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ARTICLES

# Records of volcanic events since AD 1800 in the East Rongbuk ice core from Mt. Qomolangma

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**Continuous Bi profile of the East Rongbuk (ER) ice core near Mt. Qomolangma reveals nine major volcanic events since AD 1800. Compared with Volcanic Explosivity Index (VEI), it shows that the concentrations of Bi in the ER ice core can reflect the major volcanic events within the key areas. This provides a good horizon layer for ice core dating, as well as a basis for reconstructing a long sequence of volcanic records from the Qinghai-Xizang (Tibet) Plateau ice cores.**

Mt. Qomolangma, East Rongbuk ice core, volcanic events, Bi

Volcanic eruptions eject large amounts of gas (mainly sulphur dioxide) and dust (generally silicate ash) into the atmosphere that can be transported via atmospheric circulation and deposited on the surface of the ice sheets or mountainous glaciers. This provides a useful method to study the past volcanism by ice core records. Hammer[1] first identified volcanic events by sulfuric acid layers preserved in a polar ice core. Afterwards, a number of major volcanic events were ascertained from ice cores[2,3]. Delmas et al.[4] detected 23 major volcanic events in a 1000-year Antarctic ice core. The records of volcanic events at millennial scale were gradually reconstructed by the Antarctic and Greenland ice cores[5,6], and provided evidence that volcanism may contribute to climatic cooling[7]. The good agreement between the ice core based volcanic events and the well-established volcanic sequence validates the application of ice cores for reconstructing past volcanism[3]. The significance of ice core volcanic records lies in (1) determining eruption time, estimating the contribution of volcanic eruption to the atmospheric aerosol loading[8,9] and enhancing our understanding of the climate effects of volcanism[10], and (2) providing horizons for ice core dating[11,12].

More and more ice cores are available for studying volcanic events[12−16], which provides a reliable method to understand the global historical volcanic eruptions. However, few ice cores from the low-latitude mountainous glaciers have been used for reconstructing the volcanic events due to the disturbance of high dust background. For instance, an ice core from the Canadian Yukon Territory did not provide a good record of a certain remote volcanic events due to too large $SO_4^{2-}$ contribution from local dust[17]. Even for some Antarctic ice cores, the volcanic sulfate of a certain volcanic event accounts for only 13% of the total sulfate deposition[4]. In fact, the materials of major volcanic eruptions are transported mainly in the stratosphere to the polar regions, resulting in an even more obvious signal in the polar ice sheets than that in the mountain glaciers.

Recently, Kaspari et al.[11] identified major volcanic events in the ER ice core by applying the element of Bi. Here we explore this new way to recover a detailed volcanic events record since AD 1800 from the ER ice core.

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GEOGRAPHY

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## 1 Sampling and analytical methods

### 1.1 Sampling

Two ice cores to bedrock (108.83 m and 95.80 m, respectively) and a 40 m shallow ice core[18] were recovered in 2002, on the col of the ER Glacier (28°01'05"N; 86°57'52"E, 6518 ma.s.l.). The drilling site is located in the accumulation zone of the Glacier with a weak horizontal movement (identified by repeat survey in 1998 and 2002 with a GPS). Bore-hole temperatures in the 108.83 m core hole ranged from a minimum of −9.6℃ at 20 m to −8.9℃ at bottom. These features indicate that the ER Glacier is an ideal place for ice core study.

The 108.83 m ice core was melted into 3123 samples and analyzed for soluble ions ($Na^+$, $K^+$, $Mg^{2+}$, $Ca^{2+}$, $Cl^-$, $NO^{3-}$, $SO_4^{2-}$), hydrogen isotopes ($\delta$D), and trace elements[11]. The ice core was annually dated to AD 1534 at a depth of 98 m according to seasonal variations in $\delta$D and soluble ions, and the timescale was verified by identifying large volcanic horizons. Below 98 m, annual layer counting is not possible due to layer thinning, thus prior to AD 1534 the ice core was dated by using a flow model. The age of the bottom two meters was constrained using methane and the isotopic composition of atmospheric $O_2$ with the results of 1498—2055 BP[19]. Dating uncertainties are ±0 years at AD 1963 and ±5 years at AD 1534. More details can be found in Kaspari et al.[11].

### 1.2 Volcanic record index

Bi is an excellent tracer of volcanic event because it is highly enriched in volcanic eruptions, and volcanic events are the largest source of global Bi[20]. To identify enriched volcanic Bi, we calculated Bi enrichment factors (EFc) defined as the concentration ratio of Bi to that of a crustal element and normalized to the same concentration ratio of the upper continental crust. EFcBi = median[(Bi/x)ice/(Bi/x)upper crust]; x = Sr, Ca, La, Fe and Al.

