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Taphonomy of Fossil Resins: A Petrological and Geochemical Approach Using the Van Krevelen Diagram

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Abstract

Fossil resins from the area of Gulf of Gdańsk, Lublin area, Denmark, Bitterfeld, Lusatia and Ukraine, often grouped under the collective term 'Baltic amber', are complex organic mineraloids that have undergone various post-depositional transformations. Despite their role in paleontology as a source of for biological inclusions, fossil resins themselves are rarely analyzed as taphonomic objects. In this work, a new geochemical approach to fossil resin taphonomy is presented. Applying the van Krevelen diagram—traditionally used for kerogen classification—allows the diagenetic and catagenetic changes of fossilized resin maturation to be evaluated. Based on literature-derived elemental composition data of C, H, and O contents of 'Baltic amber', the diagram is interpreted as an organic matter transformation framework of fossil resins. The results suggest that the so-called 'Baltic amber' deposits represent a composite taphocoenoses of resins with different burial histories and maturation scenarios. This approach integrates petrological classification, geochemical maturation, and taphonomic analyses, offering a new way of "tracking" fossil resins maturation changes.

Keywords: fossil resin; taphonomy; Baltic amber; van Krevelen diagram; kerogen; resinite; diagenesis; catagenesis

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1. Introduction

Fossil resins are a distinct category of fossilised plant exudates, compared to other preserved plant remains such as leaves, lignified tissues, diaspores, and palynomorphs. These secondary metabolites, originally secreted as part of plant defense and physiological regulation, are predominantly composed of terpenoid compounds. Terpenes are found across diverse biological domains, including angiosperms, gymnosperms, fungi, and certain bacterial taxa. Within fossil resins, terpenoids are typically preserved as mono-, sesqui-, di-, and triterpenoid constituents, often exhibiting varying degrees of diagenetic alteration. The compositional profile of these terpenoids serves as a chemotaxonomic and paleoenvironmental source of information of the botanical affinity of the resin-producing taxa and the ecological conditions prevailing at the time of resin biosynthesis and exudation [1]. Fossil resins act as geochemical archives. Because terpenoid skeletons are highly resistant to decay, their diagenetic derivatives record both the botanical source and the burial history of the resin [2]. Classical tools—FT-IR, solid-state NMR, and Py-GC–MS—have been used to fingerprint amber varieties, yet they offer limited insight into their maturation [3].

Kerogen studies use H/C and O/C ratios on van Krevelen diagrams to visualize progressive loss of hydrogen and oxygen [4]. This simple but informative approach has never been applied to ambers, even though resins chemically belong to Type I/II kerogen.

This study proposes adaptation of the van Krevelen diagram to correlate chemo- and mineralogical types of fossil resins with taphonomy changes that link coal-petrographical, geochemical, and paleontological datasets.

2. Studies on Fossil Resins

The term 'Baltic amber' is colloquially used to refer to the Eocene fossil resins from Central and Eastern Europe [5–8]. Depending on the context, it may describe either the entire complex of fossil resins [2,9] or distinguish specific deposits as subtypes of 'Baltic amber' (e.g., Lublin amber), or mineralogically defined resin of succinite type [10]. In this study, the term 'Baltic amber' is used strictly for nomenclatural clarification and its implications for paleontological research. Each fossil resin type, commonly subsumed under the 'Baltic amber' label, will be described individually and named after the corresponding deposit of origin.

Paleontological studies of fossil resins have traditionally been focused on inclusions [11–14]. These can be classified into two main categories: organic and inorganic [15]. Inorganic inclusions include features such as pyrite (often in the form of marcasite) precipitates, fluid-filled bubbles, or resin-in-resin inclusions (often described as stalactites or flow structures). Organic inclusions, biological or bioinclusions, are the primary source of paleoenvironmental data from fossil resins. Plant, fungal, and animal remains preserved in resin offer significantly more information about biological structure and function than those preserved as impressions or casts in sedimentary rock. Consequently, such inclusions provide a rich fossil record that allows for detailed taxonomic descriptions as well as reconstructions of both life and death environments of the included organisms [16,17].

