

Inertinite Reflectance in Relation to Combustion Temperature

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Abstract: Inertinite, a product of wildfire, holds important information on global temperature change. The relationship between its reflectance and temperature has been widely used to identify wildfire events in paleo-sedimentary environments, but the currently used equations relating inertinite reflectance and combustion temperature are subject to large errors. Therefore, to clarify the relationship between inertinite reflectance and combustion temperature further, we systematically analyzed changes in inertinite reflectance under different combustion durations based on the literature's data. Results confirmed that inertinite reflectance is related to combustion duration. Disregarding combustion duration, the combustion equation is $T = 267.52 + 110.19 \times Ro (R^2 = 0.91)$, where T is the combustion temperature, Ro% is the measured inertinite reflectance, and R^2 is the correlation coefficient. Under a combustion duration of 1 h, the equation is $T = 273.57 + 113.89 \times Ro (R^2 = 0.91)$, and under a combustion duration longer than 5 h (including 5 h), the equation is $T = 232.91 + 110.6 \times Ro (R^2 = 0.94)$. These three equations not only account for the temporal factor, but are also more precise than the commonly used formula. This study provides a scientific basis for research on paleo-wildfire.

Keywords: inertinite; paleo-wildfire; reflectance; combustion equation; correlation



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1. Introduction

Currently, Earth is experiencing climate change characterized by global warming. According to the Climate Change 2023 report released by the United Nations' Intergovernmental Panel on Climate Change (IPCC) on 20 March 2023, the global surface temperature in 2011–2020 was 1.1 °C higher than that in 1850–1900 [1], and various types of environmental problems induced by climate change seriously threaten the environment in which we live. Wildfire is an essential component of the Earth system [2]. Wildfire events play a critical role in the Earth's climate system, as evidenced by the release of greenhouse gases, such as CO₂, CH₄, NO₂, and O₃, during wildfire combustion, which exacerbates global warming and thus leads to global-scale climate change. Weather changes caused by wildfire activity can affect the characteristics of terrestrial vegetation and biogeochemical cycles [3], fundamentally alter local ecosystems [4–7], and promote the evolution of plants and animals [8–10]. In geological history, increases in wildfire frequency typically coincided with global warming [11,12]. Hence, studying interactions between paleo-wildfire events and paleoclimate can help us reconstruct climatic conditions that existed when paleo-wildfires occurred, which has significance for addressing the sixth global warming currently being experienced by Earth.

Paleo-wildfire history is mainly reconstructed based on the combustion products in strata, including charcoal, black carbon, and combustion-derived polycyclic aromatic hydrocarbons (PAHs), as well as related parameters [13]. In recent years, progressively more scholars have demonstrated experimentally that inertinites (fusinite, semifusinite, and inertodetrinite) in coal originated from wildfire activity and are equivalent to charcoal [14–19].

Fires in natural environments may be caused by many factors, such as lightning strikes, meteorite impacts, volcanic eruptions, and spontaneous combustion of vegetation, among which lightning strikes are the most common factor [20]. Based on the spatial distribution of burning materials and combustion intensity [21], wildfires can be classified into surface fires, ground fires, and crown fires [20,22]. Surface fires usually burn at a temperature below 400 °C, ground fires burn at a temperature as high as about 600 °C, and crown fires burn at a temperature of 800 °C or even higher [23] (Figure 1).

Temperature variation during combustion determines the isotopic composition, physical appearance, and chemical structure of charcoal [24,25]. Inertinite reflectance is an indicator with important information on the carbonization process, as it can be used to calculate the maximum temperature to which biochar was exposed during pyrolysis. Additionally, inertinite (charcoal) reflectance has long been applied to estimate the burning temperature of paleo-wildfires. Many studies have suggested a positive correlation between inertinite reflectance and combustion temperature [11,14,15,20,21,26], and correlation equations are available. Jones et al. investigated the relationship between the reflectance of charcoal and the maximum pyrolysis temperature for three types of plants (*Picea abies*, *Betula pendula*, and *Pinus*) by controlling the heating duration, the part of the plant, and other influencing factors and obtained the equation $T = 198.8Ro + 237.6Ro^2 + 9.36Ro^3$ ($R^2 = 0.98$) [27]. Jones further explored the relationship between temperature and reflectance and obtained the linear relationship $T = 184.10 + 117.76 \times Ro$ ($R^2 = 0.91$) [28]. Hudspith heated wood samples of trembling aspen, dwarf birch, paper birch, black spruce, and white spruce at 300 °C to 800 °C with temperature increments of 100 °C for a duration of one hour for each temperature. The charcoals obtained were then embedded in epoxy resin and polished. Data from the five types of wood were combined to generate the following polynomial curve: $T = -6.0 \times 10^{-8}Ro^3 + 1.0 \times 10^{-4}Ro^2 - 4.4 \times 10^{-2}Ro + 5.9$ ($R^2 = 0.99$) [29].