## 2 Results and discussion

### 2.1 The possible source areas

The strength of a volcanic eruption, usually expressed as VEI[21,22], primarily links to the volume of tephra and the eruption column height. The volume of VEI⩽3 eruption is less than 0.1 $km^3$, the eruption column height is mainly in the troposphere, and the eruption material has a weak impaction on the climate and environment. The eruptions of VEI⩾4 usually produce a large quantity tephra, a higher eruption column than troposphere, and a wide climatic and environmental impaction. For instance, the eruption of Pinatubo in June 1991 (VEI=5) caused a major increase in the aerosol loading in the stratosphere. The cloud column reached at 30 km and the tephra accumulated primarily at 20—25 km[23]. The amount of mass ejected by this eruption was about 20 Mt of $SO_2$[24]. Within 2 weeks the bulk of the resulting stratospheric aerosol cloud had circled the planet while spreading to the tropical latitudes between 20°S and 30°N[23,25]. For such a violent volcanic eruption, most of the eruption materials are ejected into the stratosphere, and transportation mainly occurs in the stratosphere. These materials deposit to the surface in the high latitudes[26,27]. Although the aerosol in the troposphere falls out of the atmosphere very rapidly on timescales of minutes to a few weeks, the aerosol in the stratosphere can stay on timescales of a few months to several years[10].

Our ice core drilling site is located on the southern margin of the Qinghai-Xizang (Tibet) Plateau (QXP), and is influenced remarkably by monsoon circulation, namely, westerly in the winter half year and Indian monsoon in the summer half year. Therefore, the volcanic materials in the troposphere are mainly transported through these two weather systems. Cong et al.[28] showed that there exists strong air transport from troposphere to stratosphere in summer, and weak transport from stratosphere to troposphere in winter over the QXP and its surroundings. So the volcanic material in the ER ice core is mainly transported in troposphere, but does not rule out the possibility to transport through stratosphere for a major volcanic eruption. Figure 1 shows the geographical distributions of volcanic events since AD 1800 based on VEI[21]. Judged from the winter and summer air transport routes, we tag two most likely volcanic source regions. Region 1 represents westerly transport region, and region 2 (to the southern of 20°S[29]) represents Indian monsoon transport region. Table 1 shows the list of VEI⩾4 volcanic eruptions in these two regions. The longest lag time in the ER ice core volcanic record should be 1—2 years, less than that of the polar ice cores[7].

### 2.2 The volcanic events record

The changes of EFcBi are shown in Figure 2, and high

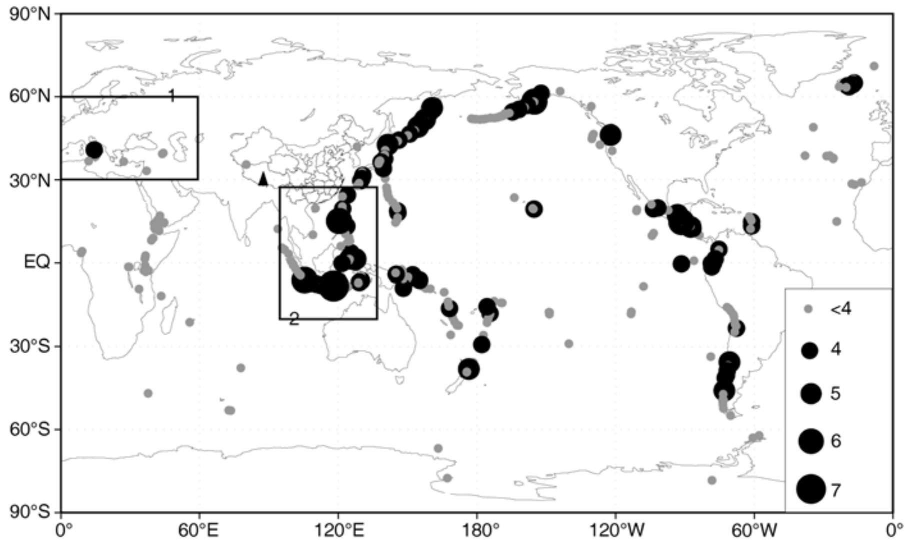


**Figure 1** Geographical distributions of volcanoes since AD 1800. The size of dot represents the value of VEI. Triangle mark is the location of Mt. Qomolangma. The two boxes represent the two most likely source regions of the volcanic eruptions to Mt. Qomolangma area.

