

Coupling between the Cenozoic west Pacific subduction initiation and decreases of atmospheric carbon dioxides

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Abstract At the beginning of the Cenozoic, the atmospheric CO₂ concentration increased rapidly from ~2000 ppmv at 60 Ma to ~4600 ppmv at 51 Ma, which is 5–10 times higher than the present value, and then continuous declined from ~51 to 34 Ma. The cause of this phenomenon is still not well understood. In this study, we demonstrate that the initiation of Cenozoic west Pacific plate subduction, triggered by the hard collision in the Tibetan Plateau, occurred at approximately 51 Ma,

coinciding with the tipping point. The water depths of the Pacific subduction zones are mostly below the carbonate compensation depths, while those of the Neo-Tethys were much shallower before the collision and caused far more carbonate subducting. Additionally, more volcanic ashes erupted from the west Pacific subduction zones, which consume CO₂. The average annual west Pacific volcanic eruption is 1.11 km³, which is higher than previous estimations. The amount of annual CO₂ absorbed by chemical weathering of additional west Pacific volcanic ashes could be comparable to the silicate weathering by the global river. We propose that the initiation of the western Pacific subduction controlled the long-term reduction of atmospheric CO₂ concentration.

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1 Introduction

Atmospheric CO₂ concentration fluctuated significantly in the Early Cenozoic (Pearson and Palmer 2000; Hansen et al. 2013). Boron isotopes show that the atmospheric CO₂ reached peak values of ~2000–4600 ppmv between 60 and 51 Ma, in the Early Cenozoic (Hansen et al. 2013; Rae et al. 2021). Consistently, the deep-sea benthic foraminiferal oxygen-isotope curve shows that the deep-sea temperature at ~51 Ma was much higher than that in the present day, and the global surface temperature was more than 25 °C, then declined quickly afterward (Fig. 1) (Hansen et al. 2013). The reasons behind such major

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fluctuations in temperature and atmospheric CO₂ remain obscure. In particular, it remains unclear why the atmospheric CO₂ concentration exhibited a long term decrease starting at ~51 Ma (Beerling and Royer 2011).

Previous studies suggested that low-latitude collisions lead to uplifting and exposure of mafic and ultramafic rocks that are subjected to chemical weathering in the warm, wet tropical climate, and sequester carbon (Jagoutz et al. 2016), i.e., the collision between the Indian and the Eurasian continents led to fast uplifting and the formation of the Tibetan Plateau in the Early Cenozoic (Ding et al. 2014), and was taken as the main reason responsible to the major decrease of atmospheric CO₂ concentration. However, the growth history of the Tibetan Plateau involves a much more complex process (Spicer et al. 2020). Importantly, the atmospheric CO₂ concentration did not change much between 23 and 25 Ma, when the Tibetan Plateau uplifted very fast (Ding et al. 2022).

Here we show that the closure of the Neo-Tethys Ocean triggered the initiation of west Pacific plate subduction, which were responsible to the declining of atmospheric CO₂ concentration.

Plate reconstruction shows that the northward drifting rate of the Indian plate dropped significantly, from ~18 cm/year at ~58 Ma to ~8 cm/year at ~53 Ma, whereas that of the Australian plate dropped from ~7 cm/year at ~58 Ma to nearly zero at ~50 Ma, indicating that the “hard collision” commenced at ~53 Ma (Sun et al. 2020). As a result, the amount of CO₂ released through volcanic activities in the Tibetan Plateau and the whole Neo-Tethys subduction zone should have declined dramatically since ~53 Ma. Meanwhile, the hard collision between the Indian + Australian plate and the Eurasian continent triggered the initiation of the Cenozoic west Pacific plate subduction at ~51 Ma (Sun et al. 2020). Significantly, all these are coincident with the inflection point in the paleoclimate curve, when temperature and atmospheric CO₂ started to decline (Hansen et al. 2013; Rae et al. 2021), implying that the Cenozoic plate

subduction in the west Pacific had a major influence on the atmospheric CO₂.