These aspects fall within the domain of taphonomy—the branch of paleontology concerned with the processes of decay, burial, and fossilization [18–20]. The concept of a taphocoenosis (fossil equivalent of a biocoenosis) refers to the assemblage of co-buried biological remains [18–21]. Taphonomic studies are inherently more complex than modern ecological surveys, as they must account for post-mortem alterations affecting the integrity of the preserved remains.

A key taphonomic consideration is the spatial relationship between remains and their depositional environment, typically categorized as follows:

- Autochthonous: Fossils originate from the very location in which the organism lived and died, indicating no post-mortem transport. This implies overlap between life, deposition, and fossilization environments;
- Para-autochthonous: Slight transport occurred (e.g., within several meters), often due to gravity or mild current action, but the organism still originated from a nearby habitat;
- Semi-autochthonous: The organism was transported a greater distance but still within the same sedimentary or ecological system;
- Allochthonous: Remains were transported significantly, often from a different environment or region, typically resulting in partial damage or fragmentation.

Importantly, these definitions also include the possibility of redeposition between sedimentary environments [22]. Thus, remains that were reworked from older to younger sediments are classified as allochthonous even if their geographic position remains unchanged. Conversely, within-environment redeposition does not necessarily imply an allochthonous origin.

Throughout the processes of fossilization, organic remains and resin itself are subject to various taphonomic alterations such as abrasion, fragmentation, deformation, diagenesis, and bioerosion. Abrasion and fragmentation typically affect the outer surface of resin nodules. Bioerosion involves damage caused by living organisms, while deformation and diagenesis occur deeper in the sedimentary sequence. Inclusions may deform due to pressure from overlying sediments, and during fossilization, chemical alterations such as pyritization may occur.

Understanding these processes is essential for reconstructing taphonomic conditions. Fossil resins, as buried organic remains, are subject to the same suite of geological transformations. Proper interpretation of these modifications provides insight into the burial history and preservation potential of both the resin and its inclusions.

3. Fossil Resins as Buried Organic Remains

The origin of fossil resin deposits—especially those of non-autochthonous nature—requires a comprehensive understanding of the transformation processes involved in their burial and preservation. These transformations include a wide range of geological, taphonomic, and petrological processes. A key point in the interpretation of fossil resin taphonomy is the consideration of the resin-producing plant's remains. When fossil resins are autochthonous, plant remains are typically preserved in the same stratigraphic layer, often as lignite or carbonized wood [23,24]. This overlap forms the foundation for an integrated paleontological and petrological approach.

In coal petrology, classification is based on lithotypes—rock types composed of microscopic organic constituents known as macerals. Analogous to minerals in rocks, macerals are optically distinguishable, homogeneous components of coal; these are grouped into three major types: inertinite, vitrinite/huminite, and liptinite [25].

The vitrinite/huminite group is derived primarily from woody tissues of terrestrial plants (e.g., cell walls, xylem, vascular tissue), with varying degrees of carbonization. In hard coals, these are classified as vitrinite, whereas in lignite, the term huminite is used. Representative macerals of these types include the following (after [25–32]):

- Telinite/textinite—showing well-preserved wood structure;
- Desmocollinite—preserving linear or mesh-like vascular arrangements;
- Liptinite group (formerly exinite)—comprised of plant remains rich in biopolymers, as well as plant secretions such as resins and waxes. Major liptinite macerals include the following:
- Sporinite—derived from pollen and spores;
- Cutinite—from leaf cuticles;
- Alginite—from algal cell walls;
- Resinite—derived from resins and waxes;
- Inertinite group: This represents highly altered or oxidized organic matter, including charcoalified remains (e.g., due to wildfires) and fungal fragments. Characteristic macerals include the following:
- Fusinite—charcoal from combustion or oxidation;
- Semifusinite—intermediate maceral between telinite and fusinite.

