

Fusinite of Fossil Coals as an Information Source about the Anatomy of Ancient Plants

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Abstract—“Clarification” and ion and high-frequency etching of fusinite are described. These methods allow microscopic examination of fusinitized plant tissues in fine anatomical detail, revealing the outlines of cells, the structure of cell walls, the outlines of bordered pits, and, occasionally, even cellular microstructures. It is supposed that the effects of “clarification” and etching are caused by those optical differences between the composition of organic biopolymers that constituted the anatomical structures of plants that have been preserved in the fossil state.

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INTRODUCTION

Fossil plant material preserved in coals is not a common object of paleobotanical studies, because the organic matter of coals in most cases is strongly crushed and biochemically transformed (degraded) by saprophytic microorganisms at the first stage of coalification (peat formation). It is believed that during this process coal-forming plant material generally loses its anatomical characters.

According to the petrographic classifications of coals, the foundations of which were laid as early as the beginning of the previous century, coals include three types of plant components (=microcomponents or macerals): vitrinite, fusinite (inertinite), and liptinite (Zhemchuzhnikov and Ginzburg, 1960).

Vitrinite is formed by biochemical degradation of plant tissue in the aqueous medium of peat with limited access of air. These complex processes are finished with the formation of colloid organic gel; thus, microcomponents of the vitrinite group are called “gelled.”

As a rule, liptinite is formed of epidermal plant tissues, which are usually well preserved in terms of morphological detail. These are spore and pollen walls, cuticles, algal coats, bark, and cork. The specific biochemistry of these tissues in living plants, which is determined by their protective physiological functions, makes them relatively resistant to microbial degradation in peat and to the subsequent processes of coal formation.

Fusinite was described as a separate component among other components (microcomponents) of coal and named “fusain” by the founder of coal petrography English scientist M. Stops. Later, when the nomenclature of coal components changed, fusain was renamed

“fusinite” and was classified among macerals of the inertinite group. Fusinite is a constant element of peats and coals. It forms individual inclusions or sublayers varying in thickness from a fraction of a millimeter to a few tens of millimeters. In the reedy subtropical swamps of the Everglades National Park (southern Florida), the fusinite content occasionally reaches tens of percent (Stakh et al., 1978). Coal seams of some coalfields are composed exclusively of this maceral (e.g., Uzbekistan, Angren Basin, Jurassic deposits). However, more often the fusinite content of coals varies from a few percent to a few tens of percent (Kizil'stein and Shpitsgluz, 1992).

THE COMPOSITION AND ORIGIN OF FUSINITE

Etymologically, the term fusinite comes from the Latin *fuscus* (fibrous). Because of their various orientations, fusinite fragments on bedding planes of coal seams actually resemble fibers in a tissue. The silky luster, softness, and the property of staining fingers make fusinite similar to charcoal, and, in fact, it is a true charcoal in many cases (see below). In transmitted light, fusinite looks opaque at any stage of metamorphism. In reflected light, it exhibits the highest reflectivity (is the brightest) in comparison with other macerals. With increasing rank (grade of metamorphism), fusinite's reflectivity increases to exceed 5% in anthracites (in immersion).

In chemical composition fusinite differs from other macerals in having a higher carbon and lower hydrogen content. When heated, the output of volatile matter in fusinite is lower than in other macerals (Kameneva, 1974). About 90% of carbon in fusinite is bounded in aromatic structures of organic molecules. In fusinite,

the degree of orientational supramolecular order of packages of aromatic layers along the bedding of a coal seam is significantly lower than in gelled macerals. This means that fusinite formation occurred without directional pressure of deposits that covered coal seams, i.e., at the premetamorphic stage of coal formation (Skripchenko, 1994). Leifman (1990) believes that the formation of fusinite is a specific case of the formation of fossil organic matter caused by the rapid accumulation of carbon in plant tissues during peat formation. This point of view is supported by experiments: the formation of fusinite occurred under temperatures that do not exceed several hundred degrees C (Vasil'ev et al., 1972). Van Krevelen and Schuyer (1957) concluded that inertinite reaches its final structural state as early as the early stages of metamorphism.

