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Original article

Crack morphology and its correlation with ground materials used in paintings by Danish portrait painter Jens Juel

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ABSTRACT

Jens Juel (1745–1802) was a prominent Danish portrait painter, mainly known for creating over 600 portraits during his prolific four-decade career. This study investigated 22 canvas paintings by the artist, the majority of which are well preserved despite displaying typical signs of ageing like cracking. Crack formation in paintings results from a combination of external factors, such as environmental conditions, and inherent properties, including the composition of painting materials. Different materials used in the layers of a painting contribute to distinctive crack patterns, and this work focused on understanding how the composition of the ground layer and the density of the canvas influence these patterns. By employing a multi-analytical approach involving imaging, elemental and molecular analysis, along with data-driven methods such as dimensionality reduction, cluster analysis and statistical tests, the research established relationships between crack patterns and ground layer compositions in Juel's paintings. The findings unveiled significant physical and chemical differences between artworks created in Denmark (and partly Germany) and those from France and Switzerland, which can be attributed to different canvas preparation traditions. Crack patterns in Danish paintings are primarily characterised by orthogonal patterns with jagged lines, and these artworks have ground layers rich in calcium carbonate with minimal lead white and denser canvases. In contrast, French and Swiss paintings exhibit diagonal cracks in larger islands, and predominantly contain lead white with little to no presence of calcium carbonate in their ground layers. By integrating visual and chemical data, the investigation revealed four distinct crack pattern groups aligned with four ground types, underscoring the resilience of lead white-rich grounds, which are likely to be less susceptible to canvas-induced cracking compared to calcium-based grounds. Hence, the research uncovered a correlation between the proportion of these two components in the ground and the observed variations in crack patterns across different geographical and temporal contexts. These insights are crucial for conservators aiming to preserve not only Juel's artworks but also those of his contemporaries. The study highlights the significance of linking material choices to natural ageing patterns, and emphasises the importance of material analysis in predicting responses to ambient conditions and guiding conservation strategies for long-term stability of paintings.

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1. Introduction

1.1. Artist's background and paintings' preservation status

Jens Juel (1745–1802) (Fig. 1) was the most renowned portrait painter and the most productive artist of his time in Denmark. His production spans four decades and during his career, he created over 600 portraits on canvas [1]. At the age of fifteen, Juel initiated his apprenticeship in the studio of painter Johann Michael Gehrmann (1707–1770) in Hamburg, Germany. Around 1765, he returned to Denmark and enrolled as a student at the newly established (1754) Royal Danish Academy of Fine Arts (as it was later

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Fig. 1. Jens Juel. Self-Portrait, 1766. Oil on canvas, 34 cm × 43 cm. The Royal Danish Academy of Fine Arts, Copenhagen.

named) in Copenhagen. In 1772, Juel embarked on his grand tour, travelling through the most important artistic hubs in Europe, such as Hamburg, Dresden, Rome, Paris and Geneva. He successfully extended his travels to eight years by painting portraits on commission, especially in Switzerland, where he remained for three years. Following his return to Copenhagen in 1780, Juel was appointed as the official court painter (1780), and subsequently became member (1782), professor (1784) and director (1795–1797 and 1799–1801) of the Royal Danish Academy of Fine Arts, while simultaneously maintaining a busy private studio with assistants and students of the Academy.

The majority of Juel's paintings are in a well-preserved state. This is evidenced by minimal paint losses, the canvases performing well (on average 7.7 out of 10) in a thread-folding test [2,3], and the overall visually intact appearance of the paintings (Table 1S of the supplementary material). As is common for aged canvas artworks, Juel's paintings display cracking throughout the surface. The presence of various types of cracks and crack patterns indicates that different deterioration processes have occurred in the paintings over time. Interestingly, several paintings examined in this research, which were executed during Juel's European travels, display a distinct crack pattern compared to those produced in Denmark.

1.2. Crack formation and material influences in paintings

The definition and characterisation of crack patterns have been explored in various studies, and several articles propose methodologies for distinguishing one type of cracking from another [4-11]. The formation of cracks and crack patterns is triggered by stress resulting from the interplay of tension and compression within the structure of a painting and the mechanical properties of the materials in its different layers [12]. Cracks are likely to appear in oil paint layers regardless of the ambient climate due to a combination of increased brittleness and shrinkage [13]. However, the impact of climatic conditions on crack patterns in paintings is supported by the observation that the perimeter area of canvas paintings that are protected by a stretcher or strainers shows fewer cracks. This area seems to play a protective role by maintaining tension, minimising stress, and thus inhibiting crack building [14]. Therefore, crack formation depends on a combination of inherent properties and external physical factors to which the painting is exposed over time. Moreover, different ageing cracks and crack patterns have been correlated with specific painting techniques and materials [7-9]. The materials in each layer of a painting (traditionally canvas, glue sizing, ground layer, paint layers and varnish layers) have distinctive chemical and mechanical behaviours, and consequently, every layer contributes in its own way to the formation of cracks and other patterns of natural ageing. The characteristic crack patterns that develop depend on the type and properties of the canvas as well as the materials used for the preparation and paint layers, such as glue, binding media and pigments [5,7,12,15,16]. Different pigments and fillers affect both the drying time and the strength of the paint film, resulting in ground and paint layers with very different mechanical properties that range from weak to strong, and from flexible to stiff and brittle [17-20]. The amount of stress required to induce a crack is dependent on the thickness and tensile strength of the ground and paint layers [5,7,12,15,16]. For example, pigments such as earth colours were shown to form oil paint films with high shrinkage, low tensile strength and low E-modulus compared to oil paint films with lead white [13,19,21]. Furthermore, ground and paint layers made with earth colours can exhibit a severe loss of strength and stiffness, becoming sensitive to relative humidity fluctuations and solvent exposure [21,22]. Various fillers, such as chalk, gypsum and silicates, do not affect the drying of the oil and, similar to pure drying oil or paints containing earth colours, they were shown to develop oil paint films with low tensile strength and low E-modulus [21,23]. A stiffer and stronger ground or paint layer based on or containing lead white is more resistant to relative humidity fluctuations and exposure to solvents [21,24]. All the above-mentioned factors can affect the long-term stability of paintings, potentially leading to the delamination and loss of paint layers over time. Studying the materials comprising the paintings, together with insights into the artists' intentions and work practices, can enhance our understanding of ongoing ageing processes, which, in turn, can aid in predicting the responses to ambient conditions and selecting specific conservation treatments. Once cracks occur, they act as a stress-relieving mechanism within the painting structure [5,12,25]. It has been hypothesised that the creation and propagation of cracks continue until crack saturation is reached [26,27]. Therefore, once cracking and/or permanent deformation occurs and tension is relieved, the stresses arising from historically similar levels of environmental fluctuations are practically eliminated; according to the well-recognised theory of "proofed fluctuations", paintings become less susceptible to environmental changes, requiring considerably more tension to accumulate in the structure before demanding additional stress relief [28,29]. This essentially means that paintings with well-developed craquelure patterns are significantly less vulnerable to climate variations when they have remained stable within a specific environment for many years.

