



# Early Oligocene—Late Miocene Wildfire History in the Northern Tibetan Plateau and Links to Temperature-Driven Precipitation Changes

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Late Cenozoic wildfire evolution in Inner Asia has been attributed to both ice-volume modulating precipitation changes and surface uplift of the Tibetan Plateau. Whether this is the case or not requires additional research and wildfire records from older periods. In this study, 251 microcharcoal samples from the Huatugou section in the western Qaidam Basin are used to reconstruct the early Oligocene-middle Miocene wildfire history of the northern Tibetan Plateau. The results show that wildfires remained relatively frequent before ~26 Ma, then reduced gradually until ~14 Ma, and finally increased slightly but still at low level between 14 and 12 Ma. The wildfire variations can be correlated to the steppe-based dryness changes, and both of which are coincident with global temperature changes. We infer that mean annual temperature might have played a dominant role in controlling wildfire frequencies in the northern Tibetan Plateau through modulating atmospheric moisture content. This conclusion is in line with previous studies including microcharcoal-based wildfire records of 18–5 Ma successions from the Qaidam Basin as well as soot-based wildfire records from Quaternary glacial–interglacial cycles of the Chinese Loess Plateau.

**Keywords:** wildfire, global temperature, vegetation, moisture, Tibetan plateau

## INTRODUCTION

The Earth's surface has experienced wildfires since the appearance of terrestrial plants around 420 million years ago (Ma) (Scott and Glasspool, 2006). Wildfire is driven by factors such as carbon-rich vegetation, seasonally dry climates, atmospheric oxygen, widespread lightning, and volcanic ignition sources (Bowman et al., 2009). Wildfire records can therefore provide useful information about the evolution of vegetation, climate, atmosphere, and human society (Dale et al., 2001; Bowman et al., 2009; Edwards et al., 2010; Burton, 2011; Miao et al., 2016b).

For example, charred grass cuticles from tropical Africa have been used as a proxy for late Cenozoic wildfires, which indicates essentially dry periods since 8 Ma (Morley and Richards, 1993). Charred grains from southern Africa have also been used as a wildfire proxy but showing that wildfire

reached a maximum at 7–6 Ma ago under moderately dry conditions (Hoetzel et al., 2013). Similarly, wildfire and its potential links with monsoonal precipitation have been studied in inner Asia for the past 7 Ma (Zhou et al., 2014) or 16 Ma (Hui et al., 2021). Wildfire patterns in East Asia have changed during the last 13 Ma, possibly influenced by regional hydroclimatic changes (Shen et al., 2018). In East Asia, the high-resolution soot record shows unique and distinct glacial–interglacial cycles that are synchronous with marine  $\delta^{18}\text{O}$  records, suggesting that aridity, which was driven by global ice volume, controlled wildfire intensity during the past 2.6 Ma (Han et al., 2020). Similar correlations between global temperature and regional wildfire intensity have also been found in the northern Tibetan Plateau for the middle Miocene–early Pliocene (18–5 Ma) period, while tectonic activities of the northern Tibetan Plateau may have only played a secondary role (Miao et al., 2019).

Globally, late Cenozoic wildfire patterns varied between different places, and a diverse range of driving mechanisms have been proposed (Bond, 2015), such as precipitation amount, degree of aridity, and hydroclimatic conditions, etc., that are further driven by either solar radiation (Han et al., 2020), atmospheric circulations (Jia et al., 2003), seasonality (Shen et al., 2018), or topographic changes (Miao et al., 2019). These hypotheses are largely based on evidence from individual sites, which may not extend to other sites or different time intervals. Extending such site-specific records to regional scales will help improve our understanding of the driving forces of wildfire.