This outline of current knowledge of the fusinite structure shows that the formation of its molecular structure can be dated by its stage of diagenesis, and that this structure transforms during metamorphism to a lesser degree than other macerals.

The hypotheses of the origin of fusinite have been repeatedly discussed in the literature (Zhemchuzhnikov and Ginzburg, 1960; Shtakh et al., 1978; Kizil'stein, 1984). It was supposed that fusinite is a result of (1) desiccation of plant tissues either before they enter a peat deposit or during their time on the surface of peat, (2) partial combustion of plant material during fires in or outside peat bogs (forest fires and subsequent wind transportation), or (3) biochemical oxidation of plant tissues in peat by microbes. These hypotheses have the following in common: fusinite is formed as the result of degradation (desiccation) and oxidation of plant tissues that leads to chemical inertness resembling that of charcoal.

MATERIAL AND METHODS OF STUDY OF ANATOMICAL STRUCTURES OF FUSINITE

Anatomic ultrastructures in fusinites are observable using methods of "clarification" (Egorov and Kizil'shtein, 1963) and etching with argon and oxygen plasma (Kizil'shtein and Shpitsgluz, 1982, 1983).

"Clarification" of fusinite. Since fusinite is opaque in transmitted light (see above), fusinitized tissues are treated to make them transparent and, therefore, suitable for anatomical examination.

Such material is usually obtained from sublayers and lenses of fusinite, which are easily distinguishable in coals because of their "dull luster." The most suitable for sampling are surfaces that are parallel to the bedding plane with such sublayers and lenses. Fusinite fragments shaped like separate elongate plates of varying sizes are easily extracted with a scalpel.

The largest fragments measure 10 × 15 mm on average. However, fusinitized tissues usually decay into smaller fragments (5–10 × 2–5 mm) after the subsequent acid-alkali treatment. As a rule, such fragments

are sufficient for anatomical observations. The method under description does not demand any prior fragmentation of the material.