However, after fitting all data regarding inertinite reflectance and combustion temperature collected from the available literature, we found that the combustion temperature of paleo-wildfires calculated using the resulting equation had a large error. In addition, because combustion duration has a significant impact on inertinite reflectance, it is necessary to construct more accurate equations between inertinite reflectance and combustion temperature by fitting data under different combustion durations so as to provide a basis for further research in related fields.

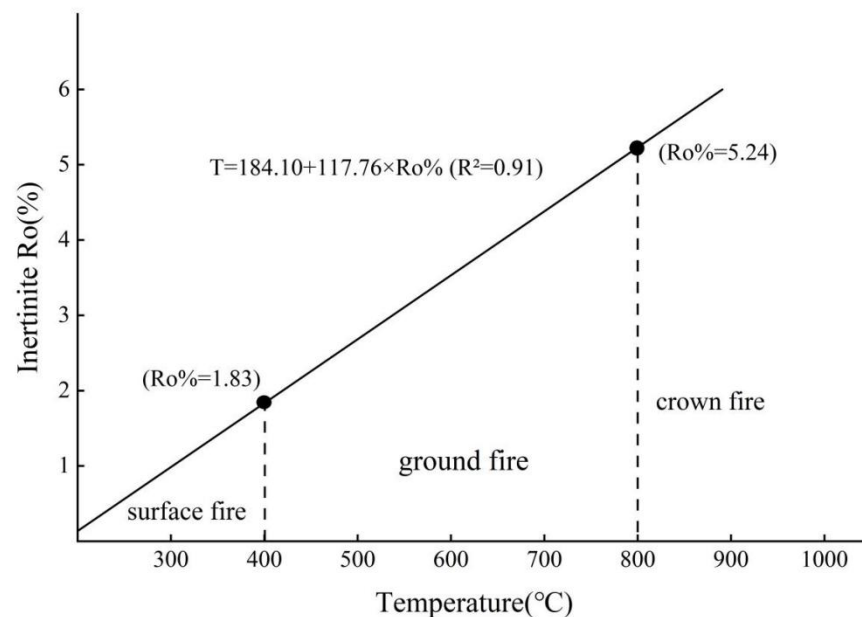


Figure 1. Diagram of the relationship between combustion temperature and fire type (according to Petersen and Lindström, 2012 [30], with modifications). In the figure, T is the combustion temperature and Ro is the reflectance of the inert group.

2. Materials and Methods

To clarify the relationship between inertinite reflectance and combustion temperature further, we collected 137 sets of data from the published literature in the SCI database and the CNKI Chinese Academic Journal Database (Table 1). The methods for obtaining charcoal reflectance mainly included muffle furnace pyrolysis and modern vegetation fire experiments [31–33]. Studies have shown that the charcoal produced in muffle furnaces reflects the maximum internal temperature of the charcoal produced by plant fires [34]. Therefore, we collected data from pyrolysis experiments and simulated fires for efficient analysis. These data contain inertinite (charcoal) reflectance values obtained under different combustion durations, different fuel materials, and different combustion temperatures. Studies have shown that it is inappropriate to ignore the influence of combustion duration on the relationship between inertinite reflectance and combustion temperature. Therefore, in this study, we analyzed the relationship between inertinite reflectance and combustion temperature under different combustion durations based on available data.

Table 1. Statistical table of data sources on the relationship between combustion temperature and inert reflectivity.

