Eur. Phys. J. Plus (2021) 136:899
https://doi.org/10.1140/epjp/s13360-021-01758-5

THE EUROPEAN PHYSICAL JOURNAL PLUS

Regular Article

Munch and optical coherence tomography: unravelling historical and artist applied varnish layers in painting collections

Thierry Ford[1,2,a], **Magdalena Iwanicka**[3], **Elena Platania**[2,4], **Piotr Targowski**[5], **Ella Hendriks**[6]

[1] The National Museum of Art, St. Olavs Plass, P.O. Box 7014, 0130 Oslo, Norway
[2] Department of Archaeology, Conservation and History (IAKH), Conservation Studies, University of Oslo (UiO), Postboks 1008 Blindern, 0315 Oslo, Norway
[3] Department for Conservation and Restoration of Paintings and Polychromed Sculpture, Faculty of Fine Arts, Nicolaus Copernicus University, ul. Gagarina 7, 87-100 Toruń, Poland
[4] Hylleraas Centre for Quantum Molecular Sciences, Department of Chemistry, University of Oslo, Blindern, Post Box 1033, 0315 Oslo, Norway
[5] Institute of Physics, Nicolaus Copernicus University. Ul, Grudziadzka 5, 87-100 Toruń, Poland
[6] Programme Conservation and Restoration of Cultural Heritage, University of Amsterdam (UvA), Johannes Vermeerplein 1, 1071 DV Amsterdam, Netherlands

Received: 1 November 2020 / Accepted: 14 July 2021

Abstract Effective care of large-scale museum collections requires planning that includes the conservation treatment of specific groups of art works, such as appropriate cleaning strategies. Optical coherence tomography (OCT) has been successfully applied as a non-invasive method for the stratigraphic visualisation of the uppermost transparent and semi-transparent layers in paintings, such as varnishes. Several OCT case study examples have further demonstrated the capabilities of the non-contact interferometric technique to measure the thickness of the various varnish layers, to help monitor cleaning and associated optical changes, and to detect past restorations. OCT was applied for the detection of varnishes to 13 paintings by Edvard Munch (1863–1944) owned by the Norwegian National Museum of Art. The paintings have a controversial and complex varnish history and are displayed as a group according to their acquisition legacy. A prototype high-resolution portable SdOCT instrument was used in combination with complementary imaging techniques. Questions concerning thickness, stratigraphy and the identification/location of the artist's original varnish layers and/or pigmented glazes were addressed. Findings confirmed the complexity of the historical layers present and provided new evidence for Munch's use of transparent and semi-transparent layers as part of an occasional, localised varnishing and/or glazing technique.

1 Introduction

The 57 paintings by Edvard Munch (1863–1944) housed at the Norwegian National Museum of Art (NaM) represent the first historic public collection by the artist. Acquired over a period of 79 years (1891–1970), the paintings are a hand-picked *ensemble* of Munch's earlier

[a] e-mail: thierry.ford@nasjonalmuseet.no (corresponding author)

and mid-career masterpieces (1881–1920). Their international *renommé* and significance, in terms of national cultural identity, are coupled with their distinct display history as a specific group, exhibited in a dedicated space known as the *'Munch Room'* [1, 2]. Munch's attitude to varnish as a surface coating and its employment in his painting technique has been described as 'unclear', and a prior survey of conservation documents recommends that *'best source for investigating Munch's varnishing practice is the paintings themselves'* [3].[1] Munch's paint surfaces are typically associated with a matt and unvarnished finish, yet there are several recent references from works dated between 1880–1900, inferring his employment of varnish resins as part of an occasional, localised saturation/gloss effect [4–9]. Today, many of Munch's original surface effects have been visually reduced by past restorations and natural ageing. Evidence of the museum's repeated often controversial application of non-original varnishes has been both documented and recently investigated [3, 10]. A large proportion of the paintings (48 out of 57) were initially varnished and then re-varnished by the NaM between 1891–1993, with either a natural varnish resin, a synthetic one or a mixture of both. The overall goal of this study was to gain a better insight into the non-original varnish coatings and Munch's own intended surface finishes from the specific period, 1880–1900.

To understand the current visual relationship of these works displayed as a group requires a proper discernment of the stratigraphy, composition and condition of their surfaces, especially given that there is recent evidence to suggest that Munch practised local varnishing or the application of pigmented glazes to adjust matt–gloss relationships.[2] These subtle orchestrated effects are now lost due to the application of later varnishes so that they can no longer easily be discerned using visual or ultraviolet-induced fluorescence (UVA) inspection and require other means of clarification. Given this reason, and in line with the collection's long and complex conservation history, this study explores the diagnostic capabilities of optical coherence tomography (OCT) as a promising non-invasive detection method to investigate this phenomenon [12]. The benefit of employing OCT is its ability to non-invasively provide a cross-sectional imaging of the uppermost transparent and semi-transparent layers in paintings, such as varnishes and glazes, without physical sampling [13–19].

Thirteen paintings were investigated with a specific selection criterion. All works represent early acquisitions by the NaM and date from the period 1884–1900. The study also includes one of the few paintings where there is both documentary and analytical evidence of Munch's use of varnish in his painting technique, *The Sick Child* (Woll M 130) [8]. Two paintings have unvarnished and unrestored paint surfaces, serving as a comparison (*The Scream* Woll M 333 and *Self-portrait with Cigarette* Woll M 382). Questions concerning the layering and morphology of the later non-original varnish coatings (either lying on top of the paint surface or absorbed into the ground layer) were also addressed.

The study represents the first OCT non-invasive investigations of original and secondary stratigraphic varnish layers present across a specific group of late nineteenth-century Munch paintings (1880–1900). Complementary investigations were adopted to support the OCT analyses; optical and digital microscopy, visible photography, UVA-induced fluorescence photography, infrared reflectography (IRR) and portable X-ray fluorescence spectroscopy (pXRF).

The findings aim to contribute to long-term preservation and conservation decisions, namely how to design suitable methods and protocols for the removal of later non-original

[1] The term varnish refers to the resinous coating (natural or synthetic) which has been applied as final and unified transparent top layer to a paint surface. It can also be used as an intermediate layer, selectively employed by the artist to control the saturation of the paint.

[2] The term glaze refers to the application of transparent pigments in clear vehicle. It can be used locally to either modify the colour of the paint underneath or as an 'over-all toning layer' [11].

varnish coatings. In addition, this paper builds on an earlier study whilst also laying the foundation for further research, for the characterisation of the varnish layers in the Munch collection [10].

2 Material and methods[3]

2.1 Imaging techniques

The paint surfaces, varnish coatings and their condition were first documented through the combination of optical and digital microscopy with photographic techniques. A Leica Wild M8 stereomicroscope, ($5\times - 50\times$ magnification range, Ortomedic AS, Lysaker, Norway) and Hirox RH-2000-3D digital microscope (Full HD $20\times - 160\times$ zoom lens, Hirox Europe, Limonest, France.) were employed to study and capture the surface topography relevant for finding appropriate locations for OCT readings. All thirteen paintings were also examined with UVA-induced fluorescence photography following the CHARISMA standards [20]. A Hasselblad H6D-400C MS digital camera (Interfoto AS, Oslo, Norway) with a Baader UV/infrared (IR) Cut/L-Filter (Baader Planetarium, Mammendorf, Germany) was employed in conjunction with a Target-UV calibration patch (Image Science Associates, LLC, Williamson, NY, the USA) to control colour and intensity of UVA-induced visible fluorescence. Two UVA luminaires were placed at equal distance, on either side of the painting, with three 40-W UVA fluorescent tubes per luminaire, radiating in the 355–360 nm region. IRR was taken using the Apollo digital scanning InGaAs IRR camera (operation wavelength 0.9–1.7 μm, Opus Instruments, Norwich, the UK).

2.2 pXRF

pXRF measurements were taken with a Thermo Niton XL3t 900 energy dispersive pXRF spectrometer (Thermo Scientific, Holger Hartmann, Oslo, Norway) with a Si-drift detector (GOLDD—Geometrically Optimized Large Drift Detector) attached to a tripod. Multiple readings were taken from the same areas analysed by OCT or adjacent passages with dominant primary, secondary, black and white colours. The proprietary "Mining Cu/Zn Testing Mode" was used. Total measurement time was ca. 60 s for each reading and the instrument switched automatically from main (Al/Fe filter, maximum current: 40 μA, operating at 50 kV) to low (Cu filter, 20 kV, operating at 50 kV maximum current: 100 μA), high (Mo filter, maximum current: 40 μA, operating at 50 kV) and light range filters.

2.3 OCT

OCT is a non-contact interferometric scanning technique employing broadband infrared radiation which is either scattered or reflected by the surface. The depth of penetration is determined by the absorption properties of the medium examined and allows the precise measurement of the various varnish layers (and/or glazes) present, as well as detecting past restorations [14, 16]. A virtual cross section (OCT tomogram) can be rapidly created from the consecutive and adjacent set of penetration scans (B-scans) along a specific line [15].

OCT examinations were carried out using a prototype high-resolution portable SdOCT instrument designed and built under the EU FP7 CHARISMA and H2020 IPERION CH Pro-

[3] The description of the following techniques and analyses, except for OCT, are revised from an earlier methodology text [10].

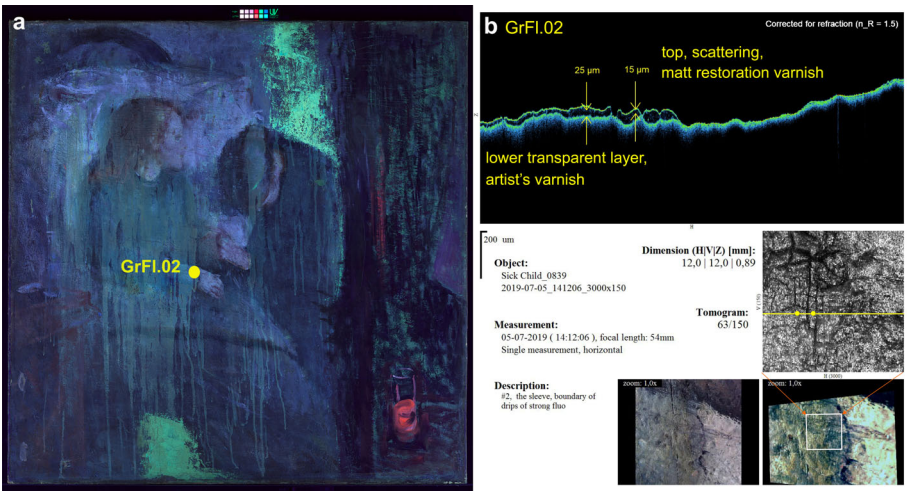


Fig. 1 *The Sick Child* (Woll M 130), **a** UVA-induced fluorescence photography with location of OCT examination spot, **b** OCT tomogram and IR reflectogram from same examination spot GrFl.02 (green sleeve/girl's hand)

grammes (at Nicolaus Copernicus University, Toruń, Poland) [21]. Scanning was performed at a 43 mm distance to the surfaces, with the paintings placed horizontally on a table. The OCT instrument was operated with a broadband superluminescent light source with a spectral range of 750–950 nm (M-T-850-HP broadlighter, Superlum, Ireland) and a maximum of 800 µW of probing light at the object's surface. A complete set of resultant vertical and/or horizontal 2D tomograms (B-scans) were obtained from selected areas of interest, previous analysis and/or from pXRF spots. These images were obtained with a 2.2 µm axial resolution in the varnish and with a lateral resolution of 15 µm. The OCT tomograms were corrected for refraction of light, using a common value of refracting index $n_R = 1.5$ and are presented in a false colour scale (blue to green for low and moderate scattering, yellow to red for high scattering and black for complete transparency or beyond the range of penetration). Horizontal and vertical scale bars correspond to 200 µm with the vertical axis stretched tenfold for readability. The data were collected in the form of 150 parallel 2D slices acquired from a 12×12 mm^2 area with the most representative slice presented in the figures. The OCT data presented as composite panels (see Figs. 1 and 2 and A.1in Electronic Supplementary Materials) show the whole cross section $12 \times 0{,}89$ mm^2, complemented by an IR reflectogram generated directly from the OCT data and two macrographs of the scanned area. The positions of the measurement readings and annotations in the OCT cross section are also marked on the corresponding yellow scan line in the IR reflectogram.

3 Groups and categories

Thirteen paintings were selected from the period 1884–1900 and divided into three categories according to date, painting technique and surface finish (Table 1). The OCT findings were closely correlated with previous treatment histories recorded in either post 1949 conservation dossiers or from other archival sources [12]. Dammar, Mastic, Laropal K-80 and MS2A var-

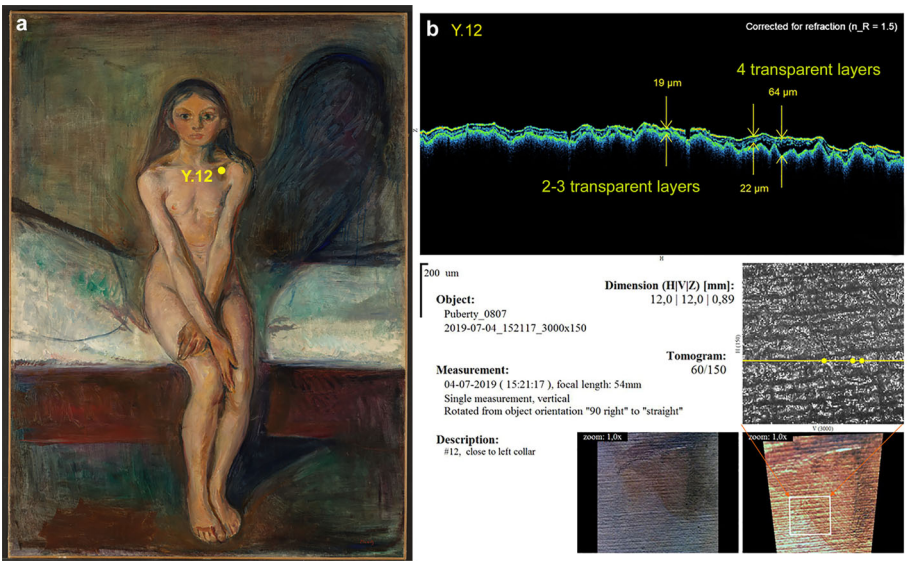


Fig. 2 *Puberty* (Woll M 347), **a** normal light photography with location of OCT examination spot Y.12, **b** OCT tomogram and IR reflectogram from same examination spot Y12 (3 locally applied transparent layers underneath restoration varnish)

nish resins are documented as having been used by the NaM since the first Munch acquisition [10].

3.1 Group 1: 1884–1889

In 1885, Munch was awarded a travel grant to study in Paris and was both accompanied and surrounded by an important group of Norwegian painters [22–24]. The five paintings selected for group 1 (Table 1) share visible common traits in the form of thicker paint application, combined with prominent brush work and uneven surface topographies. This characteristic in Munch's painting technique during the 1880s has been described as *'in keeping with the naturalistic trend and Parisian influence*' [25].

3.2 Group 2: 1890–1900

Group 2 features the NaM's versions of the paintings, *Puberty, The Day After* and *Madonna* (Woll M 347, 348 and 366) which have interesting similarities in terms of their acquisition, conservation history as well as paint technique and production date (Table 1). Moreover, all three works are central to Munch's conceptualisation of the woman, and in the scholarly literature, they are often discussed as a group [26]. All three were acquired by the NaM in 1909 and have undergone cleaning, lining and varnishing treatments.[4] The paintings are early versions of Munch's iconic motifs and *Puberty* and *The Day After* were named as being *'vandalised'* by the museum through varnishing in 1909 [27]. The group also includes two early works, *Night in Nice* (Woll M 224) and *Winter in the Woods, Nordstrand* (Woll M 445). The former represents the NaM's first Munch acquisition in 1891, and both works bear

[4] NaM conservation dossiers; NG.M.00807, NG.M.00808 and NG.M.00841.

