Equatorial cold-water tongue in the Late Ordovician

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ABSTRACT

The eastern equatorial Pacific cold tongue (EEP-CT) today asserts a vital influence on ocean-atmosphere CO₂ exchange and global climate patterns. Here, we report a similar equatorial cold tongue in the Late Ordovician peri-Gondwana region during drastic greenhouse-icehouse climate swings and the first mass extinction. Paleontological, sedimentological, and new stable-oxygen-isotope data from conodont apatite point to a change from warm-water to cool-water tropical depositional environments in the South China plate from Early to Late Ordovician. This apparently contradicts the current paleogeographic reconstructions of a coeval northward drift of South China from subtropical peri-Gondwana to the equator. The trend of climate cooling coincided with the origin and diversification of the *Foliomena* fauna in South China during the Late Ordovician, and the absence of reef-building sponges and corals. This was in sharp contrast with the *Calathium* calcareous sponge reefs in Early Ordovician warm-water settings. In this study, we compare the paleogeographic setting of the South China plate in the Late Ordovician with the EEP-CT today where cool-water depositional environments prevail because of cold upwelling and westerly currents.

INTRODUCTION

Recent paleogeographic reconstructions place the South China plate in paleoequatorial latitudes during the Late Ordovician (e.g., Cocks and Torsvik, 2013; Fig. 1). The northward drift of South China has been extrapolated based on paleomagnetic data, which point to a southern subtropical position in the Early Ordovician and equatorial latitudes by the mid-Silurian. This paleogeographic reconstruction, however, apparently contradicts sedimentary, faunal, and newly acquired $\delta^{18}\text{O}_{\text{conodont-apatite}}$ data, which show an overall change from Early Ordovician warm-water to Late Ordovician cool-water depositional environments (Fig. 2). In this study, we present paleontological, sedimentological, and geochemical data to test a hypothesis, proposed as a part of general modeling of global ocean currents in several recent works (e.g., Servais et al., 2014; Rasmussen et al., 2016; Pohl et al., 2016), that a cold surface current became established by the late Middle Ordovician in the equatorial peri-Gondwana oceans, similar to the eastern equatorial Pacific cold tongue (EEP-CT) today.

INDICATORS OF DEPOSITIONAL ENVIRONMENTS

The Lower Ordovician carbonate facies of the Yangtze Platform (the main element of the South China plate) have shallow- and warm-water characteristics (Fig. 2), such as oolites of the Nantsinkuan and Fenghsiang Formations (mid-upper Tremadocian) and *Calathium* calcareous sponge reefs of the Hunhuayuan

Formation (lower Floian; Li et al., 2015). The *Finkelburgia* and *Tritoechia* brachiopod faunas that represented the predominant shelly benthos in the Lower Ordovician of South China are known to have persisted into the lower Middle Ordovician in the warm tropical seas of Laurentia and Siberia (Zhan and Jin, 2007). The *Sinorthis* warm-water fauna thrived in the early Middle Ordovician (see the GSA Data Repository¹).

In contrast, the Upper Ordovician sedimentary facies and the benthic shelly faunas on the Yangtze Platform of South China show characteristics of a cool-water origin, similar to those of modern and Ordovician examples of cool-water carbonates (James, 1997). The widespread Upper Ordovician strata of the Yangtze Platform generally lack oolite, calcareous green algae, calcareous sponges, stromatoporoids, and hermatypic corals. The Pagoda and Linhsiang Formations (Sandbian–middle Katian), for example, comprised nodular limestone with impoverished and stunted brachiopods and trilobites (Zhan and Jin, 2007). Large-shelled pentameride brachiopods such as *Tcherskidium*, *Proconchidium*, and *Holorhynchus*, which are typical of Late Ordovician warm-water carbonates of Laurentia, Baltica, Siberia, and Kazakhstan, are conspicuously missing from the Yangtze Platform.

¹GSA Data Repository item 2018277, additional details of the brachiopod faunas, geochemical data, and the fossiliferous black shale of the Miaopo Formation, is available online at <http://www.geosociety.org/database/2018/> or on request from editing@geosociety.org.

In the upper Middle to Upper Ordovician succession of the Yangtze Platform, there is a general lack of storm-generated sedimentary structures such as hummocky cross stratification (HCS) or amalgamated shell beds separated by mud drapes. Instead, the platform is characterized by several enigmatic sedimentary facies such as the network structures of the Pagoda Formation (middle Sandbian–lower Katian), interpreted by Zhan et al. (2016) as a time-specific nodular carbonate facies formed during a period of tectonic quiescence in a paleoequatorial setting.

In the Upper Ordovician, the cool- and deep-water *Foliomena* brachiopod fauna prevailed on the Yangtze Platform (see the Data Repository). This fauna occurs predominantly in the Upper Ordovician of the cold-water peri-Gondwana region, found only sporadically in tropical carbonate depositional environments such as in Kazakhstan and Baltica. However, the unusually high abundance, high diversity, and ubiquitous distribution of the *Foliomena* fauna on the Yangtze Platform are particularly striking for its interpreted paleoequatorial setting. In comparison, the *Foliomena* fauna was absent from the large epicontinental seas of Laurentia that straddled the equator and was dominated by warm-water depositional environments during the Ordovician.