Jones T. P. et al., 1991 [27]						Mcparland L. C. et al., 2009 [35]						Braadbaart F. et al., 2008 [36]						Li Gang et al., 2022 [37]					
Ro%	T (°C)	C	Ro%	T (°C)	C	Ro%	T (°C)	C	Ro%	T (°C)	C	Ro%	T (°C)	C	Ro%	T (°C)	C	Ro%	T (°C)	C	Ro%	T (°C)	C
0.49	340	1.5	0.95	300	1	0.13	300	1	0.46	300	10	0.40	310	1	0.65	400	1	0.17	250	2	1.02	400	1
1.39	440	1.5	1.13	340	1	0.80	400	1	1.46	400	24	0.65	340	1	1.20	440	1	0.51	300	2	1.26	450	1
3.7	560	1.5	1.33	370	1	1.58	500	1	2.60	500	24	0.87	370	1	1.88	500	1	0.90	350	2	1.60	500	1
4.5	640	1.5	1.83	400	1	2.34	600	1	3.55	600	24	1.30	400	1	3.17	600	1	1.07	400	2	1.73	550	1
5.4	840	1.5	2.2	500	1	3.81	700	1	4.36	700	24	1.83	440	1	4.80	700	1	1.15	450	2	2.01	600	1
5.6	920	1.5	2.5	560	1	5.05	800	1	5.05	800	24	2.50	500	1	5.89	900	1	1.43	500	2	2.16	650	1
6	1060	1.5	2.6	600	1	6.02	900	1	/	/	/	3.70	600	1	1.70	440	1	1.58	550	2	/	/	/
0.55	300	1	0.13	220	1	6.26	1000	1	/	/	/	4.09	650	1	2.21	500	1	0.20	250	4	/	/	/
1.11	340	1	0.47	220	1	6.72	1100	1	/	/	/	4.96	700	1	1.43	440	1	0.66	300	4	/	/	/
1.39	500	1	0.63	250	1	0.25	300	5	/	/	/	6.19	900	1	3.26	600	1	0.98	350	4	/	/	/
4.3	600	1	0.58	250	1	2.16	500	5	/	/	/	6.24	1000	1	5.96	900	1	1.12	400	4	/	/	/
4.6	700	1	/	/	/	6.84	1100	5	/	/	/	6.36	1100	1	5.69	800	1	0.11	250	1	/	/	/
5.2	820	1	/	/	/	5.05	800	5	/	/	/	0.20	310	1	6.24	900	1	0.33	300	1	/	/	/
0.6	270	1	/	/	/	7.22	1100	10	/	/	/	0.49	370	1	6.29	1000	1	0.52	350	1	/	/	/
Scott A. C. et al., 2007 [14]						Scott A. C. et al., 2015 [21]						Mcparland L. C. et al., 2007 [25]			Scott A. C., 2010 [15]			Hudspith V. A. et al., 2014 [29]			Braadbaart, F. 2007 [38]		
Ro%	T (°C)	C	Ro%	T (°C)	C	Ro%	T (°C)	C	Ro%	T (°C)	C	Ro%	T (°C)	C	Ro%	T (°C)	C	Ro%	T (°C)	C	Ro%	T (°C)	C
0.10	280	1	3.90	600	1	0.25	250	24	0.23	300	1	0.4	275	24	0.65	400	24	0.46	310	1			
0.27	300	1	0	300	1	1.81	400	24	0.50	350	1	0.43	300	24	1.65	500	24	1.64	440	1			
0.55	325	1	0.47	350	1	2.43	450	24	1.03	400	1	1.57	400	24	2.45	600	24	3.58	600	1			
1.00	350	1	0.86	400	1	3.68	525	24	1.14	450	1	3.33	500	24	4.47	700	24	/	/	/			
1.24	400	1	1.47	450	1	0.42	300	24	1.62	500	1	4.97	600	24	4.73	800	24	/	/	/			
1.47	450	1	1.99	500	1	1.51	400	24	2.19	600	1	6.86	900	24	/	/	/	/	/	/			
2.29	500	1	2.34	550	1	3.17	500	24	/	/	/	/	/	/	/	/	/	/	/	/			
2.81	550	1	2.59	600	1	4.73	600	24	/	/	/	/	/	/	/	/	/	/	/	/			

Notes: In the table, T is temperature and C is combustion duration (hours).

3. Discussion

As shown in Figure 2, combustion temperatures vary between 200 °C and 1200 °C, and reflectance varies greatly within the combustion temperature range of 500 °C to 600 °C, indicating that different sample materials exhibit significant differences in this combustion temperature interval. In contrast, Ro values are concentrated and distributed below the combustion temperature of 500 °C or above 700 °C, suggesting that the difference in reflectance between different fuel materials is minor under low combustion temperatures.

