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An accurate record of volcanic ash fall deposition as characterized by dispersed organic matter in a lower Permian tonstein layer (Faxinal Coalfield, Paraná Basin, Brazil)

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ABSTRACT

For the first time, the dispersed organic matter in the tonstein layer interbedded with a coal seam in the Faxinal Coalfield (Sakmarian, Southern Paraná Basin, Brazil) is characterized. The deposition of clusters of pollen grains was highly influenced by the intense ash fall process that probably occurred during seasonal dehiscence of reproductive structures. The well-preserved phytoclasts with their upper and lower leaf cuticles stuck together indicate that the rapid fall of ash on this material hindered organic biodegradation. The preservation of seemingly autochthonous *Botryococcus* colonies at the top of the tonstein layer is evidence of the subaqueous deposition of this layer. The darkening in cuticles and xylem phytoclasts can be attributed to different causes: the thermal influence of ash fall during deposition, chemical effects of the ash, prolonged oxidation of organic matter in low water level conditions or the burning of plant organs by wildfires. Analyses of dispersed organic matter along the tonstein layer showed that the organic matter succession reflects the composition of different plant strata (herbaceous pteridophytes and arboreal glossopterids-cordaitaleans) around the deposition site.

KEYWORDS **Tonstein. Organic matter. Volcanic ash fall. Southern Paraná Basin.**

INTRODUCTION

Tonsteins are altered volcanic ash layers (Bohor and Triplehorn, 1993) that extend over large distances and usually contain minerals that can be dated by isotopic analyses. Their occurrence is limited to coal-bearing sequences.

Evidence of volcanic activity is widespread in different coal successions of southern Brazil, which are historically assigned to the Río Bonito Formation, a fluvial-marine lithostratigraphic unit constituted by sandstones and shales. This unit contains discrete and continuous clay bed horizons, identified as tonsteins, interbedded within the coal seams from the western to the eastern portion of the southern Brazilian coal basins (Fig. 1; 2) (Formoso *et al.*, 1999; Guerra-Sommer *et al.*, 2008a).

Corrêa da Silva (1973) suggested, on the basis of field relationships and preliminary mineralogical and chemical analyses, that the clay beds in the Candiota Coalfield could be classified as *dichtertonstein* (*sensu* Schüller, 1951) or *stratotonstein* (*sensu* Bouroz, 1962). More recently, Formoso *et al.* (1999) indicated an acidic volcanic origin for these clay beds based on geochemical data.

This is the first characterization of organic matter from different levels of a tonstein bed in an attempt to: i) confirm the relationship between the volcanic ash fall and the process of palynodebris deposition; ii) correlate changes in fluorescence in dispersed organic matter with processes related to ash fall deposition; and iii) correlate the disperse organic matter information with other paleoecological and taphonomic evidence.

GEOLOGICAL AND STRATIGRAPHICAL SETTINGS

The Paraná Basin is a large (1,400,000km2) intracratonic basin covering part of southern Brazil, Paraguay, Uruguay and Argentina (Fig. 1). Basin floor subsidence, in addition to Paleozoic sea-level changes, created six second-order sequences deposited from the Ordovician to Late Cretaceous, separated by regional unconformities (Milani *et al*., 2007). The Gondwana I Supersequence, which includes the coal-bearing strata of the Río Bonito Formation, is a second-order transgressive-regressive cycle.

Most lower Permian coal seams are related to a paralic setting, *i.e*., adjacent to estuarine, deltaic, backshore, foreshore and shoreface siliciclastic depositional environments, and most peat-forming plants grew in back-barrier lagoonal paleoenvironments (Alves and Ade, 1996; Holz, 1998). Deposition occurred in the cool temperate climatic belt at a paleolatitude of approximately 50º (Scotese, 2002). The parautochthonous accumulation of peat in the origin of the Brazilian coal was first documented by Corrêa da Silva (1991). A similar origin was proposed

