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Paleomagnetic insights into the Cambrian biogeographic conundrum: Did the North China craton link Laurentia and East Gondwana?

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ABSTRACT

Redlichiid trilobite and small shelly fossils indicate strong ties of the North China craton (NCC) to Gondwana during the early Cambrian, while recent discoveries of the characteristic fossils of Laurentia in Wuliuan shales in the eastern NCC imply its possible connection with Laurentia during the middle Cambrian. Here we report a new paleomagnetic pole at 31.8°S, 140.4°E (radius of 95% confidence cone of paleomagnetic pole, A_{95}, = 5.3°), obtained from the Wuliuan (ca. 505 Ma) Hsuchuang Formation, by averaging our new data and existing virtual geomagnetic poles acquired from different parts of the NCC. A positive regional tilt test and the presence of geomagnetic reversals demonstrate that the remanence was primary. The paleomagnetic data permit placing the NCC near 20°N between Laurentia and Australia at ca. 505 Ma, suggesting that the NCC may have played the role of biogeographic link between East Gondwana and Laurentia in the middle Cambrian. Low-latitudinal westward ocean currents may have facilitated faunal migrations from Laurentia to East Gondwanan blocks via the NCC as well as the newly formed tectono-paleogeographic archipelago, which likely further enhanced biological exchange in the late Cambrian.

INTRODUCTION

The Cambrian trilobite biogeographic differentiation between the olenellid realm in Laurentia and the redlichiid realm in Gondwana (Zhang, 2003; Álvaro et al., 2013) has been considered the result of a newly opened deep ocean, named Iapetus, separating Laurentia from Gondwana at the beginning of Cambrian Series 2 (before ca. 520 Ma; Dalziel, 2014). However, it is puzzling that as the Iapetus Ocean widened, the late Cambrian witnessed more common biogeographic features between Laurentia and Gondwana (Álvaro et al., 2013; Collette, 2014; Wernette et al., 2020). Interesting questions are when and how the trilobites in different realms began to communicate with each other. The North China craton (NCC) has long been considered to have a close biogeographic association with East Gondwana because it yields the typical redlichiid trilobites (e.g., Zhang, 2003), but recent discoveries of a few characteristic fossils of Laurentia in Wuliuan shales in the eastern NCC (Sun et al., 2020a, 2020b), together with the mixture of middle and late Cambrian trilobites among the NCC, East Gondwana, and Laurentia (e.g., Zhang, 2003; Álvaro et al., 2013; Collette, 2014; Wernette et al., 2020), prompt us to investigate the role of the NCC in biogeographic changes between East Gondwana and Laurentia in the middle to late Cambrian.

In this paper, we report paleomagnetic results newly obtained from the middle Cambrian (Wuliuan) Hsuchuang Formation in the eastern NCC. Based on a combination of the updated paleomagnetic data and the paleontological information available, we provide a new solution to the Cambrian biogeographic conundrum by placing the NCC as a biogeographic link between Laurentia and Gondwana initiated in the middle Cambrian.

GEOLOGICAL SETTING AND SAMPLING

Our new paleomagnetic investigation was conducted in the Tai'an region in western Shandong Province and the Xuzhou region in northern Jiangsu Province, eastern NCC (Figs. 1A and 1B), where Cambrian strata disconformably overlie Mesoproterozoic–Neoproterozoic sedimentary rocks or unconformably overlie metamorphic basement rocks, and in turn conformably underlie Lower Ordovician carbonate strata. The strata in the region were folded during the middle Jurassic (JBGMR, 1984; SBGMR, 1991). The sampled Hsuchuang Formation, ranging from 70 to 130 m in thickness, mainly consists of red siltstone and shale in the lower part and gray limestone in the upper part (JBGMR, 1984; SBGMR, 1991). The trilobite biozones, including the *Hsuchuangia-Ruichengella*, *Sunaspis laevis*, *Poriagraulos natum*, and *Bailiella lantenoisi* zones, indicate that the strata are of the Wuliuan Stage (Zhu et al., 2019, and references therein), which is estimated to be ca. 506–503.5 Ma based on new isotopic ages (Karlstrom et al., 2020; Sundberg et al., 2020).

