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Assessing the sediment factory: The role of single grain analysis

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ABSTRACT

Type and amount of sediment generation are intimately connected to tectonic and climatic processes active at the earth's surface today as well as throughout the geologic past. Detrital single grains (sand to very coarse silt sized) from well-dated sedimentary formations serve as mineral tracers in sedimentary systems and record the sediment-forming processes. In this review, a selection of individual methods available to extract petrogenetic and chronological information from detrital mineral grains is compiled. Emphasis is placed on techniques, concepts, and their possibilities and shortcomings in defining the type and geologic history of source rocks, as well as the rates and relative proportions at which sediments are being eroded and delivered to basins. Statistical issues intrinsically coupled to the interpretation of detrital single-grain distributions are highlighted, as well as new emerging techniques. These include geochronology of phases like e.g. titanite, monazite, or rutile to overcome the common restriction to apatite or zircon bearing lithologies, as well as any kind of double or triple dating to extract both high-T and low-T thermochronological information from the very same detrital grains. Mineral pairs are especially suited to quantify the relative contributions of well-defined source rocks or areas to the sediment when the two phases (i) occur in contrasting rock types, (ii) are relatively stable under sedimentary conditions, and (iii) allow for extracting significant and detailed information on source rock petrology and chronology. In general, however, multi-method approaches are the only way to overcome ambiguous information from the sedimentary record. In combination with either independent information on sediment flux or erosion rates derived from single-grain thermochronology, the sediment-forming processes as well as their controlling mechanisms and overall geologic settings can be properly assessed.

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1. Introduction

The sediment factory, i.e. the system that generates detrital material from solid rocks and delivers sediment to sedimentary basins, is controlled by a variety of processes including the lithology of the source rocks, tectonic activity, relief and climate in the source area, as well as the modes of sediment transport, dispersal, and alteration on transit (e.g. Johnsson, 1993; Weltje and von Eynatten, 2004). The lithology of the source rocks defines the "potential" detritus spectrum, i.e. the types and relative abundances of minerals and composite grains that may enter a specific sedimentary system. Tectonics, relief, and climate control the amount and rates of sediment delivery to the drainage basin and sediment transporting systems. Within the latter, sediment is abraded and chemically weathered depending on transport mechanisms and climate, as well as fractionated according to grain size, shape, and density. The complexity of the processes involved implies that largely similar sediment may be produced from different sources as well as different sediments may be produced from similar source rocks. Despite all these pitfalls, however, reconstructing sediment provenance in all its facets constitutes a widely used approach in geosciences, mainly because (i) distinct breaks and/or trends observed in the detrital record (that reflect distinct events and/or processes in the hinterland) can be precisely dated by stratigraphic means, and (ii) technical advances allow for extracting more and more sophisticated information from single detrital grains such as host rock lithology (e.g. Zack et al., 2004b; Morton et al., 2004), metamorphic conditions (e.g. Triebold et al., 2007), crystallization and cooling ages (e.g. Sircombe, 1999; Sha and Chappell, 1999; von Eynatten et al., 1999; Mikes et al., 2009), and cooling and exhumation rates of the host rocks (e.g. Whipp et al., 2009).

Basically sedimentary provenance analysis is a deductive approach, trying to unravel the processes that generated the sediment under investigation from the characteristics of the sediment itself. Traditional approaches rely on bulk sediment composition based on petrography (modal composition of framework grains, e.g. Blatt, 1967; Dickinson, 1970; Ingersoll et al., 1984) or geochemistry (major and trace element composition, e.g. Pettijohn, 1963; Potter, 1978). The growing data base for different tectonic settings allowed for developing tectonic discrimination schemes based on bulk sediment composition (e.g. Dickinson and Suczek, 1979; Bhatia, 1983; Dickinson, 1985; Bhatia and Crook, 1986; Roser and Korsch, 1986). These unifying and frequently-used concepts in provenance analysis became recently challenged (Armstrong-Altrin and Verma, 2005; Weltje, 2006; Garzanti et al., 2007; Pe-Piper et al., 2008; von Eynatten et al., 2012) and should be used with great care. Besides high degrees of wrong classifications when applied to Neogene to modern systems (i.e. samples are assigned to incorrect tectonic settings), statistical flaws in the construction of both discriminating fields and confidence intervals became evident (Weltje, 2002; von Eynatten et al., 2002).