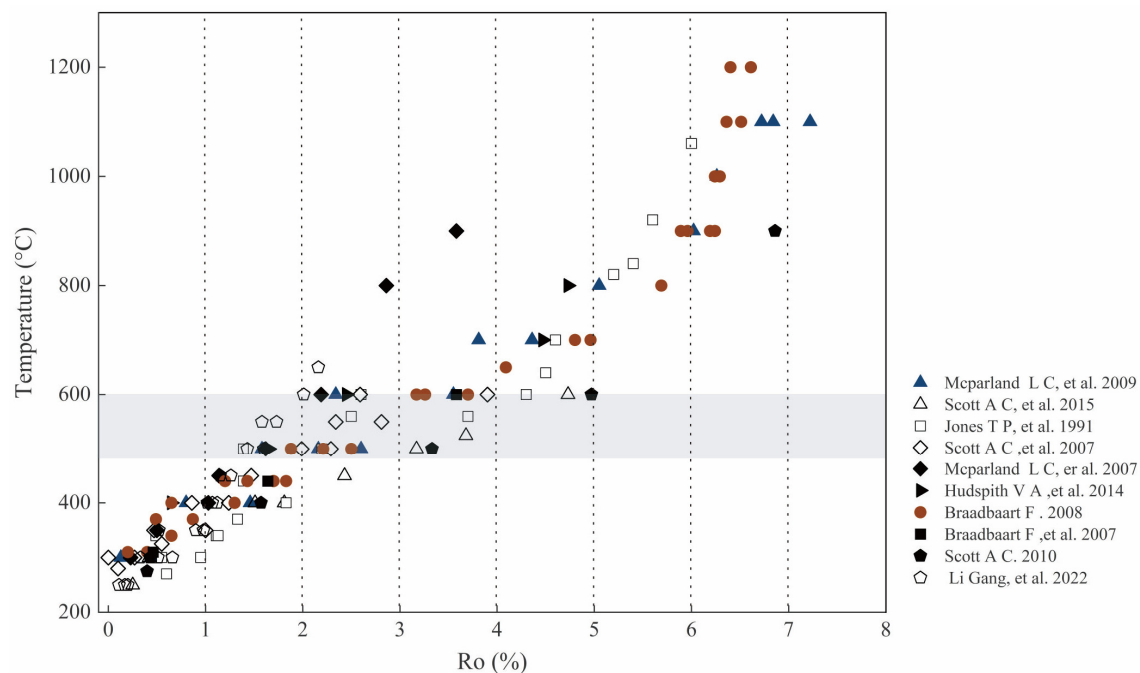


Figure 2. Scatter plot of combustion temperature versus inertinite reflectance and data sources, produced by OriginLab Corporation. (2021). OriginPro 2021 [Computer software]. OriginLab Corporation. <https://www.originlab.com>. Replot based on the original paper data: Mcparland, L.C., et al., 2009 [35]; Scott, A. C. et al., 2015 [21]; Jones, T. P. et al., 1991 [27]; Scott, A. C. et al., 2007 [14]; Mcparland, L. C. et al., 2007 [25]; Hudspith, V. A. et al., 2014 [29]; Braadbaart, F. 2008 [36]; Braadbaart, F. et al., 2007 [38]; Scott, A. C. 2010 [15]; Li, Gang, et al., 2022 [37].

Currently, the formulas $T = 198.8Ro + 237.6Ro^2 + 9.36Ro^3$ ($R^2 = 0.98$) and $T = -6.0 \times 10^{-8}Ro^3 + 1.0 \times 10^{-4}Ro^2 - 4.4 \times 10^{-2}Ro + 5.9$ ($R^2 = 0.99$) are not widely used in relevant fields, which limits their practical applicability and comparability. Additionally, there are significant discrepancies between data calculated using these two formulas and experimental data, making it inappropriate to present their results in the error comparison graph. Therefore, we chose empirical formulas as a reference for comparison.

Data were fitted considering the time factor, and results are shown in Figure 3. With increases in temperature and time, reflectivity data show an obvious upward trend. Based on this, we analyzed the relationship between inertinite reflectance and combustion temperature under different combustion durations based on available data.

3.1. Results Disregarding Combustion Duration

As shown in Figure 4, the relationship between temperature and inertinite reflectance fitted based on the literature data is $T = 267.52 + 110.19 \times Ro$ ($R^2 = 0.91$). To verify the accuracy of this equation, we compared its error with that of the empirical formula $T = 184.10 + 117.76 \times Ro$ ($R^2 = 0.91$) by substituting experimental data into the empirical formula and calculating the error between the resulting combustion temperature and the actual combustion temperature.

