

© 2020 Rolls-Royce Corporation and/or its subsidiaries The information in this document is the property of Rolls-Royce Corporation and/or its subsidiaries and may not be copied or communicated to a third party, or used for any purpose other than that for which it is supplied without the express written consent of Rolls-Royce Corporation and/or its subsidiaries.		MATERIALS EVALUATION REPORT Materials Engineering Department		
 Rolls-Royce	Rolls-Royce Corporation 450 S. Meridian Street Indianapolis, Indiana 46225-1103, USA	REPORT NO. 20FAE-014-PR	REV. Initial	PAGES 1 of 135
TITLE METALLURGICAL INVESTIGATION OF A HELICAL POWER TURBINE PINION GEAR, P/N 6893672, INSTALLED IN AN M250-C47B ENGINE, S/N CAE847031, OPERATED BY PANTHER HELICOPTERS		PREPARED Signatures on file		
		APPROVED Signatures on file		

IDENTIFICATION

Part Name:	See Table 1
Part Number:	See Table 1
Part Serial Number:	See Table 1
Processes:	Not Applicable
Part Time:	7584.7 hours TSN
Engine Model:	M250-C47B
Engine Serial Number:	CAE847031
User:	Panther Helicopters
Removal Station:	Southern Aircraft Salvage
Evaluations:	Failure Analysis

1 Foreword

An aircraft, installed with M250-C47B engine S/N CAE847031 and operated by the Panther Helicopters, was reported to have gone missing while transiting between offshore platforms in the Gulf of Mexico. The subject engine reportedly experienced extended exposure to an underwater environment before the aircraft's eventual recovery. During engine removal at Southern Aircraft Salvage in Baton Rouge, damage was reportedly observed on the helical power turbine pinion gear, and the No. 3 and 4 bearings reportedly exhibited deterioration. The pinion gear, No. 3 bearing, No. 4 bearing, and related components (see Table 1) were then submitted to the Rolls-Royce Corporation Materials Laboratory in Indianapolis, IN for detailed metallurgical investigation.

2 Summary of Findings

- 2.1 The helical power turbine pinion gear exhibited fatigue fractures at six consecutive gear teeth. The fractures initiated from multiple origins at the drive side tooth root fillets and progressed in fatigue towards the coast side flanks. No material or geometric anomalies were observed near the fracture origins or the adjacent tooth root surfaces. All the pinion gear teeth exhibited circumferential rub and smearing.
- 2.2 The No. 3 and No. 4 bearing journals on the pinion gear exhibited rub damage and thermal distress.
- 2.3 The composition and core microstructure away from the thermal distress for the pinion gear were consistent with the material type required by the component definition.
- 2.4 The No.3 bearing outer ring exhibited material removal at the roller path and circumferential rub damage on the forward shoulder corner. The metallographic evaluation of the outer ring revealed thermal distress on the raceway and forward shoulder corner, as well as transferred material at the roller path. The inner ring, rollers, and separator for the No. 3 bearing were not recovered.
- 2.5 The composition and microstructure away from the thermal distress for the No. 3 bearing outer ring were consistent with the material type required by the component definition.
- 2.6 No. 4 bearing outer ring exhibited material removal at the roller path and circumferential rub damage on the aft shoulder corner. The inner ring exhibited transferred material on the raceway and forward deformation on the forward shoulder. The inner diameter of the inner ring exhibited circumferential rub and transferred material. The No. 4 bearing separator and three of the rollers were not recovered.
- 2.7 Metallographic evaluation revealed thermal distress on the No. 4 bearing outer ring raceway and forward shoulder corner, the roller diameter, and throughout the inner ring.
- 2.8 The composition of the No. 4 bearing outer ring, inner ring, and rollers was consistent with the material type required by the component definition, and the microstructure away from the thermal distress in the outer ring was consistent with the material type required by the component definition.

3 Results and Discussion

Table 1 lists the part names, part numbers, and serial numbers of the engine components submitted for metallurgical investigation to the Rolls-Royce Corporation Materials Laboratory. Figure 1 shows a partial schematic cross-section of the gearbox, which highlights the submitted components. Due to the engine's reported exposure to an underwater environment, many of the submitted components were ultrasonic cleaned and manual cleaned with pumice soap in the laboratory to remove oxidation and lighter colored deposits in order to reveal the condition of the components.

Table 1: List of components submitted to the laboratory for investigation.

Part Name	Part Number	Serial Number
Helical Power Turbine Pinion Gear	6893672	NN74678
Bearing-Stepped Pinion Cage	Illegible	Not serialized
No. 3 Bearing	23066678	JJ07323
No. 4 Bearing	23066678	JJ07333
No. 4 Bearing Retaining Ring	6726656-356	Not serialized
Flanged No. 2.5 Bearing-Support Cage	23035272	Not serialized
No. 2.5 Bearing	Illegible	Illegible
Oil Delivery Tube	23063357	53281
Pinion Bearing Oil Nozzle	Illegible	Illegible
Turbine Shaft to Pinion Coupling	6889069	L-128
Helical Power Takeoff Gearshaft Assembly	Illegible	Illegible
Pressure Oil Filter	Illegible	Not serialized
CEFA Oil Filter Bowl	Illegible	Not serialized
CEFA Oil Filter	Illegible	Not serialized

3.1 Helical Power Turbine Pinion Gear

3.1.1 Visual Examination

Figure 2 and Figure 3 show the general condition of the helical power turbine pinion gear after ultrasonic cleaning and manual cleaning with pumice soap in the laboratory. For the purposes of this investigation, a circumferential location was arbitrarily designated the 0° position. Other circumferential locations increased by degrees in the direction of engine rotation. The pinion gear exhibited oxidation and lighter colored deposits. All the gear teeth exhibited circumferential rub and smearing. The least severe rub damage was observed at the 90° position, and the most severe rub damage was observed at the 270° position. Six consecutive gear teeth exhibited intact fracture surfaces at the approximate 0° position, as shown in Figure 4. The No. 3 bearing journal exhibited deterioration. Figure 5 and Figure 6 show detailed views of the No. 4 bearing journal, which also exhibited circumferential rub and transferred material. Figure 7 shows a lip of aftward deformed material localized near the 270° position of the No. 4 bearing journal at the same circumferential location as the most severe rub damage on the gear teeth. The aft end of the gear teeth, the inner diameter, and the inner flange forward face exhibited circumferential rub (see Figure 8 and Figure 9). Figure 10 shows representative views of the loaded and unloaded flanks of the inner splines, which exhibited mechanical deformation on the aft end of both sides. The loaded flank on one spline exhibited a region where material had fractured away.

3.1.2 Non-Destructive Examination

The pinion gear was subjected to magnetic particle inspection by the Rolls-Royce Development and Test Non-Destructive Testing Department. No crack-like indications were apparent on the gear teeth.

3.1.3 Fractography / Scanning Electron Microscope Examination

After ultrasonic cleaning and manual cleaning with pumice soap, the fracture surfaces at the gear teeth (see Figure 4) were also dry ice blasted in the laboratory to remove deposits. Figure 11 through Figure 19 show detailed views of fracture surfaces at gear teeth numbers 1 and 6. In general, the fractures progressed in fatigue from the drive side tooth root fillets towards the coast side flanks. The fracture surfaces at gear teeth numbers 2, 3, and 4 (see Figure 12, Figure 13, and Figure 16) exhibited ratchet marks, which are consistent

with multiple origins. Figure 14 and Figure 15 (tooth number 3), as well as Figure 17 (tooth number 4), show scanning electron microscope images of representative origin areas, which exhibited localized smearing damage, but no material or geometric anomalies were observed at the fracture surface or adjacent tooth root surface. Smearing damage precluded examination of the fracture origins and full extent of the fracture areas, and oxidation obfuscated fine fracture features.

3.1.4 *Metallographic Examination*

Axial metallographic sections were made through the most severely damaged locations on the No. 3 and 4 bearing journals (see yellow and orange dashed lines in Figure 3), and a circumferential metallographic section was made through the fracture surface at gear teeth number 3 (see red dashed line in Figure 13). The cross sections were mounted, polished with typical procedures, and etched with Vilella's (bearing journals) and 5% Nital (fracture surface).

Figure 20 and Figure 21 show a metallographic cross-section through the fracture surface at gear tooth number 3. The fracture origin was located at the tooth root fillet. No material anomalies were observed near the fracture origin, but smearing damage precluded detailed examination of the fracture origin. Figure 22 shows metallographic cross-sections through the No. 3 and No. 4 bearing journals, which both exhibited thermal distress (lighter etched regions). Thermal distress also extended from the No. 3 bearing journal to the gear teeth forward face and the pinion gear inner diameter surface. The core microstructure of the pinion gear away from the thermal distress, as shown in Figure 23, was consistent with the material type required by the component definition.

3.1.5 *Chemistry*

Semi-quantitative x-ray fluorescence (XRF) analysis determined that the pinion gear was consistent with the material type required by the component definition.

3.2 *Bearing-Stepped Pinion Cage*

3.2.1 *Visual Examination*

Figure 24 shows the general condition of the bearing-stepped pinion cage after ultrasonic cleaning and manual cleaning with pumice soap in the laboratory. The pinion cage exhibited oxidation and lighter colored deposits. The No. 3 and 4 bearing outer rings were assembled in the bearing-stepped pinion cage, as shown in Figure 25.

3.3 *No. 3 Bearing*

3.3.1 *Visual Examination*

The No.3 bearing outer ring was sectioned out of the bearing-stepped pinion cage in the laboratory, then ultrasonic cleaned and manual cleaned with pumice soap. Figure 26 and Figure 27 shows general and detailed views of outer raceway surface of the No. 3 bearing outer ring, which exhibited material removal at the roller path. Circumferential rub damage was observed on the forward shoulder corner. The outer ring also exhibited oxidation and lighter colored deposits. Figure 28 shows a representative view of outer diameter of the outer ring, which exhibited discoloration.

The inner ring, rollers, and separator for the No. 3 bearing were not recovered.

3.3.2 *Metallographic Examination*

A metallographic section was made through a representative location on the outer ring (see yellow dashed line in Figure 26). The cross section was mounted, polished with typical procedures, and etched with Vilella's. Figure 29 and Figure 30 show a metallographic cross-section through the outer ring, which exhibited thermal distress on the raceway and forward shoulder corner (lighter etched regions), as well as material removal and transferred material at the roller path. The outer ring microstructure away from the thermal distress (see Figure 31) was consistent with the material type required by the component definition.

3.3.3 *Chemistry*

Semi-quantitative XRF analysis determined that the outer ring was consistent with the material type required by the component definition.

3.4 **No. 4 Bearing**

3.4.1 *Visual Examination*

The No.4 bearing outer ring was sectioned out of the bearing-stepped pinion cage in the laboratory, then ultrasonic cleaned and manual cleaned with pumice soap. Figure 32 and Figure 33 shows general and detailed views of outer raceway surface of the No. 4 bearing outer ring, which exhibited material removal at the roller path. Circumferential rub damage was observed on the aft shoulder corner. The outer ring also exhibited oxidation and lighter colored deposits. Figure 34 shows a representative view of outer diameter of the outer ring, which exhibited discoloration.

The general condition of the inner ring, after ultrasonic cleaning and manual cleaning with pumice soap, is shown in Figure 35 and Figure 36, which exhibited transferred material on the raceway. Figure 37 shows the profile of the inner ring raceway. Roller impressions were observed on the raceway, and the forward shoulder was deformed forward. The inner diameter of the inner ring exhibited circumferential rub and transferred material (see top image in Figure 38), and the forward face of the forward shoulder exhibited rub damage (see bottom image in Figure 38).

Figure 39 shows the general condition of the No. 4 bearing rollers after ultrasonic cleaning and manual cleaning with pumice soap. Nine out of the twelve rollers were recovered. A circumferential rub step was observed on one corner of the roller diameters (see Figure 40). The rollers also exhibited oxidation and lighter colored deposits.

The No. 4 bearing separator was not recovered.

3.4.2 *Metallographic Examination*

Metallographic sections were made through representative locations on the outer ring, inner ring, and a representative roller (see yellow dashed lines in Figure 32, Figure 35, and Figure 40). The cross sections were mounted, polished with typical procedures, and etched with Vilella's. Figure 41 shows the metallographic cross-sections through the outer ring, roller, and inner ring juxtaposed with one another. The cross sections exhibited thermal distress (lighter etched regions) on the outer ring raceway and forward shoulder corner, the roller diameter, and throughout the inner ring. The outer ring raceway also exhibited material removal at the roller path. Figure 42 shows transferred material on the inner ring raceway. Figure 43 shows cracking on the inner diameter of the inner ring. The outer ring and roller microstructures away from the thermal distress (see Figure 44 and Figure 45) were consistent with the material type required by the component definition.

3.4.3 *Chemistry*

Semi-quantitative XRF analysis determined that the outer ring, inner ring, and rollers were consistent the material types required by the component definition.

3.5 Flanged No. 2.5 Bearing-Support Cage and No. 2.5 Bearing

3.5.1 Visual Examination

Figure 46 shows the general condition of the flanged No. 2.5 bearing support cage after ultrasonic cleaning and manual cleaning with pumice soap in the laboratory. The bearing support exhibited oxidation and lighter colored deposits. Figure 47 and Figure 48 shows the outer diameter of the bearing support cage, which exhibited circumferential rub. Figure 49 shows detailed views of the aft face to outer diameter chamfer, which exhibited localized circumferential rub at the 12:00 position (see left image in the figure). The aft face of the flanged No. 2.5 bearing-support cage also exhibited localized forward mechanical deformation (see Figure 50) at the 12:00 position.

Figure 51 shows detailed views of No. 2.5 bearing assembled in the flanged No. 2.5 bearing support cage.

3.6 Oil Delivery Tube

3.6.1 Visual and Non-Destructive Examination

Figure 52 shows a partial schematic cross-section of the gearbox, which highlights the oil delivery tube, oil nozzle, oil screen, and gearbox housing. The schematic also identifies the locations of the No. 3 and No. 4 bearing oil jets and the pinion gear oil jet on the oil delivery tube and oil nozzle.

Figure 53 shows the general condition of the oil delivery tube, assembled to a fragment of the gearbox housing, which exhibited oxidation and lighter colored deposits. The component was subjected to a computed tomography (CT) scan at outside test facility prior to its arrival in the laboratory to check for blockage in the internal passageways. Figure 54 through Figure 57 show detailed optical images and CT cross sections of the pinion gear oil jet and the No. 3 bearing oil jets on the oil delivery tube. All three oil jets were coated in deposits and exhibited internal blockage. Figure 58 and Figure 59 show detailed views of the location where the oil delivery tube and oil screen were assembled to a gearbox housing fragment. The right image in Figure 59 and Figure 60 show an optical image and a CT scan of blockage material in a passageway of the gearbox housing fragment.

3.6.2 Metallographic Examination

The oil delivery tube was sectioned open to expose the internal passageways, and the component was submerged in epoxy to encapsulate debris within passageways. A vacuum was applied during the encapsulation process to ensure epoxy infiltration in all voids and the purging of bubbles. A metallographic section was made through the pinion gear oil jet and the adjacent passageway (see red dashed line in Figure 54), as well as a representative region of the main passageway upstream of the pinion gear oil jet (see orange dashed line in Figure 54). A metallographic section was also made through No. 3 bearing oil jet A and the adjacent passageway before polishing further to No. 3 bearing oil jet B (see steps 1 and 2 in Figure 56, respectively). The oil screen and gearbox housing fragment were also sectioned (see red dashed line in Figure 58) and mounted in cold-set epoxy.

Figure 61 through Figure 64 show detailed views of the metallographic sections through the pinion gear oil jet, the main passageway adjacent to the pinion oil jet, and the No. 3 bearing oil jets of the oil delivery tube, which all exhibited blockage material. Figure 65 shows a detailed view of the metallographic section through the gearbox housing and oil screen.

3.6.3 Chemistry

Semi-quantitative energy dispersive x-ray spectroscopy (EDS) analysis was performed on the oil delivery tube and the gearbox housing fragment, which were consistent the material types required by the component definition.

Semi-quantitative EDS analysis was performed on the blockage material observed in the pinion gear oil jet, main passageway, and the No. 4 bearing oil jets. EDS results for the blockage material were consistent with corrosion product of the oil delivery tube and terrestrial material (dirt). EDS results of finer metallic particles in the oil jets were consistent with an iron-based alloy type material. Semi-quantitative EDS analysis was also performed on the blockage material observed in the gearbox housing fragment and oil screen. EDS results for the blockage material were consistent with corrosion product of the gearbox housing. A detailed examination of blockage material observed in the oil delivery tube, gearbox housing fragment, and oil screen is discussed in Section 3.10.

3.7 Pinion Bearing Oil Nozzle

3.7.1 Visual and Non-Destructive Examination

Figure 66 shows the general condition of the pinion gear oil nozzle, which exhibited corrosion and lighter colored deposits. Figure 67 through Figure 69 show detailed views of the No. 4 bearing oil jets on the pinion gear oil nozzle, which exhibited blockage. The component was subjected to a CT scan at outside test facility prior to its arrival in the laboratory to check for blockage in the internal passageways. Figure 70 shows a CT cross section of the oil nozzle, which exhibited blockage material in the No. 4 bearing oil jets and in the main passageway between both oil jets.

3.7.2 Metallographic Examination

The oil nozzle was submerged in epoxy to encapsulate debris within passageways. A vacuum was applied during the encapsulation process to ensure epoxy infiltration in all voids and the purging of bubbles. A metallographic section was made through No. 4 bearing oil jet A and the adjacent passageway (see step 1 in Figure 70). Then the specimen was step polished to a location between the two No. 4 bearing oil jets where debris was observed in the CT scan of the main passageway, to the location of No. 4 bearing oil jet B, and to a location in the main passage past the No. 4 bearing oil jets where debris was observed in the specimen (see steps 2 through 4 in Figure 70, respectively).