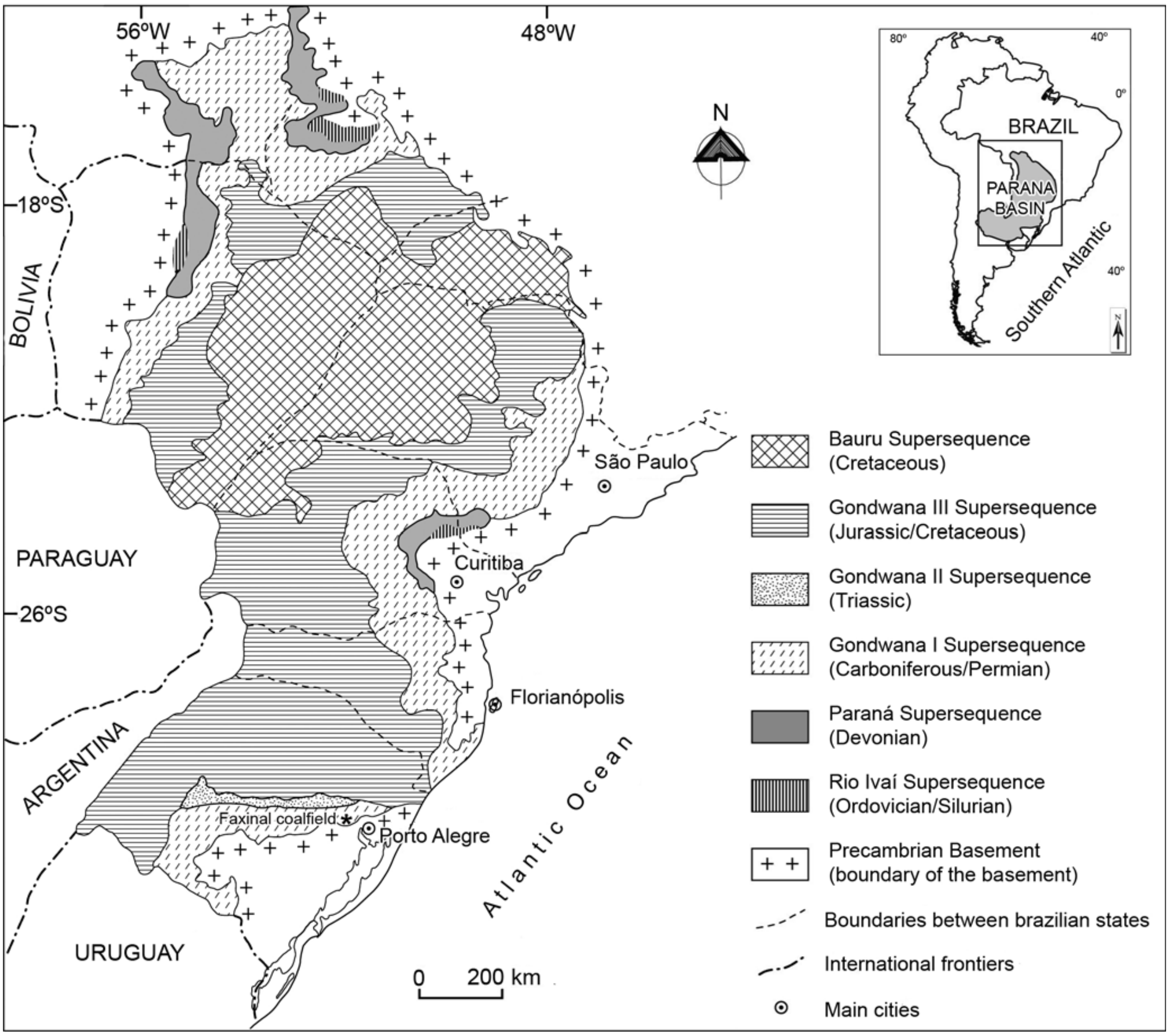

FIGURE 1 | Simplified geological map of the Paraná Basin in Brazil with major tectonic elements, geographic references and location of Faxinal Coalfield (after Santos *et al*., 2006).

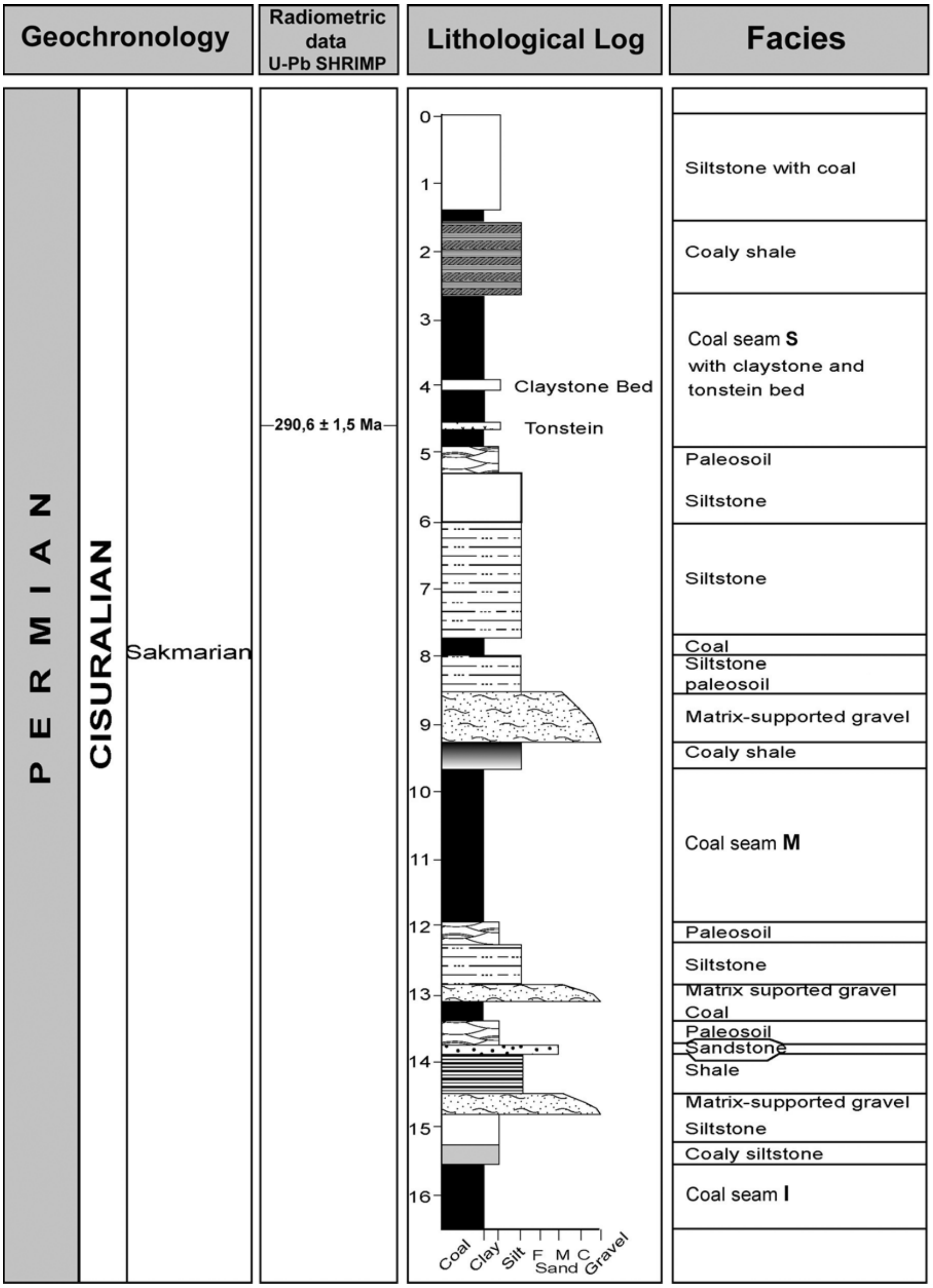

FIGURE 2 | Geochronology, radiometric data, lithological log and facies of the Faxinal Coalfield (after Guerra-Sommer *et al.,* 2008b).

by Glasspool (2003) for peat deposition in the Permian Gondwana of South Africa (Witbank Basin).

The study area comprises the Faxinal Coalfield, which is located along the southeastern outcrop belt of the Río Bonito Formation of the Paraná Basin, southern Brazil (Fig. 2, UTM E432.7 and N6651.5), mined by the Companhia de Pesquisas e Lavras Minerais (COPELMI). The Faxinal Mine is close to the Água Boa and Sul do Leão coalfields, which are situated in an elongated structure trending SE-NW in its eastern portion and E-W in the western, referred to by Ribeiro *et al.* (1987) as a graben. The presence of a tonstein layer as a continuous, regional horizon interbedded within the uppermost coal seams in these coalfields was first noticed by Ribeiro *et al.* (1987).