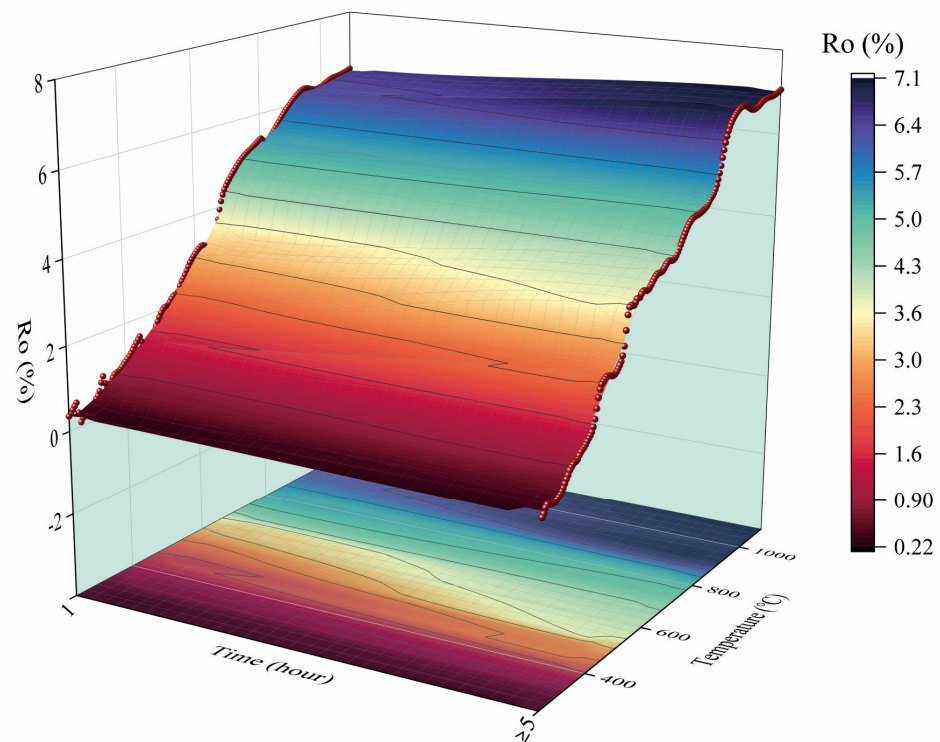


Figure 3. Trend diagram of the relationship between combustion temperature and inertinite reflectance, produced by OriginLab Corporation. (2021). OriginPro 2021 [Computer software]. OriginLab Corporation. <https://www.originlab.com>. The red spheres in the figure represent the data points from the transformed matrix of experimental data, and the surface is fitted from the matrix data. The data for >5 hours includes combustion times of 5 h, 10 h, and 24 h.

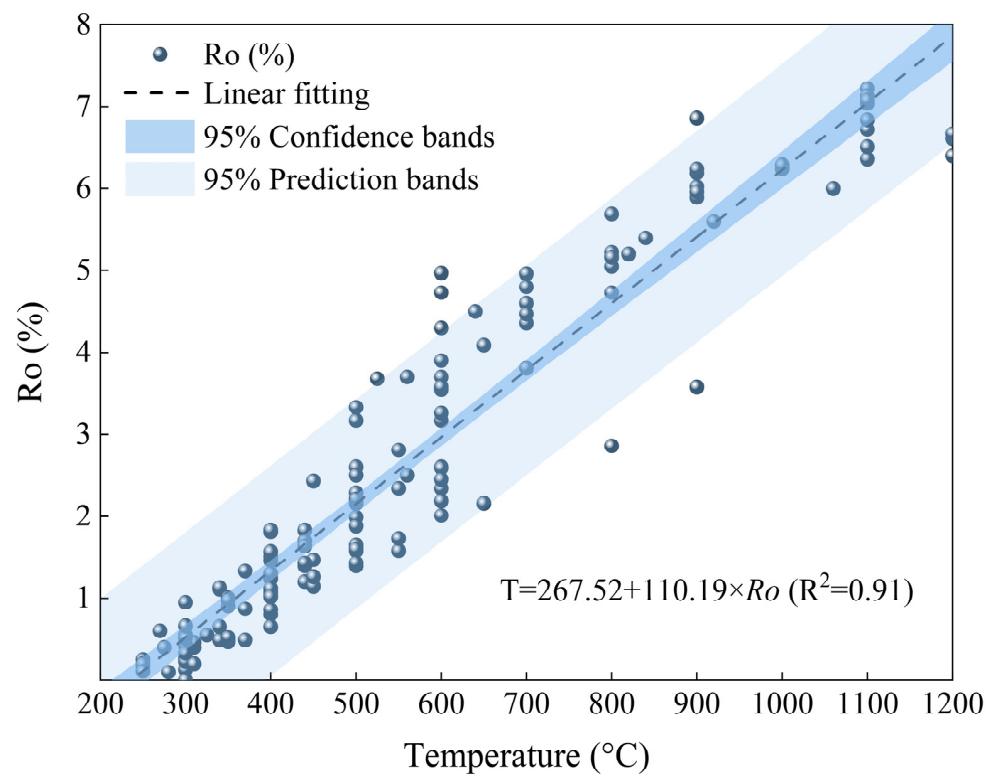


Figure 4. Relationship between combustion temperature and inertinite reflectance (disregarding combustion duration).

Comparison results are plotted in Figure 5. These results show that the fitted equation has higher accuracy. When the combustion temperature is below 500 °C, the error in this equation is significantly smaller than that of the empirical formula, and this temperature level is the most commonly reached level by low-temperature surface fires. The error corresponding to the combustion temperature interval of 700 °C–900 °C is relatively higher, which may be attributable to the following reasons. First, most of the experimental samples (60% of all samples) were heated for one hour. Second, the combustion durations of samples were 1 h, 1.5 h, 5 h, and 24 h, respectively, which were significant differences in duration. Finally, only a small proportion of samples experienced a combustion temperature higher than 700 °C, and most samples were treated below 600 °C.