Following a few early attempts and statements (e.g. Krynine, 1946; Blatt, 1967) the first detailed studies on heavy mineral chemistry and detrital zircon dating date back to the 1980s (Morton, 1985; Dodson et al., 1988). Since then a wide range of analytical techniques has become available to study geochemical and isotopic composition of individual sand-sized grains. The principal advantage of single-grain studies is based on the assumption that differential fractionation of grains from a single mineral phase is negligible, i.e. variability within that mineral phase is considered to be not affected by fractionation due to mechanical and chemical processes in the sedimentary system (see Section 3 for some critical points regarding this assumption). The potential of single-grain techniques with respect to mineral chemistry in provenance research was first summarized by Morton (1991) and further developed towards so-called *varietal studies*, i.e. investigating the characteristics and variability of single grains of a single mineral phase (e.g. garnet, tourmaline, zircon). Initially morphological and other light-microscopic features and their variability within single mineral phases were also investigated (high-resolution heavy mineral analysis; cf. Mange-Rajetzky, 1995). The fast development of geochemical and isotopic techniques, especially regarding electron microprobe (EMP) and laser-ablation inductively-coupled-plasma mass-spectrometry (LA-ICP-MS) and the ever-improving high spatial resolution (i.e. small beam diameter), has made these techniques the most prominent in the last decade (e.g. Najman, 2006; Foster and Carter, 2007; Košler and Sylvester, 2007; Frei and Gerdes, 2009).

This review paper concentrates on accessory minerals (mainly heavy minerals) as they provide more distinct information from single grains on sediment sources in many cases. Typical sand(stone) framework grains such as quartz, feldspar (except for isotopic analysis), and lithoclasts will not be considered here. For detailed lithoclast classifications as well as quartz cathodoluminescence studies we refer to, for instance, Garzanti and Vezzoli (2003) and Bernet and Bassett (2005), respectively. Regarding sediment grain size, we will focus on sand to very coarse silt sized detrital grains because this grain size range is (i) readily available from most sedimentary basins (in contrast to coarser-grained sediment), and (ii) allows for applying a wide range of analytical techniques which is not the case for finer grain sizes. This implies, however, that we will not consider pebble, cobble, or boulder sized material although such coarse material may provide important additional information on pressure–temperature(–time) paths of metamorphic clasts (e.g. Cuthbert, 1991; Spalla et al., 2009), or on the relation of age components to specific lithologic clast types (Dunkl et al., 2009).

Emphasis is placed on techniques, concepts, and their possibilities and shortcomings in defining the type and geologic history of source rocks, as well as the rates and relative proportions at which sediment is being eroded and delivered to the basins. Specific case studies which are often fraught with unique geological circumstances are beyond the scope of this paper that is more intended as a state-of-the-art methodological overview designed for researchers applying single-grain techniques to their respective geological problem. We will first review and evaluate the wealth of possible information extractable from single grains to characterize the nature and chronology of specific rocks and rock associations in the source area. Problems and pitfalls associated with the individual methods will be highlighted. We will further tackle the problems of sediment modification associated with weathering, transport, and deposition, and its possible effects on the significance of detrital single-grain studies. Finally, the link between sophisticated source rock information obtained from single-grains and the bulk sediment transfer from source to sink will be addressed.

2. Source rock characterization

Beyond basic discrimination of different sources and/or the detection of analogy with known sources, single-grain analysis attempts to constrain source rocks and their geologic context from the detrital grains itself, i.e. information from a specific type of grain is used to detect (i) lithology and petrologic conditions of the source rocks, (ii) their ages of crystallization and/or metamorphism, and (iii) the timing of late stage cooling and exhumation to the surface as determined by low-temperature thermochronometers.

In principal, the techniques applied cover nearly all methods developed to study crystalline rocks, too. However, detrital grains have mostly lost their paragenetic context. Therefore, petrologic information on geothermometry and/or geobarometry relying on coexisting mineral pairs or triples (e.g. Powell and Holland, 2008) cannot be applied to detrital sand grains. Instead, such information must be derived from the occurrence and characteristics of single phases that either reflect well defined metamorphic conditions like, for instance, glaucophane or aluminum-silicates such as kyanite or sillimanite (e.g. Yardley, 1989; Evans, 1990), or provide thermobarometric information based on single phase geochemistry and some reasonable assumptions. The latter include Zr-in-rutile geothermometry (Zack et al., 2004a; Tomkins et al., 2007), celadonite content in muscovite (i.e. phengite geobarometry; Massonne and Schreyer, 1987), and Al-in-hornblende