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Sol de Jesus Moreno Roso

Dedicatoria

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Índice

Resumen

El fuego ha sido una herramienta elemental en el desarrollo del humano desde hace miles de años, pues ha estado presente en diversas prácticas desde el calentamiento y la iluminación hasta en la caza y las ceremonias. A través de las quemas antrópicas los humanos han modificado el paisaje, usando el fuego para el manejo de la vegetación y la agricultura. No obstante, el uso del fuego en el paisaje conlleva impactos directos e indirectos en los ecosistemas y especialmente en los suelos, dejando así grabadas ciertas evidencias de su uso en la "memoria edáfica", siendo estos rasgos pirogénicos muy útiles en las investigaciones geoarqueológicas. Sin embargo, aún existen algunas dificultades en la identificación de rasgos pirogénicos en contextos geoarqueológicos, pues es común confundirlos con rasgos pedogénicos debido a la similitud de las señales. En la presente investigación se emplearon prácticas recientes como la quema prescrita para el manejo de bosques y la roza-tumba y quema para la agricultura, como modelos para entender los efectos del fuego en las propiedades de los suelos e identificar sus evidencias con diferentes técnicas analíticas para la posterior aplicación en la detección de paleo-quemas en los registros edáficos y la interpretación de los cambios producidos en el paisaje. En la identificación de rasgos pirogénicos orgánicos y minerales, se utilizó como técnica principal la micromorfología, tanto en suelos y paleosuelos, soportada además por análisis físico-químicos de los suelos, siendo estos útiles principalmente en contextos actuales. Por otra parte, la caraterizaciόn térmica de la materia orgánica de los suelos, se encontró como una herramienta valiosa para la detección de compuestos orgánicos altamente recalcitrantes, producidos durante la combustión tanto en eventos del pasado como del presente. Mientras que, el uso de indicadores magnéticos demostró ser una técnica ventajosa en la identificación de minerales pirogénicos fundamentalemente en registros paleopedológicos. Gracias a diferentes combinaciones de dichas técnicas de acuerdo a las características de cada sitio estudio, se logró la discriminación de señales de quema en secuencias pedológicas y edafo-sedimentarias. Asimismo, se encontró que los efectos del fuego en el suelo son diversos y que la magnitud de estos efectos (severidad de la quema en el suelo) va a depender de diferentes factores previos a la quema (características del suelo, de los combustibles y

del paisaje) y durante el evento mismo (características del fuego, condiciones atmosféricas y ejecución de la quema). Mientras que la preservación de los rasgos pirogénicos en los registros edáficos además, va a depender de las condiciones posteriores a la quema (clima, erosión, sedimentación, pedogénesis, diagénesis, biodegradación, actividades antrópicas y edad del evento). Por lo tanto, los efectos de la quema en los suelos y los rasgos pirogénicos derivados, poseen un tiempo de residencia que va estar definido por el contexto natural y cultural del paisaje.

Abstract

Fire has been a fundamental tool in human development for thousands of years, as it has been present in various practices, from heating and lighting to hunting and ceremonies. Humans have modified the landscape through anthropogenic burns, using fire for vegetation management and agriculture. However, the use of fire in the landscape has direct and indirect impacts on ecosystems and especially on soils, thus leaving certain evidence of its use in "soil memory," with these pyrogenic traits being very useful in geoarchaeological research. However, there are still some difficulties in identifying pyrogenic features in geoarchaeological contexts, as it is common to confuse them with pedogenic features due to the similarity of the signals. In the present research, recent practices such as prescribed burning for forest management and slash-and-burn agriculture were used as models to understand the effects of fire on soil properties and to identify its evidence using different analytical techniques for subsequent application in the detection of paleo-burns in soil records and the interpretation of landscape changes. In identifying organic and mineral pyrogenic features, micromorphology was used as the main technique in soils and paleosols, supported by physical-chemical analyses of soils, which were mainly useful in current contexts. On the other hand, thermal characterization of soil organic matter was a valuable tool for detecting highly recalcitrant organic compounds produced during combustion in past and present events. Meanwhile, using magnetic indicators proved to be an advantageous technique in identifying pyrogenic minerals, primarily in paleopedological records. Thanks to different combinations of these techniques according to the characteristics of each study site, the discrimination of burning signals in pedological and edaphic-sedimentary sequences was achieved. Likewise, it was found that the effects of fire on the soil are diverse and that the magnitude of these effects (severity of soil burning) will depend on different factors prior to burning (soil characteristics, fuel characteristics, and landscape) and during the event itself (fire characteristics, atmospheric conditions, and burning execution). Meanwhile, preserving pyrogenic features in soil records will also depend on conditions after burning (climate, erosion, sedimentation, pedogenesis, diagenesis, biodegradation, anthropogenic activities, and the age of the event). Therefore, the effects of burning on soils and the

derived pyrogenic features have a residence time that the natural and cultural context of the landscape defines.

1. Introducción

1.1. El uso del fuego por el humano en el paisaje

Las quemas antrópicas han moldeado el paisaje desde hace miles de años, debido a que los humanos han usado el fuego como una herramienta para el manejo de la vegetación, la limpieza de terrenos, la caza y la agricultura (Gowlett, 2016; Martin, 2016; Pyne, 2016; Santín y Doerr, 2016; Scott *et al*., 2016). Además, el humano ha empleado el fuego para otras actividades como iluminación, calentamiento, cocción de alimentos, ceremonias, entre otros (Alperson-Afil, 2012, Santín y Doerr, 2016; López-Martínez *et al*., 2020). Es por ello que el fuego es considerado como una herramienta fundamental en el desarrollo de la humanidad (Bowman *et al*., 2013; Gowlett, 2016). Sin embargo, el uso del fuego en el paisaje conlleva efectos directos en los ecosistemas (Ambrosia y Brass, 1988), particularmente, el uso tradicional del fuego puede tener impactos severos en los suelos, como en la práctica agrícola de roza-tumba y quema, donde los bosques son talados y seguidamente quemados, conduciendo a que el suelo superficial alcance altas temperaturas (Santín y Doerr, 2016).

En la época moderna el fuego es utilizado también en la quema prescrita, la cual es una quema controlada que se induce con diferentes objetivos como, el manejo de bosques, la reducción de combustibles, el control de plagas, la generación de pastos, fertilización, entre otros, procurando tener una baja severidad de la quema para evitar que el suelo mineral sea perturbado (Stacey, 2012; Vega et al., 2013; Scott et al., 2014). Además, hoy en día se continúan utilizando las quemas de pilas de combustibles con diversos propósitos (fogatas en campamentos, quema de desechos, quema de rastrojos de los cultivos, entre otros), causando estragos importantes en los suelos a escala local, debido a la quema durante varias horas de una gran cantidad de combustibles gruesos, provocando que la superficie alcance muy altas temperaturas (Busse *et al*., 2014). Todas estas prácticas con el fuego en algunas ocasiones se salen de control, intencionadamente o no, provocando incendios forestales de origen antrópico, siendo la causa más común de este tipo de eventos (CONAFOR, 2010). Asimismo, cada uno de este tipo de quemas poseen rangos de temperaturas probables y posibles, determinando así los efectos del fuego en las propiedades de los suelos (Fig. 1; Santín y Doerr, 2016).

1.2. Efectos del fuego en los suelos

El fuego influye directamente en las propiedades biológicas, físicas, químicas y mineralógicas de los sistemas edáficos (Fig. 1; Certini, 2005). La magnitud de los efectos de los incendios en los suelos (severidad de la quema) depende de las características del fuego (p. ej. temperatura máxima y duración del incendio), de la disponibilidad de oxígeno, de la profundidad del calentamiento, y de las características del suelo, como el contenido de humedad y de materia orgánica, la composición mineral y las propiedades térmicas (Neary *et al*., 1999; Ketterings *et al*., 2000; Neary *et al*., 2005; Bryan *et al*., 2005; Shakesby y Doerr, 2006; Santín *et al*., 2016; Badía *et al.,* 2017), así como también del tipo de uso del fuego, en el caso de quemas antrópicas, ya que ello define la extensión de la quema.

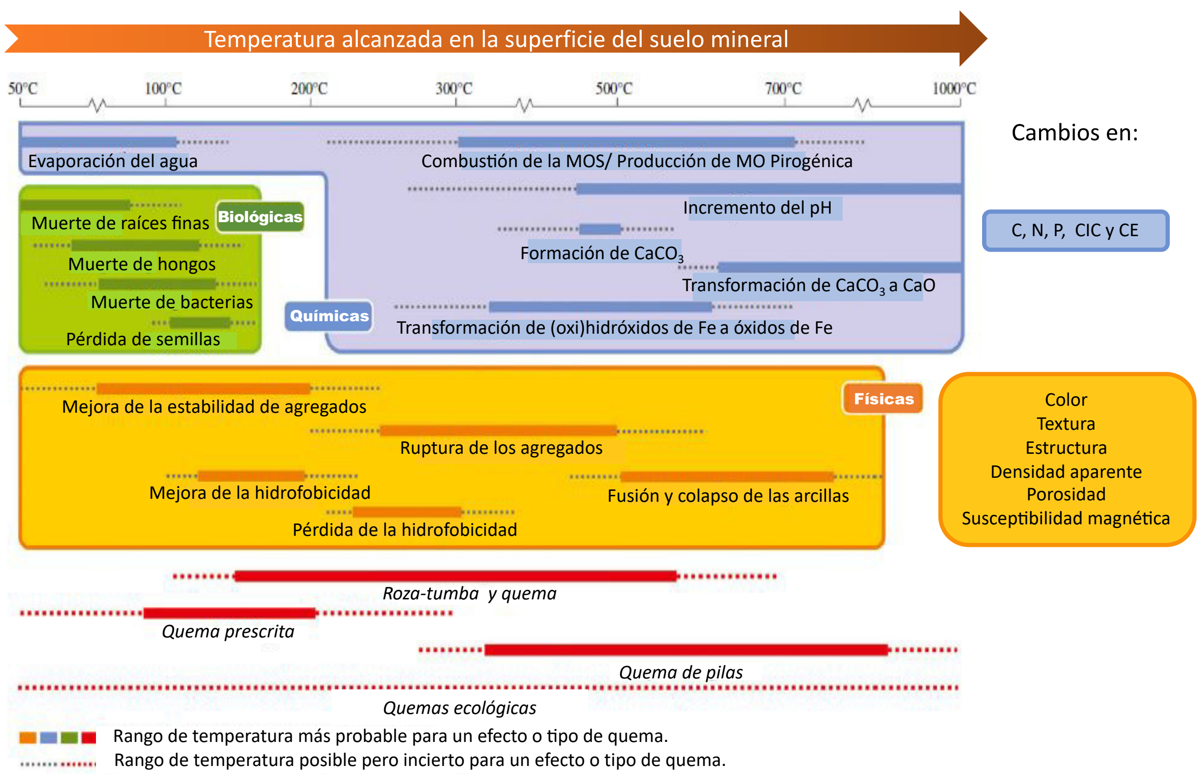

Figura 1. Efectos del fuego en las propiedades del suelo y rangos de temperaturas asociados a cada tipo de quema (Modificado de Santín y Doerr, 2016).

Los primeros efectos en el suelo son observados a temperaturas menores a los 100 °C y corresponden a los cambios en sus propiedades biológicas, las cuales involucran los materiales térmicamente más sensibles como, raíces finas, semillas, hongos y microrganismos (Neary *et al*., 2005). Consecuentemente, a temperaturas menores a los 200 °C empiezan a ser modificadas algunas propiedades físicas como la estabilidad de los agregados y la hidrofobicidad. A temperaturas por encima de los 200 °C, ciertas propiedades químicas son afectadas debido a la combustión de la materia orgánica y al incremento del pH del suelo, con la producción de carbón y ceniza. Asimismo, otras propiedades físicas del suelo como la estructura y la textura comienzan a transformarse debido a la ruptura de los agregados (>200 °C) y a la fusión y el colapso de las arcillas (>450 °C) (Neary *et al*., 1999; Santín y Doerr, 2016; Shakesby y Doerr, 2006).

El contenido de carbono orgánico total en el suelo varía de acuerdo con la severidad de la quema, ya que el consumo crítico del carbono orgánico comienza entre los 200 y los 250 ºC, su combustión completa finaliza a los 460 ºC y su pérdida total ocurre a temperaturas mayores a los 500 ºC (Giovannini *et al*., 1988; Terefe *et al*., 2008). Para el caso del contenido de nitrógeno total en el suelo, su comportamiento después de la quema no es claro, según la revisión de diferentes estudios (Alcañiz *et al*., 2018). En algunos estudios el nitrógeno total resultó invariable, mientras que en otros casos su contenido incrementó a temperaturas <200 ºC y en otros se redujo significativamente a los 500 ºC (Guinto *et al*., 2001; Arocena y Opio, 2003; Badía y Martí, 2003a; Úbeda *et al*., 2005; Afif y Oliveira, 2006).

Se ha planteado que solo los incendios moderados (250–500 °C) y severos (>500 °C) pueden generar transformaciones en los minerales del suelo (Ketterings *et al*., 2000). Sin embargo, otros autores han detectado cambios mineralógicos a temperaturas un poco más bajas (Mataix-Solera *et al*., 2011). Dichas transformaciones mineralógicas van a depender de la condición de humedad del suelo (Reynard-Callanan *et al*., 2010) y pueden variar de acuerdo con el tipo de suelo, debido a que las diferencias en las propiedades estructurales de los minerales derivan en la variación de su conductividad térmica y de su umbral de temperatura (Ngole-Jeme, 2019).

Otro de los efectos de la quema en los suelos es el aumento de la susceptibilidad magnética, debido a que la combustión de la materia orgánica produce gases como el monóxido de carbono que reducen los óxidos e hidróxidos de hierro a magnetita y posteriormente pueden oxidarse a maghemita cuando entra aire al suelo durante el enfriamiento del incendio (Le Borgne; 1955, 1960; Mullins, 1977). Posteriormente, Oldfield y Crowther (2007) demostraron que los incendios a temperaturas altas, en este caso a 650°C, producen un arreglo de minerales magnéticos con tamaños de grano característicos, lo cual permite diferenciarlos de minerales magnéticos de origen pedogénico o biogénico. El aumento máximo de la susceptibilidad por calentamiento habitualmente se logra entre los 600 – 900 °C, sin embargo, también se puede producir un aumento moderado de la susceptibilidad incluso con temperaturas mucho más bajas (< 200°C) (Oldfield et al., 1981; Crowther, 2003; Oldfield y Crowther; 2007). Por otra parte, el aumento de la susceptibilidad magnética en sitios arqueológicos no solo depende del aumento de la temperatura sino de otros factores como el contenido de óxidos de hierro en el suelo, el poder reductor de la combustión de la materia orgánica y la intensidad y tiempo de ocupación humana en el sitio (Tite y Mullins, 1971; Tite; 1972).

El cambio de color de los suelos después de la quema, es otra de las propiedades físicas que es modificada por el fuego y puede usarse como un indicador de la severidad de la quema en los suelos (Certini, 2005; Vega *et al*., 2013). El oscurecimiento inicial del color del suelo se asocia a la carbonización de la fracción orgánica (Ketterings y Bigham, 2000), mientras que el enrojecimiento de algunos suelos sometidos a incendios severos, se debe a la transformación de los óxidos de hierro y a la eliminación casi total de la materia orgánica (Ulery y Graham; 1993). Por otra parte, la presencia de partículas de ceniza blanca, constituidas principalmente de carbonato de calcio, pueden aclarar los colores del suelo (Ulery y Graham, 1993). El color del suelo resultante después de la quema va a depender de la duración de la exposición y de la temperatura máxima alcanzada en el incendio; por lo tanto, la medición del color puede representar diferentes combinaciones de ambos factores (Ketterings y Bigham, 2000).

1.3. Dificultades en la identificación de evidencias pirogénicas en suelos de contextos geoarqueológicos

La determinación del uso del fuego por el humano a lo largo de la historia es compleja, debido a las modificaciones tafonómicas que sufren los rasgos quemados en el transcurso del tiempo (Melson y Potts, 2002), pues muchas de las evidencias de la quema en el suelo son borradas, diluidas o solapadas por procesos naturales o antrópicos en el sitio. No obstante, algunos rasgos pirogénicos logran permanecer en los suelos por tiempos prolongados, constituyendo parte de la “memoria edáfica” y consecuentemente, pueden ser empleados en investigaciones sobre la historia del fuego en el paisaje (Holliday, 2004). Sin embargo, en los estudios geoarqueológicos es común confundir rasgos pirogénicos con rasgos pedogénicos debido a la similitud de sus señales (Kurgaeva *et al*., 2023).

Algunas de las dificultades a las que se enfrentan los investigadores de quemas en contextos geoarqueológicos corresponden a que las evidencias de algunos tipos de quemas antrópicas en los suelos pueden llegar a ser idénticas a las evidencias de quemas naturales (Marlon *et al*., 2013) o incluso algunos rasgos pirogénicos son muy similares a productos de la pedogénesis natural, como cuando se encuentran horizontes muy oscuros, los cuales pueden estar pigmentados con materia orgánica (MOS) muy humificada o con carbono pirogénico (PyC). Además, el PyC producido a bajas temperaturas posee propiedades que se solapan con las de la MOS no quemada (Knicker, 2023). En otros casos, la aparición de pigmentación roja en los suelos, puede deberse tanto a la conversión de minerales por calentamiento intenso o prolongado (Ketterings y Bigham, 2000), así como también a procesos pedogenéticos naturales en sitios tropicales. Otra de las señales en las que resulta difícil discriminar su origen son los máximos de susceptibilidad magnética, pues los mismos pueden estar asociados a minerales magnéticos pirogénicos, así como también a minerales magnéticos de origen biogénico o pedogénico (Oldfield y Crowther, 2007). Asimismo, la presencia de carbonatos en los registros pedológicos en algunas ocasiones puede generar duda con respecto a su origen, pues además de los carbonatos pedogénicos también existen carbonatos pirogénicos derivados de la quema de vegetación leñosa (Karkanas, 2021).

El problema aumenta si consideramos que en muchos sitios arqueológicos las capas de asentamientos humanos coinciden con paleosuelos donde los procesos antropogénicos y naturales están interconectados y separar ambas señales resulta un reto aún mayor (Kurgaeva *et al*., 2023). Además, en las investigaciones de quemas antiguas asociadas a paisajes kársticos las dificultades se incrementan aún más, con el hallazgo de evidencias de quema erosionadas y transportadas a depresiones formando parte de secuencias edafo-sedimentarias, donde ya los rasgos pirogénicos no se encuentran *in situ* y al mismo tiempo pueden ser afectados por las condiciones cálidas y húmedas de ambientes tropicales (Moreno-Roso *et al*., in press).

El estudio del uso del fuego por humanos antiguos y sus efectos en el paisaje, ha sido de gran relevancia en las investigaciones geoarqueológicas (Alperson-Afil, 2012). Sin embargo, aún existe la necesidad de encontrar metodologías integrales que permitan identificar de manera acertada las evidencias de quemas del pasado preservadas en registros pedológicos y edafo-sedimentarios. Para ello es necesario primero estudiar cuáles son los rasgos que resultan de quemas actuales en los suelos y los métodos usados para su reconocimiento. Luego, distinguir cuáles evidencias se logran conservar en paleosuelos de diferentes contextos y cuáles son los factores que influyen en su preservación en los registros edáficos.

1.4. Hipótesis

Así como las quemas antrópicas modernas ejercen un impacto directo en los suelos dejando asociados ciertos rasgos pirogénicos se espera que, de igual manera, las quemas del pasado afectaron al suelo, generaron una serie de indicadores del fuego y que algunos de ellos lograron preservarse en los registros pedológicos y edafo-sedimentarios, permitiendo de esta manera, reconstruir el uso del fuego en el sitio.

1.5. Objetivos

1.5.1. Objetivo general

Desarrollar una serie de indicadores de quemas antrópicas recientes y de paleoquemas en secuencias pedológicas y edafo-sedimentarias que permitan entender la historia del fuego y su efecto en el paisaje.

1.5.2. Objetivos específicos

- Identificar el impacto del fuego en el suelo y los rasgos pirogénicos asociados a quemas recientes.
- Detectar señales de quemas antiguas en contextos geoarqueológicos.
- Definir las condiciones que determinan la producción y preservación de rasgos pirogénicos en los suelos.

1.6. Estructura de la tesis y metodología empleada en la investigación

El cuerpo de la presente tesis doctoral está conformado por tres artículos científicos, donde se abordan evidencias de quemas en suelos de diferentes contextos, utilizando en primer lugar, quemas recientes como modelos para entender los efectos del fuego en los sistemas pedológicos y discriminar los rasgos pirogénicos asociados para luego detectarlos en paleo-quemas de contextos geoarqueológicos.

Para la identificación de rasgos pirogénicos orgánicos y minerales, se utilizó como técnica principal la micromorfología, tanto en suelos, paleosuelos y pedosedimentos, apoyada por análisis físico-químicos. En contextos de quemas actuales además se empleó morfometría para la semicuantificación de los rasgos de la quema en los suelos. Por otra parte, se caraterizó térmicamente la materia orgánica de los suelos, para la detección de compuestos orgánicos altamente termo-recalcitrantes, producidos durante la combustión tanto en eventos del pasado como del presente. También se usaron parámetros magnéticos para la identificación de minerales magnéticos pirogénicos fundamentalemente en registros paleopedológicos. Asimismo, algunos carbones fueron fechados por radiocarbono para contextualizar temporalmente los eventos de quema en algunos de los sitios estudiados. Cabe destacar, que las técnicas no fueron usadas de manera aislada, sino al contrario, para cada una de las investigaciones se empleó una metodología multi-proxy, usando diferentes combinaciones de dichos métodos de acuerdo al contexto, con el fin de definir los efectos del fuego en los suelos o identificar evidencias de quemas del pasado.

Finalmente, en las discusiones de la tesis se expone cuál ha sido el tiempo de permanencia a largo plazo de ciertas evidencias de quema en los diferentes sitios investigados y por otra parte, se indaga sobre cuáles son las condiciones que inciden en la preservación o pérdida de los rasgos pirogénicos antiguos en los registros edáficos de manera general y cómo estos factores definen el tiempo de residencia de dichos indicadores del fuego en los suelos.

2. Resultados

2.1. Soil burn severities evaluation using micromorphology and morphometry traits after a prescribed burn in a managed forest

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Soil Burn Severities Evaluation Using Micromorphology and Morphometry Traits After a Prescribed Burn in a Managed Forest

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Prescribed burn is a tool that must imply low soil burn severity (SBS) levels; however, a wide range of soil impacts have been demonstrated because of the influence of very variable factors. The effects on biological, physical, and chemical soil properties are well reported in numerous studies; nonetheless, there are still questions about the effect of prescribed burns on soils at the micro-scale. As a result, an analysis of the link between micromorphological features and SBS does not currently exist. Thus, the main aim of the present study is to perform a micro-scale evaluation for complementing the SBS visual examination after prescribed burning in a managed pine forest in western Mexico. Morphometry and micromorphology analyses of mineral soil revealed that at low SBS levels, only the soil structure in the first centimeter is affected by prescribed burns. While at high SBS, the prescribed burn affected the first 2 cm, showing soil structure disturbance, ash filling porous, and soil aggregates getting reddish. Therefore, immediate actions have to be made by land managers after applying prescribed burns before the first rain to prevent post-fire surface soil erosion, particularly in bare soil patches where the burned aggregates are more susceptible to rain splash and runoff.

Keywords: prescribed burn, fire, soil burn severity, micromorphology, morphometry

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INTRODUCTION

The impacts of prescribed burns on soils are spatially variable due to the high heterogeneity of the environmental conditions (Hubbert et al., 2006; Girona-García et al., 2019). Although prescribed burns imply the application of low-intensity fire (Fernandes et al., 2013), different intensities and severities have been reported (Alcañiz et al., 2018). Therefore, their effects on soil properties can be very variable depending on the fire and vegetation type, the previous soil conditions, and their correct execution (Scharenbroch et al., 2012; Badía et al., 2017; Alcañiz et al., 2018; Girona-García et al., 2019). Additionally, the sampling method is another factor that can also influence the variations of soil fire impacts, such as the time elapsed after the fire, the mixture of charred O and Ah horizons, and even the depth of soil sampling with a dilution effect (Armas-Herrera et al., 2016; Lucas-Borja et al., 2019; Pereira et al., 2023). The variability of all these factors for each intervened area can produce distinctive soil impacts, resulting in patches with different soil burn severity levels (Hubbert et al., 2006; Alcañiz et al., 2018).

The degree of soil burn severity determines the modification of biological, chemical, and physical soil properties (Santín and Doerr, 2016). The effect of heating on soil properties such as pH, total organic carbon (TOC), total nitrogen (TN), and total phosphorous (TP) have been extensively studied (Alcañiz et al., 2018; García-Oliva et al., 2018; Merino et al., 2019). It is accepted that pH values, TOC, and TP contents increase after a low-severity prescribed burn (Ulery et al., 1993; Arocena and Opio, 2003; Úbeda et al., 2005; Afif and Oliveira, 2006; Scharenbroch et al., 2012), however, there is an unclear pattern in the case of TN (Alcañiz et al., 2018). After the fire, changes in soil physical properties such as aggregates stability, bulk density, and moisture have been described (Neary et al., 1999; Debano, 2000; Mataix-Solera et al., 2011; Badía et al., 2017). Some authors reported a decrease in soil structure stability because high temperatures disrupted aggregates cement, generating cracks and the disaggregation of soil peds (Badía and Martí, 2003a; Arocena and Opio, 2003; Chief et al., 2012) related to TOC losses and changes in clays or Fe contents (Mataix-Solera and Doerr, 2004; Mataix-Solera et al., 2011). Regarding bulk density, there are also controversial results because after a prescribed burn, it can increase (Hubbert et al., 2006), decrease (Chief et al., 2012), or remain unchangeable (Phillips et al., 2000). These discrepancies are likely due to the different soil burn severity (SBS). Likewise, soil moisture behavior can vary according to the soil moisture conditions and the prescribed burn type (Girona-García et al., 2019). Even depending on the previous soil moisture conditions, this property can protect the soil against the effects of fire (Badía et al., 2017). Soil moisture can have insignificant changes following a prescribed fire (Iverson and Hutchinson, 2002), and under laboratory conditions, soil moisture content can decrease dramatically in the first centimeters of soil depth (Badía et al., 2017).

For evaluating the impacts of burn areas, a classification index has been proposed to estimate the SBS with a five levels scale based on soil organic layer characteristics and mineral soil surface morphology (Ryan and Noste, 1985; Vega et al., 2013). This index is closely related to soil physico-chemical changes from unburned to high burn severity (Vega et al., 2013; Merino et al., 2018). For prescribed burns, this tool must imply low SBS levels (Scharenbroch et al., 2012) corresponding to levels without visible surface soil impact but with charred forest floor (Vega et al., 2013). Although the important contribution of the SBS index, there are still questions about the changes at micro-scale that are not visible to the naked eye, underestimating the fire effect on the soil. Micromorphology is a valuable technique to detect the combustion features (e.g., charcoal, charred plant material, ashes, and reddened aggregates) in soils and sediments, commonly used in archaeological contexts (Alperson-Afil, 2012; Berna et al., 2012; Mallol et al., 2017), making possible to interpret the fire history in a specific place. In the case of prescribed burns, micromorphology has already been used in soils of Australia, United States, and Spain (Greene et al., 1990; Phillips et al., 2000; Badía et al., 2020). Particularly, Badía et al. (2020) observed the formation of coatings of fine sand-size particles mixed with charcoal fragments present in the soil surface and infill pores. However, no studies still associate the micromorphological characteristics of burn soils with different levels of SBS.

In this study, we applied micromorphological and morphometric analyses to complement the information from the field visual examination and soil physico-chemical properties changes after a prescribed burn where different SBS levels occurred. Micromorphology and morphometry are novelty analyses that support the interpretations of the level of affection caused by the fire that can help in the future management of the forest and the understanding of post-fire soil processes.

MATERIALS AND METHODS

Study Area

The study was conducted in a managed pine forest in Ahuacapán Ejido (19° 36′–19° 41′ N and 104° 16′–104° 21′ W) of Autlán de Navarro, Jalisco, Mexico (**Figure 1**). This area is located within the upper zone of the Sierra de Manantlán Biosphere Reserve, at 1,900 m a.s.l., where the climate is temperate sub-humid Ca (w2) (w) (e) (g) (Martínez et al., 1991). The mean annual temperature, precipitation, and humidity, from 2011 to 2020, are 15.7°C ± 0.17°C, 1,771 ± 173 mm, and 80.7% ± 20.8%, respectively (Zuloaga-Aguilar, 2021). The soils are classified as Distric Cambisols, developed on Tertiary (Paleocene-Oligocene) intermediate extrusive igneous rocks (Jardel and Moreno, 2000). The forest vegetation is dominated by *Pinus douglasiana* under silvicultural practices, together with *Arbutus xalapensis*, *Fraxinus uhdei*, and *Carpinus tropicalis* in the underground (Jardel and Moreno, 2000). Because of human pressure and climatic conditions, this forest is considered a fire-prone ecosystem, subjected to moderate and low-intensity fires every 4.2–7.3 years (Rubio, 2007; Cerano-Paredes et al., 2015). Therefore, previous fires might mask part of the results of the present analysis.

Prescribed Burn Event Characteristics

The prescribed burning event was carried out on 21 March 2017, to reduce hazardous fuels and improve pine forest regeneration. Forests firefighters of the National Forestry Commission (CONAFOR), in conjunction with a local forest brigade of the Ahuacapán Ejido, conducted the burning supervised by fire management specialists from the University of Guadalajara (DERN-IMECBIO) and from the Sierra de Manantlán Biosphere Reserve.

The size of the burned area was 7.3 ha (**Figure 1**). The weather conditions were a relative humidity of 38%–76%, a temperature of 19°C–22°C, and a monthly accumulated precipitation of 3.81 mm from 1 to 21 March. The prescribed burning had a duration of 10 h, with the following observed characteristics: a flame height of 1.01–3.27 m; a rate of spread between 1.4–2.5 m min^{-1}; flame temperature between 439°C and 593°C; and total vertical consumption of 9 cm of fuel (81% of the pre-burn material, see **Figure 2**) (Pérez-Salicrup, 2018).

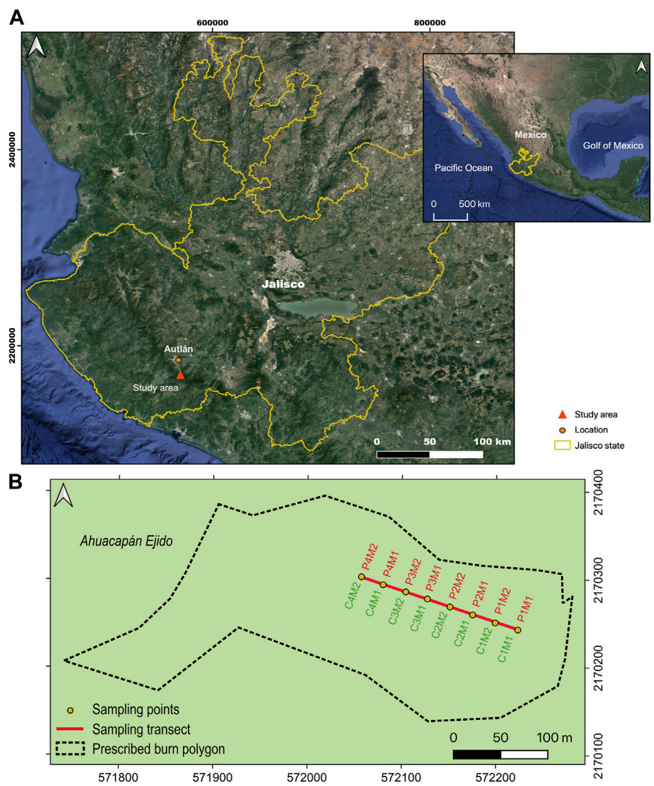

FIGURE 1 | Study area **(A)** location in the SW of Jalisco state, Mexico. **(B)** The prescribed burn area (7.3 ha) and the sampling design. The sampling was made in the same transect before and after the prescribed burn. Green names correspond to the unburned samples and red names to the burned samples.

Soil Sampling Design and Soil Burn Severity (SBS) Assessment

A transect randomly oriented from SE to NW 175 m long (**Figure 1B**) was established within the burned area. Before and after the prescribed burn, a sampling area of 1 m^2 every 25 m was delimited. After the fire event, on 22 March 2017, in the center of each square, the soil burn severity (SBS) was evaluated by a visual estimation using a 30 cm × 30 cm sampling metallic frame, following the procedure described by Ryan and Noste. (1985) modified by Vega et al. (2013). This SBS index considered the condition of the remaining soil organic layer, whether it was unburned, partially or wholly charred, or if it was completely consumed remaining only ash. Also, this post-fire assessment considered the visual characteristics of the mineral soil: if this was undisturbed, if the soil structure and the soil organic matter (SOM) were affected, and if there were soil color changes. Then, with these descriptions, a value from 0 to 5 was assigned for defining the SBS level in each sampling point, according to Vega et al. (2013) classification.

Before and after the fire, three types of samples were collected inside the 1 m^2 area from the first 5 cm of the mineral soil at each sampling point: 1) five samples integrated into one bulk sample for chemical analyses, stored in a plastic bag, 2) one unaltered sample was taken with a 118.8 cm^3 cylindrical steel core (5 cm depth), which was used for bulk density and moisture determinations, and 3) one unaltered sample was taken, from the organic layer and the upper 5 cm of the mineral soil, for micromorphological and morphometric analyses using cylindrical PVC cores.

Soil Analysis

Soil Physical Properties

The color measurements were triplicated with a colorimeter (COLORLITE Sph 870) considering the CIELAB color system (CIE, 1986). In this system, the color is represented by three scalar parameters: L*, luminosity, with values from 0 to 100 (from black to white, respectively); a*, related to changes from redness (a* > 0)

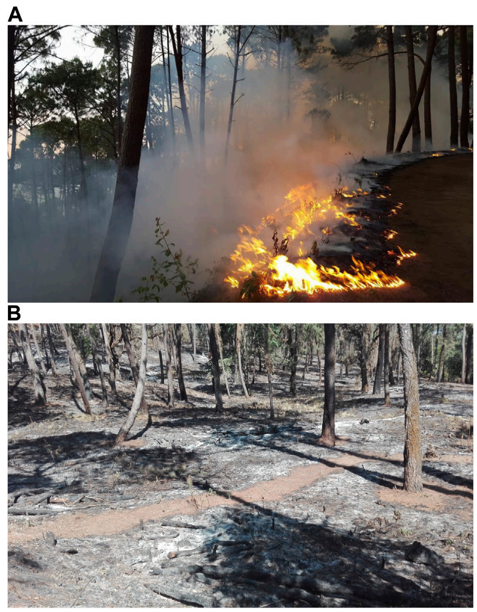

FIGURE 2 | (A) The prescribed burn event. **(B)** Features of the burned site the next day. Photos by Faviola Castillo.

to greenness (a* < 0); and b*, related to transitions from yellowness (b* > 0) to blueness (b* < 0) (Cancelo-González et al., 2014). Colors were obtained from sieved (2 mm) and homogenized samples.

Bulk density and moisture were evaluated using the cylinder method (Flores-Delgadillo and Alcalá-Martínez, 2010). Cores filled with soil were weighed fresh and dried at 105°C for 48 h until they reached a constant weight. The mass difference was used for moisture calculation, and the known volume's dry mass was used to calculate the bulk density.