**Table 1** The list of VEI⩾4 volcanic events since AD 1800 in regions 1 and 2

| Name | Latitude | Longitude | Altitude (m a.s.l.) | Time | VEI |
|---|---|---|---|---|---|
| Mayon | 13.25°N | 123.69°E | 2462 | 1814.2.1 | 4 |
| Tambora | 8.25°S | 118.00°E | 2850 | 1815.7.15 | 7 |
| Raung | 8.13°S | 114.04°E | 3332 | 1817.1.16 | 4 |
| Babuyan Claro | 19.52°N | 121.94°E | 1080 | 1831 | 4 |
| Merapi | 7.54°S | 110.44°E | 2968 | 1872.4.15 | 4 |
| Krakatau | 6.10°S | 105.42°E | 813 | 1883.8.27 | 6 |
| Vesuvius | 40.82°N | 14.43°E | 1281 | 1906.4.8 | 4 |
| Suoh | 5.28°S | 104.17°E | 1000 | 1933.7.10 | 4 |
| Galunggung | 7.25°S | 108.06°E | 2168 | 1982.5.17 | 4 |
| | | | | 1822.10.8 | 5 |
| Kelut | 7.93°S | 112.31°E | 1731 | 1990.2.10 | 4 |
| | | | | 1966.4.26 | 4 |
| | | | | 1951.8.31 | 4 |
| | | | | 1919.5.19 | 4 |
| | | | | 1826.10.11 | 4 |
| Agung | 8.34°S | 115.51°E | 3142 | 1963.3.17 | 5 |
| Taal | 14.00°N | 120.99°E | 311 | 1965.9.28 | 4 |
| Awu | 3.67°N | 125.50°E | 1320 | 1966.8.12 | 4 |
| Colo | 0.17°S | 121.61°E | 507 | 1983.7.23 | 4 |
| Pinatubo | 15.13°N | 120.35°E | 1486 | 1991.6.15 | 6 |

values represent volcanic events. Annual arithmetic average values show that after 1940, EFcBi has a high background value, which may relate with the influence of human activities. Nine major volcanic eruptions can be identified by using the EFcBi exceeding the average-plus-2 times the standard deviation ($\sigma$). Compared with the VEI⩾4 records in the regions 1 and 2, the highest three peaks are corresponding to Tambora (1815, VEI = 7), Agung (1963, VEI = 5) and Pinatubo (1991, VEI = 5) volcanic eruptions, respectively. The VEI values are consistent with the strength of volcanic events. Tambora eruption occurred on July 15, Agung on May

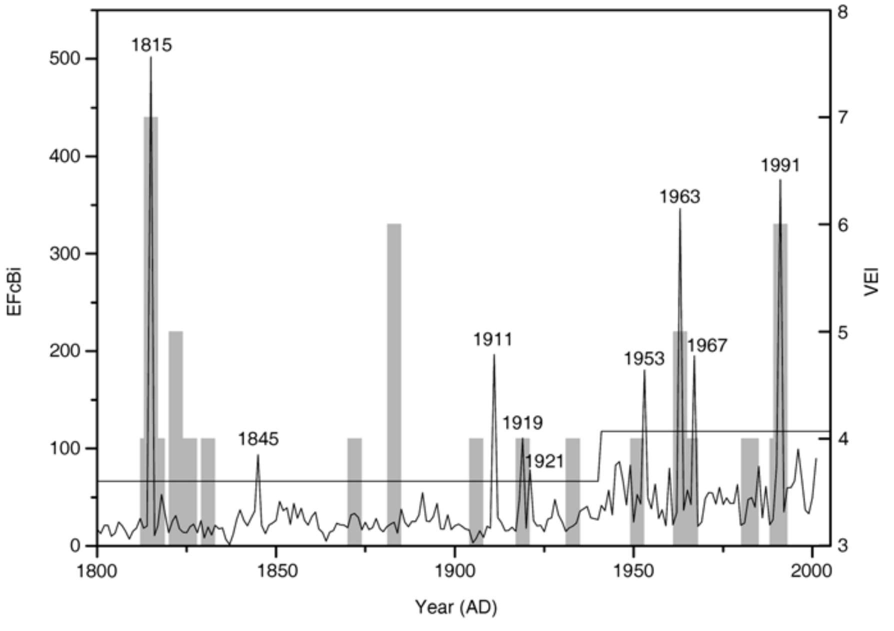


**Figure 2** Comparison between EFc Bi and VEI of the volcanic events with VEI≥4 in regions 1 and 2 since AD 1800. The fine curve stands for EFc Bi, the horizontal line for the average-plus-2 times standard deviation ($\sigma$) before and after1940, and histogram for the VEI.

