventually tabulating 243 names. Emphasis was placed on "producers," who could range from directing multi-million dollar mass spectrometer facilities to ownership of a chemical separation lab for preparing cosmogenic radionuclide samples. An email was sent to the identified geochronologists, inviting them to respond to a questionnaire and encouraging them to participate in follow-up workshops.

Five topics were identified in the questionnaire: improved knowledge of decay constants, support of single-PI labs vs. centralized facilities, supporting geochronologic innovation, development of improved standards for geochronology, developing synergies between disciplines. Response to the survey was light (21 of the 243 requests) but appeared representative of the diversity of views in the community that emerged in the course of follow-up workshops. The details of the survey, and a compilation of the responses, are available at http://sims.epss.ucla.edu/usg-survey).

V.M. Goldschmidt Pre-Conference Workshop: The annual Goldschmidt Conference, jointly sponsored by the Geochemical Society and European Association of Geochemistry, is the leading international meeting for geochemistry, typically attracting between 2500 and 3500 participants. It was felt that the popularity of that meeting among geochronologists enhanced the likelihood of participation across the broad spectrum of sub-disciplines at all career stages. The focus of the pre-conference workshop was to identify scientific breakthroughs potentially within our grasp and the new geochronologic resources that would enable those discoveries. Discussions were also designed to document the role of geochronology in facilitating our current state of knowledge. The steering committee also conducted disciplinary breakout sessions for U-Pb, K-Ar, U+Th/He (+fission track), and cosmogenic (+OSL) specialists following on the five questionnaire topics, to gauge the needs of specific producer communities. The workshop attracted 90 participants who spent a full day in Sacramento engaged in discussions of the above topics through directed/invited presentations, panel discussions, and informal exchanges. Minutes of the discussions are provided at http://sims.epss.ucla.edu/usg-workshop/.

14th International Thermochronology Conference Discussion: The biennial thermochronology conference is the principal venue for cross fertilization between practitioners of noble gas and fission track dating methods and is characterized by opportunities for extensive discussion among the over 200 international participants. Three committee members (Harrison, Baldwin, Shuster) travelled to Chamonix, France, for the 14th International Conference on Thermochronology. Our goal was to gather views from a more international community that may not have been evident in the national pre-Goldschmidt workshop. The organizers provided an hour for our discussion that included a summary of what we learned in Sacramento and a feedback session from the audience of 86 thermochronologists. This discussion in many ways mirrored the concerns expressed in Sacramento increasing our confidence in speaking for the community at large. Minutes of the discussions are provided at http://sims.epss.ucla.edu/usg-discussion/.

Geological Society of America Meeting Town Hall: The steering committee convened a Town Hall for interested consumers of geochronology at the Annual Geological Society of America Meeting in Vancouver, Canada. Approximately 60 participants discussed issues of concern to users and expressed some frustration with the existing mechanisms for supporting small facilities and funding small seed grants. While this venue could not provide an authoritative understanding of all perspectives, it did give us a sense of the concerns felt by those whose research depends on geochronologic results produced by others. Minutes of the discussions are provided at http://sims.epss.ucla.edu/usg-townhall/.

References

Alberts, B., Kirschner, M.W.,. Tilghman, S. and Varmus, S., 2014. Rescuing US biomedical research from its systemic flaws. PNAS 111, 5773-5777.

Bard, E., Hamelin, B., Fairbanks, R. G., and Zindler, A., 1990. U-Th ages from Barbados corals. Nature, 345, 3-33.

Biever, C., 2011. Push to define year sparks time war. New Scientist, April 27, 2011 (http://www.newscientist.com/article/dn20423-push-to-define-year-sparks-time-war.html#.VD69fmPYq5I).

Begemann, F., Ludwig, K.R., Lugmair, G.W., Min, K., Nyquist, L.E., Patchett, P.J., Renne, P.R., Shih, C.Y., Villa, I.M., and Walker, R.J., 2001. Call for an improved set of decay constants for geochronological use. Geochim.C osmochim. Acta 65, 111–121.

Boehnke, P. and Harrison, T.M., 2014. A meta-analysis of geochronologically relevant half-lives: What's the best decay constant? Int. Geol. Rev. 56, 905-914.

Boltwood, B., 1907. On the ultimate disintegration products of the radioactive elements. Part II. The disintegration products of uranium. Am. J. Sci. 4, 77-80.