Table 1 Summary of OCT analyses; group 1 (1884–1889), group 2 (1890–1900) and group 3 (unvarnished paintings)

Painting details	Group	Fig.	Total no. OCT examination spots	OCT Main observations and layer thickness (μm)
Woll M 113 *Inger Munch in Black*  1884, oil on canvas (97 × 67 cm)	1	Figure 3; A.1 ESM Figs. 1, 2, 3	22	Up to four transparent/semi-transparent layers (24–100 μm) in flesh areas (face, neck and hands) (spot Fl.03) Two transparent varnish layers present over dark dress and background (average total thickness, ca. 45 μm) Two thin restoration varnish layers over red signature (spot RBk.15) Artist's alterations under two restoration varnish layers (spot BkFl.09). Some of the black/dark paint layers are semi-transparent to IR

Table 1 continued

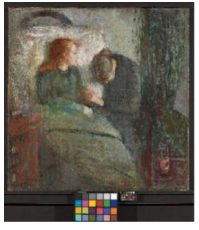
Painting details	Group	Fig.	Total no. OCT examination spots	OCT Main observations and layer thickness (μm)
Woll M 130 *The Sick Child*  1885/6, oil on canvas (120 × 118.5 cm)	1	Figure 1	5	Locally applied transparent and semi-transparent layers Evidence of the later restoration matt varnish layer (15–20 μm) over Munch's transparent varnish drips (ca 25 μm) (spots: Gr.01 and GrFl.02)

Table 1 continued

Painting details	Group	Fig.	Total no. OCT examination spots	OCT Main observations and layer thickness (μm)
Woll M 133 *Self-portrait*  1886, oil on canvas (33 × 24.5 cm)	1	A.1 ESM Figs. 9, 10	8	In all scanned areas, there are two transparent varnish layers The upper layer is generally thicker (ca 15–30 μm) and the lower, generally thinner (ca 5–10 μm) The red signature is located between the two layers (spot RGr.08)

Table 1 continued

Painting details	Group	Fig.	Total no. OCT examination spots	OCT Main observations and layer thickness (μm)
Woll M 148 *Flowery meadow at Veierland*  1887, oil on canvas on board (66.5 × 44 cm)	1	A.1 ESM Figs. 11, 12	10	Four layers of varnish (combined thickness 30–49 μm) in the foreground (spot Gr.04) One to two thin layers (5–7 μm) present in the blue sky

Table 1 continued

Painting details	Group	Fig.	Total no. OCT examination spots	OCT Main observations and layer thickness (μm)
Woll M 174 *Hans Jæger*  1889, oil canvas (109 × 84 cm)	1	A.1 ESM Figs. 15, 16	7	One transparent varnish layer present over the whole painted surface. Unevenly applied (spot Br.06)

Table 1 continued

Painting details	Group	Fig.	Total no. OCT examination spots	OCT Main observations and layer thickness (μm)
Woll M 224 *Night in Nice*  1891, oil on canvas (48 × 54 cm)	2	–	4	Only one varnish layer present (4-17 μm)

Table 1 continued

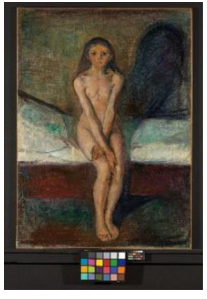
Painting details	Group	Fig.	Total no. OCT examination spots	OCT Main observations and layer thickness (μm)
Woll M 347 *Puberty*  1894/5, oil on canvas (151.5 × 110 cm)	2	Figures 2, 4; A.1 ESM Figs. 4, 5, 6	23	In most of the examined spots, there is one varnish layer (thickness usually not exceeding 20 μm) Second transparent layer identified in red drips, foreground (fig. spot R.02) Up to four locally applied transparent layers in the figure (spots: Y12-15) Some of the artist's alterations are visible in OCT (spots: Fl.04 and Y15)

Table 1 continued

Painting details	Group	Fig.	Total no. OCT examination spots	OCT Main observations and layer thickness (μm)
Woll M 348 *The Day After*  1894, oil on canvas (115 × 152 cm)	2	A.1 ESM Figs. 13, 14	20	Two varnish layers were found in most of the measured spots Semi-transparent paint was imaged in some spots as a finishing on an opaque paint layer (spots: Fl.01, Br.03, R.16 and 17, Gr.18 & 19) Previous restorations also visible

Table 1 continued

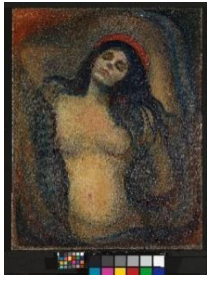
Painting details	Group	Fig.	Total no. OCT examination spots	OCT Main observations and layer thickness (μm)
Woll M 366 *Madonna*  1894, oil on canvas (90.5 × 70.5 cm)	2	Figure 5; A.1 ESM Fig. 7	10	In most of the examined spots, there are two transparent layers Three transparent layers were found in boundaries between face and hair, on top of crayon lines (spots: Bk.08, RBk.09 and 10)

Table 1 continued

Painting details	Group	Fig.	Total no. OCT examination spots	OCT Main observations and layer thickness (μm)
Woll 445 *Winter in the Woods*  1899, Oil on board (60.5 × 90 cm)	2	–	8	Two varnish layers were found in most of measured spots Artist's fingerprint (spot BrGr.05) is covered by 2 varnish layers (11–19 μm)

Table 1 continued

Painting details	Group	Fig.	Total no. OCT examination spots	OCT Main observations and layer thickness (μm)
Woll 464 *The Dance of Life*  1899-1900, oil on canvas (125 × 191)	2	Figure 6; A.1 ESM Fig. 8	28	Evidence of locally applied artist's varnish and saturation effects Drips and patches of added oil binder found (result of Munch's alterations). In some case, these have been retouched (spot R.22) The binder creates thick layers which in many cases are covered by a scattering layer, which may be ascribed to secondary restorers' attempts to even out the gloss of the surface by means of a matted varnish Blue crayon (Munch's addition) lies over a transparent layer (spot Bl.11) The dark red signature is located on top of the transparent layer (spot RBl.17)

Table 1 continued

Painting details	Group	Fig.	Total no. OCT examination spots	OCT Main observations and layer thickness (μm)
Woll M 333 *The Scream*  1893, Tempera, casein/egg, oil on unprimed cardboard (91 × 73.5 cm)	3	Figure 8; A.1 ESM Figs. 19, 20	9	Despite lack of varnish, a transparent layer is visible locally (spot Bl.05)

Table 1 continued

Painting details	Group	Fig.	Total no. OCT examination spots	OCT Main observations and layer thickness (μm)
Woll 382 *Self-portrait with Cigarette*  1895, oil on canvas (110.5 × 85.5 cm)	3	Figure 7, A.1 ESM Figs. 17, 18	9	The overall uneven surface gloss appears to be the result from locally applied semi-transparent paint layers (spot B1.04) Artist's alterations (added oil) visible (spot B1.07)

evidence of varnishes applied by the museum whilst framed.[5] *The Dance of Life* (Woll M 464) was the last motif that Munch painted for his frieze of life, summing up elements of love and the way of life [28]. Conservation dossiers record the presence of an uneven surface gloss throughout, with the possibility of a locally applied artist's varnish.[6]

3.3 Group 3: unvarnished paintings

The last category is comprised of the two iconic works, *Self-portrait with cigarette* and the first version of *The Scream,* dated 1893 (Table 1). Both paintings were chosen for comparative reasons in so far as they are unvarnished and unadulterated by previous restoration treatments.[7]

4 Results and discussion

4.1 Artist's varnish and adjustments

Munch's portrait of his 16-year-old sister, Inger, in her black confirmation dress (Woll M 113, group 1) is the earliest painting investigated in terms of production date. The realist style of the portrait has been compared to the work of the Norwegian artist Hans Heyerdahl (1857–1913) and the painting made Munch's *'international debut'* at The Antwerp International Exhibition [25]. A year later, Munch painted *The Sick Child* (group 1), which marked a turning point in the artist's career and has been described as a masterpiece [25]. Unlike his portrait of Inger, this painting created a stir at the 1886 Annual Autumn Exhibition in Kristiania (Oslo), attracting both strong criticism and praise, due to Munch's new and radical paint application [8]. The motif has been heavily reworked by Munch with deliberate scratches and scoring which break-up the texture of the thick oil paint layers. Much of the public outcry concerning the painting in 1886 was related to Munch's rough rendering of the paint surface with visible streaks of varnish running down the figures (Fig. 1a).

Conservation dossiers from 1954 record that both paintings were in poor condition after their return from the World War II evacuation sites which resulted in extensive restorations involving surface cleaning, varnish removal, lining and re-varnishing.[8] Moreover, traces of an artist's varnish had also been noted by the responsible conservator in both reports. UVA photography of *Inger Munch in Black* reveals an uneven greenish fluorescence (Fig. 3a). In addition, the visually thick, discoloured semi-transparent layers in her face further suggest the possibility of earlier resinous layers lying underneath a more recently applied restoration varnish.

In the case of *The Sick Child,* the 1886 varnish streaks which are no longer visible to the naked eye are clearly distinguishable in the UVA photograph (Fig. 1a). Furthermore, *The Sick Child* is one of the few paintings at the NaM to have undergone previous technological examinations and represents also one of the rare instances where Munch's use of a pine resin varnish has already been chemically confirmed [8].

[5] The varnish coatings stop short of the four canvas edges by approximately 5 mm and both paintings were framed by the NaM after their acquisition. NaM conservation dossiers; NG.M.00394 & NG.M.00570.

[6] NaM conservation dossier; NG.M.00941.

[7] NaM conservation dossiers; NG.M.00470 and NG.M.00939.

[8] NaM conservation dossiers; NG.M.00839 and NG.M.01862.

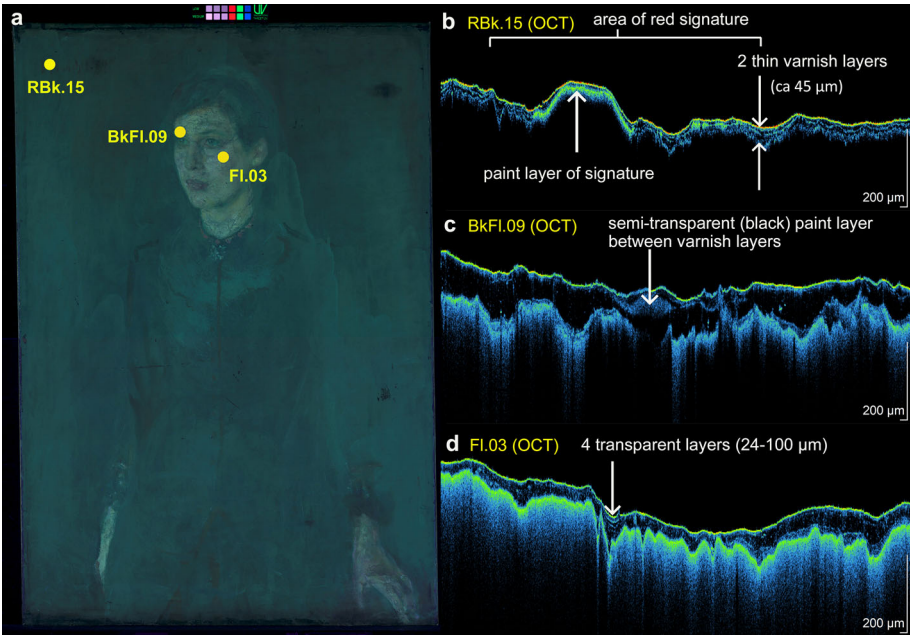


Fig. 3 *Inger Munch in Black* (Woll M 113), **a** UVA-induced fluorescence photography, **b** OCT tomogram examination spot RBk.15 (red signature under 2 varnish layers), **c** OCT tomogram examination spot BkFl.09 (right eyebrow, semi-transparent black paint, artist's alteration), **d** OCT tomogram examination spot Fl.03 (left cheek with 4 varnish layers)

The focus of the OCT examinations was thus on distinguishing between the artist's varnish layers with those applied later by the NaM. A total of twenty-two OCT scans from *Inger Munch in Black* revealed two restoration varnish layers (average total thickness, ca 45 µm) present throughout the background and lying on top of the red signature (Table 1, Fig. 1b and A.1 of ESM Fig. 1 spot RBk.15).

Compared to the background, a more complex stratigraphy of up to four layers was recorded in the face, consisting of either translucent glazes or varnish layers (Fig. 3d and A.1 of ESM, Fig. 3 spot Fl.03). Marked differences in varnish thickness were also captured with OCT corresponding to strong fluorescent boundaries around the figure of *Inger* seen in UVA (Fig. 3a). The OCT tomogram (Fig. 3c and A.1 of ESM, Fig. 2 spot BkFl.09) for *Inger's* right eyebrow captured semi-transparent black paint localised on top of a thin transparent layer but lying underneath the two restoration varnish layers. This minor retouching is most probably synonymous with Munch's own finishing touches rather than part of a later restoration.

Scans from *The Sick Child* visually confirmed the presence of the artist's transparent varnish (25 µm) lying directly under a later restoration varnish (15 µm), consistent with the previous study employing chemical analyses (Fig. 1b spot GrFl.02) [8]. The OCT tomograms also record Munch's unevenly distributed varnish over the paint surface. This suggests that he locally saturated out certain passages of paint during the process of painting. In 1928, Munch reflected on his struggles with the compositional process of the painting, *'I reworked the picture countless times in the course of a year—scratched it out'*, and *'- allowed it* [the local varnish] *to infuse the paint medium'* [25].

In summary, the OCT examinations from both *Inger Munch in Black* and *The Sick Child* were successful in locating hidden transparent layers related to the use of a locally applied artist's varnish. This new evidence supporting Munch's experimentation with surface finishes, in terms of interplay between matt and glossy passages of paint, relates closely to contemporary practices noted amongst French artists. At the end of the nineteenth century, many artists are known to have questioned the academic tradition of applying an overall varnish coating [29]. Inspired by the impressionists, a variety of techniques are documented, involving the use of either, homemade and commercial retouching varnishes, transparent glazes or mixing varnish or extra oil to paint layers for increased saturation [11, 30–32]. Likewise, there was an increase in the use of absorbent grounds and thinning of paint with diluents to create matt counter effects to glossy areas [33].

4.2 Munch's surface finishes

OCT scans taken from 23 different regions on *Puberty* (group 2), identified an even upper varnish layer present over the entire pictorial surface (20 μm), corresponding to the most recent synthetic varnish applied in 1979 (A.1 of ESM, Fig. 4). Tomograms from drips in the red foreground (A.1 of ESM, Fig. 5, spot R.02), visible in UVA fluorescence, identified a second transparent layer lying between the paint layer and the upper varnish. Reminiscent of the varnish drips in *The Sick Child*, a similar effect is also present in the Munch Museum's (MM) earlier and sketchier version of *Puberty* painted in same year (Woll M 346). Previous comparative research between the MM and NaM versions of *Puberty* concluded that there were marked differences in terms of surface finish and technique [7]. In particular, the rendering of the flesh tones in the NaM's version appears more integrated, with fewer marked boundaries between matt and glossy areas. In the MM's *Puberty*, the visible application of a localised artist's varnish denotes the relationship between different saturated passages of paint, whilst in the NaM's version, traces of any original surface saturation effect are completely masked by the later restoration varnish. However, OCT scans taken from different areas of flesh tones (Fig. 2) were able to reveal up to three additional transparent (varnish) layers beneath the upper varnish coating. These appear to be locally applied and have a total thickness range between 29 and 42 μm. Although invisible to the naked eye, these findings suggest the presence of a more layered and saturated approach present in the contours of the girl's body flesh tones than previously observed. Given that Munch painted both versions in 1894, it is plausible that they were in fact not so dissimilar in terms of the original interplay between matt and glossy surface finishes.

pXRF readings from the bright orange-red highlight in the figure of *Puberty*, identified mercury (Hg) confirming the presence of a vermilion pigment (HgS) (A.1 of ESM, Fig. 4, spots: R.28–30). However, Munch appears to have also used a synthetic red lake pigment for certain passages. The tomograms from red bed base captured a thinly applied semi-transparent paint layer (9–19 μm) lying beneath the varnish (Figs. 4a, b spot R.06). pXRF spectra from the same examination spots showed no peaks for Hg but instead, very small peaks for aluminium (Al) indicative of a red lake pigment bound to an alum substrate (Fig. 4c, and A.1 of ESM, Fig. 6) [34].[9]

Like *Puberty* and *The Day After*, the NaM's version of *Madonna* (group 2) also appears to have been exhibited in numerous international exhibitions by Munch prior to its donation to the museum in 1909 [35]. All three works were painted in 1894 with a similar palette, on

[9] Five different pXRF readings were taken from spots in the red bed base colour (R.06, R.07, R.Bl.08, R.24 & R.25). Peaks for Al were present in all readings. The paint layer is thinly applied in this passage and the dominant peaks for Pb are from the commercially prepared lead white lead ground (A.1 of ESM Fig.6).

