Short Communication

The formation of supercritical carbon dioxide hydrothermal vents in the Okinawa Trough

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Science Bulletin 68 (2023) 154–156

Contents lists available at ScienceDirect
Science Bulletin
journal homepage: www.elsevier.com/locate/scib

Supercritical carbon dioxide (scCO₂) has been observed in hydrothermal vents in the Okinawa Trough [1]. This is the first natural scCO₂ so far reported. Pure carbon dioxide becomes supercritical under pressures higher than 7.38 MPa and temperatures higher than 31.1 °C. The occurrence of scCO₂ in the Okinawa Trough indicates high flux of subducted carbon returning back to the atmosphere. It, however, remains obscure how scCO₂ vents formed, why they appear in the Okinawa Trough and what’s the implication of such geologic process. Here we show that these scCO₂ hydrothermal vents are closely associated with the subduction of the Gagua Ridge.

The Okinawa Trough is a backarc basin formed by the north-westward subduction of the Philippine Sea plate. Supercritical CO₂ was detected at the Yonaguni Knoll IV (YK-IV) hydrothermal field [1]. Significantly, YK-IV hydrothermal vents are located right above the subducting Gagua Ridge (Fig. 1). The Gagua Ridge is the east boundary of the Huatung Basin. It is 20–30 km wide, 300 km long. The water depths of the Philippine Sea plate and most of the Huatung Basin range from 5000 to 6000 m, which are considerably deeper than the carbonate compensation depth (CCD, 4500 m) [2]. Therefore, carbonate on the seafloor of the Philippine Sea and most of the Huatung Basin is readily dissolved. The Gagua Ridge itself is about 2000–4000 m above the seafloor, i.e., its water depths are much shallower than the CCD (Fig. 1). Therefore, carbonate and/or carbonate-rich sediments on the Gagua Ridge are expected. Previous researcher suspected that carbonate on the ridge is less than 10 m thick, because they dredged volcanic rocks there, i.e., the Gagua Ridge is not fully covered by carbonate. To us, the Gagua Ridge is a failed subduction initiation belt with arc volcanic rocks that may cover carbonate sediments. Given that the Gagua Ridge was located in tropical regions with abundant coral reefs, the carbonate layer on it should be much thicker than 10 m.

Seismic images show that the Gagua Ridge reached depths of ~100 km right underneath the YK-IV scCO₂ hydrothermal vents (Fig. 1). Under such depths, amphibole decomposes, releasing hydrous fluids. Serpentinite may also decompose depending on the temperatures [3]. Subduction-released fluids dissolved carbonate on the subducting Gagua Ridge and carried it up into the magma chamber and/or directly into the hydrothermal system, forming the supercritical carbon dioxide vents in the Okinawa Trough (Fig. 2). The scCO₂ suggests that carbonate was dissolved as HCO₃⁻, and/or carbonate was decomposed in the magma chamber.

Remarkably, the YK-IV hydrothermal vent is the only scCO₂ hydrothermal vent so far reported all over the world [1]. Although this is at least partially due to the lack of deep ocean scientific expeditions, it indeed indicates that scCO₂ hydrothermal vent is rare. This is consistent with the low CO₂ emission from global volcanos nowadays [5].

The atmospheric carbon dioxide concentration fluctuated dramatically in the history of Earth. In the Early Cenozoic, the atmospheric carbon dioxide concentration increased rapidly from ~1000 ppmv (1 ppm = 1 × 10⁻⁶ L/L) to 2000–4600 ppmv [6], which is ~5–10 times as high as the present day value. The mechanism that drives such rapid growth remains controversial [7].

Large igneous provinces (LIPs) are responsible to most of the catastrophic events. They, however, usually only last for a short period of time (e.g., <1 million years for a LIP). The Early Cenozoic super greenhouse period occurred between ~58 to 50.9 Ma, which lasted several million years and was about 10–15 Ma later than the
eruption of the Deccan large igneous province. It started \( \sim 2 \) Ma earlier than and lasted till \( \sim 5 \) Ma after the North Atlantic Igneous Province. Note, the North Atlantic Igneous Province was arguably taken as the causal reason of the Paleocene-Eocene thermal maximum (PETM) at 56 Ma.