Chemical Properties

Soil pH was measured in deionized water (1:10 W:V ratio) with a portable pH meter (Corning) in fresh samples. The total organic carbon (TOC), total nitrogen (TN), and total phosphorous (TP) were obtained after dry samples to 105°C until constant weight. The TOC was determined by combustion and coulometric detection (Huffman, 1977) in a UIC CM150 carbon analyzer. The TN and TP were determined in dry samples after acid digestion in H_2SO_4, H_2O_2, K_2SO_4, and $CuSO_4$ mixture at 360°C for 4 h. The TN was determined by the micro-Kjeldahl method (Bremner, 1996) and TP by the colorimetric method with molybdate after ascorbic acid reduction (Murphy and Riley, 1962); both elements were quantified by colorimetry in Seal AA3 segmented continue flow analyzer.

Morphometric and Micromorphological Analyses

The unaltered soil samples were previously dried and then impregnated with polyester resin. Thin sections (30 μm) were prepared at the Institute of Geology (UNAM). Morphometric analysis was done on high-resolution scanned images (2,400 dpi and 24 bits) of the thin sections using an EPSON scanner (Perfection V700 Photo). The Image-Pro Plus 7.0 software was used for processing the images. We selected a representative area (6 cm^2) of each thin section for developing the analysis. This analysis visually identified some burn features classified, such as charred elements, reddened zones, and ashes. The unburnt soil matrix and the porous space were also identified. The software separated and grouped the elements into five classes of different colors. Finally, we obtained a reclassified image, from which we calculated the proportion of each group per area.

The micromorphological analysis was made using a petrographic microscope (OLYMPUS). The analysis focused on identifying combustion features in thin sections such as charcoal, ashes, burned shells, charred aggregates, and reddened aggregates, according to Nicosia and Stoops. (2017) and Stoops et al. (2018).

Statistical Analysis

A correlation analysis (significance of $p \leq 0.05$) was performed among physical, chemical, and morphometric variables to avoid redundancy in the principal component analysis (PCA). The PCA was done to explain the changes due to the fire effect considering samples before and after the prescribed burn. The selection of the variables for the PCA considered the highest significance among them, demonstrated by their highest correlation. A JMP trial software was used for statistical analyses (JMP Statistical Discovery LLC, Cary, NC, United States).

RESULTS

Soil Burn Severity Levels Recorded After the Prescribed Burn

The prescribed burn event in the Ahuacapán Ejido (**Figure 1**) left a heterogeneous mosaic of areas with different SBS (**Figure 2**). Although most of the area was affected by low SBS (levels 2 and 1), high SBS levels (4 and 5) were only found in smaller areas (only in two sampling sites of eight, **Table 1**; **Figures 3C, D**). In level 1, the organic layer was partially burned; in the case of level 2, the Oa layer was completely charred, and gray ash was present. In these low SBS, the temperature did not affect the mineral soil and remained undisturbed (**Figures 3A, B**). On the contrary, in the highest SBS areas, the organic layer was entirely consumed (levels 4 and 5). In SBS 4 level, high temperatures also affected the uppermost mineral soil horizon in the 0–2 upper cm, showed a slightly reddish color, lack of fine roots, and degraded structure. Besides, in SBS 4, a thick layer of white ash covered the mineral soil; while in SBS 5 most of the surface soil was bare, with black and reddish colors (**Figures 3C, D**).

TABLE 1 | Visual description of the soil burn severity (SBS) levels found after the prescribed burn according to Vega et al. (2013).

SBS Level		Sampling sites	Visual characteristics
Low	1	P3M1 P4M4	The organic layer is partially intact and there is charred material. The forest floor can be distinguishable
	2	P1M1 P1M4 P2M1 P4M1	The organic layer was totally charred/Grey ash, and charcoal is covering the soil. The mineral soil is undisturbed
High	4	P2M4	The organic layer was completely consumed, and a thick layer of white ash is covering the soil. The uppermost mineral soil horizon (0–2 cm) is lighter and, without fine roots and lack of structure
	5	P3M4	The organic layer was completely consumed. The soil is partially covered by charred vegetal material and gray ash. The uppermost mineral soil horizon (0–2 cm) is dark and partially bare

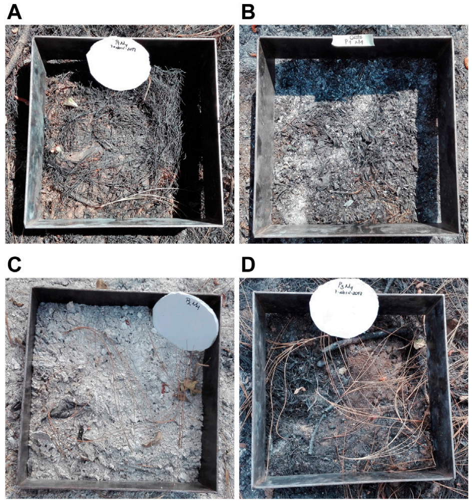

FIGURE 3 | Examples of the different levels of SBS after the prescribed burn in Ahuacapán Ejido: **(A)** low SBS (level 1), sample point P4M4; **(B)** low SBS (level 2), sample point P1M1; **(C)** high SBS (level 4), sample point P2M4; **(D)** high SBS (level 5), sample point P3M4. Photos by Faviola Castillo. The sampling metallic frames are 30 cm × 30 cm.

Changes in Physical and Chemical Soil Properties After the Prescribed Burn

Soil color measurements and mean moisture values for samples collected in the uppermost 5 cm showed changes after the prescribed burn (**Figure 4**). The mean values of the color parameters (L*, a*, and b*) decreased after soil burning, no matter the severity level. The reduction of luminosity (L*) mean values evidenced a soil darkening after the burn (**Figure 4A**). The decrease in the mean value of the a* and b* parameters showed fewer reddish and yellowish colors than the unburned condition (**Figures 4B, C**, respectively). Regarding soil moisture, this property tended to decrease slightly after the fire (**Figure 4D**). On the other hand, the soil bulk density increased 21.4% in the burned soils affected by low SBS and 22.6% by high SBS (**Figure 4E**).

Concerning the chemical soil properties, the pH values slightly increased after burning, especially in the high SBS (**Figure 5A**). The total organic carbon (TOC), no clear trend could be distinguished; it was reduced in soils affected by low SBS and increased in high SBS (**Figure 5B**). The TN concentrations did not show evident changes either (**Figure 5C**). Different trends in C/N ratios were evident because this ratio decreased in the low SBS. However, remarkable increases were found in the high SBS (**Figure 5D**). The TP values increased from unburned to burned condition 0.7 mg g^{-1} (**Figure 5E**).

Morphometric Analysis in Soils Affected by Different SBS

Images from thin sections with the organic layer and the upper 5 cm mineral soil from unburned and burned samples were morphometrically analyzed (**Table 2**; **Figure 6**). As logical, the lowest percentage of charred features was found in soils unaffected by fire (**Figure 6A**). All the scanned thin sections from the burn samples exhibited a darker layer on top (**Figure 6**). Samples with SBS level 1 showed the lowest number of unburned elements (e.g., aggregates, seeds, and plant tissues), coinciding with the highest porosity (46.3%, **Table 2**; **Figure 6B**) and followed by samples from SBS level 2 (37.5%, **Figure 6D**); the lowest porosity was found in the soil with SBS level 5 (14.5%). On the other hand, the morphometric analysis demonstrated that the highest number of elements with evidence of burning (e.g., charred and reddened aggregates, burned plant remains, and charcoal) was related to level 5 of the SBS index, reaching 50% of the considered area (**Figure 6E**; **Table 2**). Although level 4 showed fewer percentages of burning elements, only here mineral ash was detected (**Figure 6E**; **Table 2**).

In general, we identified a loss of structure and a reduction of the number of unburned elements and porosity with the increasing SBS. Additionally, ashes percentages and reddened aggregates were more significant in the highest SBS levels (4 and 5, respectively, **Table 2**). The morphometric data showed that the prescribed burn affected the soil organic layer and the first centimeter of the mineral soil for low

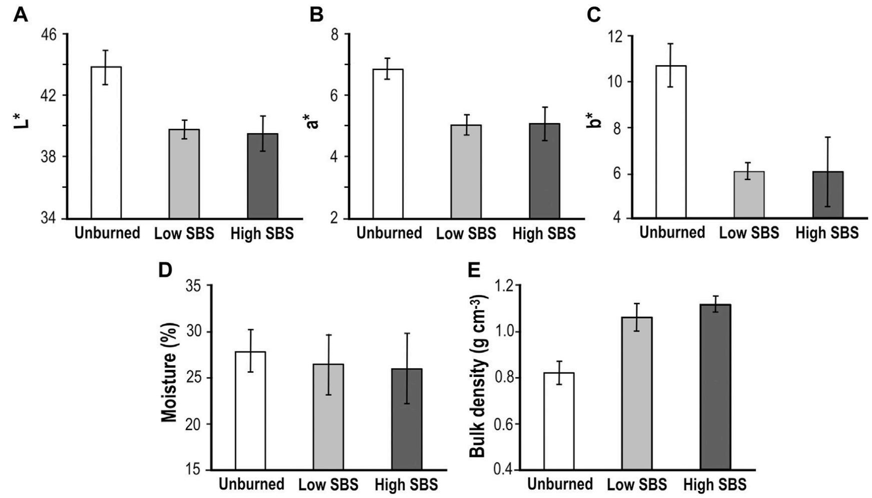

FIGURE 4 | Mean values and standard errors of physical properties of the soil samples collected from uppermost soil layer, before (unburned) and after the prescribed burn (low and high SBS). Low SBS corresponds to levels 1 and 2 (n = 6), and high SBS to levels 4 and 5 (n = 2). **(A)** L*; **(B)** a*; **(C)** b*; **(D)** Moisture; **(E)** Bulk density.

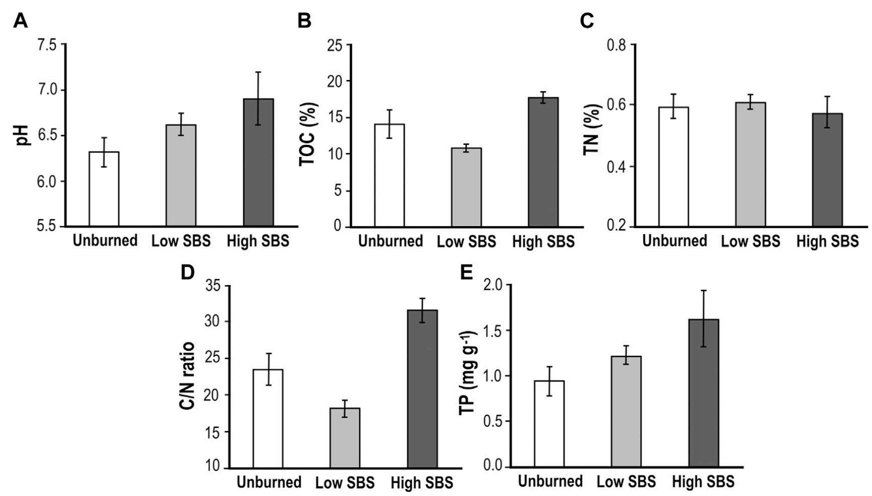

FIGURE 5 | Mean values and standard errors of chemical properties of the soil samples collected from uppermost soil layer, before (unburned) and after the prescribed burn (low and high SBS). Low SBS correspond to levels 1 and 2 (n = 6), and high SBS to the levels 4 and 5 (n = 2). **(A)** pH; **(B)** TOC; **(C)** TN; **(D)** C/N ratio; **(E)** TP.

SBS levels (**Figures 6B, C**) and the first 2 cm for high SBS levels (**Figures 6D, E**). The main proportion of burned remains corresponded to charred elements from the organic layer and the upper Ah horizon (**Figure 6**). It is important to mention that this examination might be including burning residues from previous fire events preserved in the soil. However, this previous evidence was discriminated by micromorphology analysis.

TABLE 2 | Soil morphometry results for the unburned and different SBS levels samples, showing the percentages related to the unburned and burned elements in a representative area (6 cm^2) of each thin section.

Classes	SBS level	Charred elements (%)	Reddened elements (%)	Ashes (%)	Total[a] (%)	Unburned elements (%)	Air and porous (%)
Unburned	0	4.2	0.03	—	4.2	78.2	17.6
Low SBS	1	19.7	7.8	—	27.6	26.0	46.3
	2	10.7	4.3	—	15.0	47.3	37.5
High SBS	4	10.3	3.4	15.0	28.7	48.7	22.5
	5	26.4	23.6	—	50.0	35.4	14.5

The data correspond to the soil organic layer and the upper 5 cm of the mineral soil.
[a]Elements with evidence of burning.

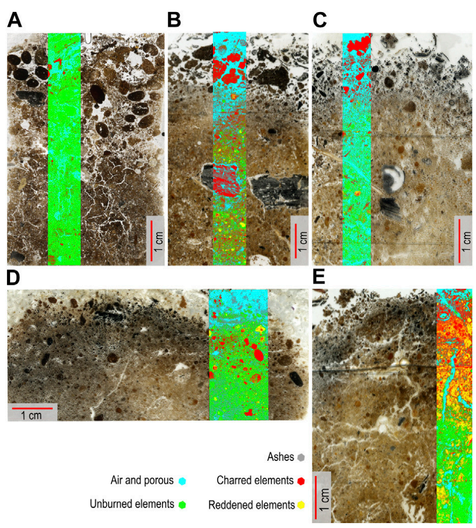

FIGURE 6 | Soil thin sections from the soil organic layer and the upper 5 cm of the mineral soil with the selected area used for the morphometry analysis: **(A)** Unburned topsoil with brown aggregates and fresh plant remains; **(B)** Sample at low SBS 1, burned aggregates at the surface soil; **(C)** Sample at low SBS 2, completely charred topsoil; **(D)** Sample at high SBS 4, ashes covering the burned soil. **(E)** Sample at high SBS 5, absent organic layer and the mineral soil with charred and reddened aggregates.

Soil Micromorphological Changes Due to the Prescribed Burn

The following descriptions will relate to the main micromorphological characteristics of unburned and burned samples from the organic layer, the top 5 cm of the mineral soil, and the burned features associated with each SBS level.

In the organic layer of unburned samples, fresh plant and animal residues, such as wood fragments (**Figure 7A**), seeds (**Figure 7B**), and shells (**Figure 7C**), were frequent and could be distinguished. The mineral topsoil showed an organic soil structure (sub-rounded aggregates pigmented by organic matter) (**Figure 7B**). Although these thin sections belong to unburned soils, a few rounded charcoal fragments were identified, possibly from previous fire events. A zoogenic structure (dark rounded peds) integrated by coprolites was also common (**Figure 7D**). Brown subangular aggregates were frequent from a depth of 3 cm and onward (**Figure 7C**).

At this microscopic scale, samples from low SBS level 1 areas showed an organic layer with partially charred plant tissues and some burned vegetal remains, such as charred wood, roots, and spikes. The mineral soil exhibited an organic structure, where some aggregates get darker after burning in all samples affected by this low SBS level (**Figures 8A–D**).

In the thin sections that showed a low SBS level 2, the prescribed burning heat induced a color change in the first centimeters of the soil, commonly covered by a black organic layer of 1 cm thick (**Figure 6C**). This layer comprised charcoal fragments from the charred organic layer remains, such as seeds, leaves, needles, stems, roots, and spikes in all samples (**Figures 8E–H**). These charred organic materials were frequently complete and preserved their cellular structure (**Figure 8F**). The surface soil aggregates for SBS level 2 was charred, fractured, and partially or totally disaggregated; a loss in the soil structure was also identified (**Figures 8G, H**, **9B–D**).

The organic materials were reduced to ash in the samples showing SBS level 4, (gray material in **Figure 6D**, yellowish material associated with charcoal in **Figures 9B, C** and small shiny crystals in **Figure 9D**). Some ash particles fill the pores of the surface soil (**Figures 6E**, **9C, D**). At this level, the combustion process of the organic layer was completed. In the mineral soil, the organic matter in aggregates, fine roots, and seeds were charred or turned to ash; rounded reddened aggregates appeared (**Figure 9A**); the porosity decreased; and the surface soil lost its structure (**Figure 6A**). The organic layer was absent in the SBS level 5, while the soil organic matter was charred in the first centimeter (black aggregates) (**Figure 6E**, **9E–H**).

Principal Components Analysis (PCA) of the Unburned and Burned Soils Data

In the PCA model, the first two principal components (PC) together explained 63% of the variance in the data (**Figure 10A**). The *L and pH are the variables that explain the most variance in PC1, while TOC and TN are in PC 2 (**Figure 10B**). On PC1, unburned samples are far from burned samples, mainly from those at SBS level 5 (**Figure 10A**). In contrast, on PC2 is possible to identify the overlaying by SBS level; in the center of the plot, the

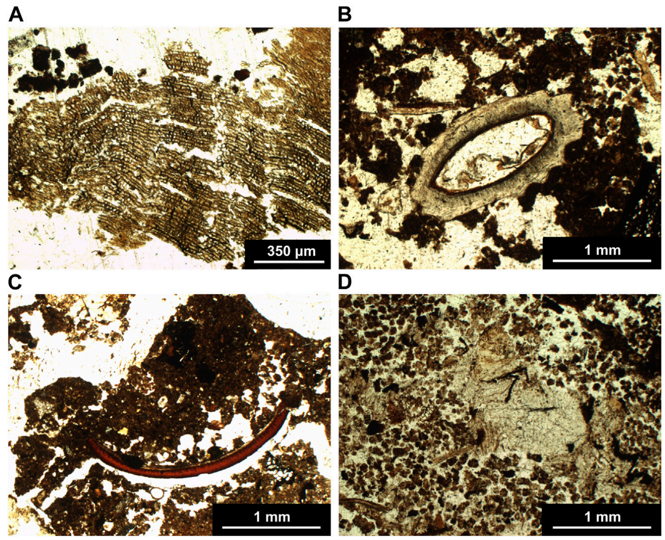

FIGURE 7 | Micromorphology characteristics from the unburned organic layer and unburned mineral soil: **(A)** fresh wood; **(B)** seed into the organic soil structure; **(C)** fresh shell with subangular soil aggregates; **(D)** rounded coprolites and vegetal remains.

unburned samples are together to SBS level 1. The SBS 2 samples are in lower values related to an increment of TN concentration and bulk density (**Figure 10**), while SBS levels 4 and 5 group are in higher values related to the increment of TOC concentration and reddened elements (**Figure 10**).

DISCUSSION

Changes in Soil Physical and Chemical Properties and Their Relationship With Micro-Scale Analyses

The effect of fire on soil physical-chemical properties has been described in several studies. Soil organic layer amount and composition can be affected (Nave et al., 2011; Merino et al., 2015; Santín et al., 2016). With respect to mineral soil, important changes in morphological, physical, and chemical properties can happen (Neary et al., 1999; Mataix-Solera et al., 2011), particularly in the uppermost 5 cm, where the highest temperature is reached (DeBano et al., 1979; Neary et al., 1999; Mataix-Solera et al., 2011; Badía et al., 2017). All these perturbations depend on the heating and are reflected as SBS levels. In the case of low-intensity prescribed burns, the heating caused minimal adverse changes in mineral soils (Debano, 2000; Mataix-Solera et al., 2011). The present study's PCA analysis separates the unburned from the burned samples by burn severity (**Figure 10A**), which agrees with the findings of Vega et al. (2013). The burned samples generally showed a darker color (L* value decrease), higher bulk density, higher pH values, and a higher percentage of charred and reddened elements than the unburned samples. Mainly, these properties explained 63% of the variance in the PCA analysis (**Figure 10A**). In addition, we observed modifications in other soil properties, such as moisture, TOC, TN, and TP.

Changes in the mean values of the chromatic parameters (L*, a*, and b*) indicate a darkening and a decrease in the redness and yellowness colors in the burned bulk samples (**Figure 4**). These results coincide with those obtained by Badía and Martí (2003a), where both value and chroma decrease as temperature increases, suggesting a darkening of the soil color of the charred samples. On the contrary, in the experiment conducted by Cancelo-González et al. (2014), the color parameters increased with the temperature rise in soils with different moisture contents (0%, 25%, and 50%). On the one hand, our unburned samples showed a mean value of soil moisture around 27%, and after the prescribed burn, a slight reduction of moisture was detected due to the water loss by vaporization in the uppermost 5 cm (Badía et al., 2017). On the other hand, Cancelo-González et al. (2014) experiment was done in soils derived from granitic rocks, whose mineralogy differs from that of our study (intermediate extrusive igneous rocks). Another difference was that we evaluated the color in sieved and homogenized samples, while Cancelo-González et al. (2014) measured the post-fire color on the undisturbed surface, which proved to be the best way for the evaluation. Nevertheless, the decrease in the L* parameter coincided with the morphometric and micromorphological

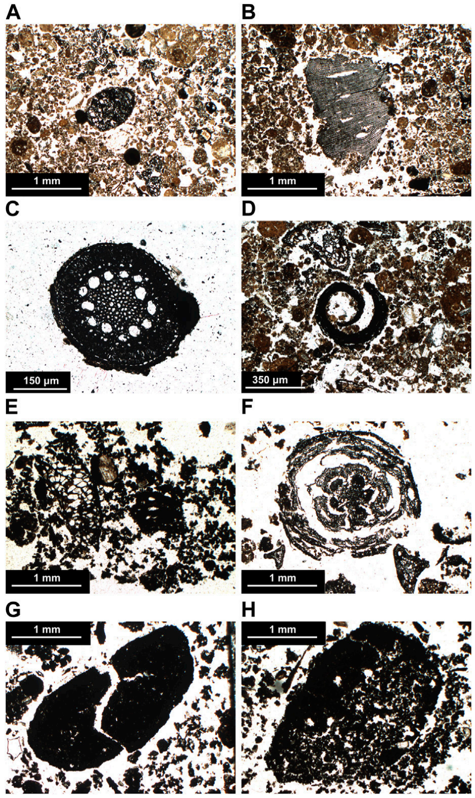

FIGURE 8 | Micromorphological combustion features of burned soils at low SBS levels 1 and 2: **(A)** charred aggregates and charcoal mixed with no burned aggregates, SBS 1; **(B)** charred wood, SBS 1; **(C)** charred root, SBS 1; **(D)** charred spike and needles in soil organic matter, SBS 1; **(E)** charred topsoil and charcoal, SBS 2; **(F)** charred pine stem, SBS 2; **(G)** charred and fractured aggregate, SBS 2; **(H)** charred partially disintegrated aggregate and soil structure disaggregation by fire, SBS 2.

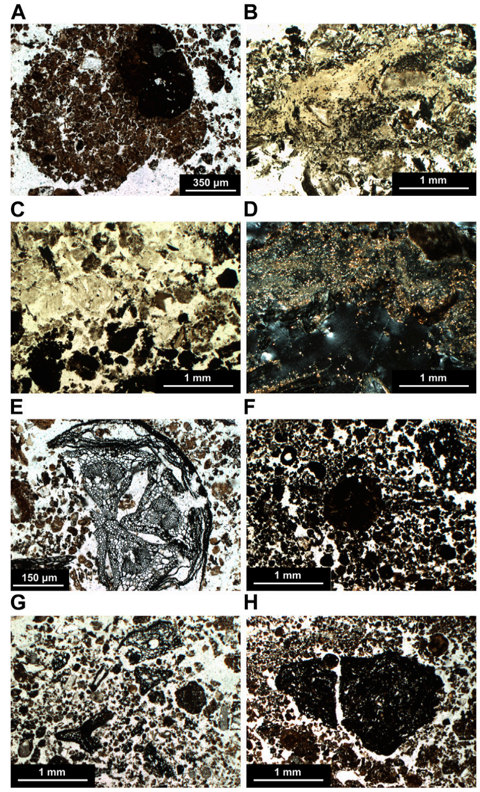

FIGURE 9 | Micromorphological combustion features of burned soils at high SBS levels 4 and 5; **(A)** reddened and rounded aggregate, SBS 4; **(B,C)** ashes in PPL, SBS 4; **(D)** ashes in XPL, SBS 4. PPL and XPL refer to plane and cross polarized light, respectively; **(E)** charred needles with its cellular structure well preserved, SBS 5; **(F,G)** charred aggregates and disaggregated soil structure, SBS 5; **(H)** charred and cracked aggregate, SBS 5.

analyses of the burn soils, where a dark black layer on the topsoils was identified. The darker color measured on burn samples with the colorimetric method corresponded to the abundant charred elements from the organic layer and the upper Ah horizon. Ketterings and Bigham. (2000) showed that soil became darker after fires at low temperatures (<250°C) of short duration because charred organic materials are dominant in the soil. Also, Cancelo-González et al. (2014) showed that organic matter content, temperature, and fire duration affected the color of burn soils. Concerning the reddened elements identified by micro-scale analyses of the samples with high SBS (**Figure 9A**), the colorimetric measurements did not detect them because this reddening was punctual, and the colorimeter performed an average of soil bulk samples color.

The observed increase of bulk density with heating (**Figure 5**) coincides with several studies where prescribed burn has been applied, independently of the kind of vegetation, brushes (Hubbert et al., 2006) or oak forest (Phillips et al., 2000), and for different soils heated under laboratory conditions (Badía and Martí, 2003a). Morphometric and micromorphological results showed the collapse of soil aggregates and the ash presence into the voids (**Figures 9G, H**), which can be other reasons to elevate the bulk density in the Ahuacapán Ejido. Likewise, Badía and Martí. (2003a) also found a moderate diminution of aggregate stability at 250°C, and Agbeshie et al. (2022) exhibited the breaking of organo-mineral aggregates and the clogging of porous by the ash-like causes of the bulk density increase. Moreover, this increase would indicate soil organic matter composition changes affecting the soil structure. Different

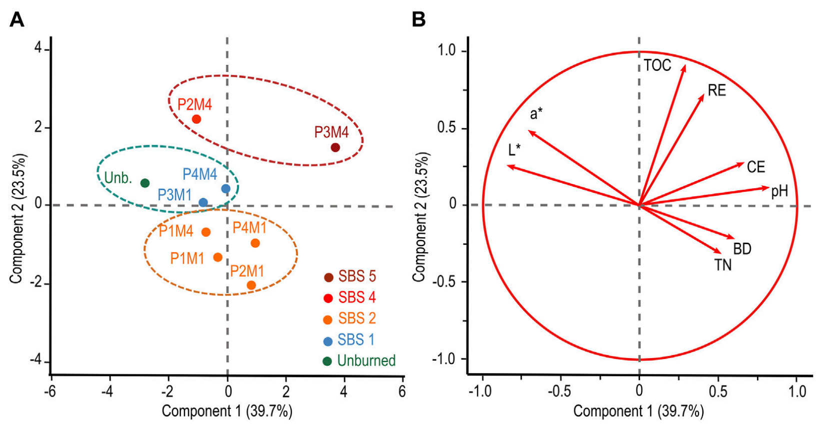

FIGURE 10 | (A) Principal components analysis for the unburned (average) and the burned samples before and after the prescribed burn, respectively; the soil burn severity level of the samples are represented in different colors. **(B)** The right plot showed the correlation between soil variables, considered for the analysis, and the principal components. TOC, total organic carbon; RE, reddened elements; CE, charred elements; BD, bulk density; TN, total nitrogen. L*: luminosity, a*: redness to greenness.

studies have revealed carbohydrate decreases with heating, implying lower aggregate stability (Gregorich et al., 1996; Kavdir et al., 2005; Merino et al., 2018). Another process involved in structure stability is the loss of binders, such as fine roots, hyphae, and microorganisms (Mataix-Solera et al., 2011). Additionally, decreases in biological properties in the soil surface after controlled burn have been reported both in the lab (Badía and Martí, 2003b) and in the field (Armas-Herrera et al., 2018; Girona-García et al., 2018; Alfaro-Leranoz et al., 2023).

We observed a decrease in TOC in the low SBS samples but an increase in the soils with a high-level SBS (**Figure 5**). The critical consumption of organic carbon starts between 200oC and 250°C and is completed approximately at 460°C (Giovannini et al., 1988; Vega et al., 2013); however, when the temperature is higher than 500°C, a total loss of organic matter occurs (Terefe et al., 2008). Likewise, Badía and Martí. (2003a) found a coefficient of correlation of R = −0.84 ($p <$ 0.01) between the SOM and heat, due to a significant decrease of the organic matter with temperature increase at 250°C and almost the completed consumption at 500°C. Therefore, no conclusive trend could be distinguished with the TOC, probably because of mixed effects: the unfinished combustion process of the organic matter and the integration of charred materials into the first centimeter of the mineral soil (Soto and Díaz-Fierros, 1993; Úbeda et al., 2005; Afif and Oliveira, 2006; Scharenbroch et al., 2012). Thus, it is possible that the light increases in TOC in the area showing high SBS were due to the presence of charcoal, as the high C/N ratios suggest it. This is supported by the important percentage of charred organic fragments integrated into the mineral topsoil detected in thin sections from the high SBS (**Figures 6D, E**).

Regarding another chemical property, the slight rise in pH registered after the prescribed burn is described by the whole oxidation of organic matter producing ash with high Ca, Mg, K, and carbonate content (Ulery et al., 1993; Arocena and Opio, 2003; Certini, 2005), as well as by the formation of Fe-hydroxides (Schwertmann and Fisher, 1973). Under the microscope, calcite crystals were detected in high-level SBS (**Figures 9F–H**). Higher pH values in burned samples are often reported (e.g., Alcañiz et al., 2018).

Little change in TN concentrations was noted after the prescribed burn (**Figure 5**). Similarly, Arocena and Opio. (2003) found no important modifications in the TN; the authors considered that TN loss was mainly restricted to the forest floor, or TN losses were compensated by atmospheric N deposition. However, this last possibility can be considered in the long term. Another explanation for this slight change in TN is that the maximum temperature on the soil surface of the prescribed burn was not enough to allow the organic nitrogen volatilization from the soil (Neary et al., 1999), and only a minor portion of the nitrogen was thermally mineralized and integrated into the soil from the forest floor as NH_4^+ (Dannenmann et al., 2011; Bird et al., 2015). On the other hand, Badía and Martí. (2003a) found a significant (R = −0.70; $p < 0.01$) reduction of TN at 500°C for two different soils under laboratory conditions. According to a review of several studies (Alcañiz et al., 2018), the behavior of TN after burning remains unclear. Due to the insignificant TN variations, the mean values of the C/N ratio showed the same trend as TOC concentration, with a reduction of the C/N ratio from the unburned to the burned samples at low SBS and an increment for the burned samples at high SBS.

The increase in the TP content after the prescribed burn (**Figure 5**) coincides with the results reported by other studies

(Wienhold and Klemmedson, 1992; Úbeda et al., 2005; Afif and Oliveira, 2006; Merino et al., 2018). Besides, the available P (Olsen extractable P) showed a significant increase by heating ($R = 0.48$; $p = 0.01$) in lab conditions (Badía and Martí, 2003a). This TP enrichment is mainly favored by the mineralization of organic matter (García-Oliva et al., 2018), together with the increase in pH, due to the liberation of basic cations during the organic matter combustion and the ash production (Ulery et al., 1993; Kennard and Gholz, 2001; Arocena and Opio, 2003; Certini, 2005).

Soil Burn Severity Index and Soil Micro-Scale Changes Due to Prescribed Burn

As mentioned before, one of the properties affected by fire is the soil structure. However, changes are not completely visible to the naked eye; consequently, the different SBS degrees are not identified. Micromorphological characterization is a complementary tool to evaluate the effect of the prescribed burns, as shown by Badía et al. (2020). The classification proposed by Vega et al. (2013) considers a macromorphological analysis, where the SBS 1 is associated with partial changes of the organic layer, while the mineral horizon remains unaltered. Our microscopic observations document some charred elements and burned features in the organic and mineral horizons (charred aggregates, partially charred plant tissues, burned roots, wood, and spikes). Although part of these charred materials can be formed during the present burn, it is important to notice that some features might also originated in previous fires (**Figure 6B**), as they were also identified in the unburned samples (**Figure 6A**). However, charcoals from prior fire events are easier to identify with micromorphological methods because they are more rounded than the fresh ones due to mechanical breaking during time (Ponomarenko, 1997; Ponomarenko and Anderson, 2001). Hobley et al. (2017) documented that charcoal fragments are quickly integrated into the soil profile after a fire event and can persist in the soil environment for a long time. In many archaeological sites, burnt features, identified at micro-scale, are well preserved, providing information about human impact on the ecosystem (Mallol et al., 2007; Huisman et al., 2019).

Similarly, in the SBS 2 Vega et al. (2013) index, the mineral soil is also undisturbed. However, the thin sections showed that the soil was covered by a 1 cm-thick black organic layer (**Figures 3B, 6C**). Under the microscope, we observed a loss of the structure while charred aggregates are fractured and partially or completed disaggregated, in the first centimeter of the mineral soil (**Figures 8E–G**). This observation might explain the increase of the soil bulk density (**Figure 4E**). Greene et al. (1990) showed that frequent prescribed burnings can break down aggregates surface. These results have been also confirmed by Arocena and Opio. (2003), who demonstrated the presence of cracks on soil aggregates through SEM-EDS observations. They interpreted these cracks as a thermal shock related to the temperature growth. Other studies, however, have not found immediate effects on mineral topsoil aggregates after the low-intensity sand rapid prescribed burn in shrubland in Central Pyrenees, Spain (Badía et al., 2020). In agreement to our findings, DeBano et al. (1998) and Mataix-Solera et al. (2011) mentioned that even low-intensity fires can affect soil structure and aggregate stability due to the combustion and/or transformation of the organic matter compounds that binds soil aggregates; this generates a loss of soil structure, a porosity reduction, and a bulk density increase (DeBano, 1981). Moreover, Badía et al. (2017) revealed that controlled burning only affects the physical and chemical properties of the first centimeter of dry soils. Another explanation for the loss of aggregate stability after prescribed burnings, without significant loss of organic matter, was exposed by Albalasmeh et al. (2013) and Chief et al. (2012), who found that steam pressure can break down aggregates at temperatures of 150<u>o</u>C and 175°C in soils with high initial moisture. Nevertheless, it is important to mention when the fire temperature rises, an increment in the ped stability is noted because of the low contents of clay and Fe oxides in the soils (Thomaz, 2021). With these findings, we can complement the SBS Vega et al. (2013) index adding a slight perturbation of the first centimeter of the mineral soil at level 2.

For the SBS level 4, the micromorphological and morphometric descriptions agree with the general properties proposed by Vega et al. (2013), where the organic layer was completely consumed and transformed into a thick ash layer. The fire also affected the uppermost mineral soil structure and the surface fine roots and seeds (**Figures 3C**, **6D**, **9A–D**). The ash layer resulted from the oxidation of vegetal materials beyond charring during the fire, where the calcium oxalate was transformed into calcium carbonate by loss of TOC (Canti and Brochier, 2017). Calcite crystals were identified in the thin section of the SBS level 4 (**Figure 9D**). Reddened aggregates were also detected under the microscope. However, they were not recognized in the SBS index of Vega et al. (2013) because it is hard to identify them at a macroscopic scale. Our micro-scale study demonstrated that these mineralogical transformations expressed by reddened aggregates could start even before SBS level 5.

Regarding the Vega et al. (2013) index for the SBS 5, the micro-scale analyses showed that the soil organic layer was absent because it was completely consumed (**Figure 6E**). This characteristic can result from a higher temperature during the prescribed burn in this specific zone. The forest floor may have reached a temperature of around 460°C, in which the organic carbon consumption is completed (Giovannini et al., 1988), or the organic layer was absent in this area before de fire. In our study, the micromorphological and morphometric results showed that the aggregates and soil structure were slightly affected in the first 2 cm of the mineral soil (**Figure 6E**). Additionally, soil organic matter was charred and some aggregates were reddened in the surface soil (**Figure 6E**). The incipient soil reddening is a consequence of Fe oxides transformation due to heating; however, a continuous reddened layer covered by ash is expected only for severe fires and for SBS level 5 (Wells et al., 1979; Ulery and Graham, 1993; Ketterings and Bigham, 2000; Vega et al., 2013).