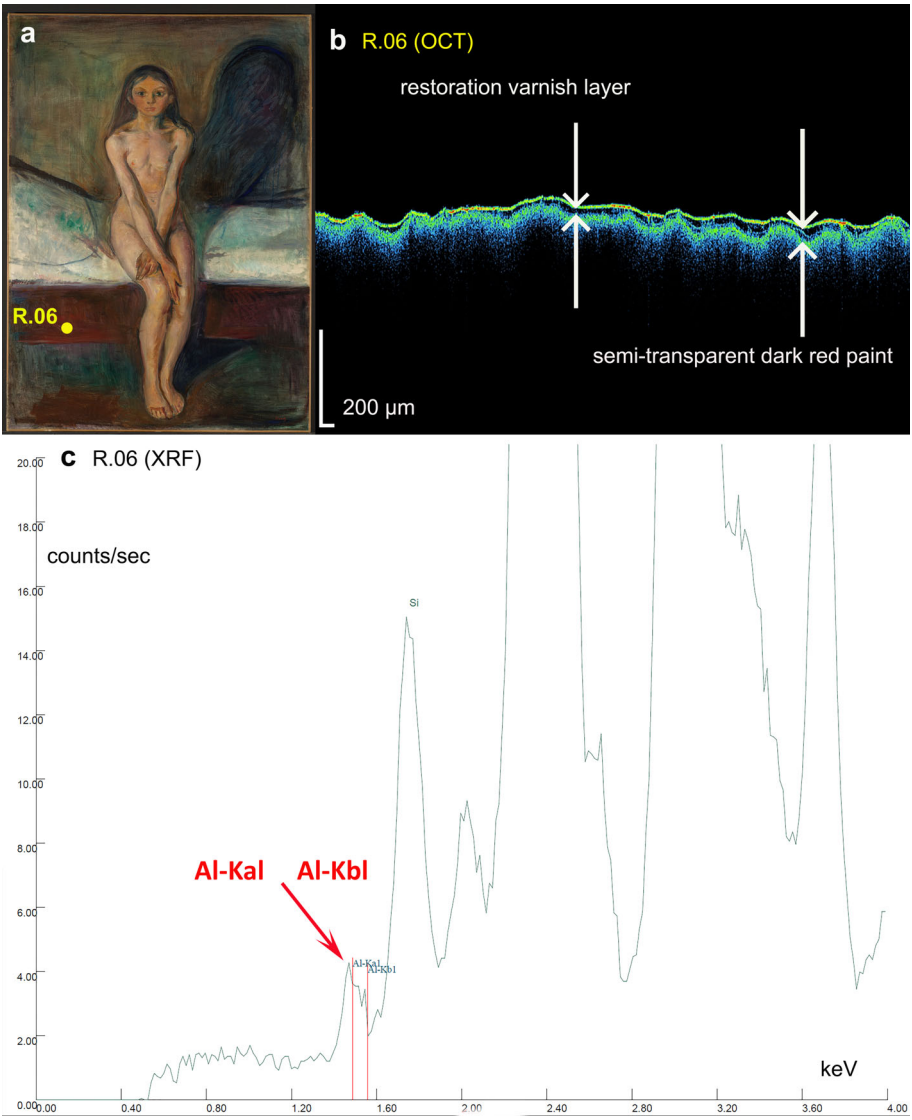


Fig. 4 *Puberty* (Woll M 347), **a** normal light photography with location of OCT & pXRF examination spot R.06, **b** OCT tomogram, examination spot R.06, **c** pXRF interval spectra (0.40–4 keV), spot R.06, showing small peaks for Al

a commercially prepared canvas with a lead white ground. Munch used the same model for *Madonna* as in *The Day After* (group 2) and there exist five similar-sized painted versions (Woll M 365, 366, 367, 368 and 369) [35]. The chronology in which Munch painted the five is uncertain, yet evidence of pentimenti (alterations to her right arm), revealed by the dark underdrawings from recent IRR examination (September 2020), supports earlier theories that the NaM's version is the first in the series (Fig. 5b) [35, 36]. As with *Puberty*, the female

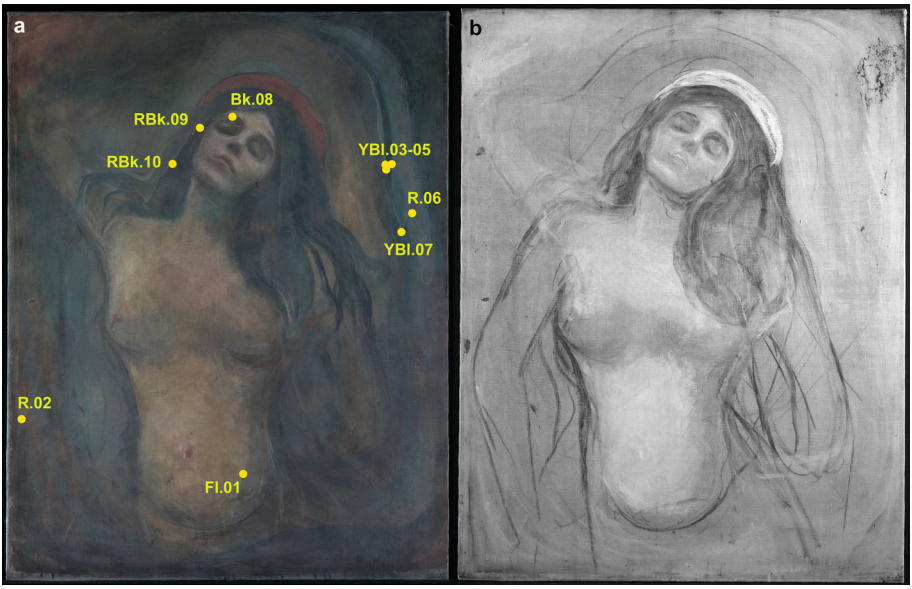


Fig. 5 *Madonna* (Woll M 366), **a** UVA-induced fluorescence photography with location of OCT spot examinations, **b** IRR image showing artist's underdrawings/contours (NaM©)

figure is painted in a relatively subdued palette employing thicker brush strokes which follow the contours and under-drawing of the figure.

Madonna's conservation history at the NaM can be traced back to 1955, and in 1968, it was wax-lined and varnished with a synthetic coating of MS2A.[10] OCT examinations revealed two restoration varnish layers present over the whole pictorial surface (Table 1). Conservation reports from 1964 also document previous restorations (localised retouches) executed with tempera colours (Couleures de Muzii LeFranc) which are clearly visible in the top right-hand corner of the IRR photograph (Fig. 5b). OCT tomograms taken from regions above the underdrawings revealed a third and lower transparent layer located beneath the two restoration varnishes and on top of the dark paint layer (Fig. 5a spots: Bk.08, RBk.09 and RBk.10 and A.1 of ESM, Fig. 7 spot RBk.10). Like *Puberty*, variations in thickness and morphology were recorded between the tomograms acquired from the three examination spots. These findings suggest the presence of locally saturated finishes along contours, as the result of either touches of a medium-rich glaze or varnish, rather than a residual oil skin.

A similar interplay between matt and glossy passages of paint can be seen in *The Dance of Life* (group 2), created by differences in paint media. Munch used a matt, dark blue crayon over the thin oil wash for the rendering of the sea in contrast to the medium-rich paint for the figures. There is an uneven distribution of UVA-induced greenish fluorescence present over the paint layers in some of the figures and the foreground (A.1 of ESM, Fig. 8). Like Madonna, there is IRR evidence of Munch's preparatory dark under-drawing. Furthermore, a solvent etched paint effect (paint thinned with turpentine) remains in the upper region of the red dress and yellow drips are clearly visible running halfway down the back of the white dress in the right figure. OCT examinations confirmed a complex surface topography. Thick transparent layers (34–84 μm), corresponding to the visible yellow drips in the white dress seen in the

[10] NaM conservation dossier; NG.M.00841.

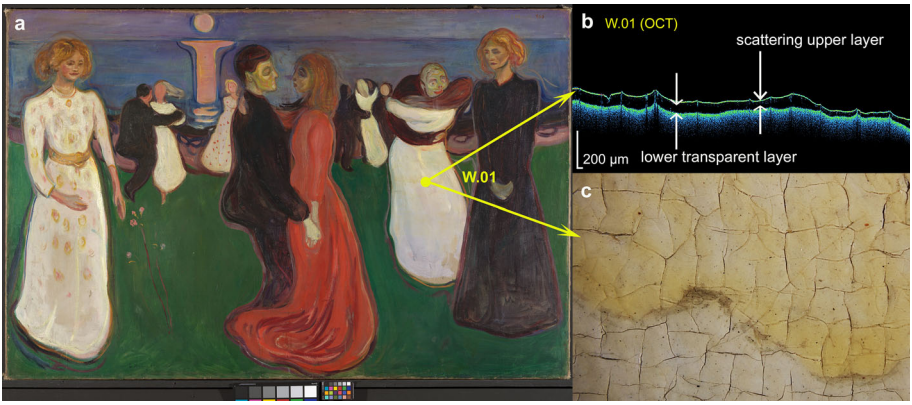


Fig. 6 *The Dance of Life* (Woll M 464), **a** normal light photography with location of OCT examination spot, **b** OCT tomogram examination spot W.01, **c** microscope detail of yellow drip, spot W.01 (Hirox, normal light, 20 ×, FOV 15,155.01 µm, resolution 7.89 µm)

Hirox microscope image, are also clearly visible in the OCT tomograms (Fig. 6b-c). Given their yellow colouring in UVA, these could be associated with an excess of oil medium rather than an artist's varnish. In some cases, these thicker layers lie beneath a thinner scattering layer (10–17 µm), indicative of the later and locally applied matt restoration varnish with a wax content.[11] In contrast, both the dark red signature and the blue crayon, top right, appear to lie over a greenish fluorescing transparent layer (artist's varnish). Furthermore, many of the red, blue and green pigmented paint layers were found to be semi-transparent to the OCT infrared radiation. This suggests that Munch also manipulated the translucency of his paints in certain passages to create variations in saturation.

OCT was successful in visually capturing the disparity in the varnish stratigraphy present in each painting in terms of the mismatch between restoration interventions (matting down of glossy drips and complete varnishing of the paint surfaces) and the surface effects envisaged by Munch. The evidence of the artist's interplay between saturation and gloss brings a new and invaluable understanding about Munch's paintings that will help make informed conservation choices in the future.

4.3 Restoration varnishes and former cleaning treatments

OCT was also employed to understand and locate past restorations and restoration varnishes that remain undocumented in the NaM's archives. For example, there exist no past conservation records for Munch's small *Self-portrait* (Woll M 133, group 1) acquired by the NaM in 1938, yet the canvas has been wax-lined at some point in time. Furthermore, the uniform greenish fluorescence present over the whole surface under UVA examination is indicative of a varnish coating (A.1 of ESM, Fig. 9). The portrait dates from the same period as *The Sick Child* and has a similar paint technique, thickly applied, raised impasto, scratches, scoring and the additional traces of the use of a palette knife (see Sect. 3.1, group 1 and Table 1). OCT was successful in quickly establishing the presence of two distinct transparent layers over the whole surface. A relatively evenly distributed upper layer (average thickness, 16–24 µm) corresponds to the evenly distributed top restoration varnish seen in UVA. However, there are

[11] Partial varnishing and matting of glossy drips were carried out during the 1958 restoration. NaM conservation dossier; NG.M.00941.

marked differences in thickness between the flesh paint (average thickness, 12–18 μm) and the background (average thickness, 7–9 μm) in the lower transparent layer. These variations could be assigned to a selective cleaning of the background in conjunction with the previously mentioned lining. Furthermore, OCT tomograms from the signature (A.1 of ESM, Fig. 10, spot RGr.08) revealed it to be lying on top of the lower transparent layer. This suggests that the first varnish was most probably applied by the artist. Given the comparative evidence from the OCT tomograms combined with similarities in painting technique, it is probable that Munch's *Self-portrait* could have originally had a similar surface finish to *The Sick Child*, in terms of glossy effects from an artist's varnish.

If left undocumented, the specifics of past cleaning and selective cleaning in terms of varnish removal can be difficult for a conservator to establish based solely on UVA photography of paint surfaces. Equally, there are practical and ethical limitations with micro-destructive samples for cross-sectional analysis of varnish stratigraphy. In the case of *Flowery meadow at Veierland* (Woll M 148, group 1), the benefits of OCT facilitated an understanding of the distribution of the various transparent layers. The small plein-air study was painted in the summer of 1887, whilst Munch was residing on the island of Veierland, south of Oslo. Like the four other paintings from group 1, Munch's paint during the 1880s is relatively thickly applied with many areas of impasto (Sect. 3.1 and Table 1). Recent chemical analysis confirmed the presence of an upper varnish coating of Laropal K 80 which is also noted in the treatment record from 1983 [10]. However, OCT examinations identified up to four layers of varnish (combined thickness 30–49 μm) in the foreground (A.1 of ESM, Figs. 11, 12 spot Gr.04) compared with only 1–2 thin layers (5–7 μm) present in the blue sky. The information retrieved from the OCT tomograms thus gives a more precise insight into the spatial locations of past and undocumented restorations and highlights the complexity of multiple varnished-layered regions.

The NaM's controversial varnishing of two paintings from group 2 (1890–1900) *Puberty* and *The Day After* is well documented in the Norwegian press of 1909 (Table 1, and group 2) [27]. Both paintings were purchased by the NaM in 1909 from Munch. Painted in Berlin, The *Day After* (A.1 of ESM, Fig. 13) remained in the artist's possession since its creation in 1894 and travelled to no less than nineteen exhibitions [35]. The international travel and handling of the painting appear to have taken a toll on the painting's condition. Prior to its acquisition, a letter addressed to Munch from the museum's conservator, Harald Brun (employed 1905–1921) commented on the need for restoration [37]. The canvas was described with several holes which had been badly filled and poorly retouched by Munch and without a proper colour match to the surrounding area. In addition, Brun recommended cleaning and varnishing. Since its acquisition, the painting has been restored several times at the NaM and has a history of unstable paint.[12] When selecting suitable spots for OCT, care was taken to identify areas of past and existing restorations with regions remaining relatively untouched apart from varnishing. In most of the OCT scans, two distinct varnish layers were detected, both lying over Munch's red signature. These findings suggest the presence of two restoration varnishes with the possibility of the lower layer being Brun's controversial 1909 varnish. OCT was also able to detect semi-transparent paint layers present beneath the two varnish layers in the cracked deep red and green bottles (A.1 of ESM, Fig. 14). This is indicative Munch's use of lake pigments as suggested in the findings from *Puberty* (Fig. 4).

OCT was also used to correlate varnish treatments noted in past conservation dossiers with the physical paint surfaces and to check for any inconsistencies. Only one treatment

[12] The painting underwent major structural treatments in 1909 & 1956 and remedial treatments between 1986–2012. NaM conservation dossier; NG.M.00808.

record from 1954 survives for Munch's portrait of the bohemian writer and critic, *Hans Jæger* (Woll M 174, group 1).[13] It describes a glue-paste lining, cleaning and varnishing with mastic. The OCT tomograms confirmed the presence of a single varnish layer with no evidence of residual transparent layers. Large variations in layer thickness, concentrated in the recesses surrounding areas of impasto (52–75 μm) and resulting in an uneven distribution of the varnish, are perhaps indicative of a brushed application of varnish over an undulated surface (A.1 of ESM, Figs. 15, 16).

The inconsistency between written conservation records (two varnish layers) and the actual physical state of the varnish (one layer) on the painting *Night in Nice* was discovered in a recent study that employed various analytical methods [10]. Only one thin transparent varnish layer (average thickness, 4–17 μm) instead of the documented two was also confirmed, over the whole painted surface with OCT (Table 1). This highlights the usefulness of OCT as a viable non-invasive diagnostic screening tool for entire painted surfaces.

4.4 Unvarnished paintings

Self-portrait with cigarette (group 3) represents a rare example of an oil paint surface that appears to have evaded restoration and conservation interventions since its acquisition from the artist in 1895.[14] Notwithstanding the ageing processes inherent in painting's materials, which have altered the original visual effect, Munch's paint surface remains physically intact. UVA and reflected light photography reveal an uneven and locally distributed glossy residue over the surface (Fig. 7a). The paint technique varies from thicker brushstrokes used for the face and hands, combined with a diluted wash employed in the dark blue background. Paint, possibly thinned with turpentine, has dripped vertically down the canvas and along the bottom tacking margin (Fig. 7d). The OCT imaging identified a technique involving the application of local glazes with semi-transparent paint layers, resulting in marked differences between glossy finishes and the matter diluted paint. Residues of excess oil were also detected suggesting that Munch manipulated the medium to achieve the variations in gloss and saturation rather than adding a local varnish (Figs. 7b-c and A.1 of ESM, Figs. 17, 18).

The fragile and absorbent nature of *The Scream's* (group 3) paint media and unprimed cardboard support probably explains why earlier restorers refrained from varnishing the painting. Having abandoned a first sketch to the reverse, Munch flipped the board over and repainted *The Scream* motif using, matt tempera-based paints containing casein, egg and some drying oil [38]. Since the donation of the painting to the NaM in 1910, by the wealthy patron Olav Schou, the paint surface has retained Munch's reparations, alterations and early candlewax deposits, previously thought to be bird excrement (Figs. 8a–c and A.1 of ESM, Figs. 19, 20) [39]. Despite the lack of an overall varnish, a locally applied transparent layer is visible in the blue passages (fjord) with OCT (Figs. 8b and A.1 of ESM, Fig. 19 spot Bl.05). This surface coating varies in thickness and has also been identified as a main source of colour change in a recent micro-lightfastness study (MFT) [40].

5 Conclusion

The application of OCT on 13 paintings belonging to the NaM has been proven as a valuable non-invasive methodology to clarify hidden complexities and diversities between original

[13] NaM conservation dossier; NG.M.00485.