We collected a total of 122 paleomagnetic core samples from 12 sites from the red siltstone in the middle part of the Hsuchuang Formation in both regions (six sites in section A [Fig. 1D] and six sites in section B [Fig. 1C]) (Table S1 in the Supplemental Material[1]). Samples were collected using a portable drill and oriented by using both a magnetic compass and a solar compass. Consistent results between using the compasses indicate the absence of magnetic anomalies in the sampling regions.

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[1]Supplemental Material. Detailed paleomagnetic statistical parameters, four supplemental figures, three supplemental tables, and references. Please visit https://doi.org/10.1130/GEOL.S.13182974 to access the supplemental material, and contact editing@geosociety.org with any questions.

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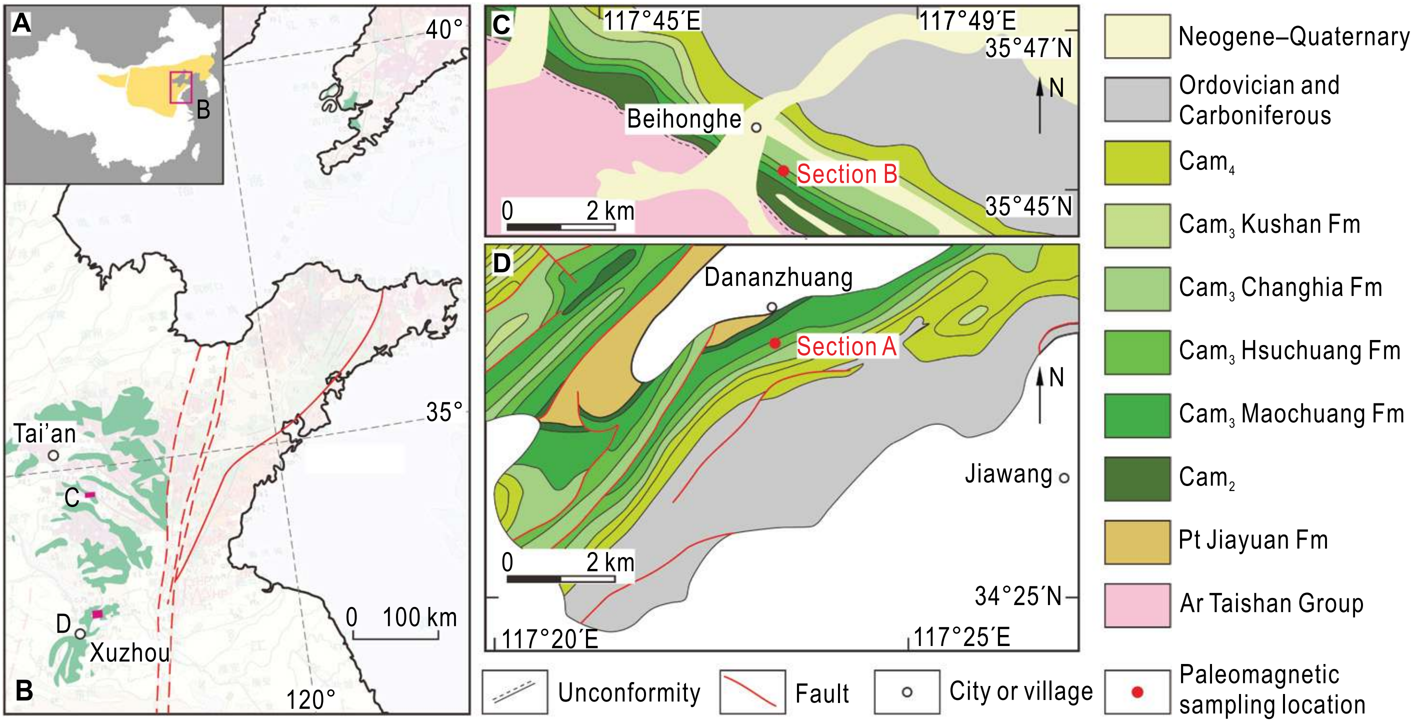