2. Research aim

This study investigated the influence of variations in painting materials on the diverse morphologies of crack patterns in Juel's paintings, aiming to understand how different materials contribute to crack formation across various temporal and geographical contexts. Preservation efforts can be informed by identifying the correlation between materials and crack patterns, which is crucial for conservators seeking to maintain the integrity of Juel's artworks over time. Hence, the goal of this research was to characterise the general crack pattern and examine how the differences in morphology correlate with the materials present in the layers of the paintings, exploring their potential impact on future preservation. Using a multi-analytical approach involving imaging, elemental and molecular analysis, along with data-driven methods such as dimensionality reduction, cluster analysis and statistical significance tests, the study revealed that differences in the morphology of the

Table 1
Overview of the paintings examined in the study. The paintings marked with one asterisk were produced in Germany, while those with two asterisks were created in France or Switzerland. All other paintings were produced in Denmark.

Portrait of	Collection	Inventory number	Year	Dimensions, cm (h × w)
Self-Portrait by Candlelight*	SMK	KMS3990	c. 1764	57.1 × 49.7
Peder Rahr, Merchant in Ribe	SMK	KMS3499	1770	78 × 62.1
Anna Elisabeth Battier née Storp	SMK	KMS3634	1771	79 × 63.8
The Sculptor Jacques-François-Joseph Saly	SMK	KMS4801	1772	83 × 67.3
Self-portrait with Portfolio*	SMK	KMS3275	1773–74	56.4 × 44.5
Postmaster General Frederik Hauch**	SMK	KMS349	1776	59 × 49
The engraver Johann Friderich Clemens**	SMK	KMS396	1776	52.4 × 41.8
Susanne Elisabeth Holm**	SMK	KMS1766	1778–79	52.7 × 42.8
Madame de Prangins**	SMK	KMS4810	1778–79	87 × 72.5
Jean-Armand Tronchin**	SMK	KMS6151	1779	71.7 × 57.2
Henrik Hielmstierne	SMK	KMS349a	1780	64.2 × 49.9
Henrik Gerner	SMK	KMS1444	1785	70.5 × 55
Charlotte Sophie Gerner née Rasch	SMK	KMS1445	1785	70.5 × 55
Peter Johan Schouw	SMK	KMS1113	1799–1800	69.5 × 54
Ane Christine Schouw née Poulsdatter	SMK	KMS1114	1799–1800	69 × 53.5
Anne Marie Bagge née Eegholm	SMK	KMS1115	1799–1800	69.4 × 53.4
Jens Bruun Neergaard of Svenstrup	Svenstrup	SV1	1788	69.8 × 54.6
Anne Marie Bruun Neergaard née Møller	Svenstrup	SV2	1788	69 × 53.5
Marie Christine Buchwaldt, née de Svanenskiold	Svenstrup	SV3	1780s	69.9 × 54.5
Jens Peter Bruun Neergaard to Eckhof	Svenstrup	SV4	1790	68.5 × 53.5
Joachim greve Moltke to Rønnesbækholm	Svenstrup	SV5	1797	69 × 53.4
Ellen Moltke née Bruun Neergaard	Svenstrup	SV6	1797	69 × 53.5

general crack pattern can be linked to the properties of the ground layer, acting as a principal source. Since the ground layer presented systematic differences that were not evident in any other layers, only the results of the ground layer analyses are included in this report, while the results from the additional layers are available elsewhere [3].

3. Materials and methods

3.1. Selection of paintings

For this investigation, 22 paintings on canvas by Danish portrait painter Jens Juel were selected: 16 paintings from the collection of the National Gallery of Denmark (SMK) and six paintings from a Danish private estate, Svenstrup (SV). This selection includes one of the earliest portraits by Juel—his self-portrait from 1764, painted during his apprenticeship in Hamburg; three paintings from his formative years in Copenhagen while enrolled at the art academy; six paintings from his sojourns in Dresden (Germany), Paris (France), and Switzerland; finally, six portraits from the latter half of his career, spanning the period from 1780 to 1800, shortly before his death. In addition, the six paintings from the private estate, Svenstrup, further add to the timeline of Juel's artistic production during the latter half of his career. An overview of the selected paintings is presented in Table 1.

3.2. Visual characterisation of crack patterns by X-radiography

To characterise the specific primary crack patterns observed in the examined paintings, Bucklow's eight dichotomous distinctions were applied for numerical representation using X-radiographs, since these images provide a clearer visualisation of the cracks compared to regular images [9]. X-radiography of the 16 paintings from the collection of SMK was performed using a Yxlon portable constant potential X-ray unit SMART Evo 160D X-ray tube at 30 to 34 kV, 5 mA, and exposure times ranging from 30 to 100 s on 30 cm × 40 cm DürrNDT high-definition image plates (HD-IP). The distance between the X-ray source and the film was 110 cm, employing a 3-mm AlMg3 filter. For the eight paintings from the Svenstrup Estate, X-radiography was executed with a Yxlon portable constant potential X-ray unit SMART 160E/0.4 X-ray tube at 25 to 30 kV, 3 mA, and exposure times of 60 to 70 s on 30 cm × 40 cm high-definition image plates. The distance between the X-ray source and the film was 110 cm, with no filter employed. The characteristics of the crack patterns in each painting were evaluated numerically on a scale from 1 to 5; a rating of 1 represents an adequate description by the left term, 5 indicates an adequate description by the right term, and 3 signifies that either both or neither term is adequate (Table 2).

Table 2
Eight dichotomous distinctions for numerical representation of different crack patterns according to Bucklow [9]. On a rating scale of 1 to 5, 1 means the left term is the best description and 5 means the right term is the best description; a rating of 3 means either both terms are equally accurate or neither term is a good descriptor.

Score	Characteristic	1	2	3	4	5
i	cracks	CONNECTED				BROKEN
ii	network	ORDERED				RANDOM
iii	direction	HORIZONTAL				VERTICAL
iv	islands	SQUARE				NOT SQUARE
v	cracks	SMOOTH				JAGGED
vi	cracks	STRAIGHT				CURVED
vii	thickness	UNIFORM				SECONDARY
viii	islands	SMALL				LARGE

3.3. Multi-analytical characterisation of ground layers

A range of analytical techniques was utilised to investigate the underlying layers of the selected paintings. The analysis of cross sections revealed the layered structure and enabled the identification of pigments and fillers that influence the colour and composition of the ground layers.