During the latest Ordovician (Hirnantian), South China was occupied by the *Hirnantia* fauna, a cool-water brachiopod fauna typical of the peri-Gondwana Kosov province and Avalonia, similar to the *Foliomena* fauna (see the Data Repository).

Geochemical Proxies

Most recent geochemical studies show a prevailing trend of climatic cooling from the Early to Late Ordovician, leading to the terminal Hirnantian glaciation (e.g., Trotter et al., 2008; Finnegan et al., 2011; Swanson-Hysell and Macdonald, 2017). Here, we present a new stable-oxygen-isotopic curve, the first such analysis based on conodont apatite from the entire Ordovician succession of South China. This $\delta^{18}\text{O}_{\text{apatite}}$ curve is in general agreement with the $\delta^{18}\text{O}_{\text{apatite}}$ curve of Trotter et al. (2008), showing a broad trend of positive excursion (Fig. 2). This

Figure 1. Late Ordovician paleogeography, showing similarity between equatorial position of South China plate to that of modern Galápagos Islands. Red dots mark global distribution of predominantly cool-water *Foliomena* faunas, showing their rare equatorial occurrences. (Areas with blue shading denote major occurrences of the *Foliomena* fauna.) For details of *Foliomena* fauna, see Data Repository (see footnote 1). Sea-surface temperature map is from U.S. National Oceanic and Atmospheric Administration (<http://www.ospo.noaa.gov/Products/ocean/sst.html>).

overall cooling trend through the Ordovician has been observed for tectonic plates that remained largely stationary in the tropics (e.g., Laurentia; Trotter et al., 2008), or drifted from temperate to tropical paleolatitudes (e.g., Baltica; Rasmussen et al., 2016) or even from the subtropics to the equator (South China). The positive shift, however, was abrupt in the Darriwilian in Baltica but gradual from the Floian to Darriwilian in South China and Laurentia.

The Yangtze Platform received shallow-water carbonate deposits during the Early Ordovician, represented by widespread peritidal and shallow subtidal facies of the Nantsinkuan and

Fenghsiang Formations. The $\delta^{18}\text{O}_{\text{apatite}}$ values derived from conodonts of these formations are the lowest for the entire Ordovician in South China (Fig. 2), corroborating the warm-water interpretation based on sedimentary and faunal data.

In South China, a major positive excursion in $\delta^{18}\text{O}_{\text{apatite}}$ values (from 17‰ to 18.4‰) occurs in the Pagoda and Linhsiang Formations (early Sandbian–middle Katian), interpreted as an episode of cool-water depositional setting. This was followed by a negative excursion (from 18.4‰ to 16.6‰) from late middle to late Katian. This significant negative shift was not recognized by

Trotter et al. (2008), but the late Katian data agree with the major sea-level rise and marine transgression in the Richmondian of Laurentia and the Boda event in Baltica, coinciding with an episode of global warming (Fortey and Cocks, 2005). The *Hirnantia* fauna-bearing carbonate beds of the Kuanyinchiao Formation show a prominent positive excursion in $\delta^{13}\text{C}$ values, with a shift of 3‰ in relation to the pre-Hirnantian and late Hirnantian (deglaciation episode) isotopic values (Fig. 2).

The stable-isotope data, therefore, corroborate the faunal data to indicate a broad transition from a warm-water to a cool-water tropical environment, in apparent contrast to the northward drift of South China from subtropical to equatorial latitude from Early to Late Ordovician.

CONTROLLING MECHANISMS FOR A PALEOEQUATORIAL COLD-WATER SETTING

In this study, the apparent contradiction between the equatorward drift of South China from the Early to Late Ordovician and the shift from warm-water to cool-water sedimentary facies and benthic shelly faunas is interpreted to indicate an equatorial cool-water tongue, analogous to the modern EEP-CT (Karnauskas et al., 2007).

The Eastern Equatorial Pacific Cold Tongue—A Modern Analog

Despite its small area relative to global oceans, the EEP-CT plays a vital role in modulating global climate. It acts as a major source of CO_2 to the atmosphere via degassing of the upwelled CO_2 -rich water, hosts high primary productivity, and has a strong effect on atmospheric temperature and moisture around the Pacific (Takahashi et al., 2009; Kubota et al., 2014). In the modern EEP, the shallow-water temperature experiences warm-cool cycles seasonally or episodically (Mitchell and Wallace, 1992; Nigam, 1997). This is the result of cool water upwelling along the Chilean coast and the equator, driven by a longshore trade wind, the Ekman divergence, and the westerly equatorial Humboldt Current, bringing nutrient-laden cool waters to the shallow ocean surface to form the EEP-CT that sweeps the Galápagos Islands archipelago (Karnauskas et al., 2007).