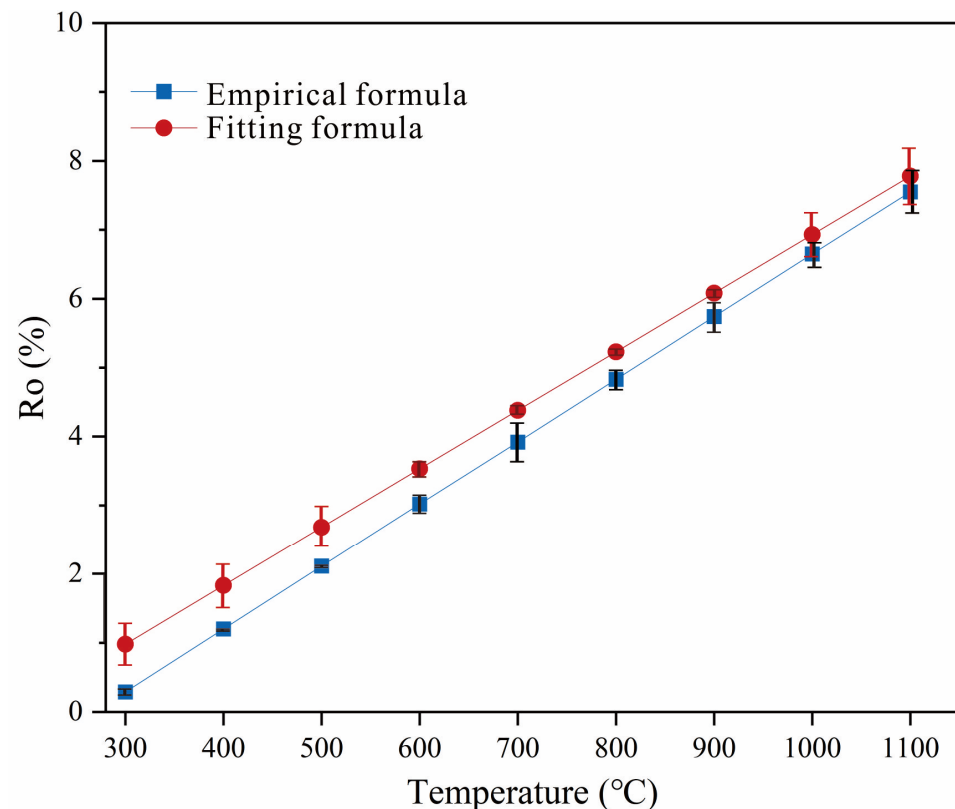


Figure 5. Comparison of inertinite reflectance changes at different combustion temperatures (disregarding combustion duration).

3.2. Results Under a Combustion Duration of 1 h

The correlation analysis results of data are shown in Figure 6. As shown, the inertinite reflectance increased significantly with increasing combustion temperature, and the relationship can be expressed as $T = 273.57 + 113.89 \times Ro$ ($R^2 = 0.91$). The error analysis shows that the overall error value of the fitting relation was smaller than that of the empirical formula, and the error was smallest when the combustion temperature was below 500 °C (Figure 7).

3.3. Results Under a Combustion Duration Longer Than 5 h (Including 5 h)

After analyzing data with a combustion duration longer than 5 h (including 5 h), we obtained a relationship between combustion temperature and inertinite reflectance of $T = 232.91 + 110.6 \times Ro$ ($R^2 = 0.94$) (Figure 8). The results of the data analysis, as shown in Figure 9, indicate that when the combustion time greater than 5 h (including 5 h), the overall error value of the fitting relation was smaller than that of the empirical formula.

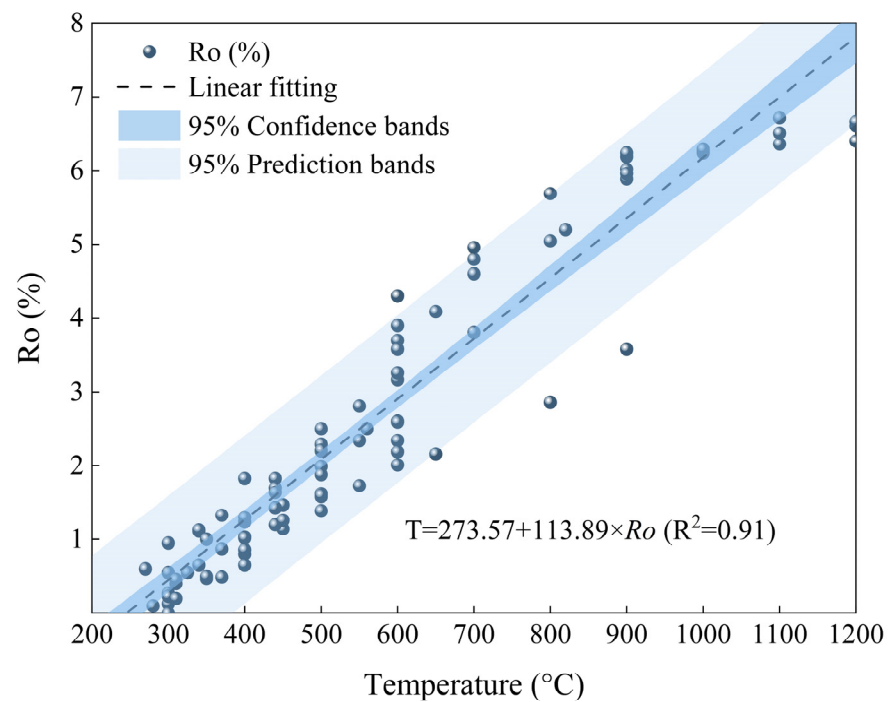


Figure 6. Relationship between combustion temperature and inertinite reflectance (combustion time is 1 h).