CONCLUSION

The physical-chemical characteristics of burned samples showed clear differences with unburned samples. After the prescribed burn, soils exhibited a darker color with a decrease in redness and yellowness, a slight reduction in soil moisture, an increase in bulk density, higher pH values, an inconclusive trend for TOC content, insignificant variation of TN, and an increase in TP content. Besides these changes in the physical and chemical properties, already well documented in other studies, micromorphological and morphometrical characteristics are useful techniques for revealing how deep the effect of prescribed burning reached into the soil and for complementing the diagnosis of post-fire soil physical alterations that SBS assessment cannot identify due to the evaluation scale.

Some of our results agree with to the SBS Vega et al. (2013) classification, particularly for the organic layer. However, the microscale analyses of mineral soil revealed that even from the SBS 2, the first centimeter of soil structure was affected by a prescribed burn. This might be attributed to changes in soil organic matter content and composition and to the thermal shock and steam pressure suffered by the aggregates due to temperature increase. Despite these features, some living seeds and fine roots could be distinguished, indicating a potential for plant and microorganism regeneration. Additionally, the Fe oxides transformations that reddened soil aggregates can start even before the soil gets the SBS 5. For high SBS levels, the micro-scale analyses revealed that the prescribed burn affected the first 2 cm of soil depth, disrupting soil structure, porous clogging with ash, and the reddening of soil aggregates. These effects resulted in higher bulk density and changes in surface soil porosity.

Land managers must consider these soil alterations at low and high SBS after applying prescribed burns to avoid post-fire erosion of the first-centimeters mineral soil. The actions to protect the soil must be applied following the prescribed burn and before the first rain, especially in the bare soil areas where aggregates disrupted by the fire can be susceptible to dispersion and erosion by the rain splash and runoff. Therefore, the SBS assessment can include an additional section about the microscopic characteristics of burn soils. Likewise, a micro-scale characterization of different SBS levels for wildfires could be interesting because it can reveal soil perturbation that we cannot see directly on the field.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

BC-V conceived the general idea and led the project. SQ-G and BC-V designed the sampling and took the samples. BC-V and MR-R performed the soil physicochemical analysis. MR-R prepare the thin sections. SM-R carried out the morphometric and micromorphological examination. SM-R and BC-V performed the statistical analysis. ES-R supervised the project. AM, BC-V, and ES-R contributed to the analysis of the results and the discussion section. SM-R wrote the manuscript with support of BC-V, ES-R, AM, and SQ-G. All authors contributed to the article and approved the submitted version.

CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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2.2. Burning effects on the soils of the Mexican Maya Lowlands: Current evidence for understanding past events

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Ciudad de México, 3 de marzo, 2024

A QUIEN PUEDA INTERESAR

En mi calidad de editor en jefe del *Boletín de la Sociedad Geológica Mexicana*, me complace hacer constar que el manuscrito intitulado "**Burning effects on the soils of the Mexican Maya Lowlands: Current evidence for understanding past events.**", enviado a esta revista por **Sol Moreno-Roso**, Elizabeth Solleiro-Rebolledo, Sergey Sedov, Bruno Chávez-Vergara, Agustín Merino, ha sido **ACEPTADO** para su publicación en nuestra revista tras su revisión por dos árbitros expertos independientes y un editor a cargo.

La publicación de dicho manuscrito en nuestra revista está contemplada para el vol. 75 no. 3 de 2024.

Atentamente,

Dr. Antoni Camprubí | *Editor en jefe*
Boletín de la Sociedad Geológica Mexicana

Burning effects on the soils of the Mexican Maya Lowlands: Current evidence for understanding past events

Condensed title: **Soil burning in the Mexican Mayan Lowlands**

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Resumen

La roza-tumba y quema es una práctica agrícola milenaria que tiene un fuerte efecto sobre el medio ambiente. Sin embargo, no es fácil identificar las señales de esta práctica en los registros edáficos debido a factores naturales y antrópicos. Particularmente en la Península de Yucatán, los antiguos mayas utilizaron la roza-tumba y quema en un ambiente kárstico tropical muy dinámico, en donde, reconocer el inicio y las consecuencias de esta práctica, es aún controversial. En esta investigación, utilizamos una quema agrícola reciente en el paisaje kárstico de Chiapas, como modelo para entender las alteraciones de las propiedades del suelo e identificar qué rasgos permanecen en un sitio Maya antiguo de la Península de Yucatán. Para ambos casos, realizamos análisis micromorfológicos, caracterización fisicoquímica de los suelos y pedosedimentos, análisis térmicos de la materia orgánica y dataciones de radiocarbono (exclusivamente en Yucatán). Encontramos efectos intensos en los suelos del sitio de Chiapas después de la quema, con cambios en la distribución granulométrica, en el pH y en el carbono orgánico e inorgánico. Estos resultados se compararon con los obtenidos en los suelos y pedosedimentos de la Cantera Coyote. Los principales hallazgos están relacionados con las características micromorfológicas: presencia de carbón vegetal y otros materiales quemados, así como la identificación de carbono pirogénico en los análisis térmicos. La preservación de estos rasgos de quema se ve favorecida por la erosión vertical del suelo en el karst y la redeposición de estos pedosedimentos en depresiones kársticas. La asociación intrínseca de la señal del uso del fuego encontrada en estas depresiones y sus dataciones nos permiten relacionar esta evidencia con el inicio de la práctica de la roza-tumba y quema por los Mayas en la Península de Yucatán en la transición entre el Arcaico y el Preclásico Temprano.

Palabras clave: Maya, agricultura de roza-tumba y quema; carbono pirogénico; erosión de suelos; pedosedimentos; bolsas kársticas.

Abstract

The slash-and-burn cultivation system is a millenarian practice still applied in many countries, which has a strong effect on the environment. However, it is not easy to identify the signals of this agricultural practice in soil records due to both natural and anthropic factors that can erase or modify the fire signal. Particularly in the Yucatán Peninsula, the ancient Mayas used slash-and-burn agriculture in a very dynamic tropical karst environment, where recognizing the beginning and the consequence of this practice is still controversial. In this research, we use a recent agricultural burning in Chiapas karstic landscape as a model to understand the soil properties alterations and then to identify which features remain identifiable at a Maya site of the Yucatán Peninsula, specifically in the Coyote Quarry. For both cases, we did micromorphological analyses, soil's physical-chemical characterization, thermogravimetry and differential scanning calorimetry analyses, and radiocarbon dating of mollusk shells, soil organic carbon, and charcoal fragments (this exclusively in Cantera Coyote). We found intense effects on soils from the Chiapas site after burning, such as changes in grain size distribution, in pH, in total organic and inorganic carbon. These results were compared to those obtained in the Coyote Quarry soils and pedosediments. The main findings are related to micromorphological features, the presence of charcoal and other burned materials, as well as pyrogenic carbon identified in the thermal analyses. The preservation of these burned features was favored by the typical karstic vertical soil erosion and the re-deposition as pedosediments in karstic depressions. The intrinsic association of the fire signal found in these karstic sinkholes and their radiocarbon dates allows us to relate this evidence to the initiation of slash-and-burn agriculture by Mayas in the Yucatán Peninsula in the transition between the Archaic and the Early Pre-Classic period.

Keywords: Maya**;** slash-and-burn agriculture**;** pyrogenic carbon**;** soil erosion**;** pedosediments**;** karstic pockets.

1. Introduction

The use of fire by humans began ~1.6 million years ago by early hominins in Africa (James, 1989), although this date is still controversial (Gowlett *et al.*, 1981; Clark and Harris, 1985). However, there is no doubt that fire has constituted a crucial tool in humanity's development (Bowman *et al.*, 2013; Gowlett, 2016) and its use can be considered as a tracker of anthropic environmental impacts (Pyne, 2020). The fire impact on the environment is found in the sedimentary record with charcoals and burned rocks, which, in consequence, have been used as a signal of human presence and different fire utilities in archaeological contexts such as heating, illumination, cooking, ceremonies, landscape clearance for agriculture or hunting, among others (Alperson-Afil, 2012, Santín and Doerr, 2016; López-Martínez *et al.*, 2021).

Ancient use of fire could be subdivided according to its spatial dimensions into local, i.e., restricted to settlements, or regional. Local burning for domestic needs was strictly controlled; it usually took place in special constructions or marked and arranged places (ovens, hearths, etc.) and presented small-scale but frequently repeated action. Usually, it is easy to identify fireplaces in archaeological contexts with the help of geoarchaeological tools. Regional burning is aimed at landscape and ecosystem change for certain economic activities. Already hunter-gatherer Palaeolithic societies of the Old World used fire throughout the Late Pleistocene to open the landscape for grass vegetation, which was attractive for large herbivores – the main hunting object (Roebroeks *et al.*, 2021; Thompson *et al.*, 2021). Much more extensive and frequent vegetation burning started with the onset of agricultural economy. Fire is an essential factor in the origin of agriculture and is still present in the millenarian "slash-and-burn" or "shifting cultivation" system around the world (Palm *et al.*, 2005). However, identifying the slash-and-burn impact in the paleoenvironmental and archaeological records is not easy due to the existence of diverse agricultural practices and the scarce empirical information on how farming burning is recorded in soils (Eckmeier, 2007a; Arroyo-Kalin, 2012; Dussol *et al.*, 2021). Micro-charcoals (<1 mm) in lacustrine sedimentary records have been used to infer slash-and-burn practices on the regional scale (e.g., McMichael *et al.*, 2012; Dietze *et al.*, 2018). In soils that could provide indicators of local burning, this method is known as "pedoanthracology" (or the study of charcoals in soils) which in combination with other paleoenvironmental and archaeological tools has helped to identify this agricultural practice (Carcaillet, 1998; Morin-Rivat *et al.*, 2016; Ponomarenko *et al.*, 2018). Eckmeier *et al.* (2007a, 2007b) performed an experimental burning of a temperate deciduous forest in Germany to mimic Neolithic agricultural slash-and-burn, finding a heterogenous charcoals spatial distribution with a domain of macro-charcoals (>1 mm), immediately after burning. After one year, a few charcoals were incorporated into the soil by bioturbation. A similar study (Dussol *et al*., 2021) was done in an agrarian area within a tropical forest in the north of Guatemala, where ancient Mayas used slash-and-burn agriculture, and the signature of this practice was identified by combining pedoanthracology and the analysis of infra-millimetric soil charcoals (100–400 μm).

Although slash-and-burn practices have important impacts on soil properties (Ketterings *et al.*, 2000; Ketterings and Bigham, 2000; Santín and Doerr, 2016), the majority of the studies use only charcoals as the main proxy of fire evidence, due to: 1) pedoturbation processes that can erase or overlap the signals (DeBano *et al.*, 1998; Dussol *et al.*, 2021); and 2) the resistance of pyrogenic carbon whose biochemical stability depends on its formation temperature, aromaticity, and degradation environmental settings (Knicker, 2023). Even more, its translocation or burial after erosion/deposition processes deeper into the soil can help its preservation for thousands of years due to the oxygen decline that can decrease the biodegradability rate of this material (Hobley *et al.*, 2017; Abney and Berhe, 2018; Knicker, 2023).

The Yucatan Peninsula, located in SE Mexico, represents an area of long-term human development since the Pleistocene–Holocene transition (González *et al.*, 2008). The oldest charcoal concentrations associated with anthropic combustion structures are dated between 10740 and 7951 cal BP. They were found in different submerged caves in Quintana Roo, suggesting that they corresponded to hearths used for illumination or heating when the caves were dry even before the development of agriculture in the region (González *et al.*, 2008; Hering *et al.*, 2018; López-Martínez *et al.*, 2020).

In the Maya Lowlands, the early agriculture evidence was determined by the finding of *Zea mays* pollen around 7000 years BP ago (Pohl *et al.*, 2007). However, the intensification of the deforestation started 5000–4000 years BP (e.g., Jones, 1994; Pohl *et al.*, 1996; Pope *et al.*, 2001; Wahl *et al.*, 2006). Deforestation together with the slash-and-burning agriculture in the Maya territory could produce changes in climate, vegetation, and soil erosion rate (Beach *et al.*, 2015; Schüpbach *et al.*, 2015; Dunning *et al.*, 2023) although this anthropogenic environmental impact is still a topic of discussion; however, some researchers consider that these changes could result from the interaction of both factors (Schüpbach *et al.*, 2015). One of the difficulties to understand such changes in the karstic landscapes of the Maya lowlands is the preservation of ancient burnings signals into the soil due to a reduction of the soil memory because of the active surface erosion as well as by the warm and humid conditions that increase the microbial degradation of pyrogenic carbon (Knicker, 2003; Sedov *et al.*, 2023). Nevertheless, the preservation of charcoals in different karstic landscapes from Mexico and Russia has been already documented (Cabadas-Báez *et al.*, 2010; Mergelov *et al.*, 2020; Sedov *et al.*, 2023). The conservation of burned features (charcoals, burned shells, charred rocks) can be favored by the vertical soil erosion or "soil piping" process, which transports surficial particles to the karstic depressions (White and Culver, 2012; Sedov *et al.*, 2023).

Although there are several studies on the effects of local burning on soils in geoarchaeological contexts, research on the effects of ancient burnings on soils at the landscape level is scarce. In this work, we study two sites in the karstic landscapes of the Maya lowlands, related to a recent burning induced by humans to prepare the land for cultivation in the state of Chiapas; and soils and pedosediments (redeposited soils) located inside a quarry in the Yucatan Peninsula, an area deeply impacted by slash-and-burn agriculture during the ancient Maya occupation. We consider the effects of the recent burning on soils in the Chiapas area as a model to understand the transformations in soil properties that remain stable in time. We hypothesize that these alterations can be extrapolated to other karstic landscapes, such as the Yucatan Peninsula, where similar soils and ecosystems are found. Thus, this work aims to establish the burning indicators after an intentional burning in an agriculture field in Chiapas and compare them with ancient soils and pedosediments properties at the karst system at Yucatan. With this information, reconstruct the effect of ancient agriculture on the soils impacted by the ancient Maya societies.

2. Materials and methods

2.1. Geological and environmental characteristics of the studied sites

Chiapas (CHI): The recent burning site is found at Sierra de Chiapas (Figure 1), near the Mexico-Guatemala border, in a farm field (17°3'48.06" N; 91°16'3.90" W) recently burned for agriculture purposes. Sierra de Chiapas belongs to the southern area of the Maya block, a tectonostratigraphic terrain with Permian–Triassic igneous and metamorphic rocks in its basement, overlain by continental volcanic and sedimentary deposits from the Lower Jurassic to Cenozoic (Garduño-

Monroy *et al.* 2015). The Sierra is folded with anticline and syncline structures, oriented E-W to NW-SE. The Sierra is constituted by limestones and sandstones to claystones, which is affected by neotectonics (García-Molina, 1994; Meneses-Rocha, 2001). It represents the biggest mountainous tropical karst in Mexico (Espinasa-Pereña, 2007: Andreani and Gloaguen, 2016). The region has a humid tropical climate with strong wet and dry seasons, where the mean annual precipitation recorded in the area was 2000–2800 mm between1960 and 2016, with 24°C for the mean annual temperature (Johnson *et al.*, 2007; Andrade-Velázquez and Medrano-Pérez, 2020). These climatic conditions allow the development of an tropical humid forest (INEGI, 2019a).

Coyote Quarry (CQ): The Pre-Hispanic burning site is found in the coastal plain of Quintana Roo, NE Yucatan Peninsula (Figure 1), at the Coyote Quarry (20°31'52.30"N, 87°12'34.92"). The Yucatán Peninsula comprises a thick marine sedimentary sequence of limestones, dolomites, and evaporites from Cretaceous to Quaternary over a Paleozoic basement that conforms an uplifted carbonate karstic platform of a low geomorphic relief (Lopez-Ramos, 1975; Weidie, 1985; Ward, 1985). According to Fragoso-Servón *et al.* (2019), this area corresponds to an erosive-accumulative littoral geomorphic environment at the transition between the undulated plains tecto-karst and the sea. The climate in this zone is hot and sub-humid, with a mean annual temperature of 26 ºC and 1234 mm of annual precipitation (García, 2004) with a tropical sub-humid forest (INEGI, 2019b).

According to Sedov *et al.* (2023), who studied soil toposequences in tropical karstic landscapes of southern Mexico, there are two main soil types in both the Yucatan Peninsula and Chiapas areas: shallow Rendzinas (Rendzic Leptosols (Humic)) and deep *Terra Rossas* (Chromic Luvisols (Humic); soil classification according to INEGI, 2007a, 2007b). The karstic agricultural landscape in the Maya Lowlands has been characterized by the transformation of areas covered with natural vegetation to cultivation land and, more specifically, to the slash-and-burn agriculture where the forest is cleared and converted into a farmland. This clearance is accompanied by burnings, producing ashes that represent a source of some nutrients (Wilhelmy, 1989; Faust, 2001).

The Quintana Roo area has abundant archaeological evidence of Maya settlers, with important Classic (AD 250–950) and Post-Classic (AD 950–1539) cities such as Coba and Tulum, respectively. However, sedentary human occupation started during the Middle Pre-Classic (1000–350 BC), which represents a long period (more than 3000 years) of continuous Maya settlements. During the 3000 year-period, the enormous transformation of the tropical ecosystem caused by ancient Mayas has been registered in several places. Particularly, Beach *et al.* (2015) recognized large environmental changes due to the impact of Maya Civilization (from 3000 to 1000 BP), that even name such period periods as Mayacene or Maya Early Anthropocene. Evidence of the impact has been also connected to accelerated fires (Beach *et al.*, 2015).

2.2. Field work

We collected samples from the two sites in 2019 following the same procedures: around 1 kg of bulk samples for laboratory analyses and unaltered soil blocks for micromorphological observations. However, according to the characteristics of each site, the morphological descriptions were not done homogeneously. In Chiapas, a portion of an open agricultural area had recently burned for cultivation purposes, and this slash-and-burn shifting has been a recurrent practice; here, four soils were sampled the same day that the burn occurred: i) unburned black soil (CH03), ii) unburned red soil (CH01), iii) burned black soil (CH02), and iv) burned red soil (CH04). The sampling and descriptions were limited to the top layer (6 cm) of soil as this is the part most affected by slash-and-burn agricultural practices (Ketterings and Bingham, 2000;

Thomaz *et al.*, 2014). The black soils correspond to Rendzic Leptosols (Humic), and the red ones belong to Chromic Luvisols (Humic) (INEGI, 2007a, 2007b); however, as we did not pay attention to the taxonomy of the soils, we further refer to black and red soils.

Three different materials were studied at the Coyote Quarry in Quintana Roo: The first one, in a soil profile excavated on top of the quarry where the vegetation was still preserved; and the other two on the quarry walls: i) a modern Rendzina type soil (Selva-depresión profile; Rendzic Leptosols (Humic) (INEGI, 2007b)), ii) a modern soil in a karstic pocket (Negra Gorda profile; Rendzic Leptic Phaeozem (Humic) (INEGI, 2007b)), and iii) pedosediments located at the floor level of a collapsed cave (PSPO1 and PSPO2, Figure 2).

2.3. Laboratory analyses

In this study, micromorphology was used as the primary method for the determination of the burning evidence. In the soil thin sections, ash, charcoal, burned and reddened aggregates, charred rocks, burned bones, and charred shells were identified according to Nicosia and Stoops (2017), Stoops *et al.* (2018) and Moreno-Roso *et al.* (2023). However, micromorphology has some limitations for the discrimination of pyrogenic evidence from similar features of pedogenic processes, such as pigmentation of the soil groundmass with dark humus or reddish aggregates product of advanced pedogenesis. For this reason, micromorphology is accompanied by specific methods to differentiate pyrogenic and pedogenic features, such as the evaluation of selected physical and chemical properties and thermogravimetry.

2.3.1. Micromorphological analysis

The unaltered soil blocks collected in the field were used to prepare thin sections (30 µm-thick). The samples were dried and impregnated at the laboratory with polyester resin (Fig. 3b). The micromorphological analysis was performed with a petrographic microscope (OLYMPUS). A digital camera connected to the microscope and a computer with the Image-Pro Plus 7.0 software was used to capture the fire evidence images in soil-thin sections.

2.3.2. Physical analyses

Changes in soil color after burning have been reported in several studies (e.g. Ulery and Graham, 1993; Terefe *et al.*, 2005; Ketterings and Bigham, 2000; Badía and Martí 2003; Cancelo-González *et al.*, 2014). Therefore, we evaluated the changes in the color of the studied samples to, at first glance, determine if the soil was or was not affected by fire. For color measurements, we used a portable spectrophotometer (ColorLite Sph 870). This colorimeter follows the CIELAB color system (CIE, 1986), which characterizes the color by three parameters: L* (luminosity), from 0 (black) to 100 (white); $a^* > 0$ (redness) and $a^* < 0$ (greenness); and $b^* > 0$ (yellowness) and $b^* < 0$ (blueness) (Cancelo-González *et al.*, 2014). Colors were measured in triplicated on sieved (2 mm) and homogenized samples.

Some studies have reported changes in soil texture in burned soils (Ulery and Graham, 1993; Ketterings *et al.*, 2000). Thus, the soil texture was determined following Flores-Delgadillo and Alcalá-Martínez (2010). First, to eliminate carbonates, samples were treated with sodium acetate ($C_2H_3NaO_2$ 1 M pH 5, 1:10, 10 ml mixed with 100 ml of distilled water, discarding the supernatant after centrifugation and repeating three times the procedure); to remove the organic matter, 5ml of 10 % H_2O_2 was added and the mixture heated at 60 ºC and until the reaction ended; to eliminate free iron oxides a dithionite-citrate-bicarbonate solution was added (for details see Flores-

Delgadillo and Alcalá-Martínez, 2010). The particle size distribution was quantified, separating sand (2–0.05 mm) by sieving (53 μm mesh) and silt (0.05–0.002 mm) and clay (>0.002 mm) by gravity sedimentation (pipette method).

2.3.3. Chemical analyses

We determined soil pH in distilled water (1:2.5 W:V ratio) by a portable pH meter (Thermo) on previously dried samples. This property usually increases after fires (see Alcañiz *et al.*, 2018; Agbeshie *et al.*, 2022).

Changes in soil carbon after fires have been extensively studied (Alcañiz *et al.*, 2018; Agbeshie *et al.*, 2022). The quantification of the total carbon (TC) and the inorganic carbon (IC) was made by the coulometric method (Huffman, 1977) with a total carbon analyzer (UIC model CM5012, Chicago, USA) on previously dried soil samples at 105 ºC until constant weight. At the same time, the total organic carbon (TOC) concentration was obtained by the difference between TC and IC.

2.3.4. Thermal analysis

Soil organic matter is modified during fire events, losing the most thermolabile (microbial functional groups and carbohydrates) and alkyl compounds together with an increase of aromatic compounds, such as pyrogenic carbon (Knicker *et al.*, 2008). Pyrogenic carbon is a recalcitrant product, more resistant to microbial attack and thermal oxidation, than fresh vegetal remains or labile organic matter (Singh *et al.*, 2014; Dell' Abate *et al.*, 2002). Therefore, to discriminate the soil organic matter (SOM) of pyrogenic origin from that formed by pedogenic processes, some samples were selected to characterize their organic matter thermo-quality (Barros *et al.*, 2010). Five samples (unburned and burned red soils (CH01 and CH04) from Chiapas; A horizons from

Selva-depresión and Negra Gorda profiles, and the PSPO1 pedosediments from the collapsed cave were analyzed by Differential Scanning Calorimetry (DSC) and Thermogravimetry Analysis (TGA) with a TGA/ DSC1 thermogravimetric analyzer, Mettler Toledo, following the method described in Merino *et al.* (2015). The samples (4 mg) were placed in open aluminum containers with dry air (under O2 flux; flow rate, 50 mL^{-1}) and scanned at a rate of 10 $ºC^{-1}$ in a temperature between 50 and 600 ºC. With the temperature increase, the loss of matter (TGA) and the heat or energy release (DSC) were measured (Merino *et al.*, 2015). The obtained data were processed using STARe Mettler Toledo software to generate the DSC and TGA curves and other thermal parameters described in Merino *et al.* (2015). According to Dell' Abate *et al.* (2002) and Fernández *et al.* (2011), the obtained thermogram curves can be divided into three regions that represent the resistance to thermal oxidation: labile organic matter (200–375 °C, carbohydrates, and aliphatic compounds); recalcitrant organic matter (375–475 °C, lignin and polyphenols); and highly recalcitrant organic matter (475–550 °C, polycondensed aromatic compounds). We also obtained the parameter T_{50q} to indicate the temperature at which 50% of the energy is released.

2.3.5. Radiocarbon dates

The age of the materials inside the karstic depressions was established by radiocarbon dating analysis done by the International Chemical Analysis Inc. (ICA; Table 1). The selected samples were: 1) soil organic matter of the AB1 horizon from the Negra Gorda profile; 2) charcoals and a terrestrial mollusk from the cave pedosediments (PSPO1); 3) a charcoal fragment from the same cave pedosediments PSPO1, previously published in Sedov *et al.* (2023). The sampling depth of each material is presented in Table 1.

3. Results

3.1. Soil characteristics as a consequence of the burning in Chiapas

3.1.1. Macromorphological characteristics

The topsoil of the materials not affected by burning preserved the natural colors (Figure 2a). Organic materials on the A horizons were detectable in different stages of decomposition. The unburned black soil (CH03) showed a dark brown color, with a primary subangular blocky structure (dominant aggregates size is 3–5 cm diameter) and scarce minor granular aggregates; few thin roots and degraded vegetal remains were present. The unburned red soil (CH01) showed a dark reddish color, a clayey texture, and a subangular blocky structure. The aggregate size varied between 3 and 0.5 cm. There were no roots or vegetal remains.

In the case of the soil affected by burning (Figure 2b), we observed changes in color, structure, and in the organic materials. The burned black soil (CH02) presented a dark black Ah horizon with a subangular blocky structure. However, it showed aggregates of smaller size (2–0.5 cm in diameter) with respect to the unburned soil. Most of the aggregates were charred, but few aggregates exhibited a reddish color. The surface of this burned horizon showed completely and partially charred vegetal remains. The burned red soil (CH04) was reddish, showing a subangular blocky structure. The aggregate size was comparable to the unburned red soil, with a few black-colored aggregates. It was highly clayey, with burned and unburned vegetal remains on the topsoil.

3.1.2. Micromorphological features

The unburned black soil (CH03) showed a brown clayey groundmass with a subangular blocky structure (Figures 2, 3a, 3b). Silt and sand-size quartz grains and few coprolites were common. Although this soil was considered unburned, fragments of charcoal and rounded reddish and charred dark reddish pedosediments were frequently included in the groundmass. These were evidence of previous burnings. In contrast, the burned black soil (CH02) exhibited a reddish color on the first 4 cm and a dark reddish color below (Figure 2). Ashes were common and showed the characteristic individual rhomboidal shapes of calcite crystals forming clusters filling pores (Figures 3c, 3d). Very few charcoal fragments were present. In the first centimeter of the burned red soil (CH04), a dark black color constituted by charred aggregates forming a loose and sub-rounded blocky structure was observed (Figure 3e, 3f). Then, in the next centimeters, a clayey and rubified soil groundmass appeared, showing a subangular blocky structure. Some aggregates presented a dark center with a reddish border. There were ashes associated with a few small charcoals. Other charcoals were included in the groundmass, possibly from previous burned events. Besides, some reddish and dark brown rounded pedosediments were present.

3.1.3. Physical and chemical characteristics

The particle size distribution of the Chiapas unburned soils indicated a clear difference in the clay and sand contents concerning their respective burned samples (Figure 4). The unburned black soil was dominated by 94.4% of clay, while the burned black soil just exhibited 46.0%, reaching up to 42.4% of sand-size particles. The unburned red soil showed 88.0% of clay and only 3.6 % of sand, while the burned one presented 20.4% of clay and 73.9% of sand-size particles.

All color parameters (L*, a*, and b*) slightly decreased from the unburned black soil to the burned black soil (Figure 4). These decrements represented, respectively, a slight reduction in luminosity, reddening, and yellowing of the soil color after burning. On the other hand, the unburned red soil exhibited an increased in luminosity, redness, and yellowness parameters after burning. This subtle change in soil color could not be detected with the naked eye but could be detected using the colorimeter. However, variations related to the measurement technique should be considered.

The soil pH values (Figure 4) increased after burning in both types of soils (black and red). In the black soils, the pH raised slightly from 7.1 to 8.0, from unburned to burned condition, respectively. Meanwhile, in the red soils, the increase was higher, changing from 5.4 to 7.6, from the unburned to the burned soil.

The unburned black soil showed the highest TOC (5.4%) and IC (2.1%) (Figure 4); these percentages decreased with burning to 4.1% TOC and 0.5% IC (burned black soil). In the red soils, we observed the same trends: higher values in the unburned samples (4.1% TOC; 0.2% IC) and lower proportions in the burned red soil (1.1% TOC; 0.4% IC).

3.1.4. Thermal analyses

The thermogravimetry analysis (TGA) showed a significant difference between the unburned and the burned red soils (CH01 and CH04) (Figure 5a). The TGA curve for the unburned red soil CH01 (Figure 5a) exhibited a high peak (~ 350 ºC) in the thermo-labile organic compounds area, which corresponded to the higher proportion type of organic matter in the sample. The thermo-recalcitrant area (375–475 ºC) below the TGA curve was smaller than the previous one, and truncated at almost 450 ºC. There was no highly recalcitrant organic matter in the sample ~~(475–600 ºC)~~. However, an endothermic peak appeared around 475 ºC, representing the weight loss from a mineral phase.

On the other hand, the TGA for the burned red soil CH04 (Figure 5a) presented a significant reduction of the area below the curve in relation CH01 (unburned red soil). First, an exothermic curve was performed from 250–445 ºC, representing the presence of thermo-labile and thermo-recalcitrant organic compounds in the burned red soil. Then, a small endothermic peak appeared at 475ºC. Finally, the TGA curve showed a slight exothermic peak at 530ºC, corresponding to highly recalcitrant organic matter in the burned red soil. Likewise, the thermal parameter T_{50q} (Figure 5b) at 345 ºC for the burned sample indicated that this burned red soil needed more temperature to release half of the soil organic matter energy than the unburned red soil, which T_{50q} value was 321 ºC.

3.2. Soil characteristics in ancient burning site at Coyote Quarry

3.2.1. Macromorphological characteristics

The Selva-depresión profile was found beneath jungle vegetation in a depression. It measures 30 cm thick and comprises three different types of horizons: O, A, and AC (Figure 6a, 6b). The O horizon (0–4 cm) consisted of leaves, branches, and roots that decreased in size with depth. The A (4–14 cm) and AC horizons (14–30 cm) were dark brown with a granular structure and a high root density. The percentage of rock fragments is more than 50%, being more abundant in the AC horizon. At the bottom of the profile, a 1 cm clay layer was in direct contact with the limestone.

The Negra Gorda profile was in a modern soil karstic pocket constituted by Ah, AB1, and AB2 horizons (Figure 6c, 6d). The Ah horizon (0–30 cm) showed a dark brown color, a granular structure, high root density, and high content of limestone fragments. The AB1 (30–70 cm) and AB2 horizons (70–100 cm) exhibited a very dark brown-reddish color, less content of rock fragments and abundant Fe-Mn concretions.

The pedosediments from the collapsed cave (PSPO1 & PSPO2) were dark reddish brown (Figure 6e). They showed a mix of clay material, broken terrestrial shells, some charcoals, and limestone fragments (gravel size) frequently charred. Both exhibited a strong reaction to HCl. PSPO1 contained roots and was looser and less dense than PSPO2, which was more compact and contained abundant charred shells and burned limestone fragments.

3.2.2. Micromorphological features

The A horizon at Selva-depresión showed a clay-reddish groundmass with a granular structure composed of rounded and subangular aggregates. Some aggregates were pigmented with humus (Figures 7a, 7b). Fresh vegetal remains, shell fragments, small limestone grains, and iron nodules were identified. The three horizons of the Negra Gorda pocket also exhibited a clayey-reddish groundmass with a granular to subangular blocky structure. The vegetal remains were common and were fresh or decomposed at different levels or even with coprolite infillings. Different-sized anorthic Fe nodules were abundant in the entire profile; they were dispersed in the groundmass. In the Ah horizon, few carbonate fragments were detected. Charcoal fragments were common in the AB1 horizon (Figure 7c). In both AB1 and AB2 horizons, rounded black soil fragments were common (Figure 7d), with a mean size of 2 cm in diameter; besides these black fragments, reddish or dark brown soil fragments were also present, in most cases fractured.

The micromorphological analysis revealed that pedosediments (PSPO1 & PSPO2) from the collapsed cave were a mixture of clayey-reddish soil material with a sub-angular blocky structure, abundant burned shells (Figure 7f), rounded-reddish soil fragments (see Figure 7h in Sedov *et al.*, 2023), and abundant limestone fragments, which exhibited rounded or angular shapes. Most of these rocks were charred, showing a dark black color using plane-polarized light, and recrystallized calcite crystals with a triangular shape seen by cross-polarized light (Figure 7e).

3.2.3. Physical and chemical characteristics

The soil texture of the Selva-depresión profile was very clayey, and both horizons (A and AC) exhibited almost the same particle size distribution, with more than 94% clay, about 5% silt, and only 0.2% sand (Figure 8). Horizons of the Negra Gorda karstic pocket showed a clayey texture, where clay fraction was up to 55.8% in the Ah horizon (which has a high percentage of silt 43.3%) and more than 90 % in both AB horizons (Figure 8). Sand fraction was less than 3.5 % in the whole profile. The cave pedosediments (PSPO1 & PSPO2) exhibited a more heterogenous texture. They contained mainly clay 74.6–87%, 3–18.2% of silt, and 7.2–10 % of sand (Figure 8). However, these materials showed a slightly higher portion of sand than the other soil profiles studied in the Coyote Quarry.

According to soil color measurements of the Selva-drepresión profile, the A horizon was more luminous, slightly more reddish, and slightly more yellowish than the AC horizon. The soil color of the Negra Gorda profile was similar for its three horizons. For the pedosediments in the cave, these two materials showed a higher luminosity value than the previous soil profiles, whereas the redness and yellowness exhibited slightly higher values (Figure 8).

The pH of the Selva-depresión and the Negra Gorda soil profiles was near to neutrality condition, meanwhile, the pedosediments in the collapsed cave showed a basic pH with values between 8.1–8.0 (Figure 8).

In the Selva-depresión and in the Negra Gorda profiles, the TOC content was greater in the Ah horizons than in the lower horizons (Figure 8). In contrast, the IC content was higher for the AC horizon in the Selva-depresión, while in the Negra Gorda, the content was low in the whole profile. The collapsed cave pedosediments showed similar proportions of IC and TOC.

3.2.4. Thermal analyses

The TGA curves behavior for the Ah soil horizons from the Selva-drepresión and Negra Gorda profiles were similar, but they differ in relation to the cave pedosediments PSPO1 curve (Figure 9a). The Selva-depresión and Negra Gorda curves exhibited three different exothermic peaks around 350º C, 430 ºC, and 515 ºC. The higher proportion of organic compounds corresponded to thermo-labile organic matter, represented by the largest area below the curves (200–375 ºC). On the other hand, the TGA curve for the cave pedosediments PSPO1 only exhibited two exothermic peaks, at 346 ºC and 510 ºC, with lower areas below the curve than the previous one. In this case, similar to the other two samples, the thermo-labile organic matter represented the higher proportion of the organic compounds. In contrast, the thermo-recalcitrant and highly-recalcitrant compounds were present but in a lower proportion. Regarding the thermal parameter T_{50q} (Figure 9b), Ah soil horizons from the Selva-depresión and Negra Gorda profiles showed higher T_{50q} values (around 370 ºC) than the cave pedosediments PSPO1 with a T_{50q} value of 354 ºC.