Plate subduction is a key process that controls the carbon exchanges between the surface and the interior of Earth. During plate subduction, carbonates are carried down into the mantle, and then recycled back through magmatism and/or hydrothermal activities. However, the current total carbon dioxide emission rate from the global subduction system is only \( \sim 0.035-0.12 \) GtC/a in average [5], which is about 1% of the current annual emission of anthropogenic carbon (9.4 GtC/a) [8]. What was the mechanism that resulted in long term fast increasing and super high atmospheric carbon dioxide in the early Cenozoic?

The subduction of the north margin of the Indian and the Australian continents started at \( \sim 60 \) Ma [9], with hard collisions occurred at \( \sim 53 \) Ma, which triggered the anti-clockwise rotation of the Pacific plate and the initiation of the Cenozoic subductions in the West Pacific [10,11]. After that, the circum-Pacific region is the main active subduction zone in the world. However, most of the volcanos at the circum-Pacific convergent margins have low CO2 contents [12], with the exception of several large explosive volcanos [13,14]. Consistently, CO2 concentrations are also low in hydrothermal vents, in general.

The main reason is that the water depths of all the trenches in the circum-Pacific region are deeper than 8000 m, much deeper than the CCD. Therefore, carbonate on the ocean floor is readily dissolved by sea water. Carbonate veins in altered oceanic crust have higher Mg contents compared to normal sedimentary calcite [12]. They are the main carrier of carbonate during Pacific plate subduction.

High pressure experiments show that in the presence of water, carbonate in both carbonate platform and carbonate-rich sediments dissolves in subduction-released fluids [15], most of which...
was consequently released as carbon dioxide through arc volcanism, and more importantly, through hydrothermal activities (Fig. 2). Therefore, the amount of CO₂ returning to the atmosphere from a subducting plate depends not only on the amount of carbonate subducted, but also on the amount of water released during plate subduction. Although altered oceanic crust may contain up to 5% of carbonate, depending on the age and hydrothermal alteration history, considerable amount of the carbonate veins in altered oceanic crust may survive the dehydration process, with only a small portion released from arc volcanic activities (Fig. 2).

In “dry” subduction with water deficiency, calcite changes to aragonite at depths of 30–50 km, and then to amorphous carbonate at depths of 70–120 km [4]. The density of carbonate is low. During plate subduction, calcite in sediments may be enriched through the infiltration of amorphous phase, which consequently migrates from the subduction plate to the mantle wedge and is assimilated with the arc magma [4]. Subducted carbonate platform may recycle back as carbonatite, e.g., Huayangchuan.

Based on the association between the scCO₂ vents and the subduction of the Gagua Ridge, we propose the long term increases in atmospheric CO₂ in the Cenozoic was resulted from the subduction of carbonate on submarine continental margins during the closure of the Neo-Tethys Ocean.

The submarine portion of passive continental margin usually has abundant carbonate and hydrated sediments with shallow water depths that favor carbonate recycling. It is well agreed that the Indian plate had a wide continental margin that has been subducted between 60 and 53 Ma, which is coincident with the increasing atmospheric CO₂ [10]. The coincidence supports that the subduction of the Indian continental margin was the key driving force responsible to the fast increases of atmospheric CO₂ in the Early Cenozoic.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (92258303), the Strategic Priority Research Program of Chinese Academy of Sciences (XDA22050103), and Laoshan Laboratory Research Grant (2022QLM050201) to Weidong Sun. We thank constructive discussions with Profs. Lixin Wu of Laoshan Laboratory and Yi Yang of Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, and all the committee members of the Major Research Plan “West-Pacific Earth System Multispheric Interactions” in the annual meeting in Qingdao.

Author contributions

Fanfan Tian plotted seismic images; Rui Li plotted the carbonate recycling model. Weidong Sun initiated the study and drafted the manuscript together with Fanfan Tian and Rui Li, with contributions from all co-authors. All co-authors participated in discussion and revisions.

Appendix A. Supplementary materials

Supplementary materials to this short communication can be found online at https://doi.org/10.1016/j.scib.2022.12.032.

References


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