Figure 71 and Figure 72 show detailed views of metallographic sections through the No.4 bearing oil jets of the oil delivery tube, which exhibited blockage material. No debris particle was observed in the main passageway between the No.4 bearing oil jets (see step 2 in Figure 70). The particle shifted between the time the oil nozzle was CT scanned and when it was epoxy encapsulated. Figure 73 shows a detailed view of the metallographic section through the main passageway at a location away from the oil jets (see step 4 in Figure 70), which exhibited blockage material.

3.7.3 Chemistry

Semi-quantitative energy dispersive x-ray spectroscopy (EDS) analysis was performed on the oil nozzle, which was consistent the material type required by the component definition.

Semi-quantitative EDS analysis was performed on the blockage material observed in the oil nozzle. EDS results for the blockage material were consistent with corrosion product of the oil delivery tube and terrestrial material (dirt). EDS results of finer metallic particles in the oil jets were consistent with an iron-based alloy type material, as well as the material type required by the component definition of the gearbox housing material. A detailed examination of blockage material observed in the oil nozzle is discussed in Section 3.10.

3.8 Other Components

3.8.1 Visual Examination

Figure 74 shows the general condition of the both sides of the No. 4 bearing retaining ring, and Figure 75 shows the detailed views of the tabs on both sides of the retaining ring. The retaining ring exhibited oxidation and lighter colored deposits.

The turbine shaft to pinion coupling and helical power takeoff gearshaft assembly were ultrasonic cleaned and manual cleaned with pumice soap in the laboratory. Both components exhibited oxidation and lighter colored deposits. Figure 76 shows the general condition of the turbine shaft to pinion coupling after cleaning. The forward side ring seal exhibited evidence of thermal distress. Figure 77 and Figure 78 show detailed views of representative loaded and unloaded flanks of the forward and aft splines. The loaded flank on one spline exhibited a region where material had fractured away. Figure 79 shows the general condition of the helical power takeoff gearshaft assembly after cleaning, and Figure 80 shows detailed views of representative driven and coast flanks of the larger diameter gear teeth.

3.8.2 Non-Destructive Examination

The turbine shaft to pinion coupling and helical power takeoff gearshaft were subjected to magnetic particle inspection by the Rolls-Royce Development and Test Non-Destructive Testing Department. No crack-like indications were apparent on the splines of the coupling or the gear teeth of the gearshaft.

3.9 Various Filters and Associated Debris

Figure 81 and Figure 82 show the general condition of the pressure oil filter, CEFA oil filter bowl, and CEFA oil filter, as well as debris collected from CEFA oil filter prior to arrival to the laboratory.

3.10 Blockage Material in the Oil Delivery Tube

3.10.1 Metallographic Examination and Chemistry

Semi-quantitative EDS analysis was performed on the blockage material observed in the pinion gear oil jet, the No. 4 bearing oil jets, and the main passageway. EDS results for the blockage material were consistent with corrosion product of the oil delivery tube and terrestrial material (dirt). EDS results of finer metallic particles in the oil jets were consistent with an iron-based alloy type material. Figure 83 shows a color map of the EDS results for the blockage material in the oil jets and main passageway of the oil delivery tube.

Figure 84 and Figure 85 show optical and backscattered electron SEM images of the metallographic section through the pinion gear oil jet of the oil delivery tube (see Figure 54), which exhibited blockage material. Figure 86 through Figure 88 show the semi-quantitative EDS results for the blockage material. Finer, brighter (i.e., higher average atomic weight) particles (see location N in Figure 85) exhibited higher concentrations of iron, nickel, and chromium. The specific iron-based alloy could not be identified. Blockage material at location P in Figure 85 exhibited higher concentrations of oxygen, aluminum, sodium, and silicon (listed in order of concentration), which is consistent with corrosion product of the oil delivery tube. Blockage material at locations Q in Figure 85 exhibited higher concentrations of oxygen, aluminum, silicon, sodium, and magnesium (listed in order of concentration), which is consistent with corrosion product of the oil delivery tube. Blockage material at locations R in Figure 85 exhibited higher concentrations of oxygen, silicon, aluminum, and sodium (listed in order of concentration), which is consistent with terrestrial material (dirt). Blockage material at location S in Figure 85 exhibited higher concentrations of oxygen, magnesium, aluminum, and silicon (listed in order of concentration).

Figure 89 shows backscattered electron SEM images of the metallographic section through a representative region of the main passageway upstream of the pinion gear oil jet of the oil delivery tube (see Figure 54),

which exhibited blockage material. Figure 90 and Figure 91 show the semi-quantitative EDS results for the blockage material. Blockage material at location U and W in Figure 90 exhibited higher concentrations of oxygen, aluminum, magnesium, silicon (listed in order of concentration), which is consistent with corrosion product of the oil delivery tube. Blockage material at locations Y in Figure 91 exhibited higher concentrations of oxygen, silicon, aluminum, and magnesium (listed in order of concentration), which is consistent with terrestrial material (dirt).

Figure 92 and Figure 93 show optical and backscattered electron SEM images of the metallographic section through No. 3 bearing oil jet A of the oil delivery tube (see step 1 in Figure 56), which also exhibited blockage material. Figure 94 through Figure 96 show the semi-quantitative EDS results for the blockage material. Finer, brighter particles (see locations AB in Figure 93) exhibited higher concentrations of iron and chromium. The specific iron-based alloy could not be identified. Blockage material at locations AC and AD in Figure 93 exhibited higher concentrations of oxygen, aluminum, and silicon (listed in order of concentration), which is consistent with corrosion product of the oil delivery tube. Blockage material at locations AE and AF in Figure 93 exhibited higher concentrations of oxygen, silicon, aluminum, calcium, and magnesium (listed in order of concentration), which is consistent with terrestrial material (dirt). The brighter particles on the outer end of the hole (see AG in Figure 93) exhibited higher concentrations of calcium and oxygen, which is consistent with calcium deposits that covered the No. 3 bearing oil jets (see Figure 56).

Figure 97 and Figure 98 show optical and backscattered electron SEM images of the metallographic section through No. 3 bearing oil jet B of the oil delivery tube (see step 2 in Figure 56), which also exhibited blockage material. Figure 99 through Figure 102 show the semi-quantitative EDS results for the blockage material. Blockage material at location AK in Figure 98 exhibited higher concentrations of oxygen, silicon, and aluminum (listed in order of concentration), which is consistent with terrestrial material (dirt). Blockage material at location AL and AM (see Figure 98) exhibited higher concentrations of oxygen, silicon, aluminum, and magnesium (listed in order of concentration), which is also consistent with terrestrial material. Blockage material at locations AN and AP in Figure 98 exhibited higher concentrations of oxygen, aluminum, and magnesium (listed in order of concentration), which is consistent with corrosion product of the oil delivery tube. Blockage material at locations AQ and AR in Figure 98 exhibited higher concentrations of oxygen, magnesium, aluminum, and silicon (listed in order of concentration).

Figure 103 and Figure 104 show optical and backscattered electron SEM images of the metallographic section through blockage in the gearbox housing fragment and oil screen (see Figure 58). Figure 105 through Figure 106 show the semi-quantitative EDS results for the blockage material. Blockage material at locations AU and AW in the gearbox housing fragment (Figure 104) exhibited higher concentrations of oxygen, magnesium, and zinc (listed in order of concentration), which is consistent with corrosion product of the gearbox housing. Blockage material at locations AY in the gearbox housing fragment (Figure 104) exhibited higher concentrations of oxygen magnesium, calcium, sodium, chlorine, and silicon (listed in order of concentration), which is consistent with corrosion product of the gearbox housing and terrestrial material (dirt). Blockage material on the oil screen (locations AZ in Figure 104) exhibited higher concentrations of oxygen, magnesium, iron, and chromium (listed in order of concentration), which is consistent with corrosion product of the gearbox housing and oil screen.

3.11 Blockage Material in the Oil Nozzle

3.11.1 Metallographic Examination and Chemistry

Semi-quantitative EDS analysis was performed on the blockage material observed in the oil nozzle. EDS results for the blockage material were consistent with corrosion product of the oil delivery tube and terrestrial material (dirt). EDS results of finer metallic particles in the oil jets were consistent with an iron-based alloy type material, as well as the material type required by the component definition of the gearbox housing material. Figure 107 shows a color map of the EDS results for the blockage material in the oil jets and main passageway of the pinion bearing oil nozzle.

Figure 108 through Figure 110 show optical and backscattered electron SEM images of metallographic section through No.4 bearing oil jet A of the oil delivery tube (see Figure 70), which exhibited blockage material. Figure

111 through Figure 113 show the EDS results for the blockage material. Blockage material at location BA in Figure 109 exhibited higher concentrations of oxygen, silicon, and aluminum (listed in order of concentration), which is consistent with terrestrial material (dirt). Blockage material at locations BA through BF in Figure 109 and Figure 110 exhibited higher concentrations of oxygen, aluminum, silicon, and chlorine (listed in order of concentration), which is consistent with corrosion product of the oil nozzle.

Figure 114 through Figure 116 show optical and backscattered electron SEM images of metallographic sections through No.4 bearing oil jet B of the oil delivery tube (see Figure 70), which exhibited blockage material. Figure 117 through Figure 119 show the EDS results for the blockage material. Blockage material at location BG in Figure 115 exhibited higher concentrations of oxygen, aluminum, chlorine, sodium, and silicon (listed in order of concentration), which is consistent with corrosion product of the oil nozzle. Finer metallic blockage particles on the outer end of the hole (see location BH in Figure 115) exhibited higher concentrations of iron. The specific iron-based alloy could not be identified. The amorphous aggregate and courser particles at the inner end of the hole (see location BJ and BK in Figure 116) exhibited higher concentrations of oxygen, magnesium, aluminum, and silicon (listed in order of concentration). Finer, brighter (i.e., higher average atomic weight) particles at the inner end of the hole (see location BL in Figure 116) exhibited higher concentrations of magnesium, zinc, and rare earth metals, which is consistent with the material type required by the component definition of the gearbox housing material. Corroded base material adjacent to hole at location BM in Figure 116 exhibited higher concentrations of oxygen, aluminum, chlorine, silicon, and sodium (listed in order of concentration).

Figure 120 through Figure 122 show optical and backscattered electron SEM images of the metallographic section through the main passageway at a location away from the oil jets (see step 4 in Figure 70), which exhibited blockage material. Figure 123 through Figure 126 show the EDS results for the blockage material. Blockage material at location BQ in Figure 122 exhibited concentrations of oxygen, silicon, magnesium, zirconium, and aluminum (listed in order of concentration). Blockage material at locations BS through BW Figure 121 and Figure 122 exhibited higher concentrations of oxygen, silicon, aluminum, and magnesium, (listed in order of concentration). Higher concentrations of silicon, aluminum, magnesium, and oxygen are consistent with terrestrial material (dirt). Finer brighter particles (see location BY in Figure 122) exhibited higher concentrations of oxygen, magnesium, rare earth metals, zinc, and aluminum (listed in order of concentration). The surrounding amorphous aggregate (see location BZ in Figure 122) exhibited higher concentrations of oxygen, magnesium, aluminum, zinc, and silicon (listed in order of concentration). High concentrations of magnesium, zinc, and rare earth metals are consistent with the material type required by the component definition of the gearbox housing material.

4 Revision History

Issue	Change Summary	Date
Initial	Not applicable	29 Jul 2020

5 Figures and Tables

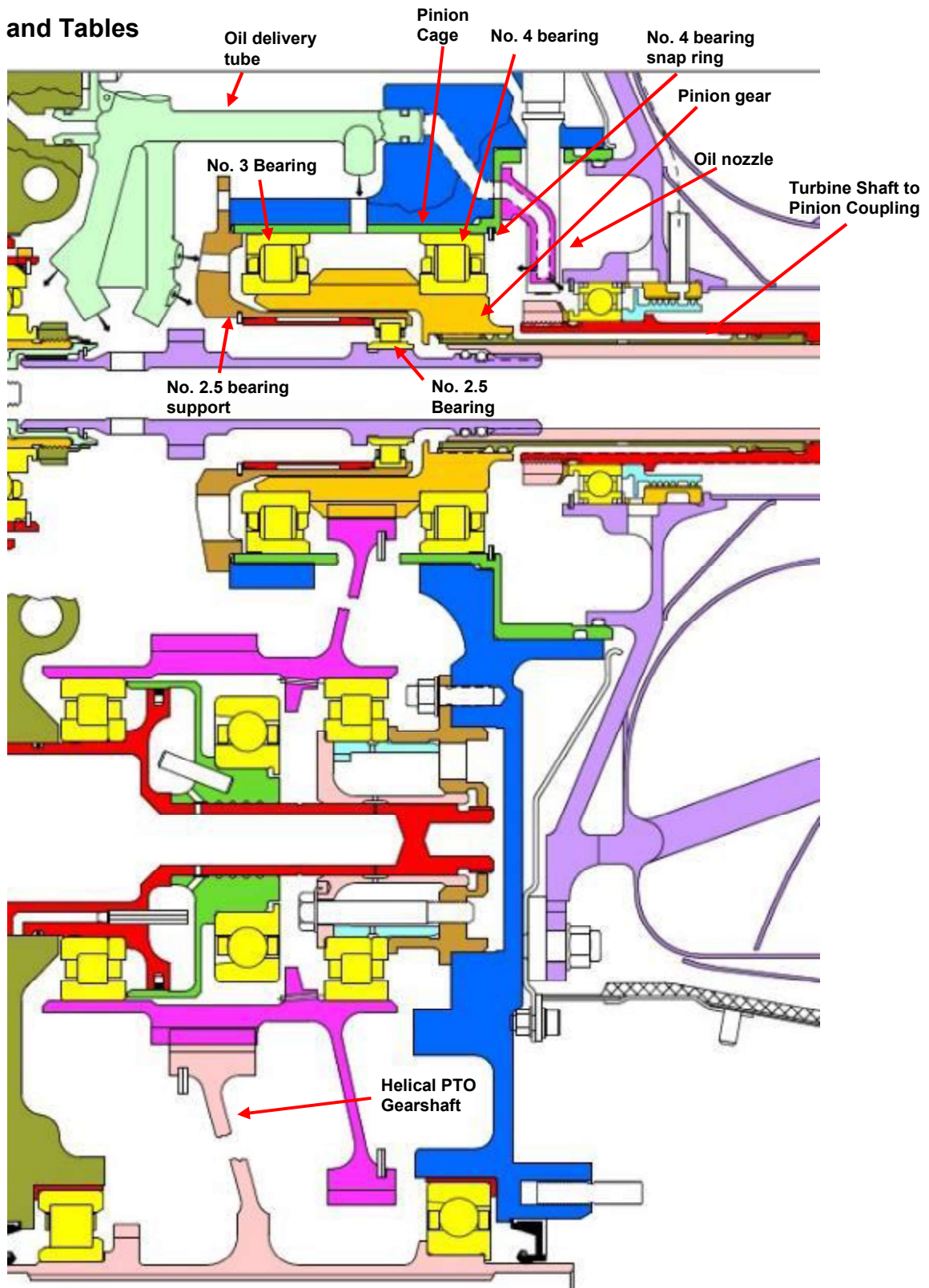


Figure 1. Partial schematic cross-section of the gearbox, which highlights the submitted components (see Table 1). Schematic is not to scale and is shown for illustration purposes only.

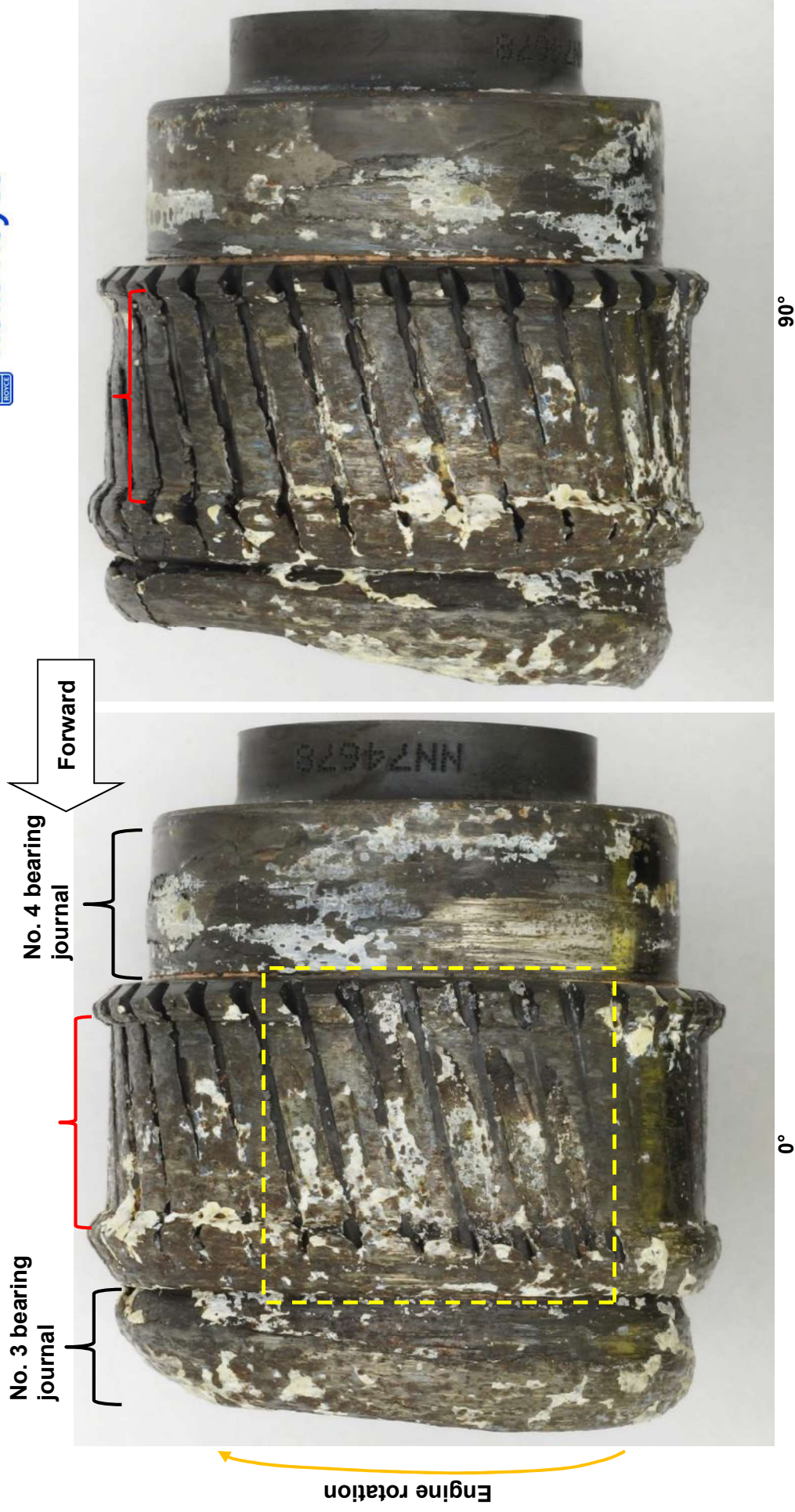


Figure 2. General condition of the helical power turbine pinion gear after cleaning. The red braces mark the location of circumferential rub and smearing on the gear teeth, the yellow boxed area is shown in more detail in Figure 4. The least severe rub damage was observed at the 90° position (right). Each image shows the part rotated ~90° from the previous.

