WORKSHOP SUMMARY:
EarthCube Domain End-user Workshop: Bringing Geochronology into the EarthCube Framework

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Co-organizers: Andrea Dutton, Rebecca Flowers, George Gehrels, Brent Goehring, Tom Guilderson, Anthony Koppers, Noah McLean, Stephen Meyers, Susan Zimmerman

Seventy on-site as well as at least eight off-site participants, representing a range of geochronology sub-disciplines and end-users of geochronology data, gathered in Madison, Wisconsin on October 1-3, 2013. This is the first meeting in the U.S. that has brought together such a large spectrum of geochronologists, whose expertise spans from near-modern to early Earth timescales. We discussed the five NSF-prompted workshop goals below from within- as well as across-discipline perspectives. We recognized that the diverse geochronology communities share many common obstacles and needs, and that each sub-discipline is at various stages of envisioning and developing domain-specific organizational tools and cyberinfrastructure that would feed into a wider EarthCube framework. There is also recognition that investment in cyberinfrastructure has the potential to improve access to high-quality dates, models, age calculation tools, and recalculation tools that will benefit geochronologists as well as the many end-users of geochronology data.

In addition to the summaries provided below regarding each of the desired workshop outcomes, there are several appendices, including: a) a list of workshop participants and affiliations; b) an inventory of current community cyber-infrastructure resources; c) specific data and cyberinfrastructure needs for the geochronology community.

Grand Challenge:

Develop a fully integrated four-dimensional digital earth, of which geochronology provides the crucial fourth dimension, to fully understand dynamic earth system evolution.

Outcome 1: Science Drivers

The primary scientific driver identified during the workshop if EarthCube were successful would be to **understand** and **test** hypotheses about the underlying controls on, and the relationships between, major earth systems. Achievement of this goal will entail establishing:

- a robust, unified chronological **framework** for all earth history;
- **correlation** of earth system records across a range of nested spatio-temporal scales;
- **causality** between forcing, responses and feedbacks, including leads and lags;
- **rates** of change of fundamental earth system processes.

The above provides a general framework for the goals of the geochronologic community within EarthCube. Specific examples of scientific opportunities and challenges facing the geochronologic community over the next 15 years that will lead to resolution of the dynamic interactions among Earth systems include, but are not limited to:

- the construction of a digital absolute geologic time scale used to resolve the times and drivers for biologic extinction as well as the rates of biologic recovery and evolution;
- the pace, magnitude and drivers of climate change through earth history (e.g., the carbon cycle, oxygen, sea level, ocean chemistry);
- addition of a 4th dimension to the construction and evolution of the North American continent, providing knowledge products to be directly integrated with EarthScope data;
- resolving interactions between rates, patterns, and magnitudes of erosion, landscape evolution, and sediment deposition, with climate change and tectonics in deep and more recent time.

Outcome 2: Data & Cyberinfrastructure obstacles

To specifically address the overarching vision of EarthCube, the geochronologic community must overcome several major and minor obstacles that require financial and cyber-infrastructure support. We also identified social/structural obstacles to success. These include:

<u>Data & Cyberinfrastructure obstacles</u>

- Geochronological data are currently difficult to access, of variable quality, and challenging to compare between labs/methods and with other information;
- Limited standardization of data acquisition, archiving and delivery protocols across the geochronologic community;
- The need to archive legacy data and develop mechanisms for managing the current data explosion, so that new and existing data can be leveraged;
- Domain-specific data architectures are vastly incomplete or absent altogether and require the development and maintenance of software designed for the reduction and archiving of geochronologic data, designed to remain flexible for unanticipated data additions;
- There is a lack of transformative technology for integrating earth system knowledge -- data at present are locked in domain-specific architectures;
- It is difficult to recognize gaps and data deserts in existing datasets, and disconnects between disparate datasets;
- To create geochronology data that is amalgamated into databases directly comparable requires financial support of EARTHTIME-like initiatives for various geochronometers to establish community-wide protocols, and evaluate and improve inter-laboratory comparison;
- It is challenging to develop ***<u>continuums</u>*** across human and geologic timescales;
- Educational content for EarthCube users that includes support for preparing the next generation of geochronologists to benefit from EarthCube's "big data world";
- A need for visualization tools that make EarthCube accessible to the non-specialist audience (e.g., non-specialist scientists, K-12 teachers, policy makers).

