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Inertinite in coal and its geoenvironmental significance: an AI and neural network analysis

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Abstract: Inertinite is an important and abundant maceral group in coal, also called fusain or fossil charcoal. Inertinite is critical for the study of palaeowildfire in coal-forming environments, as it provides an insight into the role of fire in reconstructions of the peat swamp palaeoenvironments. Today wildfires are a common natural phenomenon in different environments with crucial roles in ecosystem destruction and regeneration. It is reasonable to assume that since the evolution of terrestrial plants, wildfires have played similar roles in the geological past. Recently, there has been a significant amount of research on the relationship between palaeowildfire, palaeoclimate change and palaeobotany evolution; an understanding of these relations in the geological past are of importance for studying modern ecosystems. The rapid development of artificial intelligence (AI) and online tools to search scientific databases has presented an opportunity to find, collect, arrange, and analyze global inertinite data from the earliest published mention of inertinite to the latest publications. This has facilitated the construction of a detailed and comprehensive model of the relative abundance of inertinite over geological time, which can be correlated against other parameters such as atmospheric oxygen levels, plant evolution and palaeoclimates change. Establishing positive and negative feedback between inertinite characteristics and palaeoenvironmental evolution and discussing the role of inertinite in geologic palaeoenvironmental evolution.

Keywords: Inertinite, Palaeowildfires, Atmospheric oxygen, Palaeoclimates, Palaeoecosystems

1 Introduction

Inertinite is an important maceral group in coal (ICCP, 2001) and is also commonly found in other sediments. Because its' fire origin is widely accepted, inertinite is evidence of wildfire, with a fossil record extending back to occurrences in the Silurian (Rowe and Jones, 2000; Glasspool and Gastaldo, 2022). As a common natural phenomenon, typically ignited by lightning, wildfires have

played a significant role in various of the Earth's ecosystems (Scott, 1989). Globally, wildfires produce a significant amount of greenhouse gases (Xu et al., 2020), contributing towards global warming, and can generate toxic gases threatening the well-being of animals (Scott, 2010). It is recognized that animal and plant behavior will also have an impact on the occurrence of wildfires by moderating the amount, type, and conditions of wildfire fuel (Foster et al., 2020), there are interactions between wildfires and animal and plant evolution (Bowman et al., 2009; Belcher et al., 2021). Recently, there has been increasing amounts of research into the regular occurrence of wildfire in coal-forming environments, principally using the content and distribution of inertinite as evidence (Wang et al., 2019; Yan et al., 2019; Song et al., 2020). The results of this study elucidating issue such as palaeoclimate change, palaeoenvironments, and animal and plant evolution.

To quantify the increase in research relevant to palaeowildfires since 2000, the author conducted a literature search and cluster analysis. CiteSpace (Chen, 2004; Chen et al., 2010) metrological analysis software was used to undertake this bibliometric analysis. The Web of Science Core Collection database was automatically searched using keywords related to palaeowildfires, and indexed in SCIEXPANDED, SSCI, A&HCI, ESCI, CCR-EXPANDED, IC. The time range for the literature search was from 2000.01.01 to 2023.12.31. A total of 1038 records were obtained, including 993 case studies and 45 reviews. This facilitated a retrospective analysis and summary of the palaeowildfires literature for the past 24 years.

The statistics on the annual number of relevant publications show that the numbers of publications (Fig. 1) increased steadily from 2000 to 2009, followed by a rapid increase after 2010, the number of publications has remained above 60 per year since 2018, a result that reflects the emergence of palaeowildfires as a hotspot for global change research since 2010.

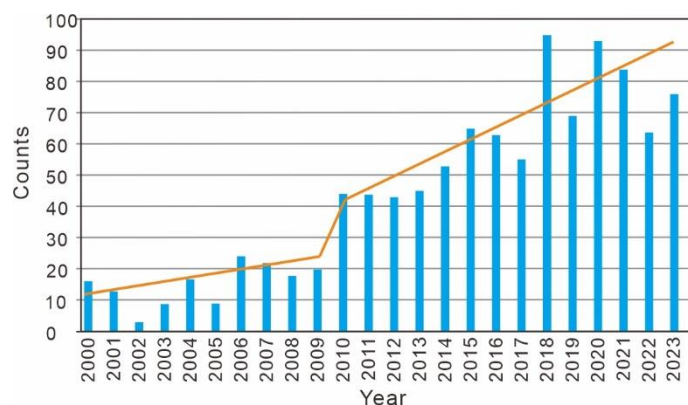


Fig. 1 Annual publications about wildfire from 2000 to 2023.

Using a theoretical framework of cluster analysis, and setting-up network algorithms (pathfinder network scaling, PF-NET), and publications a network diagram of national cooperation was constructed. In Fig. 2, the size of the nodes represents the numbers of publications, and the line between the two nodes represents collaboration ties, with dense lines indicating more intensive collaborations between two countries, and the different colored circles represent the number of publications in the corresponding year in the legend. A total of 70 countries and regions published relevant articles, with the top 10 being the United States, Britain, China, Canada, Germany, France, Australia, Spain, Brazil, and Switzerland: shown as the important nodes in the network (Fig. 2). Centrality represents the strength of the number of connections between a node and other nodes in

the entire network; a country with a high centrality means that this country has a strong influence on the relationships in the network. It can be seen in Fig. 2 that the United State has the highest degree of centrality, i.e., the greatest influence in the field of palaeowildfire research. In addition, relevant research in China started late but has grown rapidly, suggesting that palaeowildfires research has received widespread attention in China in recent years.

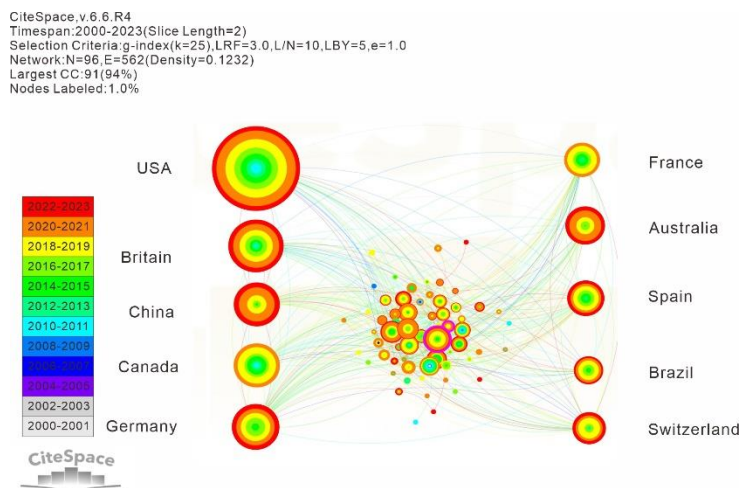


Fig. 2 Network diagram of national cooperation.

Keyword co-occurrence effectively reflects the research hotspots in this field and the ‘burst’ keywords (reflecting the emergence of certain keyword in a brief time) can indicate cutting-edge topics. The ‘burst’ keywords included fire, climate change, wildfire, charcoal, black carbon, vegetation, and fire history. After the integration of the keywords, the top five keywords are wildfire, charcoal, climate change, vegetation, and sediment. These results demonstrate a global research focus on the occurrence of wildfires, along with their impacts on palaeoclimatic change and vegetation evolution.

2 Classification and Origin of inertinite

2.1 Classification of inertinite

As defined by the International Committee for Coal Petrology (ICCP), the macerals in coal can be subdivided into three groups, which are vitrinite, liptinite and inertinite (ICCP, 2001). Inertinite is the maceral group that comprises macerals whose reflectance in low- and medium-rank coals, and in sedimentary rocks of corresponding rank, is higher in comparison to the macerals in the vitrinite and liptinite groups (ICCP, 2001). Typically, the inertinite content in coal is lower than vitrinite in most coals, but there are some coals which are rich in inertinite, for example, the Middle Jurassic coal seams in Northwest China are typical of inertinite-rich coal (Wang et al., 2021; Du et al., 2022), with examples of these coals in the Yan’an Formation of the Ordos Basin (Xu et al., 2020; Zhang et al., 2020), the Dameigou Formation of the northern Qaidam Basin (Lu et al., 2016), and the Xishanyao Formation in several basins in northern Xinjiang (Han and Yang, 1980; Yang, 1996).

Table 1 Macerals of the inertinite group (ICCP, 2001)

Macerals with plant cell structures:	Fusinite
	Semifusinite
	Funginite

Macerals lacking plant cell structures:	Secretinite
	Macrinite
	Micrinite
Fragmented inertinite:	Inertodetrinite

According to the degree of intact preservation of cellular structure, inertinite is further subdivided into fusinite, semifusinite, funginite, secretinite, macrinite, micrinite, and inertodetrinite by the ICCP (2001) (Table 1). Scott and Glasspool (2007) proposed a revision of the definition of inertinite within this classification, with: "fusinite is a maceral of the inertinite maceral group in which anatomical preservation is discernible, cell walls are typically, but not invariably homogenized. $R_o > 2\%$. Size $> 50 \mu\text{m}$ " and "semifusinite is a maceral within the inertinite maceral group which has $R_o < 2\%$ which is greater than that of the associated vitrinite. The semifusinite does not have good anatomical preservation. Size $> 50 \mu\text{m}$ ".

2.2 Origin of inertinite

According to Stach's Textbook of Coal Petrology (1982) fusinite can be subdivided into four types according to their presumed origins, including degradofusinite, primary fusinite, rank fusinite and pyrofusinite (Taylor et al., 1998), primary fusinite and rank fusinite can be classified as biochemical alteration. The possible origins of inertinite are still controversial, with three suggested modes of formation: oxidative degradation, biochemical alteration, and wildfire (O'Keefe et al., 2013).

1) Oxidative degradation. The cellular structures of these degradofusinite are poorly preserved and their reflectivity is at semifusinitic levels, and the consensus is that they formed by dehydration and oxidation (Taylor et al., 1998). Stach et al. (1982) showed that the reflectivity of coal of different ranks increase markedly when those coals are treated with concentrated sulfuric acid with reaction temperature ca. 100°C . For example, the reflectivity of lignite could be raised to that of medium-volatile bituminous coal through oxidation and dehydration. The high reflectivity of degradofusinite has been attributed to similar processes (Taylor et al., 1998). In later experiments of this same peat the initial oxidized material accounted for 17% by volume of the peat but after artificial coalification oxidized material increased to 28% (Shearer and Moore, 1997).

2) Biochemical alteration. Sen (1999) proposed that the precursor of fusinite originates from the residual lignin-rich cell walls of plant debris, and semifusinite from the partial removal of the cellulosic layer. O'Keefe et al. (2013) suggests that some inertinites were derived from biochemical changes of primitive and altered fungal materials. Hower et al. (2009) suggested that although fungi can be carbonized, they are obviously different from other inertinite components in that they are non-plant materials. In addition, not all funginite possesses high reflectance. Studies on the high-resinite Paleogene coals in India have demonstrated that some macrinites are created by bacterial decomposition (Hower et al., 2010).