[14] NaM conservation dossier; NG.M.00470.

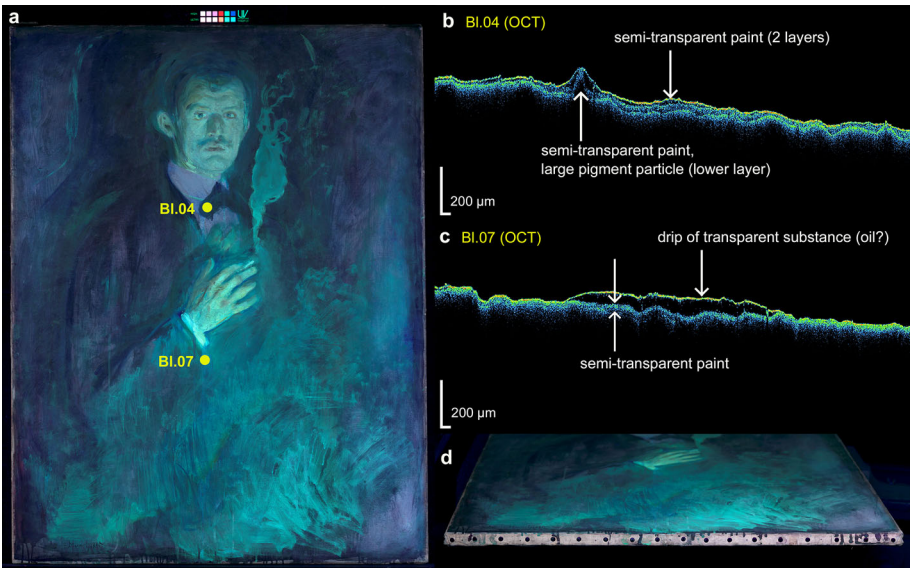


Fig. 7 *Self-portrait with cigarette* (Woll M 382) **a** UVA-induced fluorescence photography, **b** OCT tomogram examination spot Bl.04 (evidence of semi-transparent paint layers/glazes), **c** OCT tomogram examination spot Bl.07 (residues of excess oil), **d** lower tacking margin edge with drips from thinned paint (UVA)

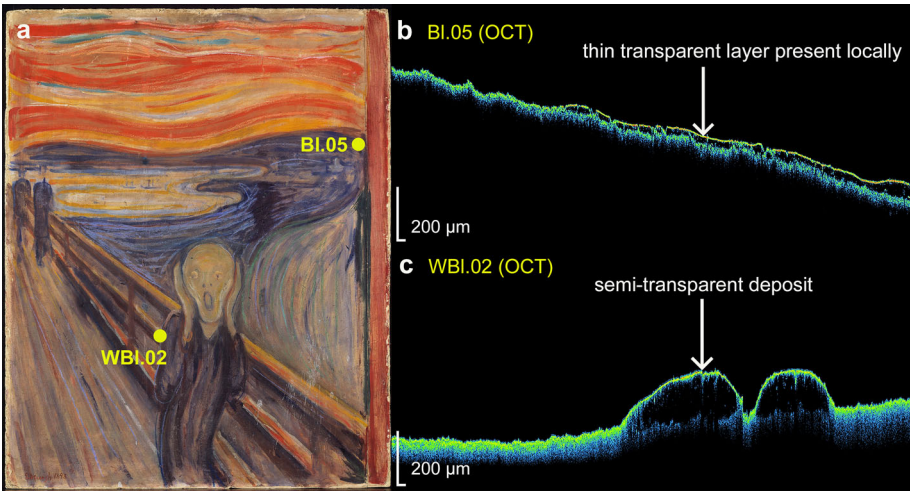


Fig. 8 *The Scream* (Woll M 333) **a** normal light photography, **b** OCT tomogram examination spot Bl.05 (evidence of locally applied transparent layer), **c** OCT tomogram examination spot WBl.02 (candlewax deposit)

and secondary varnish layers present across three groups of Munch paintings dating from 1884 to 1900. This information is of paramount importance when translated to the visual relationship of these works displayed as a group regarding future preservation and restoration strategies.

OCT tomograms revealed the presence, thickness and the precise location of locally applied artist's varnish layers and/or transparent glazes in seven artworks; *Inger Munch in Black, The Sick Child, Puberty, Madonna, The Dance of Life, Self-portrait with Cigarette and The Scream.* Despite the documentary uncertainty concerning Munch's own attitude towards varnishing, the present findings highlight the high suitability of OCT as a non-invasive diagnostic technique for mapping transparent paint layers at the painting surface. OCT analyses of *Puberty, Madonna* and *The Dance of Life* give an important insight into Munch's varied paint technique and the intricate surface qualities lying beneath the NaM's application of later restoration varnishes. This finding has important art historical implications when evaluating Munch's early painting technique, in terms of surface finish and interplay between saturated and glossy passages of paint contrasted against matt areas. Until now, this surface effect has been previously misunderstood with the past restoration varnishing and toning down of the glossy areas in paintings, such as *The Dance of Life*. In all but two cases, the Munch's original though aged surface effects are no longer visible, nor can be retrieved, but the results of this research allow for a more informed assessment of the intended appearance as a basis for deciding conservation and lighting strategies. Furthermore, the OCT results clearly unveiled variations and discrepancies in the conservation varnish history within the group.

Several of the OCT tomograms recorded an uneven distribution of varnish layers and spatial location of Munch's adjustments. This further underlies the non-invasive technique's success in supplying a more realistic overview of varnish layers across an entire paint surface. Nevertheless, there are several practical challenges with the portable SdOCT equipment in terms of the limited and small surface scanning area (12×12 mm) combined with the post-processing of large image data files. Moreover, OCT remains essentially a diagnostic method for the stratigraphic visualisation of the uppermost transparent and semi-transparent layers. This is due to the use of near-infrared radiation (750–950 nm), close to the visible, limiting the imaging to surface layers since most paint layers strongly absorb the probing light in this spectral range. This makes it difficult to detect the extent of possible varnish penetration into the ground or paint layers underneath.

Notwithstanding these impediments, the complementary information gained from OCT scans in this study, combined with historical records, UVA, IRR, and pXRF have revealed new insights concerning Munch's technique and surface effects on paintings created between 1884 and 1900.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1140/epjp/s13360-021-01758-5.

Acknowledgements The authors are grateful to the National Museum of Art, Norway, for full access to the paintings. The authors would also like to thank Børre Høstland for assistance with the UVA and IRR and photography.

Authors' contributions TF contributed to conceptualization, investigation, data curation, interpretation, resources, writing—original draft, writing—review and editing, visualisation. MI was involved in investigation, data interpretation—OCT, writing—review and editing. EP and EH contributed to supervision, writing—review and editing. PT was involved in investigation, data curation—OCT, resources, writing—review and editing.

Funding Open access funding provided by University of Oslo (incl Oslo University Hospital). The project is part of Thierry Ford's PhD study which is fully funded by the National Museum of Art, Norway.

Availability of data and materials Raw data are available from the authors on request.

Declarations

Competing interests The authors declare that they have no competing interests.

Data Availability Statement This manuscript has associated data in a data repository. [Authors' comment: The additional raw data that support the findings will be made available following a (6 month) embargo after the completion of the PhD program (2022/23).].

References

1. S. Willoch, Nasjonalgalleriet gjennom hundre år (Gydendal, Oslo, 1937, Oslo)
2. N. Messel, Kunst og Kultur. A **95**, 4 (2012)
3. M. Stein, J. Rød, in Public paintings by Edvard Munch and his contemporaries. Change and conservation challenges, ed. T. Frøysaker et al. (Archetype, London, 2015), pp. 257–270
4. B. Topalova-Casadiego, in Edvard Munch Samlede Malerier Catalogue Raisonne Vol II., (Cappelen Damm, Oslo, 2008), pp. 425–458
5. B. Singer et al., Stud. Conserv. A **55**, 4 (2013)
6. J. Wardius, in Public paintings by Edvard Munch and his contemporaries. Change and conservation challenges, ed. T. Frøysaker et al. (Archetype, London, 2015), pp. 39–51
7. B. Topalova-Casadiego, in Puberty, ed. I. Ydstie, (Orfeus, Munch Museum, Oslo, 2012), pp. 66–84
8. T.E. Aslaksby, in The Sick Child: The Story of a Masterpiece, (Nasjonalmuseet for kunst, arkitektur og design, Oslo, 2009), pp. 135–155
9. Frøysaker, T., Zeitschrift für Kunsttechnologie und Konservierung, A 30 (2016)
10. T. Ford et al., Herit. Sci. A **7**, 1 (2019)
11. L. Carlyle, *The Artist's Assistant : Oil Painting Instruction Manuals and Handbooks in Britain 1800–1900, with Reference to Selected Eighteenth-Century Sources* (Archetype, London, 2001)
12. T. Ford, An integrated conservation approach to a historic collection: The controversial varnishing of Munch's paintings. 19th ICOM-CC Triennial Conference, (Beijing, 2021).
13. P. Targowski et al., Acc. Chem. Res. A **43**, 6 (2010)
14. H. Liang et al., Opt. Exp. A **13**, 16 (2005)
15. M. Iwanicka, M. Sylwestrzak, P. Targowski, in Advanced Characterization Techniques, Diagnostic Tools and Evaluation Methods in Heritage Science, ed. D.M. Bastidas and E. Cano (Springer, Cham, 2018) pp. 49–59
16. M. Iwanicka, et al., Microchem. J. A 138 (2018)
17. P. Targowski, M. Iwanicka, Appl. Phys. A-Mater. Sci. Process. A. **106**, 2 (2012)
18. R. Fontana et al., Appl. Phys. A-Mater. Sci. Process. A **122**, 3 (2015)
19. A.J. DeCruz, J. Izatt, D. Nankivil. Proceedings of the 4th International Conference on Photonics, Optics and Laser Technology (PHOTOPTICS, 2016)
20. J. Dyer, G. Verri, J. Cupitt, Multispectral Imaging in Reflectance and Photo-induced Luminescence modes: A User Manual (CHARISMA, The British Museum, 2013) p. 192
21. P. Targowski, et al., OCT for examination of cultural heritage objects, in Optical Coherence Tomography and Its Non-medical Applications (IntechOpen, 2020) https://www.intechopen.com/books/optical-coherence-tomography-and-its-non-medical-applications/oct-for-examination-of-cultural-heritage-objects. Accessed 19 October 2020
22. I.L. Langaard, *Edvard Munch: Modningsår: En Studie i Tidlig Ekspresjonisme Og Symbolisme* (Gyldendal, Oslo, 1960)

23. S. Biørnstad et al., *Munch Og Frankrike: Paris, Musée d'Orsay 24 Sptember 1991–5 Januar 1992, Oslo, Munch-Museet 3 Februar - 21 April 1992* (Munch-museet, Oslo, 1991)
24. E. Mørstad, Edvard Munch : formative år 1874–1892 : norske og franske impulser Universitetet i Oslo, Det humanistiske fakultet, Institutt for filosofi, ide- og kunsthistorie og klassiske språk, 2016, unpublished
25. Ø. Ustvedt et al., The Sick Child: The Story of a Masterpiece, (Nasjonalmuseet for kunst, arkitektur og design, Oslo, 2009), pp. 105–134
26. I. Owesen, in Edvard Munch: 1863–1944, ed. M.B. Guleng, B. Sauge, J.-O. Steihaug (Skira: Milano, 2013), pp. 296–305
27. J. Nilssen, *In Dagens Nyt* (Christiania, Norway, 1909)
28. E. Mørstad, Kunst og Kultur A 3 (2004)
29. M. Swicklik, Stud. Hist. Art A 41 (1993)
30. L. Mayer, G. Myers, J. Am. Inst. Conserv. A **32**, 2 (1993)
31. A. Callen, Burlington. Magazine A 136 (1994)
32. M. Jooren, in Van Gogh's studio practice, ed. M.G. Marije Vellekoop, et al. (Mercatorfonds, Yale University Press: Amsterdam; Brussels; New Haven, 2013), p. 290–305
33. A. Hoenigswald, Zeitschrift für Kunsttechnologie und Konservierung A **22**, 2 (2008)
34. J.S. Ferrer, et al., in Conservation of Modern Oil Paintings, ed. K.J. van den Berg, et al., (Cham: Springer International Publishing, 2020) pp. 209–218
35. G. Woll, *Edvard Munch Samlede Malerier Catalogue Raisonne*, vol. I (Cappelen Damm, Oslo, 2008)
36. R. Heller, *Munch: His Life and Work* (John Murray, London, 1984)
37. H. Brun, The National Museum of Art, Norway, Archives, Nasjonalgalleriet, Johannes Rød, forskerarkiv, E-0002, 1909, unpublished
38. T. Aslaksby, in Public paintings by Edvard Munch and his contemporaries. Change and conservation challenges, ed. T. Frøysaker et al. (Archetype, London, 2015), pp. 52–71
39. G. Van der Snickt, MA-XRF scanning of The Scream. Solving a Cold Case: the Bird Droppings Mystery (AXES, University of Antwerp, 2016) https://www.uantwerpen.be/en/research-groups/axes/x-ray-spectroscopy-and-imaging/research—funding/chair-for-the-arts/research-activities/the-scream-by-e–mun/. Accessed 19 October 2020
40. J. Thomas, The Scream, E. Munch in the collection of the National Museum in Oslo (NG.M.00939, Woll M 333) Micro lightfastness testing and lighting policy generation, 2020, unpublished

A.1 Supplementary figures and OCT tomograms

Munch and optical coherence tomography. Unravelling historical and artist applied varnish layers in painting collections.

The European Physical Journal Plus

Thierry Ford[1,2a], Magdalena Iwanicka[3], Elena Platania [2,4], Piotr Targowski [5], Ella Hendriks[6]

[1]The National Museum of Art, P.O. Box 7014, St. Olavs Plass, 0130, Oslo, Norway.

[2] Department of Archaeology, Conservation and History (IAKH), University of Oslo (UiO), Conservation Studies, Postboks 1008 Blindern, 0315 Oslo, Norway.

[3] Department for Conservation and Restoration of Paintings and Polychromed Sculpture, Faculty of Fine Arts, Nicolaus Copernicus University, ul. Gagarina 7, 87-100 Toruń, Poland.

[4] Hylleraas Centre for Quantum Molecular Sciences, Department of Chemistry, University of Oslo, Post Box 1033 Blindern, 0315 Oslo, Norway.

[5] Institute of Physics, Nicolaus Copernicus University. ul. Grudziadzka 5, 87-100 Toruń, Poland.

[6] Programme Conservation and Restoration of Cultural Heritage,University of Amsterdam (UvA), Johannes Vermeerplein 1, 1071 DV, Amsterdam, Netherlands.