<u>Social/structural obstacles</u>

- The need for clear mechanisms for defining data ownership and credit pre- and post-publication, which must be addressed for the community to "buy-in" to EarthCube;
- A need for benefits to individual geochronology labs and research groups to motivate their contributions to an EarthCube database;
- Improved community and institutional appreciation of the importance of and opportunities presented by cyber-infrastructure is required to promote widespread adoption of

cyber-based technique- and domain-specific tools.

Outcome 3: Existing community data and cyber resources (see Appendix 2 below)
Existing community data and cyber resources immediately relevant to the geochronological community, as well as datasets that geochronologists leverage for their larger research endeavors are summarized in an appendix. The list indicates that while some geochronologic communities are relatively well-organized in a cyber sense, others are not, but a common thread shared by all are the usage of data- and cyber-resources across the broad spectrum of Earth, Atmospheric, and Ocean sciences.

Outcome 4: Data and cyber-capabilities required
As EarthCube evolves, there needs to be a development and maturation of technique-specific to science application-specific data systems. Notably, it was identified that there is a:

- High priority for Earthcube to help communities develop their own domain-specific data-handling systems, from top-down system design to bottom-up assimilation of existing databases;
- Need for continuity in funding for cyber- and geochronological-infrastructure, including personnel;
- Need to develop expertise, communication and collaboration across a spectrum from cyber-savvy geoscientists to Earth science-dedicated computer scientists -- Marry computer scientists into the Earth science community;
- Need for development and maturation of geochronologic technique-specific to science application-specific data systems, including:
    - Tools that feed data into cyber-infrastructure, including novel systems for automating and easing the input of data;
    - Tools that extract, analyze, visualize, and integrate knowledge from Data Systems (EarthChem/Geochron, UNAVCO, EarthScope, NOAA, Neotoma) to be used within EarthCube;
    - Metadata capture adequate for automated data revisions (e.g. decay constants, reference materials);
    - Snapshots of the database (i.e. legacy) – record of previous versions.

In addition to data- and cyber-capabilities required above, there is also a general consensus that linkage to the publishing domain is important to ensure proper attribution and citation of data and data products (e.g., DOI). The establishment of working groups to discuss common protocols and community standardization, both during the development of technique-specific cyber-infrastructure and afterwards in the usage phase.

Additional required data- and cyber-capabilities identified are summarized in **Appendix 3** below.

Outcome 5: Opportunities achievable with EarthCube development and support
Three grand opportunities provided by the development and maturation of geochronological related data- and cyber-infrastructure within EarthCube are summarized below. Each is unique in its

approach and each addresses problems of such large scale that they are largely intractable in the absence of a unified approach to data integration, such as that envisioned by EarthCube. In 1988, Claude Allegre alluded to the challenges of reconstructing the complex history of the continental crust with a "statistical approach" and that we should "abandon any hope… of a cartographic synthesis". We however, are more optimistic that aspects of these complex problems could be addressed in the near future if diverse emerging and existing datasets are fully integrated in EarthCube.

Potential EarthCube Deliverable #1

A **fully digital geological time scale** is a geoinformatics knowledge product that merges all stratigraphic and chronologic records of the Earth's sedimentary carapace, from the section to basin to global scale, and thus accurately expresses all of the embedded proxies of Earth systems evolution (paleoclimate, paleobiology, critical zone interaction, landscape evolution, basin dynamics, plate tectonics) in a quantitative ordinal framework. The digital geological time scale can only emerge through the federation of multiple domain science data systems, and will provide conclusive tests of a myriad of hypotheses centered around correlation, causality and rates of Earth systems phenomena and processes.

Example outcome: The orbital versus tectonomagmatic control on extreme and/or rapid climate events remains an outstanding question in Earth systems analysis. Geochronology is uniquely suited to testing associated hypotheses that rely on **correlation** of the proxy records that contain the signal of climate change; that predict **causality** between forcing, response and feedback; and that distinguish between alternative hypotheses that predict contrasting **rates** of forcing and response.