The Faxinal succession includes five coal seams, named from base to top: I, IM, M, MS, and S (Fig. 2). The coal seams are interbedded with siltstones, mudstones, sandstones, and paleosoils (Fig. 3A). The present study focused on a light gray claystone bed, approximately 10cm thick, that is laminated, to massive, fossiliferous and interbedded within the upper coal seam (S). The tonstein bed is exposed along the cut banks of the open pit and displays mostly sharp lower and upper boundaries (Fig. 3A, B).

The mean ages of 290.6±1.5Ma obtained by Sensitive High Resolution Ion Microprobe U-Pb (SHRIMP II) zircon dating of tonsteins from Candiota and Faxinal coalfields (Guerra-Sommer *et al.*, 2008a) support that coal generation in coalfields of the southern Paraná basin is constrained to the Middle Sakmarian. The potential source for the tonsteins of the Río Bonito Formation has been related to volcanic activity in the Choiyoi Group in the San Raphael Basin, Andes (Matos *et al.*, 2000; Coutinho and Hachiro, 2005; Guerra-Sommer *et al.*, 2008b). New Sensitive High Resolution Ion Microprobe U-Pb zircon ages of these volcanic rocks obtained by Rocha Campos *et al.* (2010) at 251, 264 and 281Ma showed that they are synchronous only with the upper interval (about 25Ma) of the Late Paleozoic ash bed-bearing succession of the Paraná basin and do not include the ash fall rocks associated with coal-bearing strata studied here.

CHARACTERISTICS OF THE FAXINAL TONSTEIN

Mineralogy and petrography

The tonstein at the Faxinal Coalfield is a bed of kilometric continuity corresponding to one pyroclastic fall, about 7-10cm thick (Fig. 3B) with sharp upper and lower boundaries (Ribeiro *et al.*, 1987). Texturally, the tonstein layer is a light gray claystone, including silty clay and medium-sized sand. Irregular lamination is defined by thin coalified fragments representing leaf fragments.

This tonstein is composed of primary minerals derived from volcanic ash and dust fall, and by secondary minerals formed during the diagenetic processes. The rock is composed of 90% authigenic kaolinite (Guerra-Sommer *et al.*, 2008b). Relicts of pyroclastic minerals occur in the kaolinitic mass and correspond to i) euhedral bipyramidal β-quartz paramorph and transparent quartz splinters, ii) idiomorphic zircon, iii) euhedral apatite, and iv) sanidine pseudomorph (Fig. 3D). The granulometry of the zircons, β-quartz and apatite varies from 30 to 150μm.

Other diagenetic minerals were formed after the kaolinization of volcanic glass and pyroclastic minerals from the ash fall. The diagenetic phases were established in the sequence: kaolinite-pyrite-siderite-calcite. (Fig. 3E, F, G).

Small color differences along the tonstein profile allowed the identification of three levels; a basal level, an intermediate level and a top level (Figs. 3C). They were observed in the X ray diffraction (XRD) patterns from the sequential analyses of samples and their color distinction was attributed to variation in the mineralogical composition (kaolinite, siderite, calcite) during diagenesis. Kaolinite is the main secondary phase mineral (up to 95%) in the uppermost level (Fig. 3E). In spite of the color distinction in the levels, there is no evidence of a difference in the depositional processes, suggesting a single event.

Compaction during subsequent diagenesis and burial has been estimated by Bohor and Triplehorn (1993) to amount 4.5:1. Taking into account the 7cm of almost homogeneous thickness of the tonstein layer in the Faxinal Coalfield, it can be inferred that the original thickness of unconsolidated ash would be of about 28cm.

Taphonomy and paleoecology of plant remains

The rich parautochthonous compression of taphoflora hosted by the Faxinal tonstein (Guerra-Sommer, 1992) is predominantly gymnospermous. Fragments of glossopterid leaves (Fig. 4D) constitute 62% of the entire association (*Glossopteris brasiliensis, G. papillosa, G. similis-intermittens*); cordaitalean leaves (Fig. 4E) (*Rufloria gondwanensis*) represent (21%) of the paleoflora; reproductive structures (*Plumsteadia sennes, Scutum* sp.) and seeds (*Platycardia* sp.) correspond to 16% of the association; and fronds (Fig. 4F) (*Sphenopteris* cf. *ischanovensis, Pecopteris* sp., *Botrychiopsis* sp.) are complementary forms (1%). In spite of the presence of paleosols at the base of the coal seam, stems in growth position were absent in the sequence studied.

The dominance of *Glossopteris*, and also the presence of cordaitalean plants occurring in horizontal layers occasionally still attached to short shoots (Fig. 4D) with well-preserved epidermal patterns (Fig. 4A, B) points to a forested association. According to Stanley (1986) the canopy could be as high as about ten times the trunk width in the case of glossopterids. *Glossopteris* are known to be plants which grew in peat-swamps (Pant and Gupta, 1968; Pant and Gupta, 1971; Chandra and Srivastava, 1981) and have been interpreted as deciduous woody trees (Gould and Delevoryas, 1977; Taylor *et al.*, 2000). These data confirm the hypothesis that a peat-forming forest was in the origin of the Faxinal coals, as suggested by organic petrography analyses and palynology (Cazzulo-Klepzig *et al.*, 2007). The organic matter was defined as being derived from woody material, mainly represented by vitrinite, with subordinate exinite and inertinite constituents, which were accumulated in a telmatic environment (forest moor or vegetation *sensu* Hacquebard and Donaldson, 1969). Additionally, the extremely thin