3) Wildfire origin. Stach et al. (1982) stated that some fusinite and semifusinite must be produced in forest or peat wildfires. O'Keefe et al. (2013) noted that the primary origin of fusinite and semifusinite is palaeowildfire, although a portion of semifusinite have a potential for oxidative origin. Diessel (2010) suggested that although there are various mechanisms for the generation of inertinites, combustion as the main source of inertinite in coal. The low availability of oxygen in wildfires can lead to insufficient or partial combustion that forms charcoal (Scott, 1989). Scott (2010) considered the inertinite in coal to be equivalent to fossil charcoal, fusinite is formed by higher

temperature wildfire combustion, and semifusinite is formed by lower temperature wildfire combustion; and the reflectance difference is caused by combustion temperature, time, and initial combustion conditions (Scott, 1989). Combustion experiments have been undertaken to demonstrate the wildfire origin of the inertinite by several researchers (Jones et al., 1991; Guo and Bustin, 1998; Scott and Glasspool, 2007).

Against the idea of oxidative origin, it is difficult to have an acidic environment in nature comparable to that of concentrated sulfuric acid, and the fact that the reflectance of fusinite and semifusinite is significantly higher than that of the vitrinite in numerous low-rank coals. We suggest that fusinite may not be formed by oxidation. The role of fungi in the perspective of biogenesis, Guo and Bustin (1998) believed that fungi do not directly contribute to the formation of inertinite apart from the fungal bodies themselves (funginite: sclerotia and hyphae), however, by increasing surface area by shrinkage and cracking of the plant materials they increase susceptibility to charring.

Glasspool and Scott (2010) emphasize that both fusinite and semifusinite are indicators of palaeowildfires. The main macerals of inertinite group are fusinite and semifusinite, and the content of other macerals is less than 10% (Han and Yang, 1980; Yang, 1996). Although an exceedingly small portion of the inertinite may not come from plant materials (Hower et al., 2009; O'Keefe et al., 2013), however, the non-wildfire origin of these macerals will not have a significant impact on the determination of the genesis of the inertinite (Diessel, 2010). Therefore, most scholars use "wildfire origin of inertinite" instead of "wildfire origin of fusinite and semifusinite". The wildfire formation of inertinite has been widely accepted and applied (Jasper et al., 2011; Liu et al., 2018; Xu et al., 2020; Zhang et al., 2020).

2.3 Research methods

To study inertinite as product of wildfires, both qualitatively and quantitatively, coal petrology, organic petrology, and plant anatomy methods (scanning electron microscopy observation) are used. The combination of coal petrology and organic petrology is becoming increasingly close, and the inertinite of kerogen in mudstone can also serve as indicators of palaeowildfires. Therefore, this study briefly discusses the research methods of palaeowildfire records in mudstone. In addition, polycyclic aromatic hydrocarbons (PAHs) are increasingly being applied, and the types and relative abundance of PAHs can be used to determine the occurrence and combustion temperature of palaeowildfires, which can serve as reliable biomarkers for palaeowildfires.

2.3.1 Coal petrology and Organic petrology

According to the size, the charcoal was divided into macro-charcoal (>1 mm), meso-charcoal (180 μ m–1 mm) and micro-charcoal (<180 μ m) (Scott, 2010). The fusinite and semifusinite in coal are macro- and meso-charcoal. The fusinite in mudstone are meso- and micro-charcoal.

Each coal sample is crushed to less than 1 mm diameter and prepared as polished epoxy-bound blocks (ISO 7404-3, 2009). Identification of coal macerals is determined in polished epoxy-bound blocks under transmitted and fluorescent light using a microscope according to the International Committee for Coal Petrology (ICCP), with at least 500 valid points count for each sample.

Each mudstone sample is crushed to less than 1 mm diameter and prepared as kerogen thin sections and polished epoxy-bound blocks. Identification of kerogen macerals is determined in thin sections under transmitted and fluorescent light using a microscope according to the China national standard (SY/T 5125-2014), with at least 300 valid points count for each sample.

The maceral abundances refer to volume percentages on a mineral matter-free basis (vol%, mmf).

Inertinite reflectance is measured on polished blocks using a reflected light microscope with a microphotometer under $50\times$ oil immersion objective (ISO 7404-5, 2009). For the inertinite reflectance measurements, at least 50–60 valid points are counted on each polished block and calculate the average reflectance and the distribution frequency of different reflectance intervals.

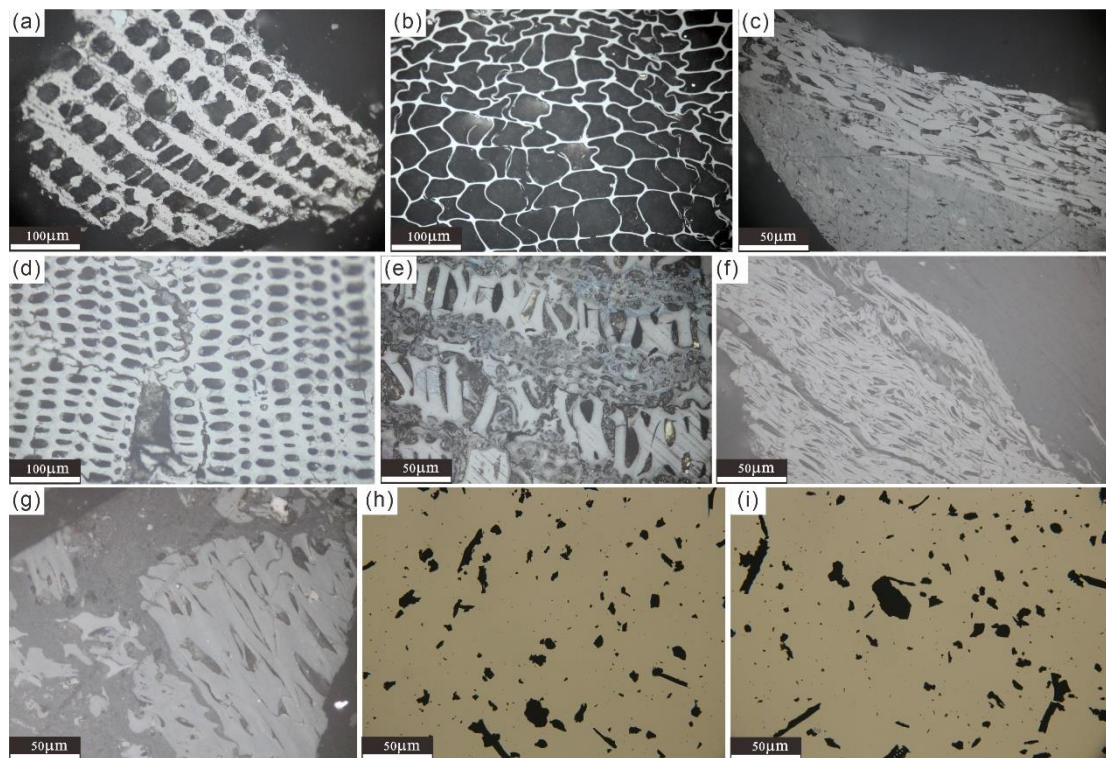


Fig. 3 Characteristics and distributions of inertinite in coal and mudstone. (a) and (b) fusinite, (c) semifusinite, coal sample from the Lopingian in the Lvtang coal mine, medium-rank coal, Guizhou, SW China. (d) and (e) fusinite, (f) and (g) semifusinite, coal sample from the Middle Jurassic in the Junggar Basin MC-2 well, low-rank coal, Xinjiang, NW China. (h) and (i) fusinite, mudstone sample from Early Triassic in the Hanjiagou coal mine, Yunnan, SW China; (a)-(g) Oil-immersed reflected light, (h) and (i) transmitted light.

2.3.2 Anatomical characteristics preserved in the fusinite

McGinnes (1971) first used scanning electron microscopy (SEM) to study fossil charcoal. Since then, scanning electron microscopy has become one of the most common methods to study fossil charcoal or inertinite (Scott, 2010; Liu et al., 2018; Cai et al., 2021). Firstly, select the fusinite fragments from coal or mudstone, and then observe them under SEM, different types of charred plant tissues are distinguished according to their gross morphology and anatomical features, such as bordered pitting, ray cells and tracheids (Fig. 4). An important characteristic of inertinites or fusain is the homogenization of previously stratified cell walls (Jones and Chaloner, 1991), as clearly seen in Fig. 3a, 3b, 3d, and Fig. 4c, 4e.

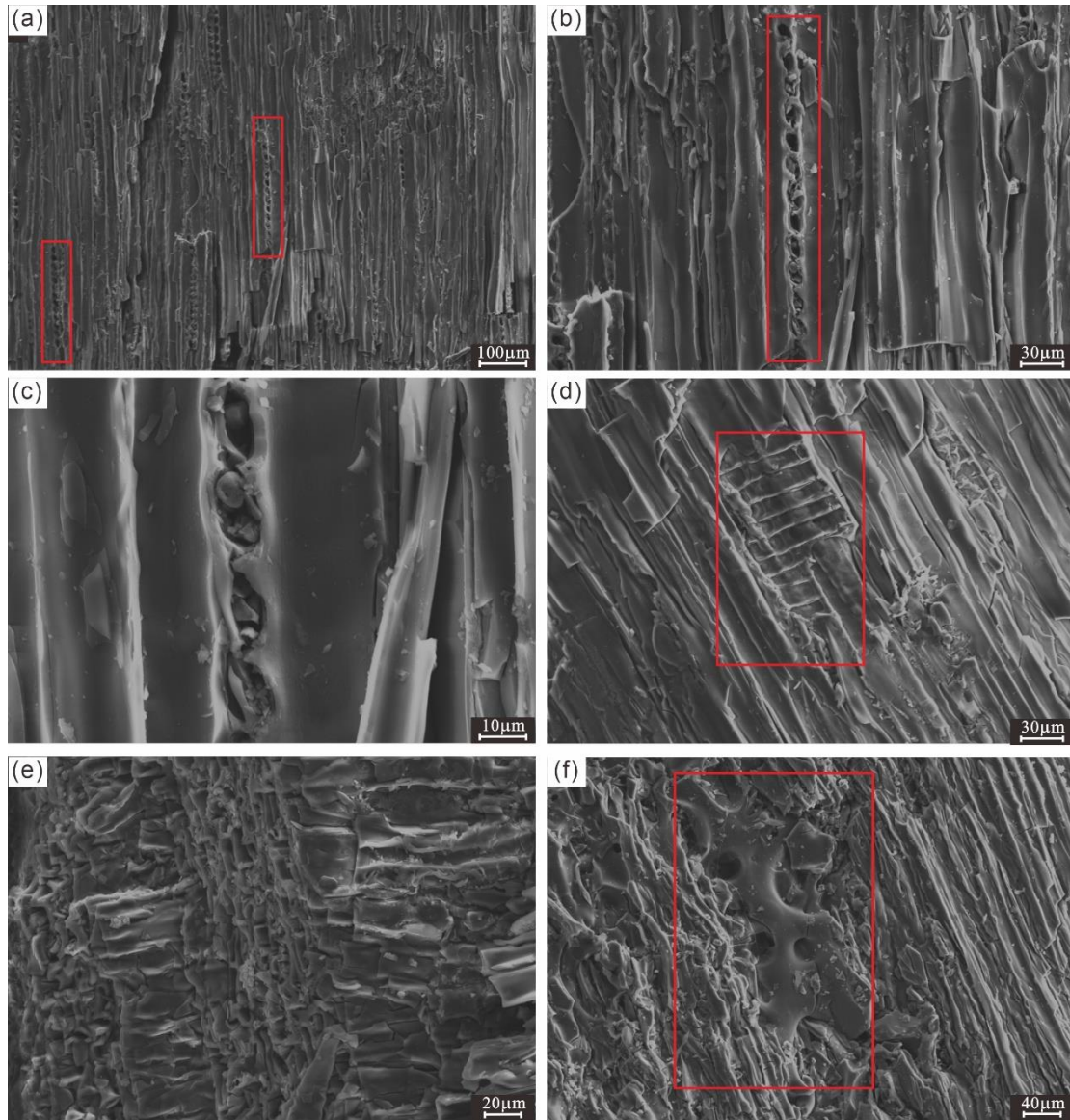


Fig. 4 SEM images of fusinite from the Jurassic coal seam. (a) Longitudinal section of fusinite shows ray cells and tracheids; (b) Uniseriate ray; (c) Close-up of (b), pit and contents in the ray cell; (d) Spiral thickening on the ray tracheid; (e) Horizontal section of fusinite shows fibrous structure; (f) Detail showing wall pitting. All coal samples from Yan'an Formation, Yushen mining area, Ordos Basin, China.

