GEOCHRONOLOGY
Toward a 4D Digital Earth

Outcomes of the EarthRates All Hands Science Priorities Workshop

November 10-11, 2017; Minneapolis, MN

Geochronology Working Group Members:

Maarten Blaauw, Julie Fosdick, George Gehrels, Nick McKay, Steve Meyers, Leah Morgan, Paul Renne, Erick Robinson, Mark Schmitz, Brad Singer, Michael Smith, Doug Walker, and Andrew Zaffos

Geochronology — measuring and interpreting time in Earth systems — is necessary to address fundamental questions relevant to science and society: *How quickly will sea level rise? When will the next volcanic eruption occur? How abrupt is a mass extinction? Do climate and erosion control the rise and fall of mountain belts? How rapidly have humans altered and adapted to their environments?*

Answers to all of these questions require quantification of both *time* and *rate* for sequencing phenomena preserved in geological records, linking to causal mechanisms and processes, and understanding feedbacks among physical, chemical, and biological systems. Geochronology thus plays a fundamental role in addressing grand challenges in Earth systems science (National Research Council, 2011a; Harrison et al., 2016), including:

- ***What are the fundamental rates at which Earth and life processes proceed, and how do rates change across timescales and under different boundary conditions?***
- ***How does the accurate sequencing of events in Earth's past reveal major physical, chemical, and biological systems states, interactions, and transitions?***
- ***When and how are both protracted changes and abrupt thresholds in Earth states driven by tectonic, volcanic, extraterrestrial, climatic, or human forcings?***

Recent community efforts have revolutionized the precision and accuracy of methodologies and developed new techniques in geochronology and thermochronology (e.g., Hodges, 2013; Schoene, 2013; Condon and Schmitz, 2013; Freeman et al., 2017). However, these advances have not yet been coupled to a complete global model of Earth's crust. Such a model would greatly improve our understanding of the timing, states, feedbacks, thresholds, and rates of change that control and pace the evolution of the Earth system (National Research Council, 2011b; Parrish et al., 2012; Harrison et al., 2016).

Critical Needs and Future Opportunities

The Earth's crust contains the geologic record of Earth systems, and while our knowledge of its 3D structure is steadily improving, our ability to add the 4th dimension of time is essential to scientific progress. Understanding past, present, and future changes in the natural environment requires **a digital four dimensional model of integrated Earth systems that intersect in the Earth's crust**. **This 4D Earth model must be *dynamic*, *resolved*, *continuous*, and *inclusive*.**

DYNAMIC

The 4D Earth model must be adaptable, evolving with development of new data, algorithms, or best practices. This dynamic character requires investment in:

- *Streamlined (and automated, where appropriate) data-metadata collection, standardization, discovery, integration, and community annotation.*
- *Protocols for data-metadata preservation that maximize the lifetime of information in the face of rapidly evolving data types and algorithms.*
- *Data acquisition workflows that reveal connections between geochronological data and spatio-temporally overlapping geological/biological data.*
- *Meta-analysis, reanalysis, versioning capabilities, and automatic re-computation of 4D models with new data.*

RESOLVED

We must increase data resolution, precision, and accuracy to measure and understand the timing and tempo of changes in a dynamic Earth. These advancements can be promoted through investments in technique and personnel development to:

- *Support the production of robust age-modeling and simulation tools to guide sampling strategies and inform proxy development.*
- *Develop new chronometers in more Earth materials, and couple geochronology and geochemistry to study more diverse rock types and timescales.*

Innovation and Transformation

- Promote cross-training, computational expertise, and cyber-skill enhancement for the next generation of Earth system scientists.
- Expand and build geoinformatics data systems to integrate stratigraphy, paleobiology, chemostratigraphy, and geochronology.

CONTINUOUS

A digital 4D Earth model requires holistic, continuous age models that integrate multiple data types and proxy records within robust statistical frameworks. The requirements for accurate age-model products include:

- *Geochronometer intercalibration: Diverse radioisotopic and sidereal dating methods must be accurately comparable, requiring continued physical constant measurement and calibration efforts.*
- *Multi-proxy assimilation: Geochronometric data must be embedded with geochemical, geophysical, and biological proxy records in the same high-resolution, reproducible geological frameworks to facilitate full data assimilation.*
- *Probabilistic modeling: Geochronometric data must be combined with diverse time series and physical models to achieve the highest temporal resolution; Bayesian statistics and computation provide a flexible and robust framework for continuous age models with realistic uncertainties.*

INCLUSIVE

To realize the 4D Earth model, we must build a community of time-travelers — diverse researchers who generate, assimilate, and interpret geochronological data to reconstruct past and predict future Earth system states. Steps to strengthen community identity and inclusion include:

- *Diversifying communication vehicles and forums on geochronology with the scientific community to expand accessibility of new ideas and technology.*
- *Engaging a more diverse group of researchers and individuals in conversations about information needs and accessibility.*
- *Establishing a Geochronology Division or Section in professional societies.*
- *Fostering the communication of geochronology to the public, promoting a literacy about geologic time, rates, probabilities, and risk that informs societal responses to natural hazards and resource management.*

Broader scientific and societal importance of understanding these challenges

As reviewed by Harrison et al. (2015),*"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."* These advances have revealed the age and origins of our planet, calibrated a geomagnetic time scale that led to the plate tectonic revolution, tested the causes and consequences of mass extinctions, mapped the spatial and temporal patterns of prehistoric human migration, and measured rates of environmental change. From geological to human time scales, geochronology underpins our ability to constrain the rates of processes that present key challenges to societal security and sustainability, including coastal processes, climate change, critical zone management, earthquake and volcanic hazards, and natural resources.

"...geochronology underpins our ability to constrain the rates of processes that present key challenges to societal security and sustainability"

References Cited

Condon, D. J. and Schmitz, M. D., (2013) One Hundred Years of Isotope Geochronology, and Counting: *Elements* 9, p. 15–17.

Freeman, J., Byers, D., Robinson, E., Kelly, R.L. (2017) Culture Process and the Interpretation of the Radiocarbon Record. *Radiocarbon*, p. 1-15.

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

Harrison, T.M., Baldwin, S.L., Caffee, M., Gehrels, G.E., Schoene, B., Shuster, D.L., and Singer, B. (2016) Challenges and Opportunities in Geochronology: It's About Time, *EOS*, v. 97, p. 12-13.

Hodges, K.V. (2013) Thermochronology in Orogenic Systems. In: Treatise on Geochemistry, v. 4: The Crust (R. Rudnick, ed.). Elsevier, 2nd edition. , p. 281-308.

National Research Council (2011a) New Research Opportunities in Earth Sciences (NROES), National Academies Press, 158 p.

National Research Council (2011b) Understanding Earth's Deep Past: Lessons for Our Climate Future, National Academies Press, 212 p.

Parrish, J.T., Erwin, D., Kidwell, S., Lawton, T., Mohrig, D., Nordt, L.C., Schmitz, M., Walton, A. (2012) TRANSITIONS: The Changing Earth-Life System—Critical Information for Society from the Deep Past: National Science Foundation, 64 p.

Schoene, B. (2013) U-Th-Pb Geochronology, in Treatise on Geochemistry, 2nd edition, v. 4, p. 341–378.

Learn more about the *EarthRates* Research Coordination Network

www.earthrates.org

@earthrates

earthrates@gmail.com

EarthRates

NSF