Potential EarthCube Deliverable #2

A quantitative model of the **4-dimensional evolution of the Earth's lithosphere** requires the integration of paleogeographic reconstructions, proxy records of paleoelevation and relief, landscape evolution models, and thermal and geochemical constraints on crustal volume and structure. Geochronology and thermochronology play the major role in correlating and calibrating these proxy reconstructions and models. Existing efforts toward this goal have been limited to the basin or orogen scale; EarthCube cyberinfrastructure would enable the means to generate the first continental and global 4D Earth lithosphere models through time.

Example outcome: Existing plate tectonic reconstructions are limited by the lack of extant oceanic plates older than ca. 200 million years, or less than 5% of Earth's evolution. However, the continents preserve signals of plate interaction in orogens, basins and magmatism that have been used to reconstruct more ancient plate configurations in a piecemeal way (e.g. the "supercontinental focus") since the birth of plate tectonic theory. Yet these signals are nearly impossible to consolidate into a global reconstruction using existing methods of compilation and synthesis. **Global plate tectonic paleoreconstructions**—and the very existence of plate tectonics across Earth history—could be an emergent phenomena out of an integrated 4-D digital Earth model tracking ancient plate interactions signaled by synchronous orogenic and magmatic phenomena recorded in now separated continental landmasses.

Example outcome: Elevation and relief impose first-order constraints on atmospheric circulation and modern climate dynamics. Similarly the reconstruction of paleotopography is required to provide boundary conditions for both regional climate and global circulation models seeking to reproduce "alternative Earth" climate scenarios present in deep time, for example the Paleocene-Eocene Thermal Maximum or Neoproterozoic Snowball Earth states. **Paleotopography** is a challenging reconstruction that integrates disciplines as diverse as tectonophysics, structural geology, basin analysis, paleoecology, and stable isotope geochemistry of paleosols and fossils. All of these domain sciences are linked to together by geochronology and thermochronology, whether through direct dating or correlation via the geologic time scale. A 4-D model of Earth's lithosphere could provide quantitative and reproducible paleo-topographic reconstructions of continental landmasses through time that can be used as input for modeling of climate, paleoecological response, sediment dispersal, paleohydrology, and terrestrial geochemical fluxes.

Potential EarthCube Deliverable #3

The recognized need for synthesis of paleoclimate data is a particularly pertinent issue with respect to **sea-level change**. Few efforts have been undertaken to integrate paleo sea-level data in a systematic and rigorous fashion. Indeed, the assimilation of data across multiple timescales with differing chronometers is without precedent. This hampers the interpretation of paleo sea levels on a regional scale and limits the possibilities to tune and refine models that predict sea-level change and its spatial variability and to produce a global sea-level curve.

The development of a global sea-level curve over the last full glacial cycle with the most up-to-date geochronological control requires the integration, standardization, and recalculation of thousands of different individual sea-level constraints spanning multiple chronometers (U-series, C-14). Interpretation of this sea level curve is largely meaningless in the absence of simultaneous correlation with other proxy records (e.g., ice cores, marine stable isotope records), timing of terrestrial ice sheet/glacier change (e.g., via radiocarbon or surface exposure dating), and astrochronology. The ability to establish a robust geochronological framework will allow for accurate establishment of correlation between different locations, as well as different records, determine causality of sea-level changes, including leads and lags, and determine rates of sea-level change.

Example outcome: We envision the development of a user interface to extract ages of sea-level markers (such as U-series ages and C-14) and update and normalize these ages into modern calibrations (e.g., CALIB13, updated decay constants). These updated data would be fed into a domain specific database (SeaBase) for sea-level markers and subsequently fed into existing glacial isostatic adjustment (GIA) ice models to refine their temporal framework. Combining and iterating the GIA model with the newly developed dataset would enable construction of a best-estimate global (eustatic) sea-level curve over the last glacial cycle based on absolute dates of direct markers of sea level.

While the above are grand challenges faced by the community and possibly viable with an EarthCube, **immediate next steps** have also been identified and are summarized below.