Figure 1. Geological setting, and paleomagnetic sampling sections. (A) Outline of the North China craton (NCC) and its position in China. (B) Distribution of Cambrian–Ordovician successions in the eastern NCC (as shown in the green filled parts). Modified from IGCAGS (2002). (C,D) Simplified geological maps for paleomagnetic sampling locations in the Tai'an region and Xuzhou region of China, respectively. Ar—Archean; Cam_2—Cambrian Series 2; Cam_3—Miaolingian; Cam_4—Furongian; Fm—Formation; Pt—Proterozoic.

METHODS

Each oriented core sample was cut into one or two 2.2-cm-long cylindrical specimens in the laboratory. Magnetic measurements were conducted in a magnetically shielded room with a residual field <200 nT in the Paleomagnetism and Environmental Magnetism Laboratory at China University of Geosciences, Beijing. Remanent magnetizations were measured through use of a 2G Enterprises 755-4K cryogenic magnetometer, and stepwise thermal demagnetization was carried out with an ASC TD-48 furnace, which has an internal residual field of <10 nT. Demagnetization temperature intervals ranged generally from a maximum of 80 °C for lower temperatures to a minimum of 10 °C for higher temperatures up to 690 °C. Isothermal remanent magnetization (IRM) acquisition and demagnetization, backfield IRM acquisition, and the Lowrie test (Lowrie, 1990) were conducted on representative specimens. Magnetic components of all the specimens were computed by using principal-component analysis (Kirschvink, 1980), and interval-mean directions were calculated using Fisher statistics (Fisher, 1953). Paleomagnetic data were analyzed using Enkin's (1990) and Cogné's (2003) computer programs. Plate reconstructions were generated using GPlates software (https://www.gplates.org).

PALEOMAGNETIC RESULTS

Most samples from the Hsuchuang Formation in both regions recorded two well-defined magnetic components (Figs. 2A and 2B). Directions of the low-temperature component determined below 300 °C resemble the local geocentric axial dipole field in geographic coordinates (Fig. S1 in the Supplemental Material). It is thus interpreted as the viscous remanent magnetization of the recent geomagnetic field. The high-temperature component (HTC) is defined for temperatures up to 680 °C. The presence of high-coercivity hematite is evidenced by IRM acquisition curves and the Lowrie test (Fig. S2). The HTC of section A in the Xuzhou region yields both geomagnetic polarities, with most vectors directed northeast and down (polarity 1) and a smaller number directed southwest and up (polarity 2) (Fig. 2C). The polarity 2 samples were gleaned from two sites (15DNZ08 and 15DNZ09) that are stratigraphically adjacent to each other (~2 m apart), thus representing a consistent magnetochron. The antipodal polarities of the HTC passed a positive reversal test (see the Supplemental Material and Table S1). In section B, only the polarity 1 directions were identified (Fig. 2C).