Brown, L., Klein, J., Middleton, R., Sacks, I.S., and Tera, F., 1981. ^{10}Be as a geochemical and geophysical probe. Carnegie Instit. Wash. Year Book 80, 443-448.

Berger, A.L., 1978. Long-term variations of caloric insolation resulting from the Earth's orbital elements. Quat. Res.9, 139.

Burger, S., Riciputi, L.R., Bostick, D.A., Turgeon, D.A., McBay, D.A., and Lavelle, D.A., 2009. Isotope ratio analysis of actinides, fission products, and geolocators by high-efficiency multi-collector thermal ionization mass spectrometry. Int. Jour. Mass Spectr. 286, 70–82.

Cheng, H., Edwards, R.L., Broecker, W.S., Denton, G.H., Kong, X.G., Wang, Y.J., Zhang, R., Wang, X.F., Hardt, B., and Jiang, X.Y., 2009. Ice age terminations. Science 326, 248-252. doi: 10.1126/science.1177840.

Cheng, H., Edwards, R.L., Shen, C.C., Polyak, V.J., Asmerom, Y., Woodhead, J., Hellstrom, J., Wang, Y.J., Kong, X.G., Spotl, C., Wang, X.F., and Alexander, E.C., 2013. Improvements in ^{230}Th dating, ^{230}Th and ^{234}U half-life values, and U-Th isotopic measurements by multi-collector inductively coupled plasma mass spectrometry. Earth Planet. Sci. Lett. 371, 82-91. doi.org/10.1016/j.epsl.2013.04.006.

Christie-Blick, N., 2012. Geological time conventions and symbols. GSA Today 22, 28-29.

Coleman, D. S., Gray, W., and Glazner, A. F., 2004. Rethinking the emplacement and evolution of zoned plutons. Geochronologic evidence for incremental assembly of the Tuolumne Intrusive Suite, California. Geology 32, 433-436.

Condon, D. C., Schoene, B., McLean, N., Bowring, S. A., Parrish, R. R., and Noble, S. R., 2015. Metrology and traceability of U-Pb isotope dilution geochronology (EARTHTIME tracer calibration Part I). Geochim.Cosmochim.Acta. (in press).

Cosentino, D., Buchwaldt, R., Sampalmieri, G., Iadanza, A., Cipollari, P., Schildgen, T.F., Hinnov, L.A., Ramezani, J., and Bowring, S.A., 2013.Refining the Mediterranean "Messinian gap" with high-precision U-Pb zircon geochronology, central and northern Italy. Geology 41, 323–326.

Cox, A., Doell, R.R. and Dalrymple, G.B., 1964. Reversals of the earth's magnetic field. Science 144, 1537-1543.

Christie-Blick, N., 2012. Geological time conventions and symbols. GSA Today 22, 28-29.

Craddock, P. R., Warren, J. M., and Dauphas, N., 2013. Abyssal peridotites reveal the near-chondritic Fe isotopic composition of the Earth. Earth Planet. Sci. Lett. 365, 63-76.

Davydov, V.I., Crowley, J.L., Schmitz, M.D., and Poletaev, V.I., 2010. High-precision U-Pb zircon age calibration of the global Carboniferous time scale and Milankovitch band cyclicity in the Donets Basin, eastern Ukraine. Geochem. Geophys. Geosyst. 11, doi: 10.1029/2009GC002736.

DePaolo, D.P., et al., 2008. Origin and Evolution of Earth: Research Questions for a Changing Planet. National Research Council, National Academies Press, 150 pp.

Ebata, S., Ishihara, M., Kumondai, K., Mibuka, R., Uchino, K., and Yurimoto, H., 2013. Development of an ultra-high performance multi-turn TOF-SIMS/SNMS system "MULTUM-SIMS/SNMS. Jour. Am. Soc. Mass Spectr. 24, 222-229.

Edwards, R.L., Chen, J.H. and Wasserburg, G.J., 1987. U-238, U-234, Th-230, Th-232 systematics and the precise measurement of time over the past 500,000 years. Earth Planet. Sci. Lett. 81, 175-192.

Froude, D.O., Ireland, T.R., Kinny, P.D., Williams, I.S., and Compston, W., 1983. Ion microprobe identification of 4,100–4,200 Myr-old terrestrial zircons. Nature 304, 616–618.

Grosse, A.F. and Libby, W.F., 1946. Cosmic radiocarbon and natural radioactivity of living matter. Science 106, 88-90.