- Highest Priority: Development and maturation of domain-specific cyber-infrastructure to broaden and democratize participation.
- Dissemination activities within each sub-discipline to foster national/international community buy-in and participation
- Town-hall at GSA Denver (October 2013)
- Communication with NROES committee on Geochronology
- Identify and develop RCN opportunities
    - Within the geochronology domain
    - Across domains: integrate/link with existing EarthCube domains

Appendix 1. Workshop Participants

Name		Affiliation
Sarah	Aciego	University of Michigan
William	Amidon	Middlebury College
Nathan	Andersen	University of Wisconsin-Madison
Jason	Ash	IEDA Group / University of Kansas
Yemane	Asmerom	University of New Mexico
Greg	Balco	Berkeley Geochronology Center
Andrew	Barth	Indiana University
Erin	Birsic	University of Wisconsin - Madison
Terrence	Blackburn	Carnegie Institution for Science
Kimberly	Blisniuk	University of California, Berkeley
James	Bowring	College of Charleston
Samuel	Bowring	MIT
Andy	Calvert	US Geological Survey
James	Channell	University of Florida
Drew	Coleman	University of North Carolina
John	Cottle	University of California, Santa Barbara
Andrew	Cyr	U.S. Geological Survey
John	Czaplewski	University of Wisconsin - Madison
Andrea	Dutton	University of Florida
Alison	Duvall	University of Washington

Lang	Farmer	University of Colorado, Boulder
Rebecca	Flowers	University of Colorado Boulder
Julie	Fosdick	Indiana University
George	Gehrels	University of Arizona
Brent	Goehring	Purdue University
Simon	Goring	University of Wisconsin - Madison
Eric	Grimm	Illinois State Museum
Thomas	Guilderson	LLCenter for Accelerator Mass Spectrometry
Sidney	Hemming	Columbia University
Timothy	Herbert	Dept. of Geological Sciences, Brown University
Jon	Husson	Princeton University
Brian	Jicha	University of Wisconsin-Madison
Shari	Kelley	New Mexico Bureau of Geology and Mineral Resources
Anthony	Koppers	CEOAS, Oregon State University
Todd	LaMaskin	University of North Carolina Wilmington
Todd	LaMaskin	UNC-Wilmington
Thomas	Lapen	University of Houston
Alberto	Malinverno	Lamont-Doherty Earth Observatory of Columbia University
Shaun	Marcott	Oregon State University
Michael	McClennen	University of Wisconsin-Madison
David	McGee	MIT
Noah	McLean	University of Kansas
Steve	Meyers	University of Wisconsin - Madison
Brent	Miller	Texas A&M University
Brent	Miller	Texas A&M University
Kyoungwon Kyle	Min	University of Florida
Andreas	Moeller	University of Kansas - Department of Geology

Leah	Morgan	Scottish Universities Environmental Research Centre
Roland	Mundil	Berkeley Geochronology Center
Bette	Otto-Bliesner	National Center for Atmospheric Research
Lisa	Park Boush	University of Akron
Genevieve	Pearthree	Arizona Geological Survey
Shanan	Peters	University of Wisconsin - Madison
Troy	Rasbury	Stony Brook University
Ken	Rubin	Univ. of Hawaii, Dept. of Geology and Geophysics
Brad	Sageman	Northwestern University
Allen	Schaen	University of Wisconsin - Madison
Mark	Schmitz	Boise State University
Blair	Schoene	Princeton University
Brad	Singer	University of Wisconsin - Madison
Keith	Sircombe	Geoscience Australia
Keith	Sircombe	CSIRO Australia
Stuart	Thomson	University of Arizona
Basil	Tikoff	University of Wisconsin - Madison
Laura	Webb	University of Vermont, Department of Geology
Jack	Williams	University of Wisconsin-Madison
Susan	Zimmerman	Center for AMS, Lawrence Livermore National Lab

Virtual Participants

David	Anderson	NOAA
Daniel	Condon	British Geological Survey, NIGL-NERC
Kip	Hodges	Arizona State University
Matt	Horstwood	British Geological Survey NIGL-NERC

Appendix 2: Outcome 3 - Existing community data and cyber resources

Multi-disciplinary

Databases

National Map (USGS) – GIS data and map layer files
National Mapping Center (USGS)
USGS online reports
State and country map and fault repositories
National Geochronology Database (USGS)
Supplementary data to published papers (GSA, ESA, PNAS, Science, Nature, …)
ProQuest (theses)
Earthchem/IEDA
NAVDAT
GERM – some standards data (actively updated).
USAP (US Antarctic Program) –
GNS new zealand dem and rock chem database.
NASA databases
GeoRoc – General geochemical/isotope DB (Global)
TephraBase/USGS Rock/
PetDB petrological data