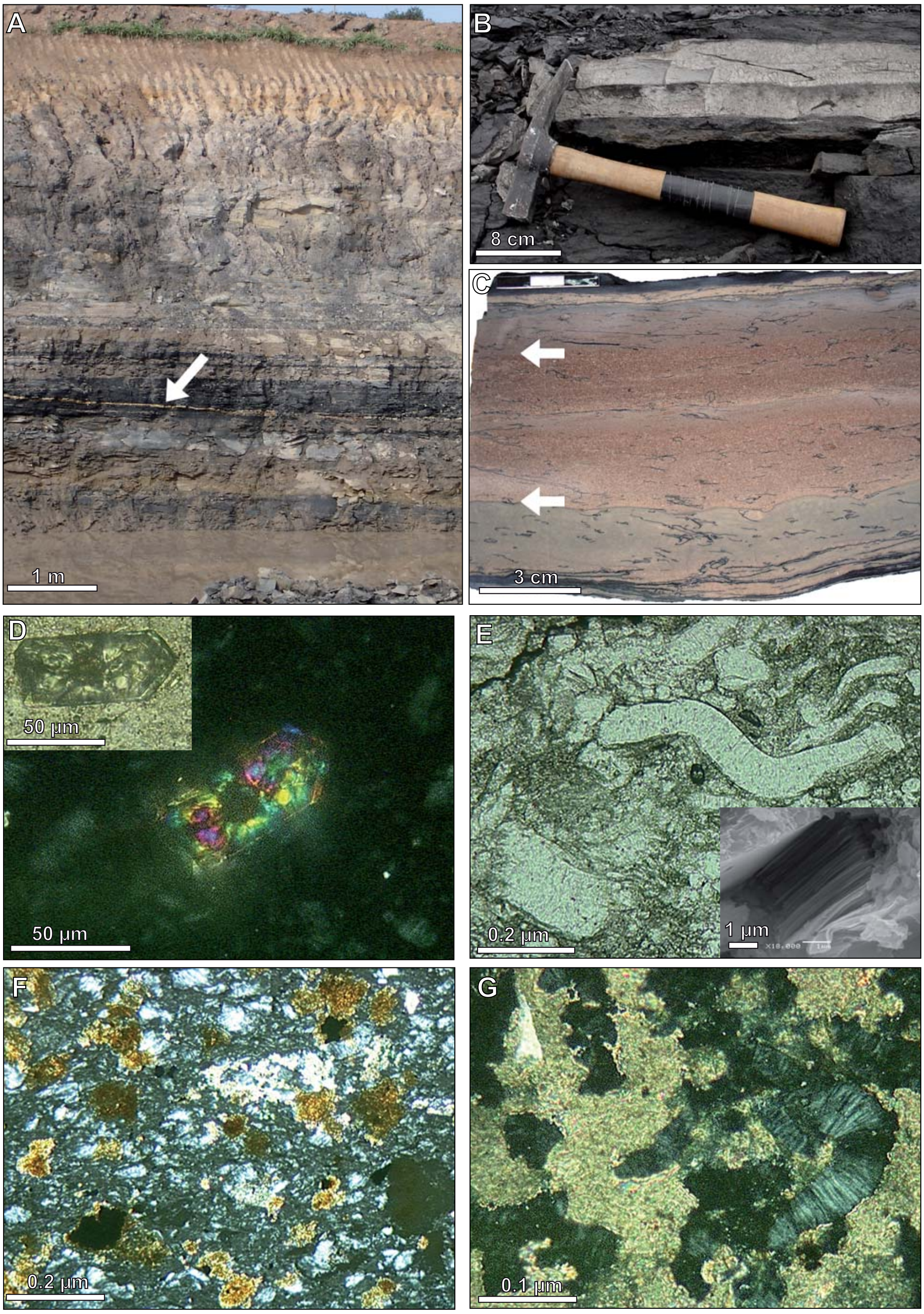

FIGURE 3 | Tonstein of the Faxinal Coalfield. A) Profile with arrow pointing to the tonstein; B) detailed view of the tonstein interbedded in the coal seam S; C) tonstein profile of the sample FX-0, showing the pronounced color differences produced by diagenetic mineral phases (kaolinite at the top, siderite in the middle and in the basal levels). D-G) Photomicrographs of thin sections showing pyroclastic minerals from the Faxinal tonstein. D) Idiomorphic zoned zircon with crystal bipyramidal termination; E) kaolinite in elongate vermicular stacks and in the right lower corner Sr (Scanning Electron Microscope-SEM) image showing "booklets" of kaolinite; F) yellowish brown siderite as granular aggregates dispersed in a kaolinitic matrix, and siderite engulfing pyrite aggregates; G) kaolinite vermicular aggregates and quartz splinters are engulfed and replaced by poikilotopic calcite (basal level).