Hanchar, J.M. and Hoskin, P.W.O., eds., 2003. Zircon. Rev. Mineral. Geochem. 53, Washington, DC: Mineral. Soc. 345 pp.

Hinnov, L.A., 2014. Cyclostratigraphy and its revolutionizing applications in the earth and planetary sciences. Geol. Soc. Am. Bull. 125, 1703-1734.

Hinnov, L.A. and Hilgen, F.J., 2012. Cyclostratigraphy and astrochronology. In F.M. Gradstein, J.G. Ogg, M.D. Schmitz, G.M. Ogg, The Geologic Time Scale 2012, Elsevier, 63-83.

Holden, N.E., Bonardi, M.L., De Bièvre, P., Renne, P.R., and Villa, I.M., 2011. IUPAC-IUGS common definition and convention on the use of the year as a derived unit of time (IUPAC Recommendations 2011). Pure Appl. Chem. 83, 1159–1162.

Ireland, T.R. and Williams, I.S., 2003. Considerations in zircon geochronology by SIMS, in Hanchar, J.M., and Hoskin, P.W.O., eds., Zircon: Rev. Min. Geochem. 53, 215-241.

Jaffey, A.H., Flynn, K.F., Glendenin, L.E., Bentley, W.C., and Essling, A.M., 1971. Precision measurement of half-lives and specific activities of ^{235}U and ^{238}U. Phys. Rev. C 4, 1889–1906.

Jordan, T.H. et al., 2003. Living on an Active Earth: Perspectives on Earthquake Science. National Research Council, National Academies Press, 430 pp.

Kohl, I., Warren, P.H., and Young, E.D., 2015. Earth and Moon are indistiguishable in δ^{17}O to several parts per million. Proc. Lunar Planet. Inst. Sci. Conf. Abstracts 46, 2867.

Kossert, K., Jörg, G., and Gostomski, C.L., 2013. Experimental half-life determination of ^{176}Lu. Appl. Rad. Isotopes 81, 140-145.

Krogh, T.E., 1982. Improved accuracy of U-Pb zircon ages by the creation of more concordant systems using an air abrasion technique. Geochim. Cosmochim. Acta 46, 637-649.

Kuiper, K. F., Deino, A., Hilgen, F. J., Krijgsman, W., and Renne, P.R., 2008. Synchronizing rock clocks of Earth history. Science 320, 500-504.

Kurz, M. D., 1986. In situ production of terrestrial cosmogenic helium and some applications to geochronology. Geochim. Cosmochim. Acta 50, 2855-2862.

Lal, D., and Arnold, J.R. 1985. Tracing quartz through the environment. Proc. Indian Acad. Sci.-Earth Planet. Sci. 94, 1-5.

Laskar, J., 1999. The limits of Earth orbital calculations for geological time-scale use. Phil. Trans. Roy. Soc. London. Ser. A, 357, 1735-1759.

Laskar, J., Fienga, A., Gastineau, M., and Manche, H., 2011. A new orbital solution for the long-term motion of the Earth. Astron. Astrophys. 532, A89.

Lay, T.H., et al., 2012. New Research Opportunities in the Earth Sciences. National Research Council, National Academies Press, 117 pp.

Mattinson, J. M., 2000. Revising the “gold standard” – the uranium decay constants of Jaffey et al., 1971: Eos Trans. AGU, Spring Meet. Suppl., Abstract V61A-02.

Mattinson, J. M., 2010. Analysis of the relative decay constants of ^{235}U and ^{238}U by multi-step CA-TIMS measurements of closed-system natural zircon samples. Chem. Geol. 275, 186-198.

McLean, N., Condon, D.J., Schoene, B., and Bowring, S.A., 2015. Evaluating uncertainties in the calibration of isotopic reference materials and multi-element isotopic tracers (EARTHTIME tracer calibration Part II). Geochim. Cosmochim. Acta (in press).

McDougall, I. and Tarling, D. H., 1964. Dating geomagnetic polarity zones. Nature 202, 171- 172.

McLeod, C.L., Brandon, A.D. and Armytage, R.M.G., 2014. Constraints on the formation age and evolution of the Moon from ^{142}Nd–^{143} Nd systematics of Apollo 12 basalts. Earth Planet. Sci. Lett. 396, 179-189.

Merritts, D., Blum, L.K., Brantley, S.L., Chin, Dietrich, W., Dunne, T., Ehlers, T.A., Fu, R., Paola, C., and Whipple, K.X., 2010. Landscapes on the Edge: New Horizons for Research on Earth's Surface. National Academies Press, 163 pp.