3.2.5. Radiocarbon dates

The radiocarbon date of the AB1 soil horizon in the Negra Gorda profile was 750 +/- 40 BP (uncalibrated age; Table 1). In contrast, the charcoals and terrestrial mollusk from PSPO1 dates varied between 3530 to 3850 +/- 40 BP (uncalibrated ages; Table 1).

4. Discussion

4.1. Fire effects on Chiapas soils as a reference of a recent burning

The slash-and-burn practices might strongly affect soil properties (Santín and Doerr, 2016), as shown in Chiapas burned samples. The changes observed there correspond to unequivocal fire effects: a) the darkening of the topsoil due to the incomplete combustion of organic materials allowing charcoal formation, and the TOC decrease in the mineral soil due to organic matter volatilization in form of CO_2 (Giovannini *et al.*, 1988; Ketterings and Bigham, 2000; Badía and Martí, 2003); b) the intense reddening of the red soil (Figure 2) attributed to the mineralogical transformation of iron oxides at high temperatures (>600ºC) causing the change in soil matrix color (Ulery and Graham, 1993; Ketterings *et al.*, 2000; Ketterings and Bigham, 2000); c) the high increase of sand fraction (Figure 4) attributed to the thermal fusion of clay particles and transformation of Fe and Al oxyhydroxides of mineral compounds during severe burnings (>500 ºC), generated sand-sized clayey aggregates with very high stability (Ulery and Graham, 1993; Ketterings *et al.*, 2000; Certini, 2005; Mataix-Solera *et al.*, 2011; Santín and Doerr, 2016); d) the increment of IC and pH (Figure 4) due to the complete combustion of biomass at high temperatures that transform plants calcium oxalate into calcium carbonates which are the main components of ashes accompanied by high contents of Ca, Mg, and K (Ulery *et al.*, 1993; Arocena and Opio, 2003; Canti and Brochier, 2017; Agbeshie *et al.*, 2022). On the other hand, the quality of the organic matter changes with the increase in temperature (Knicker, 2008). In the Chiapas unburned red soil sample, the TGA and DSC analyses reveal a modification of soil organic matter recalcitrance after the slash and burn events. In addition, the unburned red soil endothermic peak at 475 ºC (Figure 5), can be associated with the kaolinite content in the sample, which is transformed at higher temperatures, what explains the lower endothermic peak observed in the burned red soil (Figure 5). This probably results from unprotected mineral fraction by organic matter (already charred and eroded). Thus, minerals are more susceptible to the effects of high temperatures during burning.

The morphological features, observed in both macro and micro scales, are also relevant as several changes are detected after burning. These changes are related to the structure, where the size and consistency of subangular blocky aggregates diminish (Figures 2, 3e, 3f), and the redness of the groundmass with the presence of ashes, charcoal fragments, and rhomboidal calcite crystals (Figures 3c, 3d). Similar changes were reported in a prescribed fire by Moreno-Roso *et al.* (2023) in areas with a high soil burn severity.

On the other hand, using the observed organic matter thermal modifications in the soils from Chiapas as a model to identify the transformations in the Coyote Quarry materials, we suggest that the T_{50q} parameter (Figure 9b) results in temperature values between 350-370 ºC that are even higher than those of the Chiapas red burned soil, associated to the presence of organic matter with a major energy release (Merino *et al.*, 2015). Additionally, the TGA curves of soils and pedosediments in the Coyote Quarry show the presence of an exothermic peak (around 510–515 ºC) inside the highly recalcitrant organic matter zone (Figure 9a). These results can be associated with pyrogenic carbon remains in the soils and pedosediments from ancient burning events in the area. However, the dominance of thermo-labile organic matter in the TGA curves can also be explained by the incorporation of different pedosediments and new soil organic matter along the time in conjunction with the regeneration of the tropical forest vegetation after the ancient burning. These are common processes in a dynamic karstic landscape where soil and pedosediments constantly change due to pedoturbations. Consequently, the TGA and DSC analyses support the existence of fire signals within the karstic depressions and the cave resulting from eroded soils affected by past burning events.

4.2 Evidence of ancient burnings in the karstic zone of Quintana Roo: How did the ancient Mayas affect the landscape?

Although the slash-and-burn practice is considered a "controlled fire," the effects on Chiapas soils were heterogeneous, resulting in patches with different soil burn severities (SBS). These different SBS result from the environmental variations and fire characteristics in the same burned area (Hubbert *et al.*, 2006; Girona-García *et al.*, 2019). Therefore, SBS is determined by several factors such as vegetation type and characteristics, soil type, soil moisture, soil structure, soil organic matter, landscape geomorphology, fire intensity (related to the energy release and temperature), fire residence time (heating duration), and atmospheric conditions (DeBano, 1998; Neary *et al.*, 1999; Certini, 2005; Doerr and Cerdà, 2005; Badía *et al.*, 2017; Doerr *et al.*, 2023). Another variable that might influence fire impacts on soil is the burning execution. Slash-and-burn shifting cultivation techniques can vary from culture to culture or even inside the same Maya culture over time. For example, Night and Diemont (2013) indicated differences between traditional Maya and contemporaneous slash-and-burn practices in the Maya area. Meanwhile, the latter requires an annual "hot burn," in the traditional system, low-intensity burns in small areas of the field are occasionally induced throughout the year, generating charcoal and ashes, which increase soil fertility and preserve organic matter. The "hot burn" is performed only once in 25 years over the entire field (Night and Diemont, 2013). On the other hand, Thomaz *et al.* (2014) mentioned that higher quantities of fuels are accumulated during longer fallow periods; slash-and-burn practice leaves the fuel closer to the topsoil, raising the heat transfer and the impact on the soil. Therefore, in a geoarchaeological context, it is difficult to know all these conditions at the moment of the burning. However, favored by soil memory, we have traces of ancient burnings from which we can infer fire effects on soils and estimate some of these conditions.

Most of the fire evidence produced after slash-and-burn in Chiapas soils cannot be permanent over time; most of the features are erased and overlapped by natural and anthropogenic processes, such as pedogenesis, erosion, and changes on slash-and-burn regimes (DeBano *et al.*, 1998; Dussol *et al.*, 2021), especially in these dynamic and heterogeneous tropical karstic systems, where the land cover is considered to have a reduced soil memory (Sedov *et al.*, 2023). Additionally, this landscape has been used and modified by humans in different historical periods. However, karstic depressions are outstanding sinkholes for burned features preservation in soils from this kind of environment (Cabadas-Báez *et al.*, 2010; Sedov *et al.*, 2023). Therefore, we found well-preserved macroscopic and microscopic charcoals, burned shells, and charred limestones in soils and pedosediments deposits at the Coyote Quarry (Figures 7c, 7d, 7e, 7f). Actually, micro-charcoals in different environments have been used as evidence of local fires as in agricultural soils in Russia (Mergelov *et al.*, 2020), France (Carcaillet, 1998; Ponomarenko *et al.*, 2018), and lacustrine systems in the Mexican Caribbean coast (Correa-Metrio *et al.*, 2023). Although the reduced soil memory of the karstic pedogenetic records, the use of micromorphology in the study of burned features in conjunction with radiocarbon dates offers information about anthropogenic influence on the environment such as in other archaeological contexts (Mallol *et al.*, 2007; Huisman *et al.*, 2019; Sedov *et al.*, 2023).

The radiocarbon date of soil inside the modern karstic pocket, Negra Gorda profile, corresponds to the Late Classic period of Maya culture history (Table 1). In contrast, dates obtained from the terrestrial mollusk and charcoals from PSPO1 (Table 1) in the collapsed cave correspond to the limit between the Archaic and Pre-Classic periods (Sedov *et al.*, 2023). Our finding of charcoals directly associated with burned shells and charred rocks implies the occurrence of anthropogenic burnings in the region. We correlate this fire evidence to the start of slash-and-burn practices by Mayas (Brenner *et al.*, 2003). The huge pressure applied by this civilization on this delicate environment triggered extensive soil erosion throughout the region; however, in the Pre-Classic period, the most intense anthropogenic erosion occurred (Brenner *et al.*, 2002; Beach *et al.*, 2015, 2018; Dunning *et al.*, 2023).

The lateral soil movement is the most common erosive process in the mountainous areas (Sedov *et al.*, 2008). In contrast, the vertical soil movement, or "soil piping," is the dominant direction of erosional processes in this northern part of the Maya region, controlled by the geomorphology of a karstic platform with a high occurrence of vertical dissolution fissures (Sedov *et al.*, 2008; White and Culver, 2012; Sedov *et al.*, 2023). The presence of charcoal fragments, burned shells, and charred rocks of centimetric size on these karstic depressions confirms the piping process because vertical transportation of charcoals >1–2 mm is usually limited (Carcaillet and Thinon, 1996; Tinner *et al.*, 2006; Mergelov *et al.*, 2020). Therefore, it is highly possible that these charred materials came from a quite near burned site (Tinner *et al.*, 2006; Mergelov *et al.*, 2020) or directly from the surface above the cave (Sedov *et al.*, 2023). The surface soils in the quarry (Selva-depresión profile) and in the karstic pocket (Negra Gorda) show the presence of micro-charcoals (Fig. 3b, 3c), which indicate the effects of previous fires. Micro-charcoals found in the karstic depressions at the Coyote Quarry resulted from the mechanical fragmentation during transportation and post-depositional processes of larger charcoal particles (Chrzazvez *et al.*, 2014). In contrast to macro-charcoals, micro-charcoals vertical movement is dominated by soil structure and porosity, and their low concentration in soil can be related to a few or only one burn event or to easier removal of these smaller charcoal fragments (Chrzazvez *et al.*, 2014; Dussol *et al.*, 2021). Micro-charcoals can travel long distances and are deposited in lacustrine sediments, offering regional and local fire history context (Clark, 1988; Magne *et al.*, 2019). Furthermore, our findings directly correlate with lacustrine micro-charcoals records and palynological archives from other studies (Brenner *et al.*, 2002; Schüpbach *et al.*, 2015; Correa-Metrio *et al.*, 2023). For example, Correa-Metrio *et al*. (2023) found in the charcoal record of La Encantada lagoon, near the Bay of Chetumal (in the Mexican Maya Lowlands), evidence of high-frequency local fire events from 5200 to 2700 cal yr. BP and an increase of palynological taxa linked with anthropic activities. Thus, they associated these records with the beginning of burning for landscape transformation in the area.

According to pollen records and the thick unit of clay combined with sediment layers with a high organic content in Maya Lowlands lakes, a tropical forest loss started during the Early and Middle Pre-Classic when Maya people began their development across the Yucatan Peninsula more than 3000 ^{14}C year BP (Brenner *et al.*, 2002). Besides, other authors (Beach *et al.*, 2015) indicate that these environmental changes had a direct relationship with Maya burnings. However, other regional paleo-climatic studies also found a dry period that started 3000 years ago, and this signal can overlap the anthropic effect (Brenner *et al.*, 2002). Likewise, Schüpbach *et al.* (2015) detected a peak of fire activity at 3700 cal years BP from the study of lacustrine charcoal sediment and molecular fire proxies in the Maya lowlands of Petén, Guatemala, related to early agricultural activities but the authors did not exclude the possible influence of the dry climate conditions on vegetation ignition. Our findings agree with Piperno (2006) paleo-ecological research, which found that slash-and-burn practices near to the southwest Mexico lowlands forest began in the Late Archaic period (4000 years BP). Therefore, our evidence of early burning events can be associated with Maya land cultivation beginning in the Yucatán Peninsula.

5. Conclusions

This study of the impact of slash-and-burn agriculture in Chiapas can be used as a model of how a recent burning transforms specific soil properties. After the burning, the following changes were detected: darkening of the topsoil observed in the field, in the laboratory, and under the microscope; reddening of the clayey groundmass, also confirmed by colorimetric methods; formation of bigger red-clayey aggregates. Likewise, in thin sections, ashes were frequent and commonly filling pores, as well as a few charcoal fragments. According to physical-chemical analyses, soils showed a high increase in the sand fraction due to the formation of bigger red-clayey aggregates, a decrease in the TOC content, and an increase in pH and IC.

Soils and pedosediments studied in Yucatán, as an ancient human impact case, gave interesting results. This warm and humid karstic landscape has been occupied and modified for thousands of years. Anthropic, sedimentary, and pedogenetic processes have caused pedoturbation in the region. However, as demonstrated in this and other studies, karstic sinkholes represent an outstanding reservoir for eroded surficial soils (pedosediments) and stable burned features such as charcoals, burned shells, and charred limestone fragments. The association of these burned materials and their radiocarbon dates led us to relate this evidence to the beginning of slash-and-burn agriculture by Mayas in the Yucatán Peninsula between the Archaic and the Early Pre-Classic periods. Nevertheless, more work is needed to search these burned features inside other karstic depressions and into soils affected by recent burning at the Yucatán Peninsula to reconstruct the early Maya burning history and support this soil record with other paleoenvironmental proxies.

Authors contributions

(1) Conceptualization: SS and ES-R, (2) data analysis or acquisition: SS, ES-R, SM-R, BC-V, and AM, (3) methodological/technical development: SM-R, BC-V, (4) drafting the original manuscript: SM-R, (5) drafting the corrected and edited manuscript: SM-R, ES-R, SS, BC-V, and

AM, (6) graphic design: SM-R, (7) fieldwork: SS and ES-R, (8) interpretation: SM-R, ES-R, SS, BC-V, and AM, and (9) funding: SS.

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Conflict of interest

The authors declare that this research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Table 1. Radiocarbon dates (^{14}C) of the charcoals and mollusk of the selected soils and pedosediments from the Coyote quarry.

Lab code	Sample name	Material type	Sampling depth (cm)	Coventional age	Calendaric age	Reference
ICA5879	Negra Gorda AB1	Soil	60	750 +/- 40 BP	Cal 1210–1310 AD (94.0 %) Cal 1370–1380 AD (1.4 %)	This work
ICA5877	PSPO1	Carbonate (terrestrial mollusk)	280	3530 +/- 40 BP	Cal 2010–2000 BC (0.4 %) Cal 1980–1740 BC (95.0 %)	This work
ICA5886	PSPO1	Charcoal	280	3850 +/- 40 BP	Cal 2470–2200 BC	This work
ICA5880	PSPO1	Charcoal	285	3890 +/- 40 BP	Cal 2470–2280 BC (89.1 %) Cal 2260–2200 BC (6.3 %)	Sedov *et al.* (2023)

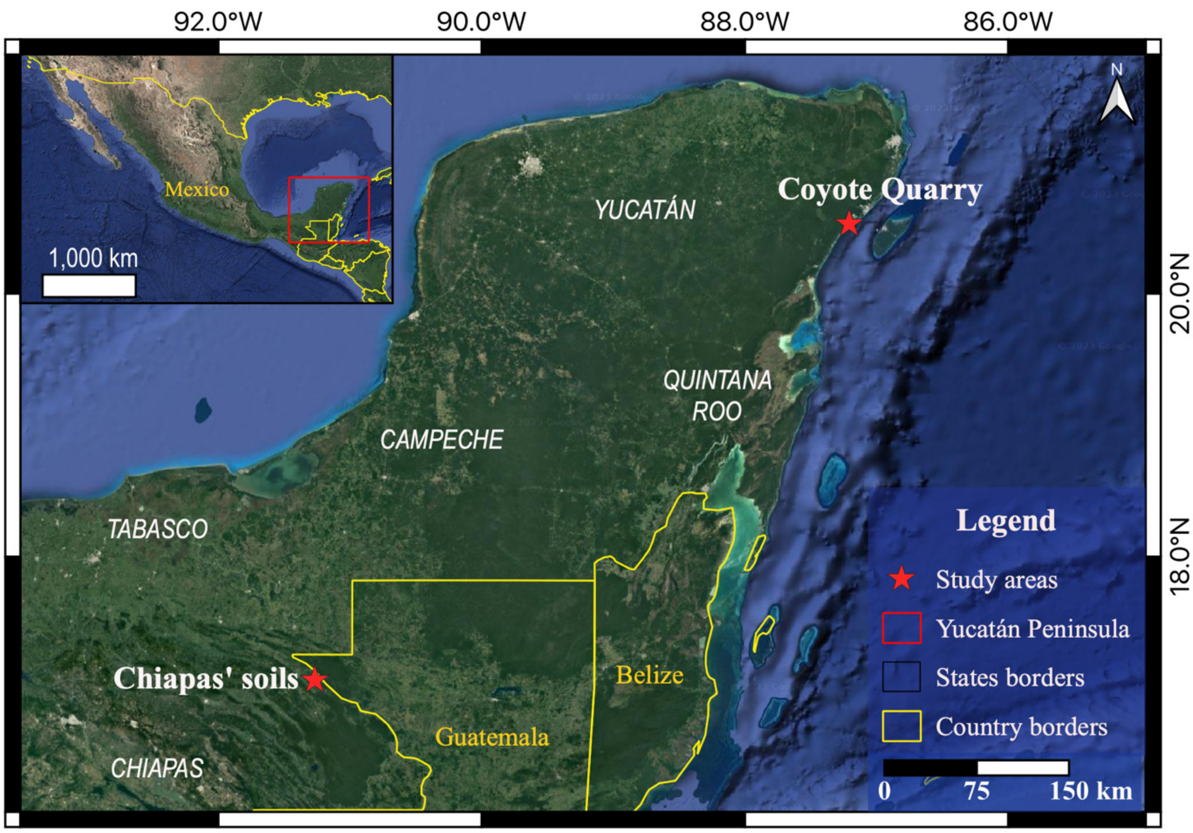

Figure 1. Studied area's location in the Maya Lowlands in southeastern Mexico. The recent burning site near to Chiapas and Guatemala border and the Pre-Hispanic Maya site in the Yucatan Peninsula at Quintana Roo northern coast.

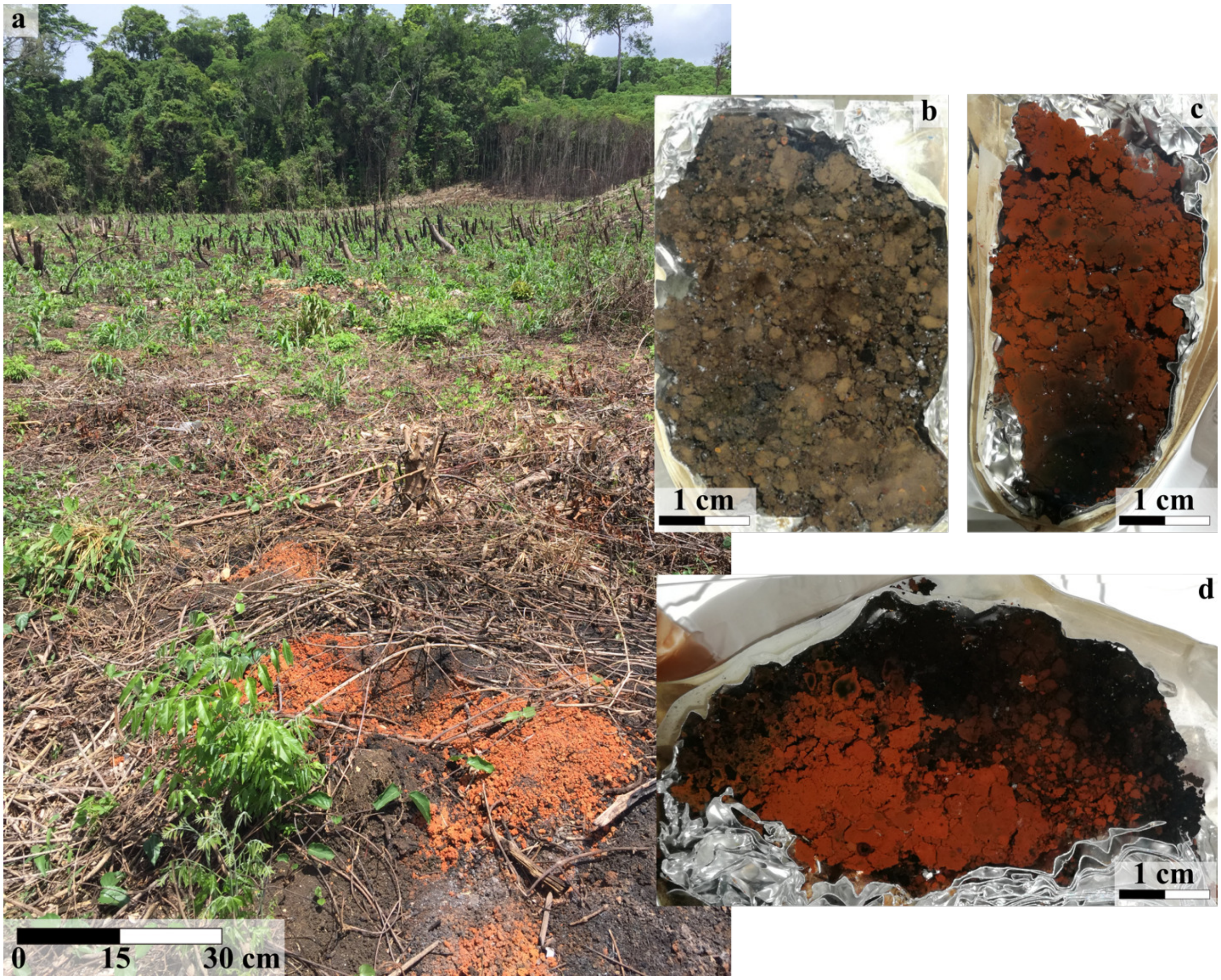

Figure 2. a) Slash-and-burn agriculture in Chiapas tropical forest. b) Unburned black soil sample (CH03, Leptosol), c) burned black soil (CH02, Leptosol), and d) burned red soil (CH04, Luvisol) from the site mentioned in a). Landscape photo by Sergey Sedov.

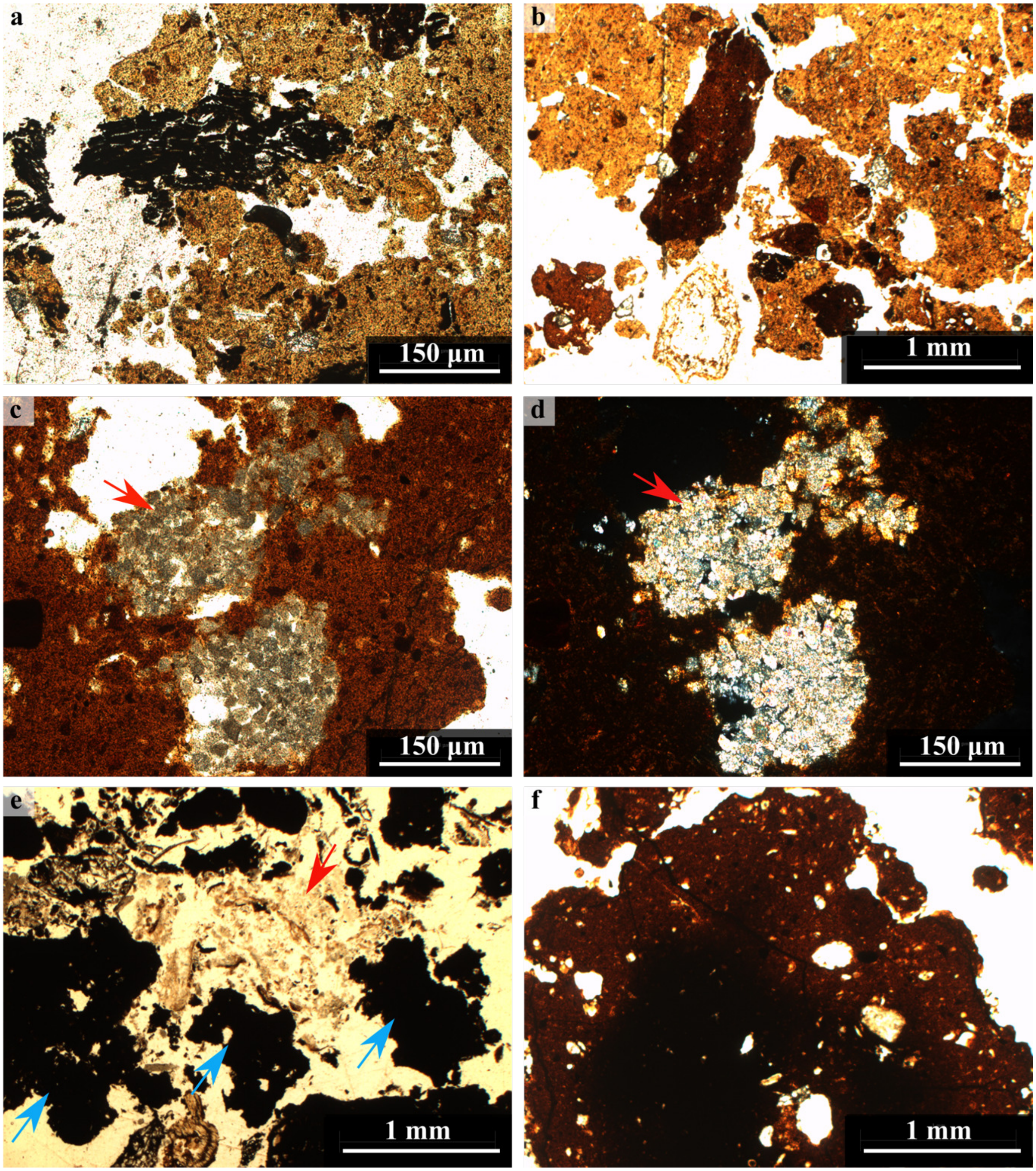

Figure 3. Micromorphology of soils from Chiapas site. a) Charcoals fragments and b) charred dark reddish pedosediments included in a clayey groundmass of the unburned black soil (CH03, Leptosol), with parallel polarized light (PPL). c) Pyrogenic calcite crystals (red arrow) with individual rhomboidal shape result of ashes filling pores in a reddish clay matrix of the burned

black soil (CH02, Leptosol; PPL). d) Same pyrogenic calcite crystals (red arrow) as c), but with cross polarized light (XPL). e) Amorphous char (blue arrows) and ashes (red arrow) in the burned red soil (CH04, Luvisol; PPL). f) Burned reddish-clay aggregate with a dark nucleus in the burned red soil (CH04, Luvisol; PPL).

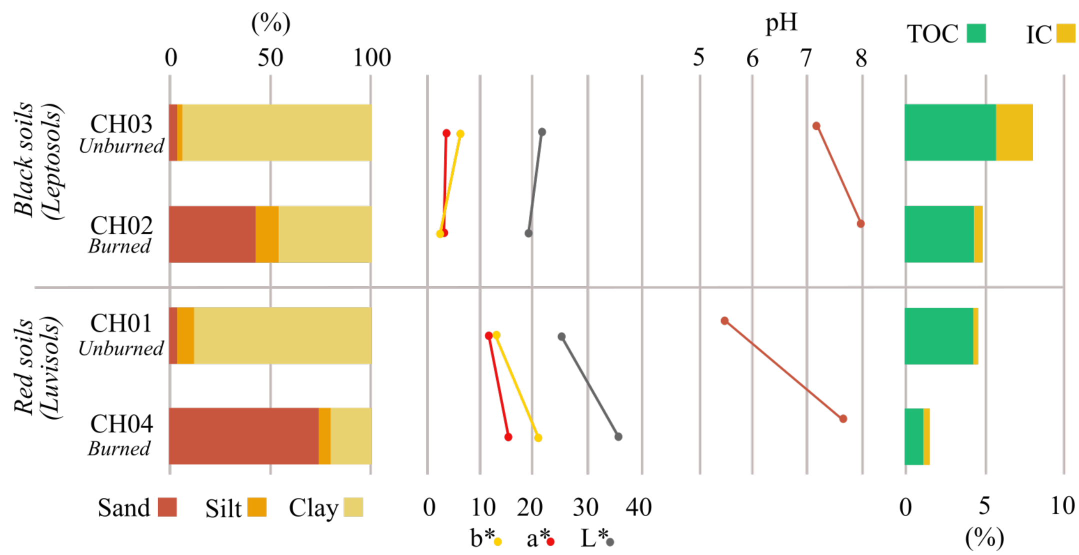

Figure 4. Physical-chemical characteristics of soils from Chiapas site. From left to right: texture, color parameters (a*, b*, and L*), pH, total organic carbon and inorganic carbon.

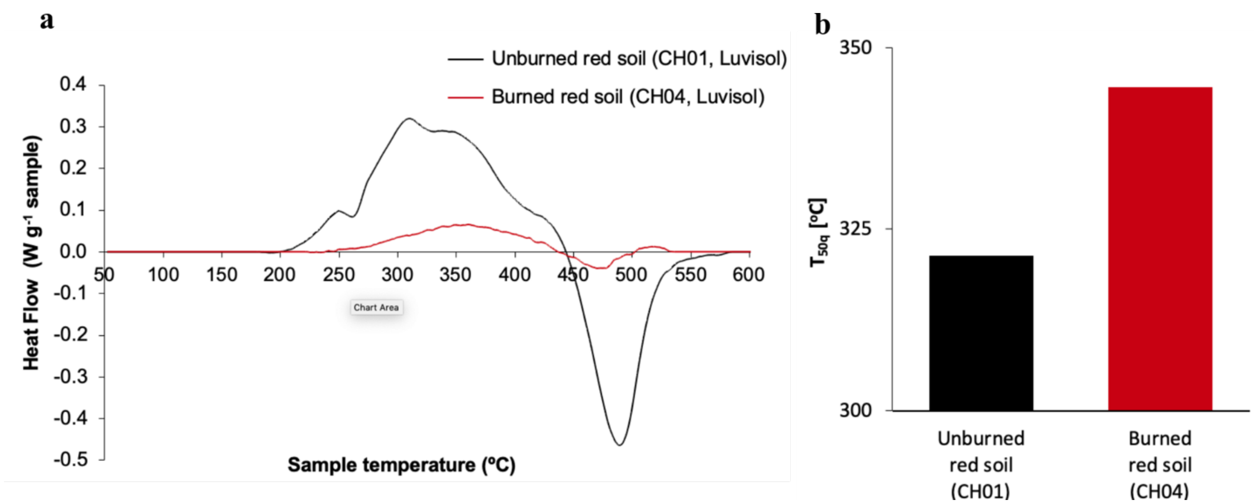

Figure 5. Thermogravimetry analysis (TGA) curves and differential scanning calorimetry (DSC) parameter T_{50q} (Temperature when the 50 % of the energy is released) from the red soils from Chiapas (unburned and burned Luvisols).

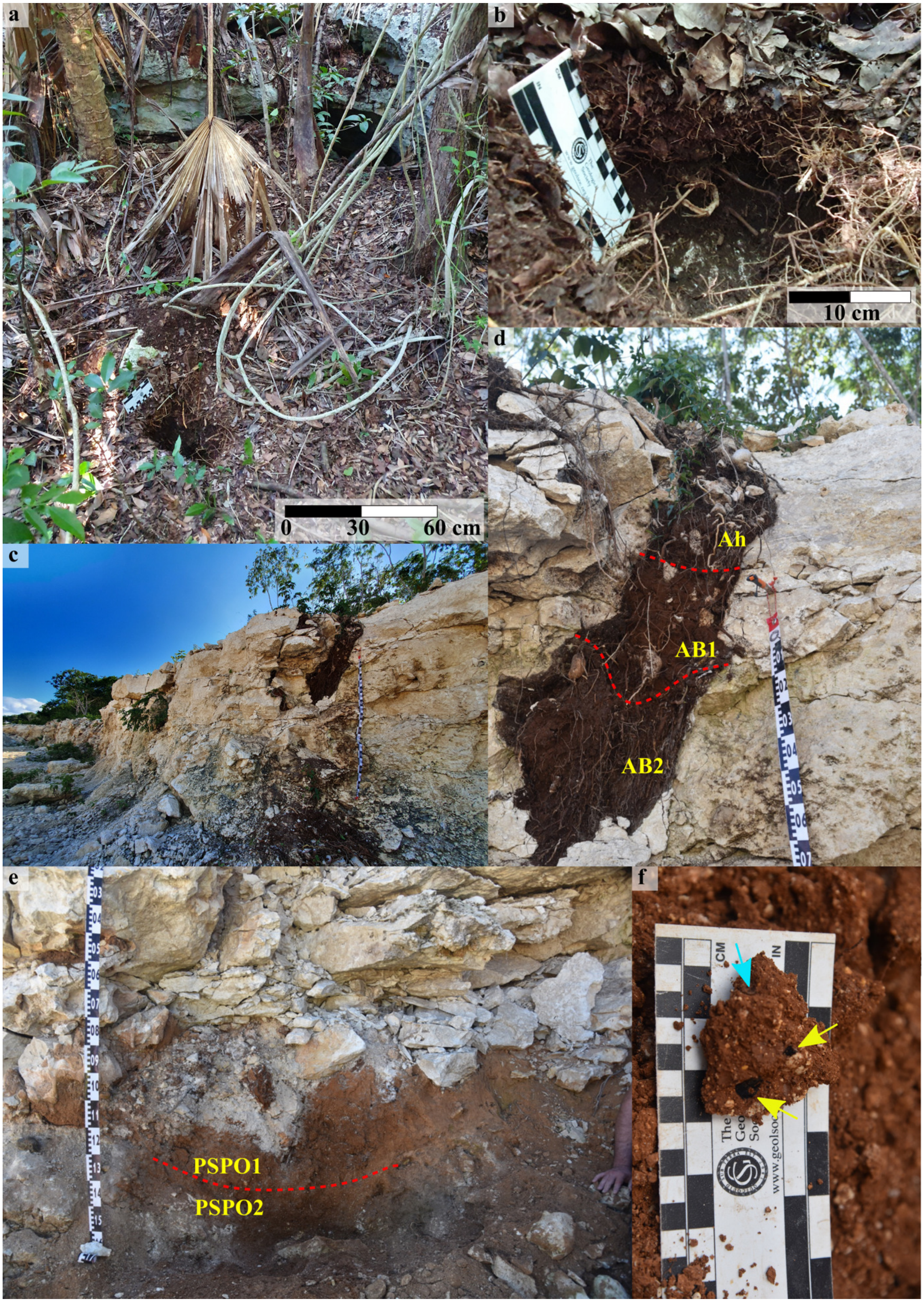
a
b
10 cm
0
30
60 cm
c
d
Ah
AB1
AB2
e
PSPO1
PSPO2
f
CM
IN

Figure 6. Coyote Quarry sampling sites. a) Selva-depresión landscape and b) soil profile. c) Coyote Quarry west wall with d) Negra Gorda soil karstic pocket. e) Collapsed cave with PSOP1 and PSOP2 pedosediments. f) Pedosediment from the collapsed cave, yellow arrows indicate charcoal fragments and the blue arrow a burned shell fragment. Photos by Sergey Sedov and Jaime Díaz.