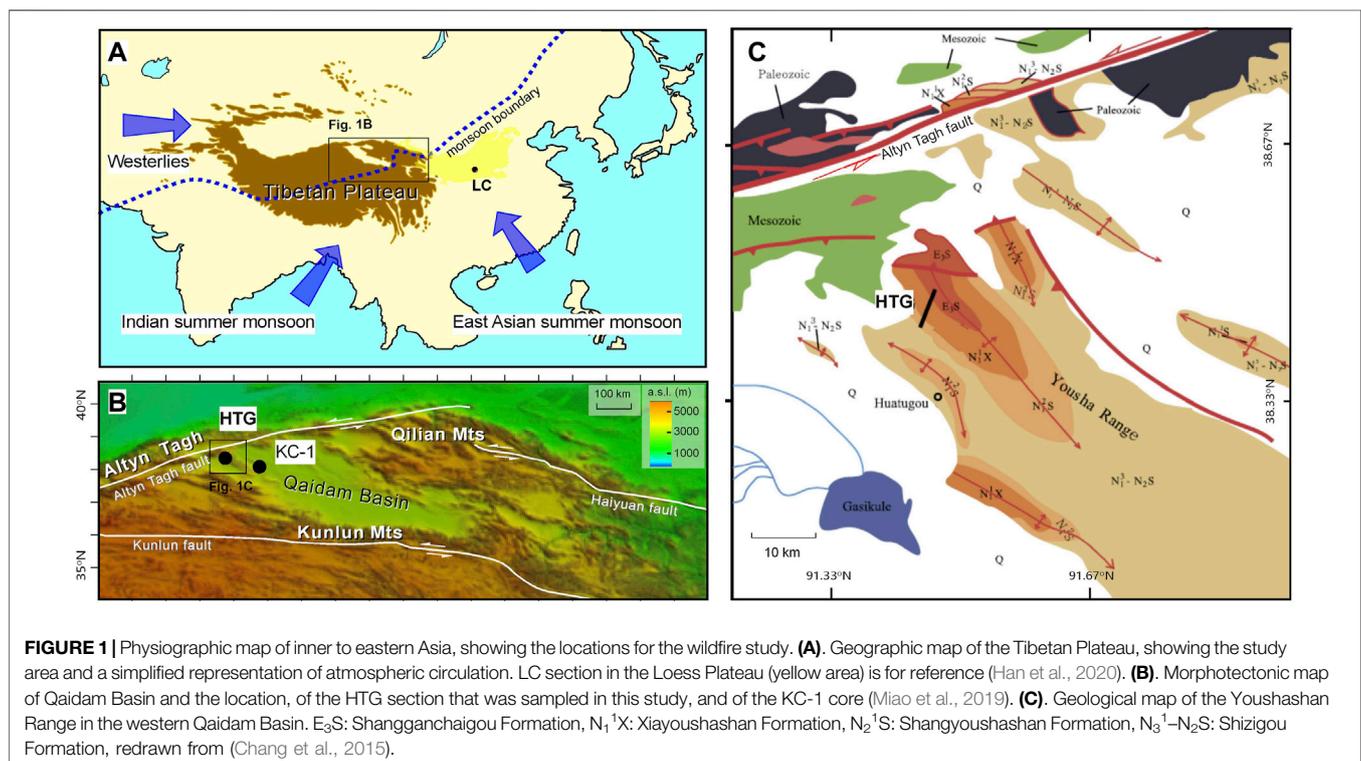
In contrast to the late Cenozoic sequences, wildfire records of earlier periods are scarce. At present, the only wildfire record that