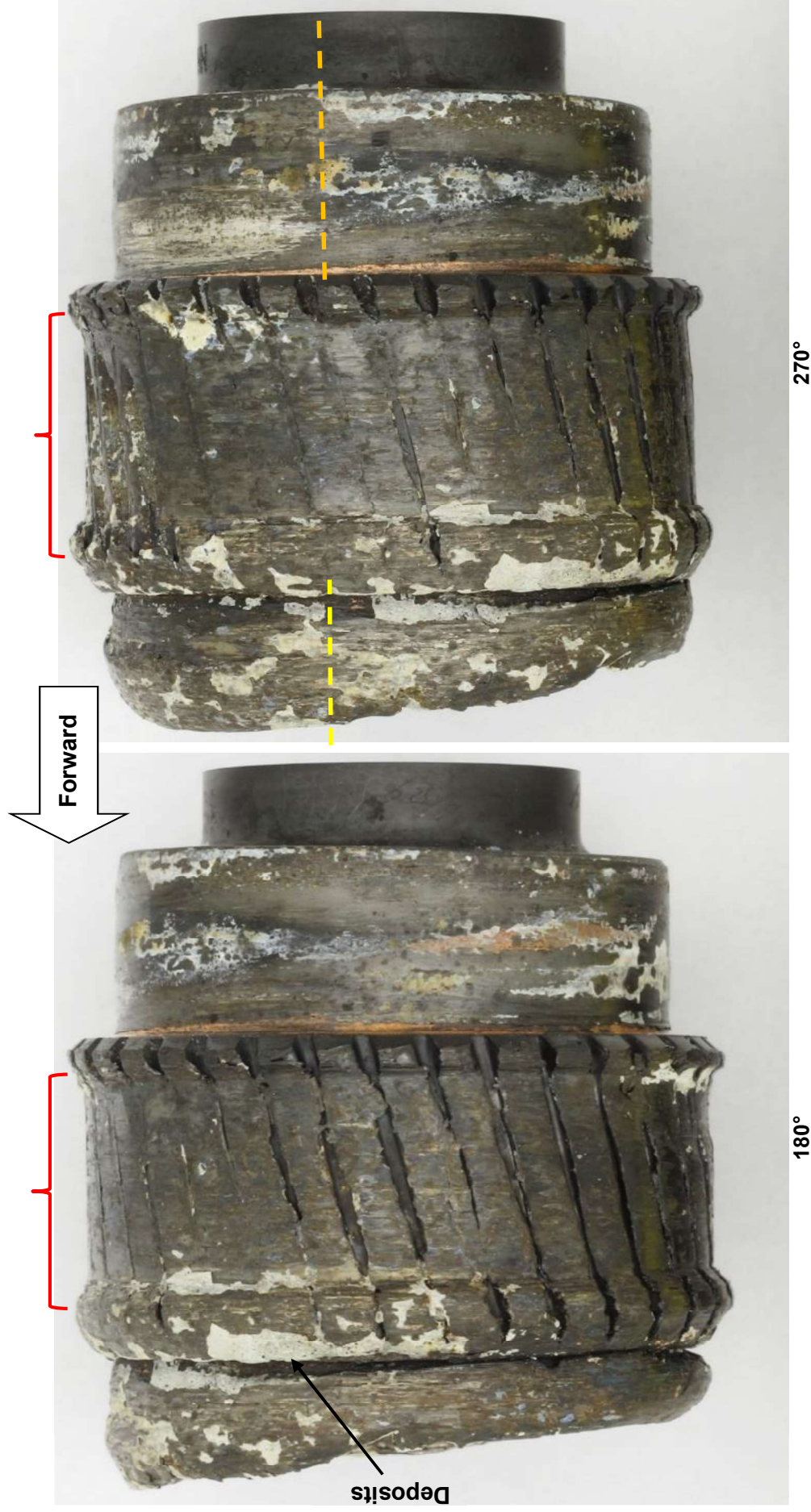


Figure 3. General condition of the helical power turbine pinion gear after cleaning. Red braces mark the location of circumferential rub and smearing on the gear teeth, and the yellow and orange dashed lines mark planes for metallographic evaluation (see Figure 22) The most severe rub damage was observed at the 270° position (right). Each image shows the part rotated ~90° from the previous.

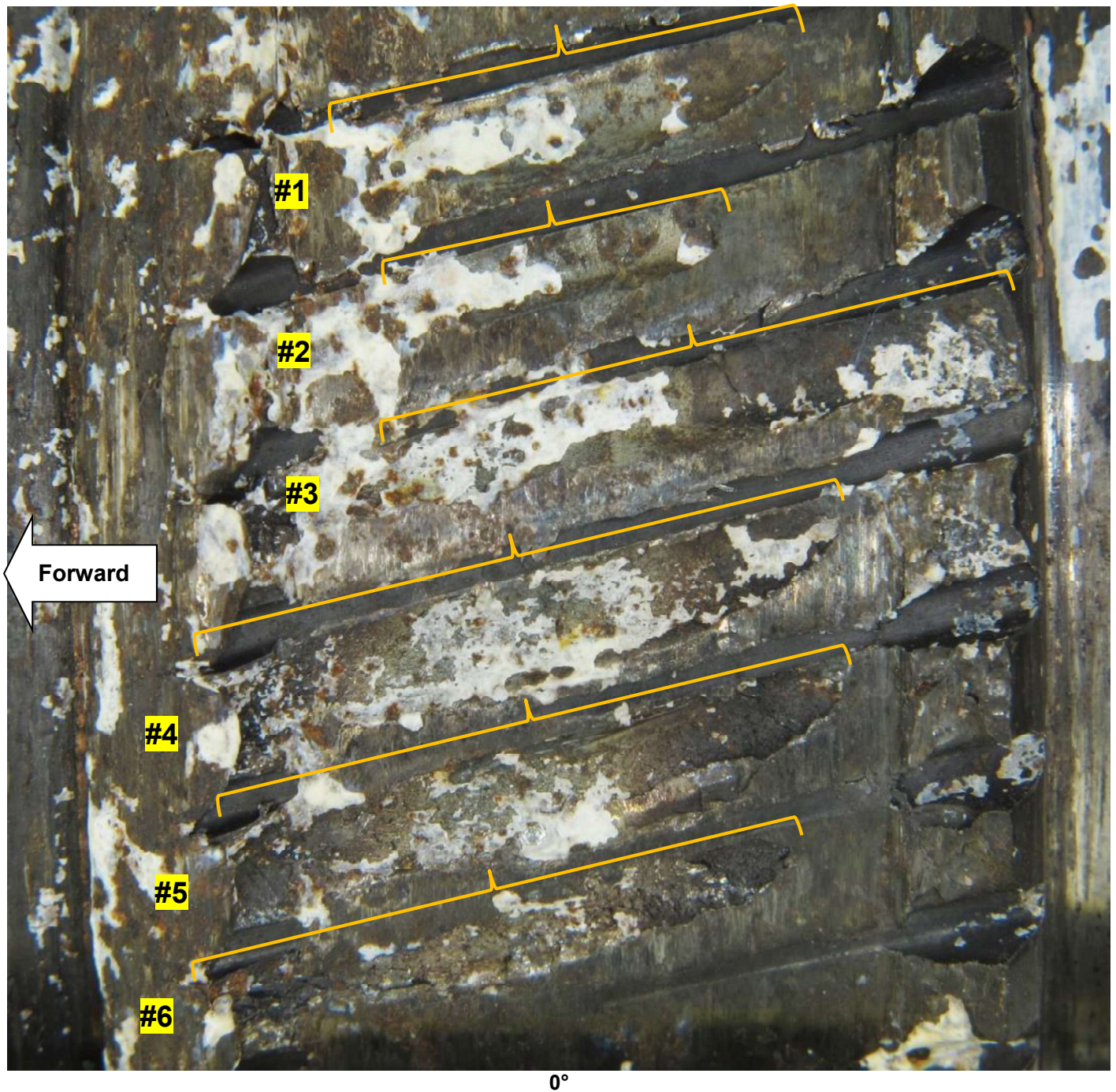


Figure 4. Detailed view of the gear teeth at the 0° position, which exhibited six consecutive intact fracture surfaces (orange braces).

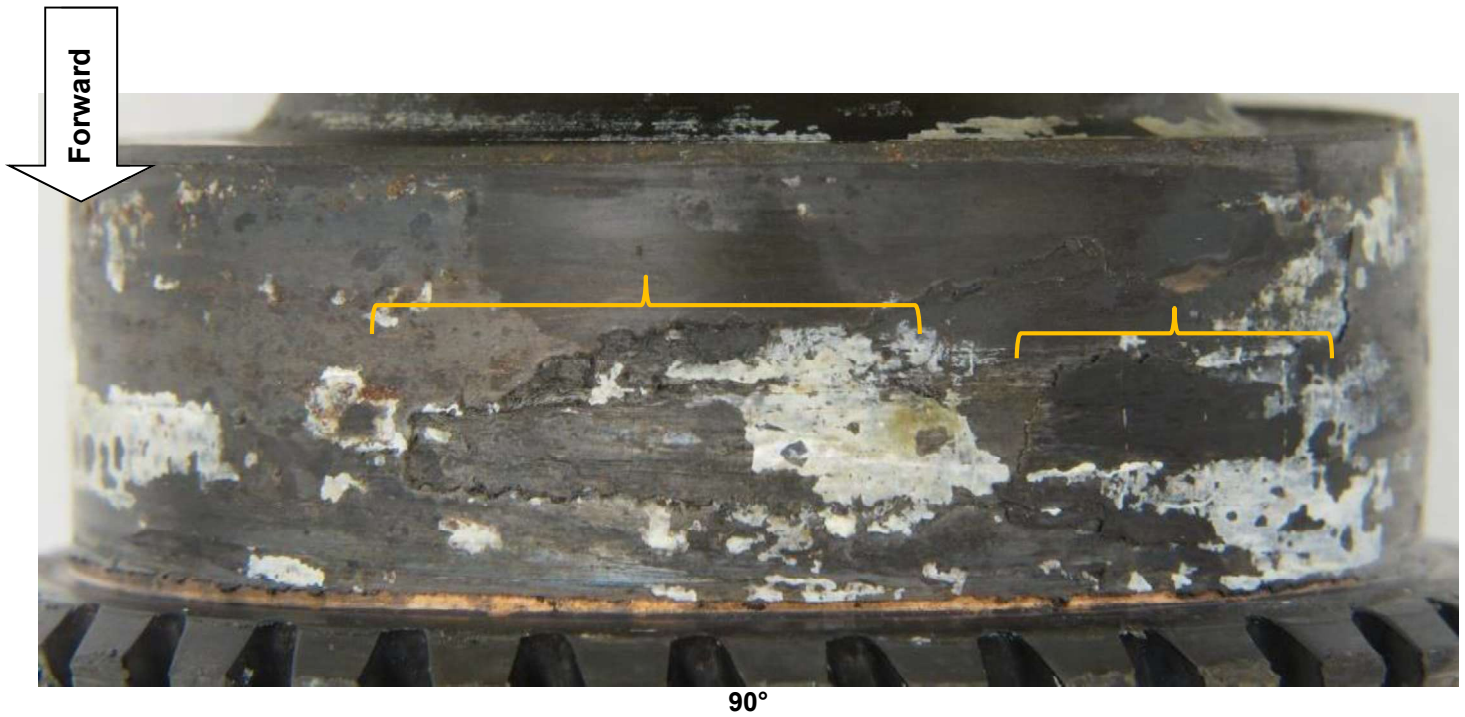


Figure 5. Detailed views of No. 4 bearing journal, which exhibited circumferential rub and transferred material (orange braces). Each image shows the part rotated $\sim 90^\circ$ from the previous.



180°

Forward



270°

Figure 6. Detailed views of No. 4 bearing journal, which exhibited circumferential rub. Each image shows the part rotated ~90° from the previous.

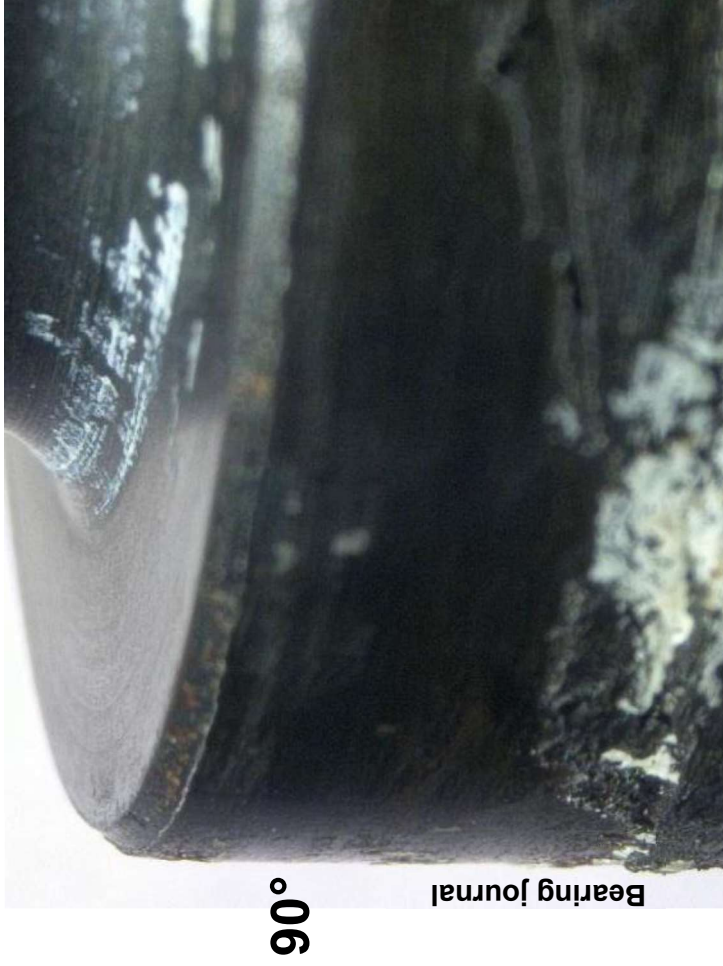
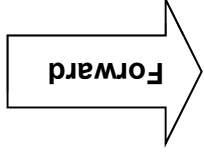


Figure 7. Detailed views of the aft end of the No. 4 bearing journal at the least severe (90° position, left image) and most severe (270° position, right image) rub damage. Red brace marks a lip of deformed material at the region of most severe journal rub damage.