2.3.3 PAHs compounds and ratios

The test methods for PAHs in coal samples and mudstone samples are basically the same, and both are tested by gas chromatography-mass spectrometry (GC-MS). The extraction time is different, if both use Soxhlet extraction, coal samples are extracted for 48 h, and mudstone samples are extracted for 72 h. The qualitative and quantitative determination of PAHs refers to the standard GB/T 18606-2017.

PAHs are commonly found from the incomplete combustion of plants and degradation of organic matter by microorganisms during diagenesis (Hossain et al., 2013). The PAHs from combustion origin usually possess more than 4 rings, and from a diagenesis origin between 2–4 rings (Nabbefeld et al., 2010). The numbers of aromatic rings tend to be associated with stronger preservation capacities (Denis et al., 2012), and are thus more likely to survive during deposition,

so aromatic compounds above 4 rings are commonly used as indicators of palaeowildfires (Xiao et al., 2020). There are multiple ratios that can determine the source of PAHs, such as "(indene [1,2,3-cd] pyrene)/(indene [1,2,3-cd] pyrene + benzene [g, h, i] perylene)" greater than 0.35 can indicate that PAHs are combustion sources (PAH_{PCD}) (Stogiannidis and Laane, 2015), and "(fluoranthene)/(pyrene + fluoranthene)" greater than 0.5 can indicate that PAHs are combustion sources (Yunker et al., 2002). The number of rings of PAHs is related to the temperature of wildfire, generally, the higher the combustion temperature, the more high molecular weight PAHs produced (Denis et al., 2012; Hossain et al., 2013). The frequency of high-temperature wildfires is generally indicated by the ratio of PAH_{PCD} from the 5-ring and 3-ring, while the ratio of PAH_{PCD} from the 6-ring+7-ring and 3-ring indicates the frequency of higher temperature fires (Kaiho et al., 2020). In addition, the ratio of low molecular weight PAHs to high molecular weight PAHs can indicate whether the source of PAHs is smoke or burn residue (Karp et al., 2020).

3 Inertinite and the study of palaeowildfires

3.1 Wildfire types inferred from inertinite reflectance

When inertinite is found in coal its properties are critical for understanding the wildfires that formed it. As the reflectance of inertinite increases with the combustion temperature, the reflectance can be used to estimate the combustion temperature and elucidate the type of wildfire (Jones et al., 1991). The relationship between the combustion temperatures and inertinite reflectance have been experimentally derived and formulae calculated. The first published formula for calculating combustion temperatures based on inertinite reflectance is:

$$T = 184.10 + 117.6 \times Ro (R^2 = 0.91) \quad (\text{Jones, 1997}) \quad (1)$$

Yan et al. (2019) proposed a revised formula based on data from Scott and Glasspool (2005):

$$T = 224.35 + 94.975 \times Ro (R^2 = 0.96) \quad (2)$$

In both formulae T is the combustion temperature (°C), Ro is the average reflectance of inertinite under oil immersion (%), and R^2 is the correlation coefficient for the experimental data.

Some case studies have shown that the inertinite reflectance value depends on the measured zone within the sample, and such zonation was formed because of temperature differences outside and inside of the wood during charring or semi-charring (Jones et al., 1993). Consequently, when calculating the temperature of palaeowildfires using inertinite reflectance, it is recommended to use the average of many data points to reduce errors.

Wildfires are divided into forest fires and more open environments fires (in modern times often generally referred to as grassland fires) according to the burning ecosystems and locations through field observations and measurements (Scott, 1989; Petersen, 1993). Wildfires can be divided into three types: crown fires, surface fires and ground fires (Scott, 1989) (Fig. 5, Table 2). Crown fires are characterized by burns in dense trees and tall shrubs as fuel, with the combustion temperatures particularly high, ranging from 600–>1200 °C. The combustion product is typically micro-charcoal (Scott, 2000). Surface fires are characterized by having herbaceous vegetation, low shrubs, or litter as fuel. The combustion temperatures are moderate to high, reaching 350–650 °C. The combustion products typically consist of macro-charcoal fragments along with smaller charcoal pieces (Scott, 2000). Ground fires are characterized by including soil humus layers in the fuel. The combustion temperatures are low smoldering burns that can last for a long time, up to several months (Scott, 2000). The combustion products tend to be macro-charcoal (Albini, 1993; Petersen and Lindstrom, 2012).

Table 2 Characteristics of different types of wildfires (Summary from Scott, 2000; Petersen and Lindstrom, 2012)

Wildfire type	Temperature	Source of fuel	Combustion products
Crown fire	600–>1200 °C	Tall plants, such as coniferous forest	Micro-charcoal
Surface fire	350–650 °C	Herbaceous vegetation, shrubs, or litter	Macro-charcoal Meso-charcoal
Ground fire	<400 °C	Soil humus layer, dead branches, and roots, decayed vegetation, or peat	Macro-charcoal

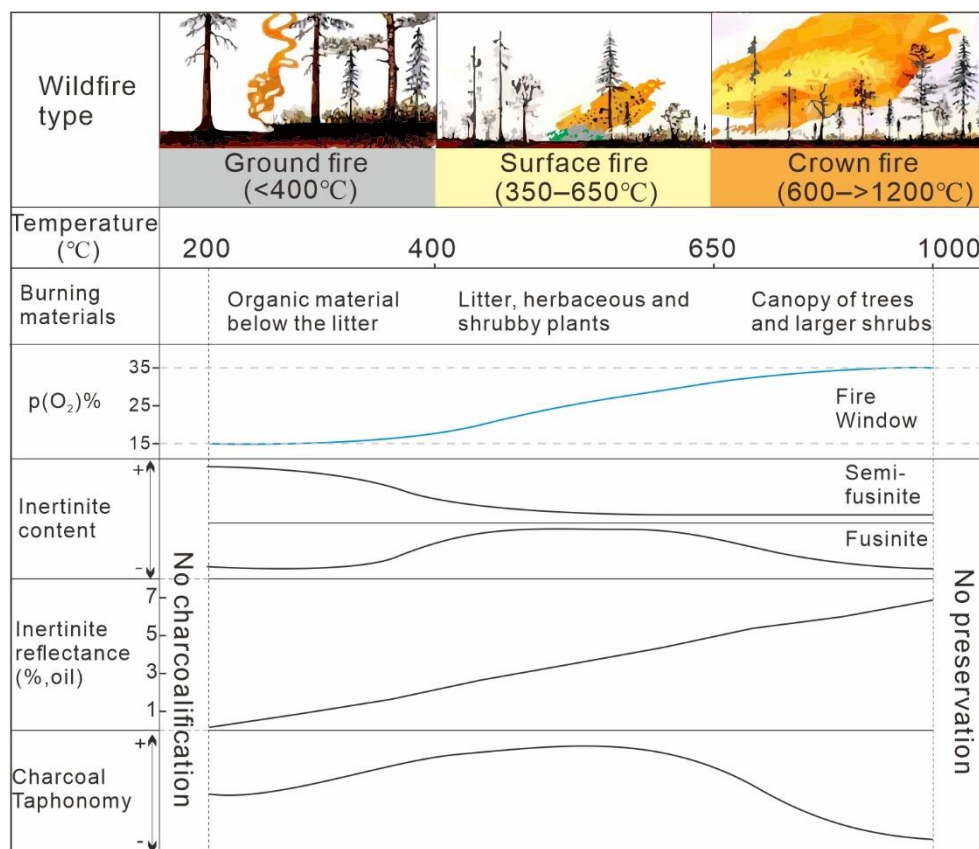


Fig. 5 The comparative summary of the charcoal characteristics seen over different types of wildfires. (Summary from Scott, 2000; Petersen and Lindstrom, 2012)

In the combustion area, the three types of wildfires often coexist and interact with each other. Surface fires are often accompanied by ground fires (Pyne et al., 1996). The probability of crown fires caused by ground fires and surface fires is small and needs fire pathways from the ground to the crowns of the trees (Scott et al., 2014). However, the potential for surface fire spread from crown fires is high because burning material can be carried by wind to the ground in non-fire zones and ignite surface and near-surface vegetation, resulting in an increase in the size of the fire zone (Scott et al., 2014).

Wang et al. (2020) and Zhang et al. (2020) investigated the inertinite from Middle Jurassic coals in the Ordos Basin of north China and obtained inertinite reflectance from 0.65% to 1.79%, which would give a low combustion temperature ranges from 261 °C to 395 °C. Indicates that the wildfire types were ground fires, supplemented by surface fires. Wang et al. (2019) used derived temperatures to suggest that inertinite from the Early Cretaceous in northeast China derived from surface fires. Yan et al. (2019) studied Late Permian coals in Xuanwei, southwest China, and calculated that the wildfire temperatures at that time exceeded 700 °C, with the highest at 930 °C, indicating crown fires.

The species and relative abundance of PAHs can provide the best corroboration of burning temperature estimates, thus enhancing the objectivity of wildfire type judgements (Keiluweit et al., 2012). Several scholars have used PAHs in coal and mudstone samples to indicate palaeowildfire (Xu et al. 2020; Zhang et al. 2020; Xie et al. 2022; Xu et al. 2022) and to indicate the intensity of wildfires at deep time (Fox et al. 2022; Jiao et al. 2023).

3.2 Atmospheric oxygen levels estimated from inertinite contents

Fire is an exothermic oxidation reaction, which requires three essential conditions: fuel, combustion (ignition), and sufficient oxygen (Glasspool et al., 2015). Meteorite strikes, volcanic eruptions, spontaneous combustion and even sparks from rock falls may be potential ignition sources, but the most extensive fire combustion source is lightning (Cope and Chaloner, 1980; He and Lamont, 2018). Today, lightning strikes occur at a rate of 44 ± 5 strikes per second across the globe (Christian, 2003). Many observations and modelling studies have demonstrated that lightning correlates positively to surface temperature, on different temporal and spatial scales (Jayaratne and Kuleshov, 2005; Price, 2013). Several scholars have proposed slightly different ranges of oxygen content available for combustion, Watson et al. (1978) carried out experiments under different oxygen content conditions, and their results show that the range of oxygen content to maintain combustion is 16–30%, namely a "fire window", and Jones and Chaloner (1991) limit the range of oxygen content that can support wildfires to 13–35%. $P(O_2)$ below 13% fires cannot be sustained, however above 35%, vegetation will burn regardless of its state. Wolbach et al. (1988) believed that the minimum oxygen content available for plant combustion is 16%. Belcher and McElwain (2008) suggested that the lower $p(O_2)$ limit for combustion should be 15%, but for the fire to widely spread required $p(O_2)$ 18.5% (Belcher et al., 2010). Most scholars now use 15% as the minimum oxygen content available for combustion (Shao et al., 2012).

