A great volcanic eruption around AD 1300 recorded in lacustrine sediment from Dongdao Island, South China Sea

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The contents of Ti, Al and Fe₂O₃ in a lacustrine sediment core (DY6) collected from Dongdao Island, South China Sea (SCS), were determined to be much higher than those in the three major sediment end-members (coral sand, guano and plants), and their likely sources include terrigenous dust and volcanic ash. At 61 cm (~AD 1300), the contents of Ti, Al and Fe₂O₃ have an abnormally high spike, which cannot be explained by terrigenous dust. The Sr and Nd isotope compositions at 61 cm are in excellent agreement with those in volcanic materials, but they are significantly different from those in terrigenous dust, implying a possible material input from historical volcanic eruptions in the lacustrine sediment DY6. The documented great Samalas volcanic eruption at AD 1257 in Indonesia is likely the candidate for this volcanic eruption.

1. Introduction

Volcanic activity is an important factor in global climate change. The large amount of magma, volcanic gases and volcanic ash injected from the inner crust into the atmosphere can change atmospheric composition, influence solar radiation and cause hydrological cycle changes and climate cooling (Kelly and Sear 1984; Briffa *et al.* 1998; Trenberth and Dai 2007). As a consequence, crops and vegetation can be detrimentally affected (McGlone *et al.* 1988), and severe flooding disasters may occur (Trenberth and Dai 2007). Progresses have been made in identifying volcanic substances and reconstructing volcanic eruption records (Zielinski *et al.* 1994; Mann *et al.* 2005; Plummer *et al.* 2012). Zielinski *et al.* (1994) reconstructed a record of volcanic eruptions since 7000 BC in northern hemisphere through sulphate content in the Greenland ice core. Plummer *et al.* (2012) reconstructed a

2000-yr volcanic record from Law Dome, East Antarctica. Similar works also used deep sea sediment (Ninkovich 1968; Watkins *et al.* 1978) and obvious tephra layers in lake sediment (Kilian *et al.* 2003; Haberzettl *et al.* 2008).

However, to our knowledge, lacustrine sediment in the SCS, without obvious tephra layers, has rarely been used to reconstruct volcanic eruption records. In this study, we determined the content of Ti, Al and Fe₂O₃ and isotope composition of Sr and Nd in the sediment core from Dongdao Island of the South China Sea in order to identify volcanic materials and eruptions.

2. Materials and methods

2.1 Study area

Dongdao Island (16°39'~16°41'N, 112°43'~112°45'E) is located to the east of Xisha Islands; it is

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18 miles away from the biggest island, Yongxing Island, in Xisha. Dongdao Island is a typical, elliptical coral island with a northwest to southeast orientation (figure 1), it has a total area of about 1.55 km², and it is about 3–6 m above sea level. The island is derived from an individual coral flat and formed since mid-late Holocene. The southern, western and eastern shores of the island are surrounded by 5–6 m high sand barriers, deposited by coral fragments, and covered by thriving vegetation, including mainly, *Scaevola sericca* and *Messerschmidia argentea*. There is a flat island basin inside the sand barriers with large tracts of *Pisonia grandis*. The island has an annual temperature of 26~27°C and an annual rainfall of 1500 mm. Dry and wet seasons are distinct, with the wet season spanning from June to November and the dry season from December to May of the next year (Lin *et al.* 1999).

Cattle Pond, a crescent-like brackish water lake, is located near the south-western sand barriers of

Dongdao Island (figure 1c). It is about 150 m long with a maximum width of 15 m. The water level is usually below 0.5 m and varies with alternation between dry and wet seasons (Liu *et al.* 2006, 2008).

2.2 Sample collection and analytical methods

Sediment core DY6 (158 cm long) was collected from Cattle Pond using clean PVC plastic pipes of a diameter of 12 cm. The sediment cores were stored in a lab freezer until analysis. In the lab, DY6 was sectioned at 0.5 cm intervals. Samples were air-dried in a clean lab environment and homogenized.

