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Key Points:
- Lhasa Permo-Carboniferous glaciogenic diamictites (PCGDs) differ in detrital zircon U-Pb age and εHf(t) from those in S. Qiangtang and Tethyan Himalaya.
- Lhasa PCGDs come from Australian Gondwana, whereas the S. Qiangtang and Tethyan Himalayan PCGDs from Indian Gondwana.
- E. Lhasa represents the outboard extension of N. Central Australia, whereas W. Lhasa was located outboard of the West Australian Craton.

Supporting Information:
Supporting Information may be found in the online version of this article.

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Abstract
The widespread Tibetan Permo-Carboniferous glaciogenic diamictites (PCGDs) are conventionally thought to be sourced from Indian Gondwana during glacier transport and deglaciation. However, the Lhasa PCGDs differ in detrital zircon U-Pb age spectra and εHf(t) values from those in Southern Qiangtang and Tethyan Himalaya. The similarities in εHf(t) values for similar-age detrital zircons, the development of glacier transport pathways, and the large volumes of the Tibetan PCGDs indicate an Australian source for the Lhasa PCGDs, and an Indian source for the Southern Qiangtang and Tethyan Himalayan PCGDs. We conclude that the Southern Qiangtang and Tethyan Himalayan are paleographically linked to northern India, whereas Lhasa is positioned adjacent to NW Australia during the Paleozoic. Magmatic and metamorphic records further indicate that eastern Lhasa (E90°–E95°) represents the outboard extension of events recorded in northern Central Australia, whereas western Lhasa (E80°–E90°) was located outboard of the West Australian Craton.

Plain Language Summary
Precisely understanding the paleogeography of the Lhasa Terrane in southern Tibet is crucial to reconstruct the opening and drifting histories of the Neo-Tethys that controls on the evolution of the India-Asia collision zone. The paleogeography of the Lhasa Terrane has been variously proposed to originate from northern India, northwest Australia, and the northern extent of the East African Orogen. Resolving this paleogeographic puzzle requires solid lines of evidence and a full understanding of the data. A combination of new detrital zircon U-Pb age and Hf isotope data of the Tibetan Permo-Carboniferous glaciogenic diamictites constrains the paleogeography of the Lhasa Terrane to a position adjacent to NW Australia. Magmatic and metamorphic records further refine that the eastern Lhasa (E90°–E95°) represents the outboard extension of events recorded in northern Central Australia, whereas the western Lhasa (E80°–E90°) was located outboard of the West Australian Craton. Our results show that a combination of provenance analysis (including magmatic history, isotopic data, and sediment transport pathway) of the widespread late Paleozoic diamictites in Gondwana, as well as magmatic and metamorphic records, can allow precise paleogeographic reconstruction of the longitudinal disposition of blocks along the northern Gondwana margin.

1. Introduction
Microcontinental fragments are important components of ancient orogenic belts, and understanding their paleogeography is fundamental for reconstructing their evolution. It is however, often problematic to establish precise paleogeographies for such fragments due to the difficulty in defining features that uniquely link them to specific regions of broader continental reconstructions. This problem is exemplified by the Lhasa Terrane in southern Tibet, now a part of the Eurasian Tethyan Orogenic Belt. This terrane has been variously positioned adjacent to northern India (Allègre et al., 1984), at the boundary between India and Australia (Guynn et al., 2012), adjacent to NW Australia (Audley-Charles, 1988; Metcalfe, 2013; Zhu et al., 2011), and even at the northern extent of the East African Orogen between Arabia and India (Hut et al., 2018; Z. M. Zhang et al., 2012). Resolving this paleogeographic puzzle of the Lhasa Terrane requires new and solid lines of evidence as well as a full understanding of existing data.

Diamictite formed through deglaciation consists of poorly to non-sorted clasts in a clastic matrix (sandstone and slate) (Rampino, 1994). Permo-Carboniferous glaciogenic diamictites (PCGDs) in India and Australia...
are a key index for paleogeographic reconstruction of Gondwana-derived terranes. This is demonstrated by those from Lhasa and Southern Qiangtang in the Tibetan Plateau (Figure 1)—where the PCGDs are accepted as geological evidence for these terranes rifting from India (cf. Jin, 2002). However, these PCGDs all show similar stratigraphic relations and petrographic compositions (Figure 2), making it difficult to tie the position of their sources with respect to proposed sources in India or Australia.