[a]corresponding author. thierry.ford@nasjonalmuseet.no

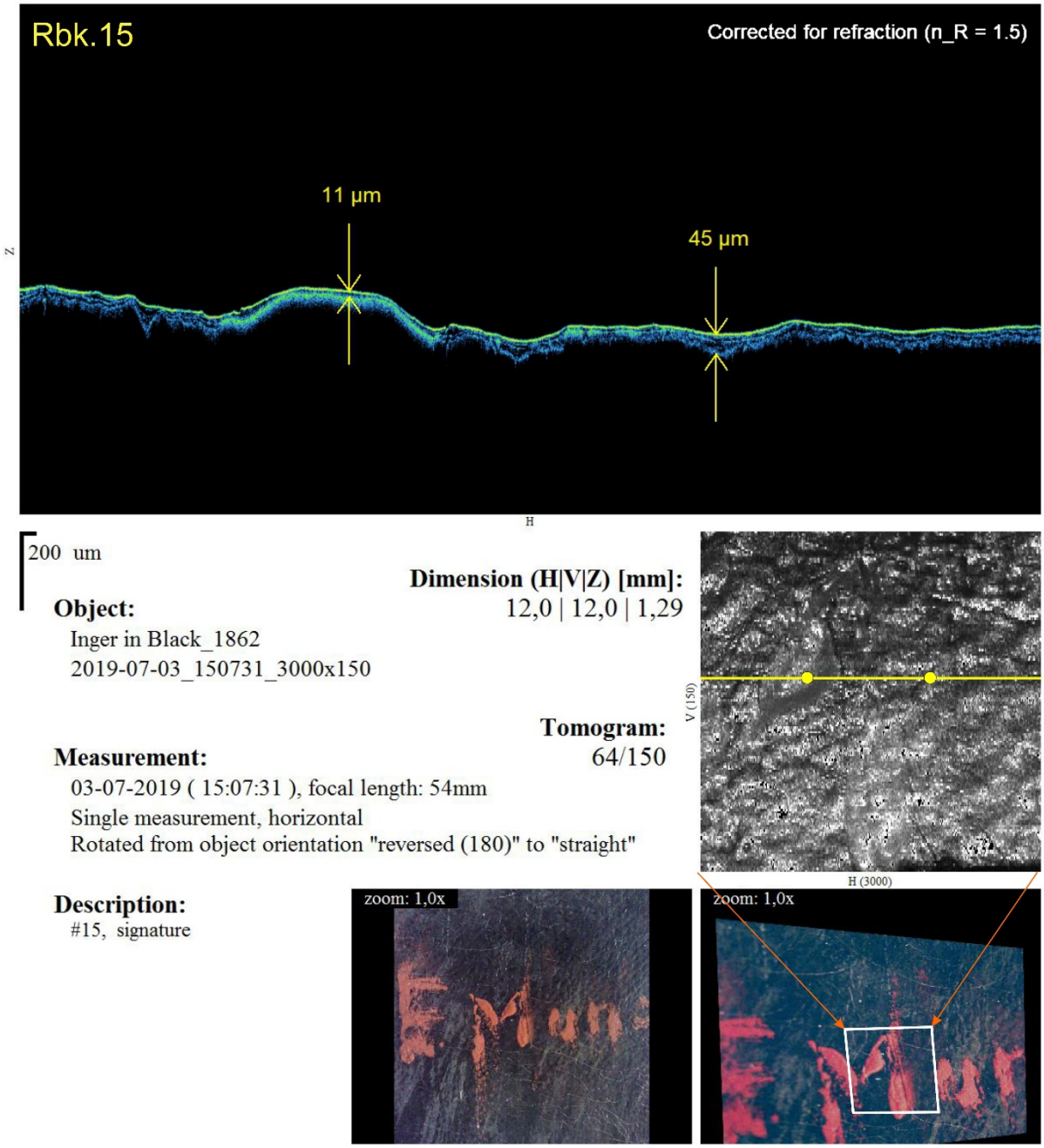


Fig. 1 *Inger Munch in Black* (Woll M 113), OCT tomogram and IR reflectogram from examination spot RBk.15 (red signature under 2 varnish layers)

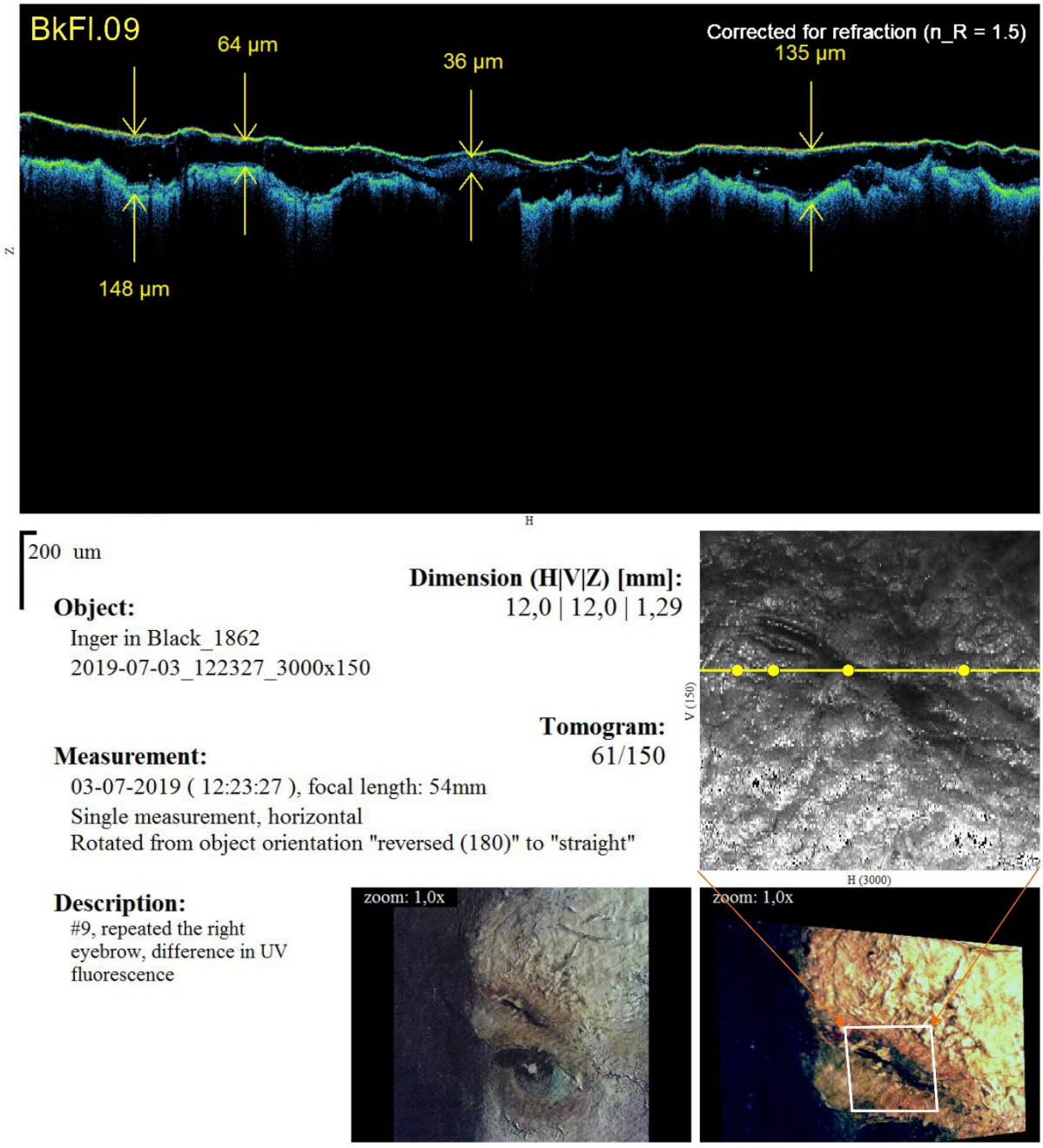


Fig. 2 *Inger Munch in Black* (Woll M 113), OCT tomogram and IR reflectogram from examination spot BkFl.09 (right eyebrow, semi-transparent black paint, artist's alteration)

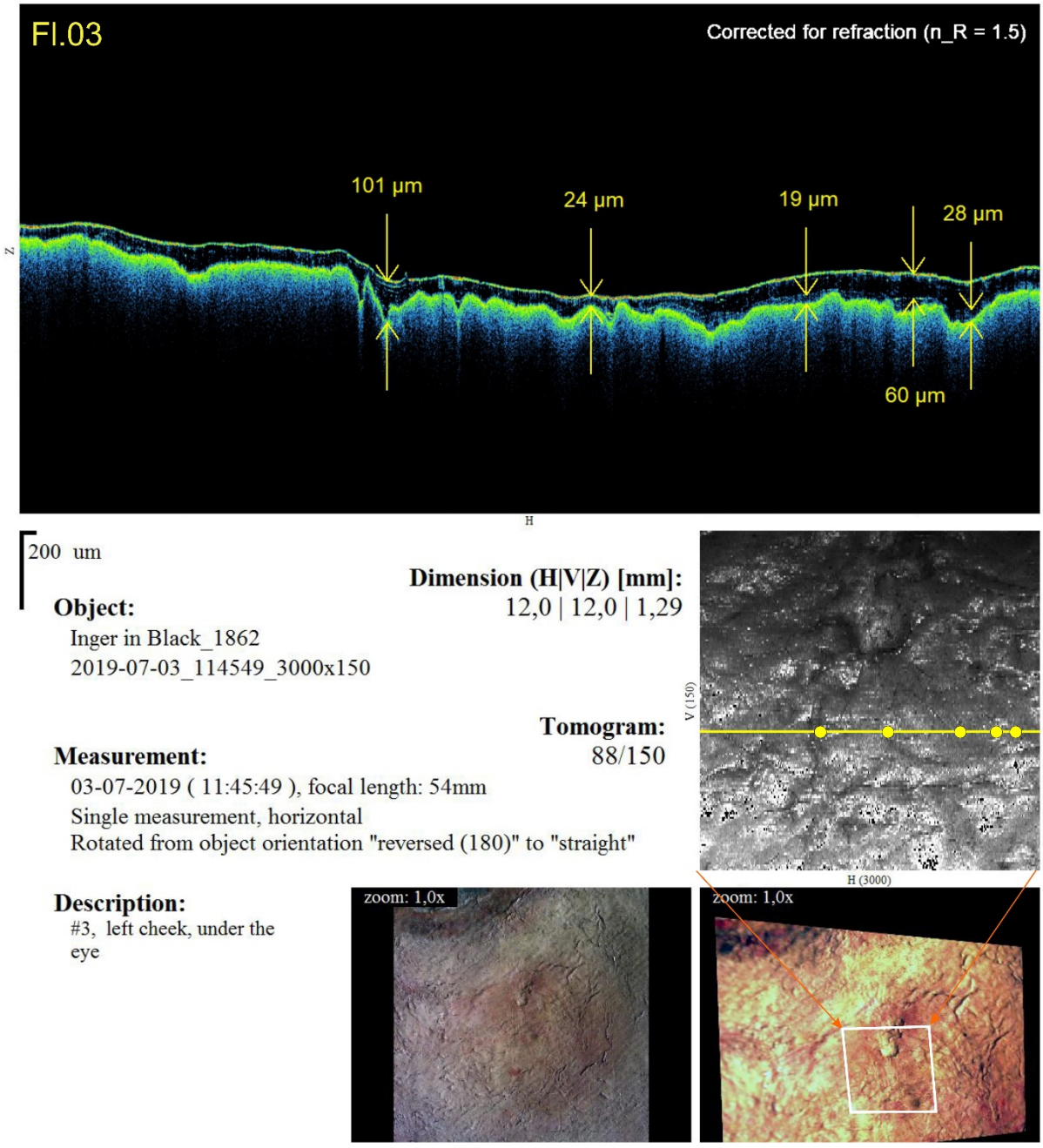


Fig. 3 *Inger Munch in Black* (Woll M 113), OCT tomogram and IR reflectogram from examination spot Fl.03 (left cheek with 4 varnish layers)

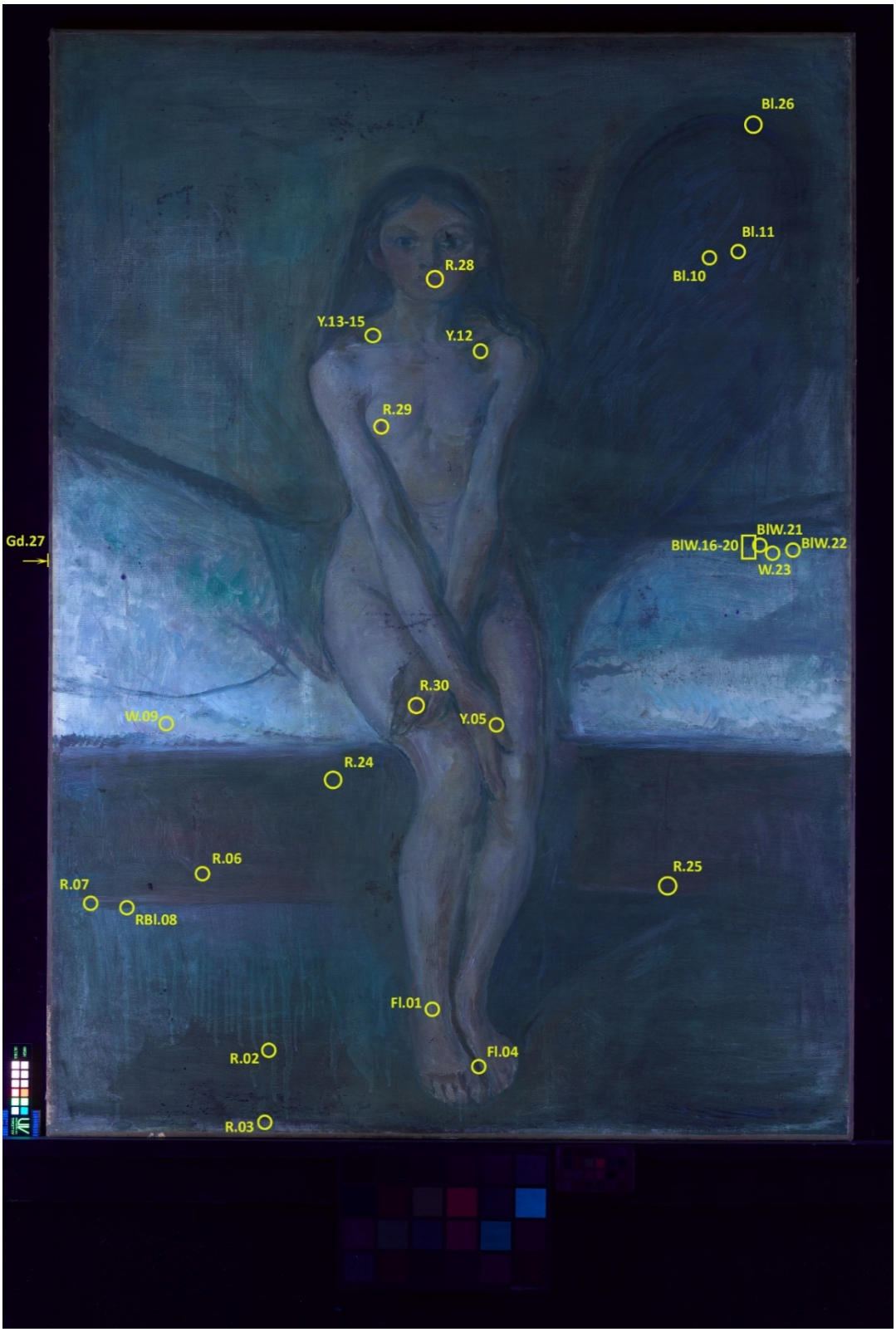


Fig. 4 *Puberty* (Woll M 347), UVA-induced fluorescence photography with location of OCT & pXRF examination spots

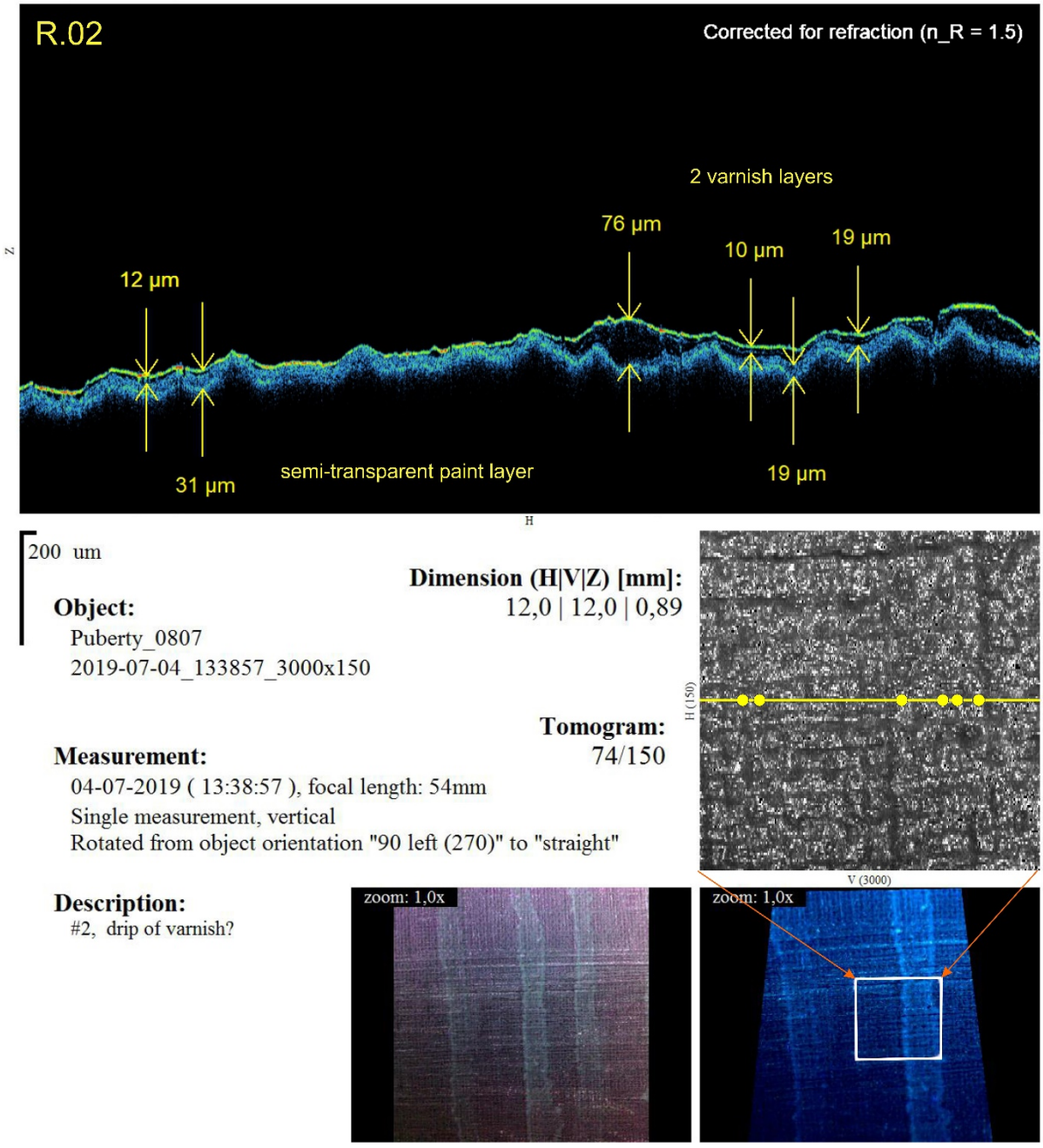


Fig. 5 *Puberty* (Woll M 347), OCT tomogram and IR reflectogram from examination spot R.02 (second transparent layer identified in drips in the red foreground)