The site-level virtual geomagnetic poles (VGPs) obtained in the Xuzhou and Tai'an regions generally overlap within error with the previously reported VGPs from sandstone, shale, and limestone of the Hsuchuang Formation in the Jingxing, Hancheng, and Zhongyang regions (Zhao et al., 1992; Huang et al., 1999) in the central and western parts of the NCC (Fig. 2D; Table S1). The 21 site-level VGPs of the two polarity groups also passed a reversal test (for the detailed statistical parameters, see the Supplemental Material text and Table S1). In all five sampled regions, fold tests were not available, but the site-level VGPs for the five regions as a whole passed a regional tilt test, confirming a pre-tilting origin of the characteristic remnant magnetizations (Supplemental Material text and Table S1). We thus calculate a mean pole at 31.8°S, 140.4°E (radius of 95% confidence cone of paleomagnetic pole, A_{95}, = 5.3°), by averaging 21 VGPs obtained from the five regions for the Hsuchuang Formation (pole XZ in Table S1). Although pole XZ is close to the Furongian and Ordovician paleomagnetic poles of the NCC (Fig. S3; Table S2), the presence of reversals and the positive regional tilt test strongly support the interpretation of primary origin. The new paleomagnetic pole yields a paleolatitude of 20.3° ± 5.3° for the reference site (34.5°N, 117.4°E) in the Xuzhou region.

DISCUSSION

In various Cambrian paleogeographic reconstruction models, the close association between the NCC and East Gondwana has been suggested, commonly based on three basic lines of evidence: (1) the redlichiid trilobite and small shelly fossils preserved in both the NCC and Gondwanan blocks are similar (Zhang, 2003; Álvaro et al., 2013; Pan et al., 2019); (2) the paleomagnetic records permit placing the NCC and the East Gondwanan blocks both in

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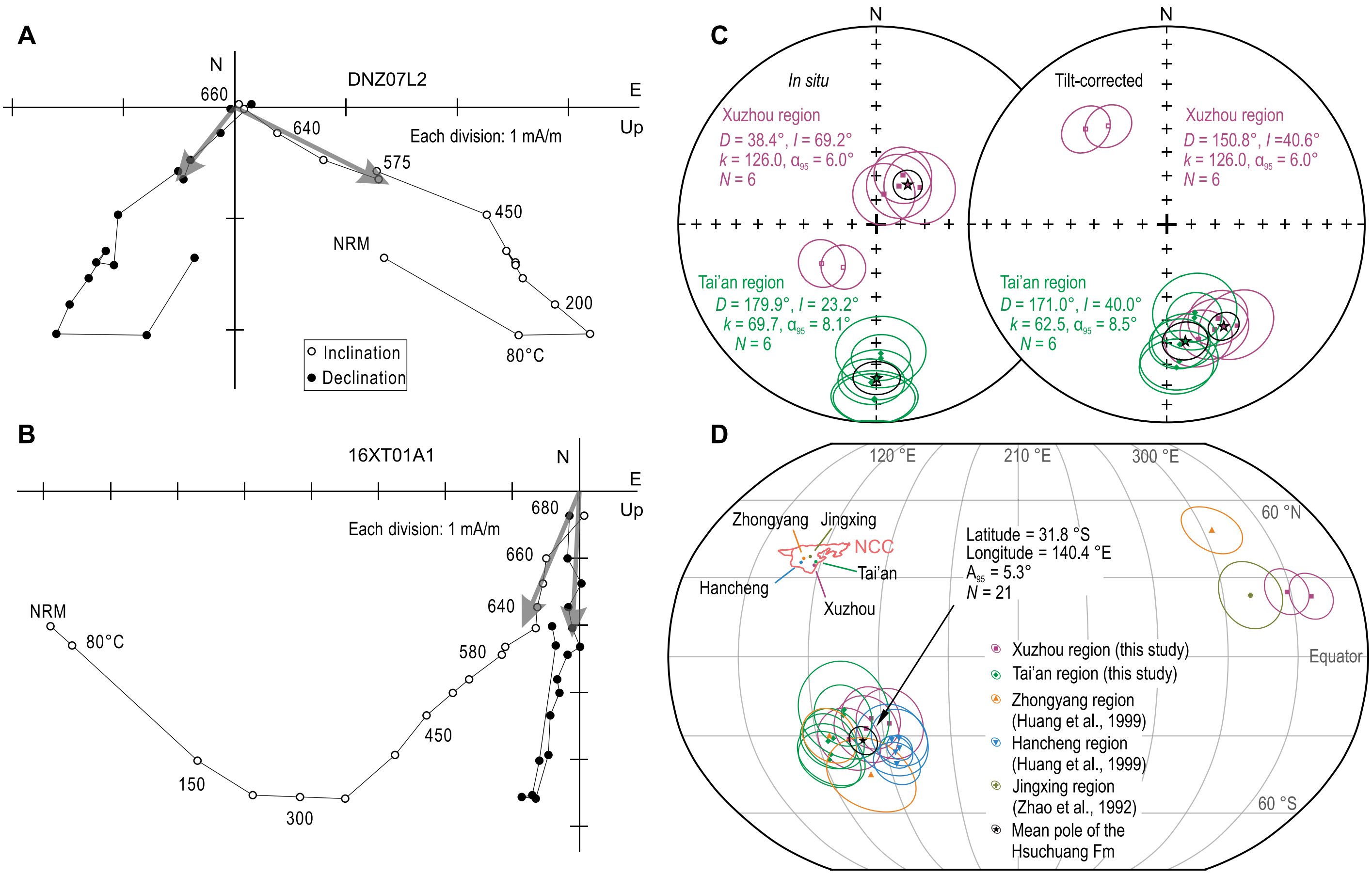