U-Pb age and Hf isotopic data of detrital zircons from clastic rocks are a well-established tool to track provenance of sediments and enable paleogeographic reconstructions that are simply unavailable from other methods (e.g., Morón et al., 2019). This article reports a large data set of in situ U-Pb dating and Hf-isotope analysis on detrital zircons from the Tibetan PCGDs (including slate and sandstone matrixes and sandstone clasts) (Figure 1). These data reveal the notable differences of provenance between the Lhasa PCGDs and the Southern Qiangtang and Tethyan Himalayan PCGDs, which together with regional magmatic and metamorphic data, enable us to precisely locate the Lhasa off NW Australia and the Southern Qiangtang and Tethyan Himalaya outboard of northern India during the Paleozoic.
Figure 2. Generalized stratigraphic columns and field occurrences of the Tibetan Permo-Carboniferous glaciogenic diamictites investigated in this study, showing the sampling locations.
2. Tibetan Permo-Carboniferous Glaciogenic Diamictites (PCGDs) and Samples

The Northern Qiangtang, Southern Qiangtang, Lhasa, and Tethyan Himalaya (Figure 1) constitute the main components of the Tibetan Plateau (Zhu et al., 2013). The PCGDs are widespread in these terranes, including the Cameng and Zhanjin formations in the Southern Qiangtang (Figures 2a and 2b), the Yongzhu, Lai-gu, and Laga formations in the Lhasa Terrane (Figures 2c–2f), and the Polinpu and Bilong formations in the Tethyan Himalaya (Jin, 2002; Li et al., 2008) (Figure 2g). The chaotic structure, glacial striations, multiple sets of fracture surfaces, and horseback-shaped clasts (Figure 2) of the PCGDs collectively demonstrate that deposition of the diamictites is associated with continental deglaciation.

A total of 16 matrix and seven clast samples were collected from seven diamictite sites in the Southern Qiangtang, Lhasa, and Tethyan Himalaya (Figures 1 and 2) for zircon U-Pb dating and Hf isotope analysis. The analytical methods are given in the Supporting Information. The matrix samples include slate, pebbly slate, feldspar/lithic/quartz sandstone, and the clast samples consist mainly of lithic/quartz sandstone (Figure 3; Table S1). Sample details and zircon U-Pb (2,065 concordant analyses) and Hf isotopic (1,371 analyses) data are provided in Tables S1–S3. Detrital zircon age spectra and $\varepsilon_{Hf}(t)$ values are illustrated in...
Results are compared with data of the Paleozoic metasedimentary rocks in southern Tibet (Zhu et al., 2011) and Permo-Carboniferous sandstone samples from Canning Basin in Northern Australia (Morón et al., 2019) (Figures 4 and 5).

### 3. U-Pb Age and Hf Isotopic Data of the Tibetan PCGDs

#### 3.1. Southern Qiangtang

A total of 560 zircons from six matrix samples in the Southern Qiangtang show age spectra concentrating at 500–1,000 Ma with four primary peaks at 584 ± 7 Ma, 816 ± 7 Ma, 957 ± 6 Ma, and 2,474 ± 9 Ma (Figure 4a). These peaks have zircon $\varepsilon_Hf(t)$ of −28.3 to +9.4 (Table S3), −21.9 to +15.1, −21.0 to +10.4, and −11.3 to +5.5 (Figures 5a and 5b), respectively. A broad age plateau (1,600–1,850 Ma) is dominated by negative $\varepsilon_Hf(t)$ up to −13.5. One sandstone clast in the Southern Qiangtang has age peaks at 566 ± 21 Ma, 822 ± 19 Ma, and 2,487 ± 25 Ma (Figure 4b), yielding zircon $\varepsilon_Hf(t)$ of −26.9 to +8.3, −16.9 to +12.7, and −6.5 to +13.2.