The reconstruction of variations of oxygen content over geological history are primarily based on model calculations. Bergman (2004) established the carbon-oxygen-phosphorus-sulfur evolution (COPSE) model to calculate the Phanerozoic geochemical cycle by using the isotopes of these four elements and reconstructed the oxygen concentrations at geological time. Based on this, Berner (2006) established the GEOCARBSULF model further refined estimations of the oxygen content of the Phanerozoic atmosphere. Later, Berner (2009) recalculated the trends of atmospheric oxygen content over geological history and adjusted the oxygen content at the Permian-Triassic boundary from about 13% to approximately 20% (Fig. 6). Mills et al. (2023) used an updated database to produce high-precision, long-scale atmospheric oxygen prediction curves using an improved computational model and taking into account feedback from wildfires, and this revision increased the Mesozoic atmospheric oxygen content dramatically, generally to more than 25% (Fig. 6).

Although the Phanerozoic pO_2 models have been widely used in palaeoclimate analysis, these models have been the subject of debate ever since they were proposed. As the inertinite represents

wildfires which are constrained by the O₂ availability over geological history, Glasspool and Scott (2010) statistically analysed a significant number of global inertinite data and found a correlation between the changes of inertinite content and atmospheric oxygen content, which is related to, but also inconsistent, with the previous oxygen content prediction models. Therefore, they devised a calculation model for predicting atmospheric oxygen levels by inertinite content in the fossil record (Glasspool and Scott, 2010; Glasspool et al., 2015).

Glasspool and Scott (2010) calculated the atmospheric oxygen content since 400 Ma BP based on the inertinite content, under the assumption that the inertinite had a wildfire origin. Then, they further expanded the database, revised the model, and concluded a linear relationship between atmospheric oxygen level and inertinite content (Eq. (3), Fig. 7). Based on this relationship, the oxygen content in the late Paleozoic atmosphere is recalculated, results match the geochemical model well (Fig. 6) (Glasspool et al., 2015).

$$I = \begin{cases} 0.5 - 0.5 \times \cos\left(\pi \left(\frac{O - O_{\min}}{O_{\max} - O_{\min}} \right)\right)^n & O_{\min} < O < O_{\max} \\ 0 & O \leq O_{\min} \\ 100\% & O \geq O_{\max} \end{cases} \quad (3)$$

The curves and formula for converting the observed inertinite concentration into estimates of past ($p(O_2)$) are based upon three points:

(1) Present day $p(O_2) = 21\%$ and is associated with a mean inertinite concentration of $4.27 \pm 0.64\%$ (Glasspool and Scott, 2010).

(2) Experimental data indicate that wildfires are unsustainable at levels of $p(O_2) = 15\%$ or less (Belcher and McElwain, 2008) and hence, at this point, inertinite concentration should be 0%.

(3) Using the best temporally constrained dataset (10-million-year binning), Inertinite % for the Late Paleozoic reaches an averaged maximum value of $50 \pm 2\%$ at 280 Ma (Glasspool and Scott, 2010), which Glasspool and Scott (2015) assume that $p(O_2) = 28 \pm 2\%$.

Since this model was proposed, several researchers have used it to infer the palaeo atmospheric O₂ levels during different coal-accumulating periods. Shao et al. (2012) studied the inertinite in the Late Permian coal of Yunnan in China and concluded that the oxygen content is 28%; Wang et al. (2019) studied the inertinite in the Early Cretaceous coal of northeast China and concluded that the oxygen content during the Albian and Aptian is 24.7% and 25.3%, respectively. Zhang et al. (2020) estimated the atmospheric oxygen content during the Middle Jurassic coal-forming period in the Ordos Basin to be about 29%. Liu et al. (2020) based on the evidence in black shales for a wildfire at the Frasnian-Famennian boundary estimated an atmospheric O₂ level of ~23–25% at this interval. These estimates correspond well with geochemical simulations (Mills et al., 2023) of atmospheric oxygen content, demonstrating the validity of this model.

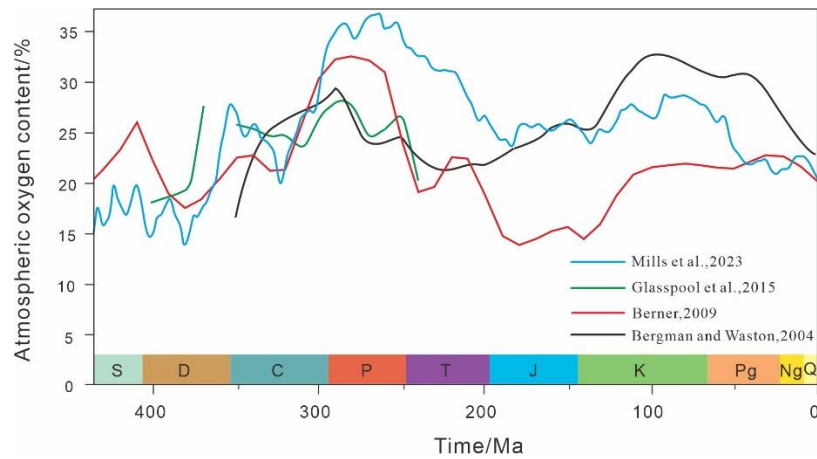


Fig. 6 Trends in atmospheric oxygen content since the Silurian

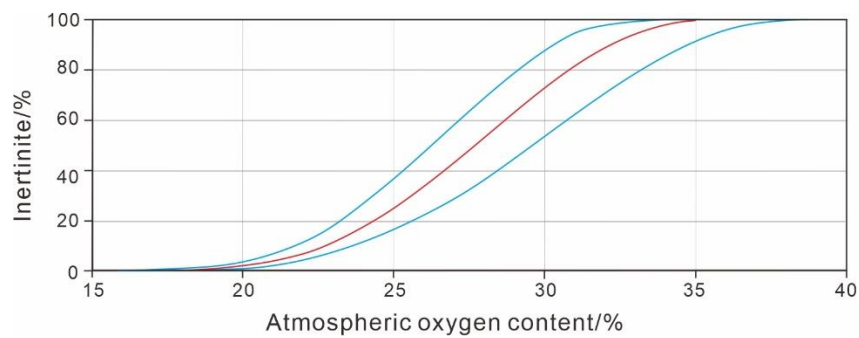


Fig. 7 Inertinite to $p(\text{O}_2)$ calibration curve (Glasspool et al., 2015) (Two blue curves define the error range,)

4 The stratigraphic and palaeogeographic distribution of inertinite

4.1 Stratigraphic distribution of inertinite

Inertinite data was collected from the scientific literature and some online databases including the USGS and WoCQI databases. Deep Shovel, a data extraction tool developed using the Deep Digital Earth (DDE) platform during the data extraction process (<https://deep-time.org/tools>). The data cleaning and visualization process is carried out using intelligent analysis software Tableau. Compared with the previous database (Diessel, 2010; Glasspool and Scott, 2010), the enlarged database is significantly supplemented with Chinese data. Importantly it can be seen from Fig. 8 that China has abundant Jurassic inertinite data. It is a favorable supplement to the global inertinite database.

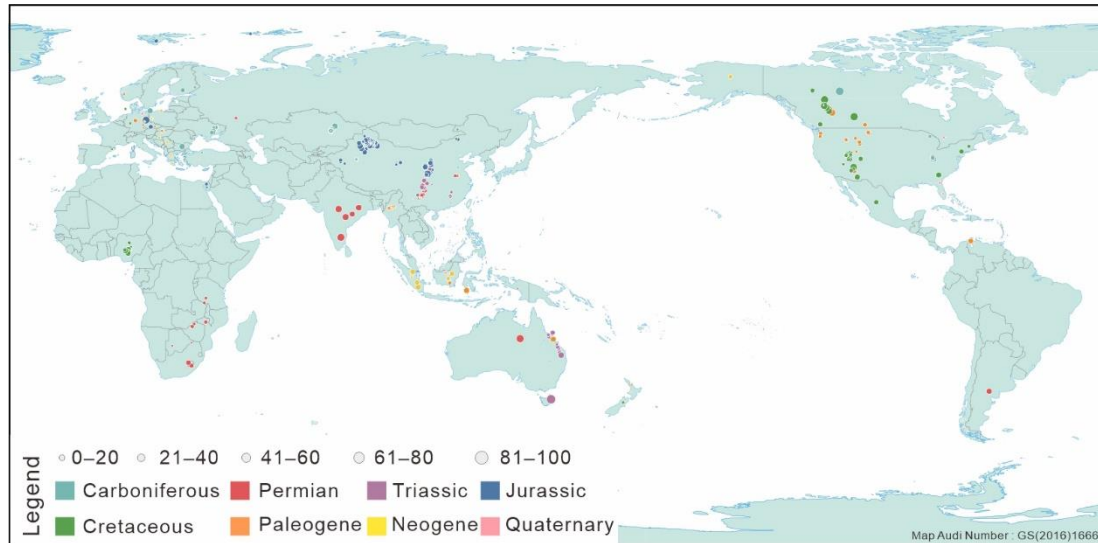


Fig. 8 Location and average content distribution of inertinite (Different colors represent different eras, and the size of the circle represents the average content of inertinite, World map from <http://bzdt.ch.mnr.gov.cn/>)

Diessel (2010) and Glasspool and Scott (2010) compiled inertinite data up to 2010. This study supplemented data from 2010 to 2023, and Figure 9b shows the display of all data. The all data are compiled in Fig. 9c as a box plot. The data is ordered into 10-million-year time binning intervals. In Fig. 9c the upper and lower boundaries of the box are the upper and lower quartiles of the data, respectively; the dividing line is the median, and the whisker range is within 1.5 times the IQR (the difference between the upper quartile and the lower quartile).