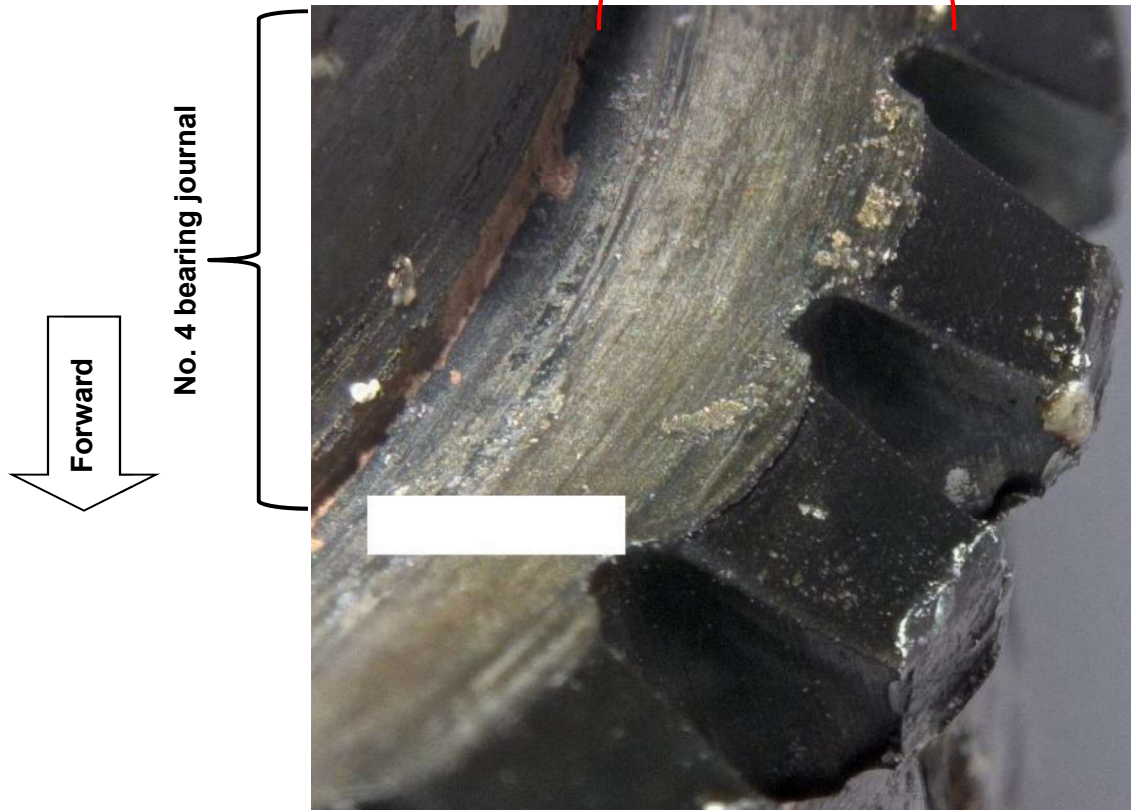


Figure 8. Detailed view of the aft end of the gear teeth, which exhibited circumferential rub (red brace).



Figure 9. Detailed view of the inner diameter and inner flange forward face, which exhibited circumferential rub.

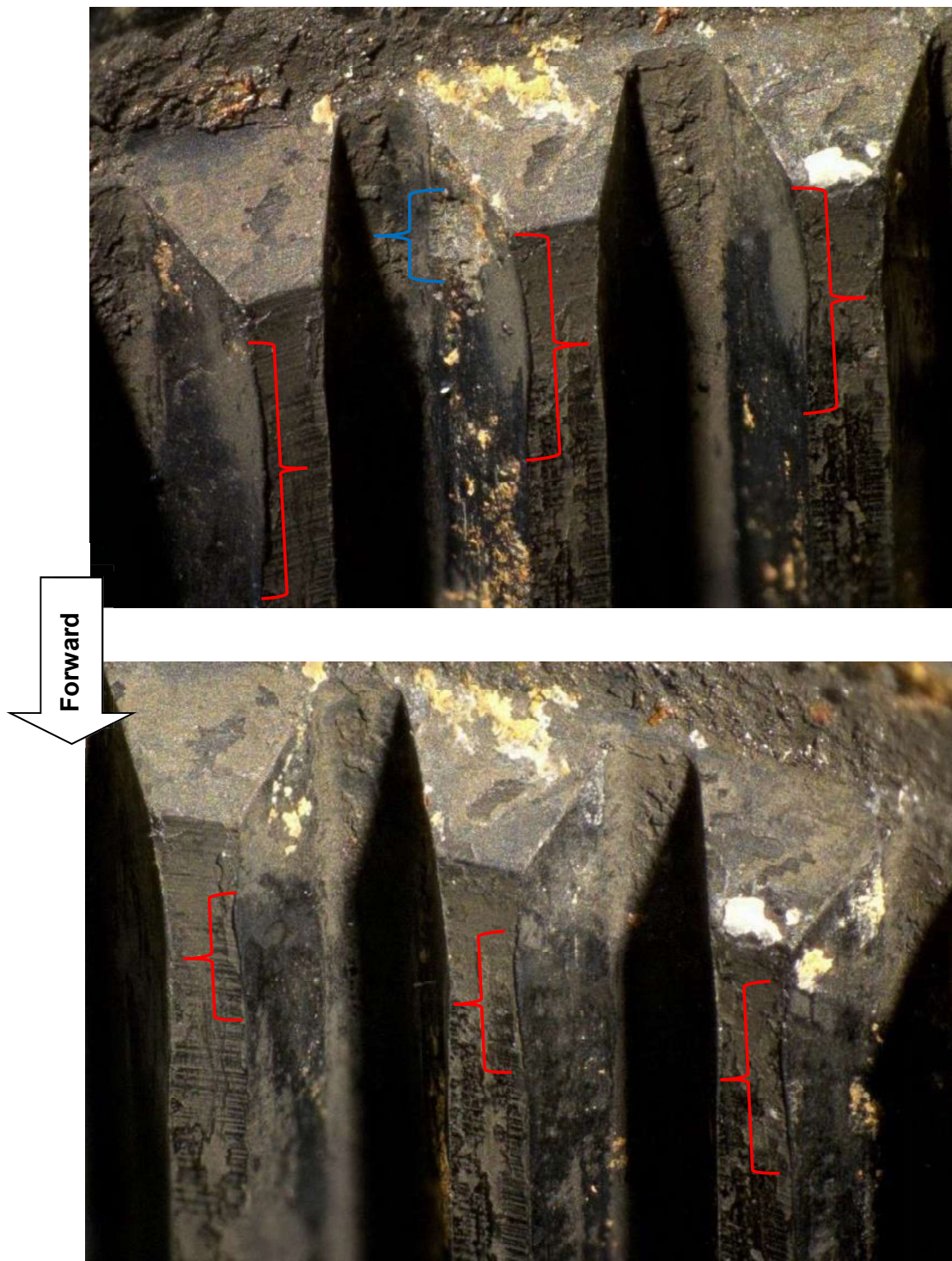


Figure 10. Detailed views of the loaded (top) and unloaded (bottom) flanks of the inner splines, which exhibited mechanical deformation on the aft end of both sides (red braces). The blue brace marks a region on the loaded flank on one spline where material fractured away.

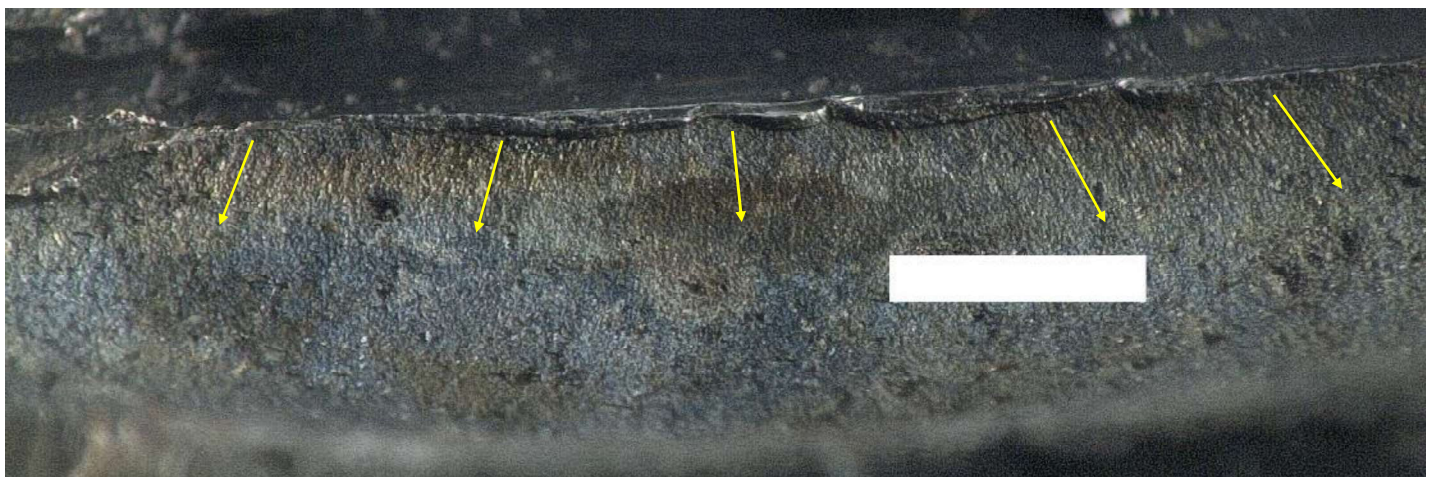
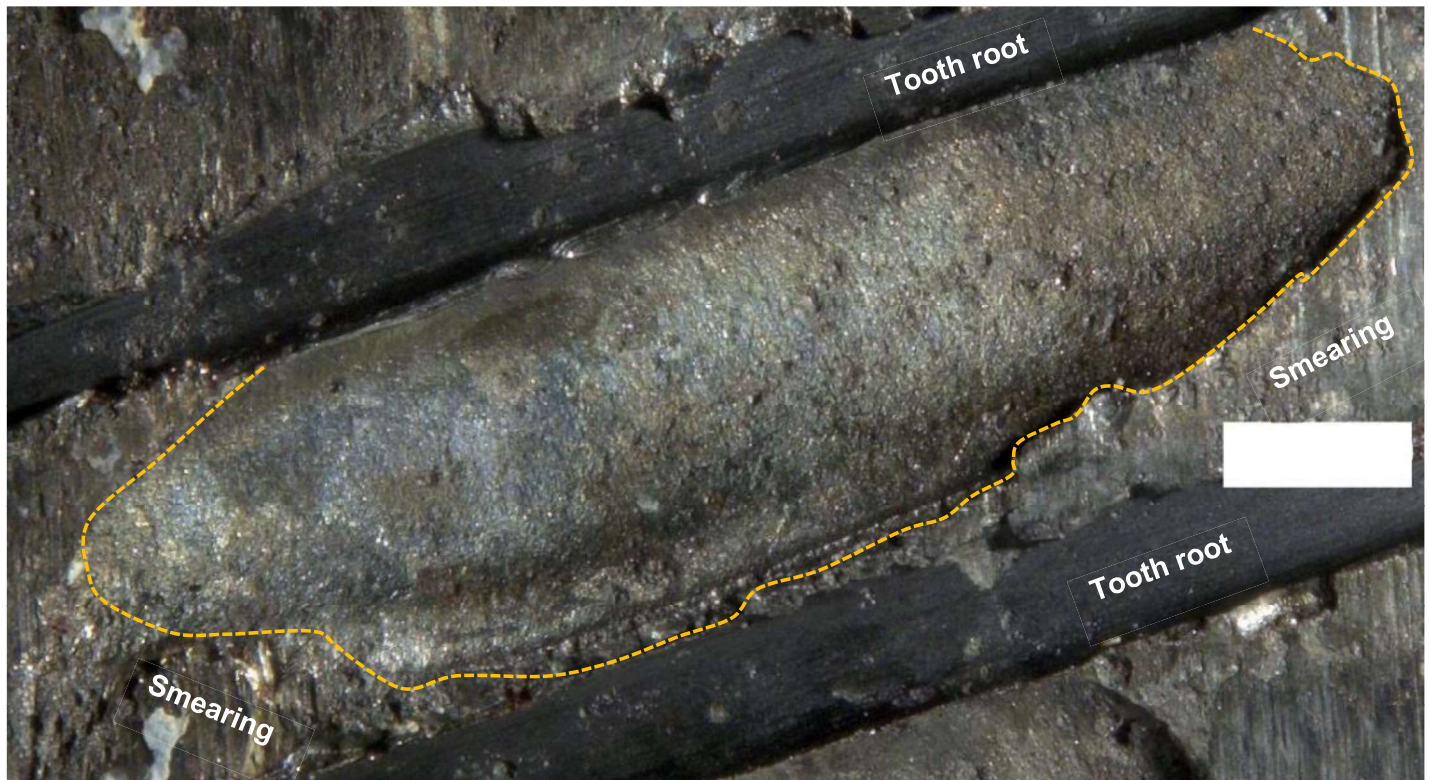


Figure 11. Detailed views of fracture surface at gear tooth number 1 after cleaning. The yellow arrows mark the direction of fatigue progression, the orange dotted line marks the transition from fatigue to smearing damage.

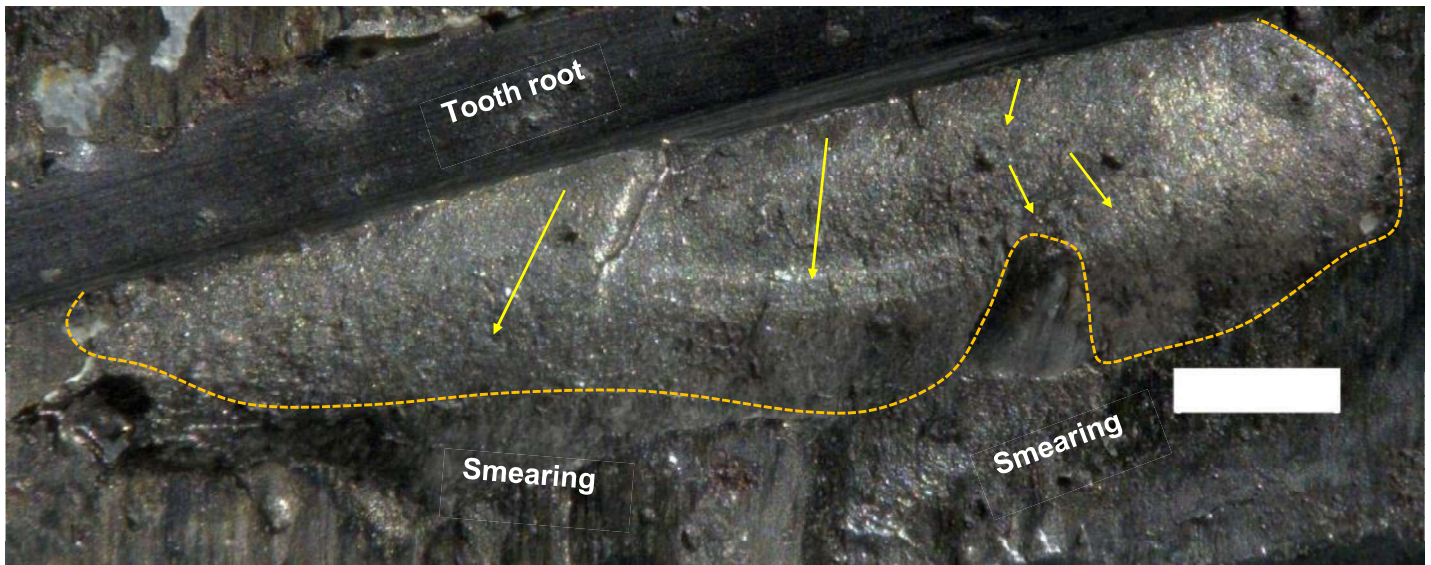


Figure 12. Detailed views of fracture surfaces at gear tooth number 2 after cleaning. The yellow arrows mark the direction of fatigue progression, and the orange dotted line marks the transition from fatigue to smearing damage.

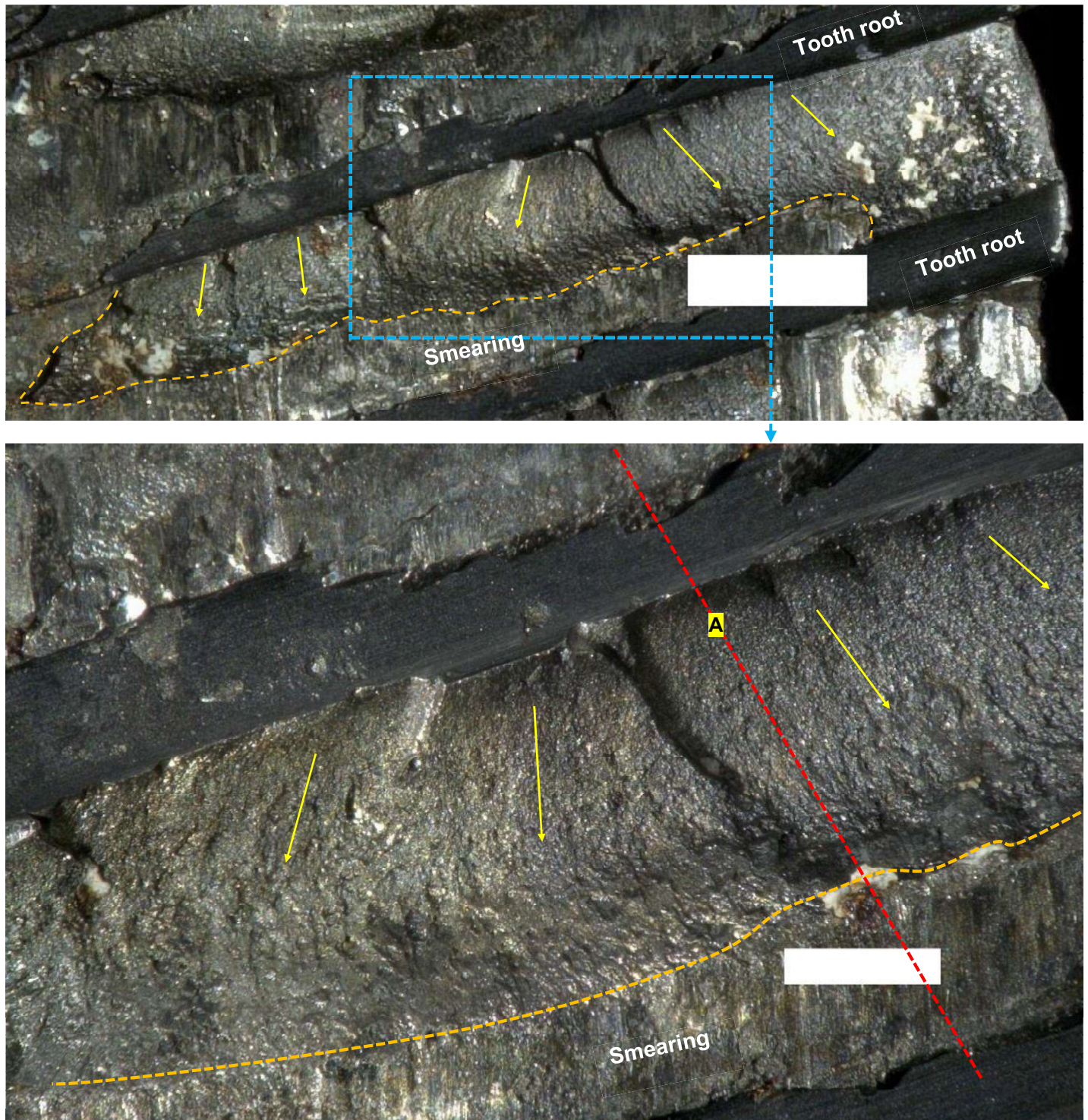


Figure 13. Detailed views of fracture surfaces at gear tooth number 3 after cleaning. The yellow arrows mark the direction of fatigue progression, the orange dotted line marks the transition from fatigue to smearing damage, the red dashed line marks the plane of metallographic evaluation (see Figure 20), and location A is shown in more detail in the following figure.