3.3.1. Production and optical microscopy inspection of cross sections

One representative sample of the ground and paint layers, approximately 1 mm in size, was collected from an area towards the edge of each of the 22 paintings selected for this study after careful visual examination of the painting surface [3]. Each sample was placed in an EasySection specifically designed for paint cross-section analysis (from Preservation Equipment Ltd, Norfolk, UK), embedded in Technovit 2000 LC acrylic resin from Kulzer Technik (Wehrheim, DE), and cured under UV-light (Technovit 2000 LC covering varnish was applied to the sample during the curing process). Subsequently, the hardened sample was prepared as cross section by polishing the transverse plane. A Leica DM2500 M optical microscope (maximum 100×) coupled with a Leica DMC4500 camera was used to examine the samples visually and to photograph the cross sections in reflected visible light (dark field).

3.3.2. Molecular spectroscopy analysis

The cross sections were analysed using attenuated total reflection-Fourier transform infrared (ATR-FTIR) and Raman spectroscopies. These analyses were utilised to provide additional information about pigments and fillers present in the ground layers by inspecting raw spectra without any manipulations or baseline corrections. ATR-FTIR mapping was performed using a Bruker Tensor 24 spectrometer, coupled with a Hyperion 3000 microscope equipped with a focal plane array (FPA) detector. ATR measurements were carried out using a 20× objective and a germanium crystal with a refractive index of 4.01, featuring an anvil design with an 80-µm tip. FPA maps were obtained in the spectral range of 3800 to 900 cm^{-1}, with a spectral resolution of 8 cm^{-1} and 128 scans. A minimum of one to four maps were acquired for each sample.

Raman measurements were executed using a Bruker Senterra dispersive Raman spectrometer coupled to an Olympus microscope and equipped with a thermoelectrically cooled charged-coupled device (CCD) detector. Raman spectra were recorded by focusing a 785-nm laser beam through a 50× objective, employing both 400 lines/mm and 1200 lines/mm gratings to achieve a balance between sensitivity and spectral resolution. The laser power at the sample ranged between 1 and 25 mW, and the acquisition time for each spot varied from 1 to 100 s, with 1 to 3 accumulations.

3.3.3. Elemental analysis

Scanning electron microscopy/energy-dispersive X-ray spectroscopy (SEM-EDX) was employed to analyse the cross sections. Elemental analysis and mapping were performed using a HITACHI S-3400 N scanning electron microscope equipped with a Bruker Quantax 200 energy-dispersive X-ray spectroscopy detection system featuring two Peltier-cooled XFlash silicon drift detectors, each with an active area of 20 mm^2. Measurements were carried out in variable pressure mode (30 Pa) on the non-coated polished sections, using a voltage of 20 kV, a probe current of 50 µA and a working distance of 10 mm. A combination of multi-point analysis and X-ray elemental mapping was employed. Specific areas to be examined for elemental composition with multi-point measurements were carefully selected onto SEM backscattered electron (BSE) images manually, making sure that the target areas on each layer were representative of the entire layer. Large particles of single pigments were measured individually for pigment characterisation purposes, and were not included in the areas representative of the layers. X-ray elemental mapping was used to visualise the distributions of the elements present in each layer. The acquisition times (live time) for analysing each selected area and producing the elemental maps were 60 s and 600 s, respectively.

3.4. Data integration

To gain deeper insights and improve our understanding of crack patterns and their underlying characteristics, an unsupervised machine learning approach was explored. The main objective was to uncover possible group separations within the crack pattern data and investigate the potential link between these distinct groups and different ground layer compositions. Therefore, after manually characterising the crack patterns through visual inspection, the generated data underwent further examination using a combination of principal component analysis (PCA) and hierarchical cluster analysis (HCA). These methods are particularly suitable for handling large data sets with a high number of features per observation, making them commonly employed in heritage science studies [30,31]. PCA served as a data-driven technique for reducing dimensionality and compressing the crack pattern information, while HCA, a method that constructs a hierarchy of clusters, was employed to group similar observations on the PCA score plot. This was achieved by utilising the numeric values representing Bucklow's system of crack pattern categorisation as reported in Table 2S of the supplementary material; dissimilarity between observations was measured using Euclidean distance, and complete linkage was employed to determine the furthest points between clusters. At the same time, the EDX data of the ground layers was also subjected to HCA to identify distinct types of X-ray spectra. This was accomplished by recording all EDX data in a single matrix composed of 22 observations corresponding to the measured cross sections and 3860 variables associated with the x-ray energies (ranging from 0.7 to 20.0 keV) of the sum spectrum of each cross section. As the morphology of the ground layers varied significantly across different samples, the net intensities for each variable were standardised to have a mean of 0 and a standard deviation of 1 within their respective ranges. Finally, the potential relationship between the observed crack patterns and the composition of the ground layers was investigated. To assess the association between the groups of crack patterns and the groups of ground compositions, Fisher's exact test, which allows the analysis of contingency tables resulting from classifying objects in two different ways [32], was chosen as the statistical significance test. Additionally, the Kruskal–Wallis test was used to compare the crack pattern groups based on the Pb/Ca net intensity ratio measured by SEM-EDX [33].

To delve further into crack pattern classification, a supervised approach using a convolutional neural network (CNN) was also adopted. CNNs excel at detecting prominent features like edges in images, but require careful parameter tuning during training, resulting in varying accuracies. To overcome this issue, a pre-trained version of the Xception network, trained on over a million images from the ImageNet database [34], was used. By adapting this well-proven, pre-trained model to our set of labelled X-ray images representing the groups identified through PCA-HCA, the requirement for extensive parameter tuning was minimised significantly. All the techniques described were performed in the R (version 4.3.0) environment using the factoextra (version 1.0.7), maptree (version 1.4–8), keras (version 2.11.1), tensorflow (version 2.11.0) and reticulate (1.29) packages on a standard mid-range laptop PC.

4. Results and discussion

This study investigated the influence of material variations in Juel's paintings on the diverse morphologies of crack patterns, and aimed to determine the correlation between these morphological differences and the specific materials present in the layers of the paintings. The results indicate that the identified pigments and fillers within the ground layers, combined with the canvas density, play a crucial role in influencing the mechanical properties of the overall structure of the painting, and, consequently, the occurrence, extent and appearance of cracking in the surface.