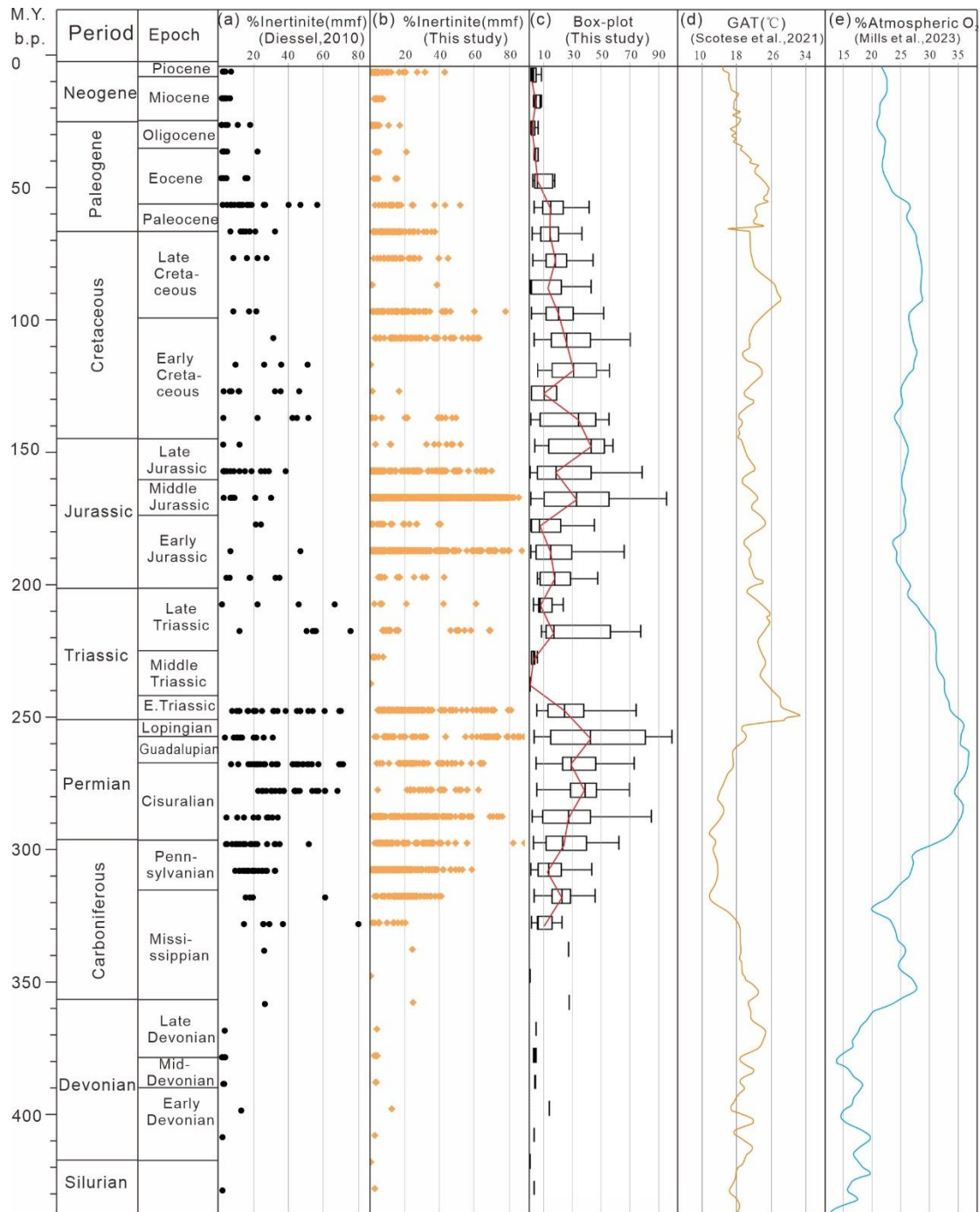


Fig. 9 Changes of inertinite and palaeoclimatic parameters in geological history; (a) Inertinite data comes from Diessel, 2010; (b) all data added to this study; (c) Box-plot represents all data; (d) GAT is Global average temperature, from Scotese et al., 2021; (e) Atmospheric oxygen content from Mills et al., 2023

4.2 Palaeogeographical distribution of inertinite

As direct evidence of wildfires, the palaeogeographical recovery of inertinite data makes it possible to estimate the distribution and frequency of wildfires in various geological periods. Using plate reconstructions from Scotese (2018), the Gplates (2.2.0) platform (<https://www.earthbyte.org/gplates/>) has been used to illustrate the palaeogeographical positions of tectonic plates throughout geological history. For the following time intervals, the data points are

positioned on the palaeomaps using ArcGIS Pro, and their palaeolongitudes and palaeolatitudes are reconstructed using Gplates.

4.2.1 The Silurian to Devonian

Plate movements at the end of the Silurian led to the formation of continental block that created conditions for plants to land. Plants have been on land since the Devonian. The evolution of significantly sized land plants provided organic materials for the formation of coal seams (Yang, 1996). The earliest records of coal produced by vascular plants are from the Early Devonian of New Brunswick and eastern Quebec in eastern Canada (Kennedy et al., 2013), while the Middle Devonian formed the landmark angular residual coal "Luquan Coal" around Luquan in Yunnan, China (Han and Yang, 1980). The evolution of plants also fuelled palaeowildfire, the fossil charcoal record of the Silurian and Devonian has been reported by several scholars (Scott, 2000; Edwards and Axe, 2004; Glasspool et al., 2006; Liu et al., 2020; Lu et al., 2021; Rahiminejad et al. 2022). Fossil charcoal from late Silurian to early Devonian sediments is generally considered more convincing as the earliest evidence of wildfire (Rowe and Jones, 2000; Rimmer et al., 2015). By Contrast, Glasspool and Gastaldo (2022) pushed the fire threshold back to at least the early Wenlock (ca. 430 Ma). Arbor began to appear in the Late Devonian, and the terrestrial plant population experienced a leap in development. The photosynthesis of plants led to a rapid increase in atmospheric oxygen content. The atmospheric oxygen content in the Late Devonian reached over 20% for the first time (Figure 9d).

4.2.2 The Carboniferous to Permian

The Carboniferous, with huge coal reserves worldwide, is the first period that records significant levels of inertinite (Fig. 9), abundant inertinite has been documented worldwide. The mid- to late Mississippian inertinite record is abundant, with a marked increase in the record and content with the transition to the Pennsylvanian. The reconstructed geographical distribution (Fig. 10) shows that Carboniferous inertinite is primarily found between the north and south 30-degree latitudes across all major land masses. With 80% of the total inertinite below 30% throughout the Carboniferous, this suggests that wildfires in coal-forming swamps may have been widespread but low intensity at that time. The overall atmospheric oxygen content during the Carboniferous period reached over 20%, began to rise rapidly in the mid- to late Mississippian, and rose to more than 30% at the end of the Pennsylvanian, which is highly consistent with the trend in the overall content of inertinite.

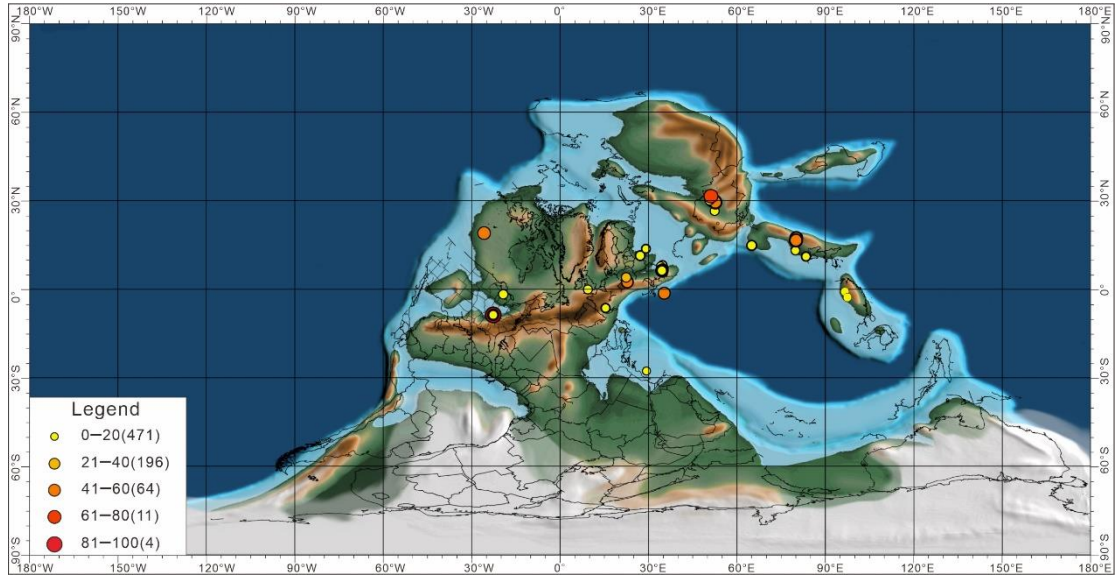


Fig. 10 Geographic distribution of wildfire evidence in the Carboniferous(330Ma). Plate reconstructions were from Scotese (2018). (The color and size of the circle represent the content of inertinite, and the number in the bracket is the amounts of data points)

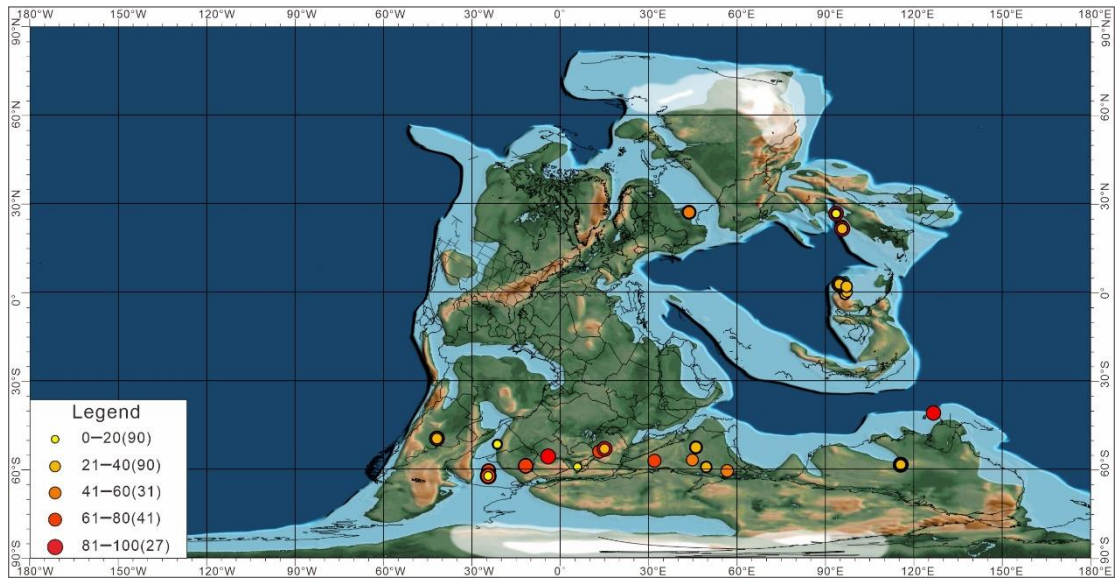


Fig. 11 Geographic distribution of wildfire evidence in the Permian (260Ma). Plate reconstructions were from Scotese (2018). (The color and size of the circle represent the content of inertinite, and the number in the bracket is the amounts of data points)

From the start of the Permian the inertinite content increases, with an average content of over 30%. The geographical distribution of the Permian inertinite is completely different from that of the Carboniferous inertinite, which is mainly distributed in the Gondwana continent near 60°S latitude (Fig. 11). In the Permian, Gondwana coal, a global inertinite-rich coal (Degani-Schmidt et al., 2015), was formed, most coals were dominated by inertinite-group macerals, primarily semifusinite and detrital inertinite (inertodetrinite). It is reported that the inertinite content in these coals reached up to 100% (Hower et al., 2012). Since the beginning of the Permian period, the atmospheric oxygen content has been continuously increasing, reaching over 30% and repeatedly exceeding 35% (Figure

9d), making it the period with the highest atmospheric oxygen content in geological history (Mills et al., 2023). The diversity of terrestrial plants increased significantly in the late Paleozoic (He et al., 2015), the development of lignin enabled vascular plants to grow larger and upright (Diessel, 2010). Abundant fuel and extremely high atmospheric oxygen levels led to the Permian being a “wildfire world”. This culminated in the typical "high inertinite content-high oxygen level" evolutionary period.