**Figure 4.** Age distributions of detrital zircons from the Tibetan Permo-Carboniferous glaciogenic diamictites (this study) and the Canning Basin in northern Australia (Morón et al., 2019). Distinctive age peaks are weighted mean ages obtained using the Isoplot 4.0 software for a given range of zircon U-Pb ages (color bands) following normal distribution. The $^{207}$Pb/$^{206}$Pb ages were used for >1,000 Ma, and the $^{206}$Pb/$^{238}$U ages for younger zircons. Analyses with >10% discordance are excluded. $N$ = number of samples, $n$ = total number of analyses.
An age plateau of 1,550–1,900 Ma, similar to the matrix samples, is also observed.

3.2. Lhasa Terrane

The 689 analyzed grains from eight matrix samples from the Lhasa Terrane define two major age peaks (Figure 4c) at 546 ± 6 Ma with ε_Hf(t) of −27.4 to +10.4 (Table S3) and 1,176 ± 5 Ma with ε_Hf(t) of −25.2 to +13.4 (Figure 5c). Two minor age peaks (952 ± 7 Ma and 2,662 ± 13 Ma) and a broad age plateau (1,600–1,800 Ma) are also documented (Figure 4c), which show ε_Hf(t) of −21.6 to +11.4, −9.4 to +2.8, and −11.3 to +13.6 (Figures 5c–5e), respectively. U-Pb ages of 329 analyses from four sandstone clasts in the Lhasa Terrane reveal three pronounced peaks (Figure 4d) at 1,177 ± 9 Ma with ε_Hf(t) of −11.2 to +16.3, 1,762 ± 8 Ma with ε_Hf(t) of −14.7 to −0.8, and 2,687 ± 12 Ma with ε_Hf(t) of −7.4 to +5.9 (Figures 5c–5e) and two minor peaks at 981 ± 11 Ma (ε_Hf(t) = −7.8 to +6.7) and 571 ± 17 Ma (ε_Hf(t) = −23.1 to 0).

Figure 5. Plots of ε_Hf(t) (parts per 10^14 deviation of initial Hf isotope ratios between zircon samples and the chondritic reservoir at the time of zircon crystallization) vs. U-Pb ages of the detrital zircons from the Tibetan Permo-Carboniferous glaciogenic diamictites (this study) and Paleozoic metasedimentary rocks (Zhu et al., 2011). The India- and Australia-derived detrital and co-magmatic zircons are shown for comparison. Data sources: Cona granitoid (Ding & Zhang, 2016), Dongargarh granitoid (Manikyamba et al., 2016), Bomi granitoid gneiss (cf. Chen et al., 2019), Canning Basin (Morón et al., 2019), Western Australia (Veevers et al., 2005), Albany-Fraser igneous rock and Musgrave Domain granite (Ameen & Wilde, 2018; Ivanic et al., 2012; Kirkland et al., 2013; Morón et al., 2019).

(Figures 5a and 5b), respectively. An age plateau of 1,550–1,900 Ma, similar to the matrix samples, is also observed.
Figure 6. Reconstruction of eastern Gondwana during the Permo-Carboniferous showing the paleogeographic locations of the Lhasa Terrane and Southern Qiangtang (basemap is from Scotese, 2012). Blue and yellow solid lines show the proposed main sediment transport pathways with headwaters in interior India, Antarctica, and central Australia, finally debouching on the margin of the Paleo-Tethys Ocean (Barham & Kirkland, 2019; Qiangtang (basemap is from Scotese, 2012)).

3.3. Tethyan Himalaya

The detrital zircon age spectra of two matrix samples from Kangmar in the Tethyan Himalaya includes multiple age peaks at 543 ± 9 Ma, 955 ± 8 Ma, and 2,497 ± 13 Ma, as well as a wide age plateau at 1,550–1,800 Ma (Figure 4e), having zircon εHf(t) of −20.2 to +11.8, −27.6 to +9.4 (mostly −10.8 to +9.4), −12.1 to +4.1, and −11.2 to +7.8 (Figures 5a and 5b), respectively. The detrital zircons from two sandstone clasts from Kangmar yield 189 U-Pb ages ranging from 584 to 2,709 Ma, with a primary peak at 832 ± 6 Ma (Figure 4f) that is, dominated by positive εHf(t) values (averaging 3.8 ± 1.1) (Figure 5a).