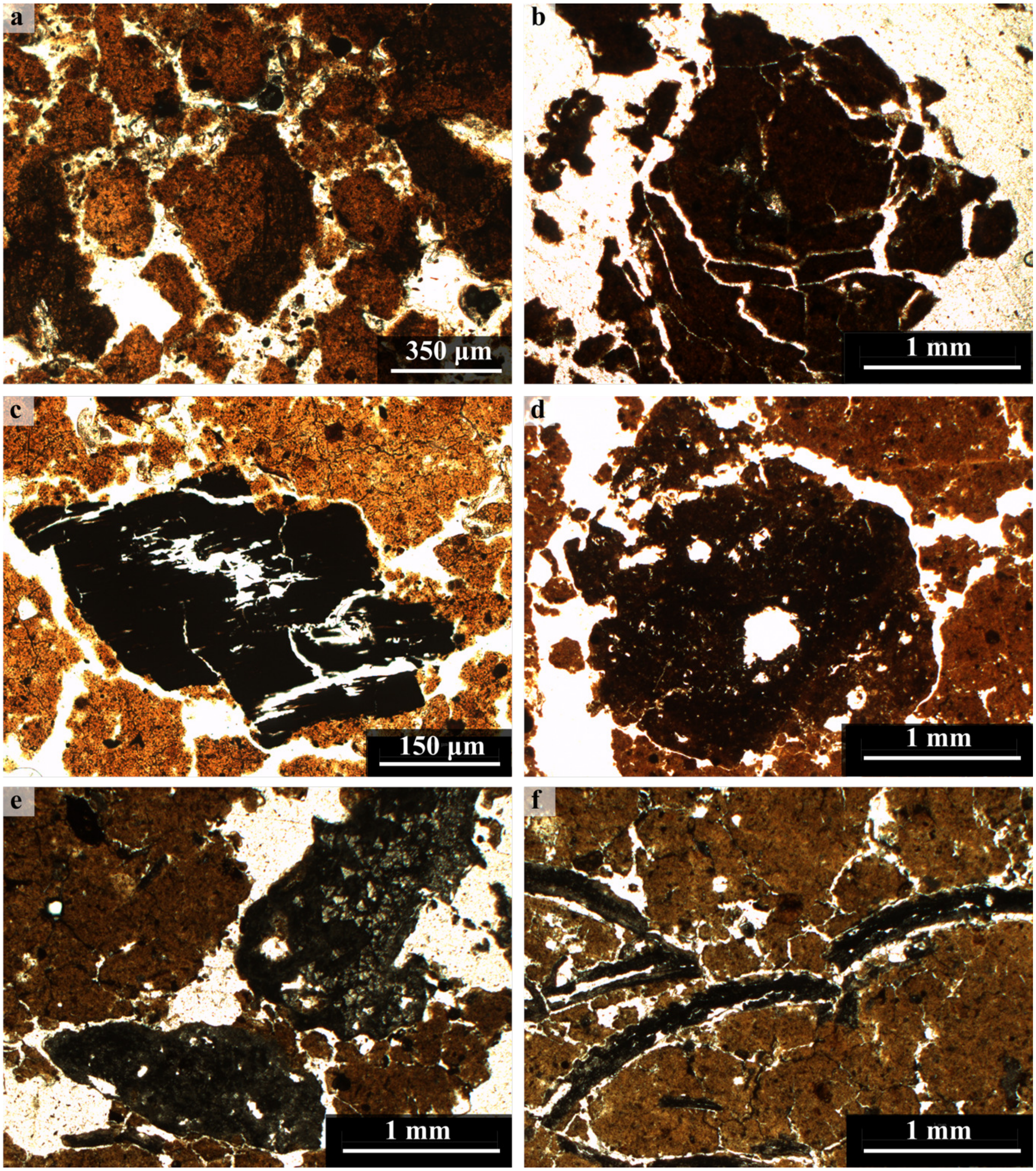

Figure 7. Micromorphological features of soil and pedosediments of Coyote Quarry. a) Granular structure with a clay-reddish groundmass and some aggregates are pigmented with humus (darker color) and b) a clay-rich subangular aggregate from Selva-depresión Ah horizon. c) Charcoal

fragment and d) dark pedosediments into the soil clayey matrix of the AB1 horizon in Negra Gorda profile. e) Charred limestones fragments and f) burned shells in the PSPO2 pedosediments.

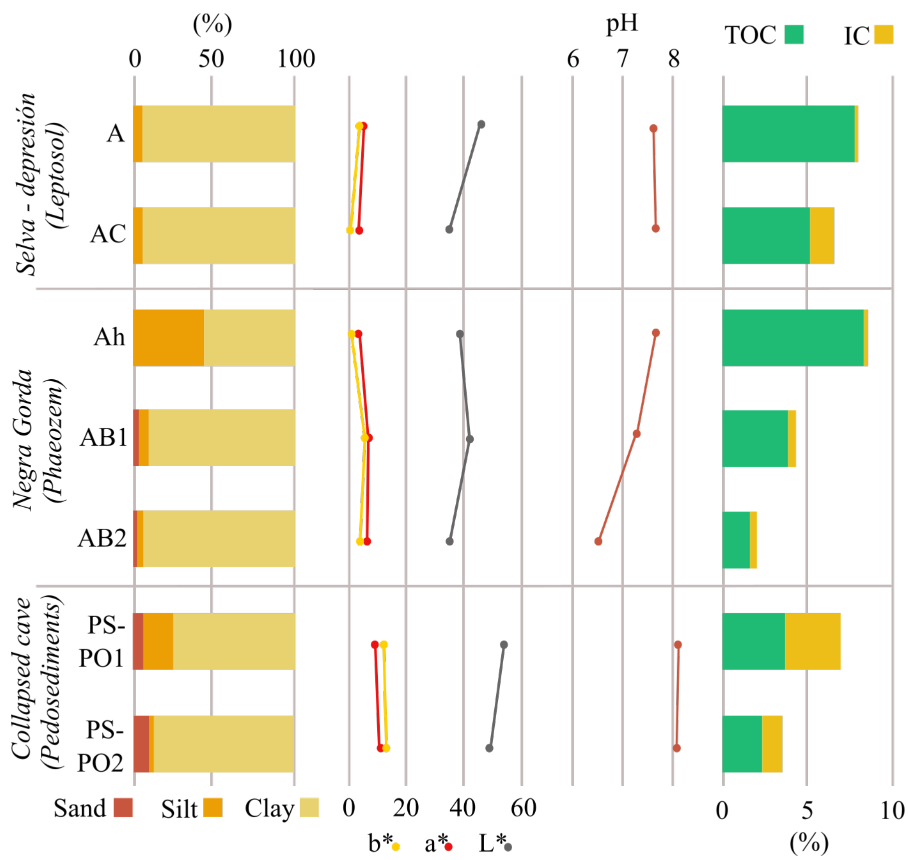

Figure 8. Physical-chemical characteristics of soil and pedosediments from Coyote Quarry. From left to right: texture, color parameters (a*, b*, and L*), pH, total organic carbon and inorganic carbon.

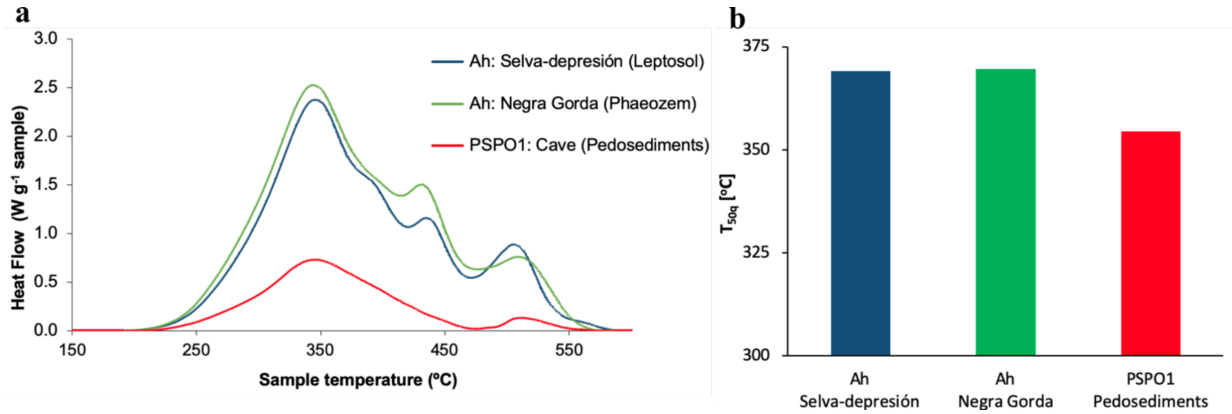

Figure 9. Thermogravimetry analysis (TGA) curves and differential scanning calorimetry (DSC) parameter T_{50q} (Temperature when the 50 % of the energy is released) from the soils and pedosediments of Coyote Quarry.

2.3. Magnetic properties as indicators of pedogenic and pyrogenic processes at the Upper Paleolithic site of Kostenki 14

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Magnetic properties as indicators of pedogenic and pyrogenic processes at the Upper Paleolithic site of Kostenki 14

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Abstract

In geoarchaeological studies, there is an issue with distinguishing between natural and anthropogenic signals in pedological paleoarchives. With the pedostratigraphy of the Upper Paleolithic site of Kostenki 14, this issue is reflected by problems with the determination of features of pedogenic and pyrogenic processes. This issue was addressed by means of a thorough analysis of the magnetic properties of paleosols accompanied by micromorphological observations. Most of the humic samples were shown to be a result of pedogenesis, but two samples (a Paleolithic hearth sample and a sample from paleosol IIc) had features of intensely burnt material. The difference in the typical intensity of large-scale (natural or human-induced) and local-scale anthropogenic fire allowed for suggesting that the magnetic properties of the burnt sample were the result of an anthropogenically controlled fire event, that is, a hearth. This study shows that the magnetic properties of paleosols can be used to differentiate anthropogenic activity, in particular—burning, from pedogenic processes. This indicator is especially helpful in finding disturbed combustion features when the hearth structure is lost. This methodology used to demonstrate the local human-induced pyrogenic effect at the Upper Paleolithic site can contribute to the discussion of the niche construction effect of human activities in the Pleistocene.

KEYWORDS
combustion features, cultural horizons, humic horizons, magnetic properties, micromorphology

1 | INTRODUCTION

During the Late Pleistocene, *Homo sapiens* dispersed over vast areas of several continents and entered the East European Plain at around 48–40 ka cal. B.P. (Hoffecker, 2009). This human migration occurred over Pleistocene soils, with humic topsoils being common at archaeological sites. Humic topsoils form under stable surface conditions with low sedimentation and erosion rates. During human occupation, the accumulation of artifacts and other products of human activity such as combustion features would lead to the formation of cultural layers (CLs). Therefore, such in situ CLs are often found within upper horizons of buried paleosols incorporated into pedosedimentary sequences at archaeological sites, although a preservation bias may also explain their frequent concurrence with humic topsoils. When CLs and paleosols coincide, the issue of distinguishing between tightly interconnected anthropogenic and natural signals arises. The natural processes are mainly represented by soil formation. The anthropogenic signals depend on the type and intensity of human activity. Even though such anthropogenic impact as organic waste disposal, which may enhance the development of humic horizons, and trampling recognized at the microscopic scale (Schilt et al., 2017) are common at archaeological sites, pyrogenic processes leave the most prominent anthropogenic indicators. Pyrogenesis may be related to natural fires (e.g., Keeley et al., 2011; Leys et al., 2013), to large-scale human-induced burning affecting territories beyond Paleolithic settlements (Roebroeks et al., 2021; Thompson et al., 2021), or to controlled regular fires in hearths (e.g., Henry, 2012; Karkanas et al., 2007).

Human activity was accompanied by complex niche construction (Boivin et al., 2016; Nikulina et al., 2022), which means that by modifying their environment, humans influenced their own and other species' evolution (Odling-Smee et al., 2003). One of the most significant aspects of niche construction is the use of fire, that is, by using fire, humans had the capacity to modify their environments, which reciprocally determined some of their genetic and cultural traits (Attwell et al., 2015, and references therein). Importantly, both local scales of human-controlled fire, that is, wood-fueled hearths (Attwell et al. [2015] and references therein), and larger-scale human-induced burning of vegetation on the landscape (Nikulina et al., 2022; Roebroeks et al., 2021; Thompson et al., 2021) have been studied in the frame of human niche construction. Even though the theoretical background of the effects of local fire use on human genetic and cultural traits has been quite well established (Attwell et al. [2015] and references therein), these ideas still need to be tested at each and every site where local-scale fire traces are preserved. New evidence from the sites of a wider geographical and temporal range could enrich or question the current knowledge on niche construction effects of fire use. In addition, only after human-induced large-scale fire is confirmed can the advanced human–nature interaction strategies applied by inhabitants be suggested. These strategies are mainly centered on manipulation of food resources, that is, the presence and abundance of vegetation and animal species (Nikulina et al., 2022). Therefore, within the rapidly developing concept of human niche construction during the Paleolithic (e.g., Attwell et al., 2015; Boivin et al., 2016; Kendal et al., 2011; O'Brien & Bentley, 2021; Odling-Smee et al., 2003; Thompson et al., 2020), the identification of pyrogenic signals of combustion features (both local and large-scale) and, most significantly, such features with lost structure due to postdepositional processes, becomes a particularly important task. This task is especially urgent in Upper Paleolithic sites for several reasons. First, there is a lack of detailed studies of the combustion features at Upper Paleolithic sites (Murphree & Aldeias, 2022). Second, in the Upper Paleolithic, *H. sapiens* dispersed across wider environments, including the colder tundra steppe landscapes of Europe, which required cultural adaptation to survive. Fire was likely one of the main adaptation tools (Attwell et al., 2015; Gowlett, 2006). Finally, the Upper Paleolithic population already had symbolic thinking and could be characterized by modern behavior (Kissel & Fuentes, 2018; Meneganzin & Currie, 2022), which could result in a more diverse use of fire than before. For example, there is evidence that in the Upper Paleolithic, fire was used to produce objects of mainly symbolic significance (Murphree & Aldeias, 2022). Therefore, the task of detecting and studying the combustion features at Upper Paleolithic sites is crucial for understanding the diverse application of fire as a tool by behaviorally modern humans during the process of their adaptation to new environments.

The issue of equifinality of pedogenesis and pyrogenesis in dark humus soil horizons often arises at archaeological sites (Alperson-Afil, 2012; Barbetti, 1986; Bellomo, 1993; Deldicque et al., 2021; Stahlschmidt et al., 2015). Common analyses such as magnetic susceptibility and micromorphology often fail to identify the origin of dark material. In thin section, for example, dark pigment resulting from burning and consisting of dispersed "black carbon" (Gerlach et al., 2012) is difficult to distinguish from humus. When using magnetic susceptibility to identify the pyrogenic signal, the natural topsoil horizons enriched with humus due to pedogenesis might have equally high values of magnetic susceptibility and dark color due to a high amount of dispersed organic matter. This discrimination of two signals is especially important for cases where CLs do not contain (or have only few) macroscopic wood charcoal fragments—the direct indicators of burning, which is a common situation at Paleolithic sites (Marquer et al., 2012), and, thus, requires additional diagnostic criteria. We suggest solving this issue by means of a detailed analysis of magnetic properties.

Magnetic characteristics are frequently used in pedological (e.g., Blundell et al., 2009; Clement et al., 2011; Dearing et al., 1996), paleopedological (e.g., Kravchinsky et al., 2008; Kukla, 1987; Maher, 1998), and geoarchaeological (e.g., Crowther, 2003; Lowe et al., 2016; Ozán et al., 2020; Wang et al., 2010) studies. The values of magnetic parameters depend on the concentration of iron-bearing magnetic minerals, their grain size, and mineralogical composition (Maher, 1998). For example, magnetite and maghemite (ferrimagnetic minerals) show the strongest magnetic properties, while other major iron oxides have very weak magnetic properties (Schwertmann & Taylor, 1977). At high temperatures (above 350°C), produced by burning, weakly magnetic iron oxides, hydroxides, and carbonates are transformed into magnetite or maghemite, which results in magnetic enhancement (Le Borgne, 1960; Kletetschka & Banerjee, 1995; Schwertmann & Heinemann, 1959). Therefore, burning often results in magnetic enhancement of soil samples (e.g., Clement et al., 2011; Jordanova et al., 2019). In addition, the smaller the grain size of magnetic particles (single-domain and superparamagnetic [SP]) (Dankers, 1978; Maher, 1988) and the higher their concentration, the stronger the magnetic properties of the material (Evans & Heller, 2003; Maher, 1998).

Various physical, chemical, and biological processes in soils often result in their magnetic enhancement relative to sedimentary layers (Le Borgne, 1955; Kukla et al., 1988; Maher, 1998). Some of these processes are in situ formation of magnetite under oxidizing conditions (Maher & Taylor, 1988; Taylor et al., 1987) or its destruction under reducing conditions; precipitation/formation of magnetic minerals due to bacterial activity (Fischer, 1988; Lovley et al., 1987; Stanjek et al., 1994); or weathering of iron-bearing minerals as a result of repeated wetting–drying cycles (Dearing et al., 1996). Thus, pedogenetic processes could produce a quite similar effect as burning, resulting in the increase of magnetic susceptibility in the topsoil horizons. Detailed magnetic measurements allow for the differentiation between pedogenic and pyrogenic signals, even though they might not be detected by other methods.

The magnetic response of soil material to burning is complex and variable (Gedye et al., 2000). It depends on fire intensity (Roman et al., 2013), fire temperature (Bailey & Anderson, 1980; Till et al., 2021), fire duration (Roman et al., 2013), magnetic mineralogy of the soil, organic matter content, and the heterogeneity of its distribution (Blake et al., 2006; Canti & Linford, 2000). Both fire intensity and fire temperature depend on the quality and quantity of fuel (Bailey & Anderson, 1980; Bellomo, 1993; Roman et al., 2013). Moreover, it was experimentally shown that magnetic properties do not change unless the burning temperature is above 200°C (Roman et al., 2013; Till et al., 2021), which is considered a fire of moderate intensity in many experiments.

To differentiate between pedogenic and pyrogenic magnetic minerals, a method was proposed by Oldfield and Crowther (2007). It is based on two facts: (1) finer ferrimagnetic minerals are produced during pyrogenesis rather than during pedogenesis (Longworth et al., 1979; Rummery et al., 1979) and (2) for grains of the size below the stable single-domain/SP transition, values of quotients χ_{ARM}/χ_{lf} and χ_{ARM}/χ_{fd} increase with an increase in the magnetic grain size, where χ_{lf}—low field magnetic susceptibility, χ_{fd}—frequency-dependent magnetic susceptibility, and χ_{ARM}—anhysteretic remanent susceptibility. The original experiment consisted of burning samples from the humic horizons of forest soils developed on Jurassic bedrock in England at 650°C under reducing conditions for 1 h. As a result, it was demonstrated that the burnt and unburnt samples are distinguished into two separate envelopes on the bilogarithmic plot of the quotients χ_{ARM}/χ_{lf} and χ_{ARM}/χ_{fd}. This temperature is significantly higher than most of the temperatures reached at the soil surface in field experiments during burning under natural conditions (Bailey & Anderson, 1980; Canti & Linford, 2000; Ketterings & Bigham, 2000; Mallol et al., 2013). Thus, considering the temperature and duration of burning of the material in the original experiment, the researchers followed mimicking of strong and intense fires. It should be highlighted that the method suggested by Oldfield and Crowther (2007) is unable to detect the influence of low or moderately intense burning by design or distinguish them from the absence of burning. Nonetheless, the expectation arises that the analysis of the distribution of samples on the bilogarithmic plot of these quotients developed for the recent soils and their experimental burning may also be applied for the interpretation of magnetic properties of paleosols associated with CLs at Paleolithic sites.

We applied the methodology of Oldfield and Crowther (2007) to the paleosol–sedimentary sequence at the archaeological site of Kostenki 14 (K14), where the problem of distinguishing between pyrogenic, that is, archaeological (assuming that pyrogenesis is related to anthropogenic activity), and pedogenic, that is, natural, processes, remains unsolved. One of the most prominent units of the paleosol sequence at K14 is paleosol unit II[1] or the so-called Upper Humic Bed, which contains several dark humic horizons (Ah). It consists of 2–4 levels of polygenetic paleosols consisting of Ah-BCk horizons, overlain by a gleyed Bg horizon. Several hypotheses of its pedogenesis have been suggested: soil development influenced by springs and groundwater seepage (Holliday et al., 2007), "cryo-arid" soil formation under cold steppe (Sedov et al., 2010; Velichko et al., 2009), and Rendzina development under boreal coniferous forest (Sedov et al., 2022), all focused on the natural pedogenic processes. We propose a fourth scenario, first presented at the conference "Routes of Evolutionary Geography—2021" (Kurgaeva et al., 2021), which states a pronounced effect of burning related to anthropogenic activity on the paleosols associated with CLs at Kostenki. Analysis of the magnetic susceptibility of paleosols and sediments indicated significant peaks in Ah humic horizons of unit II, which was previously attributed solely to pedogenic enhancement (Sedov et al., 2010). However, the frequent concurrence of these humic horizons with CLs at K14 (Sinitsyn & Hoffecker, 2006; Velichko et al., 2009) has led us to consider the hypothesis that anthropogenic fires could have affected at least some humic horizon(s). Therefore, according to this hypothesis, high values of magnetic susceptibility are assumed to be mostly the result of pyrogenic processes, which might be related to the anthropogenic impact of Upper Paleolithic people.

The objective of this study is to differentiate the pedogenic and pyrogenic origins of the dark organic soil horizons at the archaeological site of K14 by analyzing the magnetic properties of the material and applying the method proposed by Oldfield and Crowther (2007), supported by micromorphological observations. In addition, the anthropogenic nature of the detected fire impact and its relation to fire intensity were thoroughly discussed. Such complete characteristics of rock magnetic properties of paleosols and CLs for the Paleolithic sites of Eastern Europe are obtained for the first time.

[1]In this study, we use the designation of paleosol units developed by Sedov et al. (2010).

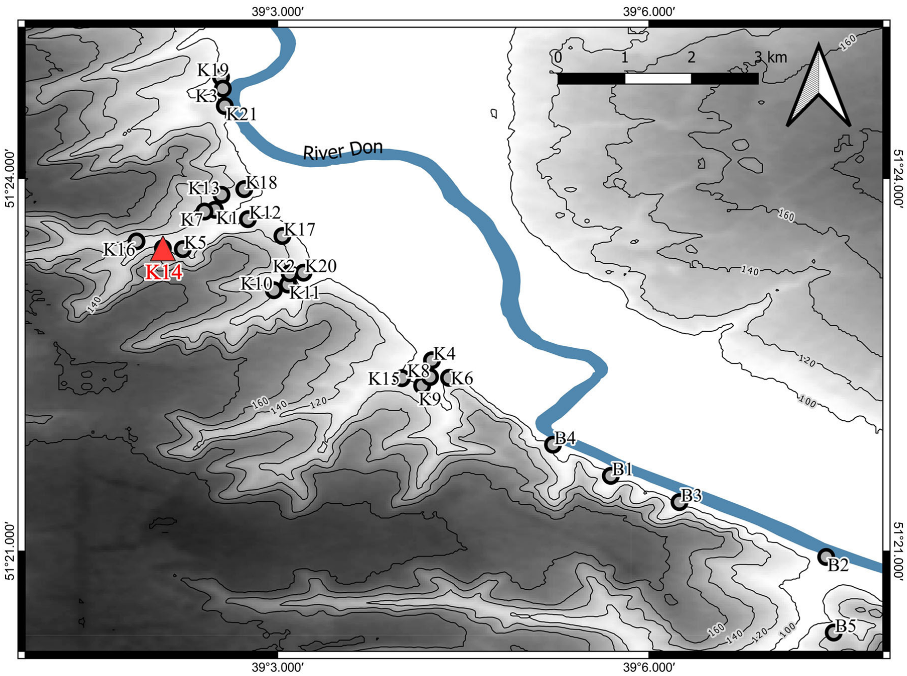

FIGURE 1 Location of the archaeological sites of the Kostenki–Borshchevo complex. Kostenki 14 (K14), the key section of this study, is marked by the red triangle; other sites are marked by circles. K in a title of a site represents "Kostenki"; B represents "Borshchevo." The elevation model represents highs with darker shades and lows with lighter shades of gray.

2 | THE STUDY SITE

2.1 | Landscape setting and archaeological context of the site

The Kostenki–Borshchevo archaeological complex is one of the best-known Upper Paleolithic sites located in the center of the East European plain, close to the city of Voronezh, in the upper reaches of the River Don Valley. Here, there are nearly 30 sites with signs of Paleolithic human habitation, 10 of which are multilayered (Figure 1) (Anikovich et al., 2008; Praslov & Rogachev, 1982; Rogachev, 1957; Sinitsyn, 2015). One of the most comprehensively investigated and richest sites is K14 (e.g., Rogachev, 1957; Sinitsyn, 1996, 2015). The site is positioned on the right slope of the Pokhrovskii Ravine—the right tributary of Don. The excavation trench cuts through the deposits of the colluvial fan overlying the alluvial deposits of the second terrace of the river Don (Velichko et al., 2009).

According to the numerous radiocarbon dates available for K14, this area was repeatedly occupied between ~36.5 and ~22 ^{14}C ka B.P.[2] The excavations, which started in the early 2000s and continue to this day, have revealed eight CLs[3] and three paleontological layers, represented by faunal remains without any archaeological components (Sinitsyn, 2015) (Figure 2). The overview of all CLs as well as corresponding paleosols and sedimentary units are presented in Table 1. The selected radiocarbon ages and their calibration dates are shown in Table 2. Besides CLs, there is a burial under CL 3 (Debetz, 1955; Rogachev, 1955), which contains the oldest dated skeletal remains of anatomically modern humans (AMHs) in Eastern Europe, according to a direct radiocarbon date of 33.3 ^{14}C ka B.P. (Marom et al., 2012). The layer of Campanian Ignimbrite tephra dated to 34.3 ^{14}C ka B.P. (Dinnis et al., 2021; Giaccio et al., 2008; Pyle et al., 2006) is considered a crucial reference chronostratigraphic marker within the Kostenki–Borshchevo archaeological complex. Currently, the series of lowermost CLs (4a, 4b, 4w) are the most significant for understanding the history of the primary dispersion of early AMHs within the East European Plain.

A so-called "horizon of hearths", which is important for the purpose of our study, was identified as an in situ part of CL 4b in paleosol V, as the hearths of CL 4b likely belong to the same

[2]Hereafter, all given dates are radiocarbon and uncalibrated.

[3]In archaeological articles, cultural layers (CLs) at Kostenki sites are attributed by Roman numerals (I–IV). However, to differentiate them from paleosol units, which are also indicated by Roman numerals after Sedov et al. (2010), for CLs, we use Arabic numerals (CL 1–4).

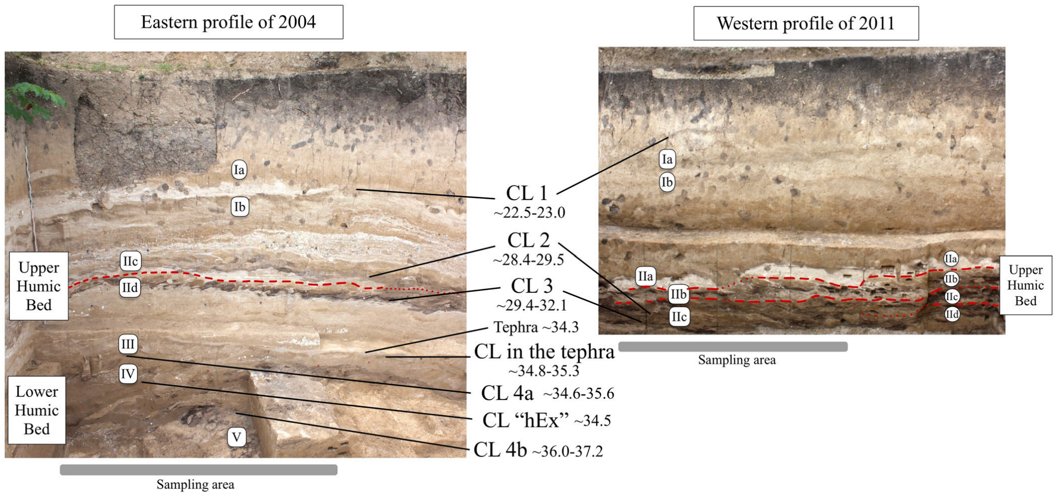

FIGURE 2 Stratigraphy of the southern wall of the key section Kostenki 14. Archaeological cultural layers are stated between the photographs of the profiles with radiocarbon dates in ^{14}C ka B.P. The paleosols are marked by Roman numbers in rounded squares. They are attributed according to Sedov et al. (2010), with minor changes (Figure 3). Paleosols IIc and IId at the eastern profile were originally entitled IIa and IIb (Sedov et al., 2010) (Figure 3). The red dashed lines distinguish the borders between paleosols of unit II. The dotted red line illustrates the approximate border, which is shown with a certain degree of uncertainty. The gray areas under the profiles show the approximate area of the profile, where the sampling was performed (the sampling schemes are shown in Figures 4 and 5). The eighth CL 4w (~36.2–36.8 ^{14}C ka B.P.) is out of the scope of these photographs.

settlement phase. The horizon contains "sharply limited lenses of redbrick burnt loam within black humic sediment that also exhibits a restricted spatial distribution" (Sinitsyn & Hoffecker, 2006, p. 168) (Figure 4). In the field, these lenses were identified as preserved in situ hearths (Sinitsyn & Hoffecker, 2006).

Geologically, the K14 section represents a sequence of paleosols and sediments, which is common for many other sites of the Kostenki–Borshchevo group. This sequence of pedosedimentary units is as follows: two humic beds are separated by loamy colluvial sediments containing a volcanic ash layer and are overlain by a pale brown silty cover bed of colluvial origin with the admixture of loess. Within this cover bed, incipient brown paleosols were developed and it served as parent material for the Holocene Chernozem, which caps the sequence (Sedov et al., 2010; Velichko et al., 2009) (Figure 2). From the pedostratigraphical perspective, the section of K14 consists of five paleosol units,[4] every one of which contains at least one CL (Sedov et al., 2010; Velichko et al., 2009) (Table 1). Most of the paleosols are represented by weakly developed slope soil varieties. They are relatively thin and disturbed by slope and cryogenic processes (Sedov et al., 2010). The special interest of the study is related to paleosol unit II because of its distinguished appearance and still ambiguous genesis. It was formed during the second half of Marine Isotope Stage 3, simultaneous with the formation of the Bryansk soil in watershed position (analogs of the Bryansk soil in Western Europe are Lohne in Germany, Stillfried B in Austria, Vytachiv and Dubno paleosols in Ukraine, etc.) (Sycheva & Khokhlova, 2016).

2.2 | Previous paleopedological research

In 2004, the excavation opened up the profile at the eastern part of the site (eastern side of the promontory) with two full paleosol subunits within unit II. These subunits were originally labeled as IIa and IIb (Sedov et al., 2010; Velichko et al., 2009). In 2011, the western part of the site, representing the crest of the promontory, was excavated. There, the profile included three (IIa, IIb, IIc) to four (IIa, IIb, IIc, IId) full subunits of unit II (Korrka et al., 2017). Since the correspondence of the subunits has not yet been observed in the field, this issue is still under discussion. Our understanding of this matter is presented in a scheme in Figure 3. At the western profile, the transition of paleosol IIc at the profile with three full subunits to paleosols IIc and IId at the profile with four full subunits was observed in the wall of the excavation pit (Figure 2). CLs 2 and 3 became the specific markers of this unit. Their positions allowed for correlating paleosols as shown in Figure 3. The presence of remnants of eroded paleosols at the eastern profile explains the observed situation: paleosols IIa and IIb existed at the eastern profile but were eroded. Thus, in our opinion, two paleosols of the eastern section should be renamed IIc and IId as a result of their spatial correlation

[4]Paleopedological units are titled by Roman numerals after Sedov et al. (2010).

TABLE 1 Overview of the cultural layers and corresponding pedosedimentary characteristics.

No.	Cultural layer	Age, ^{14}C ka B.P. (Table 2)	Archaeological characteristics	Paleosols (Sedov et al., 2010)	Geological unit (Holliday et al., 2007; Pietsch et al., 2014; Velichko et al., 2009)
1	CL 1	22.5–23.0	The Kostenki–Avdeevo culture of the Late Gravettian period; a series of typical shouldered points (Sinitsyn, 2015).	Paleosol Ib—"Gmelin soil" AB-BC-C profile, ephemeral and deformed.	*Unit 1* Loamy colluvial deposits with lenses of fragments of cretaceous chalk.
2	CL 2	28.4–29.5	The Gorodtsovian archaeological culture, distinguished by particular lithic and bone assemblages (Rogachev, 1957; Sinitsyn, 2015).	Paleosol IIc (IIa by Sedov et al., 2010). Bg-Ah-BCk profile, deformed (discussed in detail below).	*Unit 2* So-called Upper Humic Bed; paleosol unit II (Sedov et al., 2010). Colluvial deposits of high stratigraphic heterogeneity of debatable origin (discussed in detail below).
3	CL 3	29.4–32.1	The absence of prominent typological features of artifacts poses the problem of cultural identification of the assemblage of this CL (Sinitsyn, 2015).	Paleosol IIc/IId (IIb by Sedov et al., 2010). Bg-Ah-BCk profile, deformed (discussed in detail below).	
4	CL in the tephra layer	34.8–35.3	The Early Aurignacian (Sinitsyn, 2003, 2014).	Paleosol III AB-BC-C profile, poorly developed and deformed.	*Unit 3* Silty loam colluvial deposits with calcareous material, which contains the discontinuous layer of Campanian Ignimbrite tephra.
5	CL 4a	~34.6–35.6	A horse slaughtering and butchery site, a result of one or two driven hunting events (Prilepskaya et al., 2020; Sinitsyn, 2015).	Paleosol IV A-AC profile, cryogenically deformed.	*Unit 4* So-called Lower Humic Bed Loam colluvial deposits cut by a shallow ancient erosion gully (mainly filled with layered sandy loam).
6	CL "hEx"	~34.5	Horse remains with few lithics and bone artifacts. Cultural identification is impossible because of the low number of artifacts.	The base of the paleosol IV, containing the geomagnetic Laschamp-Kargapolovo excursion (Gernik & Guskova, 2002; Guskova et al., 2012).	
7	CL 4b (eastern part of the site)	36.0–37.2	New cultural unit comparable to the European Proto-Aurignacian: it includes a combination of the Aurignacian and Proto-Aurignacian features (Dinnis et al., 2021; Sinitsyn, 2014).	Paleosol V Developed on slope (~20° to the present-day surface), Ag-Bg-CG profile contained distinct gley features.	
8	CL 4w (western part of the site)	36.2–36.8	Most probably the same settlement as the one within CL 4b but distinct by "domestic" activities connected with dwelling construction and storage pits. Includes pendants on Black Sea mollusk shells with the perforation for suspension (Sinitsyn, 2020).	Paleosol V In comparison with the eastern part of the site, this paleosol is less humified and more layered.	

Abbreviation: CL, cultural layer.

TABLE 2 Selected radiocarbon dates and their calibrated dates for cultural layers at K14.