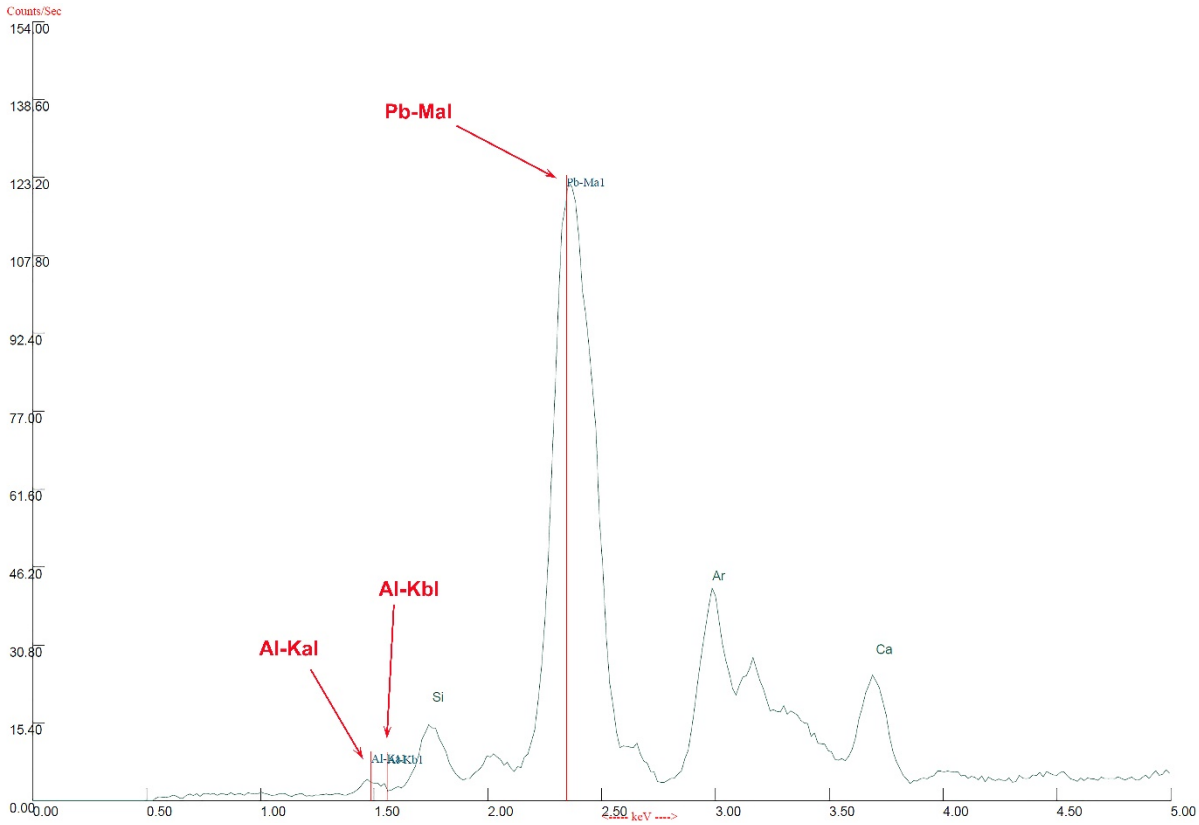


Fig. 6 *Puberty* (Woll M 347), XRF full spectra, spot R.06. The paint layer is thinly applied in this passage and the dominant peaks for Pb are from the commercially prepared lead white ground

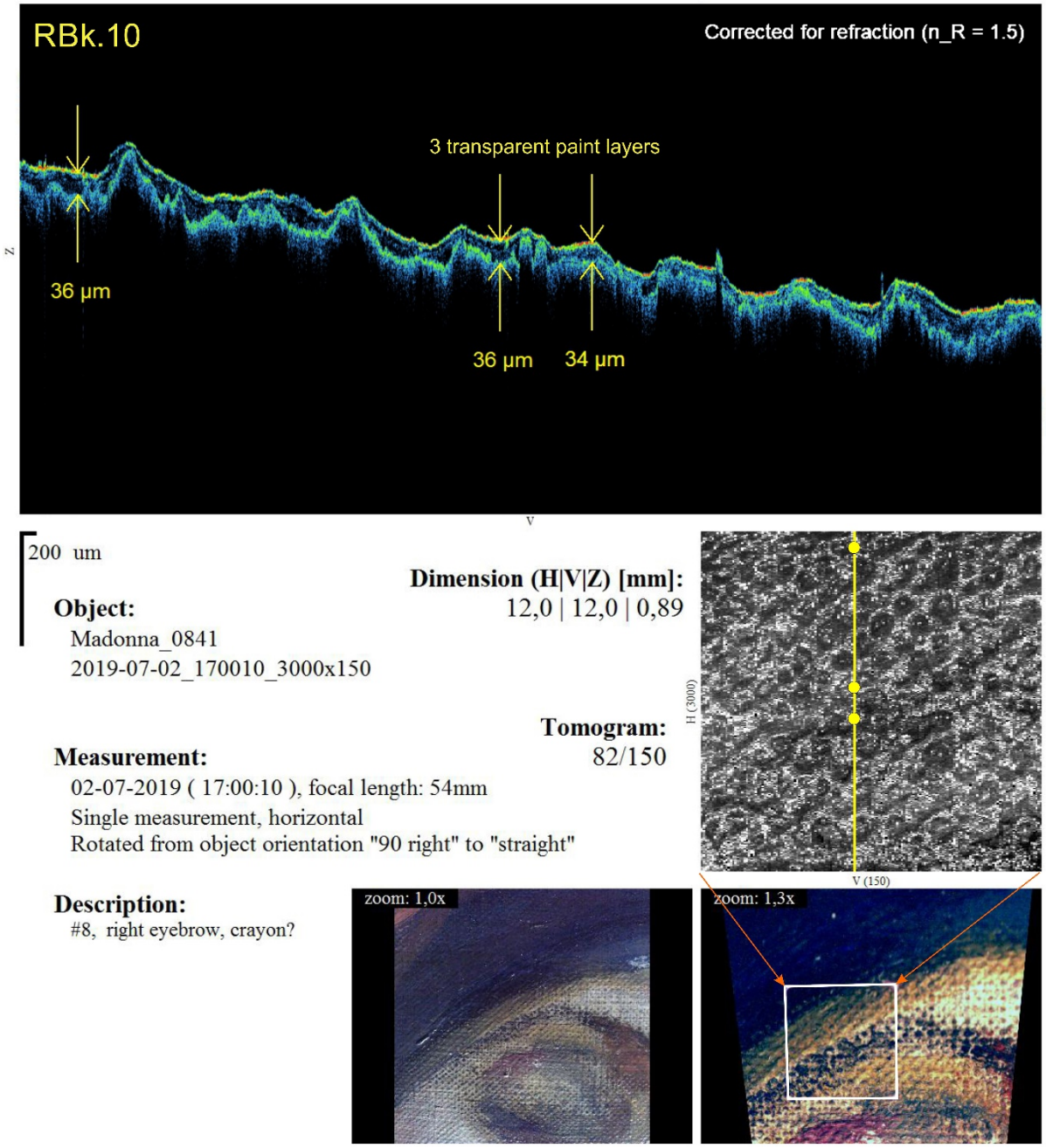


Fig. 7 *Madonna* (Woll M 366), OCT tomogram and IR reflectogram from examination spot RBk10 (lower transparent layer located beneath upper two restoration varnishes and on top of the dark contours)

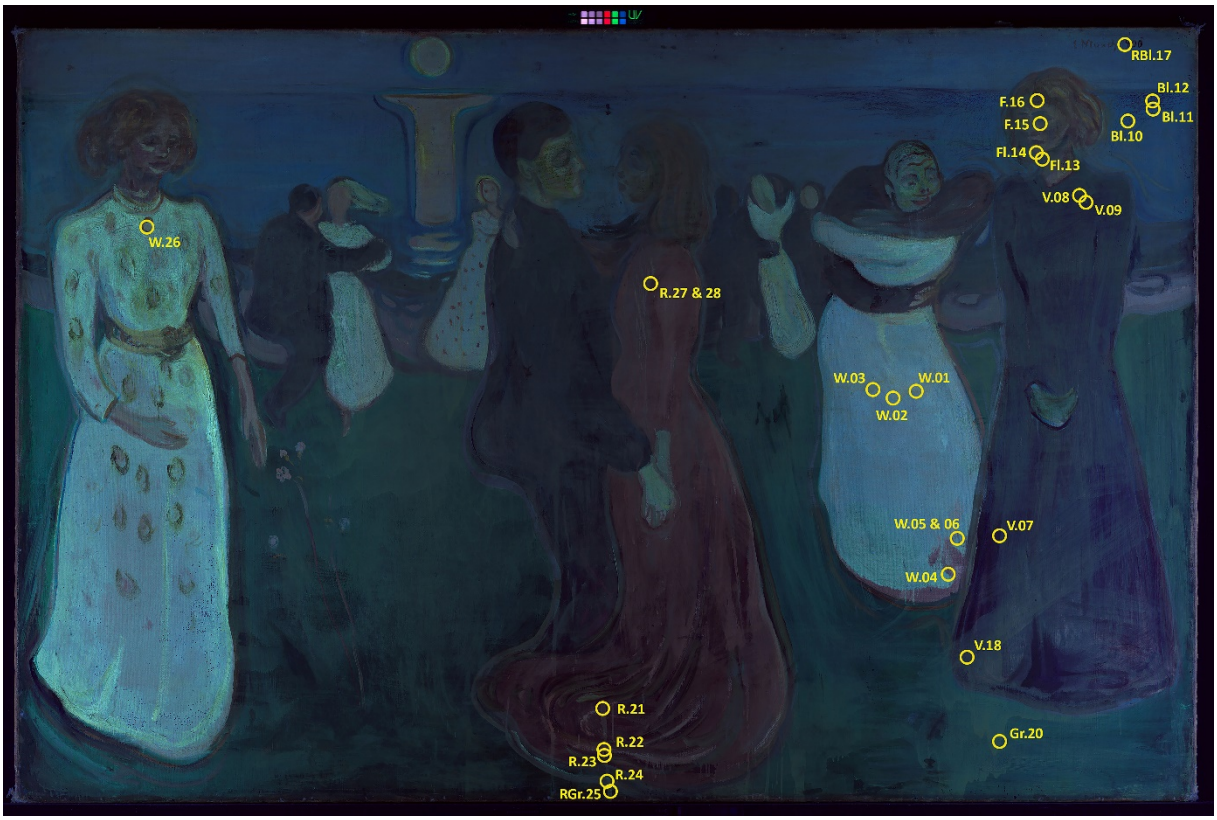


Fig. 8 *The Dance of Life* (Woll M 464), UVA-induced fluorescence photography with location of OCT examination spots

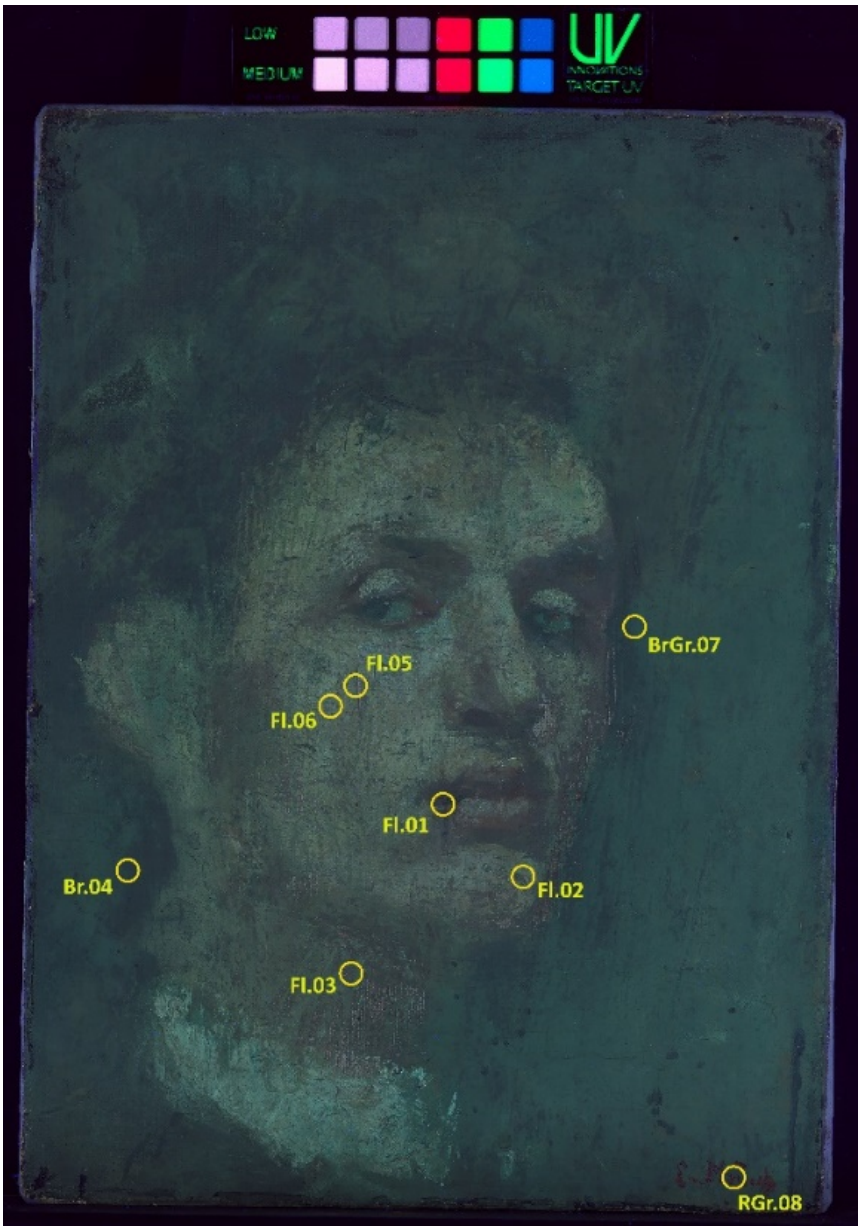


Fig. 9 *Self-portrait* (Woll M 133), UVA-induced fluorescence photography with location of OCT examination spots