In coal petrography, microscopic resin fragments are typically identified as resinite (Figure 1A). However, larger macroscopic resin bodies within the same lignite matrix may be described as retinite, organic inclusions, or fossil resins (Figure 1B,C). This apparent duality stems from the maceral definition standardized by the International Committee for Coal and Organic Petrology (ICCP) and codified in ISO 7404-3:2009 [33].

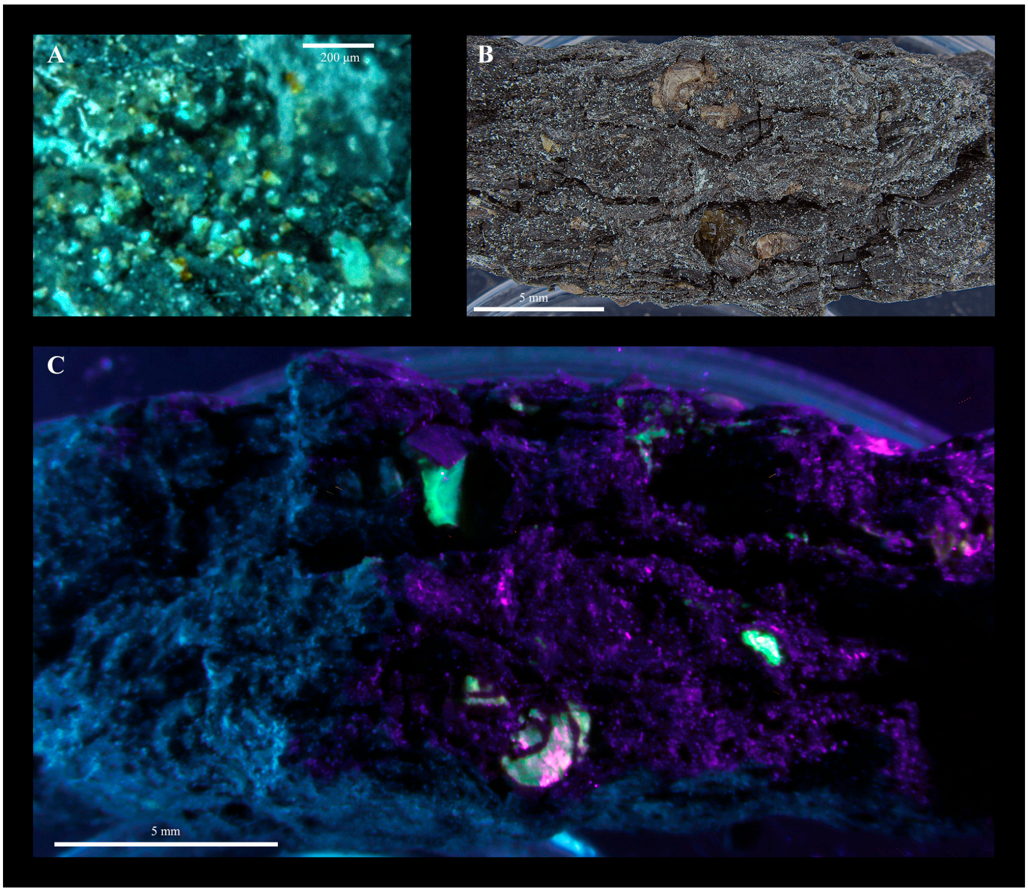

Figure 1. Piece of lignite with Lebanese amber from Jezzine deposit, showing both ambers and resinites. (**A**) Microscopic pieces of fossilised resins, considered as resinites; (**B**) lignite with Lebanese amber in regular light; (**C**) placement of Lebanese amber in lignite visualised in UV light.