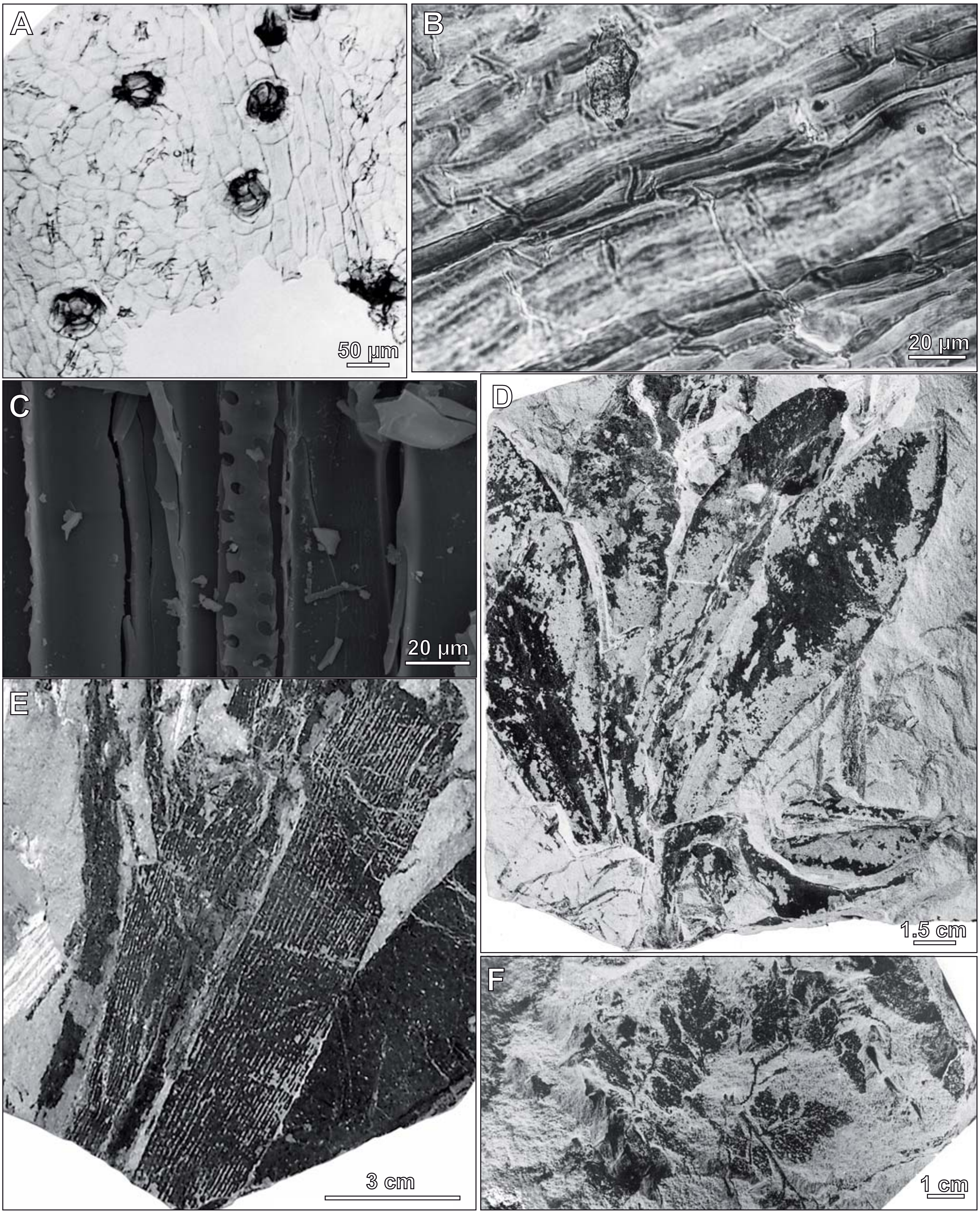

FIGURE 4 | Plant remains from the tonstein bed of the Faxinal Coalfield. A) Lower epidermis of *Glossopteris* leaf showing trichome bases and stomata; B) rectangular shaped and thick-walled epidermal cells of upper surface of *Glossopteris* leaf; C) gymnosperm charcoal similar to the *Aghatoxylon* wood type; D) leaf tuft of *Glossopteris*; E) cordaitalean leaves (*Rufloria gondwanensis*); F) sphenopterid pinnules.

layer of cutin detected in *Sphenopteris* fronds (Fig. 4F) was considered by Guerra-Sommer (1992) as an indication that the plant debris corresponds to herbaceous plants, being rarely affected by wind and water transport (parautochthonous origin according to Martín-Closas and Gomez, 2004).

Jasper *et al.* (2011), based on a vertical analysis of macroscopic charcoal distribution within the Faxinal tonstein layer, observed that charcoal fragments were rather abundant in the basal horizon of the tonstein. Otherwise, macroscopic charcoals are rare in the intermediate levels and absent in the top horizon. The dominant wood-charcoal, *Agathoxylon* (Fig. 4C) has been associated with several gymnosperm groups, including the Glossopteridales (Prevec *et al.*, 2009). Otherwise, both the large size and the absence of abraded edges in the original charcoal fragments may indicate low-distance transport from the original source.

CHARACTERIZATION OF DISPERSED ORGANIC MATTER

Methodology

Attempts were made to develop a more holistic approach to deal with all of the organic matter observed in unoxidized palynological preparations. This analysis involves the identification of the individual particulate components and assessment of the absolute and relative proportions, their size and preservation states (Tyson, 1995; Combaz, 1980; Caratini *et al.*, 1983). Thus, taxonomic descriptions are based on broad morphological groups, and are intended to permit a broad reconstruction of the parent biological structure.

Kerogen classification

The organic matter characterization was based on the qualitative examination of particulate organic matter using microscopy techniques. A total of 300 to 500 particles were counted for each sample, and normalized in percentiles according to the criteria of Tyson (1995) and Mendonça Filho *et al.* (2002).

The scheme used to classify dispersed organic matter by transmitted light microscopy and blue light excitation or ultraviolet irradiation is derived and simplified from the classification of Tyson (1995), based on Combaz (1964), which recognizes four main groups of palynological organic matter, corresponding to I. Structured: 1) palynomorph, 2) phytoclast, 3) zooclast, and II. Structureless: 4) amorphous.

Sampling

The five tonstein samples were collected in a 1km west-east transect, separated from each other by approximately 200m from the open pit area. This technique allowed the comparison of the distribution of the palynological organic matter along the ash fall profile in different, simultaneous depositional sites. The three different levels (basal; intermediate; and top) were independently analyzed in each sample.

Analytical techniques

The samples were first macerated with HCl and HF, followed by heavy liquid (ZnCl2) concentration. The isolated organic matter was then mounted on strewn slides. The preparation technique employed was the standard non-oxidative palynological procedure.

RESULTS

Quantitative analyses of the kerogens for the three different levels of five tonsteins samples are presented in Table 1. High percentages of the structured organic matter of the phytoclast group (arithmetic mean 91.14%) and low percentages for the palynomorph group (arithmetic mean 8.86%) were observed.

Palynomorph Group

Terrestrial plant palynomorphs (pollen grains and spores) dominate over aquatic palinomorphs (*Botryococcus*). The palynomorph group was concentrated in the basal level, decreasing towards the top level. Nevertheless, while dispersed spores were rare and restricted to the top of the five samples, pollen grains were well represented in all three levels (Table 1). A good preservation of pollen clusters (mainly bisaccates) was observed in almost all samples (Fig. 5A, B, C, D), mainly at the base of the tonstein bed (basal level).

Botryococcus colonies (Chlorococcales) occur in the top level of the tonstein bed in different samples (Fig. 5E, F) as evidenced by blue light excitation (Fig. 5E). Some of the colonies are poorly preserved, granular in appearance, and show relatively weak fluorescence. *Botryococcus* is a multicellular colonial chlorophyte from freshwater lacustrine, fluvial, lagoonal and deltaic facies (Traverse, 1955; Pocock, 1972; Claret *et al.*, 1981; Cole, 1987; Batten and Lister, 1988; Riding *et al.*, 1991; Williams, 1992), but this colonial chlorophyte also occurs in eurihaline regimes (Nagappa, 1957; Hunt, 1987).