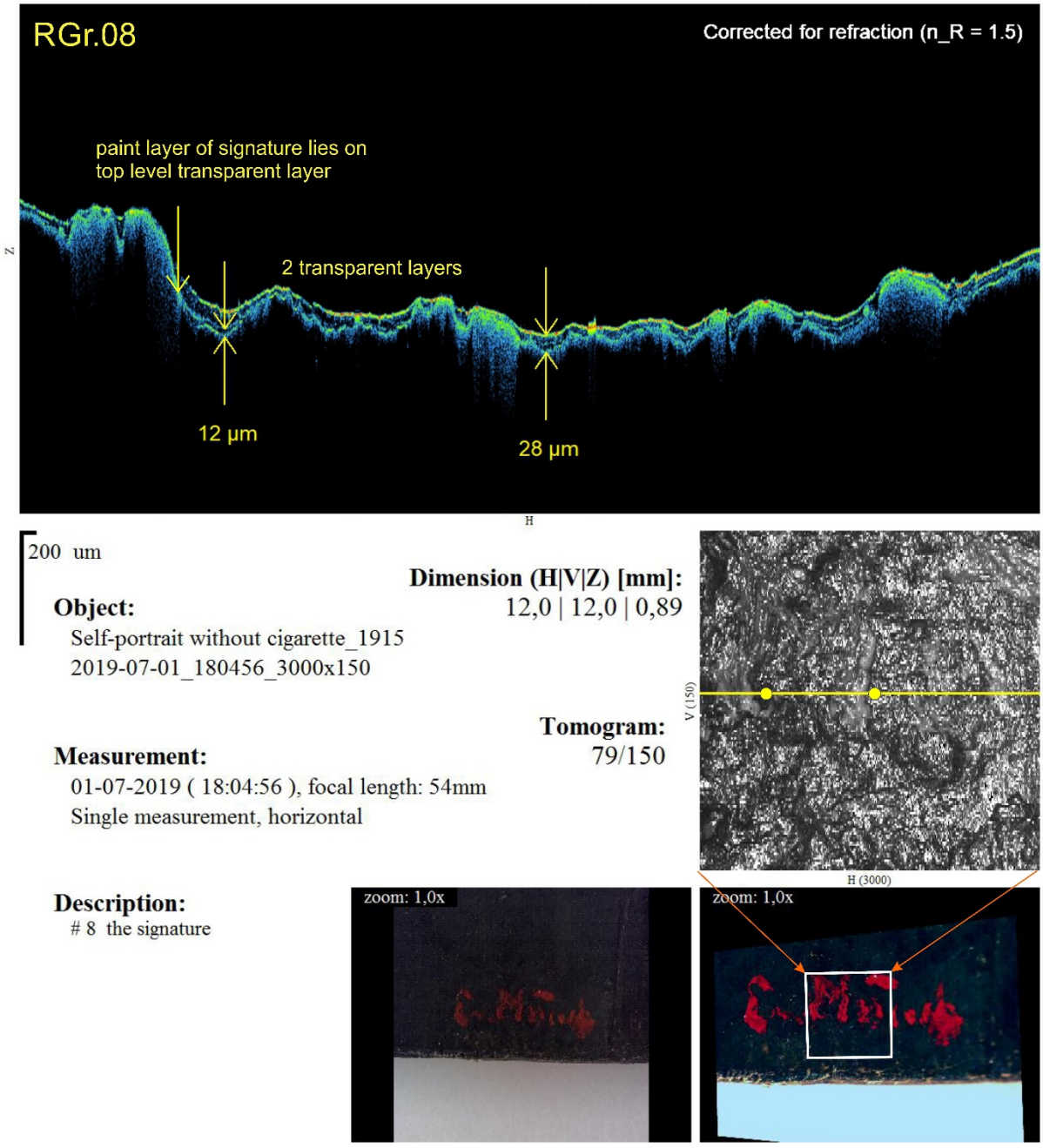


Fig. 10 *Self-portrait* (Woll M 133), OCT tomogram and IR reflectogram from examination spot RGr.08 (red signature lies between two transparent varnish layers)

Fig. 11 *Flowery meadow at Veierland* (Woll M 148), UVA-induced fluorescence photography with location of OCT examination spots

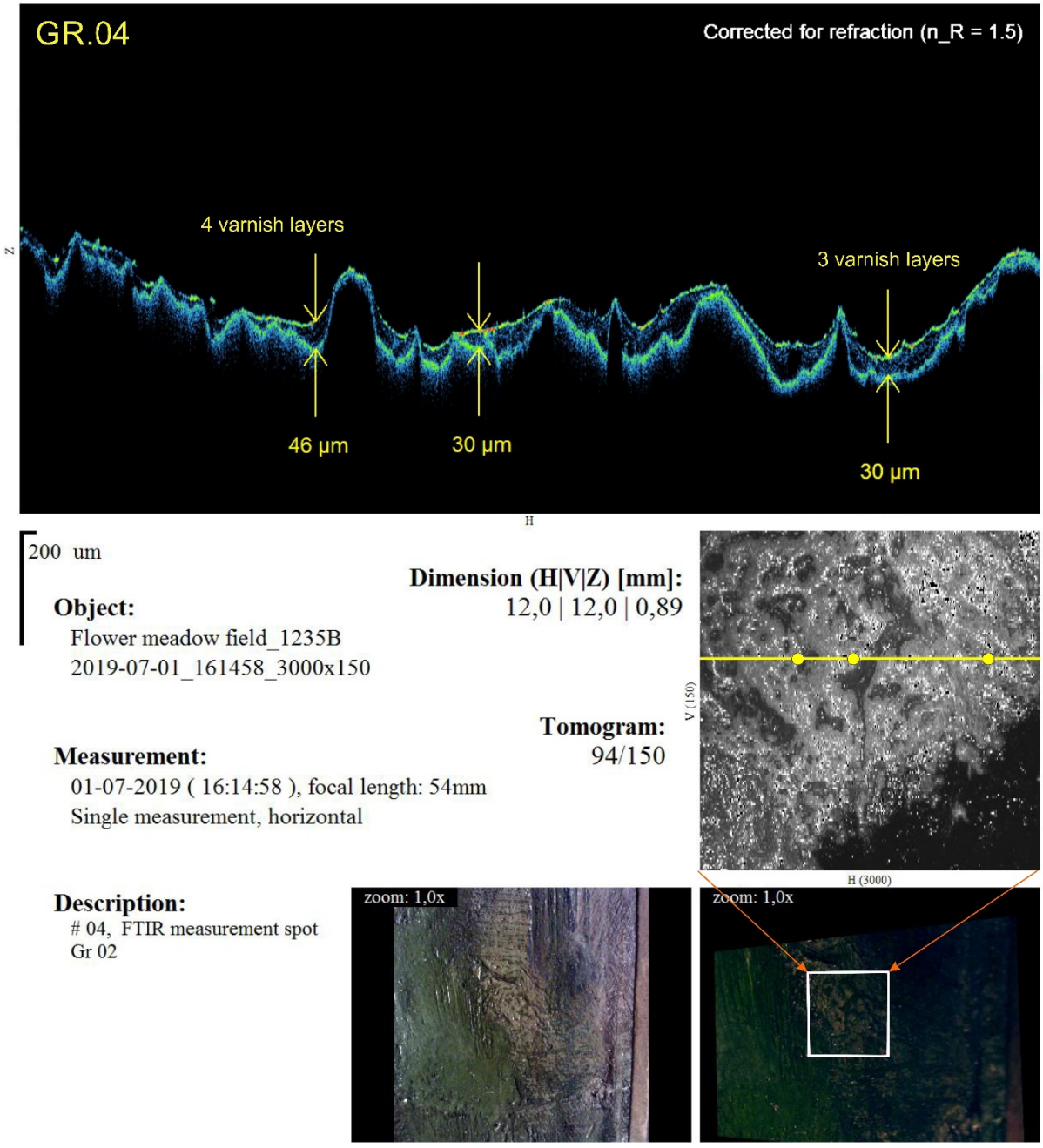


Fig. 12 *Flowery meadow at Veierland* (Woll M 148), OCT tomogram and IR reflectogram from examination spot Gr.04 (Four layers of varnish in the foreground)

Fig. 13 *The Day After* (Woll M 348), UVA-induced fluorescence photography with location of OCT examination spots

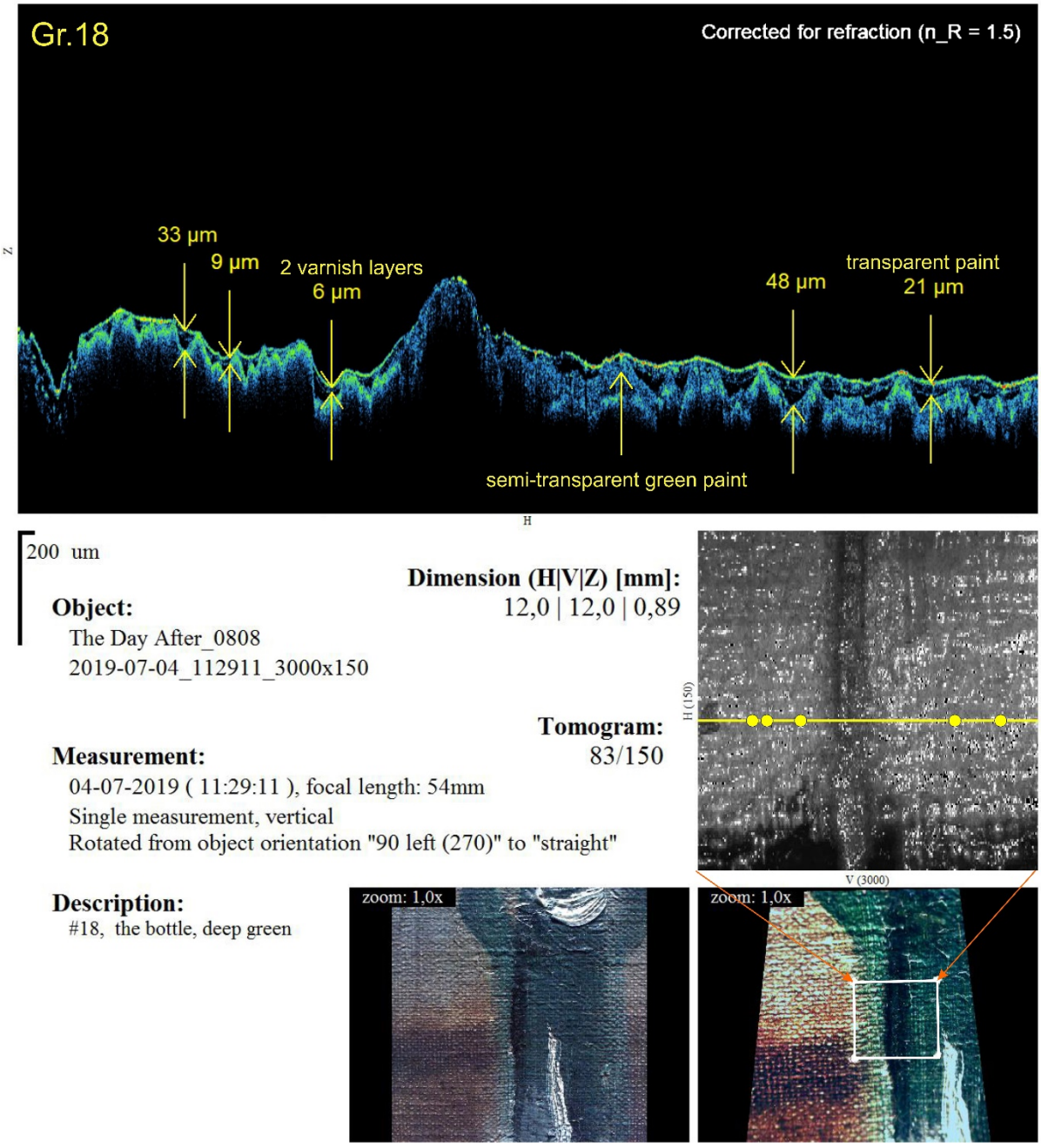


Fig. 14 *The Day After* (Woll M 348), OCT tomogram and IR reflectogram from examination spot Gr.18

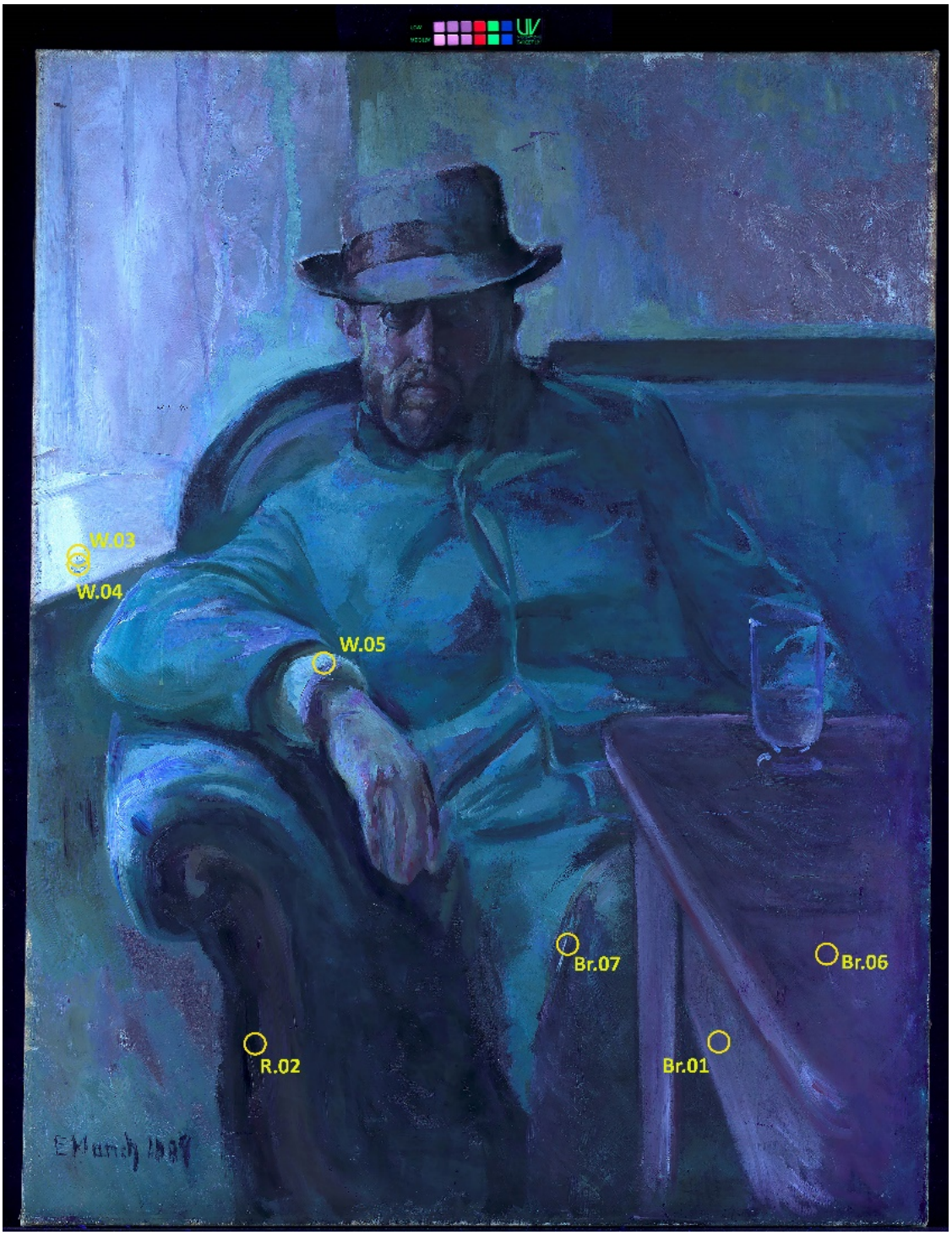


Fig. 15 *Hans Jæger* (Woll M 174), UVA-induced fluorescence photography with location of OCT examination spots

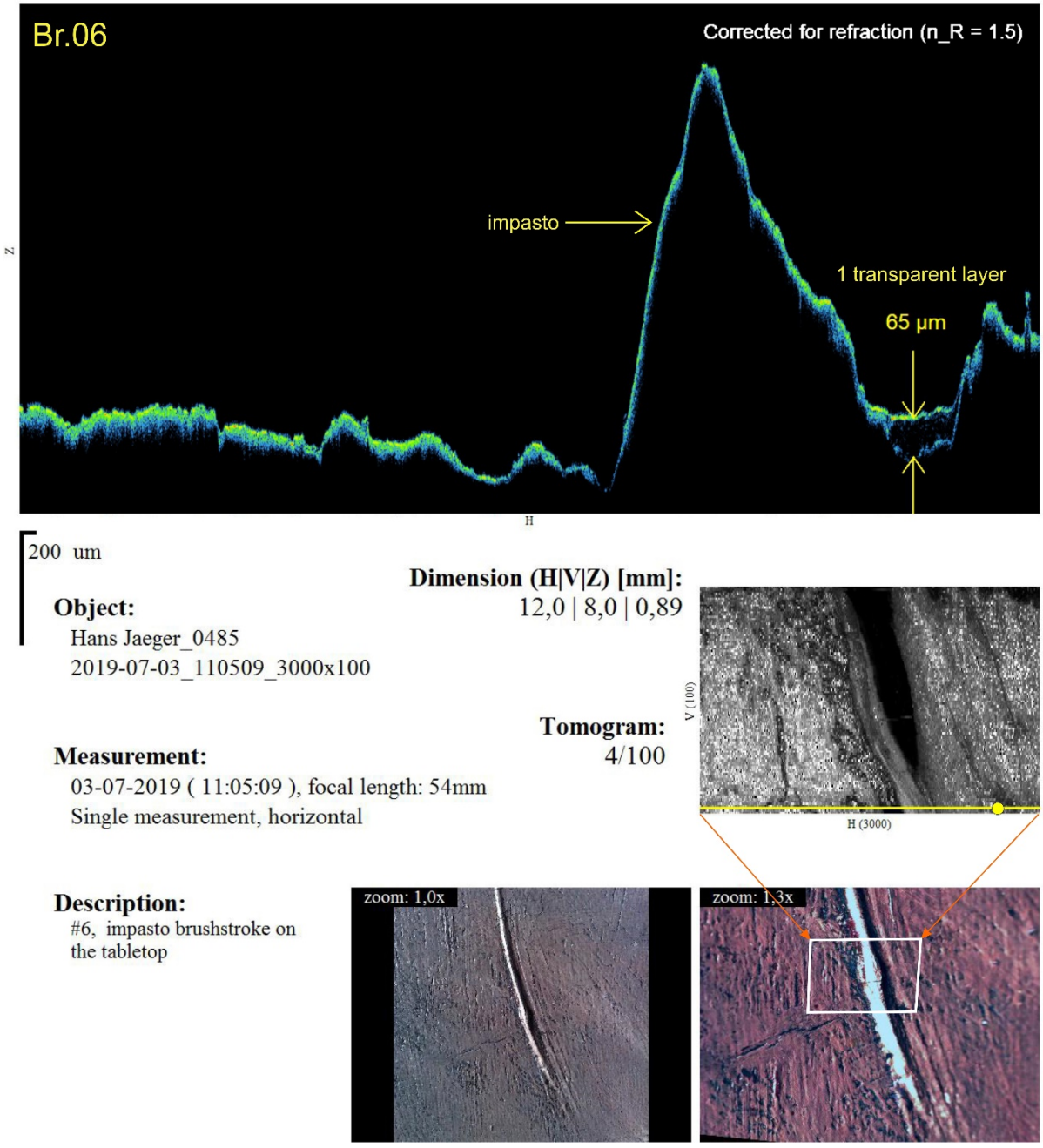


Fig. 16 *Hans Jæger* (Woll M 174), OCT tomogram and IR reflectogram from examination spot Br.06