4.1. Visual characterisation of crack pattern morphology

When examining the general crack pattern across the 22 paintings included in the study, the paintings produced in Denmark and, to some extent, Germany, display distinct morphological differences compared to those created in France and Switzerland. Specifically, paintings from Denmark and Germany are characterised by a rather orthogonal pattern within a random network of larger and smaller islands, primarily composed of straight lines. Most cracks tend to be slightly jagged, with few prongs and barbs (pattern 1, Fig. 2). In certain cases, a slightly dominant direction in the crack

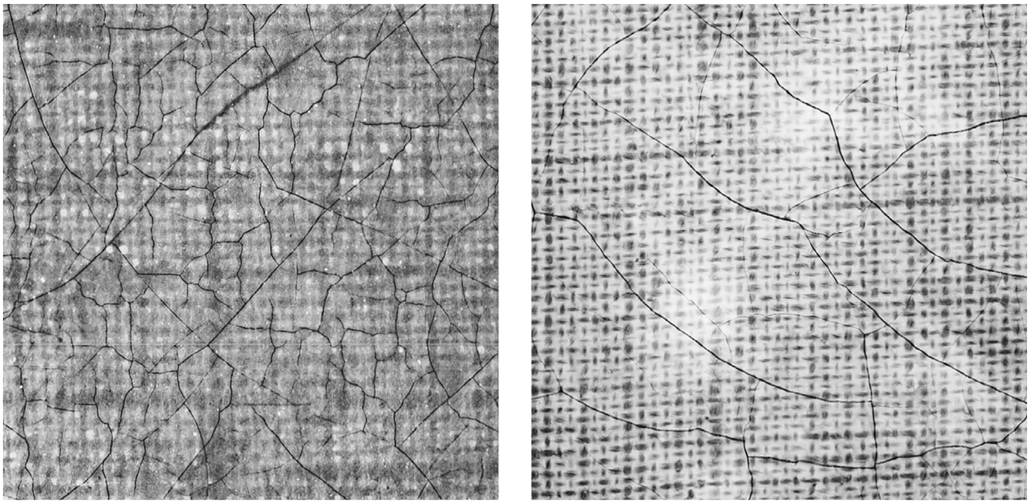

Fig. 2. Detail from the X-radiograph of *Battier KMS3634* (left) showing the characteristic crack pattern typically observed in paintings produced in Denmark (pattern 1), and *Holm KMS1766* (right) displaying the typical crack pattern found in paintings produced in France and Switzerland (pattern 2). Images represent an area of approximately 3 cm × 3 cm.

pattern becomes visible under raking light, aligning with overall directions, which so far has not resulted in severe cleaving and flaking [3]. The paintings produced in Paris and Switzerland display different global crack patterns when compared to those produced in Denmark, at both macro- and microscopic levels. These paintings are typically characterised by patterns lacking a particular direction, often showing diagonally oriented cracks that are smooth, curved, and predominantly spaced in larger islands (pattern 2, Fig. 2).

The analysed paintings exhibit localised variations in the prominence of the crack pattern, such as in relation to the wooden auxiliary support, thickness of layers, or specific colour segments. Generally, areas coinciding with the original strainer tend to show a less dense crack pattern. This is likely due to both the moisture-buffering properties of the wood, which reduces relative humidity and temperature fluctuations from the surrounding environment, and the strainer acting as a rigid substrate [14,35-38]. Most paintings display cracks or creases that are related to the inside edge of the original strainer. These occur independently of the materials structure in the ground and paint layers, and result from climate fluctuations and impacts or bending of the support against the bars [5,36,38]. In addition, localised cracking such as spiral or sigmoid cracks as well as fishbone- or feather-type cracks, caused by mechanical impacts and tacking, cusping and keying-out cracks, are present and interconnected with the global crack pattern. The X-radiography detail images in Table 2S of the supplementary material provide an exemplified visualisation of the observed cracks.

4.2. Multi-analytical characterisation of ground layers

The primary systematic differences in materials between the two groups of paintings (i.e., produced in Denmark and abroad) examined in this study, which show variations in the crack patterns, were observed in the ground layers. The range of pigments and fillers used in Juel's ground layers is limited. Lead white, hematite or red earth (rich in ferric oxide), carbon-based black, and vermilion were identified in various quantities. In isolated cases, the presence of amorphous arsenic sulfide [39], bone black, massicot and goethite was detected. The fillers identified in the different ground layers include calcium carbonate (likely chalk), kaolin, gypsum, as well as occasional quartz and silicates. The qualitative and semi-quantitative compositions of the ground layers are presented in Table 3S of the supplementary material. The binding media of the ground layers were consistently identified as drying oil in all cases (Table 4S of the supplementary material). The main differences in the ground layers of the two groups lie in the quantity and distribution of calcium carbonate and lead white. The paintings produced in Denmark generally feature ground layers with high amounts of chalk and little lead white. In contrast, the other group of paintings from France and Switzerland shows high amounts of lead white and almost no chalk. The difference in the distribution of lead white and calcium carbonate is illustrated in Fig. 3, showing the SEM-EDX elemental maps of lead (Pb) and calcium (Ca) in the cross sections of *Hauch KMS349* and *Battier KMS3634*. In Fig. 4, the grounds are categorised into four types and sub-categories, primarily based on the relative distribution of the two compounds: type I mainly consists of lead white with minimal calcium carbonate (type I.B displays a lower layer of red earth and an upper layer of lead white); type II contains nearly equal amounts of lead white and calcium carbonate; type III is predominantly composed of calcium carbonate with minimal lead white; type IV represents mixed compositions, including other pigments. Other potential factors commonly associated with variations in craquelure morphology, such as differences in canvas characteristics, sizing and ground layer thickness (as detailed in Tables 5S, 6S and 3S of the supplementary material, respectively), could not be conclusively identified or confirmed as the determining factors between the two types of crack patterns [3].

The contraction and swelling of the canvas resulting from relative humidity cycles may cause the initiation of cracks in the ground layer [40]. In the paintings produced in Denmark, the canvas supports generally exhibit higher density (i.e., a higher cover factor) and thicker, tightly spun threads compared to those in paintings produced in France and Switzerland [3]. This characteristic makes the canvases from Denmark more prone to swelling and contraction, which may initiate cracks. The combination of a calcium-rich ground, expected to have lower tensile strength than the lead-rich ground [41], and a more reactive canvas leads to a higher likelihood of crack initiation. In the paintings created in France and Switzerland, the cracks display larger islands of diagonal and straight lines, seemingly unrelated to the canvas-weave structure. Therefore, the swelling and shrinkage of the canvas during relative humidity cycles may play a lesser role in influencing the initiation and propagation of cracks in these ground layers. The small amounts of lead white in some of the ground layers of the paintings from Denmark likely provide increased stiffness