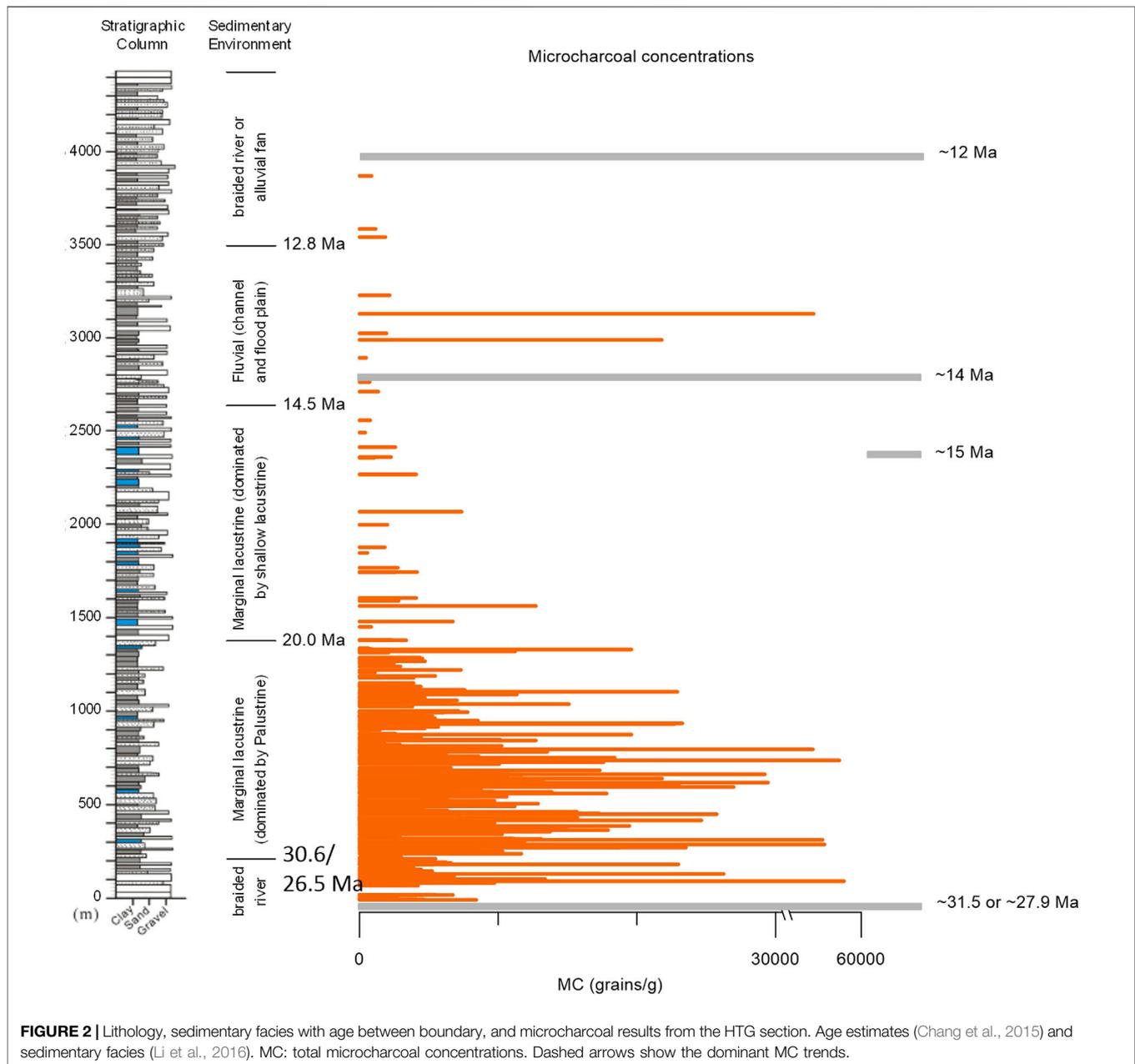
covers the whole Cenozoic period comes from the northern Pacific Ocean (Herring, 1985), and the only record from the southern hemisphere (Australia) covers the middle Eocene (Kershaw et al., 2002). Records from the South China Sea cover periods since the early Oligocene (Jia et al., 2003). However, none of these Paleogene records can be directly compared to the late Cenozoic wildfire records on land due to their far localities and wildfire proxies. In this study, we focus on sedimentary records of the microcharcoals from the Qaidam Basin to reconstruct the early Oligocene–middle Miocene wildfire history of the northern Tibetan Plateau, and then integrate this new record with our previous reconstruction from the same basin for the middle Miocene–early Pliocene (Miao et al., 2019), to assess the drivers of wildfire in this region over a long period.