17, Pinatubo on June 15. All of them are in the period of Indian monsoon season. Tambora is the largest eruption ever recorded since AD 1800, causing a global climate anomaly. Many parts of the world showed abnormal weather phenomena in AD 1815—1817, and AD 1816 was known as a year without a summer in North American and European. Agricultural crops failed and livestock died in many areas of the Northern Hemisphere, resulting in the worst famine of the 19th century. The three years' famine (1815—1817) in the Yunnan Province, China, was also likely caused by the Tambora eruption [30]. The eruptions of Pinatubo and Agung had also an obvious influence. After the Pinatubo eruption, volcanic ash layers were observed by satellite to transport quickly to the Bay of Bengal[25]. A ground-based radiometer also observed the Pinatubo volcanic aerosol over India[31]. Fallout from these three events had been identified in the Antarctic and Greenland ice cores[32,33]. Therefore, these three volcanic eruptions are most likely to be recorded in the ER ice core.

Although the peak of AD 1845 does not correspond with any volcanic signal in regions 1 and 2, it is probably connected with a well-dated eruption in AD 1846 in Armagura of Tonga Islands, located near the margin of region 2. This eruption has an equivalent strength of Pinatubo[34]. Many historical documents had recorded this volcanic event[35]. Because this eruption occurred in June, it was very likely to be recorded in the ER ice core.

The Krakatau eruption on August 28, 1883 was one of the most devastating hazards in history (VEI = 6), including ash falls, pyroclastic flows, and deadly tsunami waves that affected areas thousands of miles away, and death of up to 36,000 people. However the ER ice core does not capture a good signal of this eruption, probably due to unfavorable atmospheric circulation and snow accumulation rate. Delmas et al.[36] suggested that the deposition of volcanic ash depended strongly on the snow accumulation rate of the site, and the signals of volcanic eruption could be more significant at low accumulation rate sites. In addition, the volcanic eruptions vary remarkably in respect of the eruption materials, eruption ways, and deposition processes[4,37]. As to a Greenland ice core, about 1/3 of the volcanic events were obscured due to the local environmental conditions[33]. Whether or not the Krakatau signal could be detected in the other QXP ice cores remains an open question.

To take account of the ice core dating uncertainty, the EFc Bi peak of AD 1911 represents probably a signal of Novarupta eruption on June 6, 1912. This eruption occurred in the present Katmai National Park and Preserve of Alaska. It was the largest volcanic eruption in the 20th century. By modeling, Oman et al.[38] showed that aerosols from the Novarupta eruption tended to stay around 30ºN, and could have weakened Indian summer monsoon. In order to verify the results, Robock and colleagues are also looking for proofs from Asia and Africa (http://science.nasa.gov/headlines/y2006/03oct_novarupta.htm). In addition, no volcano had ever erupted around AD 1912 in central Asia according to the VEI index, and abnormal atmospheric optic phenomena in AD 1911 were also recorded in the Chinese historical literature[39].

The EFc Bi peak of AD 1919 is probably corresponding to the Kelut eruption on May 19, 1919 (VEI = 4), while the peak of AD 1921 cannot be determined. The peak of AD 1953 is probably corresponding to the Kelut eruption on August 31, 1951 (Vei = 4). The peak of AD 1967 is difficult to assign to a specific eruption using the VEI index, but two eruptions, namely Taal (1965) and Awu (1966), may have a potential contribution. The best way for identifying this kind of signals is to compare the volcanic ash in the sediments and volcanic eruption sites by the geochemical method[32].

Given the volcanic eruptions occurred during the periods of December—April and late May—September should be recorded, the recording efficiency of the volcanic signals in the ER ice core is 67%. Nevertheless, the ER ice core preserves a good record of Tambora (1815), Agung (1963) and Pinatubo (1991), which provides faithful horizons for ice core dating.

## 3 Conclusions

By using the element Bi, the ER ice core records nine major volcanic events since AD 1800. The faithful volcanic horizons of Tambora (1815), Agung (1963) and Pinatubo (1991) are beneficial for mountain ice core dating. This kind of pioneer work ever done on a QXP ice core may provide a basis for reconstructing a long sequence of volcanic records from QXP ice core.

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