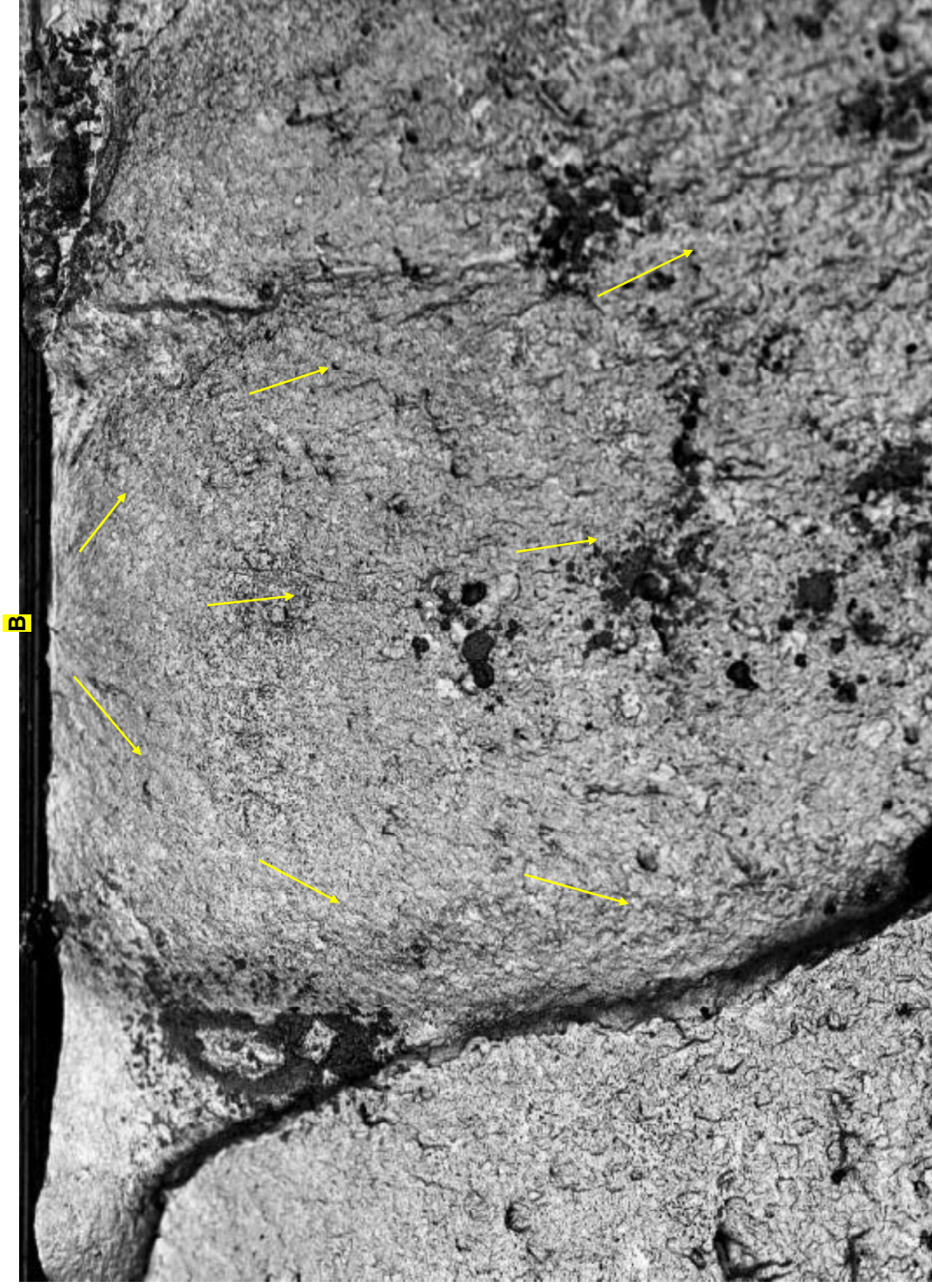


Figure 14. Backscattered electron SEM image of fracture surfaces at gear tooth number 3 (location A in previous figure). The yellow arrows mark the direction of fatigue progression, and location B is shown in more detail in the following figure.

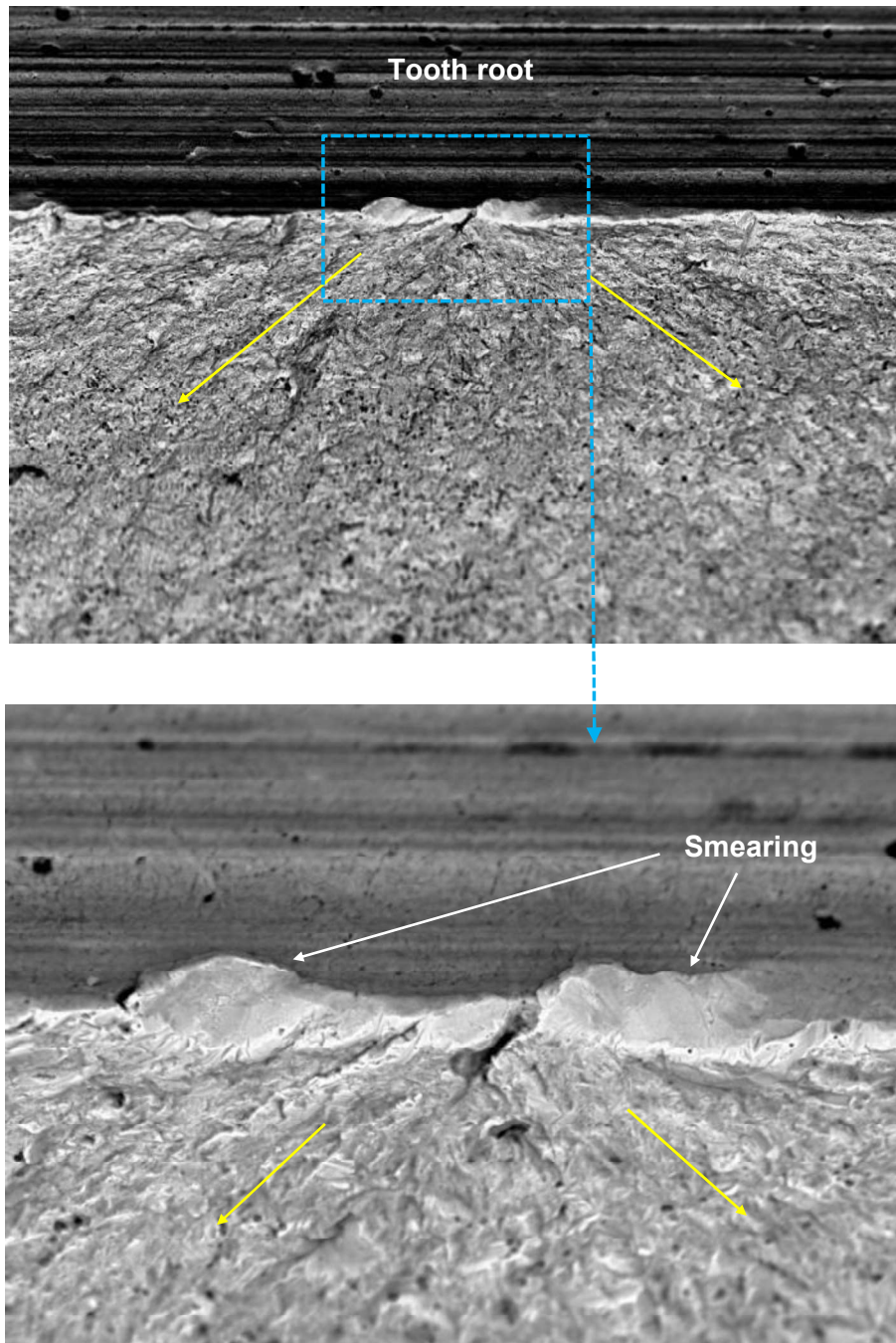


Figure 15. Backscattered electron SEM images of fracture surfaces at gear tooth number 3 (location B in previous figure). The yellow arrows mark the direction of fatigue progression.

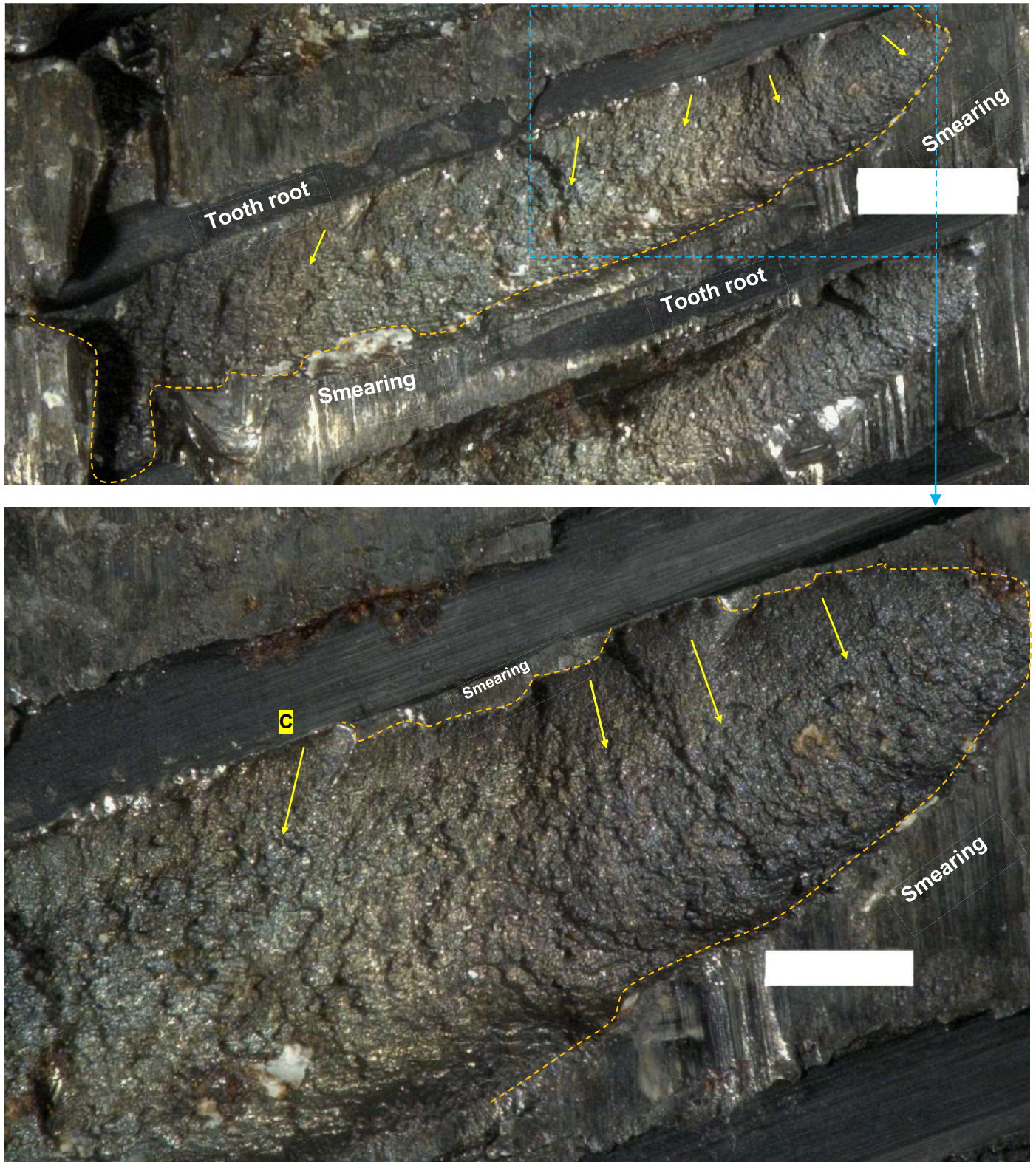


Figure 16. Detailed views of fracture surfaces at gear tooth number 4 after cleaning. The yellow arrows mark the direction of fatigue progression, the orange dotted line marks the transition from fatigue to smearing damage, and location C is shown in more detail in the following figure.

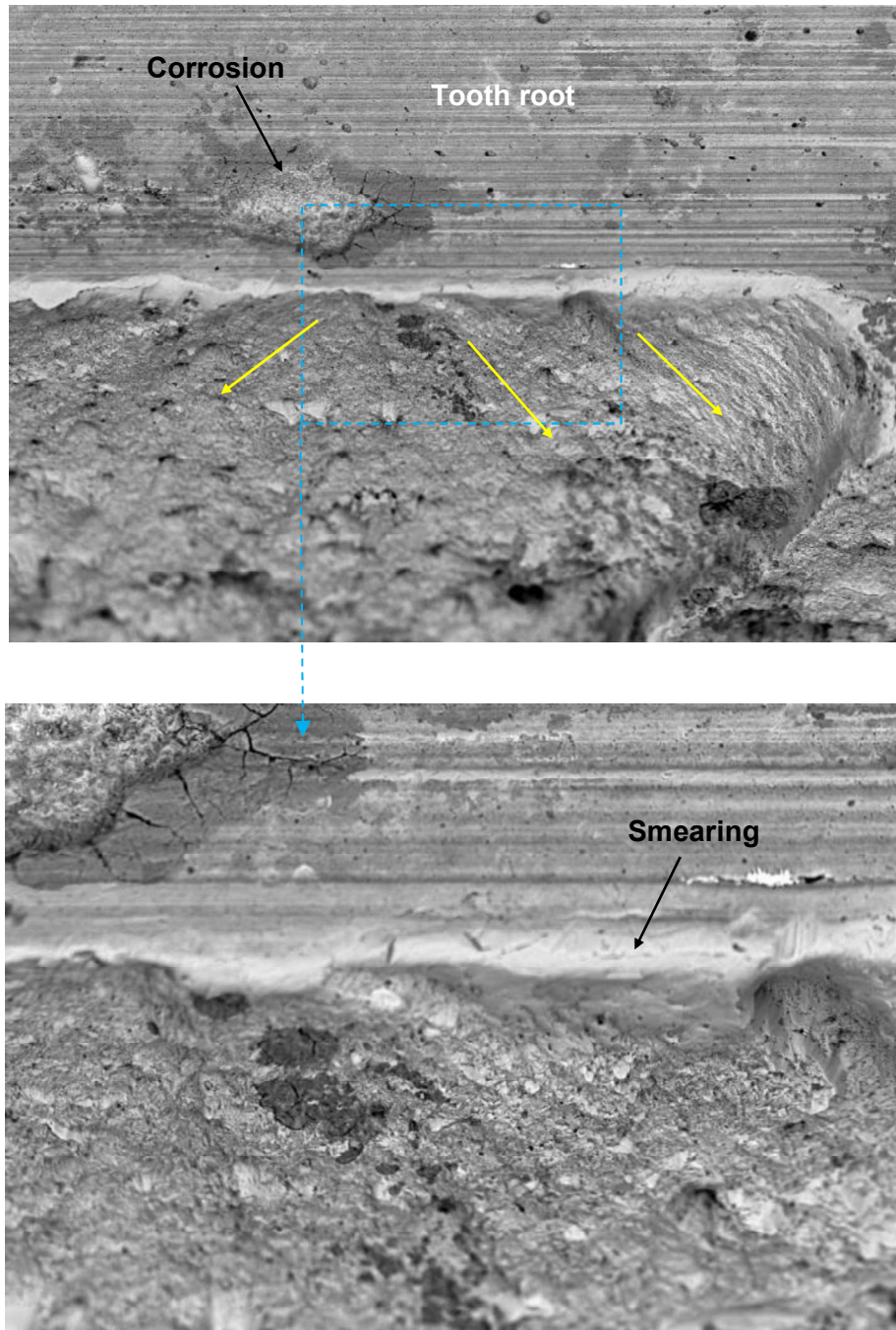


Figure 17. Backscattered electron SEM image of fracture surfaces at gear tooth number 4 (location C in previous figure). The yellow arrows mark the direction of fatigue progression.