The west Pacific subduction zone consists of the Izu–Bonnie–Mariana, the Tonga–Kermadec, the Kuril, and the Aleutian trenches, with a total length of ~20 thousand kilometers. The water depths of the oceanic crust subducting along these subduction zones are mostly deeper than 5000 m (Fig. 2), which is much deeper than the carbon compensation depth (CCD) of ~3000–3500 m in the Early Cenozoic and ~4600 m nowadays (Paelike et al. 2012). Therefore, carbonates on the surface of the ocean floor are dissolved by seawater, and thus far less carbonate has been subducted through the west Pacific subduction zones, compared to the subduction of the passive continental margins along the Neo-Tethys convergent margin. Consequently, more volcanic ashes were erupted with much less efficient CO₂ emissions.

The thickness of the arc crust along west Pacific subduction zones is mostly less than 30 km, which is less than half of the thickness of the Tibetan Plateau continental crust. Thin arc crust favors the eruption of volcanoes, e.g., more volcanoes erupted in the west Pacific margin than in the east Pacific margin (Fig. 2). The west Pacific subduction initiation produces massive amounts of volcanic ashes, which consumes CO₂ through chemical weathering. Meanwhile, volcanic ashes also provide nutrients to the marine flourishing of ecosystems.

Previous studies suggested that average ca. 1 cubic kilometer (km³) of volcanic ashes have been erupted along the global convergent margins every year. It is well known that volcanoes cannot preserve long, due to erosion. Therefore, the eruption in the history is usually underestimated.

Many attempts have been made to quantify the magnitude of volcanic eruptions, leading to the development and refinement of the Volcanic Explosivity Index (VEI) in the 1980s (Newhall and Self 1982). This index is divided into nine levels, ranging from 0 to 8, corresponding to different erupted tephra rates (including pyroclastic-flow deposits

Fig. 1 The evolution of atmospheric CO₂ concentration and global surface temperature. The data are obtained from Hansen et al. (2008)

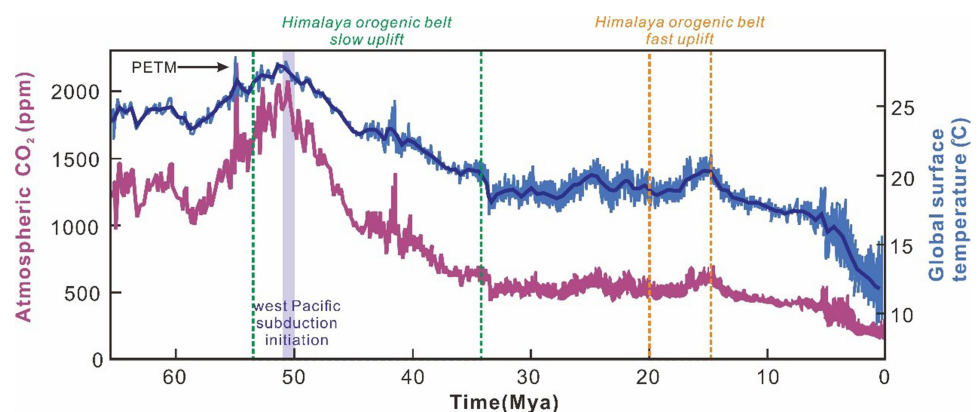


Fig. 2 Distribution of volcanos in the circum-Pacific region during the last 12,000 years. Compared to the east Pacific margin, more volcanos erupted along the west Pacific subduction zones that were initiated in the Cenozoic, i.e., from the Tonga–Kermadec trench in the south to the Kuril and the Aleutian trenches in the north. Data are obtained from the Global Volcanism Program (2022)

