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Constraining the transport time of lithogenic sediments to the Okinawa Trough (East China Sea)

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ABSTRACT

The transport time of siliciclastic sediments from their continental sites of formation to their final location of deposition on the seafloor is an important parameter bearing on land–sea interactions, climate variability and understanding of marine sediment record. $^{234}U/^{238}U$ activity ratios of the lithogenic fraction from late Quaternary sediment deposited in the Okinawa Trough, East China Sea, were reported in this study. On basis of $^{234}U/^{238}U$ activity ratios, the comminution ages and transport times were calculated using recoil loss factors (f_α) derived from different equations based on grain size distribution. The transport times were longer (approximately 200 ± 100 kyr) for the Okinawa Trough sediments deposited between 27 and 14 ka, decreased gradually between 14 and 7 ka, and stayed relatively short (<100 kyr) thereafter. Mineralogical, geochemical and isotopic evidences indicate that changes in sediment transport time correspond well with the shift of sediment provenance predominantly from Asia's interior prior to 14 ka to Taiwan Island after 7 ka. This study offers the first and robust constraint on time scale of sediment transport process in East Asia marginal sea, which is constrained by unique sediment source-to-sink transport pattern. The result illustrates the potential of this approach to decipher climate-related changes in the mode of supply of lithogenic sediment to marginal seas. It also highlights current difficulties in obtaining quantitative estimates of comminution age, mostly because of uncertainties in estimating the recoil loss factor.

1. Introduction

The East China Sea (ECS) links the Eurasian continent and the Pacific Ocean, and it is characterized by broad continental shelf and huge terrigenous sediment input from adjacent rivers. The river-dominated marginal sea witnessed the complex sediment source-to-sink transport and sedimentary environmental changes during the late Quaternary (Li et al., 2014). Particularly, two distinct river systems predominantly determine the sediment source-to-sink process in this region, the Changjiang (Yangtze River), one of the largest river in the world, and the small mountainous rivers, especially those in Taiwan Island (Yang et al., 2015). The sediment transferring from both river systems is thus of great significance to the sedimentary records and chemical evolution in the ECS. In view of this, the sediment provenances, depositional processes and paleoenvironmental changes in the ECS have been extensively investigated over the last decade (Dou et al., 2010a, 2015; Li et al., 2015b). However, the absolute time scale of sediment transport in the ECS and East Asia continental margin, which is critical to the sediment source-to-sink processes and marine records, remains unknown (Li et al., 2015a).

The timescale of lithogenic sediment cycling is crucial for assessing the long-term carbon burial by erosion, determining the factors controlling the flux of lithogenic material to the ocean, and understanding the stratigraphic evolution of continental margins and marine records. The lithogenic material accumulating in the Okinawa Trough (OT), was mostly derived from the Changjiang and Taiwan Island (Dou et al., 2010a,b, 2016), and has formed continuous and thick sediment strata during the late Quaternary. As one of the major sinks for terrigenous input in the ECS (Qin et al., 1987), the late Quaternary deposition in the OT provides an important archive for investigating the evolution of Changjiang and Taiwan Island river systems in response to climate change and sea level rise (Li et al., 2015a).

U-series nuclides are widely used to constrain the rates of earth surface processes (Bourdon et al., 2003; Chabaux et al., 2008, 2011; Dosseto et al., 2008; Ma et al., 2010; Vigier and Bourdon, 2011; Dosseto, 2015; Dosseto and Schaller, 2016), and a new approach has recently been proposed to estimate the “transport time” of lithogenic particles from their comminution ages (i.e. the time that has elapsed since their formation by weathering) based on their $^{234}U/^{238}U$ activity ratios (DePaolo et al.,

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2006, 2012; Maher et al., 2006; Dosseto et al., 2010; Lee et al., 2010; Handley et al., 2013a). This comminution dating approach is primarily based on $^{234}U/^{238}U$ disequilibrium resulted from recoil loss in fine-grained sediments. The method has been applied in North Atlantic deep sea sediment (DePaolo et al., 2006), paleo-channel sediment (Dosseto et al., 2010; Lee et al., 2010; Handley et al., 2013a,b) and Antarctica ice core (Aciego et al., 2011), which yielded reasonable time-scale of sediment transfer across various geology settings. However, its theoretical basis, parameter calculation (e.g. recoil loss factor) and external constraint are still under debate. Therefore, further testing and consideration of the methodology are necessary to improve the accuracy of age estimation and to develop its application in future studies.

The goal of this study is to apply the comminution age method to estimate the transport time of lithogenic sediments deposited in OT, and further to compare the results with changes in sediment provenance deduced from a series of mineralogical (Dou et al., 2010b), geochemical (Dou et al., 2010a) and isotopic analysis (Dou et al., 2012, 2016). Besides, this study also makes the first attempt of applying the comminution age method in the river-dominated marginal sea, which will be an important exploration and contribution to the U-series disequilibrium study.