Sea-surface temperature in the EEP-CT, as measured in the vicinity of the Galápagos Islands, usually varies between 18 and 25 °C annually (U.S. National Oceanic and Atmospheric Administration, <http://www.ospo.noaa.gov/Products/ocean/sst.html>), being cooler from June to December and coolest from September to November, notably below the equatorial average temperature of 27 °C. In La Niña years, the water temperature can be 5 °C cooler. More importantly, temperatures below the thermocline, which is present at varying depths between 12

Figure 2. Stratigraphic distribution of sedimentary facies, faunas, and stable-oxygen-isotope excursions in Ordovician succession of South China plate. (Scale on top is for the Hirnantian portion of the isotope curve. Error bars represent standard deviations given in Data Repository [see footnote 1], Table DR1.) Paleogeographic reconstruction is based on Cocks and Torsvik (2013). Note relatively small land areas exposed along margin of South China plate during Middle and Late Ordovician (see Zhan et al., 2016). For details on key faunas listed see Data Repository. Hirn.—Hirnantian; VSMOW—Vienna standard mean ocean water.

and 40 m, can drop to 13 °C (Rosenberg and Bassett, 2016). During the wet season (December to June), the southeast trade wind and the cool-water upwelling are weaker, keeping the Panama Basin warm, bringing a typical tropical climate to this region, including the Galápagos Islands.

Hurricane-Free Equatorial Zone

In the EEP, the unusually shallow thermocline (e.g., 12 m to 18 m in the water around the Galápagos Islands) corresponds approximately

to the fair-weather wave base. The lack of hurricane-grade storms in this equatorial zone (for a summary, see Jin et al., 2013) greatly reduces vertical mixing below the fair-weather wave base, and thus the cool water mass (such as the equatorial undercurrent) experiences limited disturbances, forming a distinct thermocline at relatively shallow water depth. The lack of vertical mixing below the thermocline or pycnocline in the EEP also facilitates the formation of a thick, extensive, cold, hypoxic to oxygen-minimum

zone (see the Data Repository, Part 6). In the hurricane-dominated Caribbean Sea, in contrast, the thermocline is typically >100 m deep (Alvera-Azcárate et al., 2011) due to effective vertical mixing by hurricanes.

Paleogeographic Similarities

The driving force for the EEP-CT is the Humboldt (or Peru) Current system that brings cold Antarctic water to the EEP along the western coast of South America. This cold current

is deflected westward along the equator by the trade winds, causing multiple upwellings of cold, nutrient-rich intermediate waters along its path, leading to high primary productivity and a rich and diverse marine ecosystem (Field et al., 1998; Montecino and Lange, 2009).

In the Ordovician, the long coastline of Gondwana (Fig. 1) had a geographic setting similar to that of modern Antarctica–South America (Torsvik and Cocks, 2013). The vast Gondwana land mass was centered on the South Pole. With continued global cooling during the Late Ordovician and onset of the continental ice cap, the cold water along high-latitude Gondwana likely generated deep or intermediate flows, as well as surface cold currents similar to the modern Humboldt Current (Servais et al., 2014; Rasmussen et al., 2016; Pohl et al., 2016).

Rasmussen and Harper (2011, p. 488) proposed that the high diversity of Ordovician brachiopods of South China may have been related to nutrient-rich, cool-water upwelling off the Gondwana coast, similar to that of the South American west coast today, but considered the idea “speculative” because of the lack of evidence for eutrophication. In the Upper Ordovician (lower Sandbian) succession on the Yangtze Platform, however, the enigmatic occurrence of rich and diverse shelly benthos in the Miaopo Formation black shale supports both a cool-water equatorial setting and periodic eutrophication (see the Data Repository, Part 6). South China likely drifted into the hurricane-free paleoequatorial latitudes by the early Sandbian. The lack of hurricane-grade severe storms significantly reduced vertical mixing of the Yangtze sea, making the substrate at moderate water depth (15–70 m) susceptible to oxygen starvation. In addition, South China during the Late Ordovician was similar to the Galápagos Islands today in their position within an equatorial cold tongue. This paleogeographic setting would have promoted cool-water upwelling to promote high primary productivity, episodic eutrophication, and organic-rich deposits.

CONCLUSIONS

The Ordovician was characterized by drastic climate changes between greenhouse and ice-house episodes, the Great Ordovician Biodiversification Event, and the terminal mass extinction. South China has one of the world’s best records of the biodiversity boom and bust in the Ordovician, commonly preserved in geologically and paleogeographically puzzling depositional facies. The equatorial cool-water setting proposed in this study, using the modern EEP-CT as an analog, offers a congruent interpretation of the cool-water carbonate, unusually high diversity of shelly benthos (some even in black shale),

positive shift of $\delta^{18}\text{O}$ values (cooling), and the equatorward drift of South China during the Late Ordovician. The paleoenvironmental setting proposed in this study also provides some insight into how an equatorial cold tongue system could result in eutrophication and an oxygen-poor dead zone in relatively shallow epicontinental seas.

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