4.2.3 The Triassic to Cretaceous

In the first ten million years of the Early Triassic, the "Global Coal Gap" (Veevers, 2006) was caused by the collapse of terrestrial ecosystems (Lu et al., 2020), consequently, there are no records of inertinite from this period (Diessel, 2010). During the Middle and Late Triassic, terrestrial ecosystems gradually recovered, and coal seams began to form, such as the coal seams of the Xujiahe and Baoding Formations in southern China and the Wayaobao Formation in northern China (Yang, 1996), and the record of the inertinite reappeared (Fig. 9b). The palaeogeographical reconstruction shows that Triassic inertinite is primarily distributed near 60°S and 30° N (Fig. 12). The overall inertinite content of the Triassic is low, with an average of less than 20%. It increases at the Triassic/Jurassic boundary (Belcher et al., 2010; Petersen and Lindstrom, 2012), and the atmospheric oxygen content of the Triassic gradually decreases from the ultra-high level of the Permian to around 25%.

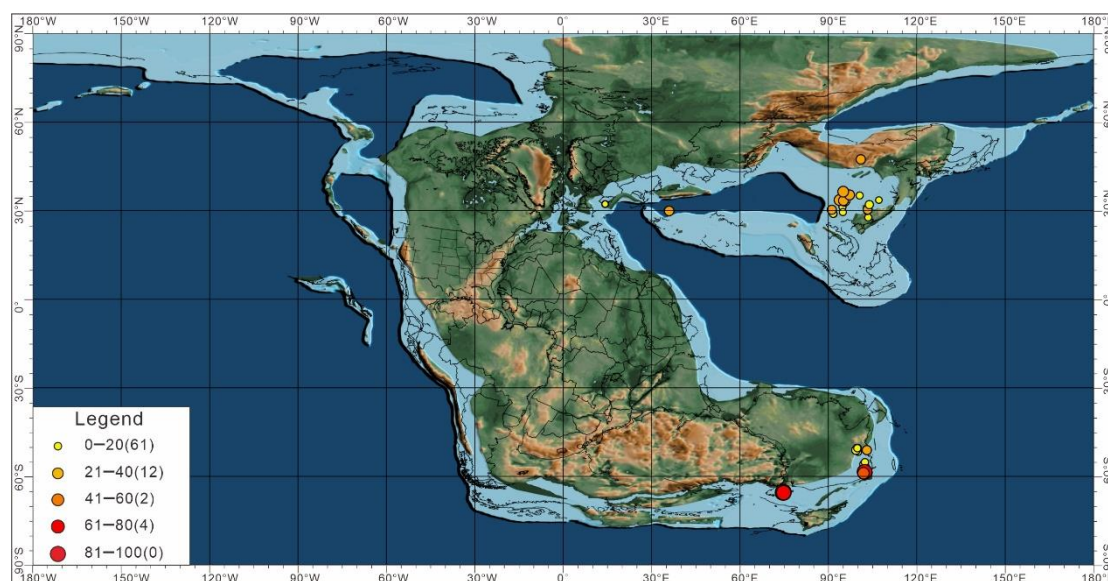


Fig. 12 Geographic distribution of wildfire evidence in the Triassic (220Ma). Plate reconstructions were from Scotese (2018). (The color and size of the circle represent the content of inertinite, and the number in the bracket is the amounts of data points)

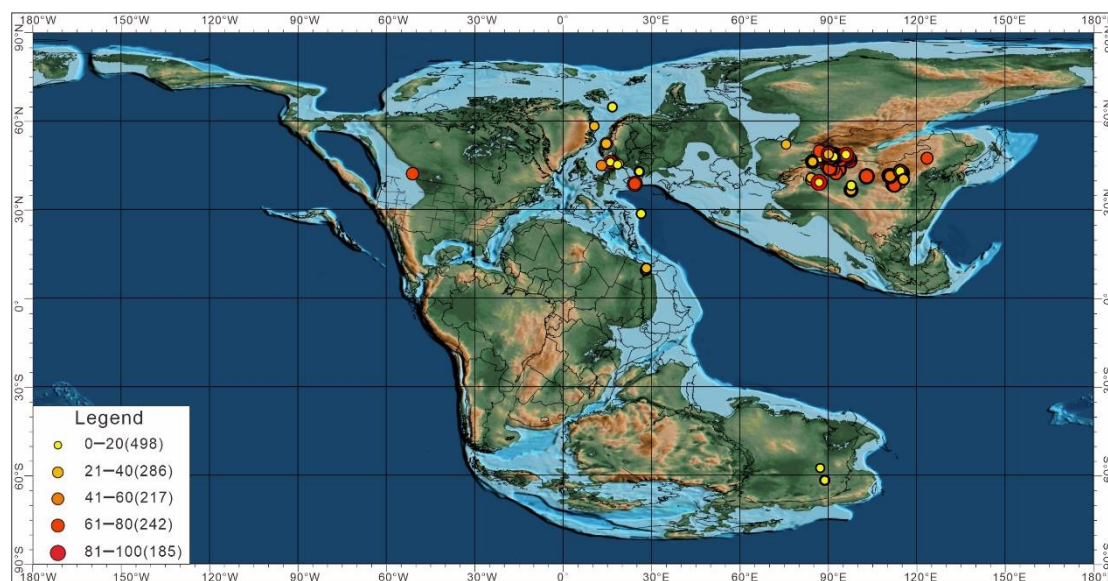


Fig. 13 Geographic distribution of wildfire evidence in the Jurassic (170Ma). Plate reconstructions were from Scotese (2018). (The color and size of the circle represent the content of inertinite, and the number in the bracket is the amounts of data points)

The Jurassic was an important coal-accumulating period worldwide (Thomas, 2020). The inertinite content in Jurassic coal varies, and is very inconsistent worldwide, the inertinite content of the Early and Middle Jurassic in northwest China is abnormally high (Du et al., 2022), with especially high semifusinite content (Lu et al., 2016; Hou et al., 2022). There are some abnormally high inertinite values with values exceeding 90%, which located in the Shenmu mine in the Ordos Basin, China (Zhao et al., 2017). The inertinite-rich coal is also found in the Late Jurassic of north America (Diessel, 2010). The Jurassic inertinite is distributed at 30–60 °N (Fig. 13), with high concentrations corresponding to modern-day Eurasia. The average content of the Middle Jurassic inertinite exceeded 30%, indicating frequent wildfires (Xu et al., 2020; Zhang et al., 2020; Hou et al., 2022). Mills et al. (2023) corrected the atmospheric oxygen content of the Jurassic to around 25% based on the wildfire events indicated by the inertinite content.

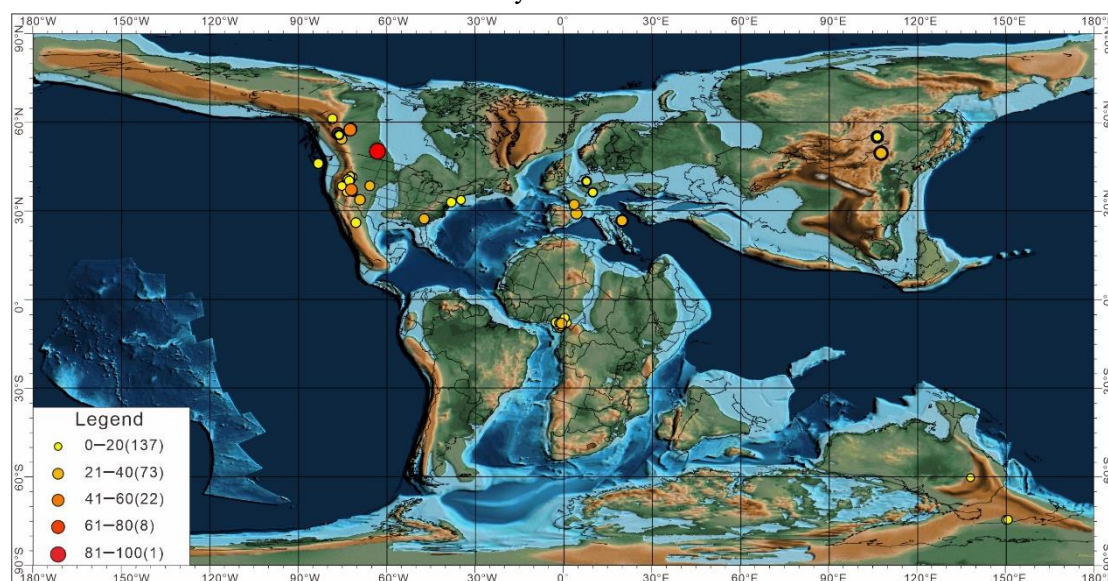


Fig. 14 Geographic distribution of wildfire evidence in the Cretaceous (100Ma). Plate reconstructions were from Scotese (2018). (The color and size of the circle represent the content

of inertinite, and the number in the bracket is the amounts of data points)

The content of inertinite in coal during the Cretaceous period fluctuated significantly, with a lower overall content compared to the Jurassic period. It was high in the Early Cretaceous and began to decrease in the late Early Cretaceous, gradually falling below 20% (Fig. 9b). The palaeogeographic reconstruction shows Cretaceous inertinite is mostly distributed at 30–60°N, with 80% of the total inertinite below 30%, but sporadic high values occur, such as in the Shengli Formation coal seams of the Shengli Coalfield in northeastern China (Dai et al., 2015) (Fig. 14). The Cretaceous atmospheric oxygen content remained between 25–30%.

Throughout the Mesozoic, the inertinite content of coals fluctuated dramatically, with the Jurassic inertinite being higher overall, comparable to the Permian, but the atmospheric oxygen content was not as high as in the Permian. This may be due to the global greenhouse climate of the Mesozoic, which resulted in higher surface temperatures (Scotese et al., 2021), leading to more wildfires, and thus the formation of typical "inertinite-rich coals" in some areas, and it can be argued that local environmental events had a greater influence on inertinite content (Diessel, 2010).

4.2.4 The Paleogene to Neogene

The Paleogene coal inertinite content is low, rarely more than 40% (Fig. 15), and in the Neogene coal is even lower, rarely more than 20% (Fig. 16), however, there is still evidence of wildfire (Liu et al., 2018). The inertinite content in Paleogene coals shows an overall decreasing trend to an average of less than 5% in Neogene inertinite content. The Paleogene and Neogene inertinite are mainly distributed near the equator and between 30–60°N. Atmospheric oxygen content continued to decline to between 20–25% during the Cenozoic, and after the Late Cenozoic (~40 Ma) icehouse period, global temperatures continued to decline (Scotese et al., 2021), leading to decreasing wildfire activity and a gradual decrease in inertinite content.