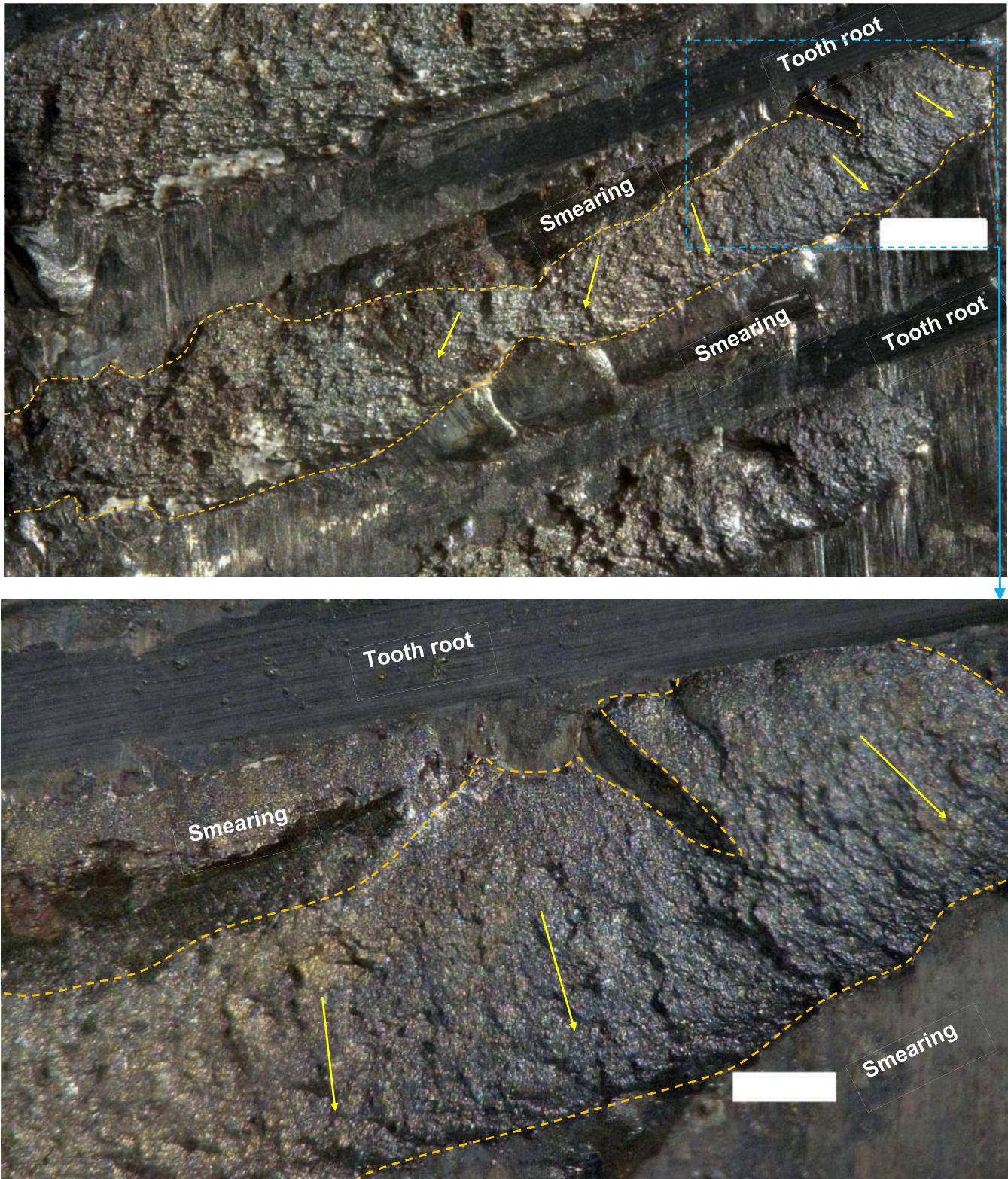


Figure 18. Detailed views of fracture surfaces at gear tooth number 5 after cleaning. The yellow arrows mark the direction of fatigue progression, and the orange dotted line marks the transition from fatigue to smearing damage.

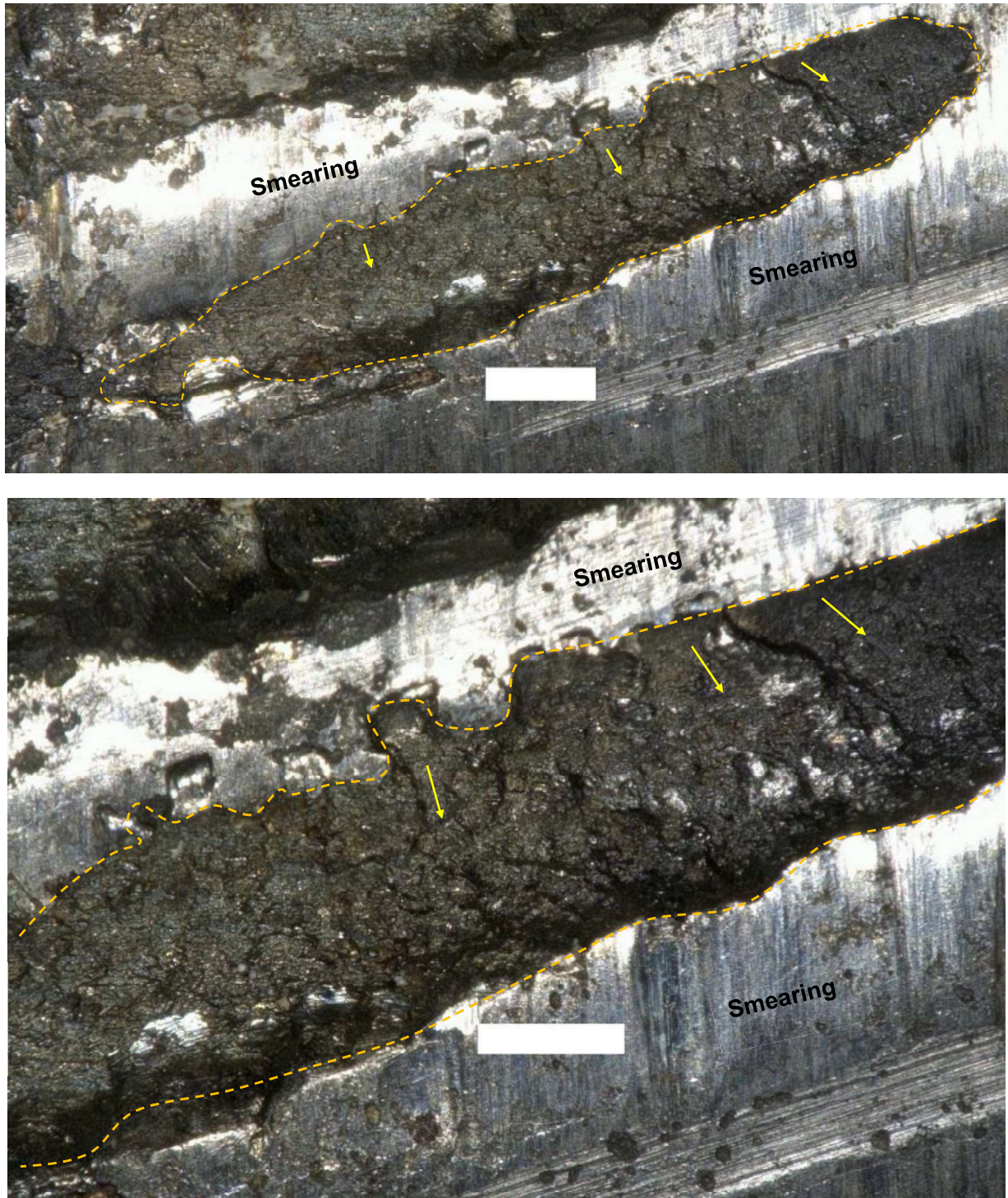


Figure 19. Detailed views of fracture surfaces at gear tooth number 6 after cleaning. The yellow arrows mark the direction of fatigue progression, and the orange dotted line marks the transition from fatigue to smearing damage.

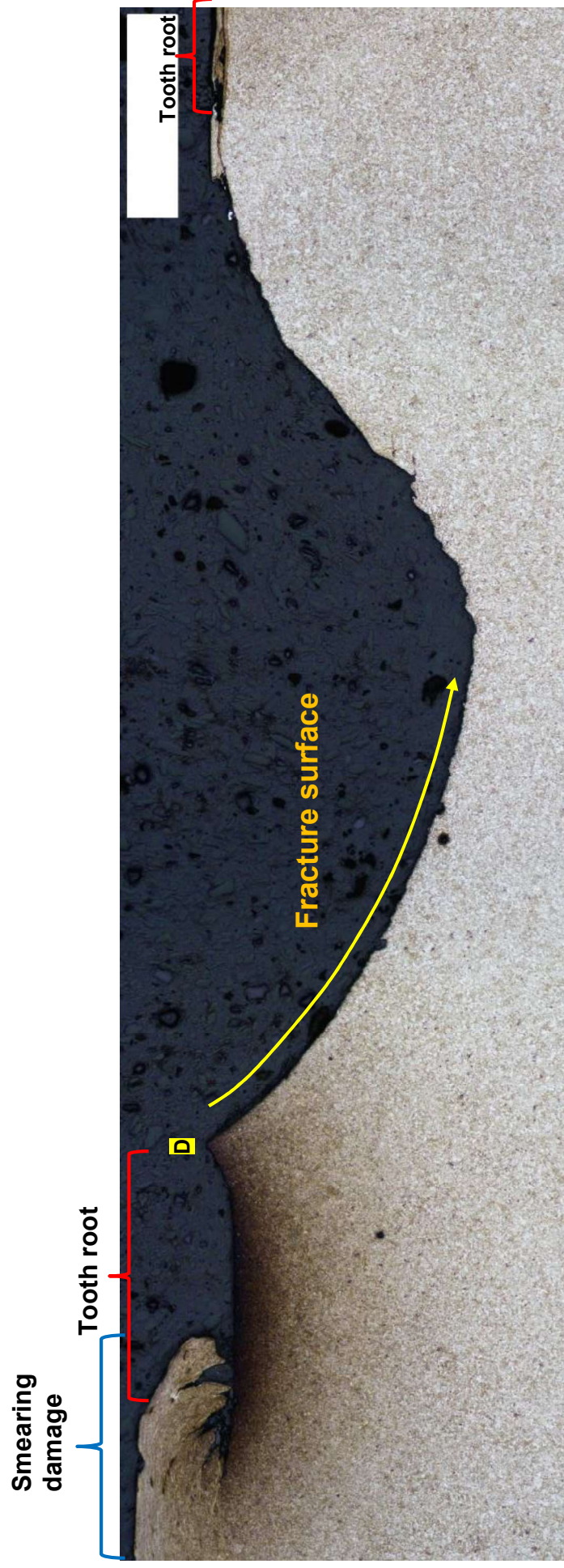


Figure 20. Metallographic cross-section through the fracture surface at gear tooth number 3 (see red dashed line in Figure 13). Yellow arrow marks the direction of fatigue progression, and location D is shown in more detail in the following figure. Etchant: 5% Nital

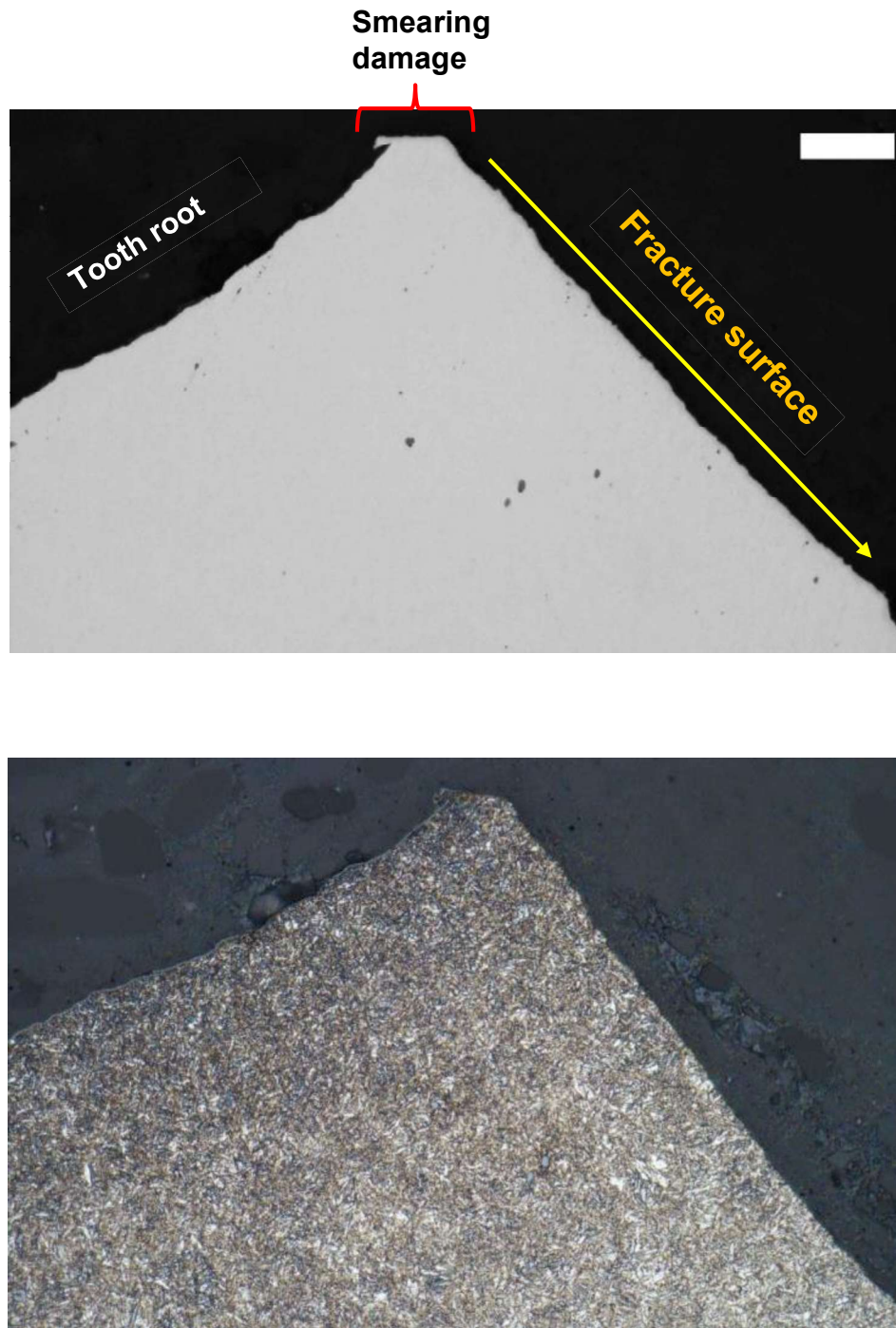


Figure 21. Metallographic cross-section through the origin area of the fracture surface at gear tooth number 3 (see location D in the previous figure) in the unetched (top) and etched condition (bottom). Yellow arrow marks the direction of fatigue progression. Etchant: 5% Nital (bottom)

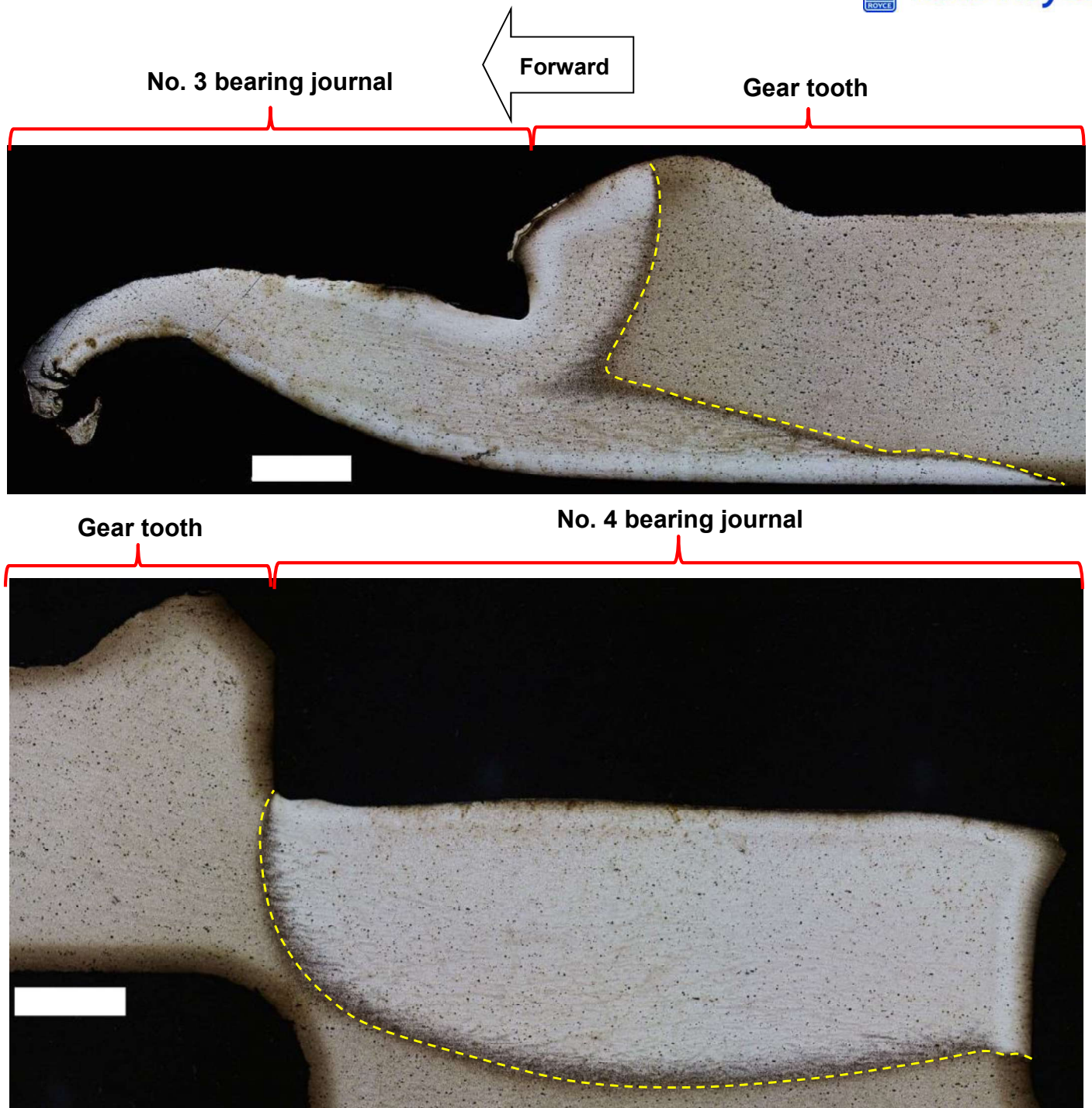


Figure 22. Metallographic cross-sections through the No. 3 (top) and No. 4 (bottom) bearing journals on the pinion gear (see yellow and orange dashed lines in Figure 3, respectively). Yellow outlines mark the locations of thermal distress on the journals. Etchant: Vilella's