The air-dried samples were ground to powder after removal of large plant and animal remains. About 0.25 g of each powder sample was taken and then digested by multi-acids in a PTFE crucible, until the acid liquid was pellucid. Following

Figure 1. Maps of study locations. (a and b) Geographical location of Xisha Islands; (c) terrain characteristics of Dongdao Island; and (d) sampling sites of sediment cores DY6 in Cattle Pond.

this, the remains were dissolved and analysed for Ti, Al, Fe as well as other inorganic elements by Inductive Coupled Plasma-Atomic Emission Spectrometry (P.E Ltd, Optima 2100 DV). The analytical errors for major and trace elements were within $\pm 0.5\%$ and $\pm 5\%$, respectively. The $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were performed on the acid-insoluble remains at 61 cm of the sediment core. Nd isotopic ratios are expressed as $\varepsilon_{\text{Nd}}(0) = [((^{143}\text{Nd}/^{144}\text{Nd}_{\text{means}})/0.512638) - 1] \times 1000$. A more detailed description of analytical method is given by Liu *et al.* (2014).

3. Results and discussion

3.1 Chronology of DY6

Reliable chronology of DY6 was established based on AMS ^{14}C dating of some caryopses and ^{210}Pb dating of the upper part of the sediment core. Considering that both DY4 (Liu *et al.* 2006) and DY6 were sampled from the same lake, it is reasonable to assume that they have the same lithological and physicochemical characteristics. Consequently, the dating results of DY4 were used to modify the chronology of DY6 according to their lithological characteristics and detailed results were reported previously by Liu *et al.* (2014).

3.2 Identification of foreign material input

Our earlier analysis of sedimentary facies of three parallel sediment cores DY2, DY4 and DY6 has indicated that the three major sediment end-members in Cattle Pond are coral sand, guano and plants (Zhao *et al.* 2007; Liu *et al.* 2013). Considering the ambient environment of Cattle Pond, it is difficult to find other obvious indigenous material input into Cattle Pond, according to our field observations. The average Ti and Al contents in sediment core DY6 are 4.25 and 110.6 mg/kg, respectively, the maximum content of Fe_2O_3 is

382 mg/kg, and contents of the three elements in DY6 are obviously much higher than those in the three major sediment end-members (table 1).

The sediments mainly produced by coral sand in Dongdao Island contain little diagenetic elements like Ti and Al (Liu *et al.* 2013). Input of plants also cannot change the contents of Ti, Al and Fe_2O_3 dramatically in sediments. Although, guano may influence element contents to some extent, input of seabird guano cannot explain the extremely high concentration of Ti, Al and Fe_2O_3 because proportion of seabird guano in DY6 is very low. Thus, the extremely high contents of Ti, Al and Fe_2O_3 are likely derived from alien materials.

Through geochemical and morphological analyses of acid-insoluble particles in the sediment core DY6, Liu *et al.* (2013) reported alien material input from terrigenous dust. In addition, we also found basalt on the island in our fieldwork. The basalt is black with vesicular structure (figure 2). Basalt is unlikely indigenous to Dongdao Island because of its sediment provenance and ambient environment characteristics. Furthermore, Ti, Al and Fe_2O_3 contents of basalt are much higher than those in the three major sediment end-members and sediment core DY6. Therefore, input of volcanic materials in DY6 is likely.

3.3 Volcanic ash as the alien source in the sediment core DY6

Liu *et al.* (2014) reported that the studied area has been influenced by terrigenous dust using Sr and Nd isotope compositions (acid-insoluble remains at 100–102 cm ($\sim$ AD 1070) and 140–154 cm (AD 700–800)) (figure 3) and established a 1400 year record of dust flux in the SCS through Ti flux. Compared with down-core variations of Ti, Al and Fe_2O_3 from DY6, we found a distinct peak at $\sim$ AD 1300 (figure 4). Interestingly, the peak of each content at $\sim$ AD 1300 has a totally different shape when compared to peaks at AD 700–800 and AD

Table 1. Al, Ti, Fe_2O_3 contents and variation range in sediment core DY6, basalt and three major sediment end-members.