Figure 2. Paleomagnetic results from the Hsuchuang Formation, North China craton (NCC). (A,B) Demagnetization trajectories of representative specimens from the Xuzhou region (A) and Tai'an region (B), plotted in geographic coordinates; arrows mark least-squares fit directions of high-temperature component (HTC). NRM—natural remanent magnetization. (C) Equal-area projections showing site-mean paleomagnetic directions of the HTC from the Xuzhou and Tai'an regions, symbols and statistical results being matched in color. *D*—declination; *I*—inclination; α_{95}—radius of 95% confidence cone of mean direction; *k*—precision parameter of Fisher (1953); *N*—number of sites. Closed and open symbols represent downward and upward inclinations, respectively. Stars with 95% confidence circles indicate Fisher statistical direction. (D) Twenty-one (21) site-level virtual geomagnetic poles from five regions of NCC and mean pole, plotted in Robinson projection. Fm—Formation; A_{95}—radius of 95% confidence cone of paleomagnetic pole.

low-latitudinal regions (Zhao et al., 1992; Huang et al., 1999; Yang et al., 2002); and (3) the Pan-African–aged detrital zircons recovered largely from the Cambrian strata in the NCC have been commonly considered to be from Gondwana (McKenzie et al., 2011; Hu et al., 2013; He et al., 2017; Wan et al., 2019).

Our new paleomagnetic results have strengthened the Cambrian database of the NCC. The existing high-quality middle Cambrian–Ordovician poles cluster (see Table S2; Fig. S3) and collectively demonstrate that the NCC was located in low-latitudinal regions without considerable motion. The lack of early Cambrian poles hampers testing of any concrete connection or kinematic linkage between the NCC and East Gondwana or Laurentia. Although an early Cambrian connection between the NCC and Gondwana supported by the biogeographic evidence and detrital zircon information is possible, a middle Cambrian to Ordovician apparent polar wander path of the NCC cannot match that of Gondwana (McElhinny et al., 2003; Mitchell et al., 2010), meaning that a solid connection model then cannot be suggested. Moreover, the large gap in the NCC paleomagnetic database between the Late Ordovician to the Early Carboniferous leaves the polarity of the early Paleozoic poles of the NCC undetermined. This uncertainty permits two options, placing the NCC either in the Northern Hemisphere (Zhao et al., 1992; Li and Powell, 2001) or in the Southern Hemisphere (Huang et al., 1999; Yang et al., 2002) in Cambrian time.