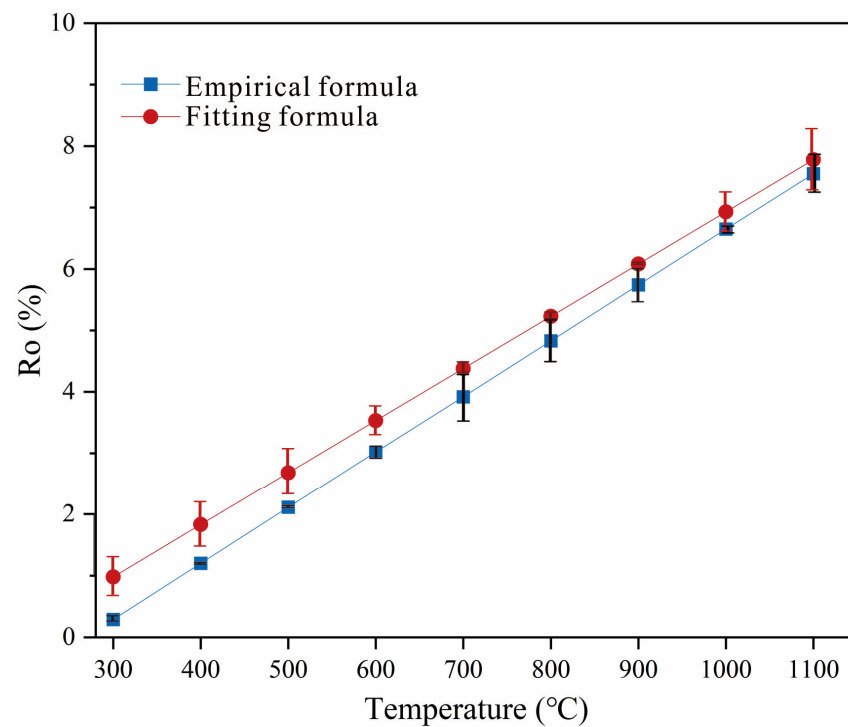


Figure 7. Comparison of reflectance change with combustion time of 1 h.

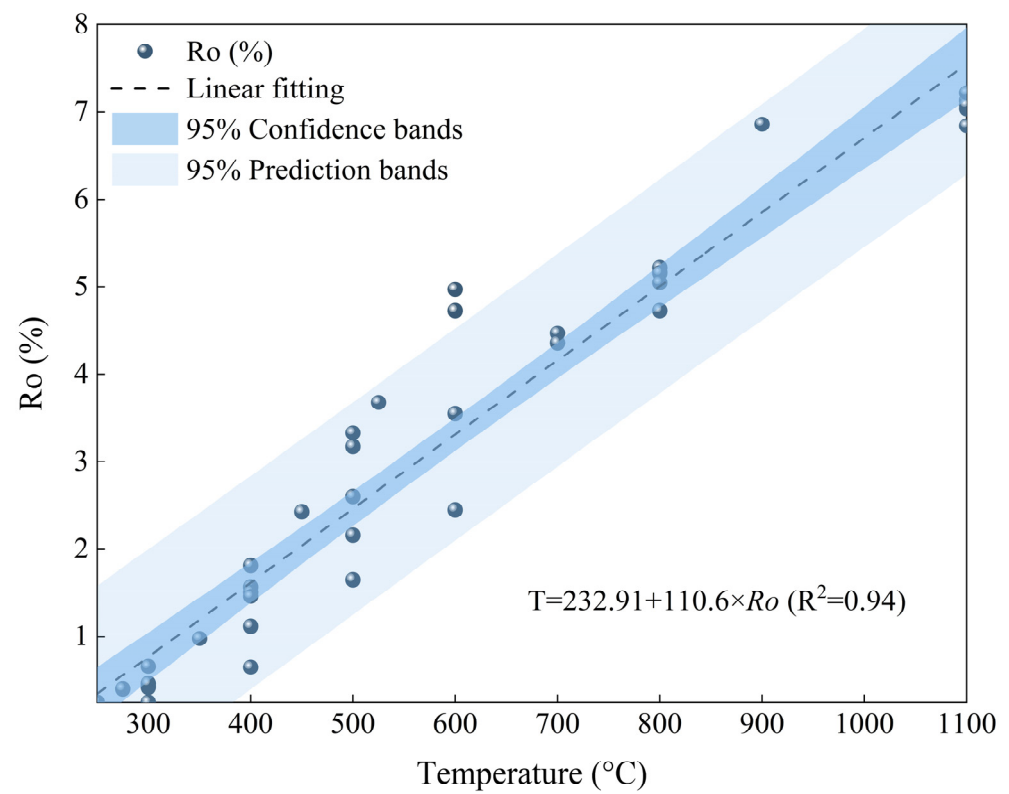


Figure 8. Relationship between combustion temperature and inertinite reflectance (combustion duration longer than 5 h (including 5 h)).