Element	Al (mg/kg)	Ti (mg/kg)	Fe_2O_3 (mg/kg)
Coral sand (n=3)	Average	6.2	ND
	Variation	5.5~6.9	ND
Plants (n=6)	Average	10.4	0.35
	Variation	3.9~19.5	0~0.95
Guano (n=3)	Average	3.45	256.6
	Variation	1.8~5.1	252~262
Basalt (n=3)	Average	95651.3	5498.7
	Variation	94924.8~96745.8	5356.2~5685.6
Sediment (n=314)	Average	110.6	120.4
	Variation	15~1002	18~382

Note: ND means below the limit of detection.

Figure 2. Basalt, discovered during field investigation, is not indigenous to Dongdao Island according to the analysis of source origin.

Figure 3. $\epsilon_{\text{Nd}}(0)$ values plotted against $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of samples from different locations, including Asian dust, North African dust, volcanic materials from Luzon Island, loess from Loess Plateau and sediments from Western Philippine sea, Northern Luzon arc and Pearl River, Red River and Mekong River. The green point is the $^{87}\text{Sr}/^{86}\text{Sr} - \epsilon_{\text{Nd}}(0)$ isotope compositions of acid-insoluble particles in DY6 at 61 cm (AD 1300), while the red points represent the $^{87}\text{Sr}/^{86}\text{Sr} - \epsilon_{\text{Nd}}(0)$ isotope compositions of acid-insoluble particles in DY6 at 100–102 cm ($\sim$ AD 1070) and 140–154 cm (AD 700–800), respectively. The red line is the mixing curve of volcanic materials and eolian dust (figure modified based on Jiang *et al.* 2013 and Liu *et al.* 2014).

1000–1100. The peak at $\sim$ AD 1300 appears abrupt and is very sharp, suggesting a sudden event at $\sim$ AD 1300, while the peaks at AD 700–800 and AD 1000–1100 are flat and these three elements stay at a relatively high level for more than 100 years. The variations of Fe_2O_3 content are very similar to Ti flux changes during the past 1400 years, except at $\sim$ AD 1300; at this point, the content of Fe_2O_3 is very high, but the dust flux is not. The spikes of Al and Ti only emerged at $\sim$ AD 1300 and their contents are far higher than those in other periods. Thus, the extremely high content of Ti,

Figure 4. Comparisons between Ti flux (Liu *et al.* 2014) and contents of Al, Ti and Fe_2O_3 in sediment core DY6. The shaded area marks spike of Ti flux and contents of Al, Ti and Fe_2O_3 , all of which emerged at about the same time, around AD 1300.

Al and Fe_2O_3 at $\sim$ AD 1300 are most likely due to input of alien materials other than terrigenous dust.

Because Ti, Al and Fe_2O_3 content is known to be high in volcanic materials (Genshaft *et al.* 1984; Muhs and Budahn 2009) and the spike of Ti, Al and Fe_2O_3 occurs so abruptly, we propose here that the abnormally high contents of Ti, Al and Fe_2O_3 at $\sim$ AD 1300 come from a possible volcanic eruption. To confirm this, we performed a subsequent Sr–Nd isotope analysis, and determined the Sr and Nd isotope compositions of acid-insoluble remains at 61 cm ($\sim$ AD 1300) in DY6. As seen from figure 3, Sr and Nd isotope compositions of terrigenous dust and volcanic materials are significantly different from each other. The $^{87}\text{Sr}/^{86}\text{Sr}$ and $\epsilon_{\text{Nd}}(0)$ values at 61 cm are consistent with those in volcanic materials (figure 3), and the $^{87}\text{Sr}/^{86}\text{Sr}$ and $\epsilon_{\text{Nd}}(0)$ isotope compositions of acid-insoluble particles at 100–102 cm ($\sim$ AD 1070) and 140–154 cm (AD 700–800) are consistent with those

Table 2. Volcanic eruption list recorded from GISP2 (Zielinski *et al.* 1994) and Law Dome (Plummer *et al.* 2012).