Regardless of scale, these resinous components are part of the same organic matter system and underwent the same diagenetic transformations. Resinites occur both in lignite and hard coal deposits as discrete particles or impregnating woody tissues (e.g., telinite, fusinite, semifusinite). From a paleontological perspective, fossil resins are often found in close association with lignite deposits [23,24].

Lignite is subdivided into lithotypes based on the form of preserved plant matter and depositional environment. Of particular relevance is xylitic coal, composed mainly of fossil wood fragments, including large plant organs such as trunks or stems. Xylitic lignite, often derived from gymnosperm trees, exhibits a high degree of resin saturation, which enhances its resistance to decay [26].

In paleontological literature, such remains are sometimes not recognized as lithified lignite but rather as isolated fossil plant fragments. This underscores a key terminological nuance, especially in Central and Eastern European scientific traditions, where fossil resins (e.g., Baltic amber) are sometimes classified as a special form of coal known as liptobioliths [27].

Liptobioliths are formed by the accumulation of decay-resistant biopolymers—primarily resins and waxes—while other organic debris decomposes. These accumulations may occur within lignite seams (typically of Paleogene or Neogene age) or as discrete resin-rich lenses [26]. Well-documented examples include pyropissite-type liptobioliths in Miocene brown coal deposits of Germany (e.g., Lusatia, Saxony, Rheinland regions), linked to paleoenvironments favouring the preservation of resinous plant matter [34–36]. Suggested depositional settings include coastal lagoons and freshwater lakes.

Similar accumulations of isolated resinite grains occur in Miocene lignite deposits of Konin (Poland) and elsewhere [31]. The most relevant cases for this study are resin–wax liptobioliths, composed almost entirely of fossil resins and waxes. In such a framework, fossil resins (i.e., ambers) are viewed not merely as inclusions, but as liptobioliths—a form of organic sedimentary rock—distinct from resinites as macerals.

This dual perspective not only aligns with taphonomic interpretations but also integrates the co-burial of fossil resin and lignite as parts of the same depositional and diagenetic continuum. It reinforces the notion that resinite macerals and macrofossil resins underwent the same transformative processes within their host sediments.

4. Transformation of Organic Matter and Geochemical Maturity of Fossil Resins

4.1. Kerogen and Organic Matter Evolution

Kerogen—sometimes referred to as organoclast—is the dispersed, insoluble organic matter within sedimentary rocks, typically of plant origin. It represents the primary precursor to hydrocarbons, undergoing thermal maturation over geological time to yield petroleum and natural gas [28,31,37]. The classification of kerogen parallels that of coal macerals, with four principal types based on origin and chemical composition [26]:

Type I and II (Liptinitic): rich in hydrogen, derived from algae, resins, and waxes.

Type III (Vitrinitic): derived primarily from terrestrial woody tissues, relatively oxygen-rich.

Type IV (Inertinitic): residual, highly oxidized, or charred organic matter, with minimal hydrocarbon potential.

Fossil resins, especially those classified petrologically as resinite, belong to Type I/II kerogen [26]. However, when severely oxidized—e.g., during wildfires—they may contribute to the inertinite group, becoming precursors of fusinite or semifusinite macerals [38].

The evolution of kerogen is typically illustrated using the van Krevelen diagram, which plots atomic hydrogen-to-carbon (H/C) versus oxygen-to-carbon (O/C) ratios [4]. This diagram effectively traces the geochemical transformation of organic matter as it undergoes progressive burial and thermal alteration. These transformations occur in three main stages [28,31,37]:

Diagenesis: shallow burial under low-temperature conditions (<50–60 °C). Organic matter retains many biochemical features, and the high H/C and O/C ratios reflect minimal alteration. Resinous compounds with high polymerization and oxygenated groups (e.g., esters) dominate this stage. Fossil resins in this state are chemically comparable to natural resins and may retain diagnostic compounds such as succinic acid.