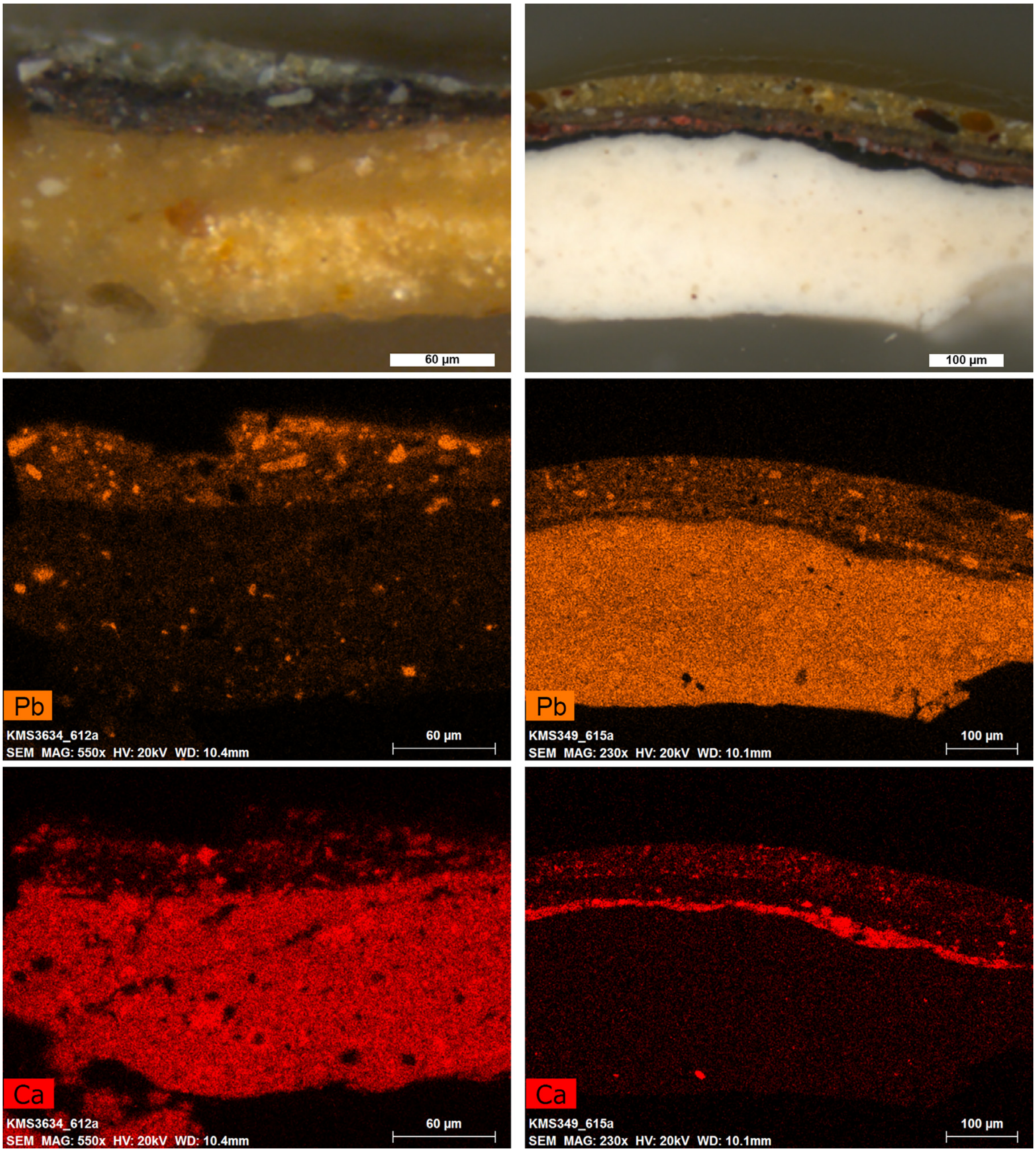

Fig. 3. Cross sections taken from *Battier KMS3634* (left) and *Hauch KMS349* (right) were imaged using optical microscopy under visible illumination (top) and SEM-EDX (middle and bottom). Elemental distributions of lead (Pb) and calcium (Ca) in the cross section of *Battier KMS3634* show minimal lead white presence and a significant amount of calcium carbonate in the ground layer (ground type IV); in contrast, the cross section from *Hauch KMS349* shows a substantial amount of lead white with no calcium carbonate in the ground layer (ground type I).

and strength to the chalk-based layer. This may be a factor explaining the enduring good condition of many of Juel's paintings. The potential strengthening effect may also explain why a painting with a double ground such as *Clemens KMS396*, whose preparation consists of a lower red-earth ground with sporadic particles rich in lead and calcium beneath an all-lead-white layer, displays a crack pattern seemingly less affected by the canvas and shares more common features with the paintings characterised by lead white grounds alone.

4.3. Data integration

An additional analysis of the numerical representations of the crack pattern morphology observed in Juel's painting (Table 2S of the supplementary material) was conducted using PCA-HCA, resulting in the identification of four distinct groups (Fig. 5a). These clusters not only included the two main groups of paintings originating from France/Switzerland and Denmark (groups 1 and 4, respectively), but also featured two additional groups, each composed of a combination of paintings produced in Denmark and Germany (groups 2 and 3). Subsequently, to validate the alignment of these four crack pattern groups with the four ground types previously identified manually, HCA was performed on the EDX data. This analysis also revealed four distinct ground types (Fig. 5b), closely corresponding to the findings from the systematic examination of the cross section micrographs and the EDX spectra. These ground types included: I) predominantly lead, II) predominantly calcium, III) equal amounts of both, and IV) a

