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Quantifying the provenance of aeolian sediments using multiple composite fingerprints

Benli Liu [a,*], Qinghe Niu [a], Jianjun Qu [a,b], Ruiping Zu [a]

[a] *Dunhuang Gobi Desert Research Station, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China*
[b] *Gansu Center for Sand Hazard Reduction Engineering and Technology, Lanzhou 730000, China*

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ABSTRACT

We introduce a new fingerprinting method that uses multiple composite fingerprints for studies of aeolian sediment provenance. We used this method to quantify the provenance of sediments on both sides of the Qinghai-Tibetan Railway (QTR) in the Cuona Lake section of the Tibetan Plateau (TP), in an environment characterized by aeolian and fluvial interactions. The method involves repeatedly solving a linear mixing model based on mass conservation; the model is not limited to spatial scale or transport types and uses all the tracer groups that passed the range check, Kruskal-Wallis H-test, and a strict analytical solution screening. The proportional estimates that result from using different composite fingerprints are highly variable; however, the average of these fingerprints has a greater accuracy and certainty than any single fingerprint. The results show that sand from the lake beach, hilly surface, and gullies contribute, respectively, 48%, 31% and 21% to the western railway sediments and 43%, 33% and 24% to the eastern railway sediments. The difference between contributions from various sources on either side of the railway, which may increase in the future, was clearly related to variations in local transport characteristics, a conclusion that is supported by grain size analysis. The construction of the QTR changed the local cycling of materials, and the difference in provenance between the sediments that are separated by the railway reflects the changed sedimentary conditions on either side of the railway. The effectiveness of this method suggests that it will be useful in other studies of aeolian sediments.

1. Introduction

Quantitative information regarding sediment provenance can inform effective measures to control erosion of soil by water or wind. However, because of the complex nature of various types of erosion and sediment transport processes, it is difficult to measure this information directly. Therefore, over the past three decades, studies have focused on methods of indirect estimation such as the sediment source fingerprinting method using a linear mixing model. A variety of fingerprint tracers can be used, including the physical, geochemical, radiological, isotopic, and mineralogical characteristics of soil. Previous studies have used both single and grouped tracers, but optimum composite fingerprinting methods that use multiple tracers are becoming increasingly common. In these methods, the mixing model is solved with complex numerical approaches such as Monte Carlo simulation, changed to different variants, or several adjustment coefficients are added (Collins et al., 1998; Gruszowski et al., 2003; Mukundan et al., 2010; Russell et al., 2001; Walling and Woodward, 1995; Wilkinson et al., 2013). However, optimum composite fingerprint methods are complex and many of their components have been called into question, including tracer selection, the treatment of conservative tracers, mixing model modification, and the validity of additional coefficients (Laceby and Olley, 2015; Sherriff et al., 2015; Smith et al., 2015).

Recently, it has been suggested that there is no single optimum composite fingerprint because the ability of a single tracer or group of tracers to discriminate between sources has no direct relationship to the error associated with the contributions of various sources (Zhang and Liu, 2016). Additionally, analytical conflicts between tracers should be used to screen tracer composites. Finally, three methods were shown to yield similar source contribution results though all differed from the estimates made using a single optimum composite fingerprint. The three methods included analytical solution using all positive-definite ($n-1$ tracers for an n-source study) tracer combinations, numerical optimization using overdetermined tracer numbers, and Monte Carlo simulation considering tracer correlations. A new approach that uses a

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[*] Corresponding author at: No. 320 Donggangxi Road, Lanzhou 730000, Gansu, China.

E-mail address: liubenli@lzb.ac.cn (B. Liu).

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maximum number of composite fingerprints to obtain multiple analytical solutions was recently proposed (Zhang and Liu, 2016). This approach was further compared to results from radionuclide analysis with greater confidence (Zhang et al., 2016).

Sediment provenance research for aeolian deposition could make use of the same sediment properties (usually geochemical and rare earth element compositions), to verify distant sediment provenances such as the sources of Loess Plateau (Ferrat et al., 2011; Hu and Yang, 2016; Kasper-Zubillaga et al., 2008; Lawton et al., 2015; Liu et al., 1993; Ma et al., 2015; Nie et al., 2015; Yang et al., 2007). However, few quantitative conclusions regarding source contributions have been reached thus far. If the contributions of different erosion sources can be identified, wind erosion control measures could be enacted in those areas. Mixing models based on mass conservation and sediment source fingerprinting are not limited by spatial scale or sediment transport processes. Therefore, the significant progress made in refining these fingerprinting techniques could be used in studies of aeolian sediment to quantify the contributions of various sources.