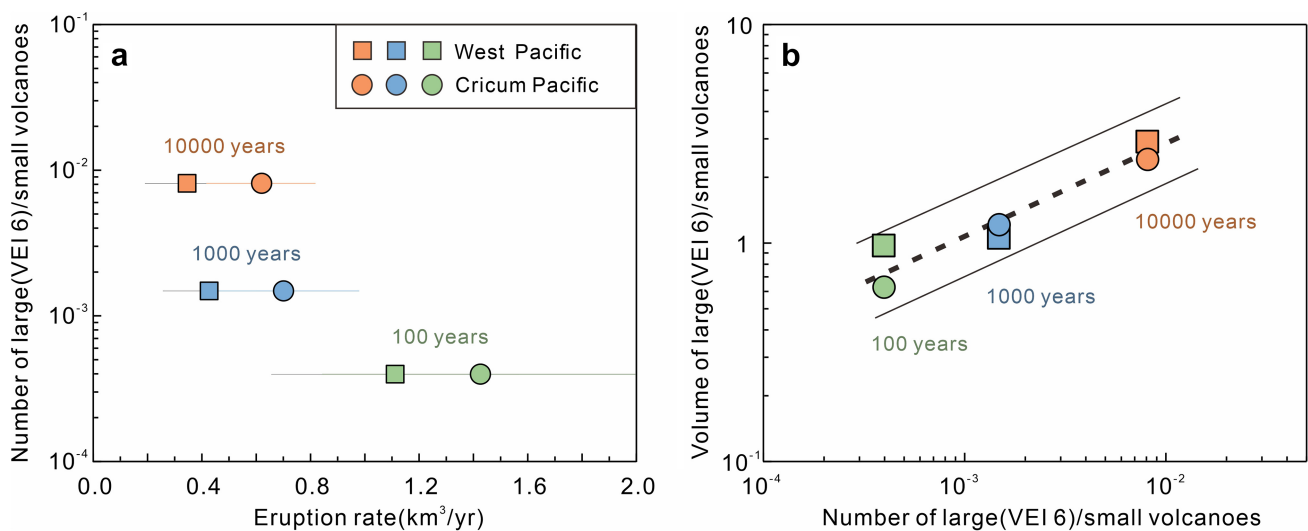
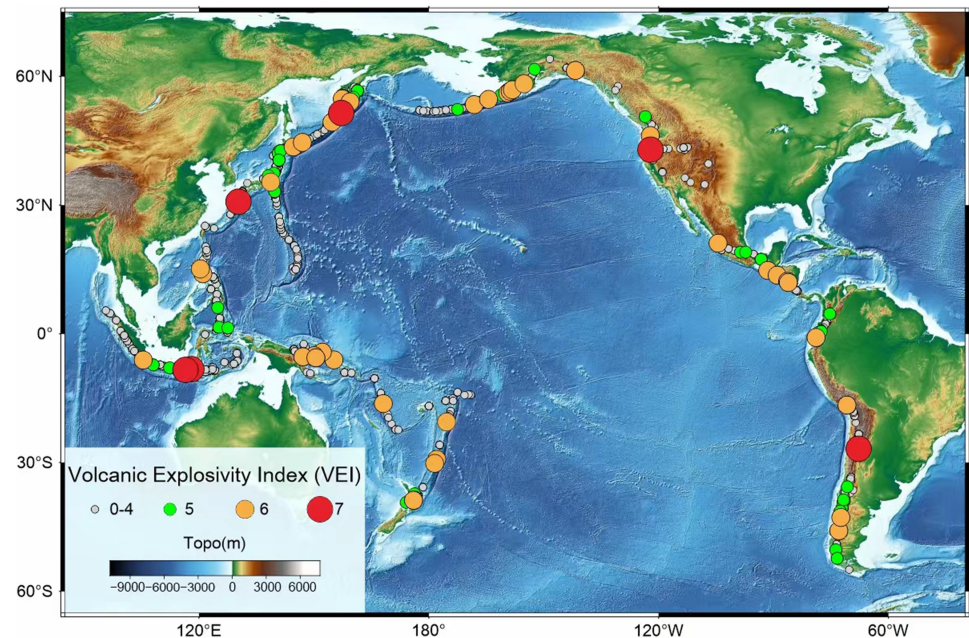