Cultural layer	Laboratory index	^{14}C age, ka B.P.	Calibrated ^{14}C age, cal ka B.P. (±1 sigma)	Analyzed material	References
CL 1	OxA-4114	22,780 ± 250	27,335–26,520	Bone	Sinitsyn (2015)
	GrA-46676	22,940 ± 100	27,313–27,193	Charcoal	Sinitsyn (2015)
CL 2	OxA-4115	28,580 ± 420	33,389–32,098	Bone	Sinitsyn (2015)
	GrA-13312	29,240 ± 330/320	34,173–33,387	Charcoal	Sinitsyn (2015)
CL 3	GrN-21802	30,080 + 590/550	35,229–4090	Charcoal	Sinitsyn (2015)
	GrA-13288	31,760 ± 430/410	36,507–35,591	Charcoal	Sinitsyn (2015)
Burial under CL 3	OxA-2395-15	33,250 ± 500	38,841–37,265	Bone	Marom et al. (2012)
CL in the tephra layer	OxA-19021	35,080 ± 240	40,530–39,945	Charcoal	Douka et al. (2010)
	OxA-35311	34,400 ± 600	40,471–38,971	Bone	Dinnis et al. (2019)
CL 4a	OxA-21871	34,900 ± 340	40,451–39,708	Charcoal	Wood et al. (2012)
	OxA-21873	35,270 ± 350	40,795–40,028	Charcoal	Wood et al. (2012)
CL "hEx"	GrA-13279	34,550 ± 610/550	40,511–39,166	Charcoal	Sinitsyn and Hoffecker (2006)
CL 4b	GrA-10948	37,240 ± 430/400	42,206–41,696	Charcoal	Sinitsyn (2015)
	Beta-195966	36,970 ± 560	42,094–41,410	Charcoal	Sinitsyn (2015)
CL 4w	OxA-33981	36,350 ± 750	41,941–40,847	Bone	Dinnis et al. (2019)

Note: The radiocarbon dates were calibrated based on the Northern Hemisphere Radiocarbon Age Calibration Curve IntCal20 (Reimer et al., 2020). Abbreviations: CL, cultural layer; K14, Kostenki 14.

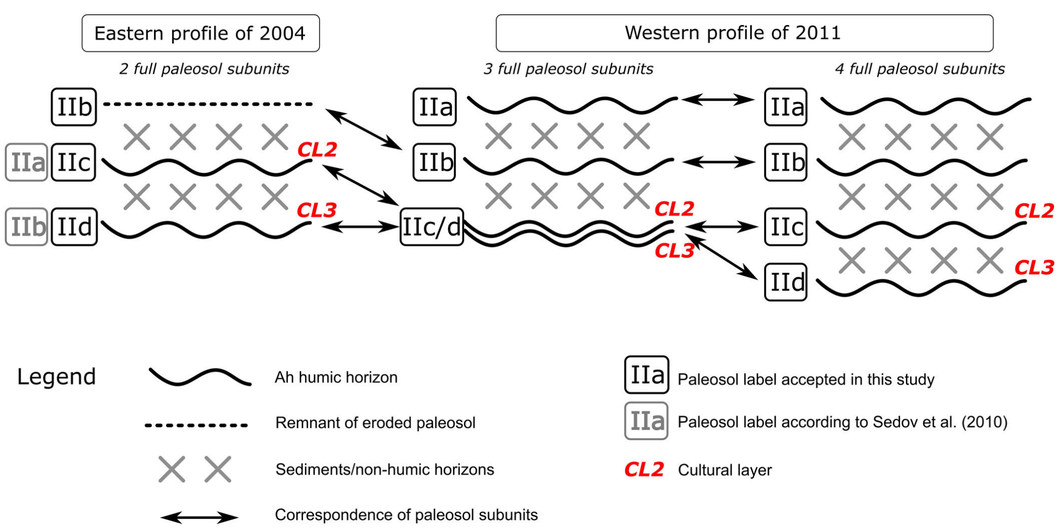

FIGURE 3 Scheme of Ah humic horizons in paleosol unit II, labels of paleosol subunits accepted in this study, and their correspondence along several profiles with different numbers of full paleosol subunits at Kostenki 14.

with paleosols of unit II of the western profile, which represent the fullest sequence of four paleosols.

Every paleosol of unit II is represented by a polygenetic paleopedological profile characterized by the same sequence of horizons: Bg-Ah-BCk. One subunit was formed as a result of two monogenetic soil formation phases, which were separated by the sedimentation event. During the first stage, the Ah-BCk profile was developed, whose genesis is still a debatable topic (the proposed models of its formation are outlined below). The second stage of soil formation was defined as redoximorphic (gleyic) pedogenesis. This type of pedogenesis took place due to waterlogging above shallow permafrost, which also triggered solifluction and cryoturbation processes. These processes were arguably responsible for the outlines of the convoluted, contorted, and wavy horizons observed in paleosol unit II (Sedov et al., 2010, 2022; Velichko et al., 2009).

As mentioned above, there are four hypotheses explaining the formation of the Ah-BCk profiles within paleosol unit II. According to the earliest hypothesis based on the macro- and micromorphological observations, the dark (corresponding to our Ah) and whitish calcareous (our BCk) horizons are soil sediments formed under the influence of local "seeps and springs" (Holliday et al., 2007, p. 218). Holliday et al. (2007, p. 221) state that the humic beds "probably represent quasistable landscape with soil formation repeatedly interrupted by slopewash sedimentation and local spring water flowing." They further suppose that "the organic-rich horizons reflect the concentration of hydrophilic plants and other intense biotic activity…", while the formation of calcareous horizons is explained as follows: "seeping, calcium-charged groundwater deposited lenses of primary carbonate…" (Holliday et al., 2007, p. 221). This scenario supposes an at least partly hydromorphic origin of the paleosols of paleosol unit II (although saturation conditions could be discontinuous and interrupted in some dry periods). It is congruent to the geomorphic position of the studied sites close to the ravine footslope, where also contemporary groundwater seepage is locally observed. However, Sedov et al. (2010) and Velichko et al. (2009) cast doubt on the hypothesis. Their micromorphological analysis revealed a well-developed granular structure that could have been formed by mesofauna activity requiring aerobic, well-drained conditions. Also, values of magnetic susceptibility demonstrated strong maxima in the dark horizons of paleosol unit II, which is atypical for a horizon formed under saturated reducing conditions (Sedov et al., 2010). The alternative hypothesis proposed by Sedov et al. (2010) and Velichko et al. (2009) states that these paleosols developed under cold steppe ecosystems; their recent analogs are known as cryo-arid soils found in south and east Siberia (IUSS Working Group WRB, 2022). Within this version, the dark horizons are the product of humification under grassland vegetation, whereas calcareous horizons are formed by carbonate illuviation (i.e., secondary calcite). The cold steppe hypothesis, however, is challenged by the contradicting evidence from the K14 palynological record showing high percentage of arboreal pollen, especially spruce in the Upper Humic Bed (Velichko et al., 2009). Therefore, the third hypothesis was recently offered, which interpreted these paleosol profiles as a forest Rendzina type. It considers the dark humus accumulation under coniferous forest on the shallow calcareous parent material to be the main soil formation process, and calcareous lenses to consist mostly of primary calcites (Sedov et al., 2022). It should be stressed that until now, all three hypotheses are insufficiently justified and none of these are free from internal constraints.

In the course of the attempts to further develop the above paleopedogenetic scenarios, a complementary fourth hypothesis arose, which focused on the anthropogenic factor of paleosol development within paleosol unit II (and probably of the other paleosol levels associated with CLs). It states that the humic beds were affected by human-induced processes: its dark color and high values of magnetic susceptibility have a pyrogenic origin, whereas numerous inclusions of artifacts and charcoal microfragments point to a large-scale incorporation of anthropic materials (Kurgaeva et al., 2021). It was even suggested that these paleosols could be classified as Urbic Technosols (according to IUSS Working Group WRB [2022]). However, it is important to note that the hypothesis of human impact does not contradict, but rather complements three previous hypotheses of natural pedogenesis: it could be combined with each one of them within a model of superimposed natural-anthropogenic soil formation.

3 | METHODS

3.1 | Sampling

The paleopedological description of the pedostratigraphy at K14 and sampling for magnetic and micromorphological analyses were performed in 2004 (the eastern part of K14) and 2011 (the western part of K14). The morphological description of the profile of the 2004 excavation year was presented in Velichko et al. (2009) and Sedov et al. (2010); the morphological description of the profile of the 2011 excavation year was presented in Korrka et al. (2017). In 2004, a continuous sampling of the profile was performed including two full paleosols IIc and IId (Figure 4), while in 2011, the focus was on a detailed sampling of three full subunits IIa, IIb, and IIc (Figure 5). In the latter case, the presence of the archaeological material or presumable evidence of burning led to the collection of additional samples (CL 2). Thus, each distinguished subunit, that is, paleosol horizon or lithological layer, was sampled; in addition, two samples (black and red zones) from the hearth of CL 4b, that is, paleosol V, were taken.

3.2 | Magnetic properties

Following the method of Oldfield and Crowther (2007), the major magnetic parameters were χ_{lf} (in $10^{-5}\,m^3\,kg^{-1}$), χ_{fd} (in $10^{-5}\,m^3\,kg^{-1}$ or %), and χ_{ARM} (in $10^{-3}\,m^3\,kg^{-1}$). χ_{lf} indicates the concentration of all magnetic minerals in a sample, with the magnetic signal of ferrimagnetic minerals being the highest. χ_{lf} is particularly sensitive to finer magnetic grains, that is, SP (particle size of 0–0.02 µm) (Maher, 1988). Therefore, its values are especially high in sediments that have been influenced by pedogenic and/or pyrogenic processes or bacterial magnetosome activity (Gedye et al., 2000). χ_{fd} indicates the grain size of magnetic particles: it is especially sensitive to the presence of ultrafine SP ferrimagnetic grains, more importantly, those at the size range boundary of fine stable single domain (SSD, particle

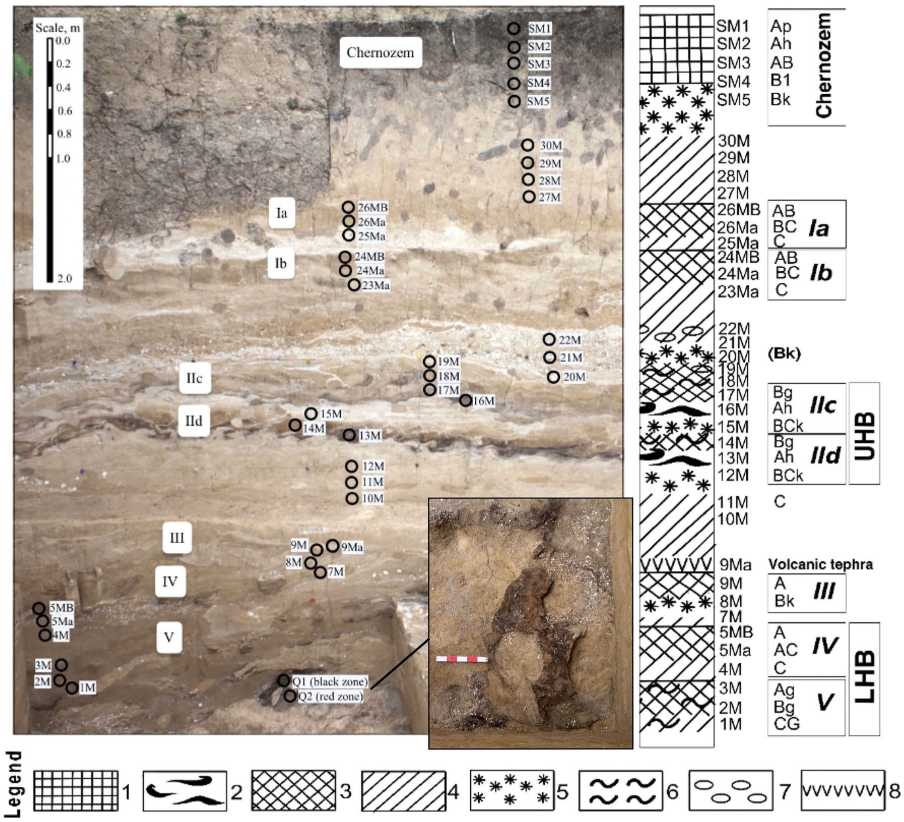

FIGURE 4 Sampling scheme for the analysis of magnetic properties and pedostratigraphic scheme at the Kostenki 14 key section in 2004 (the eastern profile of the southern wall). Black circles mark the locations of samples. Paleosols are identified by Roman numbers in rounded squares after Sedov et al. (2010) (except for paleosols of IIc and IId; see Figure 3). In the bottom right corner, one of the hearths from "horizon of hearths" (CL 4b, paleosol V) is presented. One ruler division corresponds to 10 cm. LHB, Lower Humic Bed; UHB, Upper Humic Bed; Legend: 1, Chernozem organo-mineral horizons; 2, dark humic Ah horizons of paleosol unit II; 3, A, AB, and B paleosol horizons; 4, C horizons of paleosols, sediments; 5, calcareous horizons Bk, BCk; 6, gleyzation features; 7, gravel inclusions; 8, volcanic ash.

size of 0.02–0.1 μm) and SP. χ_{ARM} is also indicative of magnetic grain size as it reflects the fine-grained magnetic minerals (SSD), those that are slightly coarser than those detected by the χ_{fd} parameter (Maher, 1988). All these parameters tend to increase as a result of burning (Roman et al., 2013).

In addition, the following magnetic parameters are used for the general characterization of the analyzed material: saturation isothermal remanent magnetization (SIRM, in $10^{-5}\,Am^2\,kg^{-1}$), natural remanent magnetization (NRM, in $10^{-5}\,Am^2\,kg^{-1}$), and quotients χ_{ARM}/SIRM (in $10^{-3}\,m\,A^{-1}$) and χ_{fd}/χ_{ARM} (dimensionless). SIRM is another concentration-dependent parameter, as is χ_{lf}. These quotients are especially sensitive to changes in the grain size of magnetic minerals. The dominance of SSD magnetic grain sizes is indicated by high values of χ_{ARM}/SIRM, whereas the dominance of SP grain sizes is indicated by low values of this quotient. The prevalence of magnetic grains that lie on the SSD/SP grain size boundary is distinguished by high values of the quotient χ_{fd}/χ_{ARM} (Oldfield, 1994).

The measurements were completed at room temperature. The air-dried samples were placed in diamagnetic acrylic cubes of a known volume (8 cm^3). The following magnetic measurements were then carried out: volume magnetic susceptibility at low (κlf; at 460 Hz) and high (κhf; at 4600 Hz) frequencies, anhysteretic remanent magnetization (ARM), and isothermal remanent magnetization including SIRM and NRM. NRM was identified before the samples were subjected to any laboratory experiments or other measurements of magnetic parameters. κlf and κhf were measured using a Bartington MS2 dual-frequency susceptibility meter. All remanences were obtained in a JR6 spinner magnetometer. ARM was transmitted in a peak alternating field of 100 mT in the presence of a direct current bias field of 40 μT. SIRM was acquired in a 1 T backfield.

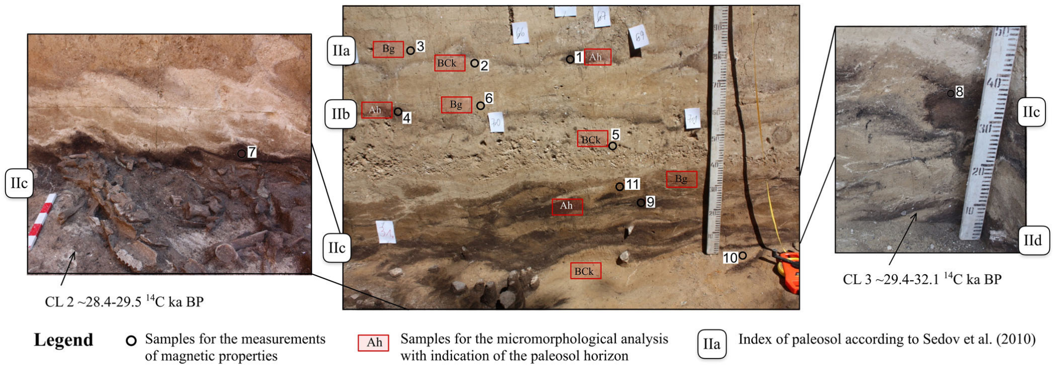

FIGURE 5 Sampling scheme for the analysis of magnetic properties and micromorphological analysis at the Kostenki 14 key section in 2011 (the western profile of the southern wall). Black circles indicate the locations of samples for analysis of magnetic properties. Red rectangles mark the locations of micromorphological samples. Paleosols are identified by Roman numbers in rounded squares after Sedov et al. (2010).

The magnetic susceptibility was expressed in mass-specific units (χ_{lf}, 10^{-5} m^3 kg^{-1}), which was calculated as χ_{lf} = κlf/density. Frequency-dependent magnetic susceptibility was calculated as χ_{fd} = (κlf−κhf)/density (in 10^{-5} m^3 kg^{-1}) and χ_{fd} = (κlf−κhf)/κlf (in %). ARM susceptibility (χ_{ARM}, 10^{-3}m^{3}kg^{-1}) was calculated by mass-normalizing ARM values and then divided by the direct current bias field. NRM and SIRM were expressed in volume units (10^{-5} Am^2 kg^{-1}). In addition to the main magnetic parameters, the interparametric ratios χ_{lf}/χ_{ARM} and χ_{ARM}/SIRM were determined. Before the calculation of quotients χ_{ARM}/χ_{lf} and χ_{ARM}/χ_{fd}, the values of the chosen magnetic parameters were expressed in the same unit of SI 10^{-8} to enable their direct comparison to the data in the original paper (Oldfield & Crowther, 2007). A bilogarithmic plot of the quotients χ_{ARM}/χ_{lf} and χ_{ARM}/χ_{fd} was constructed using RStudio software.

3.3 | Micromorphology

Within the scope of this research, micromorphology was utilized as an additional independent method to detect and evaluate paleopedogenic and anthropogenic processes that are believed to influence the magnetic signal. We selected this method, particularly relying on its capability to identify various pedogenic features (Stoops et al., 2018), even in cases of poor or incipient development, and to observe microartifacts such as charcoal, burnt, and unburnt bones (Canti, 2017; Mallol et al., 2017; Villagran et al., 2017). Since the micromorphological results from the complete section (2004) were published earlier (see Sedov et al., 2010), only observations from paleosol unit II of 2011 are presented, with a specific focus on the dark Ah horizons and a general overview of the adjacent Bg and BCk horizons.

The micromorphological analysis was performed using an Olympus polarizing microscope connected to a digital camera and computer. The images of pedogenic and anthropogenic features from these paleosols were made using Image-Pro Plus 7.0 software.

4 | RESULTS

4.1 | Magnetic properties of the pedosedimentary sequence at K14

The summary statistics calculated for all samples are shown in Table 3. The sampled horizons were attributed to several groups of different types of materials based on their morphological description. The statistical data for the material of these groups are presented in Figure 6. Humic horizons, that is, Ah buried horizons within paleosol unit II and other units, and Chernozem horizons were characterized by significantly higher values of all considered magnetic parameters as compared to those in inorganic horizons such as calcareous, gley horizons, and sediments. There was a statistically significant difference between the magnetic parameters of Ah buried horizons from unit II and other units, which might be correlated with their morphology. Volcanic ash had high values of χ_{lf} and χ_{ARM}, but, surprisingly, also extremely high values of χ_{fd}. This layer (9 Ma) mainly consists of primary magnetic minerals of volcanic origin, whose magnetic particle size is comparatively large; thus, χ_{fd} should be significantly lower, which has been confirmed by a study at Kostenki 17 (Kurgaeva et al., 2021). We suppose that the ash layer in K14 could have an admixture of soil material from paleosol III. The hearth (identified in the field by its macromorphological characteristics) is, by definition, of anthropogenic origin. Values of its magnetic parameters were high (χ_{lf} = 39.8 and 83.2 10^{-8} SI; χ_{fd} = 2.2 and 9.0 10^{-8} SI; χ_{ARM} = 161.1 and 277.5 10^{-8} SI for Q1 and Q2, respectively) and comparable to the values for Ah buried horizons from unit II (χ_{lf} = 47.2–71.5 10^{-8} SI; χ_{fd} = 5.4–9.2 10^{-8} SI; χ_{ARM} = 278.7–414.7 10^{-8} SI). Humic Ah horizons from unit II were more similar to the modern well-developed Chernozem than to A horizons from other units. High values of magnetic parameters of Chernozem were attributed to pedogenic rather than pyrogenic enhancement due to the lack of any features of burning. We believe that it is unlikely that humic horizons within unit II were magnetically enhanced solely due to pedogenic processes because they developed over a limited time period in comparison to the samples of modern Chernozem, which has similar values of magnetic parameters. Based on the correlation scheme of paleosols of unit II with Greenland interstadials (Sedov et al., 2022), the development of every paleosol could occur over a short period of ca. 0.5–2.0 ka (the approximate duration of Greenland interstadials 5, 6, 7, and 8 corresponded to the discussed paleosols). Thus, the paleosols of unit II were formed predominantly by rapid pedogenic processes (according to the classification by Targulian and Krasilnikov [2007]), which complicates their paleoenvironmental interpretation. In contrast, the development of the Holocene Chernozem on top of the studied sequence continued for about 10 ka. Development of the Chernozem profiles throughout the Holocene in the steppe zone of the East European plain is well documented by the detailed studies of soil profiles buried in the archaeological contexts, especially kurgans (burial mounds left by various nomadic cultures) (Ivanov, 1992). It is confirmed by the distribution of radiocarbon ages of humus within the Chernozem profiles: they range from ~1 ka in the topsoil to ~10 ka in the deepest part of humus horizon (Chichagova, 1985; Ivanov et al., 2009), roughly covering the whole Holocene. In addition, there are no signs that the development of the surface Chernozem started earlier in the terminal Pleistocene. Paleosols that formed in the study region during

TABLE 3 Summary statistics for the Kostenki 14 samples of 2004 and 2011 excavations.

	Mean	Maximum	Minimum	Standard deviation
χ_{lf}, 10^{-8} SI	22.20	131.77	2.64	28.16
χ_{fd}, 10^{-8} SI	2.25	13.01	0.01	3.14
χ_{ARM}, 10^{-8} SI	106.22	710.90	10.38	138.10
χ_{ARM}/χ_{lf}	4.64	10.54	3.04	1.16
χ_{ARM}/χ_{fd}	210.45	1687.09	11.36	371.74

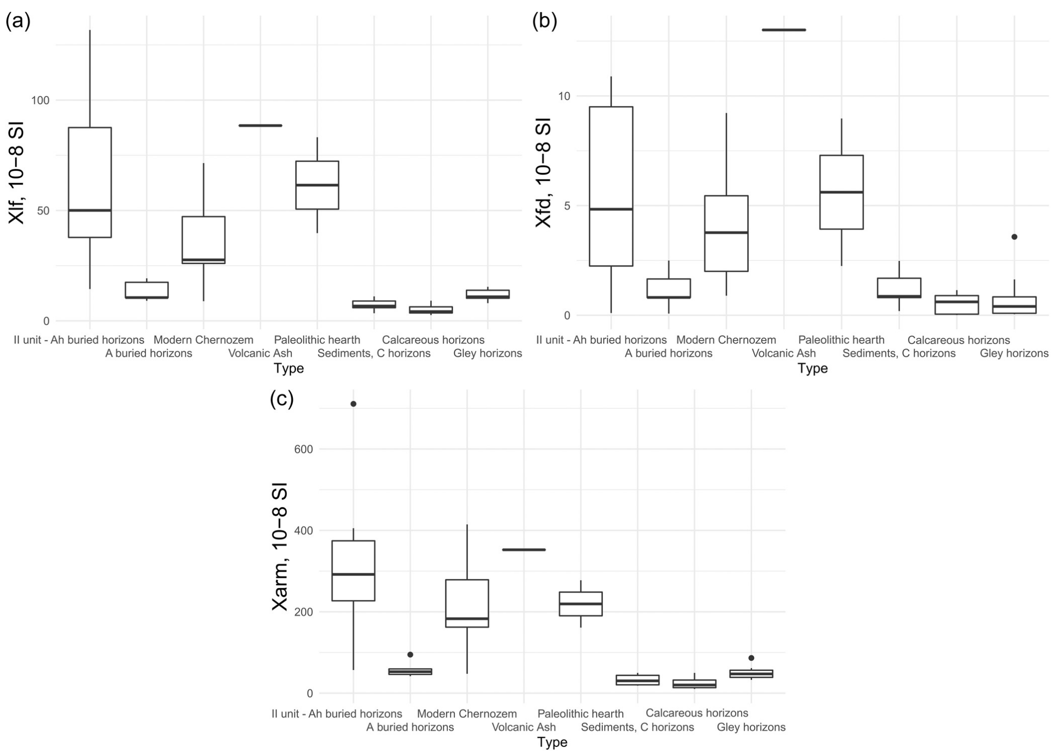

FIGURE 6 Summary statistics of χ_{lf} (a), χ_{fd} (b), and χ_{ARM} (c) for different types of horizons/layers of the pedostratigraphy at the Kostenki 14 archaeological site.

the Late Glacial (Bølling–Allerød) interstadial are poorly developed Cambisols, which differ sharply from the overlying Holocene Chernozem (Sycheva et al., 2016).

The distribution of magnetic parameter values within the pedosedimentary section is shown in Figures 7 and 8 for the 2004 and 2011 excavation years, respectively. The major peaks of the main magnetic values were observed in the modern Chernozem (Ah horizon, where the pedogenic enhancement is natural, but not in the Ap horizon, which was altered by agricultural activity), Ah buried horizons of unit II, volcanic ash, and samples from the hearth with a clear pyrogenic enhancement. There are also slight peaks in the relatively well-developed paleosols III and V (Figure 7). The frequent extreme peaks of χ_{fd} (in %), which are not accompanied by peaks of χ_{fd} (in 10^{-8} SI), especially for C horizons, sediments, and volcanic ash, are most likely the result of value overestimation due to the low values of both κhf and κlf. The calculated quotients χ_{ARM}/SIRM and χ_{fd}/χ_{ARM} are indicative of grain sizes of magnetic particles (Oldfield, 1994). The dominance of SP particles is characterized by lower values of χ_{ARM}/SIRM. The prevalence of particles at the boundary of SSD/SP grain sizes is described by higher values of χ_{fd}/χ_{ARM}. Finally, the dominance of SSD particles is indicated by high values of χ_{ARM}/SIRM. The buried humic horizons of unit II, which otherwise showed high magnetic values of other parameters and, thus, clear pedogenic and/or pyrogenic enhancement, were characterized by relatively coarse grain sizes of magnetic particles: from fine SSD (close to the boundary SSD/SP) to SSD. In contrast, the samples from the calcareous, gley, and C horizons, which did not have any signs of enhancement according to values of χ_{lf}, had the opposite values of calculated quotients; thus, the SP particles were dominant. Notably, the trend of χ_{fd}/χ_{ARM} values mainly repeats the trends of χ_{fd} (in %); therefore, some of the values for samples, which have extremely low values of χ_{lf} such as inorganic subsurface horizons, were overestimated as it was argued above for χ_{fd} (in %). Another plausible explanation is the mixed nature of horizons affected by slope processes (Blake et al., 2006; Velichko et al., 2009). The magnetic properties for two zones of the hearth are matching with a typical hearth structure. The black zone of the hearth has a slightly higher concentration of finer grains (at the boundary of SSD/SP) and a higher degree of dispersion than the red zone; however, the red zone has higher values of magnetic parameters. This is probably related to the nature of these two structural units of the hearth: the upper black zone (Q1) mainly consists of charred dispersed organic compounds, while the lower red zone (Q2) has a higher content of strongly magnetic minerals, which are responsible for its color.

Similar trends were observed for the pedostratigraphy of K14 during excavations in 2011, when the samples of unit II were

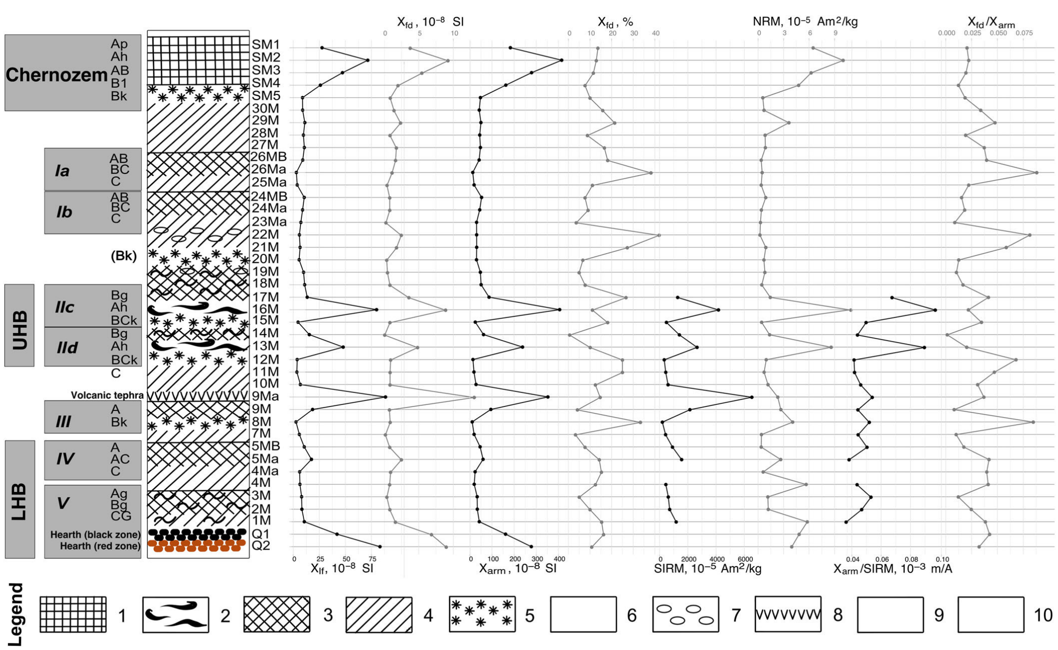

FIGURE 7 Pedostratigraphy at the Kostenki 14 site in the 2004 excavation year and its magnetic properties. LHB, Lower Humic Bed; UHB, Upper Humic Bed; Legend 1, Chernozem organomineral horizons; 2, dark humic Ah horizons of paleosol unit II; 3, A, AB, and B paleosol horizons; 4, C horizons of paleosols, sediments; 5, calcareous horizons Bk, BCk; 6, gleyzation features; 7, gravel inclusions; 8, volcanic ash; 9, black zone of the hearth; and 10, red zone of the hearth.

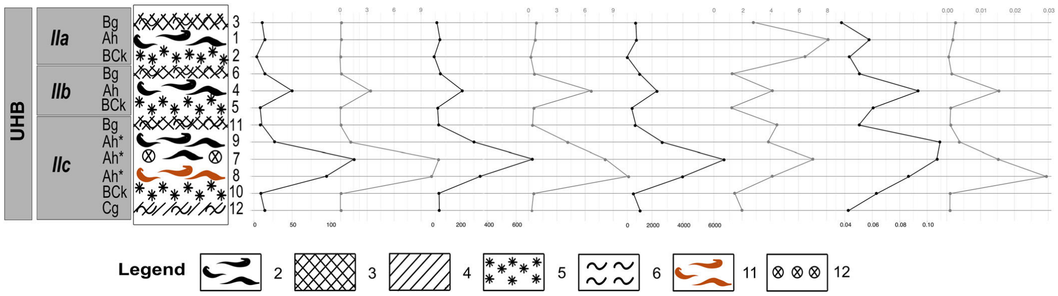

FIGURE 8 Pedostratigraphy of paleosol unit II at the Kostenki 14 site in the 2011 excavation year and its magnetic properties. Ah horizons of IIc marked with * were parallel to each other, not one on top of the other at the profile of Kostenki 14. UHB, Upper Humic Bed; Legend 2, dark humic Ah horizons of paleosol unit II; 3, A, AB, and B paleosol horizons; 4, C horizons of paleosols, sediments; 5, calcareous horizons Bk, BCk; 6, gleyzation features; 11, reddish humic material of the Ah horizon of paleosol unit II; 12, rich cultural layer (abundance of bones).

obtained (Figure 8). All buried Ah horizons have high values of χ_{lf}, χ_{fd}, and χ_{ARM}, which indicate pedogenic and/or pyrogenic enhancement. The Ah horizon of paleosol IIa has significantly lower peaks of the discussed parameters (χ_{lf}, χ_{fd}, χ_{ARM}, SIRM, χ_{fd}/χ_{ARM}) because of its clearly redeposited nature. Such redeposition resulted in a mixture of humic and calcareous materials, which is clear from the morphological description of the paleosol profile. The magnetic particles of this horizon are of larger grain sizes according to the calculated quotients. Three humic samples from the Ah horizon of the IIc paleosol differ significantly from each other (χ_{lf} = 131.8, 95.2, and 27.7 10^{-8} SI; χ_{fd} = 10.9, 10.1, and 1.2 10^{-8} SI; χ_{ARM} = 710.9, 343.482, and 291.9 10^{-8} SI for K14-7, K14-8, and K14-9, respectively). Humic material with artifact abundance (sample K14-7) and reddish humic material (sample K14-8) have higher magnetic enhancement and finer magnetic particles in comparison with typical humic material (sample K14-9). It is noteworthy that reddish humic material (sample K14-8) is characterized by a dominance of SP particles (lower value of χ_{ARM}/SIRM) and a high amount of SSD/SP magnetic particles (high values of χ_{fd}/χ_{ARM}), while humic material with artifact abundance has a higher proportion of SSD particles. This shows the high spatial heterogeneity within this Ah horizon, which includes CL. In contrast to the magnetic data in the 2004 excavation year, the calcareous and gley horizons have low values of χ_{fd} and χ_{fd}/χ_{ARM}.

The samples of both excavation years were plotted onto a bilogarithmic graph applying the methodology presented in Oldfield and Crowther (2007) (Figure 9). In the background, the known envelopes for different types of material are shown. The envelope of unburnt sediments encircled the samples from the humic horizons of forest soils. The same samples were burnt at 650°C under reducing conditions for 1 h, followed by oxidizing conditions for 45 min, and thus contributed to the determination of the envelope of burnt sediments (Oldfield & Crowther, 2007).

Most of the soil samples are plotted along the main trend line, where the samples with predominantly fine magnetic grain sizes are located. Most of the samples of calcareous, gley and C horizons, and sediments are found far from the trend line. This is associated with their larger magnetic grain sizes due to the absence of pedogenic or pyrogenic processes, and thus, these samples should be ignored in the following analysis. Sample K14-1, which is described as the buried Ah horizon of paleosol IIa with clear morphological features of mixed material, is clustered together with calcareous and gley horizons far from the trend line. Most of the soil and paleosol samples are in the envelope attributed to soils, paleosol, and catchment-derived fine sediments. The location of samples 9M and SM1 of clear pedogenic origin outside this envelope enables us to slightly enlarge its boundary. Samples Q2 (red zone of the hearth) and K14-8 (reddish humic material of paleosol IIc) are located inside the envelope of burnt sediments. Sample Q1 of obvious pyrogenic origin is located outside the envelope of burnt sediments despite its relative proximity to it. The relative position of samples Q1 and Q2 at the bilogarithmic plot is consistent with their nature mentioned earlier in this section. Other humic samples such as 5Ma and 26MB have a similar position to Q1. The position of volcanic ash (sample 9Ma) is considered incorrect because of its high χ_{fd} value, which contradicts the nature of its magnetic minerals. This may have been the result of its mixed nature influenced by humic material of 9M situated below the volcanic ash layer.

4.2 | Micromorphological observations of paleosols of unit II

Micromorphological observations were performed for the paleosols of unit II sampled in 2011 (Figures 10 and 11). Micromorphological observations have shown that the mineral groundmass of all paleosol horizons of unit II is dominated by micrite (microcrystalline calcite) with an admixture of clay. Coarse sand- and silt-sized particles are presented by primary calcites (fragments of limestone, sometimes containing marine microfossils), quartz, feldspars, and glauconite. Coarse grains are immersed in the micromass, producing a close porphyric coarse/fine-related distribution.