Phytoclast Group

The phytoclast group (terminology according to Mendonça Filho et al, 2002; Mendonça Filho *et al.*,

2009) was abundant in all samples analyzed. The most conspicuous phytoclast in almost all levels are fragments of woody elements, representing gymnosperm tracheids with helical, scalariform thickening and with bordered pits (Fig. 5G). Non-opaque xylem phytoclasts are proportionally dominant in relation to larger, opaque, angular wood phytoclasts, and non-biostructured translucent xylem phytoclasts are prevalent in relation to biostructured wood phytoclasts. Darkening was observed in some non-opaque biostructured wood phytoclasts.

Isolated thin cuticles corresponding to fragmented leaf material are not common phytoclasts, but are represented in the three levels (Fig. 5H, Table 1). Most of the cuticle phytoclasts can be correlated with the non-stomatiferous leaf surface, showing rectangular epidermal cells, with thick walls (Fig. 5M, N, O). Some of the fragments have polygonal or rectangular cell outlines, with thin anticlinal walls, showing trichome bases (Fig. 5I, J, K, L) which are a typical pattern found in lower epidermis of *Glossopteris* leaves, described by Guerra-Sommer (1992) for this outcrop (Fig. 4B). Well-preserved fragments with upper and lower cuticles stuck together (in single fragments) are common (Fig. 5M, N, O). Cuticle fragments commonly show deviation from the normal pattern in fluorescence, color and intensity.

DISCUSSION

The relative abundance of organic matter components in the Faxinal tonstein reveals that most of the structured organic matter represents fragmented terrestrial plant remains.

Particular mechanisms of the tonstein Formation, related to rapid volcanic ash fall deposition, must be taken into account to interpret the origin of the dispersed organic matter. Volcanic ash falls are considered instantaneous geological events (Prothero, 1990). During the eruption, the pyroclastic material was ejected to high altitudes and transported by stratospheric air flows over significant distances before being finally deposited over a peat surface.

There is a clear succession in the deposition of the organic matter contained in the tonstein bed. The abundance of bissacate pollen clusters at the basal level in the ash deposits suggests that parental plants growing nearby supplied the pollen grains at the time of ash fall, probably during seasonal dehiscence of reproductive structures. A similar process was suggested for the Westphalian of England by Scott and King (1981). In the present case study, deposition processes of these grain clusters were probably strongly influenced by the abundance of pollen grains in the source and the intense and rapid ash fall process.

The preservation of *Botryococcus* colonies (Fig. 5E, F) at the top of the tonstein emphasizes subaqueous deposition of this clay bed. This condition would protect thin volcanic ash deposits from subsequent redistribution by rainfall and surface runoff. Thermally altered conditions of the organic matter could be indicated by the color change of *Botryococcus*. Nevertheless, this change in the fluorescence can also be related to prolonged oxidation of organic matter within a low water table (Hutton *et al*., 1980; Livingstone and Melack, 1984).

The phytoclast group is dominated by xylem elements, but also includes cuticles at the three levels (Fig. 5; Table 1). However, as emphasized by Tyson (1995), the fragmentation of large leaf fragments during maceration may completely distort the nature and size characteristics of the palynofacies assemblage. The peculiar process of ash deposition, which prevented oxidation and minimized sorting, led to the uncommon dominance of non-opaque over opaque xylem phytoclasts. Also, opaque phytoclasts exhibit angular shapes and notable size (Table 1).

The excellent preservation of some isolated cuticles in the tonstein allowed the identification of *Glossopteris* epidermal patterns (Fig. 5I, J, K, L). The segregation of a cuticle from a leaf may occur either by biochemical activity, physical disintegration, or a combination of these processes. Thus, well-preserved leaf fragments with upper and lower cuticles stuck together (Fig. 5M, N, O) represent an uncommon degree of preservation (Garden and Davies, 1988; Spicer, 1991), which can be explained by a limited biodegradation due to the rapid ash fall process.

The weak fluorescence shown by some cuticular phytoclasts can be attributed to physical and chemical damage rather than to thermal processes, as documented by Cook *et al*. (1981), after studying the ash fall deposition following the mount St. Helen's eruption in 1980. The chemical effects of the ash would depend on the ash's characteristics, particularly acidity (pH) and any reactive chemicals. For instance, an acidic ash with a pH<3 will cause burning of plant tissues (Ministry of Agriculture and Forestry of New Zeland, 1997). Moreover, large amounts of canopy leaves may be incorporated in ash fall deposits because they are particularly sensitive to ash coating and subsequent abscission.

An absence of the Amorphous Organic Matter (AOM) Group in the Faxinal tonstein has been reported in coals and associated sedimentary facies deposited in anoxic reducing paleoenvironments influenced by freshwater (Tyson, 1995).

The dispersed organic matter characterized here, along with a previous taphonomic study by Guerra-Sommer (1992), show a direct relationship between the organic