4. Provenance of the Tibetan PCGDs

A wide age spectrum of 500–1,200 Ma detrital zircons from the Paleozoic metasedimentary rocks in the Tibetan Plateau has previously been recognized as a characteristic of a Gondwana source (Gehrels et al., 2011), but those works provided little information on the precise provenance of detritus along Gondwana’s northern margin. The similarities of zircon age spectra (peaks at ~820 Ma, ~850 Ma, and ~2,480 Ma) (Figures 4a–4b and 4e–4f) and zircon εHf(t) values of ~820 Ma and ~2,480 Ma peaks (Figures 5a–5b) between the Southern Qiangtang and Tethyan Himalaya can be best interpreted as the two terranes sharing a common source from Indian Gondwana. The ~820 Ma detrital zircons are unlikely to be sourced from the 826 to 806 Ma igneous rocks in the Lhasa Terrane (cf. Chen et al., 2019), because such detrital zircons are essentially lacking in the coeval Lhasa PCGDs (Figures 4c–4d). Instead, these ~820 Ma detrital zircons are most likely derived from a potentially extensive Neoproterozoic magmatic belt as indicated by the ~820 Ma orthogneisses with similar isotopic compositions from Chor, Bhutan, and Cona (Ding & Zhang, 2016; Singh et al., 2002) in northern India (Figures 1 and 6). Likewise, the ~950 Ma detrital zircons from the PCGDs would come from the Eastern Ghats-Rayner Provinces in SE India (Figure 6), as suggested for the derivation of the ~950 Ma detrital zircons from the Paleozoic metasedimentary rocks in the Southern Qiangtang and Tethyan Himalaya (Zhu et al., 2011, 2013). Similarly, the Dongargarh igneous rocks (2,506–2,432 Ma) in central India (Manikyamba et al., 2016) would be the dominant source of the ~2,480 Ma detrital zircons.
from the PCGDs in the Southern Qiangtang and Tethyan Himalaya as indicated by their similar ages and $\epsilon_{Hf}(t)$ values (Figure 5b).

Detrital zircon age spectra from the Lhasa Terrane (Figures 4c–4d) and Canning Basin in northern Australia (Figure 4g) are strikingly similar with peaks at $\sim$1,760, $\sim$1,170, and $\sim$570 Ma. This would suggest common derivation from Australia and Antarctica (Morón et al., 2019; Zhu et al., 2011). This provenance link is also supported by zircon $\epsilon_{Hf}(t)$ values. For example, the $\sim$1,170 Ma detrital zircons from the Lhasa PCGDs (including matrix and clast samples) have similar $\epsilon_{Hf}(t)$ values to the coeval detrital zircons from the western Australian basins (i.e., Collie and Perth basins) (Dillinger et al., 2018; Veevers et al., 2005) and igneous rocks from the Albany-Fraser Orogen in SW Australia and the Musgrave Orogen in Central Australia (Figure 6) (Haines et al., 2016; Kirkland et al., 2013). The detrital zircons with a strong peak at $\sim$1,760 Ma from matrixes and sandstone clasts in the Lhasa PCGDs correspond in ages and $\epsilon_{Hf}(t)$ values with the detrital zircons from the Canning Basin and the co-magmatic zircons from the Albany-Fraser igneous rocks, respectively (Figure 5d). These similarities indicate that the Lhasa matrixes share a common source to that of the Canning Basin, whereas the Lhasa clasts could have originally been derived from the Albany-Fraser igneous rocks. The $\sim$2,680 Ma zircon population from the Lhasa PCGDs shows a large variation in $\epsilon_{Hf}(t)$ values (>10-c), overlapping with the co-magmatic zircons from the Murchison Domain granitic rocks of the Yilgarn Craton (Ameen & Wilde, 2018; Ivanic et al., 2012) (Figure 5e). Evidence for a local source for the Lhasa PCGDs is likely provided by the ages of granitoid gneisses from the Bomi Complex (1,866–1,782 Ma and 1,343–1,250 Ma) in the Lhasa Terrane (Chen et al., 2019). However, this is not the dominant source of the Lhasa PCGDs (Figure 1), which require the input of a large volume of coeval magmatic rock-derived detritus.