Specific micromorphological imprints of soil-forming processes were detected, being rather uniform in all horizons of certain genetic

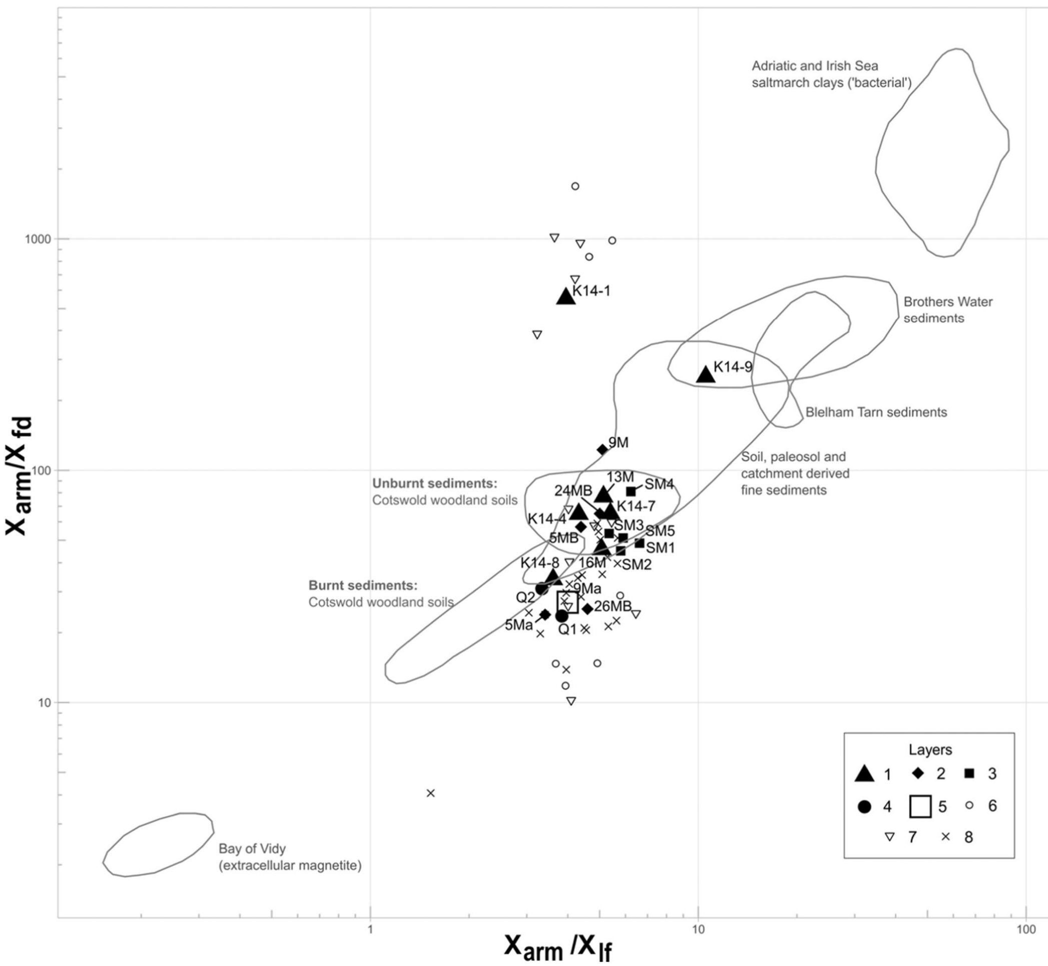

FIGURE 9 Bilogarithmic plot of the quotients χ_{ARM}/χ_{fd} and χ_{ARM}/χ_{lf} for samples of Kostenki 14 (2004 and 2011 excavation years). The background for the values plotting, that is, envelopes, is after Oldfield and Crowther (2007). Envelopes show hand-drawn zones around the different data points in the bilogarithmic plots in the original work of Oldfield and Crowther (2007). Specifically, these "envelopes" are not confidence ellipses, or other zones that have been defined using statistical analysis. Layers: 1, buried Ah horizons from paleosol unit II; 2, buried A horizons; 3, modern chernozem; 4, Paleolithic hearth; 5, volcanic ash; 6, calcareous horizons; 7, gley horizons; 8, sediments, C horizons.

type. The Bg horizons on top of each pedocomplex structure are relatively compact, with a moderately developed blocky structure. Few large biogenic channels and chambers are present; some of them are outlined by micritic hypocoatings (Figure 10a). Fe–Mn nodules of different sizes and morphologies are observed within the groundmass of these horizons (Figure 10b).

In the Ah horizons, groundmass is unevenly colored with dark organic pigment. A large part of the material has a well-developed fine granular structure and developed inter-granular porosity, giving rise to spongy fabric (Figure 10c). Most of the granular aggregates are of coprogenic origin; frequent chambers with loose infillings of excrementary aggregates are found (Figure 10d). Also, the Ah horizons show maximum frequency and variety of neoformed carbonates presented by micritic (hypo) coatings and loose sparitic infillings (Figure 10e).

Underlying BCk horizons are the most compact, the structure is poorly developed, and only in some areas is incomplete pedality observed: welded rounded blocks are only partly separated by tortuous pores (Figure 10f). The groundmass of this horizon is strongly impregnated with microcrystalline calcite; coarse primary calcite particles are common.

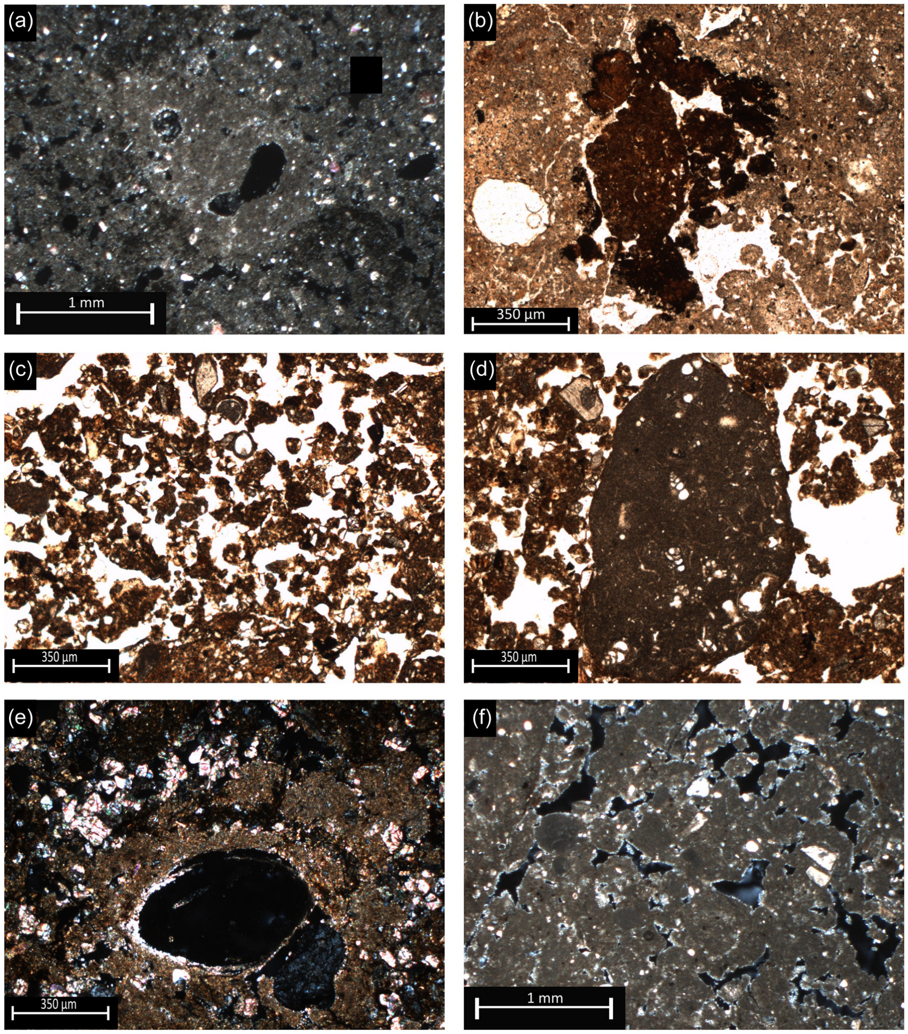

FIGURE 10 Micromorphology of paleosols of the unit II: pedogenetic features. (a) Channel pores of different sizes, micritic hypocoatings outline the largest channels; paleosol IIa, Bg horizon, N+. (b) Compound ferruginous nodule; paleosol IIb, Bg horizon, PPL. (c) Fine granular structure, spongy fabric; paleosol IIc, Ah horizon, PPL. (d) Right side— large chamber partly filled with coprogenic microaggregates, center—fragment of limestone with microfossils; paleosol IIc, Ah horizon, PPL. (e) Upper part—cluster of neoformed sparite crystals, center—micritic coating; paleosol IIc, Ah horizon, N+. (f) Groundmass saturated with micrite with compact arrangement, note welded rounded blocky aggregates in the upper part (incomplete pedality); paleosol IIa, Bk horizon, N+. N+, crossed polarizers; PPL, plain polarized light.

Human-induced materials in paleosols of unit II are represented by charcoal and bones; the latter in most cases show different grades of pyrogenic transformation. They are more common in the Ah horizons, fewer in the Bg horizons, and very few in the BCk horizons. Some larger charcoal fragments have preserved tissue cellular structure. Charcoal is differentiated from other plant residues by intense black color, opacity, and sharp contours of cell walls (Canti, 2017; Mallol et al., 2017) (Figure 11a). Most common are smaller charcoal particles, whose identification is more difficult because they are somewhat similar to other black opaque particles (charred bone, ore minerals, etc.). Investigation under oblique incident light, where charcoal stays black with a soft metallic luster (Canti, 2017), could provide an additional but not definitive indicator. In some cases, we observed clusters of charcoal specks still retaining

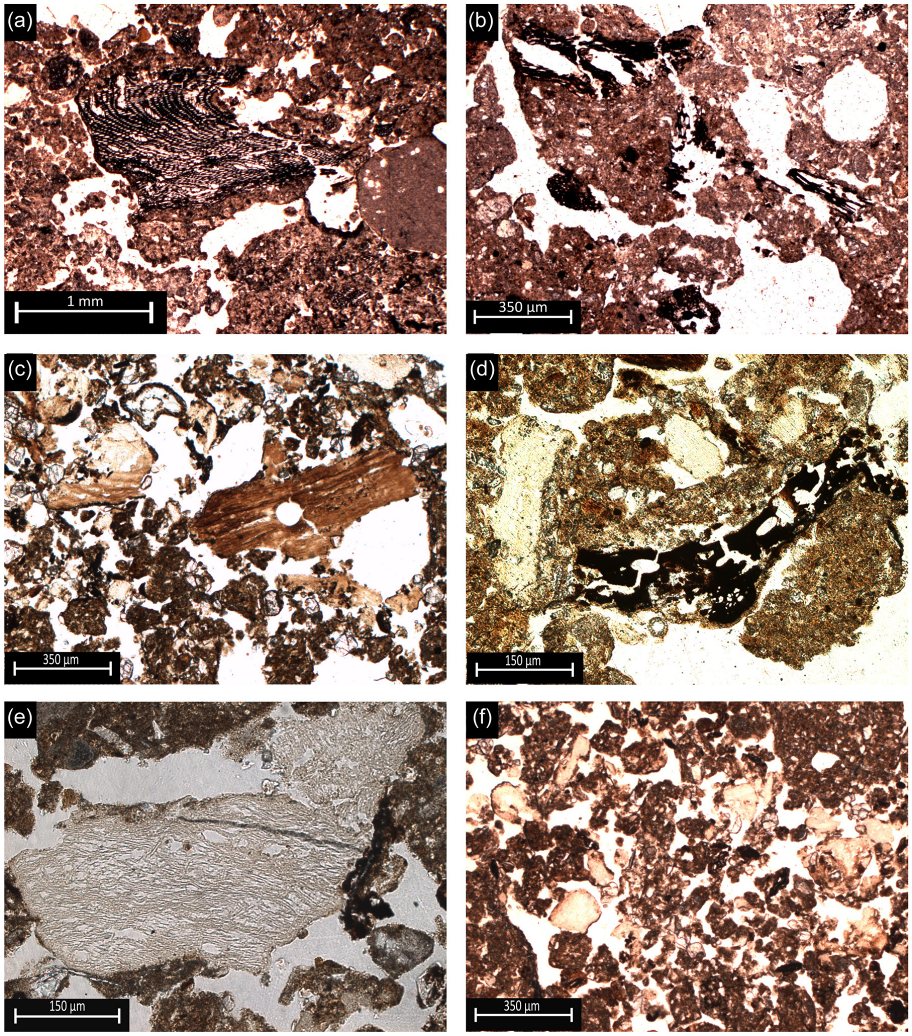

FIGURE 11 Micromorphology of paleosols of unit II: human-induced materials. Plain polarized light. (a) Large charcoal fragment with preserved tissue structure; paleosol IId, Ah horizon. (b) Cluster of small charcoal particles, probably resulting from destruction of a larger fragment; paleosol IIb, Bg horizon. (c) Fragment of burned bone; paleosol IIc, Ah horizon. (d) Charred bone, surrounded by unburned bone particles; paleosol IIc, Ah horizon. (e) Pale fragment of calcined bone; paleosol IIc, Ah horizon. (f) Area with zoogenic granular microstructure incorporating small bone fragments; paleosol IIc, Ah horizon.

some elements of cellular structure, supposedly produced by the destruction of a larger fragment (Figure 11b). We think that this observation illustrates the mechanism by which the finely divided charcoal is incorporated into the groundmass.

In the thin section from the Ah horizon of paleosol IIc, taken close to the reddish burned feature (sample K14-8), we found an especially high abundance and high variety of bone particles. The burned bone showed a variety of red–brown and orange–brown colors (Figure 11c), whereas strongly charred bone was very dark and opaque, so that only its specific morphology helped to discriminate it from charcoal (Figure 11d). We also encountered very pale whitish fragments interpreted as calcined bone (Figure 11e) (Villagran et al., 2017). Interestingly, in this sample, there was a well-developed zoogenic granular structure, and fine bone particles were incorporated into the granules (Figure 10f).

5 | DISCUSSION

5.1 | Interpretation of the pyrogenic signals at K14

Only two of the samples analyzed in this study were located in the envelope of burnt sediments and, thus, had a clear intense pyrogenic genesis: K14-8 (reddish humic material of the Ah horizon with morphological features of pyrogenesis, paleosol IIc) and Q2 (red zone of the hearth, paleosol V). The samples Q1, 5Ma, 26MB from the humic horizons were found close to the envelope of burnt sediments and outside of the envelope of unburnt sediments. One of them (Q1) has a clear pyrogenic genesis as it represents the black zone of the hearth.

The hearth in paleosol V has a structure typical for combustion features: black material on top of red material (Mallol et al., 2013, 2017). The black zone consists of a mixture of charred dispersed organic material and mineral grains, while the red zone is mostly mineral with a high amount of hematite or maghemite, which might be responsible for the red color (Canti & Linford, 2000; Mallol et al., 2013; Schwertmann, 1993). Maghemite is formed under reducing conditions in the presence of organic matter and is characterized by high magnetic properties (Oldfield et al., 1981; Schwertmann & Fechter, 1984), while reddish hematite is not as strongly magnetic as maghemite (Schwertmann & Taylor, 1977). Thus, the observed high magnetic properties of the reddish material of samples K14-8 and Q2 imply the plausible presence of both magnetic minerals.

The material of the in situ hearth was very distinctive from the hosting material of paleosol V due to its black and red color, preserved structure, and extremely high values of magnetic properties. Paleosol V had prominent gleyic features and as a consequence low values of magnetic parameters. This vividly demonstrates the substantial effect of controlled regular fire, which results in high magnetic enhancement even of weakly magnetic waterlogged materials.

Burnt reddish humic material (sample K14-8) was observed in the somewhat dislocated third Ah horizon (paleosol IIc; 2011) along with other types of humic material: typical humic material (sample K14-9) and anthropogenically influenced humic material with abundant artifacts (samples K14-7). The big difference in the magnetic properties of these three types of humic material defines the spatial heterogeneity of this Ah horizon, which indicates the presence of anthropogenic impact. This also seems evident because of CL 2 observed at this paleosol horizon. The observed strong magnetic properties and reddish chroma of sample K14-8 indicate the intensive burning of this material, which is defined by the temperature and duration of the fire event. However, such a strong change in mineralogy, the corresponding magnetic properties, and the reddening of material could occur only after around 45 min of burning at 600°C (Ketterings & Bigham, 2000).

For further discussion, we should state our understanding of how different types of burning events correspond to fire intensity (Figure 12). There are three types of fire, which might have occurred within an archaeological site: large-scale natural wildfire, large-scale human-induced fire affecting vast territories, and small-scale controlled regular anthropogenic fire in a hearth. The scale of fire, large or small, is independent of the total burnt area but defines whether the burning occurred at the landscape scale, that is, the area outside and possibly also inside a settlement (large scale), or at the local scale, that is, only area inside a settlement (small scale). Large-scale natural and anthropogenic fires have similar properties, which depend mostly on the quality and quantity of fuel, that is, vegetation (Bailey & Anderson, 1980; Bellomo, 1993; Jordanova et al., 2019; Santín & Doerr, 2016). The only difference between them is the cause of fire: a natural phenomenon or human activity. Large-scale fire, independent of its cause, is characterized mainly by low or moderate intensities because of its rather low average temperatures and duration. For forested areas, the average temperature is around 400°C, with a maximum temperature of 600°C (Bailey & Anderson, 1980), the duration of which is usually extremely short (Santín & Doerr, 2016). For shrubland, the average surface temperature is around 400°C (Bailey & Anderson, 1980). A short grass fire is characterized by lower intensity, lower temperature (around 190°C), and lower duration (Bailey & Anderson, 1980; Bellomo, 1993; Jordanova et al., 2019). Thus, wildfire usually results in a relatively small enhancement of magnetic properties (Bailey & Anderson, 1980; Bellomo, 1993;

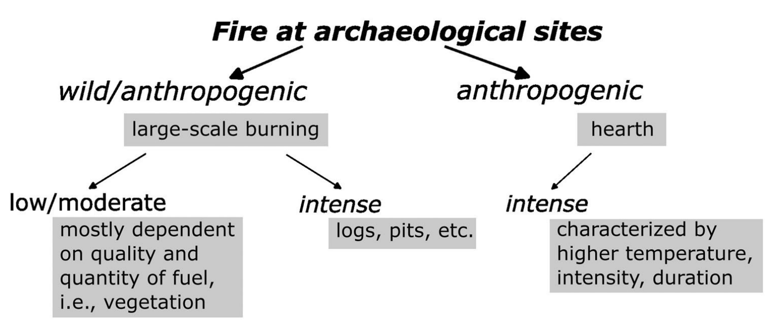

FIGURE 12 Types of fire events at archaeological sites and corresponding intensity of magnetic enhancement of the substrate.

Roman et al., 2013). In rare cases, this type of fire causes strong magnetic enhancement, when the fire is held within a limited area for a long time, for example, under a fallen tree, within the area of dry deadwood accumulation, in a pit, and so forth (Canti & Linford, 2000; Lowe et al., 2016; Roman et al., 2013; Ulery & Graham, 1993), which is likely to occur only in the forested area.

To distinguish between the natural and anthropogenic origins of a large-scale fire event, a multiproxy landscape-scale approach is required. Recently, two such studies suggested the large-scale anthropogenic burning as early as ~85–60 ka B.P. in Southern-Central Africa (Thompson et al., 2021) and ~125 ka B.P. in Germany during the Last Interglacial (Roebroeks et al., 2021). To prove their hypothesis, the researchers correlated pyrogenic records with numerous continuous paleoarchives such as archaeological, geomorphic, and environmental paleorecords on a landscape scale and ruled out the natural factor by using the climate anomaly approach (Thompson et al., 2021) or by comparing the main analyzed data set with a control data set (Roebroeks et al., 2021).

Based on literature data on the burning temperatures of different plant communities, described above, we conclude that the probability of intensive burning in forested areas is higher than that in open environments such as steppe or tundra. According to the paleoenvironmental reconstructions based on palynological analysis, the plant association of the area during the first soil formation phase (Ah-BCk) of paleosol unit II could have been periglacial steppe with areas of spruce and pine forests within topographic depressions, while during the second soil formation phase (Bg), it could have been a tundra or forest-tundra landscape (Sedov et al., 2010; Velichko et al., 2009). Therefore, the intense burning conditions that provide for a strong magnetic enhancement and reddening of the material in the case of wildfire in such landscapes could have only been formed in a lower topographic position. Since the K14 site is located in this topographic position, it is possible that the reddish lenses were formed locally during a large-scale fire event. In this case, the dark humic material of the Ah horizon of paleosol IIc was affected by fire of low or moderate intensity, which cannot be differentiated using the method of Oldfield and Crowther (2007). As mentioned above, to prove the occurrence of a large-scale fire event characterized by low or moderate intensity, the appropriate multiproxy approach applied on a landscape scale is needed, which is beyond the scope of our study.

On the other hand, anthropogenically controlled fire, that is, a hearth, is common for many archaeological sites (e.g., Alperson-Afil, 2012; Clark et al., 2022; Murphree & Aldeias, 2022 and references therein). Repetitive fire events do not enhance the magnetic properties of soil material any more strongly than a single event fire, if their intensity is similar (Roman et al., 2013). However, numerous studies have shown that human-controlled fires in hearths are often associated with intense burning and strong magnetic enhancement of the substrate due to its specific features, which provide higher burning temperature, intensity, and duration (Bellomo, 1993; Canti & Linford, 2000; Linford & Canti, 2001; McClean & Kean, 1993).

The method of Oldfield and Crowther (2007) distinguishes intense fire events from fire events of low/moderate intensity as well as an absence of burning. Therefore, once a fire event is recognized as an intense one according to the magnetic properties of paleosols/sediments at an archaeological site and the plausible effect of vegetation as a fuel source is considered, we are more likely to attribute it to small-scale anthropogenic activity, and thus a hearth. In other words, this method is appropriate for distinguishing small-scale fire events of higher intensity; to identify fire events on a landscape scale, other approaches are required. In addition to any applied method, it should be identified whether the sediment with morphological or magnetic signs of burning is in situ or redeposited; it is mainly based on the morphology of sediments.

Here, we suggest a hypothesis of the human-induced pyrogenic origin of this material (sample K14-8) within the Ah horizon of paleosol IIc, that is, a potential hearth. The abundance of charcoal and microartifacts in the micromorphological thin sections and the spatial heterogeneity of this buried Ah horizon validate the hypothesis of its anthropogenic genesis. The frequent fragments of burnt bone observed in the micromorphological thin section sampled close to the reddish humic lens in paleosol IIc additionally confirm the proposed hypothesis that the reddish material could be a locally translocated hearth material rather than a natural or human-induced fire affecting vast territories. A hearth has a poor preservation capacity, especially at open-air sites, due to transformation and translocation processes (Mallol & Henry, 2017; Mallol et al., 2007). Considering the highly deformed state of the entire paleosol complex of unit II, CL 2 (paleosol IIc) was likely also deformed, which led to the disruption and the loss of the internal structure of the hearth. Therefore, we presume that sample K14-8 was a reddish oxidized zone of the hearth analogous to the hearth with a more intact laminated structure found in paleosol V.

In conclusion, after considering the hypotheses of a large-scale and local human-controlled fire, we conclude that both are likely to explain the situation within the Paleolithic settlement at K14. However, the high heterogeneity of the CL including the magnetic properties and the spatial proximity of numerous artifacts to the reddish humic lens justify our inclination towards the hypothesis of its anthropogenic pyrogenesis in a hearth.

The question remains as to whether there are other fire events to be discovered in the pedostratigraphy at K14, especially in paleosol unit II. The pyrogenic signature could have been poorly imprinted in the soils due to the characteristics of the fire as discussed above or it could have been erased due to postfire processes. The fire alters only the magnetic properties of the surface soil layer; the subsurface soil material is not strongly magnetically affected during the natural fire (Bailey & Anderson, 1980; Roman et al., 2013), mainly because temperatures are significantly lower in deeper layers (Canti & Linford, 2000; Linford & Canti, 2001). The burnt thin soil layer is affected by the postfire processes as indicated by its altered properties. The soil water repellency characteristics of burnt soil material are changed (Doerr et al., 2000), making it more susceptible to erosion and less stable, also considering the absence of the stabilizing effect of vegetation. Therefore, it is entirely possible that surface samples could show uneven distribution of pyrogenic memory including the dilution or loss of the pyrogenic signal due to the removal of the thin burnt layer (erosion process), bioturbation (its effect has been observed in thin sections as fragmented charcoal and its incorporation into groundmass), and the dissolution of fine-grained magnetite under waterlogging conditions (postfire effect) (Blake et al., 2006). The better preservation of the magnetic signal of burning might be observed at archaeological sites as a result of rapid burial and minimal effect of diagenetic processes.

5.2 | Modification of the pyrogenic signal by natural pedogenesis and geomorphic processes

The application of the method of Oldfield and Crowther (2007) at K14 suggested that most of the humic samples of Ah horizons are situated within the envelope of unburnt soil material (Figure 9), and thus, their magnetic enhancement is attributed to soil formation processes. However, clear signs of pedogenic enhancement might or might not be accompanied by pyrogenic enhancement because of the nature of the original experiment and the magnetic response to burning. Nonetheless, the pedogenic magnetic enhancement at the Ah horizons of unit II is in accordance with the biogenic processes, observed in micromorphological thin sections sampled in the 2004 (Sedov et al., 2010; Velichko et al., 2009) and 2011 excavation years (Korrka et al. [2017] and this paper). The following indicative features were observed: rounded porous and elongated channels, a biogenic granular structure that partially fills channels and sometimes dominates the groundmass, which is occasionally pigmented by humus, bones and charcoal partially affected by fragmentation, decomposed vegetation residues, and recrystallization of carbonates.

Interestingly, the micromorphological observations demonstrate that the biogenic aggregation in these paleosols of unit II occurred before, (possibly) during, but mostly after the period of human occupation. The latter is indicated by the fragmentation of bones and charcoal due to zoogenic bioturbation, the absence of trampling features within CLs, and chambers with loose infillings of excrementary aggregates, which evidenced the biogenic activity right before the burial. Additionally, it could be related to an observed phenomenon, which has not, however, been comprehensively proven as yet, that the introduction of organic material due to human activities might result in the intensification of biological activity within a CL (Schilt et al., 2017).

The clear indications of bioturbation after the human occupation and the processes of solifluction and cryoturbation suggest that the high magnetic signal of humic material of Ah horizons of unit II might represent the mixed magnetic signal of pedogenic humic material and intensively burnt material of numerous hearths. Also, we cannot exclude the possibility that these Ah horizons could have been subject to low or moderately intense fire (possibly human-induced/wild/both) as discussed in the previous section. The application of other methods such as biochemical analysis of the organic matter at K14 is required to answer this question, which was performed at the archaeological site of Kostenki 17 (Kurgaeva et al., 2021). The biogeochemical analysis (Fourier-transform infrared spectroscopy) of the corresponding three paleosols of paleosol unit II at Kostenki 17, which also contain CLs and layers with artifacts, indicated the presence of black carbon in the Ah horizons. These results indicate a high probability of moderate- or low-intensity fire, which, as such, was most likely attributed to natural fire, as well as intense fire, whose magnetic signal was diluted by subsequent bioturbation. Moreover, the reconstruction of local vegetation using biomarker analysis rather than the regional vegetation using palynological data would be crucial for further discussion of the effect of a large-scale fire.

Additionally, the micromorphological analysis implies the colluvial origin of the parent material of the paleosols of paleosol unit II based on the content of primary calcite, quartz, and feldspar grains of silt and sand sizes. The presence of abundant primary (geogenic) calcites within the matrix suggests that the colluvial parent material of these paleosols contains many calcareous rocks, including limestone fragments with microfossils derived from the local Cretaceous limestones. The content of all these primary materials implies that leaching and weathering processes were quite weak. The formation of sparite crystals and carbonate coatings with the associated depletion of micrite in the soil mass around them suggests a local intrahorizontal migration and reprecipitation process of secondary calcites. Iron–manganic segregations and nodules in the Bg horizons indicate that they were affected by conditions of temporary water stagnation.

In conclusion, a primarily anthropogenic origin of the humic horizon of paleosol unit II could not be established. The anthropogenic version of the genesis of the humic horizons of paleosol unit II could be neither confirmed nor denied. The combined effect of natural and anthropogenic pedogenesis has been suggested. The application of this method to K14 allowed for the confirmation of the pyrogenic origin of reddish lenses, which appear sporadically across dark humic horizons of paleosol unit II.

5.3 | Application of the method to an archaeological site

The presented methodology (Oldfield & Crowther, 2007) has been applied in this case study to distinguish pyrogenic from pedogenic magnetic enhancement. When applied at an archaeological site, this method allows for distinguishing anthropogenically controlled fire, associated with intense burning (intense burning corresponds to anthropogenically controlled fire in open environments such as steppe or tundra with a higher probability than in forested areas), from the large-scale burning regardless of its cause.

This method is applicable in all environments, at open-air as well as cave sites. However, it is the most informative at archaeological sites where a CL is formed within a dark well-developed humic horizon. Otherwise, the pedogenic magnetic signal is often low (e.g., in cave sediments, desert environment), and thus, high values of magnetic susceptibility alone, which is a relatively more time- and cost-effective method, is a good proxy for pyrogenic events.

In addition, this method can be advantageous at archaeological sites where the initial structure of a CL was lost due to physical diagenetic processes such as solifluction or erosion. To identify whether burnt material has been preserved in situ or has been redeposited, the morphology of sediments and the position of the constituents of a CL such as bones and artifacts should be inspected. However, as we have seen in this study on an example of sample K14-1 plotted as an outlier at the bilogarithmic plot, the mixture (caused by erosion) of burnt material with parent material not altered by pedogenic processes might result in an increase in the average size of magnetic minerals of material; this leads to a decrease in magnetic properties proportional to the amount of its constituents (Blake et al., 2006). Therefore, the calculated quotients will not be able to indicate the effect of pedogenesis or pyrogenesis because the sample will be located outside the main axis with envelopes at the bilogarithmic plot.

Moreover, theoretically, magnetic properties might not be efficient at sites where the sediments experienced waterlogging; the reduced conditions result in the destruction of strongly magnetic minerals, even though the size of magnetic minerals distinctive of pyrogenesis and pedogenesis remains the same. Surprisingly, the reddish material of pyrogenic origin at paleosol IIc (sample K14-8) preserved its high magnetic properties even though it experienced waterlogged and possibly even permafrost conditions after burial, which is indicated by the Bg horizon developed above the Ah horizons of paleosol IIc. In contrast, in situ hearth (samples Q1 and Q2) developed its high magnetic properties while being situated in paleosol V, whose formation is characterized by gleyzation under waterlogged conditions. Further analysis and experimental studies on the destruction of highly magnetic minerals, which are formed as a result of burning, under waterlogged conditions are needed.

Micromorphology used in our study is not a necessary requirement for this method application (other than for studying microartifacts) but it is undoubtedly a valuable addition to any geoarchaeological research and might provide new insights into paleofire event reconstruction (e.g., Aldeias et al., 2012; Karkanas et al., 2007; Mallol & Henry, 2017; Mallol et al., 2007), as it was demonstrated also in this study.

The issue of identifying the anthropogenic fire at an archaeological site has been addressed by several scientists before us. Some of them also used magnetic parameters often with a combination of microscopic techniques (Barbetti, 1986; Bellomo, 1993; Deldicque et al., 2021). However, such methods are not very effective when the background material is also characterized by high magnetic enhancement such as dark humus horizons. Other researchers analyzed microcharcoal (Cui et al., 2009) because carbonized material is chemically stable and durable, although it is often subject to physical degradation, which is a core limitation of such indicators. Many strongly relied on micromorphology (Aldeias et al., 2012; Mallol et al., 2007), which is advantageous in the search of microtraces preserved after postdepositional processes, although dispersed black carbon is often undistinguishable from humus. While others proposed using archaeological approach (Alperson-Afil, 2012; Cutts et al., 2019; Plavšić et al., 2020), in most studies, the issues of equifinality and low preservation of signals of anthropogenic and natural fire are stressed. Repeatedly, it was found beneficial to apply a multiproxy approach, which increases the confidence degree of conclusions; to observe the sediments/artifacts at various scales (such studies often include micromorphology); or to develop a univocal indicator associated with anthropogenic fire.

Fire use is one of the most important behavioral adaptations in human evolution. Fire has a crucial niche construction effect, that is, by using fire, hominids actively changed their environment, which reciprocally affected their evolutional development by means of natural selection (e.g., Attwell et al., 2015; Kendal et al., 2011; O'Brien & Bentley, 2021; Odling-Smee et al., 2003). Attwell et al. (2015, and references therein) summarized the evolutionary consequence of fire use: broader dispersion into cooler regions (Gowlett, 2006); thermal treatment of raw products leading to enhanced digestion, broadened dietary niche, decreased mortality as a result of killed pathogens and deactivated toxic components (therefore, decreased mortality led to faster natural selection), decreased energy consumption needed for digestion, resulting in encephalization (Ben-Dor et al., 2011; Wrangham & Carmody, 2010); a hearth as a place for gathering and socialization (including social brain hypothesis) (Rolland, 2004); and increased daylight hours leading to physiological consequences for daily and annual cycles (Burton, 2009). In the Upper Paleolithic, the use of fire was associated with the development of nonutilitarian items such as baked clay and loess figurines, which indicated the important behavioral shift (Murphree & Aldeias, 2022); however, these authors point to the disparity between the studies of Neanderthals and early AMH pyrotechnology: "…there has been surprisingly far less research dedicated to characterizing fire use by AMH during the Upper Paleolithic" (Murphree & Aldeias, 2022, p. 1).

Combustion features at archaeological sites are a crucial puzzle piece in understanding hominid behavior. Often, the combustion features are overlooked because their structure has been lost due to the postdepositional processes; thus, the existent data set on combustion features is incomplete (Murphree & Aldeias, 2022). The presented method allows for identifying such combustion features even when dislocated and of lost structure. Its application has the potential to indicate the complexity of human behavior at an archaeological site and to document the continental-scale spatial distribution of fire use especially in the multilevel Upper Paleolithic contexts. The latter is important for the further development of niche construction theory and, consequently, a better understanding of human evolution.

6 | CONCLUSION

We were able to identify an intense fire event in one (coinciding within a CL 2) out of eight analyzed paleosols at K14 by analyzing their magnetic properties based on the method of Oldfield and

Crowther (2007). The pedogenic origin of other samples from the Ah horizons was confirmed; however, the hypothesis of pyrogenic impacts of moderate and low intensity has not been rejected. It should be highlighted that the anthropogenic impact is not opposed to the effect of natural pedogenic processes; they are strongly interconnected. On the one hand, burning related to human activity was considered an additional process, which altered the natural characteristics of paleosols formed by pedogenesis. On the other hand, high bioturbation activity after the phase of settlement deduced based on the micromorphological observations has been suggested to cause the dilution of a strong pyrogenic signal in the soil. The determined impact of the intense fire was shown to be more typical for anthropogenically controlled fire, that is, a hearth, rather than for natural/anthropogenic fire on a landscape scale. However, we also cannot deny that the strong pyrogenic magnetic enhancement and reddening of the soil material could be the local effect of a large-scale fire. Nonetheless, the high heterogeneity of the Ah horizon of paleosol IIc (CL 2) based as well on magnetic parameters and the spatial proximity of numerous microfragments of burnt bones to the reddish humic lens indicate that the hypothesis of a local human-controlled fire, i.e., a hearth, is more probable.

The preservation potential of pyrogenic signatures in pedogenic paleoarchives is quite weak. First, not all fire events are recorded in the soil memory by means of altered magnetic characteristics, which may be difficult to distinguish from similar characteristics resulting from other processes, including soil formation processes. Second, burnt soil layers are generally thin and more predisposed to erosion and other postevent processes.