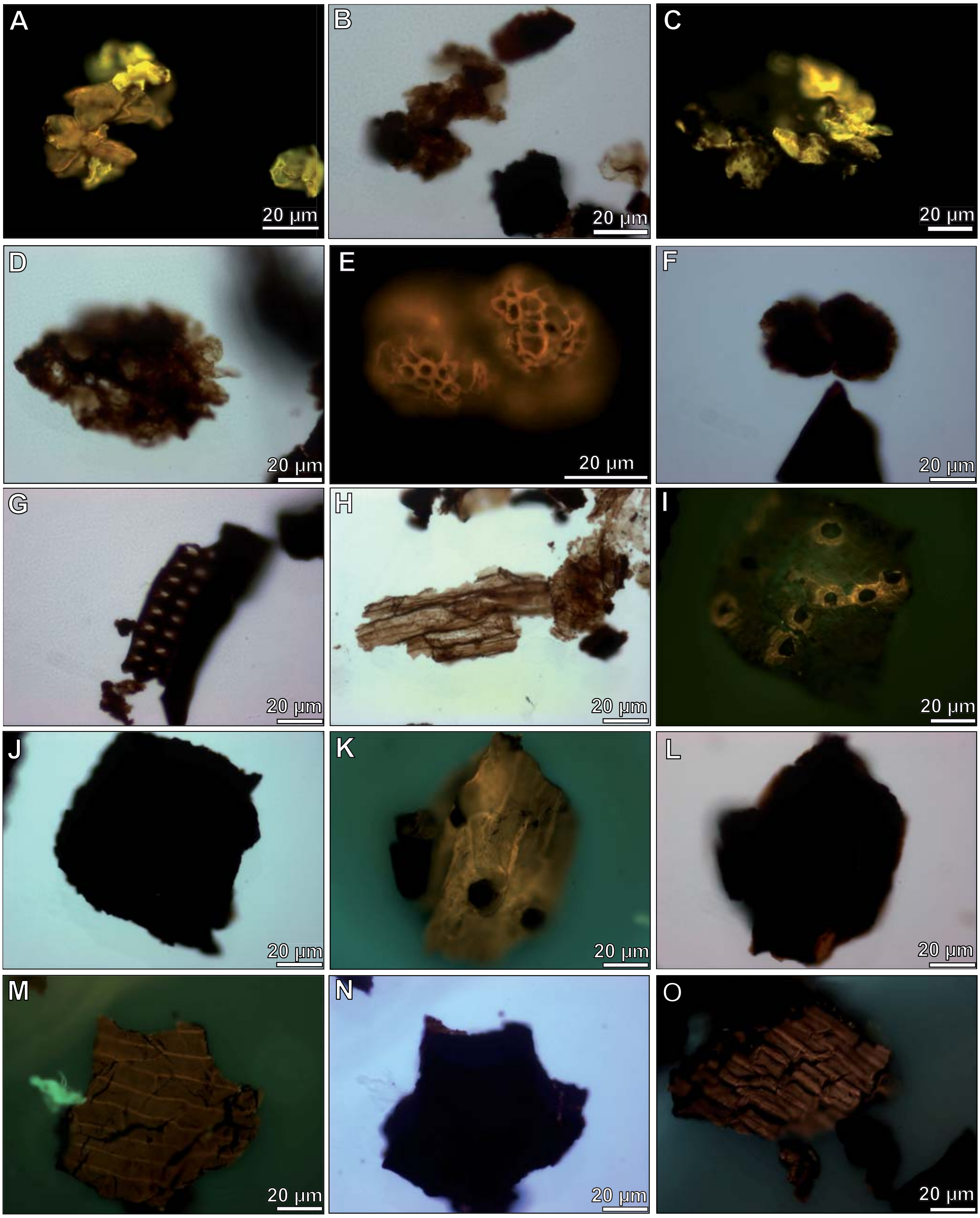

FIGURE 5 | Palynological organic matter of the tonstein bed in the Faxinal Coalfield. Note that photos A, C, E, I, K, M, O taken in fluorescent light whereas B, D, F, G, H, I, N are from the same field of view and were taken in transmitted light microscopy (white light). A-F) Palynomorph group. A-D) amalgamated and poorly preserved bisaccate pollen grains; E-F) *Botryococcus* colonies. G-O) Phytoclast group. G) gymnosperm tracheid with bordered pits; H) isolated thin cuticle; I-J) lower epidermis of *Glossopteris* typical from Faxinal tonstein (Guerra-Sommer, 1992), showing typical trichome bases; K-L) isolated cuticles showing elongated cells with papillae; M-O) upper and lower cuticles stuck together (upper surface view showing rectangular shaped cells).

composition of the tonstein and the canopy of the peat-forming vegetation. The occurrence of dense layers of *Glossopteris* and cordaitalean leaves (Guerra-Sommer, 1992), associated with amalgamated clusters of bisaccate pollen at the base and intermediate levels of the tonstein samples, indicates that the first part of the ash fall event buried the canopy of the peat-forming vegetation. The preservation of strongly horizontally compressed branches with *Glossopteris* leaves still attached (Fig. 4B) also indicates an episodic, uncommon fall of this plant material due to traumatic events (Martín-Closas and Gomez 2004). Leaf remains which are densely accumulated and horizontally layered, as shown in Figure 4C, also indicate rapid deposition. This interpretation is in agreement with the results obtained by Burnham and Spicer (1986) in recent forest litter preserved at the base of an ash bed. Nevertheless, Guerra-Sommer (1992), based on the classical view that good preservation results from slow sediment deposition and also on data from Bouroz (1962), interpreted the tonstein bed as being detritic in origin. This interpretation should now be set aside, in the light of the new data of the present study.

In a forested scena Río dominated by glossopterids and cordaitalean plants producing overlapping canopies (Walker and Hopkins, 1990) the herbaceous vegetation would be dominated by pteridophytes. The occurrence of pteridophyte spores restricted to the top level of the tonstein (Table 1) appears to reflect that the arboreal canopy near the deposition area was completely burned out at the end of the ash fall process and that only the herbaceous vegetation formed by pteridophytes was supplying spores to the lagoon (Fig. 6). A similar situation was reported by Pfefferkorn and Wang (2007) from a volcanic tuff layer overlying a coal seam in the early Permian of Mongolia. An alternative explanation was proposed by Jasper *et al.* (2011), who correlated the reduction of gymnosperm charcoal towards the top of the tonstein with a reduction in the intensity of fire at the end of ash deposition.

CONCLUSION

The results obtained from the study of dispersed organic matter within the tonstein indicate that the paleoenvironmental history of the original Faxinal peat-forming forest was strongly marked by the ash fall event. The deposition of palynomorphs and phytoclasts following an ash fall event differs clearly from previous depositional models, which proposed a detrital deposition. The new results allowed us to propose that the deposition occurred in an aquatic environment and to show that the organic matter succession reflects a vertical stratification of the original canopy around the deposition site. Additionally, the color alteration of sporomorphs, *Botryococcus* colonies, cuticles and the darkening of the xylem are attributed more specifically to the chemical effects of the ash fall deposition rather than to thermal influence. The new data are in agreement with previous paleobotanical information, which evidenced a rapid and intense leaf deposition

TABLE 1 | Percentage abundance of palynological matter in the tonstein of the Faxinal Coalfield. Quantitative analyses of the particulate organic matter of five samples with three levels (basal, middle and top). Biostr.: biostructured; Non-Biostr.: non-biostructured; Indet.: Indeterminate; Botry.: *Botryococcus*; AOM: amorphous organic matter