## GEOLOGICAL SETTING AND SAMPLING

### Geological Setting

The Qaidam Basin, covering an area of 200,000 km<sup>2</sup> and lying at an average elevation of 2,800 m, is the largest topographic depression on the Tibetan Plateau. The current climate in the basin is arid to hyper-arid, with a mean annual precipitation of less than 300 mm in the east, and less than 50 mm in the west. The basin locates in cold climate zone with mean annual temperatures ranging between 2°C and 4°C. The westerlies are the dominant atmospheric circulation pattern throughout the year, while the East Asian monsoon only reaches the southeastern basin during summer (Wu et al., 1980) (Figure 1A). Vegetation in the basin is





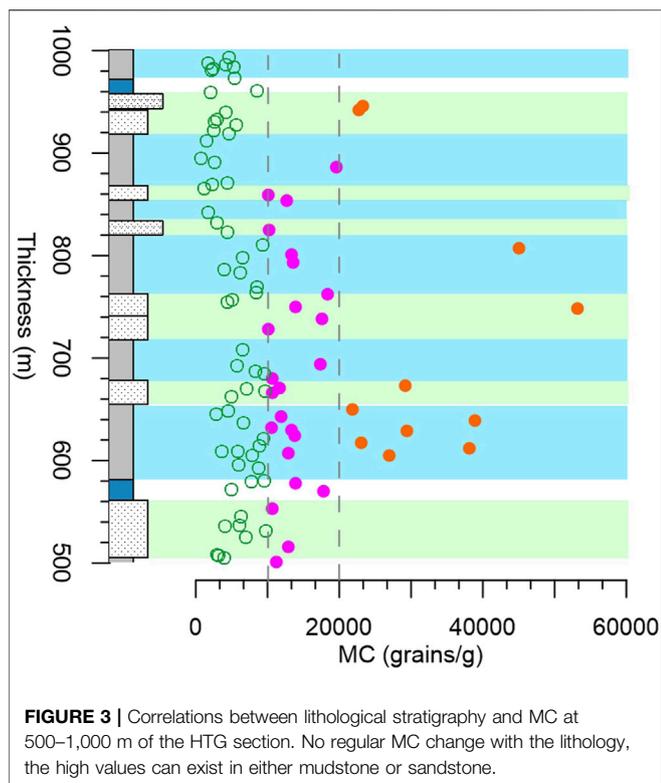
dominated by desert species, which grow on gravelly lake margins and well-drained soils on alluvial fans. The main species include *Amaranthaceae* (*Chenopodioideae*), *Ephedra*, *Nitraria*, *Tamarix*, and *Asteraceae*, etc. Occasionally, *Picea* and *Sabina*, two types of woods can be observed on high mountains in the eastern basin (Miao et al., 2019).

Geomorphologically, the Qaidam Basin is bounded by the Altyn Tagh to the northwest, the East Kunlun Shan to the south, and the Qilian Shan to the northeast (Figure 1B). Tectonically, the basin is bounded by the Altyn Tagh fault, Kunlun fault, and North Qaidam-Qilian Shan thrust belts (Song and Wang, 1993; Yin et al., 2007). Cenozoic stratigraphic units in the basin were deposited mainly in fluvial-lacustrine environments. Although disputes exist concerning

the stratigraphic ages, there is a consensus that the depositional center of the basin has shifted southeastward along the axis of the basin from the early Cenozoic to the present (Song and Wang, 1993; Métivier et al., 1998; Wang et al., 2006; Yin et al., 2007; Cheng et al., 2014). Provenance analysis indicates that the Cenozoic deposits in the Qaidam basin were mainly sourced from surrounding mountains (Rieser et al., 2005; Jian et al., 2013; Cheng et al., 2016; Wang et al., 2017; Lu et al., 2019; Nie et al., 2020; Cheng et al., 2021).