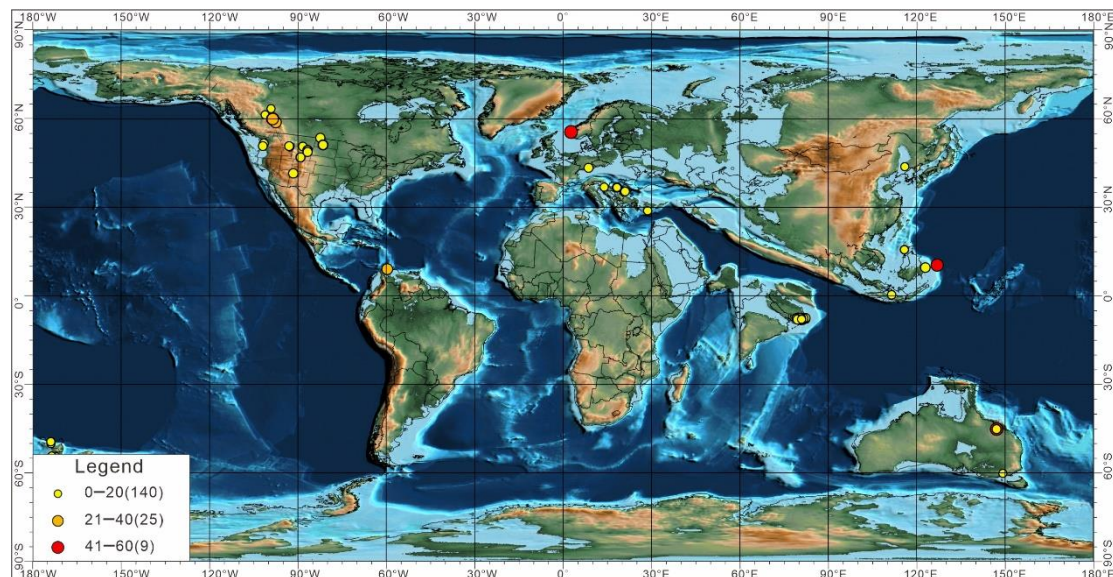


Fig. 15 Geographic distribution of wildfire evidence in the Paleogene (55Ma). Plate reconstructions were from Scotese (2018). (The color and size of the circle represent the content of inertinite, and the number in the bracket is the amounts of data points)

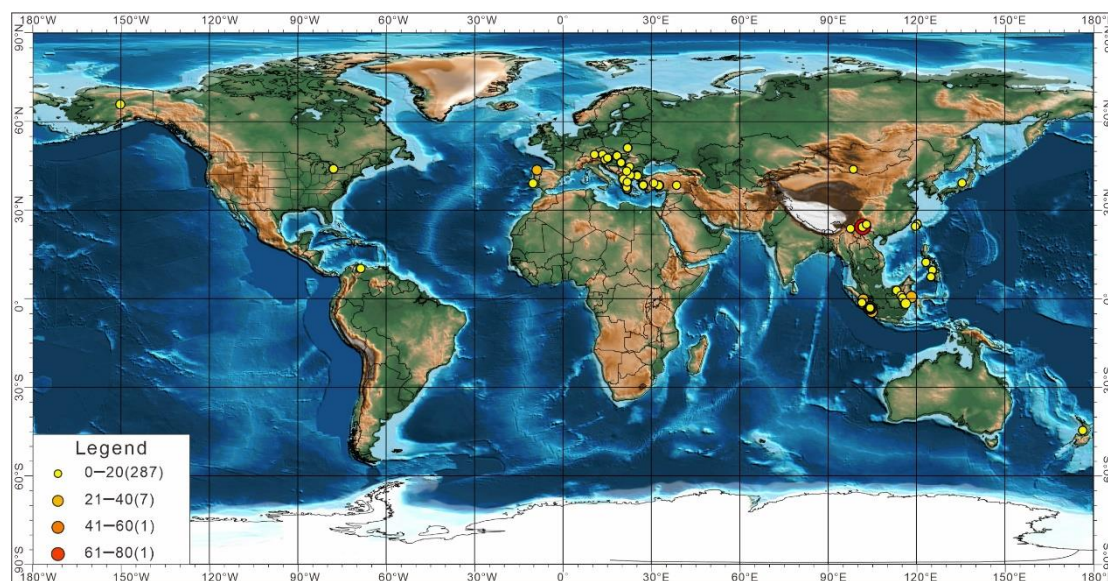


Fig. 16 Geographic distribution of wildfire evidence in the Neogene (10Ma). Plate reconstructions were from Scotese (2018) (The color and size of the circle represent the content of inertinite, and the number in the bracket is the number of data points).

5 The impacts of wildfire on animal and plant evolution and global change

5.1 Interactions between wildfire and plants

After the evolution of Silurian plants, wildfires have played complex and varied roles in the Earth's history (Wellman et al., 2003; Glasspool and Gastaldo, 2022). These include global ecological processes and cycles, animals and plants evolution, sedimentary processes such as enhanced erosion, and elemental distribution and cycling (Bowman et al., 2009). Wildfires have a major influence on the growth environment, composition, and structure of plants (Brown et al., 2012; Lindstrom et al., 2019).

Wildfires destroy vegetation. In 2020 according to a [National Interagency Fire Center report \(NIFC\) \(www.nifc.gov\)](https://www.nifc.gov), the amount of land burned by wildfires in the Western USA reached 8.8 million acres. Uncontrolled wildfires during geological history have caused even more severe damage to plants. Meanwhile, it is essential for some plant species, which depend on frequent and intense wildfires. Plant adaptations to wildfire typically require specific fire conditions, including frequency, intensity, and type of wildfire. For instance, Pinaceae began to develop fire-resistant thick bark in the Cretaceous Barremian (He et al., 2012). The evolution of plant-wildfire interaction from the Late Paleozoic onwards can be summarized as fire sensitive, tolerant, resistant, and/or requiring fire (Glasspool et al., 2015). An example of the last interaction in this evolutionary pathway are serotinous cones of some conifer species that are adapted to opening only in response to intense wildfires, and in doing so shed their seeds to ensure reestablishment of a new generation after the wildfire (Keeley et al., 2011).

The frequent occurrence of wildfire promoted the development of angiosperms. The earliest angiosperms developed slowly, but due to environmental changes influenced by wildfire, the angiosperms then developed rapidly in the Cretaceous, and diversified (Lupia et al., 1999; Friis et al., 2010). Angiosperms have the remarkable capacity to regenerate vegetatively from burned stems and therefore can re-establish forests in-situ without requiring seeding (Keeley et al., 2019), and this ability will have contributed towards angiosperms becoming the most important plant group in the Cretaceous (Belcher et al., 2021). Eucalyptus have adapted to regular wildfires, and during the

Cretaceous to Paleogene transition were found in significant numbers (Crisp et al., 2011), and this time is a period of high-frequency wildfires.

Growth characteristics of certain plants will also affect the sustainability of wildfires (Glasspool et al., 2015). An example of this relationship is the desert in the southwest of the United States. Lightning may strike cactus plants and cause small, localized burns, however because of the cactus sparse growth density, it will not facilitate the spread of wildfire. However, if some herbaceous plants are included in the ecosystem, they provide a fuel source between the cacti, potentially resulting in larger areas of cacti-dominated areas to be burnt (Scott et al., 2014).

5.2 Interactions between wildfire and animals

The most direct impact of wildfire on animals is that those animals will directly die in the fire. An additional hazard from wildfires is the smoke and toxic gases such as carbon monoxide. These interactions have been tragically observed in modern wildfires. During the seven months of Australian wildfires from June 2019 to February 2020, the World Wide Fund for Nature Australia (2020) estimated that at least 3 billion animals, including mammals, reptiles, and birds were killed, with nearly 100 species of animals in danger of extinction.

Some animal behaviors can also have an important impact on wildfires, with different animals affecting wildfires in many ways. These can include changing the quantity, structure or condition of fuel, some activities can indirectly change the nature of fuel, some activities can change the process of fuel generation or decomposition (Foster et al., 2020). More unusually, animals can affect wildfires other than by changing the nature of the fuel. An example of this is “Firehawk” Raptors (*Milvus migrans*, *Haliaeetus spheerulus* and *Falco berigora*) who deliberately drop burning branches in unburnt areas possibly as a strategy to mobilize prey food (Bonta et al., 2017). A more subtle interaction, such as small, unburned patches caused by animal footprints, may provide important shelters for soil animals (Morandini and Silvani, 2010; Carvalho et al., 2012). Zhang and Zhang (2009) studied the diversity of soil animals in the burned area of the Daxing'an Mountains and found that the individual numbers and diversity of the population would increase correspondingly with the recovery years after the fire, but in the areas with heavy fire, the soil animals would be very significantly impacted.

In certain periods of geological history, when the atmospheric oxygen levels were higher than now, forest wildfires may have lasted longer and spread on a larger scale, resulting in greater impacts on the environment. Nichols and Jones (1992) and Scott (2000) found that after the forest wildfires in Ireland, surface erosion intensified, resulting in large charcoal-rich erosion debris flows through surface runoff, resulting in siltation and a probable increase in fish deaths.

5.3 Interaction between wildfires and ecosystems

The occurrence of wildfires is closely related to climate change, a relationship that is becoming increasingly accepted today (Carnicer et al., 2022). Climate and vegetation control the intensity, type, and extent of wildfires (Fletcher, et al., 2019). In addition, carbon dioxide and other greenhouse gases emitted by burning have feedback on the environment and affect the growth of vegetation (Belcher et al., 2021). As a result of the intensity of wildfires on ground vegetation, the topography can change with enhanced erosion, redistributing some elements in the ecosystem which then affects the plants evolution and indirectly affects the animals (Scott, 2010; Brown et al., 2012).

After wildfires enhanced surface erosion can have a considerable impact on the hydrology within catchments, and can significantly change the topography (Cannon et al., 2009; Nyman et al., 2014). Bailey and Copeland (1961) studies of the Utah watershed showed that when the vegetation

coverage reaches 60–70%, only 2% of the rainfall will be surface water, whereas when the vegetation coverage is 37%, 14% of the rainfall will be surface water; and when the vegetation coverage is 10%, 73% of the rainfall will be surface water. The decrease in soil stability and the increase in soil hydrophobicity results in a decrease of the soil infiltration rate, which in turn will increase the surface runoff level leading to erosion (Brown et al., 2012). This results in elements transporting, especially phosphorus, into the ocean (Lenton, 2013) via river systems. The additional nutrients will have impacts on marine factors such as oxygen consumption. So, regional marine environmental changes may be related to frequent and strong wildfires (Lenton and Watson, 2000). Fires can also influence the supply of phosphorus by smoke aerosol in the atmosphere, causing atmospheric deposition of phosphorus to open-ocean sites (Baker et al., 2019). Yan et al. (2019) found evidence to support this suggestion when studying the coal seams in Xuanwei area, southwest China. The conclusions of Xu et al. (2022) similarly support this view. Wildfires, therefore, could provide a correlation mechanism (Fig. 17), with frequent wildfire events contributing towards ocean anoxia perturbations (Glasspool et al., 2015; Baker et al., 2019).

