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Barrier effects of remote high mountain on atmospheric metal transport in the eastern Tibetan Plateau

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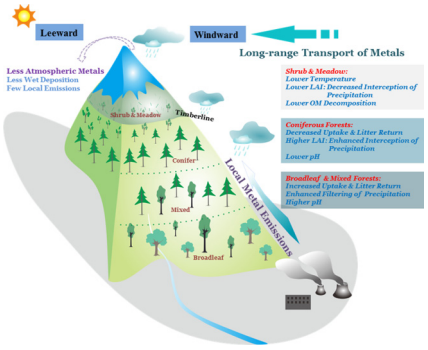
HIGHLIGHTS

- Elevation distributions of Cd and Pb in multiple archives varied clearly along three transects of the highest mountain in eastern Tibetan Plateau.
- Metal concentrations were significantly higher in windward transect than leeward transect.
- Pb isotopic ratios coupled with moss and rainfall monitoring distinguished anthropogenic metal sources.
- A conceptual model delineates environmental effects on the atmospheric transport of metals.
- High mountains in eastern TP are effective natural barrier limiting atmospheric metal transport.

GRAPHICAL ABSTRACT



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ABSTRACT

Anthropogenic metals adsorbed on suspended fine particles can be deposited on remote and inaccessible high mountains by long-range atmospheric transport. In this study, we investigated the cadmium (Cd) and lead (Pb) in the soils, mosses and rainfall of three transects on the Gongga Mountain, eastern Tibetan Plateau, to understand the mountain interception effects on their atmospheric transport. The concentrations of Cd and Pb in the soils and mosses displayed a pattern of eastern transect > northern transect > western transect. The distribution of Cd and Pb on the eastern transect increased from 2000 to 2900 m a.s.l. (above sea level), decreased toward the timberline, and increased again with altitude; on the northern transect, it generally decreased with altitude whereas a distribution trend was not clearly observed on the western transect. The Cd and Pb concentrations in the rainfall of the eastern transect generally decreased with altitude, and they were higher inside forests than outside forests and temporally higher in the winter than the summer. The Pb isotopic ratios coupled with moss bio-monitoring distinguished anthropogenic sources of Cd and Pb on the eastern and northern transects, whereas bedrock weathering was the main source of Cd and Pb on the western transect. We proposed a conceptual model to delineate the effects of terrain, local climate and vegetation on the transport of atmospheric metals. Our results highlighted the high mountains in the eastern Tibetan Plateau as an effective natural barrier limiting atmospheric metal transport.

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1. Introduction

Remote high mountains with various vegetation zones are natural archives of atmospheric pollutants (Bacardit and Camarero, 2010; Bing et al., 2014). The trace toxic metals contained in anthropogenic aerosols can be deposited on the high mountain as a result of atmospheric transport and the mountain condensation effect. The huge mountain bodies with a sharp increase in altitude in a short distance and complex underlying surfaces tend to alter atmospheric circulation (Wang and Chang, 2012; Wu et al., 2014; Xie et al., 2006), and, consequently, the transport processes of atmospheric metals. Moreover, high mountains feature complex climatic, biological and orographic conditions that may govern the distribution of deposited trace metals. However, the explicit mechanisms of high mountain barrier effects on the transport of atmospheric metals and their allocation in mountain systems remain unclear.

The observation and measurement of anthropogenic metals on remote, high mountainous areas are long-term challenges in the field due to harsh environmental conditions and logistical difficulties. Multiple environmental archives, such as soils, biological indicators, and dry and wet deposition, coupled with geochemical, statistical and fingerprint techniques, have opened up venues to distinguish the source characteristics of anthropogenic metals from atmospheric deposition (Bindler et al., 1999; Bing et al., 2016a; Harmens et al., 2010; Weiss et al., 1999). Among the trace metal isotopic fingerprints, the Pb isotopic tracing technique has been more extensively applied due to the globally comprehensive dataset of its isotopic ratios (Bi et al., 2017; Ferrat et al., 2012; Kaste et al., 2003; Klaminder et al., 2008; Pérez-Rodríguez et al., 2018; Steinnes et al., 2005).

The eastern Tibetan Plateau (TP) is characterized by many high mountains with a low population density, and these mountains form a natural ecological barrier for atmospheric metal transport. Gongga Mountain (peak: 7556 m a.s.l., above sea level) is the highest mountain in the eastern TP. It has long been recognized as an ideal natural laboratory for understanding the long-range transport of air pollutants (Liu et al., 2014, 2017; Wu et al., 2011; Zheng et al., 2015). Previous studies have conducted preliminary investigation on some trace metals on the eastern transect of Mt. Gongga, and Cd and Pb have been identified as the most possible metals with anthropogenic sources through multiple environmental archives including soils (Bing et al., 2014, 2016b; Li et al., 2015; Wu et al., 2011), plants (Bing et al., 2016a), lake sediments (Bing et al., 2016c) and atmospheric aerosols (Yang et al., 2009). This remote, high mountain is expected to play a vital role in the atmospheric transport of metals west of the TP due to its impact on the monsoon circulation in southwestern China. In this regard, we focused on the distribution of Cd and Pb in the soils, mosses and rainfall with altitude on the eastern, northern and western transects of Mt. Gongga.