The preferable option places the NCC near 20°N at ca. 505 Ma based on the newly obtained pole XZ. In a global paleogeographic context, this option permits that the NCC was located between East Gondwana and southwestern Laurentia (present-day coordinates) (Fig. 3). The NCC likely played a role as a biogeographic link between Gondwana and Laurentia and enhanced faunal exchange. The other option, placing the NCC in the Southern Hemisphere (see Fig. S4), however, requires the NCC to have entered the newly opened Iapetus Ocean in the early Cambrian, which is incompatible with the tectonic interaction models between the southern part of Laurentia and West Gondwanan blocks (Dalziel, 2014). Even if the Southern Hemisphere alternative is considered, the idea that NCC likely played a role as a biogeographic link between Gondwana and Laurentia and enhanced faunal exchange is still consistent with our data. Thus, polarity ambiguity does not alter the fundamental observation that the NCC played a role in connecting Cambrian paleobiogeographic provinces.

We speculate that the link appeared ca. 510 Ma. While redlichiids were found in both NCC and Gondwanan blocks, olenellids were distributed in Laurentia (Fig. 3). This suggests that the NCC was likely located close to Gondwana and separated more distantly from Laurentia during the early Cambrian. Recently, some exceptionally preserved fossils were reported from the middle Cambrian strata in the NCC, and a few of the fossil species have not been confidently reported outside Laurentia thus far (Sun et al., 2020a, 2020b). For example, the arthropods *Sidneyia* and *Cambroraster*, remarkable animals from the Burgess

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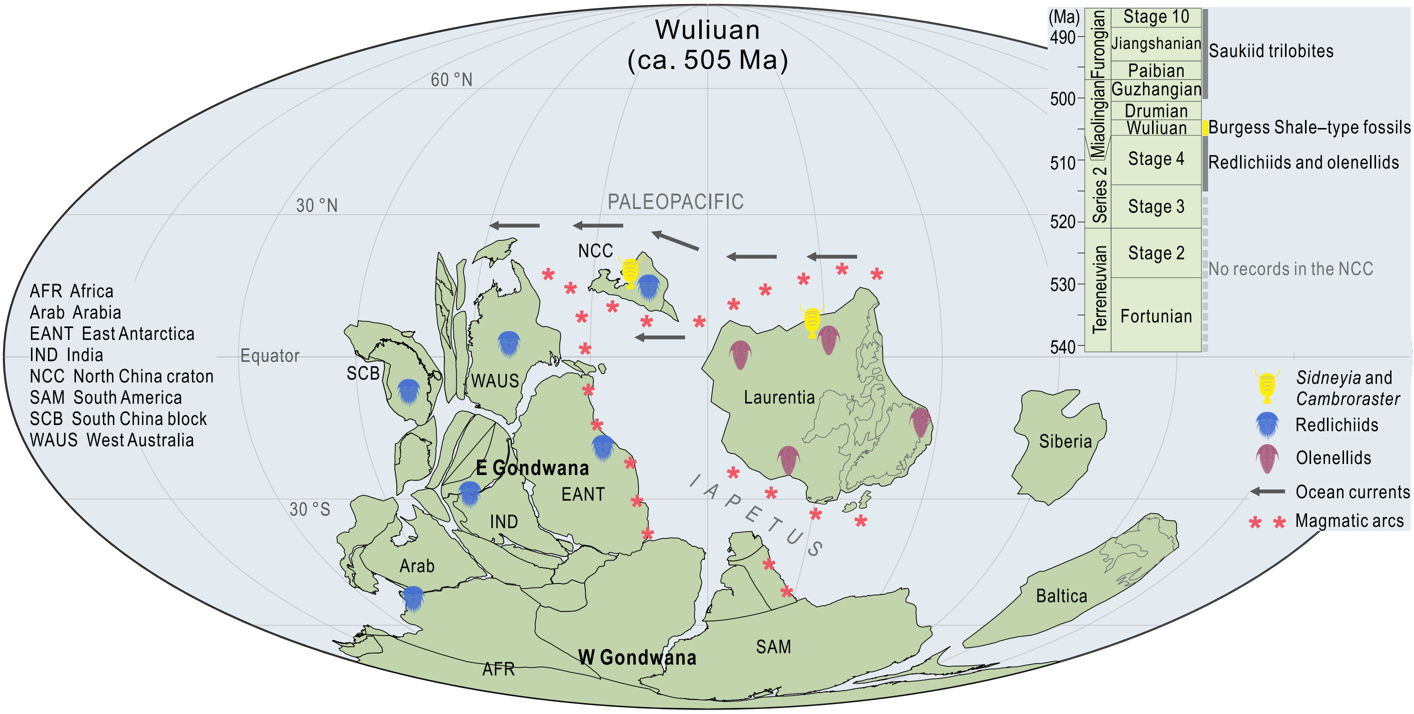