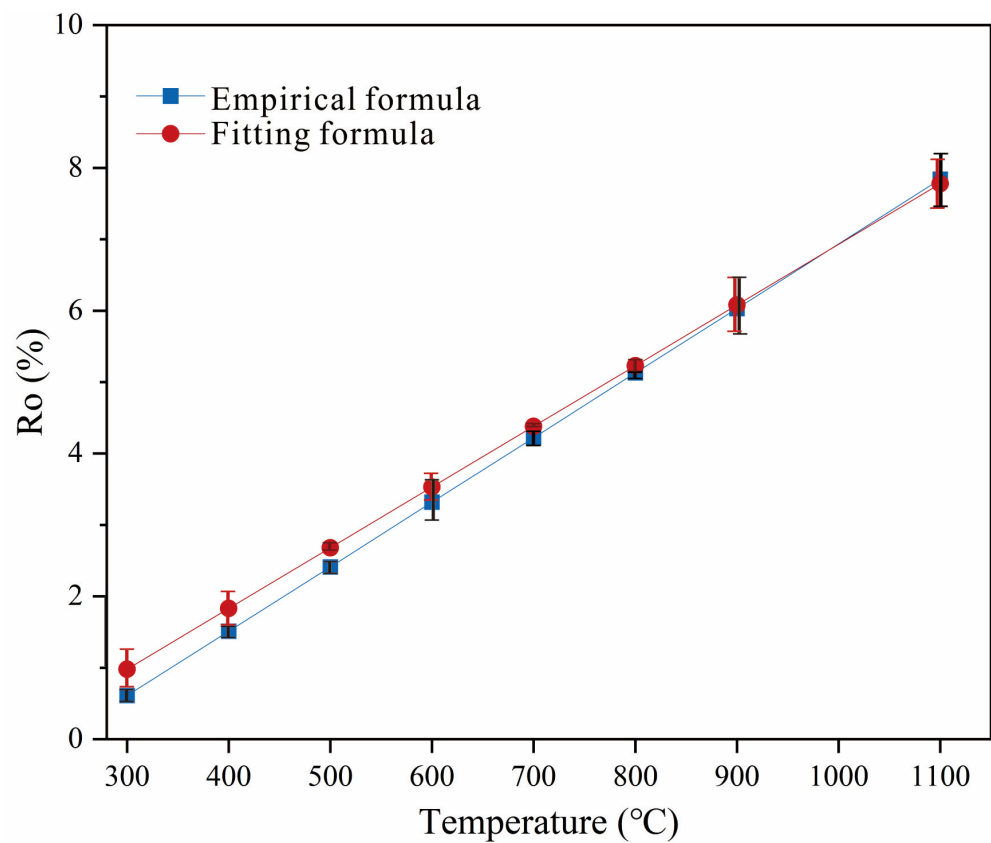


Figure 9. Comparison of reflectance changes for burning times exceeding 5 h (including 5 h).

The actual carbonization temperature of plant materials can be obtained under a combustion duration exceeding 4–5 h [6], and the increasing trend of inertinite reflectance with increasing combustion temperature leveled off when the combustion duration was more than 5 h. Therefore, this equation can be used to determine the actual carbonization temperature of inertinite. As the carbonization associated with volcanic activity is characterized by a long reaction time, the relationship between combustion temperature and reflectance fitted with data obtained under a combustion duration longer than 4 h can provide qualified support for research on charcoal generated by volcanic activity.

4. Conclusions

Our results confirm the earlier work of Jones et al., showing that the reflectivity of the inertinite group increases as the combustion temperature increases. Under the condition of considering the combustion time, the fitting results of the inertinite group's reflectivity and the combustion temperature showed obvious differences. The fitting formula was more accurate than the commonly used formula, which provides a scientific basis for the study of ancient wildfire.

- (1) The relationship between inertinite reflectance and combustion temperature disregarding combustion duration is $T = 267.52 + 110.19 \times Ro$ ($R^2 = 0.91$). Under a combustion duration of 1 h, the equation is $T = 273.57 + 113.89 \times Ro$ ($R^2 = 0.91$), and under a combustion duration longer than 5 h (including 5 h), it is $T = 232.91 + 110.6 \times Ro$ ($R^2 = 0.94$).
- (2) Error analysis results show that the fitted equation expressing the relationship between inertinite reflectance and combustion temperature has a significantly lower error than the empirical formula under any combustion duration condition. The error of the fitted equation under a combustion duration of 1 h was greater than that under a combustion duration longer than 5 h (including 5 h), and the correlation coefficient (R^2) between inertinite reflectance and combustion duration was also smaller, indicating that reflectance tends to stabilize as the combustion duration extends.

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