### Study Site and Age Constraints

The Huatugou (HTG) section (bottom: 38.43°N, 90.89°E; top: 38.36°N, 90.88°E) lies at the southwestern side of the Youshashan

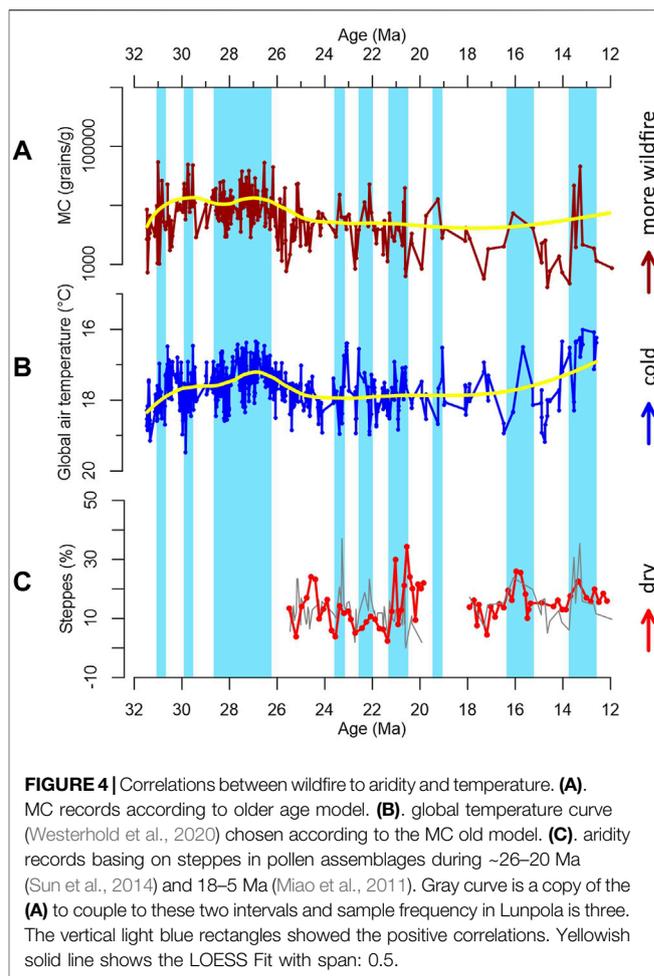


anticline in the western Qaidam Basin (**Figure 1C**) and is about 4,360 m thick (Rieser et al., 2005; Song and Wang, 1993). Strata in the section include the early Oligocene to late Miocene Shangganchaigou, Xiayoushashan, and Shangyoushashan formations. Detailed lithofacies analysis indicates that the strata between 200 and 2,700 m are dominated by marginal lacustrine facies, while the parts below ~200 m and above ~3,500 m are dominated by braided river facies (Li et al., 2016) (**Figure 2**). Magnetostratigraphic study of the HTG section indicates that the strata between 1,200 m and 4,100 m can be confidently determined to be 20.7–11.6 Ma, while there are two alternative age correlations for the lower (0–1,200 m) section: either ~28–20.7 Ma or ~31–20.7 Ma (Chang et al., 2015).

## METHODS AND RESULTS

### Microcharcoal Extraction and Identification

A total of 251 samples of mudstone, sandy mudstone, and siltstone were collected for microcharcoal analysis. Over two-thirds samples were from the lower part of the section (older than 25 Ma), while 28 samples are from the upper section (younger than 20 Ma) due to the lack of suitable sampling layers because of the coarse grain size (**Figure 2**). All samples were pretreated using the following procedures. After gentle grinding to fine powders, two different types of acid were added successively, 10% HCl to remove carbonates completely (usually 2–3 days) and then 40% HF to remove silicates; after which the remaining powders went through 10  $\mu\text{m}$  sieve again to enrich microcharcoal grains. Then,