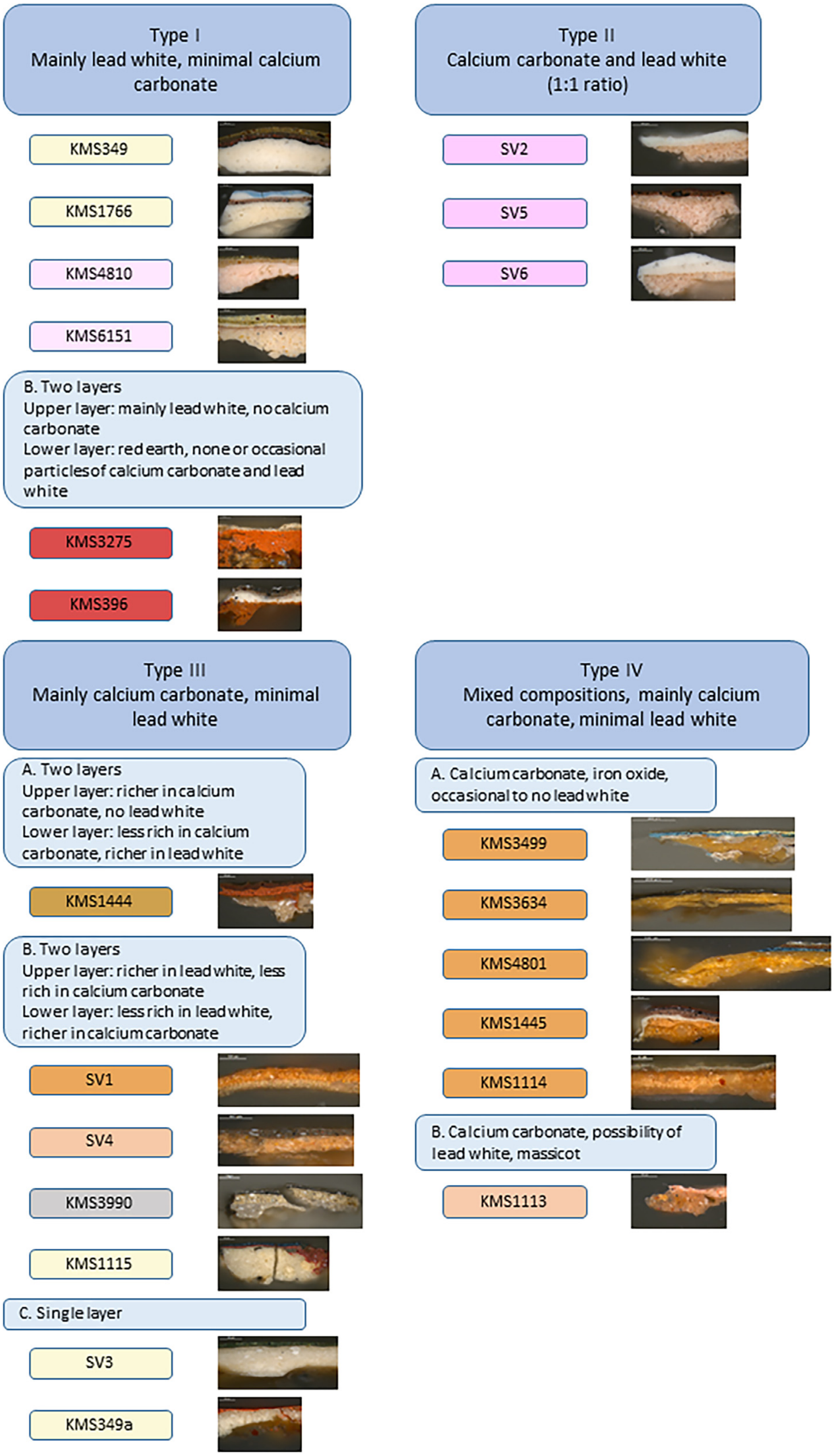

Fig. 4. Grounds from Juel's paintings were categorised into four types and sub-categories, primarily based on the relative distribution of lead white and calcium carbonate.

mixed type with a higher lead content compared to the original type IV. Only two paintings, *Schouw KMS1113* and *Neergaard SV4*, were categorised into different groups depending on whether manual or automatic classification processes were utilised. Specifically, the former painting was manually categorised as type III but automatically assigned to a group with a higher lead content (group IV), while the latter was manually classified as type IV but automatically placed in a group with a lower lead content (group III). Finally, to determine whether certain crack patterns are associated with specific chemical compositions of the ground layers,

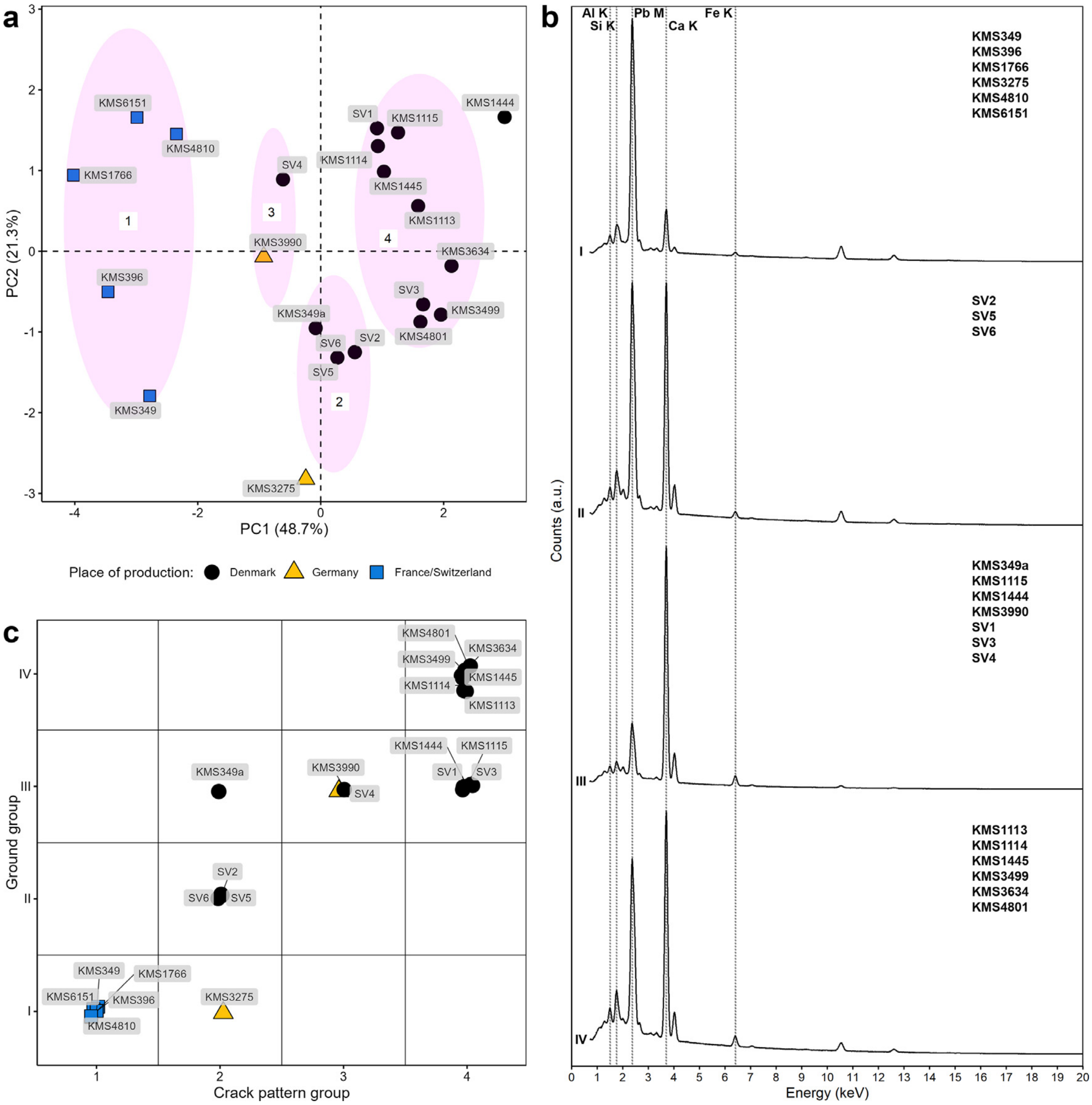

Fig. 5. Advanced data analysis revealing the relationship between crack pattern morphology and ground layer composition: (a) PCA score plot of the crack pattern visual features (percent values in parentheses represent explained variance)—HCA revealed four distinct groups; (b) mean EDX spectra representing the four types of ground layer compositions identified through HCA; (c) contingency table showing the association between crack patterns and ground layer compositions.