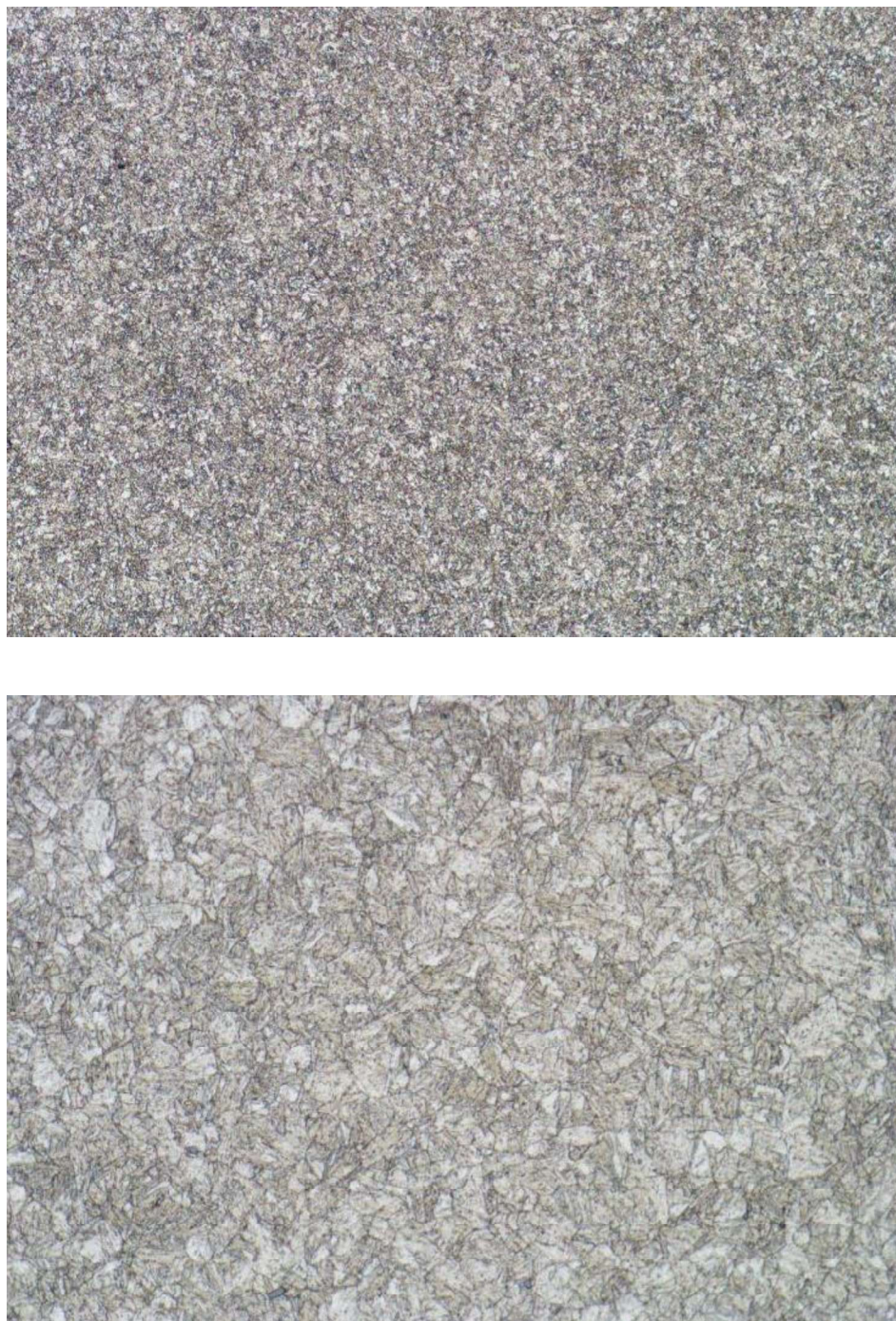


Figure 23. Representative images of the core microstructure of the pinion gear. Etchant: 5% Nital



Figure 24. General condition of the bearing-stepped pinion cage after cleaning.

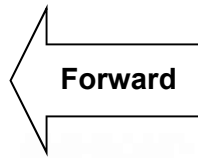


Figure 25. Detailed views of the No. 3 bearing (left) and No. 4 bearing (right) outer rings assembled in the bearing-stepped pinion cage.



Figure 26. Two views of the No. 3 bearing outer ring, after it was sectioned and cleaned, showing the condition of the outer raceway surface. Red braces mark the location of material removal at the roller path, and the yellow dashed line marks the plane of metallographic evaluation (see Figure 29).



Figure 27. Detailed inboard looking outboard and oblique views of the No. 3 bearing outer ring raceway. Red braces mark the location of material removal at the roller path, and the orange braces mark rub damage on the forward shoulder corner.

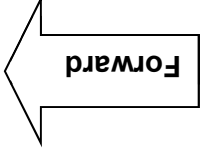


Figure 28. Representative view of outer diameter of the outer ring.

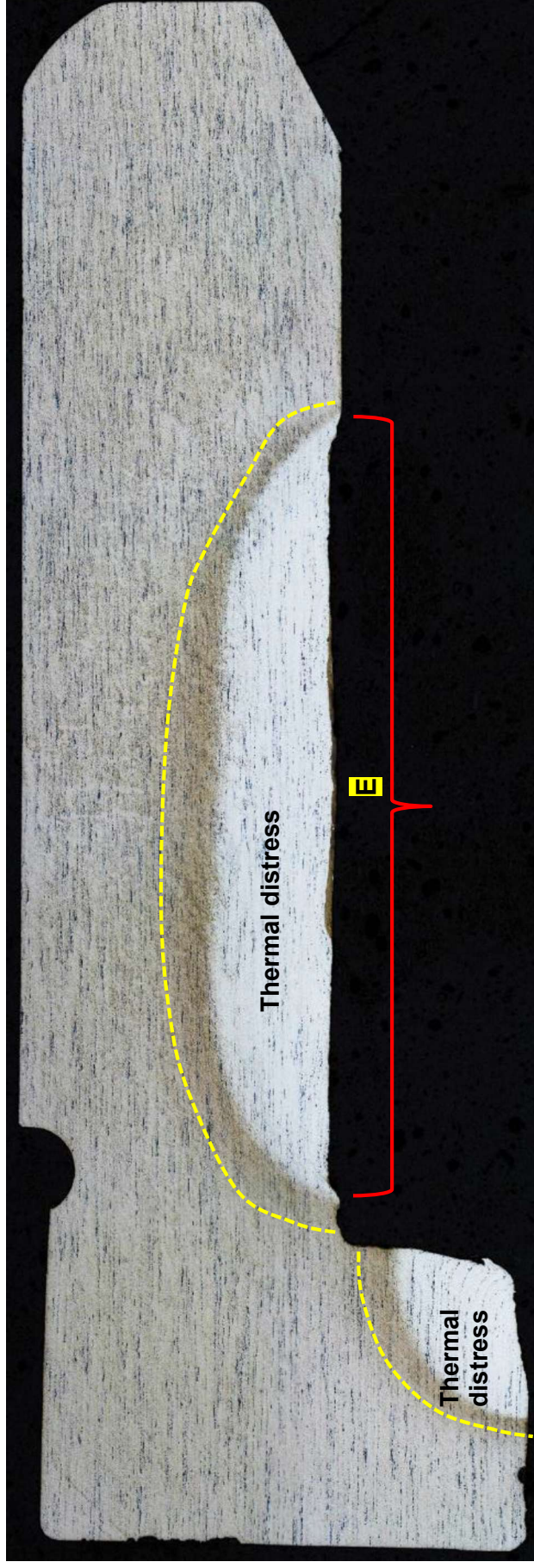
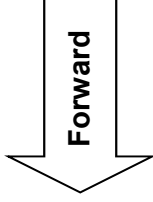


Figure 29. Metallographic cross-section through the outer ring (see yellow dashed line in Figure 26). Yellow outlines mark the boundaries of thermal distress on the raceway and forward shoulder corner, and the red brace marks material removal at the roller path. Location E is shown in more detail in the following figure. Etchant: Vilella's

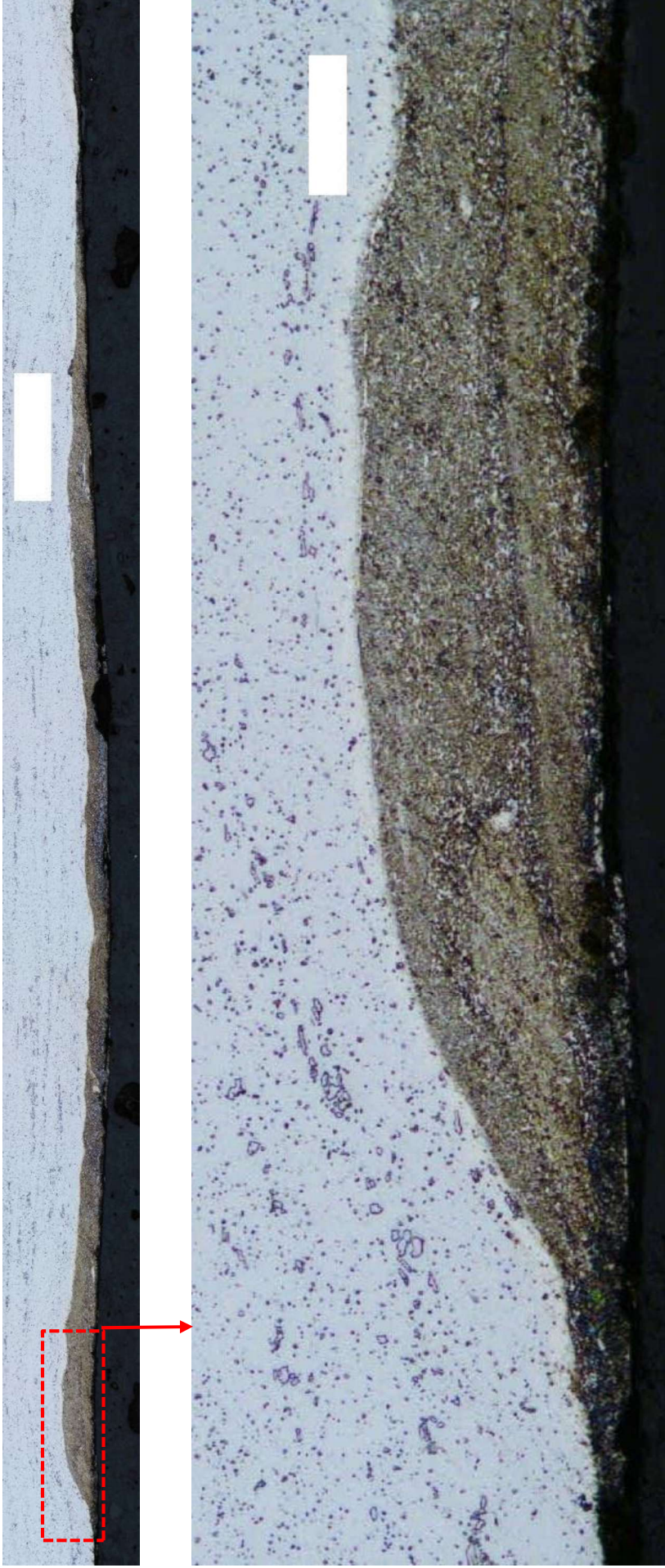


Figure 30. Metallographic cross-section through the outer ring raceway, which exhibited transferred material. Etchant: Vilella's



Figure 31. Representative outer ring microstructure away from the thermally distressed region. Etchant: Vilella's



Figure 32. Two views of the No. 4 bearing outer ring, after it was sectioned and cleaned, showing the condition of the outer raceway surface. Red braces mark the location of material removal at the roller path, and the yellow dashed line marks the plane of metallographic evaluation (see Figure 41).



Figure 33. Detailed inboard looking outboard and oblique views of the No. 4 bearing outer ring raceway. Red braces mark the location of material removal at the roller path, and the orange braces mark rub damage on the aft shoulder corner.

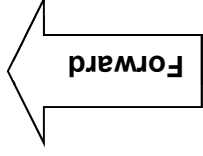


Figure 34. Representative view of outer diameter of the outer ring.



Figure 35. General views of the No. 4 bearing inner ring after cleaning showing the condition of the inner raceway surface, which exhibited transferred material. Red braces mark the location of roller impressions, and the yellow dashed line marks the plane of metallographic evaluation (see Figure 41).



Figure 36. General views of the No. 4 bearing inner ring after cleaning showing the condition of the inner raceway surface, which exhibited transferred material. Red braces mark the location of roller impressions.

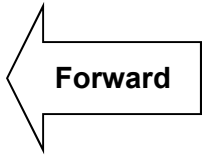


Figure 37. Detailed view of the inner raceway, which exhibited transferred material. Red braces mark the location of roller impressions. The forward shoulder was deformed forward.

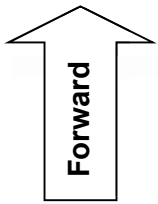


Figure 38. Top: General condition of the inner diameter of the inner ring, which exhibited circumferential rub and transferred material. Bottom: Detailed view of the forward face of the forward shoulder, which exhibited rub damage (red brace).



Figure 39. General condition of the No. 4 bearing rollers after cleaning.

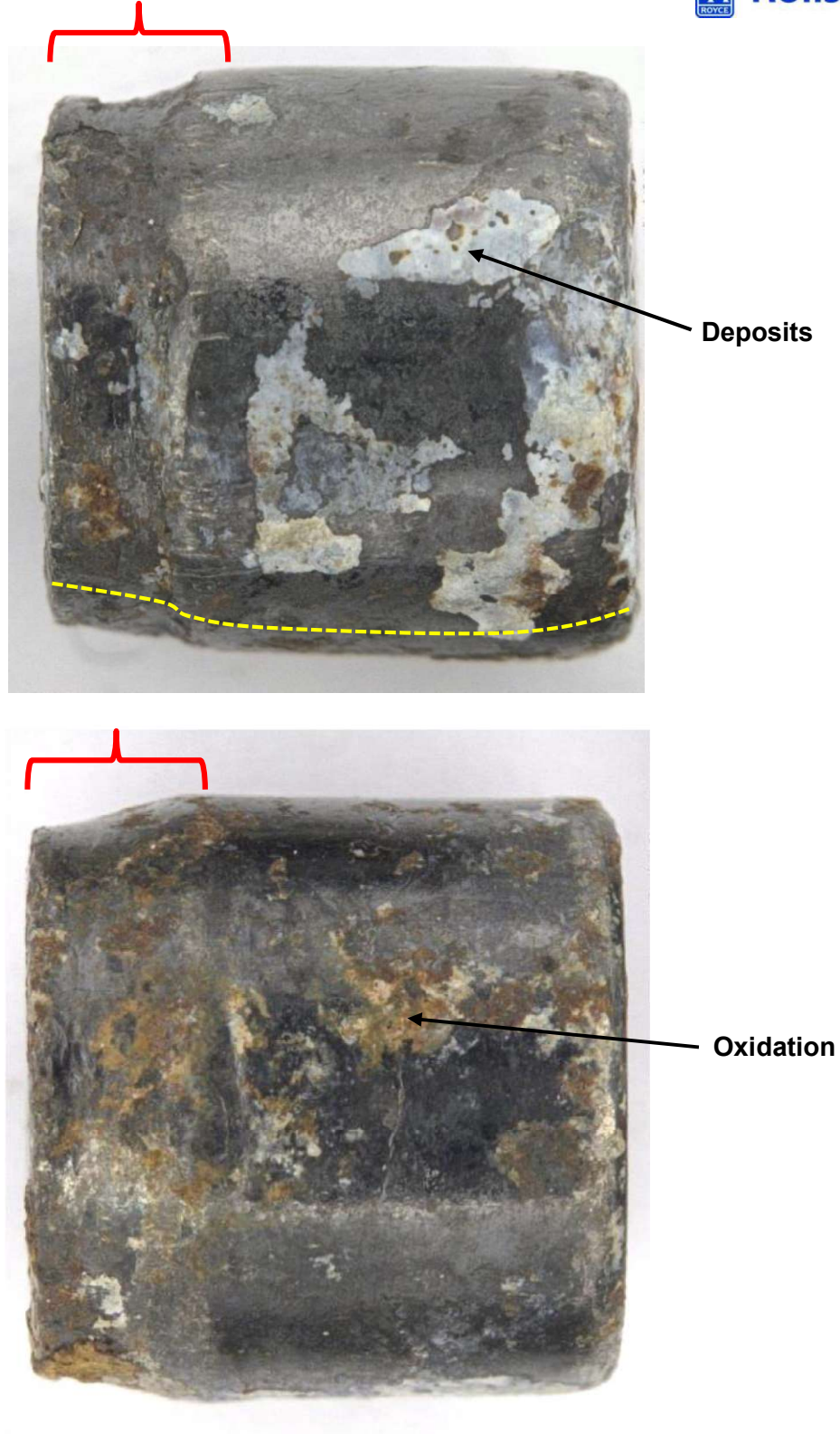


Figure 40. Detailed views of two representative rollers, which exhibited a circumferential rub step (red brace) on one corner of the diameter. Yellow dashed line marks the plane of metallographic evaluation (see Figure 41).