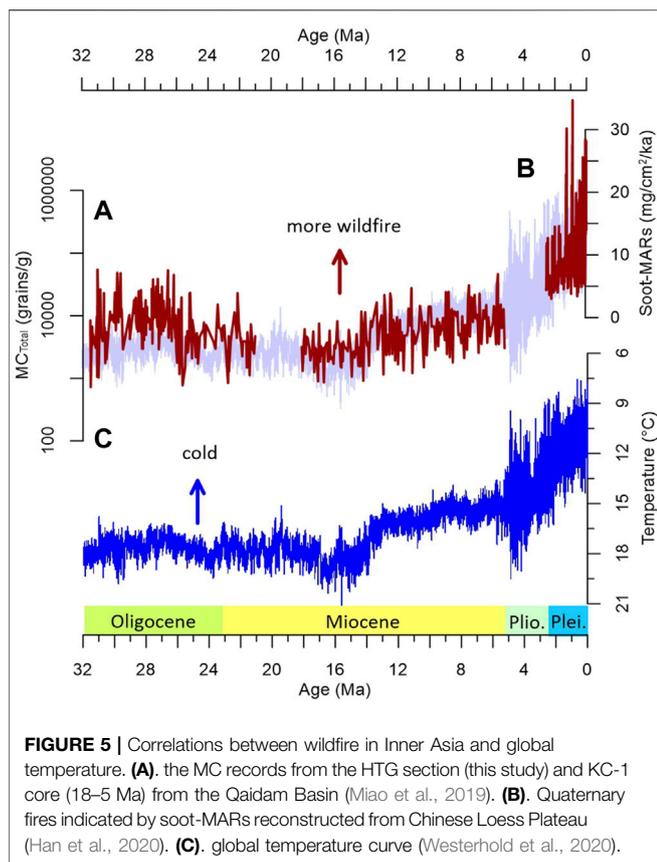
the pretreated specimens were mounted in glycerol for identification (Miao et al., 2019). Samples were counted under a light microscope at 400  $\times$  magnification with regularly spaced traverses. Microcharcoal grains were counted and photographed under the microscope. All samples were analyzed at the Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences. A known number of *Lycopodium clavatum* spores (batch # 27,600) were initially added to each sample to facilitate the calculation of microcharcoal concentrations (MC). The MC is calculated as:

$$MC = [N/L] \times 27600/W$$

$N$ , identified number of microcharcoals (grains);  $L$ , number of *Lycopodium clavatum* (grains);  $W$ , sample dry weight (g).

### Microcharcoal Results

The results show that in the HTG section the MC varied between 410 and 54,650 grains/g with an average of 9,720 grains/g. In general, the MC keeps at high values from the bottom of the section to 800 m (corresponding to ~31.0–26.0 Ma or 27.0–23.5 Ma according to the two different age models), with the MC varies between 720 and 54,650 grains/g (average of 11,240 grains/g) in 146 samples. Then the MC experiences a continuous decreasing trend until ~2,800 m



(~14 Ma), with values ranging between 410 and 45,060 grains/g (average 5,620 grains/g) in 98 samples. Except for two samples that have high MC values of 21,470 and 45,270 grains/g at 3,001 m and 3,141 m, respectively. The MC remains low in the upper section but slightly higher than that at ~14 Ma, with values ranging between 480 and 2,170 grains/g (average 1,410 grains/g) in six samples.

## DISCUSSION

### Data Evaluation and Wildfire Trends

The relationship between microcharcoal concentration and wildfire is intuitive: higher MC corresponds to wildfires with higher frequency or intensity, and vice-versa (Herring, 1985; Patterson et al., 1987; Ward and Hardy, 1991; Whitlock and Larsen, 2002; Miao et al., 2016a; Miao et al., 2019). This interpretation is based on the assumption that sediment provenance is stable and that sedimentary processes have little influence on microcharcoal transport and accumulation, or at least that any influence is constant (Patterson et al., 1987; Anne-Laure et al., 2013).

