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Differential zircon fertility of source terranes and natural bias in the detrital zircon record: Implications for sedimentary provenance analysis

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Abstract

Granitic intrusions emplaced within Laurentia during the Grenville Orogeny (1.15–1.05 Ga) are exceptionally Zr-rich, primarily a function of high modal zircon, relative to Paleozoic granitoids emplaced within eastern Laurentia during phases of Appalachian orogenesis. Erosion of Grenville source rocks would generate disproportionately large volumes of detrital zircon compared to less zircon-fertile source regions. The latter sources are difficult to detect by standard in situ U–Pb dating methods of detrital zircon (SHRIMP or LA-ICP-MS U–Pb analysis of centers of >100 μm grains), or could be overlooked during sampling. Grenvillian zircon fertility biased the Neoproterozoic to Recent sedimentary record as a result of two factors: (1) zircon durability and insolubility led to recycling during repeated orogenesis; (2) inertness of zircon below the onset of anatexis means dominantly metamorphosed sedimentary terranes failed to generate significant new zircon corresponding in age to the time of accretion of those terranes to Laurentia. Zircon growth under anatectic conditions generates new zircon, commonly as overgrowths on preexisting zircon, which may be too narrow to easily analyze by laser or ion beam techniques. Accretion of metasedimentary terranes therefore could be rendered all but undetectable via standard U–Pb detrital zircon dating. Grenville age modes dominate detrital zircon age distributions for Laurentian Neoproterozoic rift basins, Appalachian Paleozoic synorogenic clastic sequences, Appalachian metasedimentary terranes, and modern rivers draining these terranes. This is an artifact of the Grenville zircon signal that echoed throughout all Paleozoic orogenies on the eastern Laurentian margin. The natural Grenville bias in the detrital zircon record is further amplified by standard sampling biases (such that large (e.g. 100–300 μm) crystals are preferentially chosen) and analytical biases (e.g. cores are much more frequently analyzed).

Keywords: zircon; detrital; provenance; Grenville; Laurentia

1. Introduction

Rapid in situ U–Pb geochronological methods, such as sensitive high resolution ion microprobe analysis (SHRIMP) and laser ablation inductively coupled

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plasma mass spectrometry (LA-ICP-MS), have fostered a revolutionary advance in the isotopic analysis of U-bearing accessory minerals [1–3]. Rapidly expanding applications of these methods include dating detrital zircon for assessment of sedimentary provenance and terrane assembly. Zircon is an attractive provenance proxy because of its durability and remarkable chemical stability over a wide range of lithospheric pressures, temperatures, and fluid/melt compositions. Detrital zircon geochronology is a tool whose use expanded markedly in the past decade. As with dramatic advances in any new analytical methodology, there comes an accompanying increase in awareness of its limitations and potential pitfalls. For U–Pb geochronological studies of detrital zircon, it is becoming clear that considerable provenance information is unrecoverable when employing the standard approaches of sampling and in situ microanalysis of zircon [4]. This could be due to the limited amount of new zircon that crystallized from near Zr-saturated magmas, or in some cases the thermochemical conditions of a terrane were not adequate for crystallization of any new zircon. Although such terranes would contribute clastic sediment, provenance information would be lost, or not available, using standard analytical U–Pb detrital zircon methods. The very same properties that make zircon such a powerful geochronometer for dating the earliest events in Earth history render it virtually inert under conditions of regional metamorphism, except at upper amphibolite to granulite facies [5–7]. An entire cycle of terrane collision, crustal thickening, heating and loading, melt generation, and exhumation could pass and there would be no record of that cycle in the detrital zircon record. Alternatively, the specific generation of zircon produced during such a cycle could be of sufficiently low modal abundance or size to be unresolvable by conventional methods of sampling and analysis. Finally, the detrital record could be dominated by new or inherited zircon from source terranes with exceptionally Zr-rich lithologies. This paper evaluates some of the fundamental implicit assumptions of the detrital zircon provenance method, specifically those related to zircon fertility, and presents a case study examining the scope of the potential problem.

2. Assumptions of detrital zircon provenance studies

Before outlining the assumptions related to detrital zircon provenance studies, we consider the methods used to both sample and analyze zircon, as these introduce potentially inherent limitations and biases.

2.1. Analytical methods

Following heavy mineral concentration from a crushed and milled sedimentary rock, detrital zircon crystals are sampled either: (1) randomly, in order to have a basis for quantifying provenance proportions [8,9]; or (2) selectively, based on morphology, color, degree of rounding, etc. (e.g. [4,10]) to try to maximize the number of potential source regions represented by the zircon crystals. In some studies, no specific criteria are presented for selection of grains [11,12], other than (apparently) based on size, for ease of manipulation and constraints imposed by the size of analysis beam. The minimum number of grains analyzed per rock should exceed 60, in order to achieve statistically justifiable discrimination of age modes within a population [13]. Grains are usually quoted as being at least 70–100 μm in size [11,14], but most are reported to be 100 to 300 μm in maximum dimension [12,15]. Following mounting in epoxy, grains are ground down to expose cores, polished, and usually examined by cathodoluminescence (CL) and/or backscattered electron (BSE) imaging to identify growth zones. Zones sufficiently large for the ion beam (10–30 μm diameter for most work in the past decade [9] or laser beam (15–50 μm [16]), but more typically ≥ 50 μm diameter [17] are chosen for U–Pb ion microprobe or laser ablation mass spectrometric analysis; this is usually the central core of the crystal (often interpreted to be magmatic if not inherited), but may include rims of sufficient width for analysis, when present [8].

2.2. Assumptions

Numerous implicit assumptions exist in interpreting the measured age distributions, some of which are explicitly considered (e.g., [8,9,18]), but many that are not in most ion microprobe or laser ablation studies. The assumptions include those of a sedimentologic nature: e.g., the age of zircon within a sandstone is representative of the age of quartz in that sample [19]; detritus from all potential source terranes had equal probability of reaching the basin via fluvial drainage systems [20]; the number of ages defining a mode in the total age distribution are proportional to the mass fraction of detritus of that age [21] and those related to physical and petrogenetic behavior of the mineral proxy being employed (the main focus here). The assumptions related specifically to zircon may be further separated into those relating to zircon ‘fertility’ in rocks, those related to analyzing the zircon, and those related to sampling preferences.