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Uranium-series comminution ages of continental sediments: Case study of a Pleistocene alluvial fan

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ABSTRACT

Obtaining quantitative information about the timescales associated with sediment transport, storage, and deposition in continental settings is important but challenging. The uranium-series comminution age method potentially provides a universal approach for direct dating of Quaternary detrital sediments, and can also provide estimates of the sediment transport and storage timescales. (The word "comminution" means "to reduce to powder," reflecting the start of the comminution age clock as reduction of lithic parent material below a critical grain size threshold of ~50 μm.) To test the comminution age method as a means to date continental sediments, we applied the method to drill-core samples of the glacially-derived Kings River Fan alluvial deposits in central California. Sediments from the 45 m core have independently-estimated depositional ages of up to ~800 ka, based on paleomagnetism and correlations to nearby dated sediments. We characterized sequentially-leached core samples (both bulk sediment and grain size separates) for U, Nd, and Sr isotopes, grain size, surface texture, and mineralogy. In accordance with the comminution age model, where ^{234}U is partially lost from small sediment grains due to alpha recoil, we found that ($^{234}U/^{238}U$) activity ratios generally decrease with age, depth, and specific surface area, with depletions of up to 9% relative to radioactive equilibrium. The resulting calculated comminution ages are reasonable, although they do not exactly match age estimates from previous studies and also depend on assumptions about ^{234}U loss rates. The results indicate that the method may be a significant addition to the sparse set of available tools for dating detrital continental sediments, following further refinement. Improving the accuracy of the method requires more advanced models or measurements for both the recoil loss factor f_α and weathering effects. We discuss several independent methods for obtaining f_α on individual samples that may be useful for future studies.

1. Introduction

The lifetimes of clastic sediment particles in continental settings — from initial formation by weathering and erosion, to transport, storage, deposition, and lithification — both reflect and control the nature of geologic processes in the Earth's surface environment. Among the interrelated areas of interest in which the timing, rates, and durations of sedimentary processes play a key role are: understanding mechanisms of landscape evolution (Dietrich et al., 1982; Dietrich et al. 2003); modulating elemental cycles by controlling the residence time of sediments in natural reservoirs such as floodplains (Dunne et al., 1998, and refs. therein); formation and interpretation of depositional records of paleoclimate and tectonic activity (e.g., Phillips et al., 1997; Last and Smol, 2001; Molnar, 2004); influencing the long-term, erosion-driven drawdown of atmospheric CO_2 by silicate weathering (Raymo and Ruddiman, 1992); and determining sediment flux to the oceans (Hay, 1998; Syvitski et al., 2003).

Although quantifying the timescales of sedimentary cycling is important, obtaining this information is difficult, especially over geologic timescales where direct observation is not possible. Uranium-series isotopes may be helpful in this regard. The isotopic fractionation between various nuclides of the uranium-series decay chains can be used to provide information about sediment history, behavior, and weathering over time periods up to ~10^6 yr (e.g., Osmond and Ivanovich, 1992; Vigier et al., 2001; Chabaux et al., 2003; Granet et al., 2007; Dosseto et al., 2008). In particular, the uranium-series comminution age method (DePaolo et al., 2006) may provide a way to directly date detrital Quaternary sediments and yield information about the timescales of sedimentary processes (Fig. 1). (The word "comminution" means "to reduce to powder," and refers to the start of the U isotope age clock when bedrock has been reduced by

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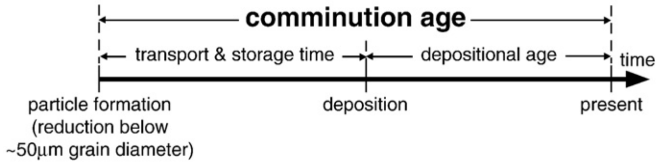

Fig. 1. Relationship of the uranium-series comminution age to other timescales of importance in sedimentary processes. The start of the comminution age "clock" is particularly well-defined for cases where the formation of fine-grained detrital clasts is rapid on a geologic timescale, such as during glacial comminution of bedrock. The utility of subdividing the comminution age is that these constituent timescales can also be determined from the comminution age, depending on the availability of additional information. The comminution age is equal to the depositional age in environments where the sediment transport + storage times are negligible. In settings where the depositional age is independently known, the comminution age is equal to the transport + storage time. Note that transport and storage of sediment particles can happen in multiple environments en route from formation to deposition (e.g., hillslope and fluvial environments in continental settings) — the transport + storage time includes the time spent in all of these environments.

weathering and erosion below a critical grain size threshold to form silt- and clay-sized detrital particles.)

This study evaluates whether the comminution age method, previously applied to well-sorted marine sediments (DePaolo et al., 2006), has applicability to the more challenging case of poorly-sorted continental sediments. Continental sediments are often not suitable for dating by other methods (e.g., cosmogenic radionuclide dating, biostratigraphy, and chemostratigraphy), and may have uranium-hosting nondetrital phases that could perturb the comminution age method as well. We measured uranium isotopes and other characteristics of alluvial fan sediments having independently-estimated depositional ages. Sample pretreatment methods for sequential leaching and sieving were also developed, applied, and evaluated.