Catagenesis: the principal phase of hydrocarbon generation (100–120 °C), marked by increased molecular fragmentation and aromatization. H/C ratios decrease, and kerogen evolves toward more condensed aromatic structures. Type III kerogen becomes dominant, producing mainly natural gas with some liquid hydrocarbons. Fossil resins subjected to catagenesis show increased crosslinking and loss of volatiles, often resulting in visible deformation of inclusions and further polymer stabilization.

Metagenesis: characterized by the highest thermal maturity (>150 °C), this stage is marked by strong aromatization and carbonization, leading to kerogen impoverished in hydrogen and almost devoid of hydrocarbon potential. The remaining organic matter, mainly Type IV kerogen, yields only dry gas (methane).

4.2. Fossil Resins on the Van Krevelen Diagram

In this study, fossil resins referred to as Baltic amber (succinite; [39]) and related materials were evaluated in the context of kerogen maturation. Published elemental data (C, H, O content by mass) were plotted on the van Krevelen diagram [25,28] to assess their diagenetic and catagenetic evolution (Figure 2). This represents a novel application of this geochemical model to fossil resins as taphonomic proxies.

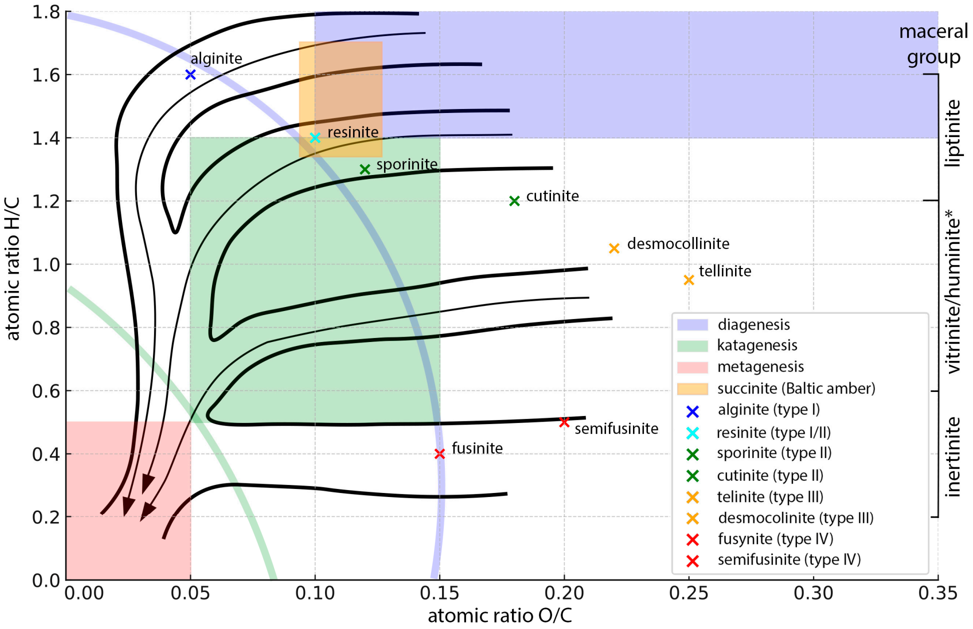

Figure 2. Lignite and kerogen macerals indicative position on van Krevelen diagram with Baltic amber position marked by orange box. Other boxes showing lignite transformation and black lines marking kerogen transformation, maturation marked with arrows. Data presented in the diagram: macerals—Table A1; Baltic amber (succinite)—Table A2 (Appendix A); kerogen transformation ranges—after [40,41]. * vitrinite—macerals found in hard coals, huminite—macerals found in lignites.

Results indicate that Baltic amber encompasses a range of compositions that reflect primarily diagenetic, but in some cases also incipient catagenetic, alteration (Figure 2). This geochemical variability supports the hypothesis that the taphocoenosis associated with 'Baltic amber' deposits represents a complex assemblage of resins from differing burial histories and thus differing original biocoenoses.