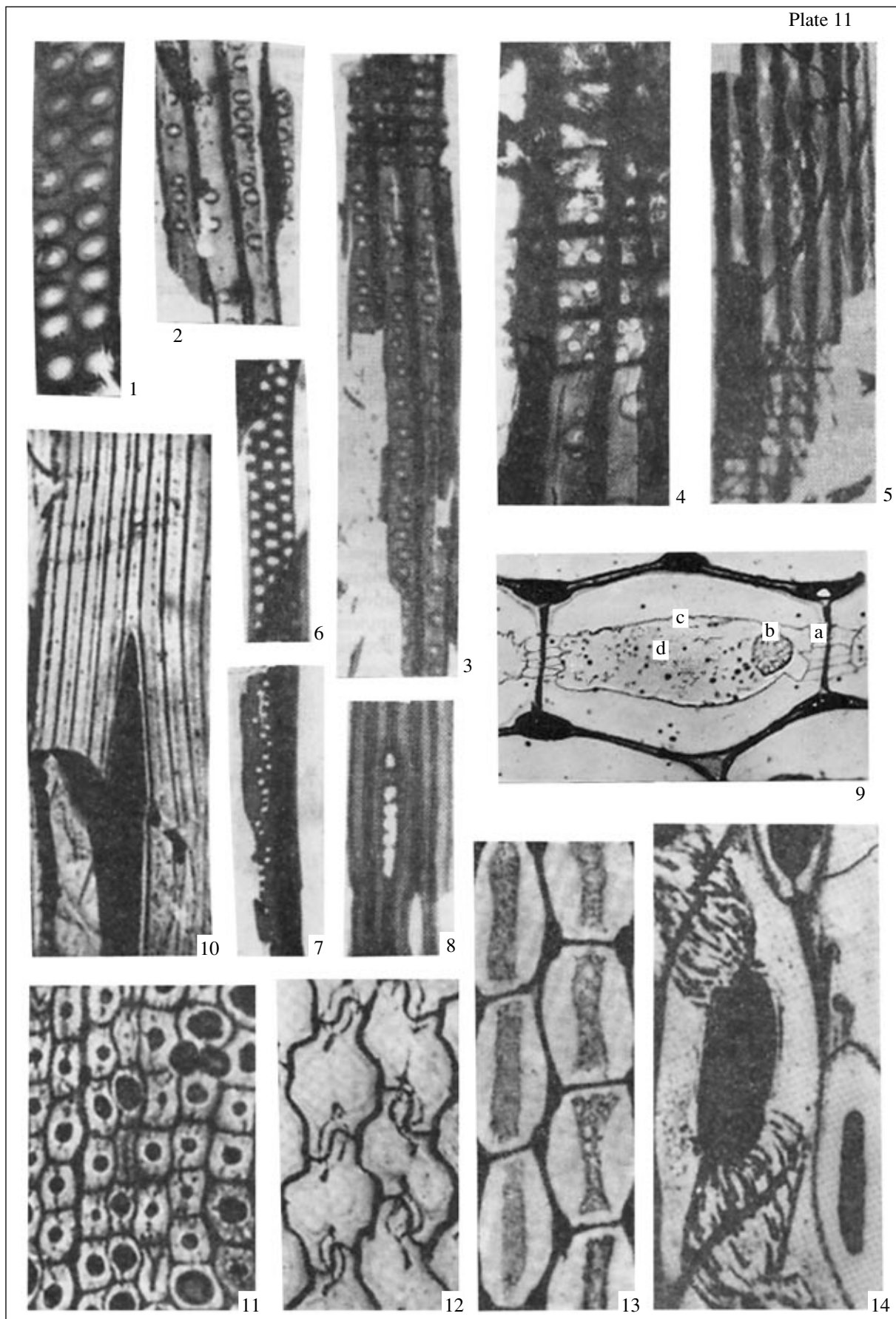
On bedding planes, fusinite fragments are distinct from each other by different orientations. From my experience, it is convenient to extract fusinite fragments one by one, since they are, as a rule, fragments of one tissue. The mass of a particular fragment in this case does not exceed several tenths of a gram. Since chemicals for subsequent treatment are taken with a significant excess of mass (usually, 50–75 g), the mass of a sample is not strictly standardized.

Representative data that allow us to examine the anatomy of fusinite are obtained by sampling and consecutive screening of a sufficient number of fragments showing statistical characteristics in the variability of different tissues. Usually, 50–75 anatomically uniform fragments is a sufficient number of specimens.

The chemical agents used for acid-alkali treatment of fusinite for its "clarification" are the same that are conventionally used for maceration of coals for paleopalynological studies (*Paleopalynology*, 1966). It is a common knowledge that palynological slides apart from spore and pollen walls also contain transparent or translucent fragments of plant tissues with traces of anatomical structures. The presence of such fragments in palynological slides is considered evidence that maceration was not completely successful (*Paleopalynology*, 1966). I noticed that such preserved anatomical structures (e.g., wood remains with bordered pits) have not been reported from petrographic observations on gelled macerals in transparent coal sections. This suggests that the occurrence of these structures is a result of maceration of fusinite. Unlike maceration for palynological studies that is aimed at the dissolution of all organic macerals as completely as possible except for those belonging to the liptinite group, "clarification" of fusinite includes a chemical treatment that changes the optical properties of this maceral.

The Luber mixture, which consists of nitric acid and sodium chloride, appears to be the most suitable for such maceration (*Paleopalynology*, 1966). For the clarification of fusinite, a boiling mixture of these reagents was used: 20 ml HNO₃ to 2 g NaCl. After boiling, the sample was cleaned with distilled water, then treated with 10% NaOH and again watered. As a result, fusinitized tissues acquired elasticity, became more or less transparent, dark brown or dark yellow. The pieces of tissues were transmitted to the slide using an iron needle or brush and covered with a cover slip. The addition of jelly allowed one to obtain durable slides, suitable for light microscope studies.