Software

GeoDeepDive

U-Pb, Ar/Ar Dating

Databases

GeoChron (EarthChem)

Software

MASS SPEC - Ar-Ar data reduction
ArArCalc - Ar-Ar data reduction
U-Pb_Redux - U-Pb Data Reduction
Schmitz and Schoene spreadsheet - U-Pb Data reduction
Tripoli - Mass spectrometer data handling
SQUID (SIMS U-Pb data acquisition and reduction)
Isoplot (calculation and plotting of isotopic data)
Iolite – used for LA-ICP-MS U-Pb data reduction
VizualAge – used for LA-ICP-MS U-Pb data reduction
UranOS – used for LA-ICP-MS U-Pb data reduction
U-Pb Age for R – used for LA-ICP-MS U-Pb data reduction
PyChron - Jake Ross, ArAr data acquisition and reduction
ArVert - Bruce Idleman - inverts thermochron data for T-t history
Ar inversion/MDD codes: Lovera, Zeitler, Lister...
Glitter

PepiAge
TrackKey
U of A LaserChron Excel macros

Low Temp thermochron (U/Th-He + Fission Track)

Databases

National geothermal data system (in development)

Software

HeFTy (low-T thermochronology thermal history modeling)
Helios ((U-Th)/He data reduction and age calculation)
TracKey - Istvan Dunkl, FT data reduction
Radial plotter - Pieter Vermeesch, visualization
FT data reduction program development in progress through EarthChem
Helioplot - Pieter Vermeesch, visualization, population deconvolution
QtQt - Gallagher, tT simulations
PECUBE/Glide - Braun, thermomechanical model
HEMP

Quaternary geochronology (cosmogenic, U-series, OSL)

Databases

Software

StalAge - stalagmite specific age model
Copra - stalagmite specific age model, linking proxy data to age models
CRONUS (Balco, Cosmogenic Radionuclide Calculator)
CosmoCALC (Vermeesch, cosmogenic)
Chloe (Fred Phillips, cosmogenic)
OxCal (Ramsey: Poisson depositional models)

Detrital geochronology

Databases

Software

Kernel density plotter - Vermeesch
MuDiSc - multidimensional scaling for matlab and r
BinomFit - thermochron data
BayesMix - Gallagher

Terrestrial Paleoclimate/paleobiology

Databases

Neotoma Paleoecology Database (and constituent databases)
Paleobiology Database

NOAA/NCDC Paleoclimatology Database
Modern taxonomic databases (e.g. Tropicos, Mammal Species of the World, WoRMS,…)
GenBank
CMIP database
National Soil Carbon Network, International Soil Carbon Network
PANGAEA

<u>Software</u>
Laboratory of Tree-Ring Research, University of Arizona repository
ITRDB Data Bank – tree ring repository

Surface process/ landscapes/ remote sensing
<u>Databases</u>
UNAVCO (GPS/geodesy data)
OpenTopography.org (database and inventory for LiDAR and topographic data)

<u>Software</u>
CSDMS (Community surface for landscape models) – repository for models and computer source
Cascade (numerical model)
CHILD (numerical model)

Radiocarbon
<u>databases</u>
14C Near Eastern Radiocarbon Context Database
Archaeological Site Index to Radiocarbon Dates
Canadian Archaeological Radiocarbon Database
New Zealand archaeological radiocarbon database
Online 14C databases
Oxford Radiocarbon Accelerator Unit
RADON – Radiokarbondaten online (European)
AUSTARCH ver. 3 - database for 14C and luminescence
INSTAAR radiocarbon date lists (not digitized but huge resource)
tDAR (the Digital Archaeological Record)

<u>Software</u>
IntCal - international calibration curve
BCal (online Bayesian radiocarbon calibration tool)
CalPal (Cologne Radiocarbon CALibration and PALaeoclimate Package)
WinCal25 (The Groningen Calibration Program)
CALIB 6.0 (radiocarbon calibration program)
CaliBomb
Metabase (laboratory management software)
OxCal

Fairbanks calibration program
Canadian Archaeological Radiocarbon Database (CARD)
Bacon/Clam/BLT
Bpeat – Age depth modeling