The interpretation of fossil resins as kerogen-type organic matter—following the same maturation trajectory as resinites in lignite and Type I/II kerogen—offers a framework for evaluating their geochemical stability and taphonomic integrity. Furthermore, it emphasizes that fossil resin inclusions may exhibit differing degrees of deformation or preservation, depending on the resin's specific transformation history.

5. Taphonomic Significance of Fossil Resin Types

Fossil resins in a modified approach after Savkevich [38] and Vávra [32].

5.1. Succinite: The Taphonomic Reference Standard

Succinite, the principal resin type within Baltic amber deposits, represents a relatively stable diagenetic product. Its widespread occurrence and relatively homogeneous taphonomic features make it a suitable reference for evaluating the transformation pathways of other fossil resins. The high degree of polymerization and presence of oxidation products, such as succinic acid, suggest deposition and early diagenesis in oxygen-rich, shallow aquatic environments (e.g., deltaic or lagoonal systems).

These conditions promoted intense oxidative alteration at the onset of fossilization, followed by stabilization within variably redox-sensitive, mildly alkaline sediments. Succinite often retains undistorted inclusions, but in some cases, it exhibits features indicative of early catagenesis, such as slight deformation of internal structures. This suggests that succinite underwent complete diagenesis and possibly limited catagenetic overprint, though not advanced enough to fundamentally alter its resinous character.

5.2. Gedanite and Gedano-Succinite: Early-Stage Taphonomic Variants

Gedanite and gedano-succinite represent less altered fossil resins, interpreted as earlier taphonomic stages in the transformation of Baltic amber. Their relatively low degree of oxidation implies initial burial in environments with limited oxygen availability—such as peat bogs or forest soils—rather than open-water settings.

These resins may have undergone fossilization in reducing organic-rich sediments, which inhibited the early oxidative pathways observed in succinite. Later redeposition into aquatic sediments could account for their co-occurrence with succinite in some deposits. However, they retain distinct geochemical and taphonomic signatures, suggesting that their inclusion in Baltic amber sensu lato reflects mixing of multiple taphonomic cohorts. Gedanite may thus be viewed as a precursor state in the resin transformation series, with the potential to evolve into succinite or further into more altered forms, depending on subsequent burial conditions.

5.3. Rumenite: A Catagenetic Endpoint

Rumenite is interpreted as a fossil resin that underwent extended burial and exposure to elevated pressure and temperature during orogenic processes. Found in tectonically active regions, such as the Carpathians, rumenite exhibits characteristics consistent with advanced catagenesis, including internal fracturing and increased brittleness.

From a taphonomic perspective, rumenite represents the terminal stage of the transformation series initiated by succinite and its precursors. Its formation required deeper burial and longer residence in the geosphere, possibly during regional metamorphic episodes. Despite its advanced alteration, rumenite can still preserve organic inclusions, albeit often significantly compressed or distorted. This suggests that, while structurally close to the limits of resin preservation, rumenite remains within the fossilization spectrum of the Baltic amber complex.

5.4. Stantienite: A Pyro-Taphonomic Anomaly

Stantienite is distinguished by its strong carbonization and near-complete loss of resinous features. It is hypothesized to have formed under high-temperature conditions associated with forest fires—either surface wildfires or subsurface smouldering events—prior to burial.

This resin likely underwent pyrolysis in a low-oxygen environment, leading to the formation of a highly crosslinked, carbon-rich material. Taphonomically, stantienite represents an alternative transformation pathway: one driven not by burial diagenesis but by pre-burial thermal alteration. Its inclusion in amber-bearing deposits suggests that fire events may have contributed to the heterogeneity of resin assemblages, potentially altering the preservation potential of inclusions and the geochemical identity of the resin.

5.5. Taphonomic Framework and Resin Cohorts

From a taphonomic standpoint, succinite serves as a central node in the transformation network of fossil resins. Other types—such as gedanite, rumenite, or stantienite—can be interpreted as earlier, later, or divergent forms along the same geochemical continuum. The variability in their preservation states suggests that the Baltic amber taphocoenosis is not monotypic, but rather a palimpsest of resins from multiple environmental and geological histories.