Not all tissues of the specimen become transparent simultaneously: some need a longer treatment or even remain opaque after a long maceration. This phenomenon may be explained by different degrees of fusinitization or, in other words, different degrees of initial oxidation.



To clarify coals of a higher grade of metamorphism more time is needed. Thus, the fusinite from Lower Jurassic G rank coals of the northern Caucasus (Bylym coal-bearing region) became transparent after 30–45 minutes of boiling in Luber mixture and 2–3 minutes of treatment with NaOH. Fusinite from the D rank coals from the bed k_2^1 of the C_2^5 Formation (Millerovo region, eastern Donetsk Basin) was boiled for approximately the same period of time and treated with alkali for 10–12 min. I failed to clarify the fusinite from anthracites of the Donetsk Basin. I know from experience that the mode of maceration of any new material needs to be experimentally calibrated. Results obtained by using “clarification” of fusinite are shown in Pl. 11, figs. 1–8.

Ion and high-frequency etching. Kizil'stein and Shpitsgluz (1982, 1983, 1992, 1994) developed methods of coal treatment in polished sections using argon and high-frequency oxygen plasma. These methods allow anatomical structures of tissues and cells that constitute macerals to be observed in unpolarized reflected light.

The methods are based on the interaction between cations of argon in a glow discharge of constant current (ion etching) or low-temperature oxygen plasma that is formed by a high-frequency electromagnetic field (high-frequency etching) and the organic matter of coal. During this process, the surface of the polished section experiences selective degradation under the impact of charged particles. It is important that the selectivity is determined by differences in crystallochemical structure of tissues and cells of fossil plants that form the coal.

Ion etching by argon plasma is applicable for the study of anthracites, coals with high conductivity (Kizil'stein and Shpitsgluz, 1992). The method of etching of coals using low-temperature high-frequency oxygen plasma, which was developed by Kizil'stein and Shpitsgluz (1994), can be used for study of coals at any metamorphic stage. Zones of etching are circular, 10–15 mm in diameter. The efficiency of etching does not depend on the orientation of the surface of the polished section with respect to the bedding surface. Because of this, it is possible to study fusinite aggrega-

tions on the least deformed planes. Moreover, as was noted above, fusinite fragments are easily detectable on such planes, and it is easy to select the most interesting objects. The proposed etching methods, unlike “clarification,” demand no extraction of fusinite from coal balls: polished sections or polished section-briquettes are used (Kizil'stein and Shpitsgluz, 1998).

The study of coals from different basins and fields (Kizil'stein and Shpitsgluz, 1998) showed that fusinite is a maceral within coals that preserves the anatomical structure and that ion and high-frequency modes of etching reveal this structure in astonishingly fine detail (Pl. 11, figs. 9–14).

PHYSICOCHEMICAL NATURE OF “CLARIFICATION” AND ETCHING

The above examples have shown that the methods of “clarification” and ion and high-frequency modes of etching of fusinite allow us to study the anatomy of ancient plants by treating one of the common macerals of coals, fusinite. Since, after high-frequency etching, anatomical structures were traced in coals of any rank and even in graphites (Kizil'stein and Shpitsgluz, 1998), one can conclude that metamorphoses of organic matter under high pressures and temperatures do not significantly affect the preservation of these structures in the fossil state. This feature allows one to study fusinites from any epoch of coal accumulation from the Devonian to the Neogene.

“Clarification” that is achieved by using strong oxidizing agents obviously leads to the process referred to by coal chemists as “regeneration of humic acids” (Kukharenko, 1972). The organic matter of fusinite acquires characteristics of gelled tissues of peat and coals of low or middle grade of metamorphism as though it had returned to a “pre-fusinitization” state. The absence of the clarification phenomenon in anthracites indicates that at high stages of metamorphism changes of the chemical structure of the maceral are irreversible.