5. Locating Tibetan Terranes in Northern Gondwana

5.1. The Paleogeographic Puzzle of the Lhasa Terrane

The Lhasa Terrane has been widely accepted to originate from Indian Gondwana based on similar pre-Mesozoic stratigraphic records with the Tethyan Himalaya (part of Greater India) (Allègre et al., 1984). The Proterozoic magmatic records (1,866–1,782 Ma, 1,343–1,250 Ma, and $\sim$824 Ma) and metamorphic events ($\sim$1,117 Ma and 625–600 Ma) (Figure 1) in the Lhasa Terrane are interpreted to support this notion (Chen et al., 2019). This notion linked the newly identified magmatic (1,343–1,250 Ma) and metamorphic records ($\sim$1,117 Ma and $\sim$625–600 Ma) in the Lhasa (cf. Chen et al., 2019; Hu et al., 2019 and references therein) with those from the Eastern Ghats Belt in southeastern India. This link is however problematic because such events are lacking in northern India (i.e., the Himalayas) (Figure 1).

The Lhasa Terrane is also inferred to lie at the northern extent of the East African Orogen between Arabia and India based on coeval Neoproterozoic magmatic ($\sim$925–900 Ma, 820–800 Ma, $\sim$760 Ma, and $\sim$650 Ma) and metamorphic (680–650 Ma) records (Figure 1) (cf. Hu et al., 2018, 2019; Z. M. Zhang et al., 2012; and references therein; Mole et al., 2018). Such an inference is incompatible with the Paleo-to Mesoproterozoic (1,866–1,782 Ma and 1,343–1,250 Ma) subduction- and collision-related records in the Lhasa that are lacking in the rocks of the East African Orogen (Figure 1) (Mole et al., 2018). Furthermore, the abundant 1,250–1,100 Ma (peak at $\sim$1,170 Ma) detrital zircons from the Lhasa PCGDs (Figures 4c–4d) contrast with the record from the East African Orogen, which is characterized by an overall younger detrital zircon signature (1,100–1,000 Ma) (Cox et al., 2004).

The late Paleozoic stratigraphy and glacial deposits, as well as the distribution of land floras and marine faunas in the Lhasa Terrane, indicate a northern Australian origin (Audley-Charles, 1988 and references therein; Y. C. Zhang et al., 2013). This interpretation is supported by the zircon provenance data (peak at $\sim$1,170 Ma) of the Paleozoic metasedimentary rocks in the Lhasa Terrane (Zhu et al., 2011, 2013). Later studies argued against this link by emphasizing the presence of 1,200–1,000 Ma detrital zircons and the small proportion of $\sim$2,650 Ma detrital zircons in the Lhasa Terrane (Burrett et al., 2014). However, the lines of evidence for this argument are not consistent with the Lhasa PCGDs, which display pronounced peaks at $\sim$1,170 Ma (i.e., 1,250–1,100 Ma, rather than 1,200–1,000 Ma) and $\sim$2,680 Ma (i.e., 2,750–2,600 Ma) (Figures 4c–4d).
5.2. Reconciling Evidence for Paleogeography of Tibetan Terranes

Our data show that the U-Pb age spectra and $\varepsilon_{\text{Hf}}(t)$ values of detrital zircons from the PCGDs in the Southern Qiangtang resemble the Tethyan Himalaya, both of which received detritus from Indian Gondwana. Likewise, the strong similarities in age and $\varepsilon_{\text{Hf}}(t)$ values of detrital zircons from the Lhasa PCGDs and Australia-derived detrital and co-magmatic zircons would indicate a paleogeographic link between the Lhasa Terrane and NW Australia. This link coincides with data on the Paleozoic and Mesozoic sedimentary sequences in Western Australia (Morón et al., 2019). These data reveal the development of similar transport pathways for glaciers and rivers commencing from headwaters in Antarctica and central Australia, flowing northward across the Perth and Canning Basins, and finally debouching on the margin of the Paleo-Tethys Ocean (Barham & Kirkland, 2020; Morón et al., 2019) (Figure 6). These transport pathways make it possible to deposit the Lhasa PCGDs and Paleozoic metasedimentary rocks (Zhu et al., 2011) that both originated from sources in Antarctica and central Australia (Figure 6). A similar notion may also be applicable to the PCGDs in the Southern Qiangtang and Tethyan Himalaya, transporting originally from headwaters in the Eastern Ghats-Rayner Orogen and interior India (Figure 6).