Sedimentology/stratigraphy/paleoclimate
Databases
SedDB (Columbia/Lamont series of databases)
Global Sand-Sea database Int Assn Aeolian Res at DRI
NOAA/NCDC - paleoclimate proxies, unstructured, standard repository, but not easily searchable
Gridded climate data (WorldClim, PRISM, HADCRU
Climate Data Guide -- an inventory of climate data with synopses of data
IODP databases - sediment data for astrochronology, age model info
NSIDC, NGDC, MGDC
PLIOMAX/EYEGLASS-- Sea level focused.
Janus (IODP)
LIMS – IODP
MagiC (magnetostratigraphic data)
CHRONOS/Neptune – foram and biostrat, timescale
NOAA, SEDIS, LIMBS, JANIS (paleo-oceanographic & magnetostratigraphic data)
PANGEA (European database w/ IODP support)

Software
LOWESS (seawater Sr)
Macrostrat

Astrochronology
Databases

Software
astro: An R package for Astrochronology, Steve Meyers
Analyseries
Laskar - astronomical solutions, widely access
SSA-MTM toolkit
K-Spectra – Commercial version SSA-MTM
Past - Time series analysis/Paleobiological analyses
Manfred Mudelsee codes - Time series analysis
Lorraine Lisiecki codes – Match and Autocomp software, astronomical stacks
Peter Huybers codes – Matlab scripts for time series analysis
Arand – Time series analysis

Visualization tools

<u>Software</u>
GeoMapApp
EarthObserver (GeoMapApp for mobile devices)
Google Earth
ArcGIS
UNAVCO viewers

Community communication/dialogue tools
<u>Discipline-specific</u>
EARTHTIME website
Noblegasnetwork
Neptune listserv
PlasmaChem
OnTrack Form (limited activity)
USeries.org (not active)

<u>Software-specific</u>
ROpenSci - open source development, R community
GitHub - online forum for code management + sharing
sourceforge,
vhub

Organizational/standardization/governance tools
SESAR – International Geologic Sample Numbers and related metadata
DOI registration services (e.g. DataCite)
NOSC
iupac for isotope compositions
ICS (internat comm. of stratigraphy) online tools, also at chronos.org

Physical sample archives
Terrestrial rock repositories - USPR (polar repository), Smithsonian
Meteorites - ASU, Smithsonian, American Mus Nat Hist, Brit Nat Hist Museum,
Antarctic meteorite collection, Southwest Meteorite lab, UNM Institute of Meteoritics
Core repositories - Lamont, IODP, OSU, FSU, LacCore (lacustrine), Houston, Rutgers, State Geo. Surveys
OSU Antarctic rock repository
Sedis – Collections based

Appendix 3- Outcome 4: Data and cyber-capabilities required

Tools that feed data into Domain-Specific Data Systems

- Community-established protocols for level 0 data acquisition
- Community-vetted algorithms that construct higher level data products

- Community-consistent and reproducible open-source data reduction platforms with “one-click” data upload (e.g., U-Pb_Redux/Gechron)
- Unique sample identification that serves to discover and federate like data across data systems
- Scalable, nestable, sub-GPS spatial reference frames (e.g. “Spot” concept of Structure domain workshop)
- Standards, spikes, reference materials
- Technique development
- Decay constant calibrations
- Each (sub)discipline establish working groups to discuss protocols
- Open workflow in terms of data reduction
- Legacy data input (e.g. DeepDive, create incentives for community participation)

Tools that extract knowledge from Data Systems to be used within EarthCube

- Linkages and nesting with related and more distant databases (stratigraphic, paleo, structural, etc.)
- Dynamic scientific computing resources for domain-specific data analysis, assessment and visualization (e.g. bolting things like Isoplot, Cronus calculators, OxCal-type resources to the data system)
- Data visualizations linking data in space and time (e.g. Corewall, Geowall, Chronozoom)
- Interface data with GIS technology

Outreach and education

- Create the connection between EarthCube and federal agencies charged with hazards (e.g. USGS)
- Create the connection between EarthCube and industry (e.g. resources)
- Parallel portal to demonstrate utility of EarthCube to K-12 teachers, Congress and other policy makers (e.g. SERC)
- Resources for general public and for other scientists to understand and interpret geochronological data
- A geochronology data guide -- web based guide to where data is, what the data are, expert assessment of the data strengths and limitations.
- Means to invite outside communities to learn about and use our databases and software resources