The specific objectives of this work are to explore the differences in the distribution patterns of Cd and Pb with altitude along the eastern, northern and western transects of Mt. Gongga, to identify their atmospheric and anthropogenic sources, and to decipher the high mountain effects on the distribution and transport of the atmospheric metals. This work provides insights into the influential roles of high mountains in pollutant transport through atmospheric circulation.

2. Materials and methods

2.1. Study area and sampling

Mt. Gongga (29°20′–30°20′N, 101°30′–102°15′E) is located in the eastern TP (Fig. 1). The climate around Mt. Gongga is a typical temperate monsoon climate. The parent materials are dominated by glacial debris and colluvial deposits from weathered Cenozoic feldspar granite and Permian quartz schist. Frequent debris flows along the altitudinal transects formed many debris flow gullies and deposits (Zhong et al., 1999). The vegetation distribution, soil types and meteorological information with altitude are summarized in Table S1.

The sampling sites of soils and mosses were selected to include all vegetation zones (Table S1). In September 2013, the sampling was carried out between 2000 and 4500 m a.s.l., 2400 and 4100 m a.s.l., and 3300 and 4100 m a.s.l. on the eastern, northern and western transects, respectively (Fig. 1, Table S2). The sampling sites of the mosses were as near as possible to those of the soils, but they were still different due to differences in the terrain, moss distribution, species, and other features. Because of the difficulty in accessibility and the differences in the vegetation distribution with altitude, the sampling sites were selected unevenly with respect to altitude.

At each site, three repeated soil profiles were hand-dug, and three soil units including the O horizon (organic matter-rich soils), A horizon (surface mineral soils) and C horizon (soil parent materials) were divided according to the field characteristics (Bing et al., 2016b, *also see the SI*). Due to differing soil development, the O horizon at several sites was absent (Table S2). The dominant moss species (*Brachythecium albicans* and *Pleurozium schreberi*) were collected from the surface of at least five blocks of rocks at each sampling site. Another moss (*Papillaria crocea*) sampled from five trees was only collected at one altitude for each transect (*see the SI*).

The rainfall was only collected between 1600 and 3615 m a.s.l. on the eastern transect. Five sites were selected close to the positions of the soil sampling sites (E1–E4, E7), and one site was set in Moxi Town at 1600 m a.s.l. (Fig. 1). All rainfall containers made from polyethylene materials were cleaned with nitric acid and deionized water before sampling, and then three replicates were placed inside and outside the forests at each altitude, respectively. The rainfall samples were collected bimonthly in the dry season and monthly in the wet season.

The soil samples were air-dried at room temperature and sieved <2 mm to remove plant residues and coarser particles. The mosses were rinsed with distilled water to remove the dust for several seconds and then oven-dried at 60 °C. Then, the soil samples were pulverized by an agate mortar, and the mosses were pulverized by a crusher with stainless steel tri-rotors, to pass through a 100-mesh Nylon screen for the element analysis. The rainfall samples were kept in a low temperature (4 °C) before analysis.

2.2. Chemical analysis

The soil samples were digested with a mixture of concentrated acid (HNO_3, HF, HCl and $HClO_4$) (Liu et al., 2013). The moss samples were digested with a concentrated acid mixture of HNO_3 and $HClO_4$ (Bing et al., 2014). The rainfall samples were digested with concentrated HNO_3 at 190 °C for 2 h. The concentrations of Cd and Pb in the digestion solution were determined by inductively coupled plasma mass spectrometry (ICP-MS, Agilent). Standard solution SPEX™ was used as the standard. Quality control was assured by an analysis of blanks, duplicate samples and reference materials (soil: GSD-9 and GSD-11; moss: GBW07603 and GBW07604). The precision and accuracy were routinely below 5% based on the relative standard deviation (RSD) of the repeated samples and standard reference materials, respectively.

The Pb isotopes (^{208}Pb, ^{207}Pb and ^{206}Pb) in the soils and mosses were determined by ICP-MS (Agilent 7700x). A standard reference material from the United States National Institute of Standards and Technology-SRM 981 was used for instrument calibration ($^{208}Pb/^{206}Pb = 2.1681 \pm 0.0008$, $^{207}Pb/^{206}Pb = 0.9146 \pm 0.00033$), and the standard material GBW04426 from China was selected for quality control ($^{208}Pb/^{206}Pb = 2.1280 \pm 0.00016$, $^{207}Pb/^{206}Pb = 0.8677 \pm 0.00007$). According to multiple measurements of GBW04426 with the calibration of SRM 981, the values of $^{208}Pb/^{206}Pb$ and $^{207}Pb/^{206}Pb$ were 2.135 ± 0.0016 and 0.869 ± 0.0009, respectively. According to the replicate analysis of the SRM 981 standard, the precision of the $^{208}Pb/^{206}Pb$ and $^{207}Pb/^{206}Pb$ ratios was <0.07% and <0.12% RSD, respectively.

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