Figure 3. Paleogeographic reconstruction showing the North China craton (NCC) as a biogeographic link between East Gondwana and Laurentia in the Wuliuan (ca. 505 Ma). Global reconstruction is based mainly on paleomagnetic data (Table S2 [see footnote 1]). Absolute longitudes for each tectonic entity are arbitrary. Configuration of Gondwana and Peri-Gondwanan terranes is modified from Xian et al. (2019). For Euler rotation parameters, see Table S3. Distribution of magmatic arcs is synthesized from Li and Powell (2001), Cawood (2005), Dalziel (2014), Han et al. (2016), and Torsvik and Cocks (2017). Inferred ocean currents are modified from Brock et al. (2000). Distributions of Burgess Shale–type fossils (arthropods *Sidneyia* and *Cambroraster*) are according to Sun et al. (2020a, 2020b). Distributions of redlichiids and olenellids are modified after Sundberg et al. (2020). The term "olenellids" includes families Olenellidae and Biceratopsidae. Term "redlichiids" includes Redlichiinae only. Inset: ICS Cambrian time scale and biological events discussed in the text.

Shale biota (Wuliuan; British Columbia, Canada), have been discovered recently from the Wuliuan shales in the eastern NCC (Sun et al., 2020a, 2020b). The Burgess Shale–type fossil biotas have been found from most continents in the Cambrian, but common fossil components among these biotas are usually pelagic and nektonic organisms. The co-occurrence of the nektobenthic arthropods (*Sidneyia* and *Cambroraster*) on both the NCC and Laurentia continents implies their possible geographic connection in the middle Cambrian. On the other hand, subduction and magmatic arc systems had widely developed along Australia-Antarctic margin of Gondwana (Li and Powell, 2001; Cawood, 2005) and around Laurentia (Dalziel, 2014; Torsvik and Cocks, 2017) and the NCC (Han et al., 2016) (Fig. 3) since at least ca. 520 Ma. Various continental and intra-oceanic basement assemblages were largely distributed outboard of East Gondwana (Cawood, 2005). The hypothesized westward ocean currents in the low latitudes (Brock et al., 2000; Collette, 2014) could have facilitated faunal migrations from Laurentia to East Gondwanan blocks via the NCC as well as the low-latitudinal offshore terranes and magmatic island arcs (Fig. 3). The newly formed tectono-paleogeographic archipelago could thus have provided young zircon grains to the sedimentary basins in the NCC and led to more extensive biological exchanges in the late Cambrian (Zhang, 2003; Álvaro et al., 2013; Collette, 2014; Wernette et al., 2020). Further phylogenetic and paleobiogeographic analyses are necessary to test this hypothesis.

CONCLUSION

New paleomagnetic results obtained from the Hsuchuang Formation (Wuliuan, ca. 505 Ma) have strengthened the Cambrian database of the NCC and permit placing the NCC between East Gondwana and Laurentia in the middle Cambrian. The NCC may have played the role of a biogeographic link between East Gondwanan blocks and Laurentia under the influence of the low-latitudinal westward ocean currents. The newly formed tectono-paleogeographic archipelago likely further enhanced biological exchange in the late Cambrian.

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