Three lines of evidence indicate that the MC variations in the HTG section are not controlled by provenance or sedimentary processes. Firstly, provenance studies of sandstones and mudstones collected in the western Qaidam Basin show negligible (Rieser et al., 2005) or a small variation (Cheng et al., 2019) during the Oligocene to the middle Miocene. Secondly, the sediment transport dynamics also have no influence on MC. As

shown in **Figure 3**, no correlations were found between MC and lithofacies, e.g., mudstone, sandy mudstone, and siltstone, which reflect different transport dynamics. Thirdly, magnetostratigraphic analyses indicate that the accumulation rate increased abruptly around 15 Ma (from 180 m/Ma or 130 m/Ma to ~500 m/Ma) (Chang et al., 2015), but no abnormal changes in MC occurred around 15 Ma (**Figure 4**). In contrast, the most significant MC change occurred within the fluvial environment at ~13.5 Ma.

Compared with the other depositional environments, e.g., shallow lacustrine and fluvial, the interval of palustrine environment shows a much higher MC (**Figure 2**). This is reasonable as palustrine is a nearly still water environment compared with the running water conditions in the other depositional environments, and thus would accumulate more microcharcoals for the same period. However, the MC variations within the palustrine environment (both the short-term large variations and the long-term general variations) and the very high MC in the braided river environments indicate that, excluding the influence of different depositional environments, the long-term general variations still reflect wildfire intensities and frequencies.

Based on the above arguments, we conclude that the MC in the HTG section can be used to reconstruct ancient wildfire activities in the northern Tibetan Plateau. The results indicate that the wildfire experienced a higher frequency and/or intensity during the Oligocene (e.g., before ~26 or ~23 Ma), then decreased gradually to stay at relatively lower levels since after and last until the middle Miocene (In this study, we prefer the later age model, see **Supplementary Materials, Figure 4A**).

### Wildfire Mechanisms

Pollen records would have been ideal for reconstruction of the aridification history of the Qaidam Basin (Cai et al., 2012; Koutsodendris et al., 2019; Miao et al., 2012; Wang et al., 1999; Wu et al., 2011), which could then be compared to the MC records (Miao et al., 2019). However, no continuous pollen records have been successfully retrieved from the HTG section or any sections within or adjacent to the Qaidam Basin with reliable age constraints. Here we compare our MC data with global mean air temperature change reconstructed from benthic  $\delta^{18}\text{O}$  changes (Westerhold et al., 2020) (**Figure 4B**) and two intervals of xerophytic pollen records from the Lunpola Basin (25.5–19.8 Ma) (Sun et al., 2014) and Qaidam Basin (18–12 Ma) (Miao et al., 2011) (**Figure 4C**).

It is observed that during stages of high amounts of steppes (such as Ephedra, Nitraria and Chenopodiaceae, etc.), the MC is also high and vice versa. This correlation indicates potential links between strong wildfire and dry conditions (low precipitation). In fact, such a correlation has also been found in other parts of East Asia. For example, high-resolution soot records from the Loess Plateau to the east, have been correlated to glacial–interglacial cycles of monsoonal precipitation during the past 2.6 Ma (Han et al., 2020) (**Figure 5B**): stronger wildfires always correlate with less precipitation during glacial periods. Similarly, two separate Miocene (e.g., 18–5 Ma) microcharcoal-based wildfire records from the Qaidam Basin also agree with enhanced aridification under a global cooling trend (Miao et al., 2019) (**Figures 5A,C**). All these records support the hypothesis that dryness (less precipitation) plays a

crucial role in driving wildfires, such that dryness (less precipitation) facilitates dehydration of vegetation, which becomes more flammable (Pechony and Shindell, 2010; Jolly et al., 2015).

