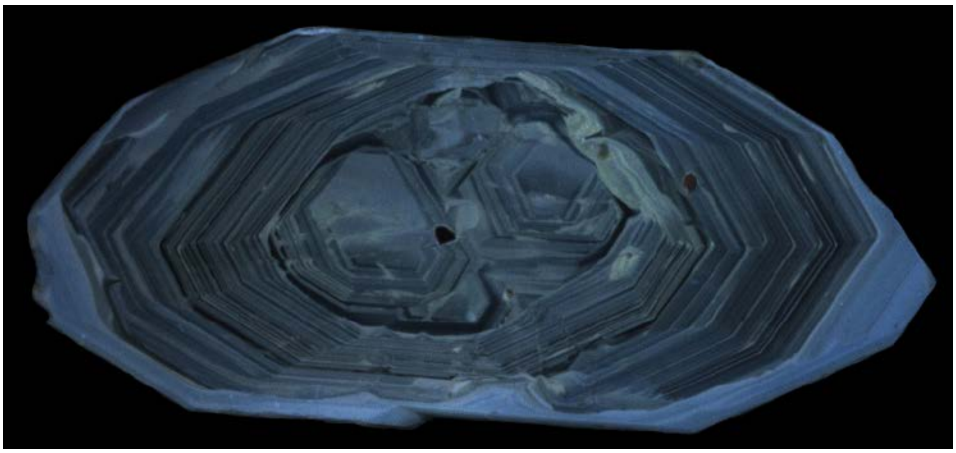
Geochronology: It's About Time



George Gehrels

A zircon crystal (approximately 0.2 millimeter long) from the Coast Mountains in western Canada shows zonation that records multiple stages of crystallization. The ages from this sample range from more than 116 million years old at their cores to 58 million years old for outer rims. Zircon plays an important role in radiometric dating because it is a common mineral in crustal rocks; it contains trace amounts of uranium and thorium, which decay to lead with reasonably well-constrained half-lives; and it preserves a record of geological processes despite younger metamorphism.

Time is at the heart of Earth sciences; every significant advance in geochronology has produced a paradigm-shifting breakthrough in our understanding of Earth's history. Without quantitative knowledge of absolute and relative time, no modern discipline with a historical focus could function.

However, when we conducted a broad consultation with geochronology experts and researchers who rely upon geochronological data, we found a strong sense that the field has been orphaned by the national science support structure and weakened by the widespread view that it is a "tool" rather than a scientific challenge.

Every discipline that benefits from geochronology should participate in the stewardship and development of this field, including scientific efforts and financial support. In return, geochronologists must address the research priorities of the disciplines they support and provide enhanced user access to data.

Radical Changes in Perception

In one instance after another, geochronology has provided information that drastically changes our understanding of natural phenomena. The earliest mineral dates, determined more than 100 years ago, catapulted Earth's estimated age from 10 million to 100 million years into billions of years. The ability to date young basalts revealed a geomagnetic timescale that led directly to the plate tectonic revolution.

The development of high-precision uranium-lead (U-Pb) zircon dating is currently revolutionizing our understanding of magmatic timescales as well as the tempo of sediment accumulation and biologic change. In situ U-Pb dating challenges our assumption that early Earth was an arid world that was 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 evolution and highlights the dependency of Earth's living systems on extraterrestrial inputs.

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By quantifying variations in rock temperature and depth through time, application of the potassium-argon (K-Ar) and uranium-thorium/helium (U-Th/He) methods to rocks and minerals has advanced our understanding of the pace of tectonic processes. Together with studies of nuclides produced by cosmic rays, this understanding has revolutionized the study of landscape evolution.

The advent of carbon-14 dating radically altered our understanding of prehistoric human migration. However, this isotope's 5700-year half-life led to an apparent concentration of events 30,000 to 40,000 years ago. This pileup only relaxed to include much older ages after the development of optically stimulated luminescence dating, which brought quantitative chronologies to systems that were historically difficult to date. Coupled with enormous advances in uranium series dating, these techniques focused on the Pleistocene have been essential for calibrating glacial-interglacial cycles from climate records.

Taking Stock: Where Are We Now?

A visionary program (EarthScope, http://www.earthscope.org) begun in 2002 has been spectacularly successful in revealing the three-dimensional structure within the North American continent. However, fulfilling its goal of understanding the evolution of the North American continent will require a major effort led by geochronologists.

The *National Research Council* [2012] report *New Research Opportunities in the Earth Sciences* recognized the central role that geochronology plays in the geosciences (Figure 1) and identified pressing instrumentation and facilities needs for fostering research and education. In response, with the support of the National Science Foundation, we led a yearlong consultation with consumers and producers of geochronology to understand their aspirations and the challenges they face.

We surveyed nearly 300 U.S.-based geochronology producers on their views regarding the role of geochronology in innovation, transformative science, facility support, synergistic research, and the status of decay constants. With these results as a guide, we hosted meetings at the 2014 Goldschmidt Conference, the 14th International Conference on Thermochronology, and the 2014 Geological Society of America Annual Meeting. The conclusions drawn from these interactions were recently published in the report "It's About Time: Opportunities and Challenges for U.S. Geochronology" [*Harrison et al.*, 2015].