Year of signal	Greenland ice core (GISP2)		Law Dome	
	SO ₄ ²⁻ residual (ppb)	Volcanic eruption with year	Year of signal	Volcanic eruption
1205	32	Oshima, Japan, 1200±50	1229	Unknown
1227	34	Unknown	1257	Samalas, 1257
1229	78	Unknown	1268	Unknown
1259	349	Samalas, Indonesia, 1257	1275	Unknown
1285	44	Unknown, Asama, Japan, 1281	1344	Unknown
1328	33	Cerro Bravo, Columbia, 1325±75		
1344	54	Hekla, Iceland, 1341		

Note: We referred to Lavigne *et al.* (2013) for the AD 1257 Samalas volcanic eruption.

in eolian dust (Liu *et al.* 2014). Thus, the Sr and Nd isotope values clearly show that volcanic ash is the primary contributor of the Ti, Al and Fe₂O₃ content anomaly at ~AD 1300. Isotope composition analysis is, thus, an indispensable tool to distinguish between different material sources of sediments.

3.4 Potential candidate for ~AD 1300 volcanic eruption

In order to find out the possible, recorded, volcanic eruption that is responsible for the sudden Ti, Al and Fe₂O₃ contents anomaly at ~AD 1300 of DY6, we compiled a list of volcanic eruptions between AD 1200 and 1400, recorded in GISP2 Greenland ice core (Zielinski *et al.* 1994) and Law Dome (Plummer *et al.* 2012) (table 2). There are 4 known volcanic eruptions around AD 1300. However, three of them are from Iceland, Columbia and Japan, far from the SCS, and their magnitude is also relatively small; thus these three volcanic eruptions are unlikely the candidate for the ~AD 1300 volcanic eruption in SCS. One great volcanic eruption (Lavigne *et al.* 2013) took place in AD 1257 in Samalas, Indonesia, very close to the SCS, and it is the greatest volcanic eruption of the past 7000 years. This huge volcanic event was also suggested by the research findings from Plummer *et al.* (2012), Zielinski *et al.* (1994) and Mann *et al.* (2005). Thus, the volcanic ashes from the Samalas eruption in AD 1257 were most likely transferred and precipitated in Dongdao Island.

The difference between our inferred time of AD 1300 and the Samalas eruption time of AD 1257 can be attributed to some error induced by the ¹⁴C dating method. In our study, the chronology of sediment core was established by linear interpolation and by assuming constant sedimentation rate along different layers, which may not always be true. Although, our identified time is not precisely AD 1257, it is nevertheless within the allowed error range. Further research and confirmation is apparently needed.

4. Conclusions

At 61 cm (~AD 1300) in the sediment core DY6, the Ti, Al and Fe₂O₃ contents are abnormally high, indicating alien sources such as eolian dust and volcanic ashes. Since the dust flux is relatively low and the peaks of Al, Ti and Fe₂O₃ at around AD 1300 are much sharper than those at ~AD 750 and AD 1050, eolian dust is unlikely the primary source of Al, Ti and Fe₂O₃ at ~AD 1300. The Sr and Nd isotope compositions at 61 cm are in excellent agreement with those in volcanic materials, but they are significantly different from those in terrigenous dust. Thus, the Ti, Al and Fe₂O₃ content anomaly is caused by volcanic material input, and the documented great Samalas volcanic eruption at AD 1257, in Indonesia, likely accounts for that eruption.

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