This complexity reinforces the need for resin-specific taphonomic analysis, wherein depositional context, alteration pathways, and co-buried plant remains (e.g., lignitic wood) are jointly assessed. In this framework, fossil resins are not merely preservative media but themselves taphonomic objects subject to the same processes—transport, decay, burial, and alteration—as the inclusions they host.

6. Discussion

The application of the van Krevelen diagram to fossil-resin research allows expanded studies of the amber diagenesis. Van Krevelen plots (H/C vs. O/C atomic ratios) are widely used to evaluate kerogen maturity and coalification [28]. When applied to ambers, they visualize progressive loss of hydrogen and oxygen as resins polymerize, defunctionalize, and aromatize during burial [42,43].

The presented compiled data show that Baltic amber (most likely succinite) occupies a field of relatively high O/C (~0.15–0.20) due to its diagnostic succinic-acid component. Although the van Krevelen diagram is the most intuitive 2-D projection of H/C versus O/C trends, the underlying dataset is intrinsically ternary (C–H–O proportions sum to unity). Plotting the same values on a C–H–O ternary diagram (Figure 3) therefore retains the full compositional space and highlights clusters that may overlap in the van Krevelen plot.

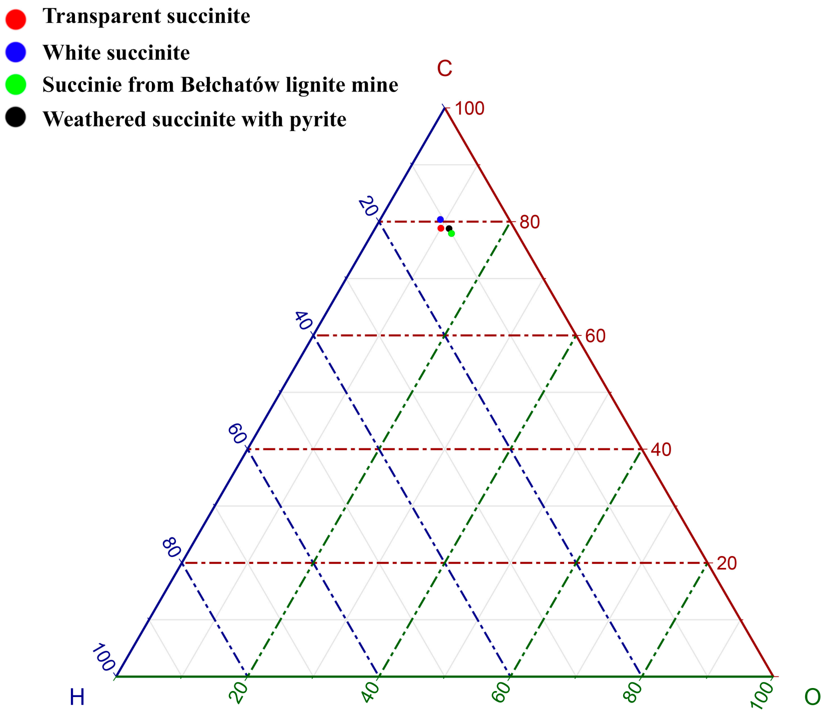

Figure 3. Example of positioning Baltic amber (succinite) samples (dataset: from [10]) on a C–H–O ternary diagram.

Ternary plots should separate gedanite and stantienite more clearly from succinite than the traditional rectangle fields, because samples with similar O/C but variable absolute carbon content plot at distinct apices of the triangle. Such a representation also allows the superposition of other tracers—e.g., S or N as bubble size or colour—yielding a multi-parametric view of resin evolution comparable to ternary diagrams used in coal facies analysis. Incorporating ternary graphics alongside van Krevelen plots would thus enrich future chemotaxonomic and taphonomic studies of fossil resins.