Data Disconnect

Our field has changed dramatically over the past 20 years. Many scientists now focus on dating youthful features at or near Earth's surface using measurement methods that didn't exist a generation ago. In situ methods have produced massive amounts of new data for those interested in deeper time or deeper Earth, whereas traditional methods have gained an exquisite degree of precision as they have matured.

Despite these advances, our consultations revealed several troubling paradoxes. Although more instruments than ever are being employed for Earth science research in the United States, the geochronologic community still has enormous demand for more data. Individual laboratories produce more, and higher quality, data than ever, but many interested parties feel that costs are prohibitive or that bottlenecks in the process preclude their participation. The techniques and instruments in use today are far more sophisticated than those in the recent past, but many are concerned by the lack of progress in putting proven advances in geochronologic instrumentation to use.

Our consultations point to a lack of optimization between geochronology producers and consumers. We believe this mismatch is driven by misdirected incentives in combination with a pervasive view that geochronology is merely a tool rather than a discipline in its own right.

Looking back, it is easy to see how this occurred. To address the specific needs of a particular Earth sciences discipline, geochronologists developed novel methods to address their challenging scientific problems. In the process, individual geochronologists became experts in an increasing diversity of specialized fields. This specialization, in turn, has separated the providers of geochronologic information from those who apply this information: In some cases, these information consumers have never actually participated in the analyses that provide them with their data.

Even within geochronology, researchers perceive different issues facing them. For example, some researchers are frustrated by the low accuracy with which decay constants are known; others would not be significantly affected by an improvement as large as an order of magnitude.

No Simple Solutions

There is not a simple solution to the challenges the geochronology community faces, but perhaps the first step is a better understanding of the landscape we live in. The most salient feature is that virtually every geochronologist operates within a different disciplinary home because no federal science program has sustaining geochronology infrastructure and innovation as its core mission.

The reasons for this are partly historical and partly due to the expansion of the field into disciplines that require different constraints on timing and rates. As geochronology spread into these emerging fields, it often failed to become firmly rooted within those cultures. Routine analyses could be supported through existing programmatic funding, but new fields lacked the tradition of sustaining the development of geochronologic protocols.

For our community to truly prosper, we must make the case across the geosciences that stewardship of geochronology is the responsibility of all disciplines that use its products. This stewardship includes the need to support high-risk research and development of equipment, methods, and applications. In return, the geochronology community needs the analytical and staffing resources to address the research priorities of supportive disciplines and to provide enhanced user access to data.

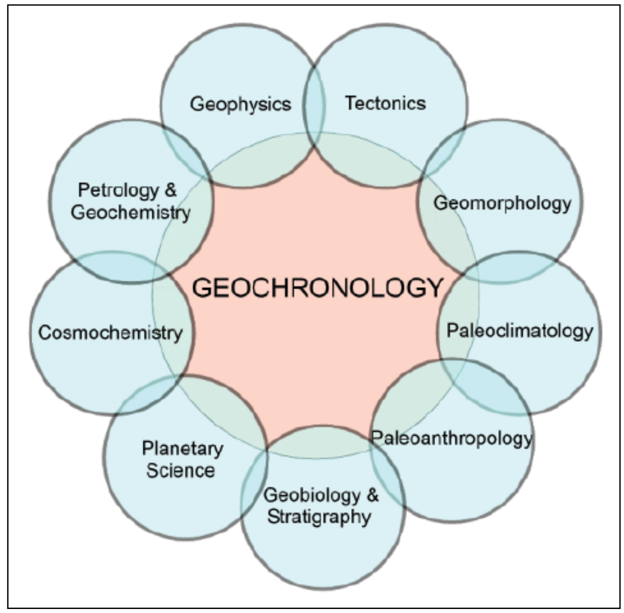

Fig. 1. Geochronology plays a central role in all historical aspects of the Earth and planetary sciences but has no disciplinary home within the federal funding umbrella.

Grand Challenges

Geochronology is poised to make unprecedented leaps in its capacity to stimulate transformative research. We envision four grand challenges for the coming decade:

- age precision and accuracy of ±0.01% from the Cenozoic to the Hadean, which requires creating methods and mass analyzers of unprecedented sensitivity and resolution with vastly improved decay constants
- continuous temporal coverage throughout the Quaternary—from 1 week to 1 million years—of processes key to today's societal security, including climate change, critical zone management, volcanic hazards, and paleoseismology
- measuring the denudation of the Earth's surface with submillimeter per year accuracy using thermochronometers, for timescales as short as 10,000 years, to place geodetic deformation rates in context with long-term geologic trends
- coverage of thermal conditions ranging from Earth's cryosphere through to the mantle to provide the deep time dimension to structures imaged by the USArray seismic observatory network

These ambitions are more than simply honing a tool; they touch on the great, unanswered scientific questions of our time (e.g., when life began on Earth) and would permit the goal of EarthScope—to understand the four-dimensional structure of North America—to be fully realized.

Our report points to the need to support foundational and potentially high-risk development of new geochronological methods, the need for greater cooperation among existing laboratories, and cooperative interactions with allied scientists. We invite you to download a copy of our report (http://bit.ly/Geochron_rpt) and join the conversation on the future of U.S. geochronology at http://bit.ly/Geochron_feedback.

References

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