the relationship between the two sets of clusters was explored by cross-classifying the analysed paintings based on their respective crack pattern groups identified by PCA-HCA and the ground groups generated by HCA (Fig. 5c). Due to the relatively small sample size of only 22 observations and the presence of multiple combinations with zero counts, the significance of the association between the two types of classification was examined using Fisher's exact test. The resulting p-value ($p = 5.1 \cdot 10^{-6}$) was substantially smaller than the chosen significance level of 0.05, indicating a significant association between crack patterns and ground compositions. These results reinforce the hypothesis that the observed crack patterns can function as reliable indicators of specific ground compositions, offering valuable insights into the mechanical behaviour of painting materials and their relationship with chemical properties. Specifically, the crack morphology observed in paintings from Denmark seems to be significantly influenced by the canvas structure due to ground layers with a low Pb/Ca ratio. In contrast, the characteristics of craquelure morphology in paintings from France and Switzerland appear to be associated with ground layers with a high Pb/Ca ratio, which play a role in decoupling the movements of the canvas support from those of the paint layers. To further support this hypothesis, a Kruskal–Wallis rank sum test was performed to assess the variation in Pb/Ca ratio (based on the normalised net intensities of the Pb M and Ca K spectral lines measured on each cross section) across the four crack pattern groups, revealing a statistically significant difference ($p = 0.0053$). This type of test was selected after conducting a diagnostic check for violations of normality in the intensity ratios split by crack pattern group (Fig. 1S of the supplementary material); however, it is important to note that the assumption of normality in this case may be complicated by the relatively small sample size.

To delve more deeply into crack pattern classification, a supervised approach using a CNN was adopted. The CNN was trained with labelled images representing the four groups of crack patterns identified through PCA-HCA. Despite the limited number of images available, the training process was highly successful, yielding an accuracy of approximately 95 % after only six iterations. This result proved the CNN's efficacy in classifying crack patterns based on the morphological features that were manually identified and subsequently grouped through PCA-HCA. To evaluate the CNN's performance further, tests were conducted on an independent data set, which was created by applying a high-pass filter to the original training images, in order to enhance crack patterns and minimise canvas texture. This process ensured reasonable independence between the test and train data sets, allowing the model's ability to make reliable predictions on new, unseen data. For each test image, the model's predicted group assignment was compared with the actual group. Despite some difficulties in correctly identifying crack patterns in group 2 (80 % correct classification), the model showed high accuracy (100 %) in classifying crack patterns belonging to the other three groups, thus validating the effectiveness of PCA-HCA grouping. In order to achieve significant improvements in the model's performance, future research should prioritise the creation of large databases comprising various crack pattern morphological types. These comprehensive data sets will enable more robust and accurate modelling, allowing for better understanding of the relationships between crack patterns and other relevant factors.

5. Conclusions

Examinations of 22 Juel's portrait paintings through imaging and material analyses unveiled distinct groups of crack patterns that correlated with different ground types, shedding light on the relationship between chemical properties and mechanical behaviour in these artworks. Additionally, utilising a combination of unsupervised and supervised machine learning methods, the study demonstrated a significant correlation between crack morphology and ground composition, emphasising the potential of crack patterns as reliable indicators in art conservation and research. The investigation revealed significant differences in the ground layers of Juel's paintings created in Denmark compared to those produced abroad. The ground layers of paintings from Denmark contain substantial amounts of calcium carbonate (likely chalk) with little lead white, while the paintings produced in France and Switzerland mainly contain lead white with little or no calcium carbonate in their ground layers. The varying proportion of lead white to calcium carbonate in the ground layers corresponds to differences in crack patterns and canvas density observed in paintings produced in different geographical locations. This heterogeneity of ground layer compositions appears to be a key factor exerting a significant impact on the mechanical and chemical properties within the structure of the painting and influencing the development of specific craquelure types. The present investigation shows notable differences in strength between the two types of grounds. Paintings with a lead white-rich ground are expected to possess greater resilience to canvas-induced micro-cracks compared to those with predominantly chalk-based grounds. Consequently, a lead white ground may be less susceptible to further cracking when new tensions are introduced through conservation treatments such as restretching and keying out or due to high humidity, resulting in an expansion of the stretcher. The variation observed in Juel's use of ground layers and their recognised influence on ageing patterns suggests a need for caution and careful consideration of the type of ground layer present in any painting undergoing conservation treatment, taking into account that paintings with different grounds may respond differently as a result.

The differences in materials and techniques observed in the examined paintings are crucial for a broader understanding of the properties of ground layers and their influence on the structural stability of the paintings. These findings are consistent with tests on the mechanical properties of different materials conducted in laboratories and documented in technical literature. Such inquiries relate to both the artist's choices and knowledge of materials based on practical experience, as well as the expected response of the paintings to conservation and restoration treatments. This study presents tangible evidence establishing a correlation between the materials employed and ageing patterns, particularly in the context of crack morphology. Given the necessity for extensive databases to enhance the accuracy of crack pattern classification, the insights gained from this research can serve as a starting point for expanding our understanding of the formation of cracks. This pertains not only to Juel's artworks but also extends to the preservation of paintings in general, contributing to our knowledge of paintings' ageing, and enabling a more targeted approach to both preventive and active conservation activities.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.culher.2024.07.010.

References

[1] E. Poulsen, Copenhagen: Selskabet til Udgivelse af danske Mindesmærker, Christian Ejlers' Forlag Jens Juel *(Vol. 1-2)*, 1991.

[2] M. Oriola, G. Campo, M. Strlič, L. Cséfalvayová, M. Odlyha, A. Možir, Non-destructive condition assessment of painting canvases using near infrared spectroscopy, in: J. Bridgland, C. Antomarchi (Eds.), ICOM-CC: 16th Triennial Conference, Lisbon, 19-23 September 2011, ICOM CC, Paris, 2011, pp. 1–8.

[3] T.L. Slotsgaard, Material and technique in portraits by Jens Juel and their correlation to degradation patterns, Royal Danish Academy - Architecture, Design, Conservation, 2020.

[4] M. Boers, Reference standards for the description of various types and degrees of cracking and similar faults in paint coats, in: 5th FATIPEC Congress, 1959, p. 824.

[5] S. Keck, Mechanical alteration of the paint film, Stud. Conserv. 14 (1) (1969) 9–30, doi:10.1179/sic.1969.002.

[6] G.L. Stout, Description of film cracks, Bull. Am. Inst. Conserv. Histor. Artist. Works 14 (2) (1974) 9–14, doi:10.2307/3179315.

[7] S. Bucklow, The description of craquelure patterns, Stud. Conserv. 42 (3) (1997) 129–140, doi:10.2307/1506709.

[8] S. Bucklow, The description and classification of craquelure, Stud. Conserv. 44 (4) (1999) 233–244, doi:10.2307/1506653.

[9] S. Bucklow, Consensus in the classification of craquelure, Hamilton Kerr Institute Bulletin (3) (2000) 61–73.

[10] S. Bucklow, 'The classification of craquelure patterns', in *Conservation of Easel Paintings*, 2nd ed., Routledge, 2020.

[11] P. de Willigen, A Mathematical Study on Craquelure and Other Mechanical Damage in Paintings, Delft University Press, Delft, 1999.

