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GR Letter

Fractal geochronology — dating of the past, planning for the future

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Abstract

Dates for regional-scale geological events are typically determined by analysis of radioactive decay processes within micron-scale closed systems, demonstrating that geochronology information is "fractal" — that is, largely independent of the scale of magnification. This has important implications for the way geochronology data should be stored, retrieved and processed in order to maximize extraction of useful geological information.

Keywords: Fractals; Geochronology; ^{40}Ar–^{39}Ar step heat; SHRIMP; U–Pb absolute age; Zircon; Xenocryst; Detrital minerals

1. Introduction

Geochronology is the science of determining the time elapsed since, or "age" for, an event – formation, heating, cooling, crystallization or recrystallization – recorded within a geological sample. A broader aim of the application of geochronology is to establish an accurate and precise absolute time frame for the geological history for the Earth. The traditional approach to the practice of radiometric geochronology begins with careful selection of a hand-specimen sized rock sample considered to be representative of a "mappable" geological unit. This rock sample is processed in the laboratory to isolate suitable chemical elements or minerals for analysis to obtain a "date", a measurement that, with skill and some good fortune, may provide the time elapsed since the event was recorded within the sample. The date obtained is commonly extrapolated to apply to the entire geological unit and beyond.

With the advent of efficient new dating techniques such as the laser ^{40}Ar–^{39}Ar microprobe, laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) and Sensitive High-Resolution Ion MicroProbe (or SHRIMP) isotopic analysis methods, the volume of available geochronology data has increased dramatically over the past decade. Along with this growth, the precision routinely attainable on dates has improved by about an order of magnitude (typically better than ±10 Ma at 95% confidence) compared to those routinely attainable using whole-rock techniques such as the ^{87}Rb–^{87}Sr and ^{147}Sm–^{144}Nd isochron techniques. Although university researchers have been the principal acquirers of geochronology data, they rarely have the resources or interest in the management of this valuable and rapidly increasing data resource. Fortunately, some national and state government geological surveys have assumed responsibility for the management of geochronology data within their state or national boundaries. For example, Geoscience Australia, the Geological Survey of Canada and the United States Geological Survey maintain on-line databases (at http://www.ga.gov.au/oracle/ozchron/, http://gdr.nrcan.gc.ca/geochron/index_e.php and http://tin.er.usgs.gov/karage/ respectively) containing geochronology compilations of data drawn from published and unpublished sources.

The aims of this contribution are to propose some improvements to the way that that geochronology information is currently organized, retrieved and stored, so that additional geological insights may in future be extracted from this valuable shared resource.

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2. Geochronology at different scales

Radiometric decay schemes in common use for geochronology are more often closed systems on a mineral scale than on the scale of a whole-rock sample. As a consequence, most widely applied radiometric dating methods rely on the dating of a chemically suitable mineral, with high parent/daughter ratio, isolated from a geological sample. Radiometric dates obtained from individual minerals can then be related to a specific chemical, thermal or mechanical process responsible for development of the observed mineralogy of the host rock, as closure of the radiometric decay system is largely dependent on the structural and chemical properties of a single host mineral. This considerably simplifies interpretation of the significance of the date obtained compared with those obtained by the whole-rock approach. For example, precise dates for igneous crystallization or metamorphism may be obtained by exploiting the radioactive decay of the parent nuclide ^{40}K to its daughter ^{40}Ar within high-K minerals such as micas, by ^{40}K–^{40}Ar or (after conversion of ^{39}K to ^{39}Ar by neutron irradiation) ^{40}Ar–^{39}Ar analysis. Similarly, zircon is a very common, highly resilient mineral that preferentially incorporates U and Th into, but excludes Pb from, its crystal structure during crystallization. Precise crystallization dates are obtainable using the coupled ^{238}U and ^{235}U radioactive decay to ^{206}Pb and ^{207}Pb within high-U minerals such as zircon, and have been widely exploited by geochronology laboratories since the mid 1980s.