Fig. 3 The average eruption rate of volcanic ashes. **a** Eruption rate versus the ratio between the number of large volcanoes ($\geq$ VEI 6) and the number of small volcanoes. **b** The correlation between the ratios of volume and number of large volcanoes ($\geq$ VEI 6) versus small volcanoes. The ratio of large versus small volcanoes is negatively correlated to the eruption rate. This is because smaller volcanoes are easier to fade away with time due to weathering. Eruptions in the last 100 years give better constraints on eruption rates, i.e., $\sim 1.43 \pm 0.58$ and 1.11 ± 0.45 km^3/year in the circum-Pacific and the west Pacific regions, respectively. Data are obtained from the Global Volcanism Program (2022)

and tephra-fall volumes, from $\sim 1 \times 10^{-4}$ to more than 1×10^3 km^3) and erupted heights (from 0.1 to more than 50 km). The Global Volcanism Program (2022) has compiled data on the sites, dates, and VEIs of volcanoes over the past 12,000 years, providing an opportunity to study the variation of volcano eruption. Using the detailed volcano database, we collated and analyzed the existing VEI data to estimate the eruption rates of different volcanoes. Based on

location data, the volcanoes were classified into the western Pacific and circum-Pacific subduction zones, and the volcanic eruption rates were calculated at various time intervals.

Based on the eruption rates of the last 100, 1000 and 10,000 years, we obtained that 1.43 ± 0.58 , 0.71 ± 0.28 , 0.62 ± 0.21 km^3/year of volcanic ashes erupted in the circum-Pacific region, respectively. These values are

negatively correlated with the ratios of large volcanos versus small volcanos both in terms of volume and number of volcanos (Fig. 3). This is because the smaller the volcano is, the easier and faster it is erased. Thus, the records of the last 100 years give better constraints of the intensity of eruptions. Using the same methods, the annual eruption rates in the last 100 years of $1.43 \pm 0.58 \text{ km}^3/\text{year}$ and $1.11 \pm 0.45 \text{ km}^3/\text{year}$ are obtained for the convergent margin volcanos in the circum-Pacific and the west Pacific subduction zones, respectively (Fig. 3). Assuming the Cenozoic volcanic activity was as strong as now, then an additional volcanic ashes of at least $1.11 \pm 0.45 \text{ km}^3$ have erupted every year in the Cenozoic west Pacific subduction zone since $\sim 51 \text{ Ma}$. The density of felsic volcanic ashes is $\sim 2000 \text{ kg/m}^3$, such that $2.22 \times 10^{12} \text{ kg}$ of arc volcanic ashes have been dumped into the ocean every year.

The weathering rates of volcanic ashes are orders of magnitude higher than basalts and another order of magnitude higher than granites. The Ca, Mg, K and Na from volcanic ashes could be released within geological time of 51–34 Ma through chemical weathering. Using the data in GEOROC (Team DIGIS 2022), we studied the composition of west Pacific arc volcanic ashes (tephra), which contain 6.4 wt% of CaO, 2.6 wt% of MgO, 3.8 wt% of K_2O and 1.1 wt% of Na_2O in average (Table 1). The total chemical weathering of these volcanic ashes releases $3.98 \times 10^{12} \text{ mol/year}$ of Ca and Mg, and $2.54 \times 10^{12} \text{ mol/year}$ of K and Na. More than half of the west Pacific subduction zones are intraoceanic, where volcanic ashes were all dumped into the ocean and chemically weathered within the geologic time of 51–34 Ma, before subaerial arcs emerged after $\sim 34 \text{ Ma}$. Assuming half of the Ca and Mg from volcanic ashes erupted in the west Pacific subduction zones between 51 and 34 Ma have been released due to chemical weathering, i.e., the silicate weathering rate is $\sim 1.99 \times 10^{12} \text{ mol/year}$ of Ca and Mg. This is comparable to the current global river silicate weathering rate, $\sim 2.17 \times 10^{12} \text{ mol/year}$ of Ca and Mg (Moon et al. 2014). In this case, the chemical weathering rates of global silicate, and consequently the CO_2 consumption rates, were doubled after the initiation of Cenozoic west Pacific plate subduction by the volcanic eruptions along the subduction zones. In addition, volcanic ashes fertilized the ocean, which also promotes CO_2 sequestration through biological processes (Lee et al. 2018).

Meanwhile, the CO_2 emission along the Neo-Tethys convergent margins declined dramatically after the hard collision. All of these push the continuous decline of global atmospheric CO_2 and temperature between ~ 51 and 34 Ma.