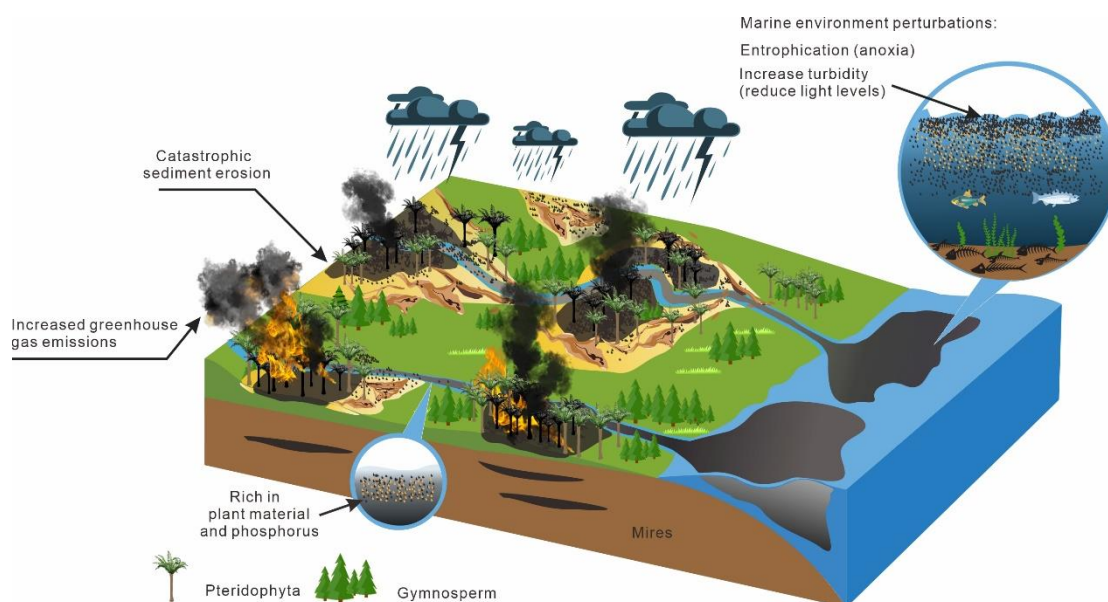


Fig. 17 Relationship between wildfire and marine anoxia perturbations (modified from Yan et al., 2019).

5.4 Interaction between wildfires and mass extinctions

Liu et al. (2020) studied Devonian wildfire events at the end of the Famennian approximately 359 Ma, in western New York, USA. Oxygen isotope records did not show any record of extraterrestrial impact events or volcanic activities as trigger factors for mass extinction. Therefore, they inferred that wildfires could have played a significant role in this mass extinction.

Shen et al. (2011) studied the Meishan section in southern China and noted the relationship between the evidence for wildfires and the Permian-Triassic Boundary mass extinction. It was suggested that wildfires may have had a causal role in the mass extinction of terrestrial organisms. Hua et al. (2023) studied the crisis of terrestrial ecosystems during the Permian-Triassic boundary mass extinction in southern China, and pointed out that increased aridity and widespread wildfires in the earliest Triassic were likely lethal factors in the terrestrial extinction scenario. Wu et al. (2024) studied the Late Permian extinction event in southwestern China and showed that increased wildfire

activity at the Permian-Triassic boundary was a major cause of ecosystem collapse.

The volcanic activity of the Central Atlantic Magmatic Province at the end of the Triassic is believed to be a main cause of the Triassic-Jurassic boundary mass extinction. The volcanism emitted a massive amounts of carbon dioxide, methane, sulfur dioxide and mercury (Lindstrom et al., 2019; Shen et al., 2022). Lu et al. (2021) and Hou et al. (2023) point to high wildfire activity at the end of the Triassic, with a significant increase at the boundary, and the possibility of a global event that also played an irreplaceable role in the mass extinction process.

It is believed that the cause of several Cretaceous oceanic anoxic events was that a large amount of carbon dioxide was emitted into the atmosphere, resulting in the rise of global temperatures, and the enhancement of surface chemical weathering (Xu et al., 2022). At the same time, an increase of nutrient input into the ocean led to the decrease of calcification rates of calcareous organisms and the increase of siliceous organisms in the ocean; resulting in ocean acidification and bottom water anoxia (Huang et al., 2008). Wildfires will have emitted massive amounts of carbon dioxide and other greenhouse climate-changing gases into the atmosphere at these times (Adair, 2010), especially given the high levels of atmospheric oxygen. Bamforth et al. (2014) pointed out it is important to consider the influence of small-scale microclimate phenomena as well as the potential effects of fire ecology when studying terrestrial diversity patterns leading up to the Cretaceous mass extinction.

The inertinite database shows a significant increase in inertinite content at several geological boundaries, indicating a significant increase in palaeo-wildfires, especially at the Carboniferous-Permian boundary and the Permian-Triassic boundary (Fig. 9b). In summary, wildfire activity has played a significant role in many mass extinctions, especially when driven by arid climates, which can deal a fatal blow to terrestrial ecosystems.

6 Quantitative calculations of greenhouse gas emission from wildfires

Wildfires produce a large amount of greenhouse gases, which are an important part of the global carbon cycle, and one of the main sources of greenhouse gases in the modern atmosphere (Fig. 17) (Crutzen and Andreae, 1990; Moraes, 2004). For example, Australian wildfires emitted 350 million tons of carbon dioxide into the atmosphere between November and December 2019 (Sanderson and Fisher, 2020).

At present, commonly used calculation models for greenhouse gas emissions are based on Seiler's Formula (Seiler and Crutzen, 1980). The residual solids formed by incomplete combustion can be obtained according to the following formula:

$$R = M \times f_c \times (1 - \beta) \quad (4)$$

Where R is the total carbon content of incomplete combustion of Mass (M), as a solid residue. Therefore, R within coal can be viewed as the inertinite content percentage. f_c is the carbon content of the fuel (%), typically taken as 0.5 as the average carbon content of tree material, and the average carbon content of litter, vegetation and humus is 0.45 (Crutzen and Andreae, 1990). β is the combustion efficiency of biomass fuel, the proportion of fuel used in the process of forest combustion per unit area (%), and the combustion efficiency β has an empirical estimation of 0.45 by the Intergovernmental Panel on Climate Change (IPCC) (Chang et al., 2015).

The total carbon emissions from biomass fuel combustion is (Kasischke et al., 1995; Levine et al., 1995):

$$C_t = M \times f_c \times \beta \quad (5)$$

Where C_t is the total amount of carbon emitted in the process of fuel combustion (unit: t), and M is the fuel load lost in the event of wildfire (unit: t).

The emission of carbon containing gases is (French et al., 2002):

$$E_s = E_{fs} \times C_t \quad (6)$$

E_s is the emission of a certain carbon gas (unit: g), E_{fs} is the emission factor of a certain carbon gas (unit: g kg⁻¹). E_{fs} has different values for different tree species, it is usually around 3000 (Hu et al., 2013).

Using the above equations, Xu et al. (2020) calculated that the total amount of carbon emitted by the ancient wildfires to the atmosphere during the formation of Jurassic peat in the northwest China was 1207Gt (Gt=10⁹t), respectively.

Li et al. (2018) calculated the Jurassic coal accumulation rate in northwestern China to be 3.7–4.1 cm kyr⁻¹, the total thickness of Middle Jurassic coal seams in Northwest China is highly variable, ranging from tens to hundreds of meters (Wang and Shao, 2013). Assuming a coal thickness of 20 meters and using a rate of 4.0 cm kyr⁻¹ to calculate the depositional time of the seam, which resulted in 500 kyr. Converting carbon emissions to annual emissions based on this deposition time results in a figure of 2.414 Mt a⁻¹. Using forest inventory data and long-term ecosystem carbon studies, Pan et al. (2011) estimated a total forest sink of 2.4±0.4 Gt of carbon per year (Gt C year⁻¹) globally for 1990 to 2007. This suggests that forests themselves are fully capable of neutralizing carbon dioxide emissions from wildfires. Lenton (2013) also suggested that carbon dioxide emissions from wildfires could be balanced by the growth of plants. Although wildfires consume organic matter and release carbon to the atmosphere, this occurs in the short term, whereas over the longer-term C fixation can be high during post-fire regeneration (Pausas and Keeley, 2019). From a broader temporal perspective, fire emissions are balanced out by previous C sinks (Yue et al., 2016), fires could increase C-sink capabilities by increasing soil charcoal (Santin et al., 2015). As a result, low-intensity wildfires may play a more key role in carbon storage (Fig. 18).

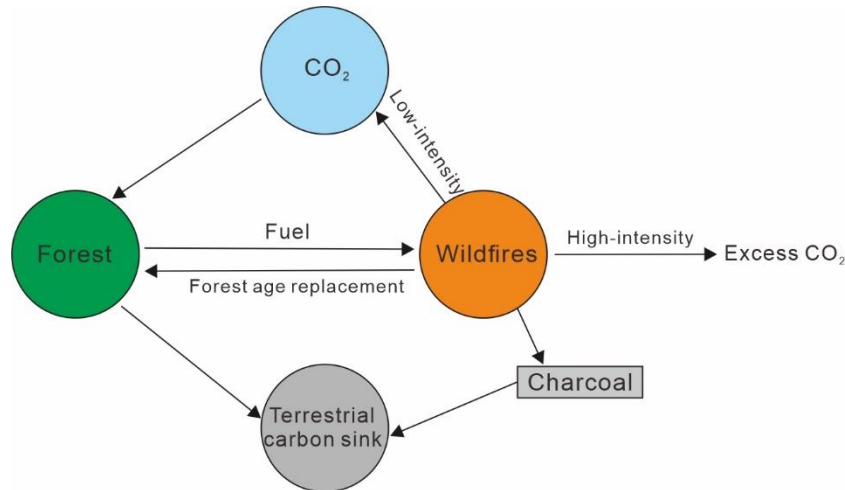


Fig. 18 Feedback of wildfires and carbon cycle

7 Conclusion and prospectives

Although the genesis of inertinite in coal is still debated, the wildfire origin of most macerals has been accepted and widely used by geologists, and the role of inertinite as indicators of palaeo-

wildfires in palaeoenvironmental studies has been increasingly valued. The reflectance of fusinite and semifusinite can be used to recover the combustion temperature and type of palaeo-wildfires, and then to judge the combustion characteristics of different wildfire types. The relative abundance of inertinite can be used to recover the palaeoatmospheric oxygen content, and the obtained results can be verified with geochemical models.

Inertinite are widely distributed in coal seams, but their time and spatial distribution varies during the major coal accumulation periods, and there are "high inertinite-high oxygen content" and "low inertinite-low oxygen content" phases of inertinite evolution in the geological history. The Jurassic high inertinite may be related to high temperatures due to the greenhouse climate, and further evidence needs to be collected for study. Palaeo-wildfire events are closely related to terrestrial dynamics, plant evolution, multiple ecosystem changes, and global carbon and phosphorus cycling, and play an irreplaceable role in global ecosystem feedback, acting as "accelerators" during mass extinctions. Large scale wildfire activities can emit huge amounts of greenhouse gases into the atmosphere, but when evaluating the positive and negative feedback of wildfire emissions on the global carbon cycle, the length of the time and the type and scale of wildfires need to be considered.

To address the above aspects, the author suggests that inertinite related research should focus more on the following aspects in the future:

1) To strengthen the integrated study of organic petrology and organic geochemistry, with a view to evaluating the type, frequency, and intensity of ancient wildfires more precisely and objectively. The research methods and ideas of the inertinite in coal should also be expanded and applied to fossil charcoal from other sedimentary rocks, to explore the inertinite's more important and comprehensive scientific significance in geological history.

2) To strengthen big data-driven research on the spatial and temporal distribution of the global inertinite, and to continue to improve the global inertinite database in conjunction with the DDE big science project. Try to combine with other palaeoenvironmental and palaeoclimatic data to explore the role of palaeo-wildfires in the Earth system in different climatic backgrounds.

3) Enhancing the study of modern wildfires in comparison to ancient wildfires. The Earth is undergoing a period of rapid climate change, and wildfires are occurring with increasing frequency around the world. The feedback mechanisms between wildfires and other factors in the ecosystem need to be further investigated. Quantifying the relative importance of different factors can have a positive impact on the study of modern wildfires by better elucidating and predicting the future frequency and intensity of wildfires due to climate change.

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