2. Comminution age theory

The determination of comminution age is based on the continuous loss of ^{234}U from the thin outer layer (~30 nm in thickness) of silicate mineral particles, which results from alpha recoil (Kigoshi, 1971). During this process, ^{234}Th is ejected due to ^{238}U alpha-decay and then ^{234}Th decays to ^{234}U with a half-life of only 24 days. Because ^{234}Th ejection from a mineral grain is only possible from this very thin outer layer, the loss of ^{234}U is a function of the surface area to volume of the particle (Vigier and Bourdon, 2011). The continuous loss of ^{234}U results in a measurable decrease in ($^{234}U/^{238}U$) (parentheses denote activity ratios throughout this paper) of the entire grain only when the surface area to volume increases to certain extent (approximately at ~50 μm diameter) (DePaolo et al., 2006). The "comminution age" is thus defined as the time elapsed since the sediment grain is smaller than ~50 μm. Once such small particles have been formed by weathering and erosion, their ($^{234}U/^{238}U$) ratios start to decrease. If the small particle undergoes no additional abrasion or loss of depleted surface, their ($^{234}U/^{238}U$) eventually reaches a steady state value, which is determined by the size and shape of the particles and the roughness of their surface. However, it is argued that preferential loss of ^{234}U relative to ^{238}U may occur via leaching during weathering of the source rock and/or sediment transport process (Eyal and Olander, 1990; Bourdon et al., 2009). However, DePaolo et al. (2006) and Maher et al. (2006) have found that the observed loss of ^{234}U can be caused by α-recoil effects only and does not require preferential leaching of ^{234}U, especially when the leaching occurs in a depth that is not much greater in magnitude than the recoil range. With all these assumptions, the "comminution age" (t_{com}) can be calculated from Eq. (1) (DePaolo et al., 2006):

$$t_{com} = -\frac{1}{\lambda_{234}} \ln\left[\frac{A_{meas} - (1 - f_\alpha)}{A_0 - (1 - f_\alpha)}\right] \quad (1)$$

where A_0 is ($^{234}U/^{238}U$) of the parent rock, A_{meas} is ($^{234}U/^{238}U$) of the sample studied, λ_{234} is the decay constant of ^{234}U, and f_α is the recoil loss factor, i.e. the fraction of ^{238}U decay in the sample that results in the ejection of a ^{234}Th atom (Kigoshi, 1971; Maher et al., 2006). The "transport time" of fine-grained particles between sites of their formation from parent rocks to sites of final deposition (e.g. seafloor) can then be calculated by subtracting the depositional age, obtained from core chronology, from the comminution age. Obviously, the calculated "transport time" integrates the storage time of particles in weathering profiles, their transport time in river channels, and residence time in alluvial plains and on the continental shelf (Dosseto et al., 2010).

3. Study area

The Okinawa Trough (Fig. 1a) is a typical back-arc basin of the Ryukyu trench-arc system, bounded by the Ryukyu Ridge and Trench to the south and east, and by the ECS shelf to the north and west. The entire OT is arcuate, convex toward the west Pacific, from Japan to Taiwan. It has a large section of more than 1000 m in depth and the deepest part, near Taiwan Island, is about 2270 m deep. The OT shoals gradually northeastward toward Japan and is underlain by about 1–2 km of sediment (Lee et al., 1980). The OT is a depositional basin with a relatively high rate of sedimentation of primarily terrigenous sediment from the East Asia continent, ECS continental shelf and island arc via the numerous adjacent rivers (Qin et al., 1987). As a passage linking East Asian continent to the west Pacific Ocean, the OT may serve as a sensitive reflection of environmental transition between the ocean and continental settings. The most striking oceanographic feature in the OT is the Kuroshio Current which is the largest western boundary current in the North Pacific Ocean.

Among the numerous rivers entering the ECS, the Changjiang (Yangtze River) is the largest one in East Asian continent. It originates from the Tibet Plateau and its catchment, which is up to 1.8×10^6 km^2 in area, is primarily situated on the Yangtze Craton. Geologically, the Changjiang catchment comprises complex rock types including Archean metamorphic rocks, Jurassic sandstone, Paleozoic carbonate and sedimentary rocks, Mesozoic–Cenozoic igneous and clastic rocks, and Quaternary detrital sediments (Yang et al., 2004). Base on the long-term hydraulic observation, the Changjiang annually delivers about 470 Mt suspended sediments to the ECS (Milliman and Farnsworth, 2011). Major part of the Changjiang-derived sediment is trapped in its estuary and deposited on adjacent ECS shelf (Liu et al., 2007), while the remainder may be transported to the Okinawa Trough, resulting in a thick sedimentary deposit (Qin et al., 1987).

Apart from the large rivers, small rivers in East Asia also play an important role in sedimentation in the ECS, in particular the small mountainous rivers from Taiwan Island (Kao and Milliman, 2008). The island of Taiwan is characterized by its strong tectonic uplift at a rate of 5–10 mm/yr (Shin and Teng, 2001), and high physical erosion rate up to 3–6 mm/yr (Dadson et al., 2003). Together with the frequent typhoon and earthquake events, the rivers in Taiwan discharge about 180 Mt/yr sediment to the surrounding marginal seas, showing one of the highest sediment yields in the world (Kao and Milliman, 2008). The Taiwan river basins are mainly composed of sedimentary rocks and epimetamorphic rocks including sandstone, shale, slate and phyllite, with rare occurrence of acidic rocks. The Zhuoshui (also named Chuoshui) River as the largest one in Taiwan, originates from Central Mountain Range, with an elevation of about 3000 m and the total length of 186 km.

4. Samples and methods

4.1. Sources of river and marine sediment samples

In this study, a total of 24 sediment samples were selected from the piston core DGKS9604 (28°16.64′ N, 127°01.43′ E, 766 m water depth) taken from the OT in 1996 during the joint Chinese–French DONGHAI Cruise (Fig. 1a). The age model is derived from oxygen isotopic composition and radiocarbon dates measured on planktonic foraminifera *Globigerinoides sacculifer* determined by accelerator mass spectrometry (Yu et al., 2009).

For constraining the sediment transport times of the modern Changjiang River, two suspended sediment samples were collected near Chongqing (CQ) and Nantong (NT), which represent the upstream and estuary (Fig. 1c), respectively. Another two riverine suspended samples from Taiwan Island were collected from the upstream (ZS-1) and estuary (ZS-2) of the Zhuoshui River (Fig. 1d), respectively. All the riverine suspended samples are collected by a 0.45 μm filter. Detailed sample information is shown in Table 1.