		Phytoclast (%)				Palynomorph (%)						
Sample	Level	Opaque	Translucent		Cuticle	Spores	Pollen	Indet.	*Botry.*	AOM	Phytoclast	Palynomorph
			Biostr.	Non Biostr.						(%)	(%)	(%)
FX-0	T	13.4	7.3	62.1	0.5	0.3	4.0	11.3	1.1	0.0	83.3	16.7
FX-1	O	15.5	8.9	69.7	0.0	1.3	4.3	0.0	0.3	0.0	94.1	5.9
FX-2	P	13.1	14.1	72.2	0.0	0.0	0.3	0.3	0.0	0.0	99.4	0.6
FX-3		3.2	3.6	86.8	4.8	0.2	0.2	0.2	1.0	0.0	98.4	1.6
FX-5		20.4	9.1	69.3	0.6	0.0	0.0	0.6	0.0	0.0	99.4	0.6
FX-0	MI	7.7	9.4	82.3	0.0	0.0	0.6	0.0	0.0	0.0	99.4	0.6
FX-1	D	1.8	3.3	92.5	0.0	0.0	2.4	0.0	0.0	0.0	97.6	2.4
FX-2	D	34.0	5.7	59.7	0.0	0.0	0.3	0.3	0.0	0.0	99.4	0.6
FX-3	L	10.6	5.7	78.2	0.3	0.0	2.3	2.9	0.0	0.0	94.8	5.2
FX-5	E	10.9	6.6	71.2	10.7	0.0	0.6	0.0	0.0	0.0	99.4	0.6
FX-0	B	9.3	6.0	69.6	2.4	0.0	2.1	10.6	0.0	0.0	87.3	12.7
FX-1	A	2.7	3.1	51.6	0.9	0.0	6.4	35.3	0.0	0.0	58.3	41.7
FX-2	S	35.1	11.9	44.6	0.0	0.0	2.6	5.8	0.0	0.0	91.6	8.4
FX-3	A	6.0	4.3	62.3	15.5	0.0	2.3	9.6	0.0	0.0	88.1	11.9
FX-5	L	16.1	4.5	55.4	0.6	0.0	4.2	19.2	0.0	0.0	76.6	23.4

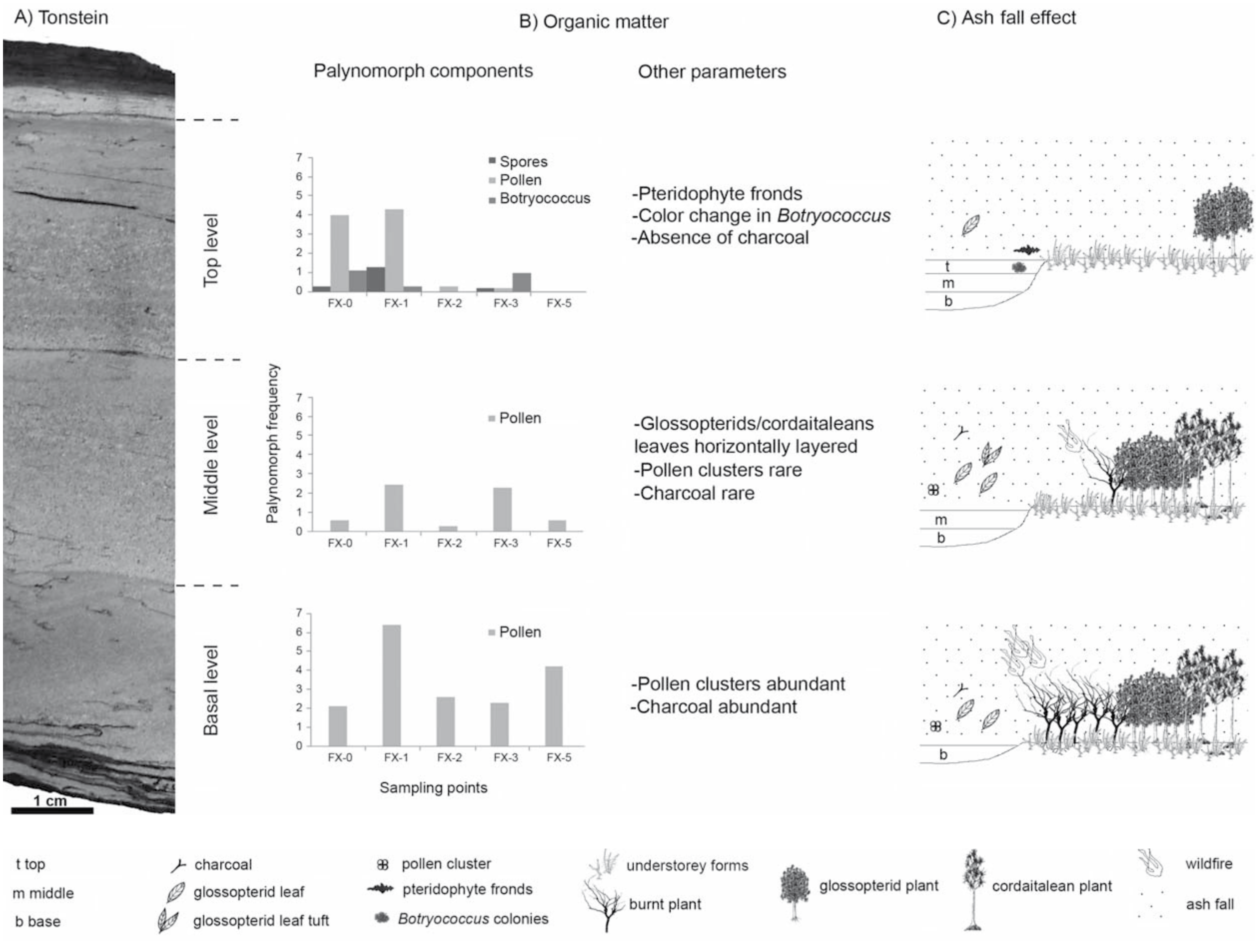

FIGURE 6 | Changes in composition of the organic matter in the tonstein bed and their interpretation. A) Tonstein profile showing the pronounced color differences produced by diagenetic mineral phases; B) organic matter patterns correlated to the correspondent tonstein levels; C) ash-fall effects on vegetation. Basal level shows evidence of intense wildfires in gymnosperm canopy during seasonal dehiscence of reproductive structures; middle level shows reduction of the fire intensity in the canopy and intense and rapid fall of glossopterid/cordaitalean leaves; top level shows elements from the herbaceous vegetation, indication of subaqueous deposition and no evidence of wildfires.

process and by macroscopic charcoal distribution, which indicated intense fires at the beginning of the ash fall. The paleoenvironmental impact of the ash fall deposition in a peat-bearing sequence is summarized in Figure 6.

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