This study aims is to use the recently introduced method of multiple composite fingerprinting to estimate provenance contributions for aeolian sediments. We test the method by comparing two spatially close but compositionally distinct deposits on either side of the Qinghai-Tibetan Railway (QTR) at the Cuona Lake section of the Tibetan Plateau (TP) in an environment characterized by aeolian and fluvial interactions.

2. Materials and methods

2.1. Study area

The study area is located next to the QTR and east of Cuona Lake in Anduo County, Tibet. Cuona Lake is at the head of the Nujiang River (called the Salween River in Burma and Thailand). East of the railway, a sandy area that occupies approximately 180 km^2 covers the hilly landscape that was carved by extensive seasonal gullies and streams flowing into the lake. The sand in the lake beach to the west of the railway has a high moisture content during the wet summers but is dry during the winter and spring. The area is characterized by high winds and pervasive movement of sand induced by wind. The average wind speed (over multiple years) is 4.1 m/s, and there are 150 days per year with high wind speeds (>17.2 m/s) (Liu et al., 2016). During the winter and spring, the prevailing winds blow from the west (resulting in a sand-drift wind direction of 259°). This moves the sands from the lakeshore to the hilly areas, while floods and secondary winds from the east transport sands towards the lake, following the terrain downhill (Fig. 1).

In the past, sands in the transition area between the lake and the sandy region were well mixed by natural cycling processes. However, this changed when the section of the QTR from Gulmu to Lasha was built in 2006. Although a long span bridge was built over the flood-affected area, most aeolian sand transport was intercepted by sections of the railway and bilateral sand control measures, resulting in serious sand accumulation on both sides of the railway.

The aeolian sands have accumulated on the two sides by winds coming from different directions. Therefore, the sands on both sides should have distinct sources. The western side should receive more beach sands, while the eastern side should receive sediment from the inland sandy area. An effective fingerprinting model should be able to distinguish between these sources and quantify the provenance of the sediments on both sides of the railway, although they are spatially very close.

2.2. Sample collection

Two surface sand sources that are moved by wind (the sandy area and the beach) and one soil source that is affected first by fluvial action and later wind (the sandy gully bank) were identified as potential sediment sources for the deposits on either side of the railway. Sands on the hilly land surface or dunes in the sandy area could be moved towards the railway by easterly winds. The prevalent gully bank sands are materials that were deposited in the past and could be disturbed by floods and spread to the sandy area surface or transported to the lake beach. In total, 13 surface sand samples were taken from across the sandy area based on their distribution within the area and accessibility; 11 gully samples were taken from near each surface sampling spot. Each sample was a composite of 3 replicates (see Fig. 2).

To collect the beach sand samples, an isolated sandy mound approximately 4 m above the water surface was found on the lakeshore; the surrounding material had been eroded to form part of the sediment supply to the area near the railway. The layers of the mound record the historical deposition process, and the deposits near the railway represent a mixture of these layers. A 2.7 m sampling profile beginning at the top of the mound was created;

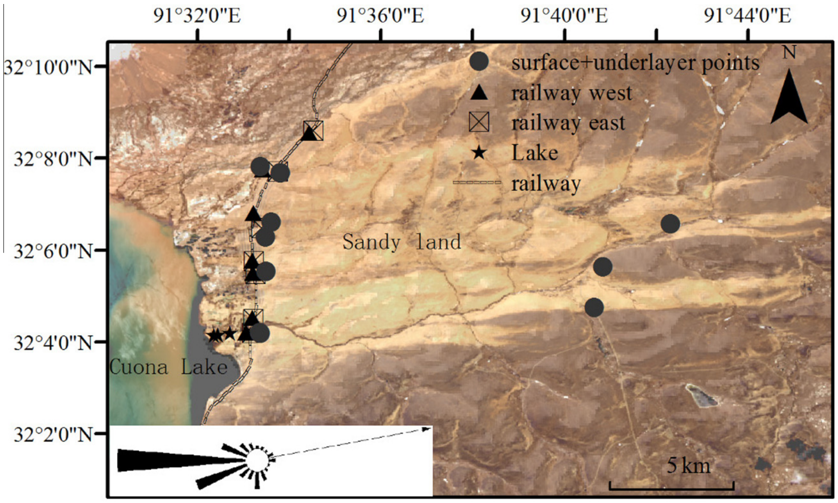

Fig. 1. Location of the study area, sampling points, and wind rose diagram.