The passive continental margin is usually submarine with abundant carbonates and hydrated sediments that favor carbonate subducting and recycling by the arc

Table 1 Mean major element compositions of the western Pacific tephra and the volcanic eruption rates

Mean compositions of tephra in the Western Pacific			
Major element (wt%)			
SiO ₂	64.90	MgO	2.58
TiO ₂	0.77	CaO	6.37
Al ₂ O ₃	14.95	Na ₂ O	3.77
Fe ₂ O ₃ T	7.12	K ₂ O	1.10
MnO	0.22	P ₂ O ₅	0.15
Trace element (ppm)			
Li	9.62	Ce	13.4
Be	1.13	Pr	2.32
Sc	25.5	Nd	10.3
V	170	Sm	3.32
Cr	9.48	Eu	1.04
Co	16.00	Gd	4.20
Ni	7.92	Tb	0.74
Cu	64.0	Dy	4.95
Zn	81.7	Ho	1.09
Ga	15.1	Er	3.24
Rb	16.9	Tm	0.53
Sr	218	Yb	3.32
Y	34.6	Lu	0.52
Zr	94.4	Hf	2.66
Nb	1.46	Ta	0.22
Cs	0.89	Pb	5.23
Ba	219	Th	0.91
La	5.36	U	0.37
Eruption rate in the whole world		$2.98 \pm 0.30 \text{ km}^3/\text{year}$	
Eruption rate in the circum-Pacific region		$1.43 \pm 0.58 \text{ km}^3/\text{year}$	
Eruption rate in the west Pacific region		$1.11 \pm 0.45 \text{ km}^3/\text{year}$	

magmatic activity (Plank and Langmuir 1998; Plank 2014). The rapid increase of CO_2 between 60 Ma and 51 Ma was attributed to the subduction of the continental margin before the hard collision (Tian et al. 2022). Many studies showed that the Indian continent “touched” with the Eurasian continent at $\sim 60 \text{ Ma}$, which was indicated by detrital zircon (Wang et al. 2003; Wu et al. 2014; Hu et al. 2016, 2017), and marked the onset of the passive continental margin subduction along the north margin of the Indian block. Passive continental margins have abundant carbonate-rich sediments (Plank and Langmuir 1998; Galvez and Pubellier 2019; Plank and Manning 2019). Therefore, large amount of carbonate have been subducted, and then participated in partially melting (Xue et al. 2020) or dissolved in fluids released through the dehydration of subducting slab (Ague and Nicolescu 2014), and consequently abundant CO_2 was emitted to the atmosphere

through metamorphic and volcanic activities (Guo et al. 2021). This plausibly explains the fast increases of atmospheric CO₂ in the Early Cenozoic (Tian et al. 2022).

After the hard collision between the Indian and the Eurasia continent, the subduction of passive margin slowed down (Aitchison et al. 2007; van Hinsbergen et al. 2012; Sun et al. 2020), such that much less carbonates and organic carbon are subducted. Consequently, much less CO₂ is released from the Neo-Tethys collision zone along the Tibetan plateau. In the meantime, it triggered the initiation of the Cenozoic plate subduction at ~51 Ma and the growth of island arcs in the west Pacific (Sun et al. 2020; Li et al. 2021; Sun and Zhang 2022), which triggered the onset of the long-term delining of atmospheric CO₂. Overall, our study emphasizes the role of west Pacific plate subduction initiation in setting the Cenozoic climate state and also the importance of volcanic ash weathering in CO₂ consumption on the tectonic time scale.

Note: The volcanic tephra geochemistry data are obtained from the western Pacific were obtained from GROROC (<https://georoc.eu/georoc>). The volcanic eruption rate are calculated from the data of the Global Volcanism Program (2022).

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Author contributions Weidong Sun designed the study and drafted the manuscript. Guozhi Xie calculated the eruption rates and plotted Figs. 1 and 3; Fanfan Tian plotted Fig. 2. All authors participated in discussion and revision of the manuscript.

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Data availability All the data used in this manuscript are from open database.

Declarations

Conflict of interest The authors declare no conflict of interests.

Ethical approval The authors declare that we follow all the Ethics rules, including those listed in the Acta Geochimica web site.

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