Future studies of other types of regional fossil resins such as gedanite and stantienite would plot at lower O/C because they are naturally poorer in, or have lost, that acid fraction as it was pointed out in the literature [32,38,44]. The opportunity to study highly matured resins, such as rumanite, that are supposed to undergo the ketogenesis stage would exhibit a position on the van Krevelen diagram that lies further along the coalification trend, lower H/C and O/C, consistent with advanced thermal modifications in the Carpathian fold-belt [45]. These geochemical separations corroborate earlier FT-IR and GC-MS studies showing that Baltic-type ambers represent a family of related but distinctly altered resins [3,6,32].

Fossil resin geochemistry could reveal its taphonomy; samples plotting closer to the high-H/C, high-O/C corner could be typical for autochthonous swamp deposits where rapid burial limited early oxidation; on the other end of the diagram, allochthonous fossil resins, which were reworked into younger deposits would show higher oxidation rate.

Future work should combine Raman/FT-IR fossil resins data and controlled laboratory maturation of fresh conifer resins with van Krevelen monitoring to define and verify trends in maturation processes of fossil resins.

7. Conclusions

Van Krevelen plots can be used to link fossil resin chemotypes with maturation states. Fully developed studies could form a coherent model of diagenetic series from oxygen-rich to aromatized end-members.

Combined geochemical–taphonomical analysis could be used for recognitions of the depositional processes. High-H/C and high-O/C ambers lacking marine traces reflect in situ swamp burial, whereas oxidized ambers bearing, for example, an ichnological record would prove a fluvial–marine transport.

Methodological integration with coal petrology enriches fossil resin studies. Viewing amber as part of the lignite–kerogen continuum links paleontological data to basin-scale burial histories and improves correlation of amber-bearing strata.

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Appendix A

These values are estimated from van Krevelen diagrams and descriptive text. No single publication provides exact CHNS/O values for all macerals. Most are derived from graphical trends or group averages. Alginite and resinite show the highest H/C, consistent with lipid- or resin-rich origins. Fusinite and semifusinite display strongly aromatic, hydrogen-poor character, typical of inertinite and highly oxidized kerogen.

Table A1. Maceral values estimated for van Krevelen diagram (see Figure 2).

Maceral	H/C (mol/mol)	O/C (mol/mol)	Kerogen Type	Main Sources
Alginite	1.5–1.7	0.03–0.07	Type I	[4,28]
Resinite	1.3–1.6	0.08–0.13	Type I/II	[28,31]
Sporinite	1.2–1.4	0.10–0.15	Type II	[28,31]
Cutinite	1.2–1.5	0.12–0.18	Type II	[28]

Table A1. *Cont.*

Maceral	H/C (mol/mol)	O/C (mol/mol)	Kerogen Type	Main Sources
Telinite	0.9–1.1	0.20–0.25	Type III	[31]; interpolated from vitrinite
Desmocollinite	1.0–1.1	0.22–0.27	Type III	[31]; descriptive values
Fusinite	0.2–0.5	0.03–0.07	Type IV	[28,31]
Semifusinite	0.3–0.6	0.05–0.10	Type IV	[28,31]

Table A2. Data for succinite box (see Figures 2 and 3).

Sample Name	C [%]	H [%]	O [%]	Source
Transparent succinite, Baltic	78.28	11.08	9.92	[10]
White succinite, Baltic	80.3	10.46	9.14	
Succinite, "rind/crust"	78.26	9.88	11.85	
Clarified succinite	78.91	9.58	11.21	
Unclarified succinite	76.17	9.55	13.54	
Weathered succinite with pyrite	76.51	9.83	11.85	
Succinite, Mikoszewo	75.64	9.48	14.28	
Succinite, Adamów lignite mine	76.9	9.79	12.71	
Succinite, Bełchatów lignite mine	78.21	9.88	11.19	

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