2. Comminution age method

The comminution age model (DePaolo et al., 2006) is based on the loss of ^{234}U from a sediment particle due to alpha recoil following decay of the ^{238}U parent (Kigoshi, 1971). In the ^{238}U decay series, this recoil loss occurs via the alpha decay of ^{238}U to an intermediate short-lived ^{234}Th, which then rapidly undergoes beta decay (without significant recoil) to ^{234}U. The ^{234}Th precursor to ^{234}U is recoiled an average distance of ~34 nm in typical silicate minerals (Sun and Semkow, 1998; Maher et al., 2006), a distance that varies only a few nm due to straggling and variations in the compositions (density) of common crustal minerals (Hashimoto et al., 1985). For grains smaller than a threshold diameter of ~50 μm, recoil loss of ^{234}U results in a measurable decrease in (^{234}U/^{238}U). (Parentheses denote the activity ratio, the ^{234}U/^{238}U isotope ratio normalized by the ^{234}U/^{238}U ratio of a standard in secular, or radioactive, equilibrium.) Therefore, if alpha recoil is the only process that separates ^{234}U from ^{238}U, the measured (^{234}U/^{238}U) ratio of a sediment grain, A_{meas}, is a function of four parameters related by the following expression:

$$A_{meas} = (1-f_\alpha) + [A_0-(1-f_\alpha)]e^{-\lambda_{234}t_{comm}} \quad (1)$$

where t_{comm} is the amount of time elapsed since the grain became smaller than the threshold size, referred to as the *comminution age*, f_α is the fraction of ^{238}U decays that result in direct recoil loss of the ^{234}U daughter (f_α thus should be correlated with the grain surface area and size), λ_{234} is the ^{234}U decay constant ($\lambda_{234} = 2.82629 \times 10^{-6}$ yr^{-1}), and A_0 is the (^{234}U/^{238}U) of the parent material from which the sediment grains are derived. A_0 is commonly assumed to be the secular equilibrium value (^{234}U/^{238}U) = 1 for nonporous, crystalline rocks. This method of determining a comminution age is limited to ages less than ~1 Ma, since A_{meas} will reach a grain-size-dependent steady state value after about four half lives of ^{234}U.

The uranium-series comminution age dating method differs from many existing methods for dating continental detrital sediment deposits in that it is a direct dating method with minimal restrictions on material requirements, and the comminution age contains information about not just depositional age, but also transport + storage timescales. The only theoretical requirement for comminution age dating, a uranium-bearing fine-grained sediment component, is easily fulfilled for most lithologic compositions and deposit types. Other dating methods are generally limited by requirements for specific types and/or quantities of material that may not be universally present in the sediment. Examples include nondetrital materials such as: organic matter (^{14}C dating), fossils (biostratigraphy), volcanic marker units (K–Ar and Ar–Ar dating), and select authigenic phases such as carbonate (U-series and stable isotope dating), as well as detrital matter: large quantities of quartz (cosmogenic radionuclide (CRN) techniques, e.g., ^{26}Al/^{10}Be burial dating and ^{10}Be exposure dating (Gosse and Phillips, 2001)), and quartz or feldspar (optically stimulated luminescence (OSL) dating (Aitken, 1998)). Nondetrital dating methods generally yield only the depositional age. Detrital sediment ages obtained by CRN and OSL dating methods should provide complementary information to comminution ages, taking into account fundamental differences in what age is being recorded in the sediments (given the different underlying physico-chemical mechanisms that produce age signals for each method), as well as potential dissimilarities in the histories of the different grain size or mineral fractions being dated.

3. Study area: Kings River Fan

There are several reasons why the Kings River Fan (KRF) was selected as a study area to test the comminution age method on continental sediments. First, the expected comminution ages can be figured out — there are independent constraints on depositional age, sediment transport + storage times can be treated as negligible, and sediment production by glacial erosion implies rapid particle formation and thus a well-defined start to the comminution age clock. Second, the parent lithology is largely crystalline, allowing the assumption of $A_0 = 1$ to hold. Third, the potential complicating effects of subaerial weathering on U isotope behavior are minimal for the samples studied.

The Kings River Fan is a large (3150 km^2) alluvial fan located off the western slope of the Sierra Nevada in central California (Fig. 2). Sediment in this fan derives from a catchment with an area of 4400 km^2 (Weissmann et al., 2005), which is underlain almost entirely by crystalline rocks of the Sierra Nevada batholith and related pre-intrusive metamorphic rocks. Approximately the upper half of the basin was covered with ice during peak Pleistocene glaciations (Wahrhaftig and Birman, 1965). In this glaciated area, where erosion was probably most rapid, the bedrock is predominantly granitic.

Samples used in this study are from a 45 m-long sediment core taken near the present-day fan apex (36°42′58″ N, 119°38′53″ W). This is designated as Core B5 in Burow et al. (1999) and Weissmann et al. (2002). Three depositional facies can be identified: channel deposits, overbank deposits, and moderately mature paleosols (Fig. 3a), all composed of glacial flour and coarser sediment originating from Pleistocene glaciations in the Sierra Nevada (Weissmann et al., 2002, and refs. therein).

Inferred depositional ages of the sediments in the KRF core as a function of depth are shown in Fig. 3b. The deepest samples have the most well-constrained ages: paleomagnetic measurements on the core samples indicate that the Matuyama–Brunhes magnetic reversal (780 ka) occurs near 41 m depth (Weissmann et al., 2002). Additional age information is obtained by correlation to type sections described in Marchand and Allwardt (1981) using the age inferences of Lettis (1988), which comprise the commonly-accepted chronology for the fan deposits of the eastern San Joaquin Valley. The age–depth model includes temporal hiatuses between major depositional units,