The application of this method at archaeological sites is beneficial for the identification of an intense fire event, that is, a hearth, even of lost structure, within CLs in dark humic paleosol horizons. The anthropogenic fire on a landscape scale requires other multiproxy methodologies because its magnetic properties are the same as those of a natural wildfire.

The impact of Paleolithic humans on soils must be studied within CLs, where the effect of human activities is the most intensive. A detailed analysis of soil properties at an archaeological site could indicate the anthropogenic activities, which caused ecosystem alterations. If these alterations reciprocally determined some of human genetic and cultural traits, the identified human activities are considered to have a niche construction effect. Anthropogenically controlled fire, one of the prominent aspects of niche construction, has been investigated in this paleopedological study. The complex of human activities and their impact on soils at Paleolithic sites are to be studied further to unravel human evolutionary history.

AUTHOR CONTRIBUTIONS

Anastasiia Kurgaeva: Conceptualization; investigation; writing—original draft; visualization; writing—review and editing; formal analysis; data curation. **Sergey Sedov**: Conceptualization; writing—review and editing; data curation; supervision; formal analysis; investigation. **Sol Moreno-Roso**: Visualization; formal analysis; writing—review and editing; investigation. **Hermenegildo Barceinas Cruz**: Investigation. **Beatriz Ortega Guerrero**: Investigation; writing—review and editing. **Elizabeth Solleiro-Rebolledo**: Investigation. **Andrei Sinitsyn**: Writing—review and editing; data curation.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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3. Discusiones

3.1. Tiempo de permanencia de los efectos de la quema del suelo y de los rasgos pirogénicos en los registros pedológicos y edafo-sedimentarios.

Los cambios en las propiedades de los suelos tras el efecto del fuego pueden ser efímeros, pueden persistir por años o incluso pueden llegar a ser permanentes (DeBano *et al*., 1998). Algunas modificaciones de las propiedades químicas del suelo después de la quema (pH, concentración de cationes intercambiables) en algunos casos pueden regresar rápidamente a los niveles previos a la quema, en cuestión de meses o pocos años (Granged et al, 2011; Maynard et al., 2014). De acuerdo a Fachin et al. (2024), la mayoría de los parámetros físicos afectados por el fuego después de la práctica de la roza-tumba y quema muestran una buena resiliencia al cabo de cinco años, a excepción de la estabilidad de agregados que mejora con el tiempo. Dichos cambios físico-químicos y su evolución en el tiempo solo es posible monitorearlos en quemas contemporáneas, en escalas máximas de décadas, debido a la limitación temporal de la información y al tiempo de permanencia de algunos efectos de la quema en el suelo.

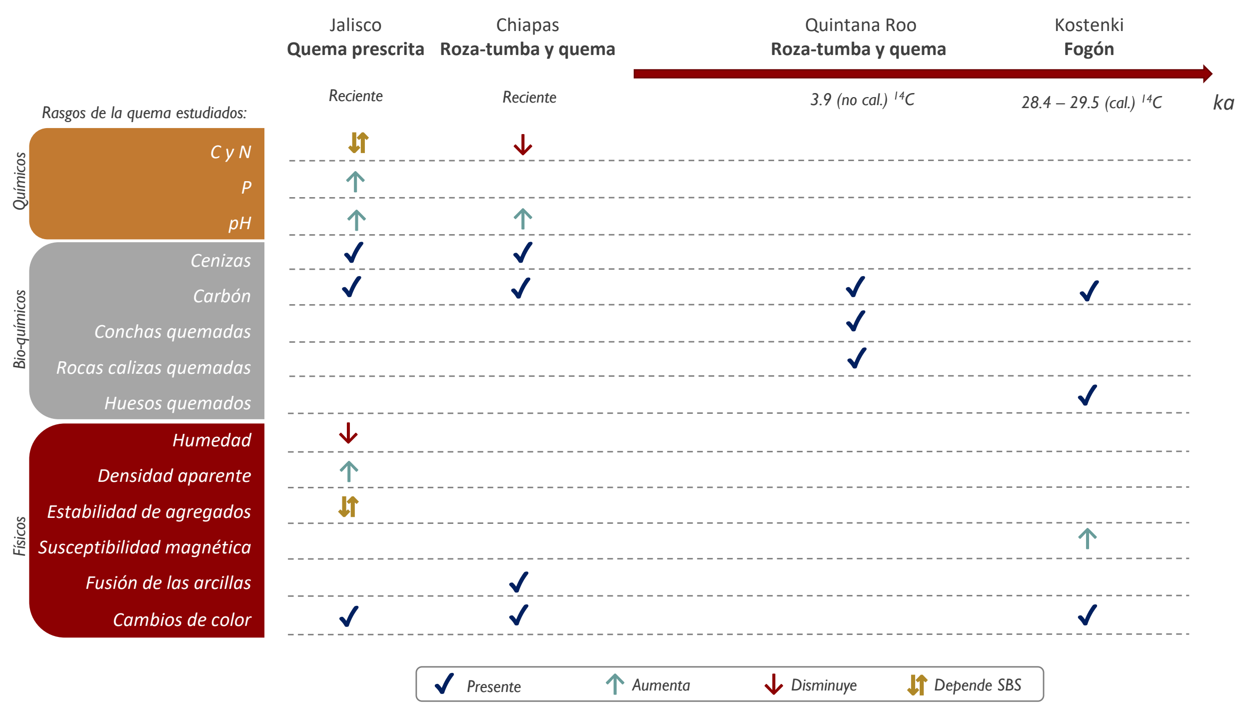

Figura 2. Tiempo de permanencia de los efectos de la quema del suelo y los rasgos pirogénicos en los registros pedológicos y edafo-sedimentarios estudiados en los tres artículos.

En el caso de la quema prescrita en Jalisco, encontramos que algunas propiedades físico-químicas fueron alteradas (Fig. 2), las cuales muy probablemente ya se han modificado con el pasar de los años y la señal de la quema ha quedado diluida. No obstante, como producto de los diferentes niveles de severidad de la quema del suelo se generaron otros rasgos pirogénicos como carbón, cenizas y agregados enrojecidos, que bajo ciertas condiciones pudieran llegar a preservarse a largo plazo. A pesar de que en el sitio se prestó especial atención a la quema reciente y a sus efectos, también fueron identificados carbones de quemas pasadas, incorporados en la matriz del suelo a unos cuantos centímetros de la superficie (Moreno *et al*., 2023), pues esta reserva tiene una alta recurrencia de incendios y seguramente un largo historial de eventos. Lo cual demuestra que el carbón es uno de los rasgos pirogénicos con mayor probabilidad de preservación y que su incorporación al suelo puede aportar información sobre quemas del pasado.

Por otra parte, en contextos geoarqueológicos difícilmente podremos obtener datos sobre las condiciones físico-químicas del suelo previas a las quemas, además, como se mencionó anteriormente muchas de las propiedades modificadas cambian a corto plazo, haciendo difícil reconstruir con exactitud los cambios ocurridos en el suelo debido al efecto del fuego. Sin embargo, ciertos productos pirogénicos logran preservarse en el registro edáfico y a partir de estas evidencias podemos descifrar distintos aspectos de la quema como, el tipo de uso del fuego, la recurrencia, los combustibles empleados, los procesos posteriores al evento, entre otros.

En la figura 2, observamos que el carbón, las conchas quemadas y las rocas calizas carbonizadas fueron los rasgos pirogénicos de paleo-quemas que lograron preservarse durante más de 3800 años en el registro edafo-sedimentario de la cueva colapsada de la Cantera Coyote en Quintana Roo (Moreno-Roso *et al., in press*). En cambio, en los fogones Paleolíticos en Kostenki 14, los rasgos de quema que se conservaron, durante más de 28000 años, incluyen carbón, huesos quemados, minerales magnéticos pirogénicos y materiales enrojecidos (Kurgaeva *et al.*, 2023). También es importante destacar que existen ciertos rasgos pirogénicos que se pierden en sitios abiertos con el pasar del tiempo como, por ejemplo, las cenizas. A pesar de que la práctica de la roza-tumba y quema en Chiapas, además de carbón y enrojecimiento del suelo, dejó cenizas en los poros (Moreno-Roso *et al., in press*), este último rasgo no fue observado en los pedosedimentos de la cueva colapsada en Quintana Roo. No obstante, en la cueva colapsada se identificaron otros productos de la combustión como conchas y rocas caliza quemadas que en Chiapas no se encontraron. Por lo tanto, se observa que el carbón es el rasgo pirogénico predominante en todos los registros estudiados. Mientras que los demás rasgos de quema, aunque también pueden mostrar una alta estabilidad en el tiempo, su aparición en un registro u otro parece depender de otras condiciones asociadas al evento de quema y al sitio o a características particulares de los mismos rasgos.

3.2. Condiciones que determinan la producción de rasgos pirogénicos y su preservación en los suelos y edafo-sedimentos

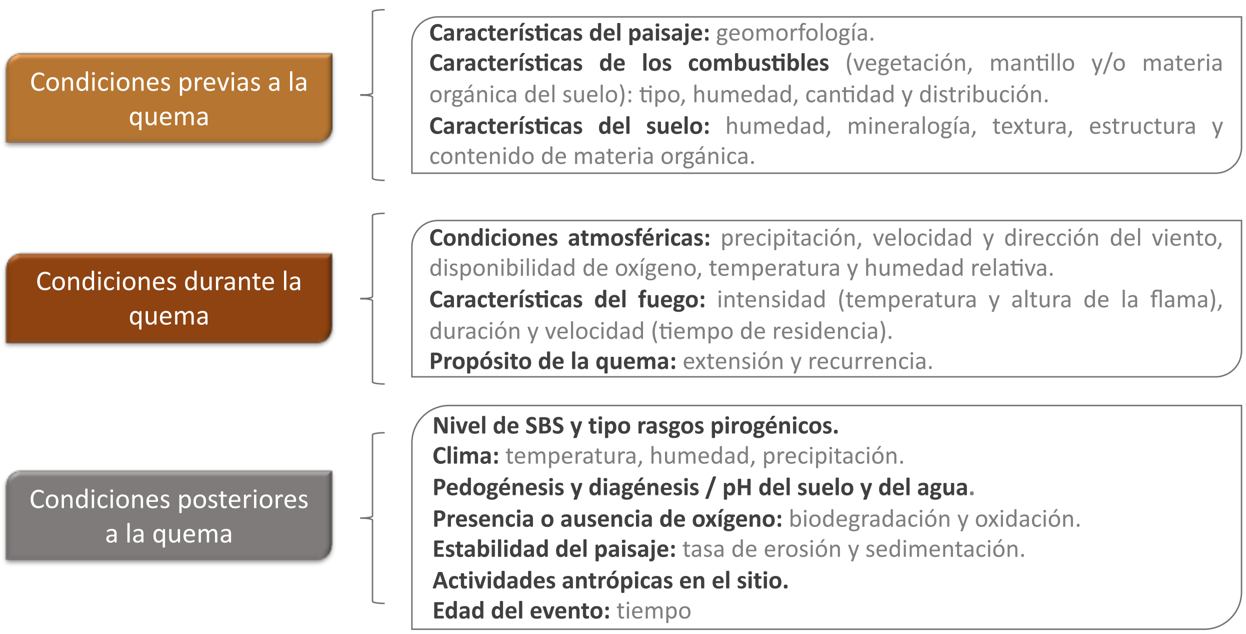

Figura 3. Condiciones que determinan la producción de rasgos pirogénicos y su preservación en los suelos y edafo-sedimentos.

La severidad de la quema en el suelo y por lo tanto los rasgos pirogénicos derivados, van a depender de diversos parámetros antes y durante la quema, sin embargo, la preservación de estos indicadores del fuego en los registros edáficos va a estar determinada, además, por condiciones posteriores al evento (Fig. 3; DeBano et al., 1998; Mallol et al., 2017).

3.2.1. Condiciones previas a la quema que influyen en la producción de rasgos pirogénicos

Las características geomorfológicas del paisaje o del sitio, definen el comportamiento del fuego, ya que la pendiente, la altitud y la exposición del terreno influyen en la forma y velocidad con la que la quema se propaga (CONAFOR, 2010). Asimismo, las propiedades de los combustibles (vegetación y mantillo) como el tipo, la composición, la humedad, la cantidad y distribución, también determinan las características del fuego (CONAFOR, 2010; Ngole-Jeme, 2019), los efectos de la quema en el suelo y el tipo de rasgos pirogénicos generados, por ejemplo, material vegetal carbonizado o cenizas. El material orgánico carbonizado incluye al carbón, el cual puede exhibir diversas formas y estructuras de acuerdo tipo vegetal y a la parte de la planta de la que procede: hojas o espículas, ramas, troncos y raíces (Canti, 2017). Por otra parte, los principales componentes minerales de las plantas son sílice y oxalato de calcio, el primero especialmente en las gramíneas y el segundo omnipresente en las hierbas, árboles y arbustos, pero es muy raro en las gramíneas (Canti y Brochier, 2017). Entonces, de acuerdo a la familia de plantas que se queman, las cenizas van a contener fitolitos de sílice o pseudomorfos de fitolitos de oxalato, que se encuentran compuestos por carbonato de calcio (Canti y Brochier, 2017).

En la quema prescrita llevada a cabo en el bosque de la Reserva de la Biósfera de Manantlán, Jalisco, el combustible principal fue el mantillo, el cual contenía dominantemente restos de la vegetación arbórea del sitio en diferentes estados de descomposición. La quema controlada y la probable humedad del mantillo permitieron una combustión incompleta del material vegetal asociado a un nivel bajo de la severidad de la quema en el suelo (SBS), generando numerosos restos vegetales quemados y materia orgánica carbonizada que produjeron el oscurecimiento de la superficie del suelo mineral en la mayor parte del área quemada (Moreno-Roso *et al*., 2023). Mientras que, en zonas específicas, asociadas a un nivel alto de SBS, se encontraron rasgos pirogénicos diferentes, como el enrojecimiento de algunos agregados y la presencia de cenizas, con formas rómbicas a escala microscópica, compuestas por $CaCO_3$ (Moreno-Roso *et al*., 2023). Probablemente, en estas pequeñas zonas había restos de troncos o ramas más gruesas que representaban una mayor cantidad de combustible, dando lugar a una intensidad del fuego mayor y/o a un tiempo de residencia del fuego relativamente más largo (Badía *et al*., 2017; Ngole-Jeme, 2019).

Por otra parte, las características del suelo como: humedad, mineralogía, textura, densidad y contenido de materia orgánica, también determinan en gran medida su nivel de severidad de la quema (Ngole-Jeme, 2019). La transferencia del calor en los suelos va a depender de un umbral del contenido de humedad, pues mientras algunos autores señalan que en suelos húmedos el agua incrementa la capacidad y conductividad térmica del suelo (DeBano *et al*., 1998), otros autores demostraron que los efectos del fuego son menos intensos y más superficiales en un suelo humedecido a capacidad de campo (Badía *et al*., 2017) o imperceptibles en un suelo húmedo de un bosque boreal (Santín *et al*., 2016). Por otra parte, la mineralogía, la textura y la densidad del suelo también definen su conductividad y capacidad térmica, debido a las variaciones en las estructuras minerales y en el tamaño y empaquetamiento de las partículas (Ngole-Jeme, 2019). Los suelos en los que predominan minerales primarios (p.ej. cuarzo o calcita) tamaño arena y limo, pueden alcanzar y soportar temperaturas más altas que aquellos suelos donde dominan minerales secundarios (Midttømme *et al*., 1998) y además, a mayor densidad del suelo la conductividad térmica mejora y las temperaturas del suelo son más elevadas durante un incendio (Giovannini *et al*., 1988), por lo tanto, los suelos arcillosos son más susceptibles a los cambios inducidos por el fuego (Neary et al., 2005). Asimismo, suelos ricos en materia orgánica poseen una conductividad térmica más elevada que suelos con un bajo contenido de materia orgánica (Ngole-Jeme, 2019).

Comparada con la quema prescrita en Jalisco, la roza-tumba y quema en Chiapas, resultó con una SBS mayor, siendo las evidencias más resaltantes el enrojecimiento de los primeros cuatro centímetros del perfil, la presencia de cenizas y el cambio textural del suelo (Moreno-Roso *et al., in press*). El fuerte incremento de la fracción tamaño arena en esos suelos tan arcillosos de Chiapas, lo atribuimos a la fusión térmica de las partículas de arcillas y a la transformación de los oxi-hidróxidos de Fe y Al de los minerales durante la quema (>500 ºC), generando así agregados arcillosos tamaño arena con una estabilidad muy alta (Ulery y Graham, 1993; Ketterings *et al*., 2000; Certini, 2005; Mataix-Solera *et al*., 2011; Santín y Doerr, 2016; Moreno-Roso *et al*., in press).

Otras de las características del suelo que determinan los cambios que van a ocurrir durante la quema son la concentración de óxidos de hierro y el contenido de materia orgánica, pues la presencia de estos dos elementos conlleva a la transformación de los óxidos de hierro (p. ej., hematita) a una forma fuertemente ferrimagnética (Tite y Mullins, 1971), denominados minerales magnéticos pirogénicos (p. ej., magnetita o maghemita), los cuales fueron detectados en los paleosuelos de Kostenki y nos ayudaron a confirmar, junto con la identificación de otros rasgos pirogénicos, la ocurrencia de quemas durante el Paleolítico como parte de las actividades humanas en el sitio (Kurgaeva *et al*., 2023).

3.2.2. Condiciones durante la quema que influyen en la producción de rasgos pirogénicos

Además de las condiciones previas al evento, el propósito de la quema (p.ej. cocción de alimentos, roza-tumba y quema, quema prescrita) y las condiciones atmosféricas en el sitio durante el evento (precipitación, velocidad y dirección del viento, disponibilidad de oxígeno, temperatura y humedad relativa) van a definir características claves del fuego (CONAFOR, 2010) como la intensidad, duración y velocidad de propagación. Dichas características del fuego determinan la magnitud del impacto del fuego en el sistema edáfico, es decir, la severidad de la quema en el suelo (SBS, por sus siglas en inglés; Vega *et al*., 2013). La intensidad del fuego se refiere a la cantidad de energía liberada y se relaciona a la altura y temperatura de la flama, sin embargo, la intensidad por sí sola, no establece el nivel de impacto de la quema en el suelo, pues la mayor parte de la energía térmica liberada durante la combustión se dirige hacia arriba y solo una pequeña parte calienta el suelo (Doerr *et al.*, 2023). Entonces, la SBS no solo va a estar determinada por la temperatura máxima alcanzada en el suelo sino además por la duración del calentamiento, es decir, el tiempo de residencia (Doerr *et al.*, 2023; Ketterings y Bigham, 2000).

Asimismo, cada nivel de SBS resultante va a tener asociados ciertos rasgos pirogénicos, como, por ejemplo, en los niveles de SBS bajos es posible encontrar abundante carbón y el suelo mineral oscurecido mientras que, en los niveles altos de SBS se puede observar una capa de ceniza blanca sobreyaciendo el suelo mineral enrojecido (Vega *et al*., 2013; Moreno-Roso *et al*., 2023). Por su parte, las variaciones del color en los suelos debidos a la quema, como el oscurecimiento, aclarado y enrojecimiento, son principalmente el resultado de la carbonización de la fracción orgánica, de la producción de cenizas y de la transformación de los óxidos de hierro, respectivamente (Ulery y Graham, 1993; Ketterings y Bigham, 2000). Entonces, dichos cambios de color van a estar en función tanto de la cantidad de vegetación, de materia orgánica y de óxidos de hierro, así como de la temperatura máxima experimentada en el suelo y el tiempo de exposición (Certini, 2005; Ketterings y Bigham, 2000).

Por otra parte, el propósito de la quema define en gran medida los alcances y efectos en el sistema pedológico, ya que, en función del objetivo del evento, el fuego va a tener una intensidad, duración, extensión y recurrencia específica. Si se trata de una quema prescrita, ésta será controlada y de baja intensidad, delimitada a un área específica, con una recurrencia definida (de acuerdo con las características del ecosistema), con el objetivo de reducir combustibles y de minimizar la probabilidad de ocurrencia de un incendio de alta intensidad (Fernandes *et al.,* 2013; Santín y Doerr, 2016), procurando que la severidad de la quema en el suelo sea baja en la mayor parte del área como en el trabajo de Moreno-Roso *et al*. (2023). Aunque la roza-tumba y quema se considera una “quema controlada”, esta práctica puede representar un fuerte impacto para los suelos (Santín y Doerr, 2016; Moreno-Roso *et al., in press*), ya que después de la roza-tumba, puede haber grandes cantidades de combustibles acumuladas directamente sobre el suelo, incrementando la transferencia de calor durante la quema (Thomaz *et al*., 2014). Sin embargo, existen diferencias significativas en la práctica de la roza-tumba de una cultura a otra y entre la quema tradicional y la contemporánea, que repercuten en el nivel de severidad de la quema en el suelo, por ejemplo, los años de recurrencia de la práctica en el sitio, es anual en algunos casos, mientras que en otros es cada 25 años (Nigh y Diemont, 2013) o la acumulación del rastrojo o combustible en pilas en diferentes puntos del área (Santín y Doerr, 2016). Finalmente, cuando el propósito de la quema es la cocción de alimentos y quizás el proveer además calentamiento, la combustión se lleva a cabo en una zona espacialmente restringida y con una alta recurrencia, como en el caso de los hornos Paleolítico hallados en los paleosuelos de Kostenki, donde los humanos tenían áreas destinadas específicamente para dichas actividades (Kurgaeva *et al*., 2023). Debido a la alta frecuencia de la quema de diferentes combustibles en una pequeña área, la afectación del suelo fue más profunda (alrededor de 10 cm) y más severa (enrojecimiento y generación de minerales magnéticos pirogénicos), con la presencia de fragmentos de carbón y de huesos quemados. No obstante, como se mencionó en el apartado anterior, la producción de anomalías magnéticas en el suelo no solo depende de la tasa de recurrencia de la quema, asociada a una ocupación humana intensa durante un largo periodo de tiempo, sino también de la concentración de óxidos de hierro en el suelo (Tite, 1972).

3.2.3. Condiciones posteriores la quema que influyen en la preservación o pérdida de los rasgos pirogénicos

La mayor parte de las condiciones previas y durante la quema, aunque algunas son difíciles de medir, pueden ser conocidas en los eventos actuales por medio de mediciones específicas en el sitio (como en Moreno-Roso et al., 2023). Sin embargo, en contextos geoarqueológicos difícilmente se logra determinar con exactitud dichas condiciones, debido a la influencia y la variación de muchos factores en el impacto del fuego y a la pérdida total o parcial de esta información después del evento. Sin embargo, de acuerdo a la SBS resultante, ciertas evidencias de la quema logran preservarse en los registros pedológicos, aportando indicios para la reconstrucción de la historia del fuego y sus efectos en el paisaje. El tiempo de permanencia de estos rasgos pirogénicos en el suelo, va a depender de diversos factores posteriores a la quema como: el clima, la pedogénesis, el pH del suelo y los fluidos, la biodegradación, la diagénesis, la estabilidad del paisaje, las actividades antrópicas en el sitio y la edad del evento.

El factor clima en conjunto con la pedogénesis y el pH, juegan un papel crucial en la permanencia de los rasgos pirogénicos, pues los climas húmedos derivan en la disolución de muchas de las evidencias de la quema en el suelo, debido al aumento de la infiltración del agua de lluvia en el suelo y/o por la subida del nivel freático. Por ejemplo, la disolución química de minerales u otros productos de la combustión por la presencia de aguas ácidas o alcalinas en el suelo, derivan en la disolución de la calcita y de la sílice en las cenizas, respectivamente (Mallol *et al*., 2017). Probablemente, esta es una de las razones por la cual no se hallaron cenizas asociadas a los rasgos de quema en los pedosedimentos de las bolsas kársticas de Quintana Roo (Moreno-Roso et al., *in press*), ya que las tasas de precipitación en la Península de Yucatán son relativamente altas. Sin embargo, Mallol *et al*., (2017) indican que, bajo condiciones con un pH neutro a básico y alta humedad, también puede ocurrir la recristalización de la calcita de las cenizas, dando como resultado la pérdida de las formas rómbicas y la cementación de agregados individuales en una masa litificada. Por otra parte, las condiciones óxicas y los climas húmedos y cálidos también favorecen la biodegradación del carbono pirogénico (Knicker, 2023). Además, en el suelo superficial el carbono pirogénico se puede mineralizar y degradar por foto-oxidación o por oxidación en quemas subsecuentes (Bird *et al*., 1999; Czimczik y Masiello, 2007; Hobley, 2019; Knicker, 2023)

No obstante, el colapso del techo de la cueva en la Cantera Coyote, en algún momento de la historia, al parecer permitió el aislamiento de los restos de la combustión (carbón, conchas y calizas quemadas) de la acción biológica y de las condiciones climáticas de la Península de Yucatán, promoviendo su preservación por miles de años a otra profundidad dentro del sistema edafo-kárstico (Moreno-Roso et al., *in press*). Por otra parte, teóricamente los minerales magnéticos se pueden disolver o transformar bajo climas húmedos en condiciones reductomórficas (Ortega-Guerreo *et al*., 2004; Kurgaeva *et al*., 2023), destruyéndose así la señal magnética pirogénica. Sin embargo, en el caso de los paleosuelos de Kostenki, la señal magnética logró preservarse a pesar de los episodios de saturación de los suelos con agua y hielo, que dejaron como resultado el desarrollo de rasgos reductomórficos y horizontes gléyicos (Kurgaeva *et al*., 2023).

Asimismo, las coloraciones oscuras y rojizas resultantes de la quema en los hornos Paleolíticos de Kostenki fueron conservadas en el tiempo, a pesar de que ciertos procesos pedogenéticos pueden conllevar a cambios en la coloración del suelo, borrando o enmascarando de esta manera los colores resultantes del efecto del fuego. En el caso de Chiapas, como resultado de la roza-tumba y quema reciente hubo un enrojecimiento intenso de los suelos, mientras que en los pedosedimentos de la Cantera Coyote en Quintana Roo, solo fue posible identificar algunos agregados rojizos y redondeados que, aunque estaban asociados a otros rasgos pirogénicos productos de quemas antiguas, no se descarta la posibilidad de que sean elementos heredados de suelos tipo *Terra Rossa* o Luvisoles crómicos, que están presentes en zonas kársticas.

Después de quemas extensivas, el terreno queda casi totalmente desprovisto de vegetación y mantillo, la hidrofobicidad y la estabilidad de los agregados cambia, por lo tanto, el suelo puede ser muy susceptible a la escorrentía y a la erosión superficial por el viento o por el agua durante las primeras lluvias después del evento, sobre todo sí la topografía es inclinada como en los paisajes montañosos (Doerr *et al*., 2023). Estos procesos de erosión lateral de los suelos borran muchas de las evidencias de la quema, arrastrando la mayor parte de los carbones, agregados quemados y cenizas de la superficie hasta otras partes más bajas del paisaje, promoviendo la fertilización de otros suelos o contaminando cuerpos de agua (Doerr *et al*., 2023; Sigmund et al., 2021; Sánchez-García et al., 2023). De esta manera muchos de los carbones son removidos de la pedósfera y se incorporan al registro sedimentario (Santín y Doerr, 2016). En el caso de plataformas kársticas, como la Península de Yucatán, es más común que ocurra la erosión vertical de los suelos (*soil pipping*), la cual suscita el movimiento de los rasgos pirogénicos junto con los pedosedimentos hacia las depresiones kársticas. El agotamiento del oxígeno a mayor profundidad en el sistema edáfico reduce la biodegradabilidad del carbono pirogénico, favoreciendo su preservación durante cientos o miles de años (Knicker, 2023), como se demostró en las bolsas kársticas y cuevas de Quintana Roo (Cabadas-Báez et al., 2010; Sedov et al., 2023; Moreno-Roso *et al., in press*).

Por otra parte, Hobley (2019) indica que la materia orgánica pirogénica (PyOM o *black carbon*) de los suelos, como por ejemplo el carbón (PyOM partículada), también se puede translocar a distintas profundidades dentro del perfil y propone tres mecanismos para explicar esta redistribución vertical de la PyOM: mezcla, percolación y cambio de superficie. i) Los procesos de mezcla o pedoturbación como, el agrietamiento de las arcillas, los ciclos de congelación-descongelación y la bioturbación, redistribuyen las partículas del suelo, incluyendo a la PyOM; ii) La eluviación de la PyOM con la percolación del agua de lluvia puede ocurrir durante precipitaciones de alta energía e incluso puede llegar a disolverse y lavarse (Hockaday *et al*., 2006), conllevando a la pérdida de la PyOM del suelo hacia las aguas subterráneas o a su inmovilización si existen cambios en el pH o en la mineralogía del suelo (Knicker, 2023); iii) Los cambios en el nivel de la superficie del suelo pueden ocurrir en ambientes deposicionales, donde la PyOM es enterrada y puede quedar protegida de la degradación (VandenBygaart *et al*., 2015). El análisis de las relaciones entre el tamaño, la profundidad y la edad de la PyOM aporta información importante sobre los mecanismos responsables de su redistribución y sobre la pedogénesis (Hobley, 2019).

La translocación de PyOM dentro del perfil de suelo fue detectada en el trabajo de Moreno-Roso *et al*. (2023), donde fragmentos de carbón (> 2 mm) de eventos pirogénicos anteriores a la quema prescrita se encontraban a varios centímetros de profundidad en el perfil (> 5 cm) e incluidos dentro de la matriz del suelo, lo cual se puede atribuir a algunos de los mecanismos antes mencionados. Además, Hobley *et al*. (2017) señalan que los fragmentos de carbón pueden ser integrados rápidamente, después de un evento de quema, al sistema edáfico, donde logran persistir por largos periodos de tiempo.

En entornos protegidos, como cuevas y espacios interiores, o en paisajes con una topografía plana, donde la tasa de sedimentación es más alta que la de erosión, es más fácil que se conserven rastros de las quemas antiguas en los suelos (VandenBygaart *et al*., 2015; Karkanas, 2021), incluso pueden conformar capas completas o morfologías de quema *in situ*, como se mostró en el trabajo de Kurgaeva *et al*. (2023). Sin embargo, en Kostenki, los rasgos pirogénicos fueron afectados por procesos geogénicos posteriores, como la solifluxión y la criogénesis, que deformaron los horizontes del suelo y fragmentaron los carbones y los huesos quemados. Mallol *et al*. (2017) explican cómo los rasgos de la combustión pueden ser re-trabajados por otros procesos geológicos donde son transportados por agentes como el agua, el viento o la gravedad (procesos coluviales y *soil pipping*), dando lugar a ciertas características de redondeo, laminación y clasificación textural de los residuos quemados que son identificables por medio de la micromorfología. Asimismo, Mallol *et al*. (2017) señalan que los rasgos pirogénicos también pueden ser re-trabajados por procesos biológicos, que son evidenciados por características de bioturbación, tales como, biogalerías, madrigueras o gránulos fecales con residuos de la combustión, donde se observa homogeneización extensa y el desarrollo de una estructura granular con restos de quema.

Las actividades antrópicas realizadas posteriores a la quema también tienen una influencia importante en la conservación y el re-trabajo de los rasgos de combustión en el suelo, pues como se mencionó anteriormente, el uso frecuente del fuego en una misma área va a promover la acumulación de una mayor cantidad de rasgos de pirogénicos, lo cual puede provocar que la señal de la quema sea más clara o, por el contrario, el fuego puede oxidar los carbones ya existentes y la acumulación de cenizas puede crear un efecto aislante al impacto del fuego en el suelo (Czimczik y Masiello, 2007; Karkanas, 2021). Los rasgos pirogénicos pueden ser mezclados con el suelo durante las actividades agrícolas como, el arado y la labranza, a lo cual se le denomina “antropoturbación” (Hobley, 2019). Por otra parte, los residuos de la combustión también pueden ser rastrillados, vertidos o pisoteados intencionalmente o no (Mallol *et al*., 2017; Miller *et al*., 2010). Por medio de experimentos, Miller *et al*. (2010) determinaron a escala microscópica ciertas características de los materiales quemados, encontrando patrones de clasificación textural y microestructuras resultantes de cada una de estas actividades posteriores a la quema, sin embargo, concluyeron que dichas características varían de acuerdo al contexto arqueológico y que es difícil distinguir entre el barrido y vertido de los residuos pirogénicos basándose únicamente en las características micromorfológicas. Por otra parte, el pisoteo puede modificar la fábrica y la estructura de los rasgos pirogénicos por medio de la distribución horizontal o vertical y la compactación de los materiales de la combustión y aplastando y rompiendo los huesos quemados (Mallol et al., 2017; Miller et al., 2010). Karkanas (2021) menciona que las cenizas son también muy vulnerables a la modificación por el peso del pisoteo o por el peso de sedimentos suprayacentes, debido a su baja densidad, alta porosidad y alta compresibilidad (alrededor del 90%). Además, el espesor inicial de las cenizas y la cantidad de carbones producidos va a depender, además de la cantidad y tipo de combustible, del número de quemas en el sitio y del control del fuego por el humano (Karkanas, 2021).

Finalmente, la edad del evento determina en gran medida la preservación de los efectos de la quema en el suelo, pues mientras mayor sea la antigüedad de la quema, menor es la probabilidad de que los rasgos pirogénicos se conserven, sin embargo, son las características de los mismos rasgos y las condiciones posteriores a la quema las que definen su tiempo de permanencia en el registro pedológico y edafo-sedimentario.

4. Conclusiones

- De acuerdo al tipo de quema realizado, el fuego va a tener diferentes alcances en los efectos provocados en el suelo y por lo tanto, van a resultar diferentes rasgos pirogénicos.

- La mayoría de las variaciones de las propiedades físico-químicas del suelo después de una quema tienen un tiempo de permanencia relativamente corto, sin embargo, algunos rasgos pirogénicos asociados pueden logar preservarse en los registros pedológicos y edafo-sedimentarios durante miles de años.

- Existen varios factores que influyen en la identificación de rasgos pirogénicos de quemas antrópicas en los registros pedológicos y edafo-sedimentarios como: la presencia de evidencias de incendios naturales, la presencia de rasgos pedogénicos con características similares a los rasgos pirogénicos, la heterogeneidad de la severidad de la quema en el paisaje, la escala y la profundidad de muestreo y el uso de técnicas de laboratorio acordes al contexto.

- El carbón resultó ser el rasgo pirogénico más común en los registros pedológicos y edafosedimentarios estudiados, además, su análisis morfológico, termo-químico y radiocarbónico puede aportar mucha información sobre las quemas del pasado.

- El enrojecimiento del suelo, los minerales magnéticos pirogénicos y los huesos, conchas y rocas quemadas, fueron otros de los rasgos de quema identificados, sin embargo, estos estaban presentes o no de acuerdo al contexto de cada sitio.

- Las cenizas fueron rasgos pirogénicos característicos de las quemas recientes, tanto de la roza-tumba y quema como de la quema prescrita; sin embargo, en los contextos geo-arqueológicos donde se identificaron paleoquemas, las cenizas no estaban presentes, probablemente debido a que éstas son fácilmente perdidas por erosión o dilución y en sitios abiertos, como los estudiados, no existían las condiciones idóneas para su preservación.

- Las condiciones previas y durante la quema determinan la severidad de la quema en el suelo y los rasgos pirogénicos generados. Además, las condiciones posteriores a la quema van a definir el tiempo de permanencia de los rasgos pirogénicos en el suelo.

- Las condiciones previas, durante y posteriores a la quema van a estar en función del contexto natural y cultural del paisaje.

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