Furthermore, positive correlations are also observed between the MC records and global temperature changes, which further support the hypothesis that stronger wildfires always occur during periods of less precipitation (dry conditions). Lower global temperature helps to reduce the amount of vapors evaporated from oceans and other water bodies, which would then reduce the precipitation amounts in continental interiors that would lead to higher fire frequency. Further detailed explanations are as follows: according to Avogadro's Law, temperature determines the maximum concentration of water vapor at sea level and standard air pressure. As temperature rises, the water vapor concentration increases significantly (Machine Applications Corporation, 1999). The higher the temperature is, the more water vapor is pumped into the atmosphere, leading to increased precipitation on land (Cai et al., 2012; Held and Soden, 2006; Miao et al., 2017; Ruddiman, 2008; Singh, 1988). For example, the annual precipitation data obtained from passive microwave radiometry are correlated well with sea surface temperatures (Stephens, 1990). Modeling studies have also shown that when annual temperatures increase by 2.0°C, the annual precipitation amount in the monsoonal Tibetan Plateau would increase by ~3.9%; while in the westerlies dominated region of the Tibetan Plateau, precipitation only increases by 0.8% (Wang et al., 2021). Over large areas such as the Asian-Australian monsoon regions, the total precipitation is likely to increase significantly (by 4.5% per °C) under the representative concentration pathways (RCP) scenarios of 4.5 anthropogenic warming scenario (Wang et al., 2014).

The positive correlations between global temperatures and evaporation rates have been observed and supported by previous studies (Machine Applications Corporation, 1999). We, therefore, consider that global temperature might have played the primary role to influence precipitation amount changes, which further drives wildfire evolution in Inner Asia.

As in Introduction, the surface uplift the Tibetan Plateau has been regarded as a dominant agent in the local and regional paleoclimate, e.g., breeding the Asian summer monsoon (wetting the East Asia) and bifurcating the westerlies, which might have influenced the wildfire evolution. However, the onset of the surface uplift of the Tibetan Plateau has been hotly debated, such as early Cenozoic (e.g., Ding et al., 2017; Wang et al., 2014; Su et al., 2019; Wang et al., 2008) versus late Cenozoic (e.g., Coleman and Hodges, 1995; An et al., 2001; Spicer et al., 2003; Deng and Ding, 2015; Sun et al., 2014), which has directly affected our judgment of the uplift of the Tibetan Plateau on the wildfire.

## CONCLUSION

In this study, we present a new microcharcoal dataset of 251 samples from the early Oligocene-late Miocene section in the western Qaidam Basin, northern Tibetan Plateau. We argue that the microcharcoal concentration is minimally controlled by sedimentation processes, and thus can be used to reconstruct wildfire activities in the northern Tibetan Plateau. The data

indicate high frequency and/or intensity of wildfire during the Oligocene (before ~26), then decreased gradually to stay at relatively low levels until ~12 Ma. Comparisons between dryness records and global temperature change indicate that high levels of wildfire are well linked to colder and drier periods. We infer that wildfire is strongly influenced by temperature changes through influencing the atmospheric moisture content that are evaporated from ocean surface and other water bodies. Such correlations have also been observed in the middle to late Miocene microcharcoal records in the Qaidam Basin and soot-based Quaternary glacial-interglacial cycles in the Loess Plateau.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

## AUTHOR CONTRIBUTIONS

YM collected samples and designed the experiment. YM and HC analyzed the data. All authors wrote and reviewed the manuscript.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/feart.2022.850809/full#supplementary-material>

**Supplementary Figure S1** | Correlations between wildfire obtained in the HTG section and global air temperature at the bottom (<1750 m) of the section by two age models. **(A,B)**, the MC curve by older age model and comparison with the global air temperature curve (Westerhold et al., 2020). **(C,D)**, the MC curve by younger age model and comparison with the global air temperature curve (Westerhold et al., 2020). The temperature curves have been also shown as gray shading in A and C for comparison. Shallow blue rectangles show the unmatched correlations and thick solid blue lines show the LOESS Fit with span: 0.5.

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