Meyers, S.R., Siewert, S.E., Singer, B.S., Sageman, B.B., Condon, D., Obradovich, J.D., Jicha, B.R., and Sawyer, D.A., 2012. Intercalibration of radioisotopic and astrochronologic time scales for the Cenomanian/Turonian boundary Interval, Western Interior Basin, USA. Geology 40, 7-10.

Montañez I.P., et al., 2011. Understanding Earth's Deep Past: Lessons for Our Climate Future. National Research Council, National Academies Press, 194 pp.

Mundil, R., Ludwig, K.R., Metcalfe, I., and Renne, P.R., 2004. Age and timing of the Permian mass extinctions: U/Pb dating of closed-system zircons. Science. 305, 1760-1763.

Nishiizumi, K., Elmore, D., Ma, X. Z., and Arnold, J. R., 1984. ^{10}Be and ^{36}Cl depth profiles in an Apollo 15 drill core. Earth Planet. Sci. Lett. 70, 157-163.

Particle Data Group, 2012. Review of particle physics. Phys. Revs. D 86, 1–1526.

Petrizzo D.A., Young E.D., and Runnegar B.N., 2014. Implications of high-precision measurements of ^{13}C-^{18}O bond ordering in CO_2 for thermometry in modern bivalved mollusc shells. Geochim. Cosmochim. Acta 142, 400-410.

Pullen, A., Ibáñez-Mejía, M., Gehrels, G.E., Ibáñez-Mejía, W.C., and Pecha, M., 2014.What happens when n = 1000? Creating large-n geochronological datasets with LA-ICP-MS for geologic investigations. Jour. Anal. Atomic Spectr. 6, 971-980.

Reid, M.R., Coath, C.D., Harrison, T.M. and McKeegan, K.D., 1997. Ion microprobe dating of young zircons reveals prolonged residence times for the youngest rhyolites associated with Long Valley caldera. Earth Planet. Sci. Lett. 150, 27-35.

Renne, P.R., Mundil, R., Balco, G., Min, K., and Ludwig, K.R., 2010. Joint determination of ^{40}K decay constants and ^{40}Ar*/^{40}K for the Fish Canyon sanidine standard, and improved accuracy for ^{40}Ar/^{39}Ar geochronology. Geochim. Cosmochim. Acta 74, 5349–5367.

Rivera, T.A., Schmitz, M.D., Crowley, J.L., and Storey, M., 2014. Rapid magma evolution constrained by zircon petrochronology and ^{40}Ar/^{39}Ar sanidine ages for the Huckleberry Ridge Tuff, Yellowstone, USA. Geology, 42, 643–646.

Roberts, R.G., Jones, R., and Smith, M.A., 1990. Thermoluminescence dating of a 50,000-year-old human occupation site in northern Australia. Nature 345, 153-156.

Rotenberg, E., Davis, D. W., Amelin, Y., Ghosh, S., and Bergquist, B. A., 2012. Determination of the decay-constant of ^{87}Rb by laboratory accumulation of ^{87}Sr. Geochim. Cosmochim. Acta 85, 41-57.

Sageman, B.B., Singer, B.S., Meyers, S.R, Siewert, S.R., Walaszczyk, I., Condon, D.J., Jicha, B.R., Obradovich, J.D., and Sawyer, D.A., 2014. Integrating ^{40}Ar/^{39}Ar, U-Pb, and astronomical clocks in the Cretaceous Niobrara Formation, Western Interior Basin, USA. GSA Bull. 126, 956-973.

Savory, J.J., et al., 2011. Parts-per-billion Fourier transform ion cyclotron resonance mass measurement accuracy with a "walking" calibration equation. Anal. Chem. 83, 1732-1736.

Schaltegger, U., Brack, P., Ovtcharova, M., Peytcheva, I., Schoene, B., Stracke, A., Marocchi, M., and Bargossi, G.M., 2009. Zircon and titanite recording 1.5 million years of magma accretion, crystallization and initial cooling in a composite pluton (southern Adamello batholith, northern Italy). Earth Planet. Sci. Lett. 286, 208-218.

Scherer, E., Munker, C., Mezger, K., 2001. Calibration of the lutetium-hafnium clock. Science 293, 683–687.

Schmitz, M.D. and Kuiper, K.F., 2013. High-precision geochronology. Elements 9, 25-30.