The Lhasa-NW Australia link can be further refined through the Proterozoic magmatic and metamorphic records of the two regions (Figures 1 and 6). These events include: (a) coeval subduction- or collision-related Proterozoic magmatic rocks from the Lhasa Terrane (1,866–1,782 Ma and 1,300–1,250 Ma) and from Koolan (1,865–1,850 Ma) (Tyler et al., 2012), Talbot (1,972–1,765 Ma), and Tabletop (1,310–1,220 Ma) regions in the Paterson Orogen (Bagas, 2004); (b) ~820–806 Ma extension-related magmatism in the Lhasa Terrane that coincides with the ~825 Ma Gairdner Dyke Swarm, which may have extended to the Paterson Orogen (Pirajno & Hoatson, 2012); (c) ~680–600 Ma magmatism and metamorphism that occur both in the Lhasa Terrane (Hu et al., 2019) and the Miles Orogen (Durocher et al., 2003) (Figure 1); and, (d) 570–540 Ma magmatism in the Lhasa Terrane (Hu et al., 2019 and references therein) that is, coeval with the ~550 Ma Paterson Orogeny (Bagas, 2004). This synchronicity of events suggests that the eastern Lhasa Terrane (longitude E90°–E95°) may have experienced similar evolutionary history with the Paterson Orogen during the Proterozoic. This similarity, along with the provenance links revealed by the Tibetan PCGDs, indicates that the eastern Lhasa Terrane may represent the outboard extension of northern Central Australia. It follows that the western Lhasa Terrane (longitude E80°–E90°) is positioned outboard of the West Australian Craton. This is supported by the ~760 Ma extension-related magmatism in the Lhasa Terrane that is, coeval with the Mundine Well (~755 Ma) Dyke Swarm in Western Australia (Wingate & Giddings, 2000).

6. Conclusions

In addition to the common age peak at 580–550 Ma, our large data set reveals that the detrital zircons from the PCGDs in the Southern Qiangtang and Tethyan Himalaya define age peaks at ~820, ~950, and ~2,480 Ma, corresponding in age and $\varepsilon_{\text{Hf}}(t)$ values with the Eastern Ghats-Rayner Orogen and Interior India. In contrast, the detrital zircons from the Lhasa PCGDs have age peaks at ~1,170, ~1,760, and ~2,680 Ma, matching in age and $\varepsilon_{\text{Hf}}(t)$ values the Albany-Fraser Orogen in SW Australia (as well as Antarctica) and the Musgrave Orogen in Central Australia. These provenance links provide direct lines of evidence for the Southern Qiangtang and Tethyan Himalaya that are paleographically located to northern India and for the Lhasa Terrane that is, positioned off northern Australia during the Paleozoic.

Precisely locating the microcontinental fragments that now constitute the Tethyan Orogenic Belt of Eurasia is hindered by the overall E-W orientation of Gondwana’s northern margin, which limits the application of paleomagnetic data to constrain longitude (cf. Li et al., 2016). Our results demonstrate that provenance analysis (including magmatic history, isotopic data, and sediment transport pathway) of the widespread late Paleozoic diamictites in Gondwana, in combination with comparisons of magmatic and metamorphic records, can allow precise paleogeographic reconstruction of the longitudinal disposition of blocks along the northern Gondwana margin.
Data Availability Statement

Supporting data are provided in Tables S1–S3, which can be found at website https://osf.io/szk2q/ (https://doi.org/10.17605/osf.io/szk2q).

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