[12] M.F. Mecklenburg, Some aspects of the mechanical behavior of fabric supported paintings, in: The Mechanics of Art Materials and Its Future in Heritage Science, 1982, p. 107.
[13] A. Janas, et al., Shrinkage and mechanical properties of drying oil paints, Herit. Sci. 10 (1) (2022) 181, doi:10.1186/s40494-022-00814-2.
[14] T. Padfield, et al., Back protection of canvas paintings, Herit. Sci. 8 (1) (2020) 96, doi:10.1186/s40494-020-00435-7.
[15] M.F. Mecklenburg and C.S. Tumosa, 'Mechanical behavior of paintings subjected to changes in temperature and relative humidity', *Art in Transit: Studies in the Transport of Paintings*, 1991.
[16] F. Giorgiutti-Dauphiné, L. Pauchard, Painting cracks: a way to investigate the pictorial matter, J. Appl. Phys. 120 (6) (2016) 065107, doi:10.1063/1.4960438.
[17] A. Toussaint, Influence of pigmentation on the mechanical properties of paint films, Prog. Org. Coat. 2 (3) (1974) 237–267, doi:10.1016/0300-9440(74)80004-4.
[18] A. Zosel, Mechanical behaviour of coating films, Prog. Org. Coat. 8 (1) (1980) 47–79, doi:10.1016/0300-9440(80)80004-X.
[19] M.F. Mecklenburg, C.S. Tumosa, D. Erhardt, The changing mechanical properties of aging oil paints, MRS Online Proc. Lib. 852 (2004) OO3.1, doi:10.1557/PROC-852-OO3.1.
[20] M.F. Mecklenburg, L. Fuster Lopez, Failure mechanisms in canvas supported paintings: approaches for developing consolidation protocols, in: The Care of Painted Surfaces. Materials and Methods for Consolidation, and scientific Methods to Evaluate their Effectiveness, Proceedings of the Conference, Milan, November 10-11, 2006, 2006 il Prato.
[21] M.F. Mecklenburg, C.S. Tumosa, and E.P. Vicenzi, 'The influence of pigments and ion migration on the durability of drying oil and alkyd paints', 2013, (Accessed 1 January 2024. [Online]. Available: https://repository.si.edu/xmlui/handle/10088/20490
[22] M.F. Mecklenburg, 'Determining the acceptable ranges of relative humidity and temperature in museums and galleries, Part 1, structural response to relative humidity', 2007.
[23] C.S. Tumosa, M.F. Mecklenburg, Oil paints: the chemistry of drying oils and the potential for solvent disruption, in: New Insights into the Cleaning of Paintings: Proceedings from the Cleaning 2010 International Conference, Universidad Politecnica de Valencia and Museum Conservation Institute, 2010.
[24] R. Mayer and E. Smith, *The Artist's Handbook of Materials and Techniques.* R. Mayer, 3rd ed.. revised and Expanded. London: Faber, 1973.
[25] A. Karpowicz, A study on development of cracks on paintings, J. Am. Inst. Conserv. 29 (2) (1990) 169–180, doi:10.2307/3179581.
[26] Ł. Bratasz, M.R. Vaziri Sereshk, Crack Saturation as a Mechanism of Acclimatization of Panel Paintings to Unstable Environments, Stud. Conserv. 63 (sup1) (2018) 22–27, doi:10.1080/00393630.2018.1504433.
[27] Ł. Bratasz, K.G. Akoglu, P. Kékicheff, Fracture saturation in paintings makes them less vulnerable to environmental variations in museums, Herit. Sci. 8 (1) (2020) 11, doi:10.1186/s40494-020-0352-0.
[28] S. Michalski, Relative humidity: a discussion of correct/incorrect values, MH. 500 (3) (1993) 100.
[29] S. Michalski, The power of history in the analysis of collection risks from climate fluctuations and light, in: *Proceedings of the ICOM Committee for Conservation 17th Triennial Meeting,* Melbourne, Australia, 2014, pp. 15–19.
[30] M. Albrecht, O. de Noord, S. Meloni, A. van Loon, R. Haswell, Jan Steen's ground layers analysed with principal component analysis, Herit. Sci. 7 (1) (2019) 53, doi:10.1186/s40494-019-0295-5.
[31] G. Pastorelli, A.S. Ortiz Miranda, A.H. Christensen, Interpretation of x-ray spectral data using self-organising maps and hierarchical clustering: a study of Vilhelm Hammershøi's use of painting materials, X-Ray Spectrom. (2023) xrs.3388, doi:10.1002/xrs.3388.
[32] R.A. Fisher, On the interpretation of χ 2 from contingency tables, and the calculation of P, J. R. Stat. Soc. 85 (1) (1922) 87, doi:10.2307/2340521.
[33] W.H. Kruskal, W.A. Wallis, Use of ranks in one-criterion variance analysis, J. Am. Stat. Assoc. 47 (260) (1952) 583–621, doi:10.1080/01621459.1952.10483441.
[34] F. Chollet, Xception: Deep Learning With Depthwise Separable Convolutions, 2017, pp. 1251–1258. (Accessed 1 January 2024) [Online]. Available https://openaccess.thecvf.com/content_cvpr_2017/html/Chollet_Xception_Deep_Learning_CVPR_2017_paper.html .
[35] G.A. Berger, W.H. Russell, An evaluation of the preparation of canvas paintings using stress measurements, Stud. Conserv. 33 (4) (1988) 187, doi:10.2307/1506314.
[36] S. Michalski, Paintings: their response to temperature, relative humidity, shock, and vibration, Art in Transit: Studies in the Transport of Paintings, 1991 vol. 26.
[37] F.J. Ligterink, G. Di Pietro, Canvas paintings on cold walls: relative humidity differences near the stretcher, in: T. Padfield, K. Borchersen (Eds.), Museum Microclimates, National Museum of Denmark, 2007, pp. 27–38.
[38] B.A. Buckley, Painting conservation catalog: Vol 2, Stretchers and Strainers, Volume 2 of Painting Conservation Catalog, American Institute for Conservation, Paintings Specialty Group, 2008.
[39] M. Vermeulen, K. Palka, M. Vlček, J. Sanyova, Study of dry- and wet-process amorphous arsenic sulfides: synthesis, Raman reference spectra, and identification in historical art materials, J. Raman Spectrosc. 50 (3) (2019) 396–406, doi:10.1002/jrs.5534.
[40] M. Scharff, C.K. Andersen, T. Filtenborg, Canvas-related micro-cracks in Danish 19th century paintings, ICOM-CC Triennial Conference in Beijing: Transcending Boundaries: Integrated Approaches to Conservation, 2021.
[41] M.F. Mecklenburg, C.S. Tumosa, D. Erhardt, The changing mechanical properties of aging oil paints, MRS Online Proc. Lib. 852 (2004).