Schoene, B., et al., 2015. U-Pb geochronology of the Deccan Traps and relation to the end-Cretaceous mass extinction. Science 347, 182-184.

Schoene, B., 2014. U-Th-Pb Geochronology. In Treatise on Geochemistry, 341–378.

Shuster D.L., Cuffey K.M.,Sanders J.W., and Balco G., 2011. Thermochronometry reveals headward propagation of erosion in an alpine landscape, Science, 332(6025), 84-88.

Selby, D., Creaser, R. A., Stein, H. J., Markey, R. J., and Hannah, J. L., 2007. Assessment of the ^{187}Re decay constant by cross calibration of Re-Os molybdenite and U-Pb zircon chronometers in magmatic ore systems. Geochim. Cosmochim. Acta 71, 1999-2013.

Shen, S.-z., Crowley, J. L., Wang, Y., Bowring, S. A., Erwin, D. H., Sadler, P. M., Cao, C.-q., Rothman, D. H., Henderson, C. M., Ramezani, J., Zhang, H., Shen, Y., Wang, X.-d., Wang, W., Mu, L., Li, W.-z., Tang, Y.-g., Liu, X.-l., Liu, L.-j., Zeng, Y., Jiang, Y.-f., and Jin, Y.-g., 2011. Calibrating the End-Permian mass extinction. Science 334, 1367-1372.

Singer, B.S., Jicha, B.R., Condon, D., Macho A., Hoffman K.A., Brown, M., Feinberg, J., and Kidane, T., 2014. Precise ages of the Réunion event and Huckleberry Ridge excursion: episodic clustering of geomagnetic instabilities and the dynamics of flow within the outer core. Earth Planet. Sci. Lett. 405, 25-38.

Steele, R.C.J., Elliott, T. , Coath, C.D. and Regelous, M., 2011. Confirmation of mass-independent Ni isotopic variability in iron meteorites. Geochim. Cosmochim. Acta 75, 7906-7925.

Steiger, R.H. and Jäger, E., 1977. Subcommission on geochronology: convention on the use of decay constants in geochronology and cosmochronology. Earth Planet. Sci. Lett. 36, 359–362.

Stephan, T., Davis, A.M., Pellin, M.J., Rost, D., Savina, M.R., Trappitsch, R. and Liu, N., 2014. CHILI-The Chicago Instrument for Laser Ionization – Ready to Go. LPI Contributions 1800, 5430.

Tatsumoto, M., 1970. Age of the moon: An isotopic study of U-Th-Pb systematics of Apollo 11 lunar samples-II. Geochim. Cosmochim. Acta Suppl. 1, 1595.

Wang, Y.G., Cheng, H., Edwards, R.L., An, Z.S., Wu, J.Y., Shen, C.-C., and Dorale, J.A., 2001. A high resolution absolute-dated late Pleistocene monsoon record from Hulu Cave, China. Science 294, 2345-2348.

Whiteside, J.H., Olsen, P.H., Kent, D.V., Fowell, S.J. and Et-Touhami, M., 2007.Synchrony between the Central Atlantic magmatic province and the Triassic–Jurassic mass-extinction event? Palaeogeog. Palaeoclim. Palaeoecol. 244, 345-367.

Wotzlaw, J-F., Husing, S.K., Hilgen, F.J., and Schaltegger, U., 2014. High-precision zircon U–Pb geochronology of astronomically dated volcanic ash beds from the Mediterranean Miocene. Earth Planet. Sci. Lett. 407, 19-34.

Yuan, D., Cheng, H., Edwards, R. L., Dykoski, C. A., Kelly, M. J., Zhang, M., Qing, J., Lin, Y., Wang, Y., and Wu, J., 2004. Timing, duration, and transitions of the last interglacial Asian monsoon. Science 304, 575-578.

Zartman, R.E., and Doe, B.R., 1981. Plumbotectonics – the model. Tectonophysics 75, 135-162.

Zartman, R.E. (ed.), 1978. Short Papers of the Fourth International Conference, Geochronology, Cosmochronology, Isotope Geology. U.S. Geological Survey Open-File Report 78-701.

A view of the Bowen River valley, demonstrating the dramatic scenery and glacial imprint found in Fiordland National Park, New Zealand. Recent innovations in geochronology have quantified how such landscapes developed through time; Shuster et al., 2011. Photo taken from near the summit of Sheerdown Peak (looking north), by J. Sanders.