Etching is explained in a different way. It is a common knowledge that selective knocking-out of lighter atoms occurs in solid bodies composed of atoms of chemical elements with various masses (Pleshivtsev, 1968). In objects that are composed of chemical com-

Explanation of Plate 11

Figs. 1–8. “Clarified” fusinite: (1–3, 6) bordered pits on radial sections of conifer (?) wood; (1) $\times 400$, (2, 3, 6) $\times 170$; (4) pitting of a pith ray, $\times 350$; (5) cross pitting at the radial wall of a tracheid, $\times 140$; (6) multiserial pitting, radial section of a tracheid, $\times 250$; (7) primitive holelike pitting, radial section of a tracheid, $\times 70$; (8) pith ray, tangential section of wood, $\times 140$; (1–5, 8) northern Caucasus, Kabardino-Balkaria, Baksan coal-bearing region, Bylym mine, coal seam M_1 , Lower Jurassic, Pliensbachian; (6) Kuznetsk Basin, Leninskii geological-industrial region, Kuznetskaya mine, coal seam k_8 , Upper Permian, Kolchuginskaya series; (7) eastern Donetsk Basin, Millerovo geological-industrial region, Glubokinskii sector, borehole no. 4675, coal seam k_2^1 , Middle Carboniferous, Formation C_2^5 .

Figs. 9–14. Etched fusinite: (9) a parenchyma cell showing intracellular structures (?): plasmodesmata (a), nuclei (b), plasmalemma (c), protoplasm (d), $\times 1800$; (10) xylem with a pith ray, $\times 530$; (11, 12) bark (periderm), $\times 830$; (13) cells with preserved cellular content (protoplasm?), $\times 700$; (14) periderm, walls of adjacent cells are connected with plasmodesmata, $\times 3300$; eastern Donetsk Basin, Shakhhtinskoye-Nesvetayevskii geological-industrial region, Yuzhnaya mine, bed t_3^n , anthracite, Middle Carboniferous, Formation C_2^4 .

pounds with different concentrations of atoms of different masses (in the case of the plant material these are mostly carbon and oxygen), ratios between chemical elements are changed, as well as their surface concentrations. I suspect that this is the reason for the optical differentiation of the material that is described above.

The main natural biochemical compounds that constitute plant tissues are carbohydrates, phenols (lignin), and lipids. All these compounds change their molecular structures during diagenesis and transform into some secondary compounds, geopolymers. However, *relative* differences between elemental compositions of geopolymers persist, as is proved by differences in the chemistry of the main macerals of coals. One can hypothesize that chemical distinctions between the elements of anatomical structures within one maceral (fusinite in our case) also persist. Predominantly, walls of plant cells are composed of cellulose and lignin, the concentrations of which vary among the layers of the plant cell wall (Frey-Wyssling and Mühlethaler, 1968). Cellulose and lignin differ in the carbon and oxygen content, thus determining the difference in intensity of ion etching and the appearance of differentiated optical images of microstructures. Intracellular elements are part of the protoplasm and are formed of proteins and nucleic acids; they also show chemical individuality. Therefore, the anatomy of tissues and cells of fusinite is revealed because of the biochemical heterogeneity of the tissues and cells of coal-forming plants, which is preserved due to molecular transformations of coal matter during metamorphism.

Modern methods of analytical physics, which have a high degree of localization, allow one to study the chemical and structural compositions of tissues and cells that become observable due to the methods described in this paper. Using these methods, changes in the anatomy of coal-forming plants through stratigraphic sections and along areas of occurrence of coal seams can also be traced and, thus, important scientific and practical problems of paleogeography can be solved (Kizil'stein and Shpitsgluz, 1990).

CONCLUSIONS

(1) Methods of "clarification" and ion and high-frequency etching of fusinite allow one to reveal fine details of the anatomy of coal-forming plants.

(2) With application of ion and high-frequency etching, the anatomy of fusinite tissues is observable at any metamorphic stages.

(3) It is supposed that the effect of "clarification" and etching is determined by the initial biochemical heterogeneity of plant cells, which is preserved in fossil state as a crystallochemical heterogeneity of resulted geopolymers.

(4) Data on the anatomy of fusinitized tissues can be used in reconstructions of the biochemical composition of ancient coal-forming plants, studies of evolution of plant anatomy, and in reconstruction of peat-accumulation environments.

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