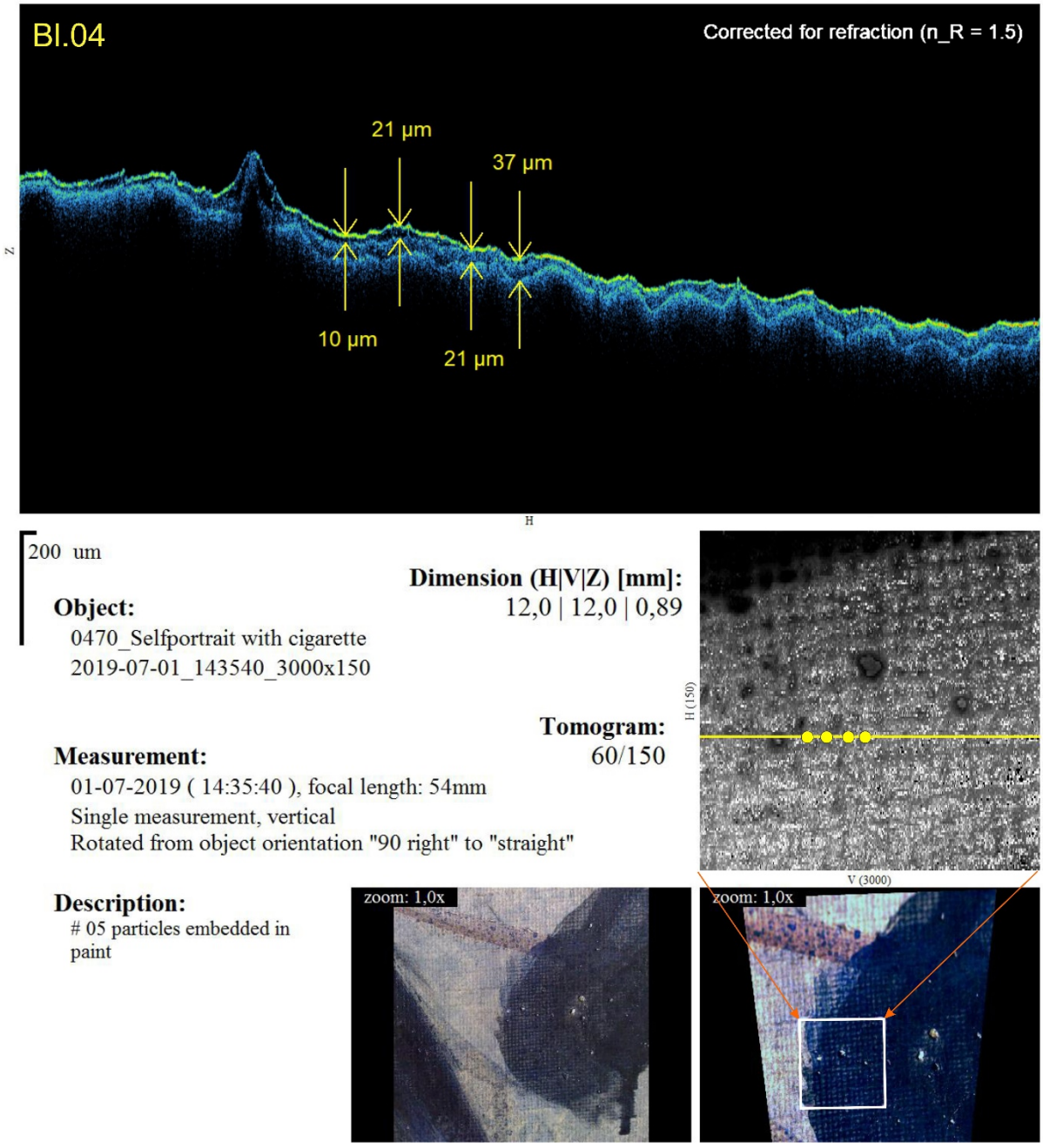


Fig. 17 *Self-portrait with cigarette* (Woll M 382) OCT tomogram and IR reflectogram from examination spot Bl.04 (evidence of semi-transparent paint layers/glazes)

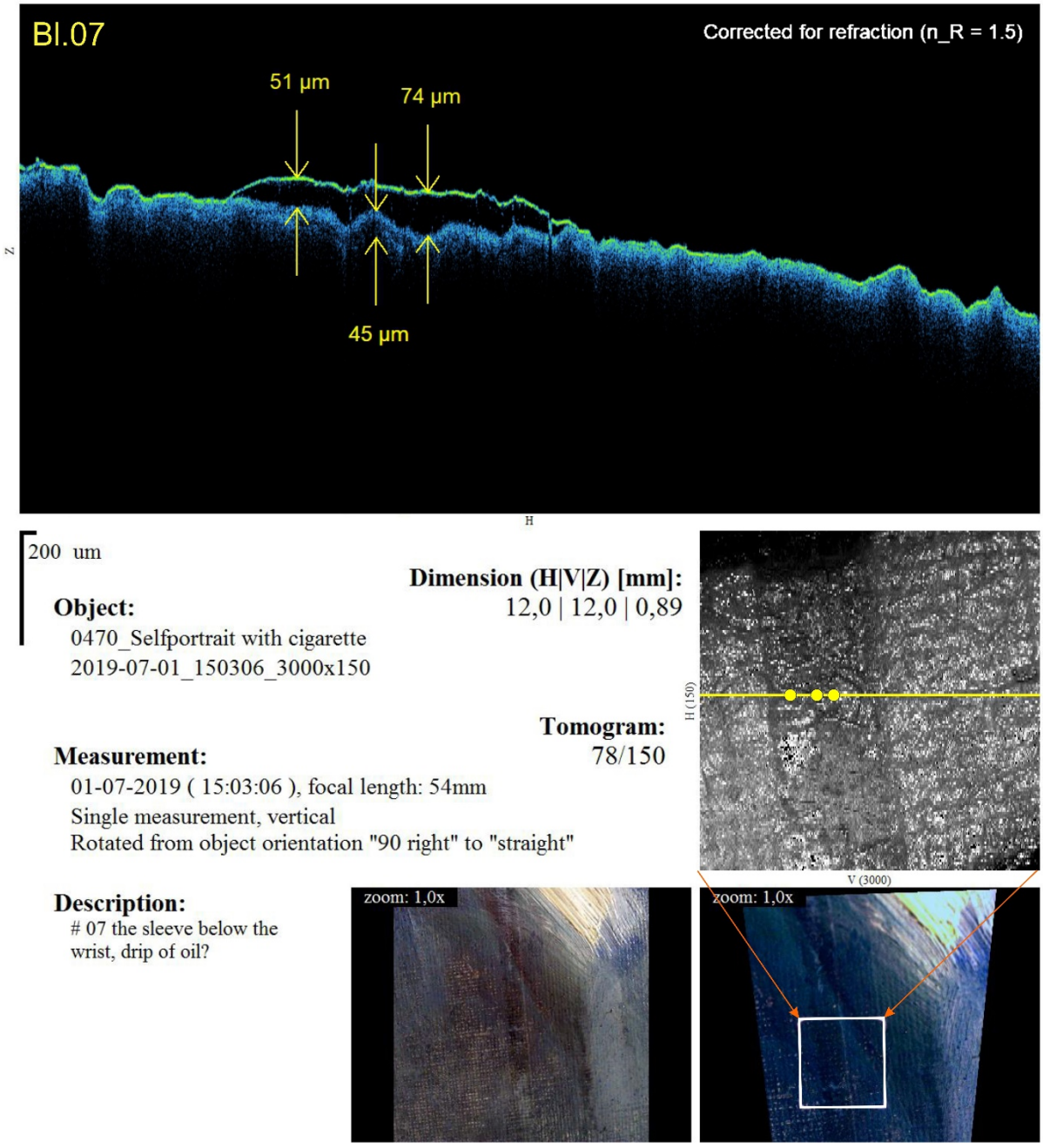


Fig. 18 *Self-portrait with cigarette* (Woll M 382) OCT tomogram and IR reflectogram from examination spot Bl.07 (residues of excess oil)

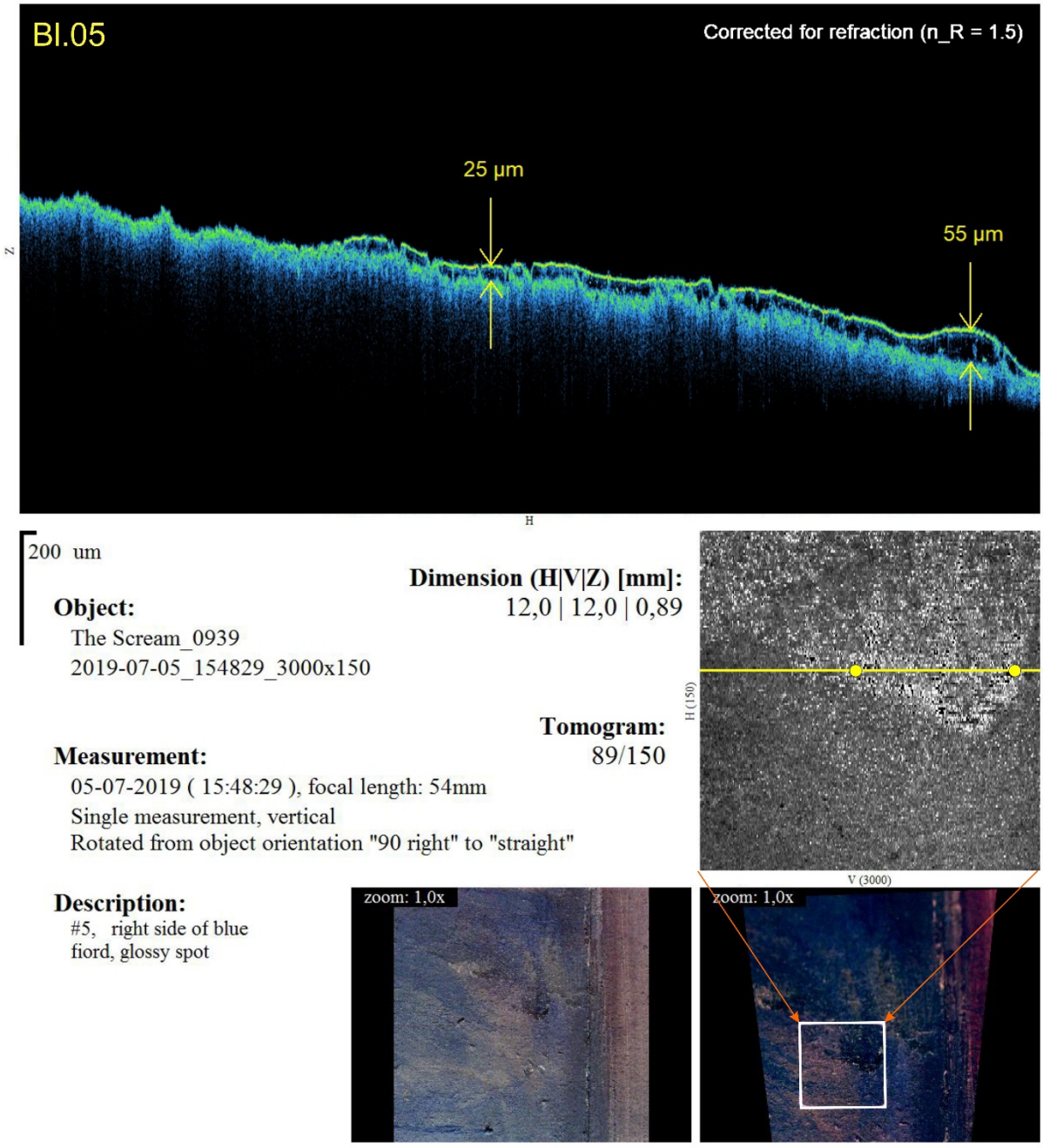


Fig. 19 *The Scream* (Woll M 333) OCT tomogram and IR reflectogram from examination spot Bl.05 (evidence of locally applied transparent layer)

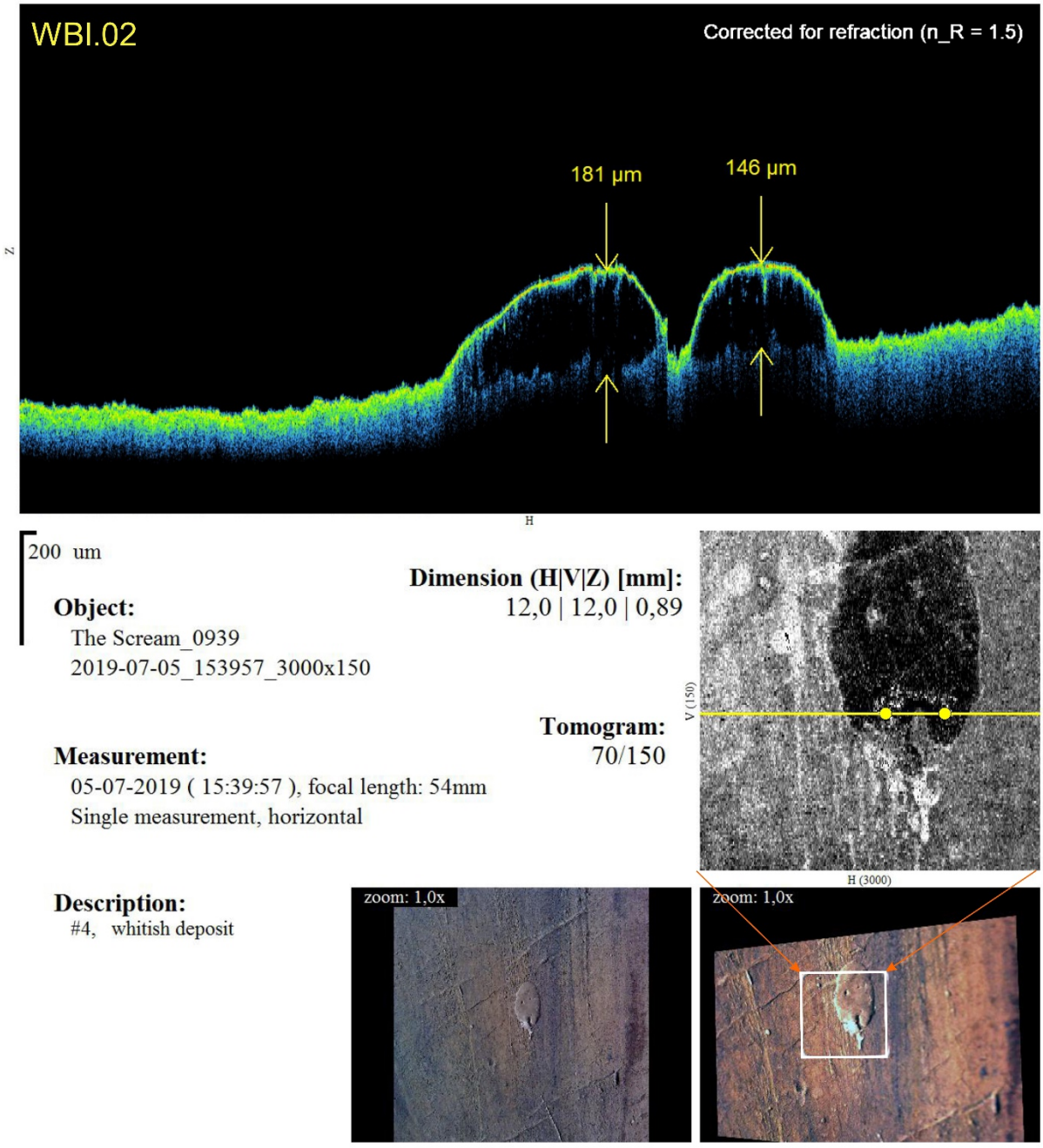


Fig. 20 *The Scream* (Woll M 333) OCT tomogram and IR reflectogram from examination spot WBl.02 (candlewax deposit),