Dates obtained by radiometric geochronology methods are therefore based on processes that operate at the sub-mineral scale, typically c. 10^{-6} to 10^{-3} m. Due to the inheritance of zircon formed during prior crystallization events, the LA-ICPMS and SHRIMP U–Pb zircon methods commonly provide complex age structures for zircon populations for many samples, particularly those of granitic or gneissic rocks. Evidence of geological events may be preserved in xenocryst zircons within granitic melts derived from the lower crustal source regions of such melts, even though all rocks formed during these events may have been destroyed. Xenocrystic zircon populations may thus preserve provenance information, in an analogous way to that of detrital zircons within clastic sedimentary rocks. Similarly, evidence of post-emplacement disturbance events may also be preserved in mineral analyses obtained by the U–Pb, ^{40}K–^{40}Ar and ^{40}Ar–^{39}Ar methods. Information about inheritance and post-crystallization disturbance events may be poorly recorded or resolved in any one single hand-specimen sample, but may be more clearly evident at the regional scale, by the pooling of the information extracted from analysis of minerals from many samples taken from the effected geological unit or region.

However, geological surveys naturally approach the storage and management of geochronology data on a regional, state or national scale, typically c. 10^{5} to 10^{6} m. Geochronology information within their on-line databases is usually organized on the basis of the hand-specimen sample, sampling site or geological unit, with geochronology information typically only retrievable by reference to a hand-specimen identification number, collection site coordinates or geological unit. Whilst maintaining the integrity of the sampling site and hand-specimen information, this approach generally results in loss of the valuable second-order information on inheritance and post-crystallization disturbance events provided by modern mineral-based dating techniques and that may be evident at the regional scale.

3. Fractal geochronology

This "scale" problem arises because geochronology is "fractal": that is, it is largely independent of the scale of magnification. Dates for regional-scale geological events such as metamorphism, volcanic eruptions or the crystallization of granite plutons, are determined by analysis of radioactive decay events that are closed systems at the μm scale. And by combining detailed examination of microstructures using specialized techniques such as back-scattered electron and cathodoluminescence imaging with trace element and laser or ion microprobe isotopic microanalytical methods, complex regional geological histories may be determined from detailed study of (suitable) individual minerals (cf. Nelson et al., 2000). Organization by reference to hand-specimen samples or by sample location of geochronology information acquired by microanalysis of minerals can therefore result in loss in information resolution, because inheritance or post-emplacement (pre- or post-hand-specimen formation) information may be degraded or lost at the hand-specimen scale.

Given its fractal nature, geochronology data should be retrievable in a way that enables it to be examined at different scales. Dates recording events at the micron scale, such as ^{40}Ar–^{39}Ar step heat or individual SHRIMP U–Pb zircon analyses, should be able to be grouped for "mappable" geological units or for regional tectonic units, and not just on the basis of individual hand-specimen samples as is conventionally the case. Important new geochronological information may be extracted from existing geochronology data sets once the fractal nature of geochronology data has been appreciated and catered for. For example, by statistical analysis of the dates obtained for xenocryst zircons within a suite of igneous rock samples from a region or geological unit, it is possible to reconstruct a regional chronological history for the interval prior to the igneous emplacement events, even though all rocks formed during these earlier events may have been spatially redistributed or destroyed by intervening tectonism or (for example) subsequent magma generation. This is in part because a record of regional-scale events can be preserved on a micron scale within a mineral that is far more resilient than a (hand-specimen scale) rock sample. As an example of the strengths such an approach, the spatial and temporal distribution of craton boundaries and basement terranes, and detailed histories of regional-scale magmatism and high-grade metamorphism, was recently reconstructed using a database of 2159 ion microprobe U–Pb zircon and monazite isotopic analyses obtained from 94 gneissic, granitic and metasedimentary rock samples from the northwestern Yilgarn Craton and southern Gascoyne Complex (Nelson, in press).

Recognition of the fractal nature of geochronology data and its storage and retrieval to enable it to be examined at different scales potentially offers unique insights into the past and should be taken into account in future.

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