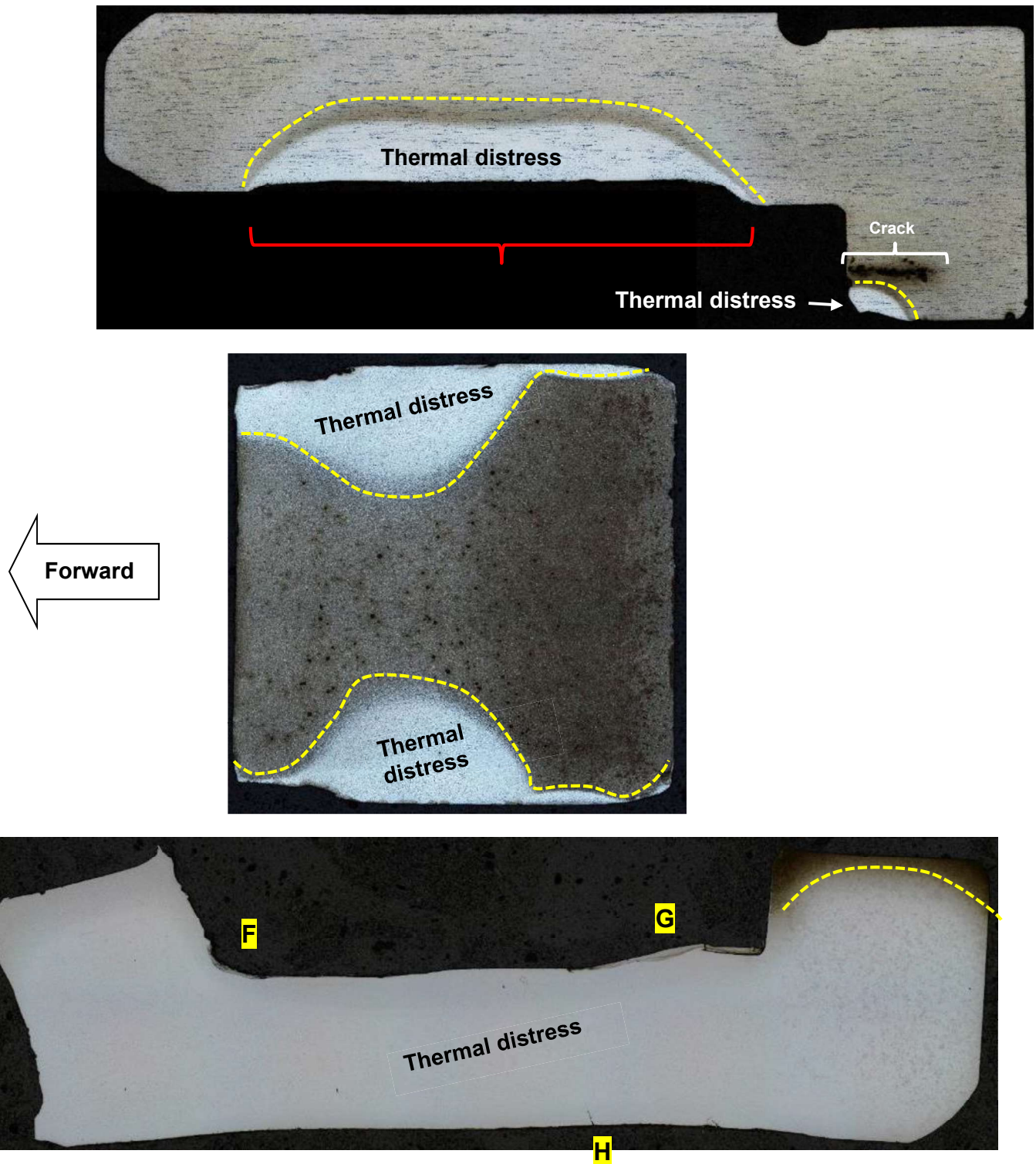


Figure 41. Metallographic cross-sections through the outer ring, a representative roller, and the inner ring (see yellow dashed lines in Figure 32, Figure 35, and Figure 40). Yellow outlines mark the locations of thermal distress on the outer ring raceway and aft shoulder corner, and the red brace marks material removal at the roller path. Locations F through H are shown in more detail in the following figures. Etchant: Vilella's

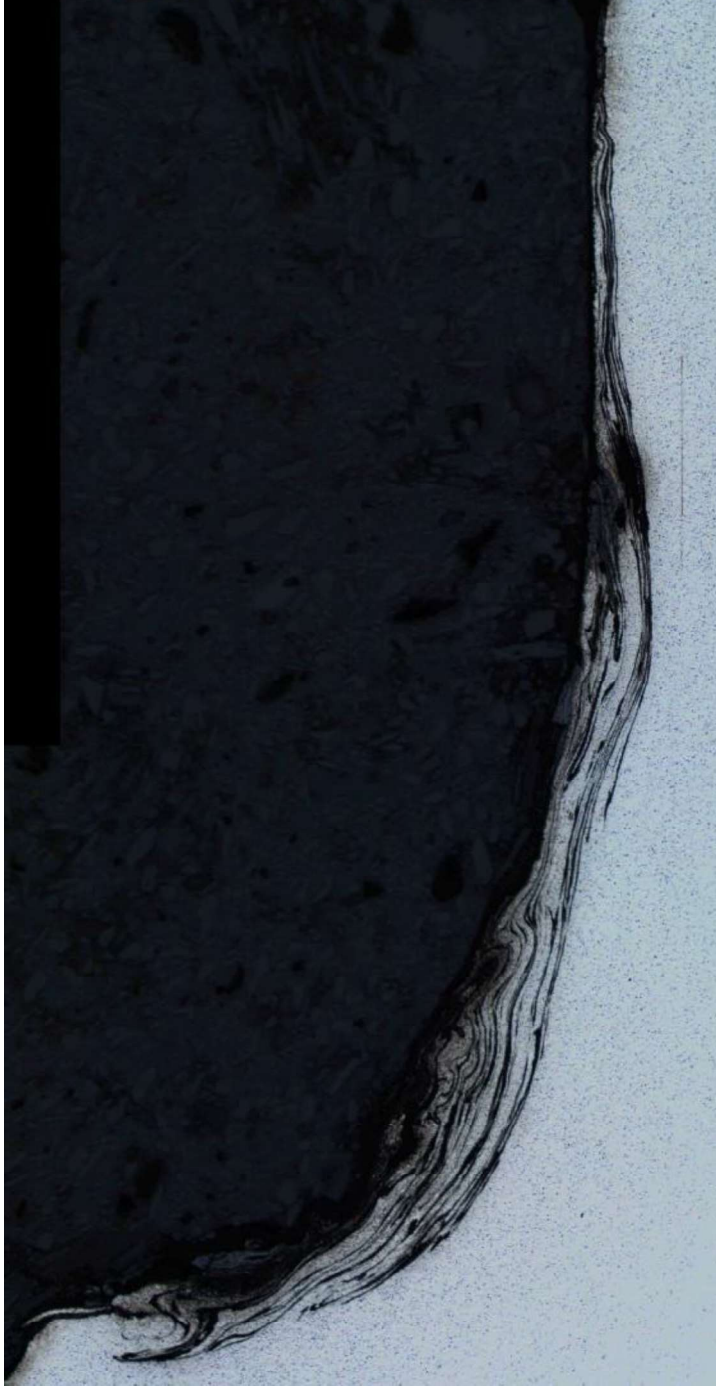


Figure 42. Metallographic cross-section through the forward (top) and aft (bottom) ends of the inner ring raceway (locations F and G in the previous figure, respectively), which exhibited transferred material. Etchant: Vilella's

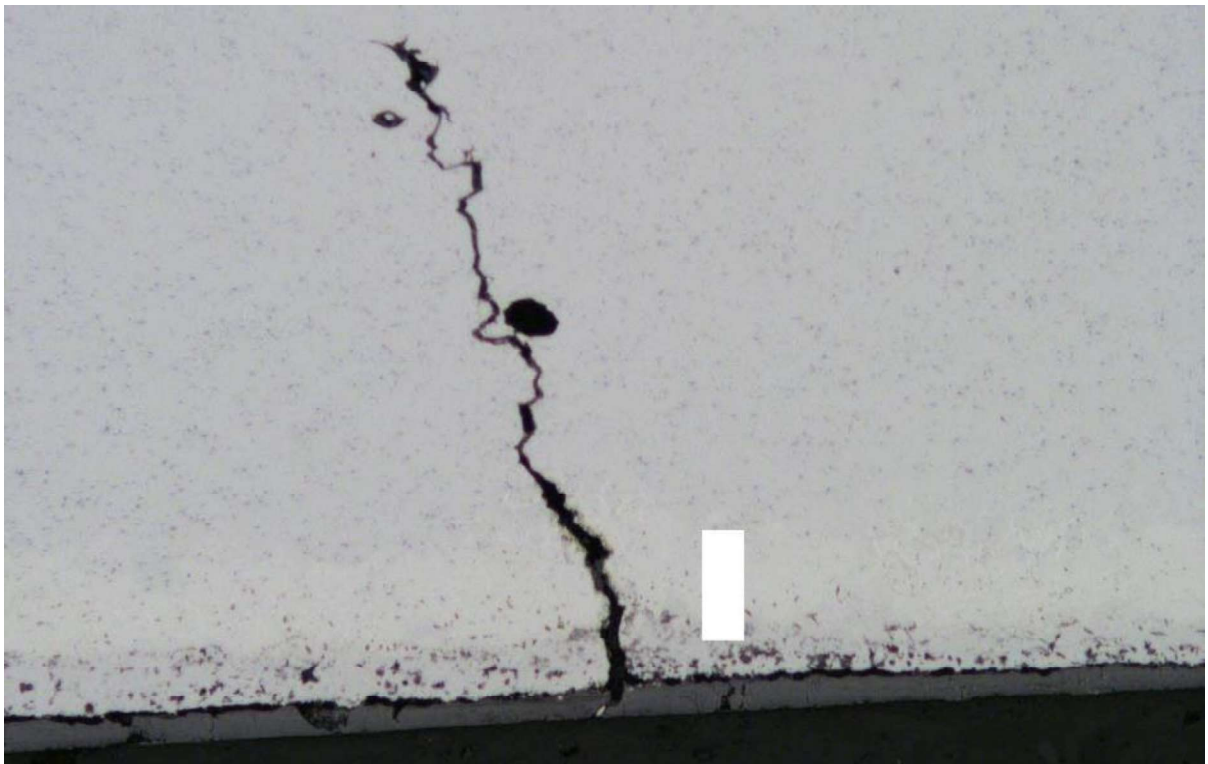


Figure 43. Metallographic cross-section through the inner diameter of the inner ring (location H in Figure 41), which exhibited cracking. Etchant: Vilella's

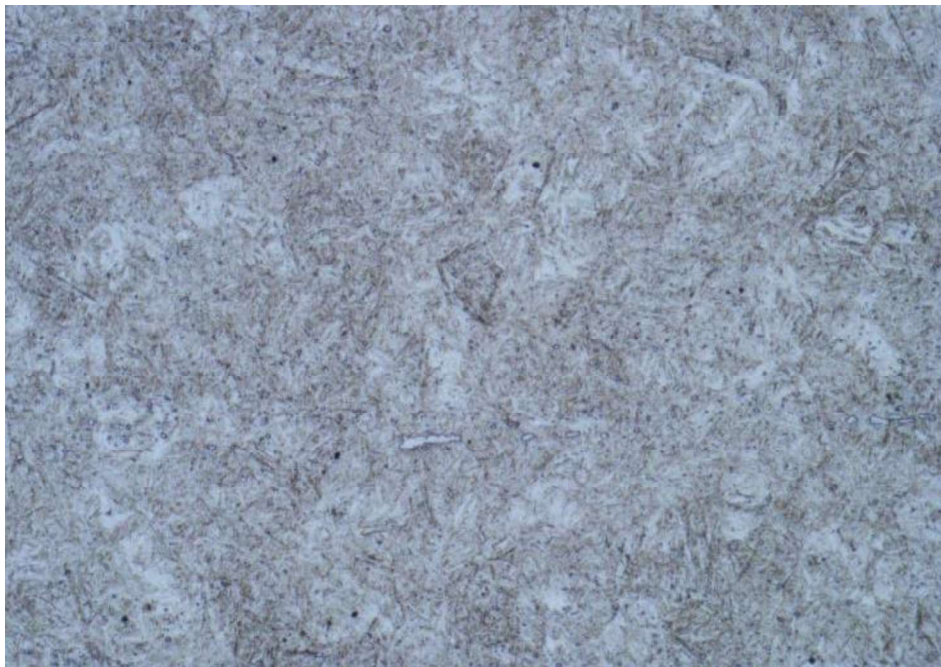
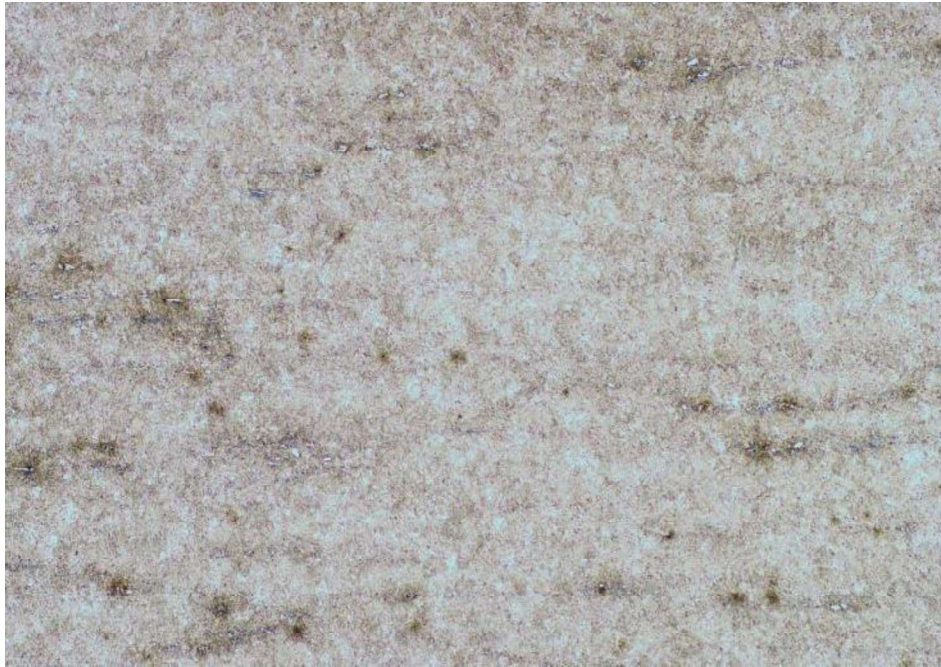


Figure 44. Representative outer ring microstructure away from the thermally distressed region. Etchant: Vilella's

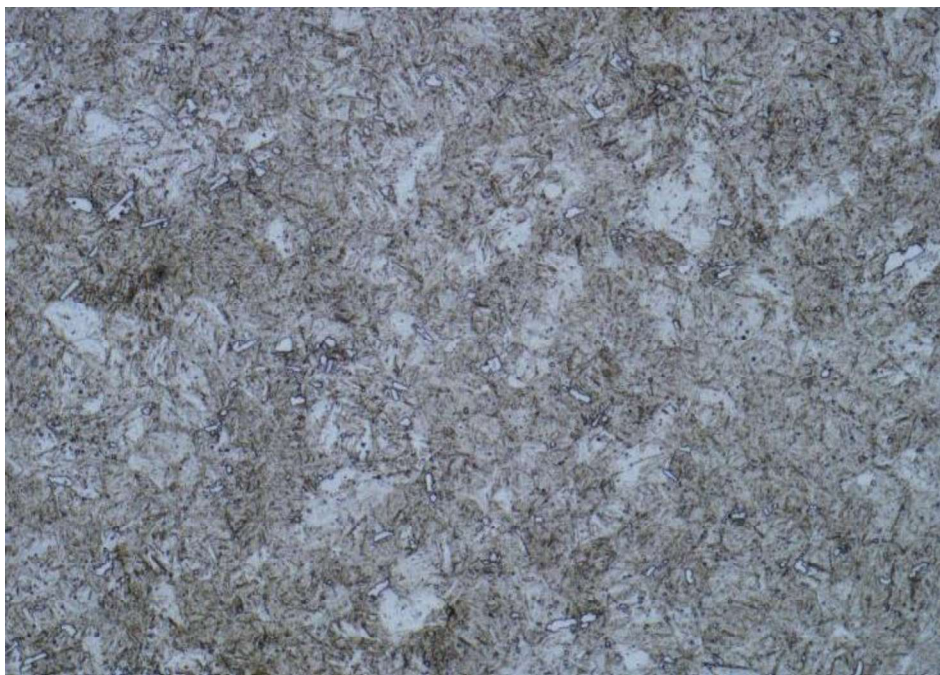


Figure 45. Representative roller microstructure away from the thermally distressed region. Etchant: Vilella's

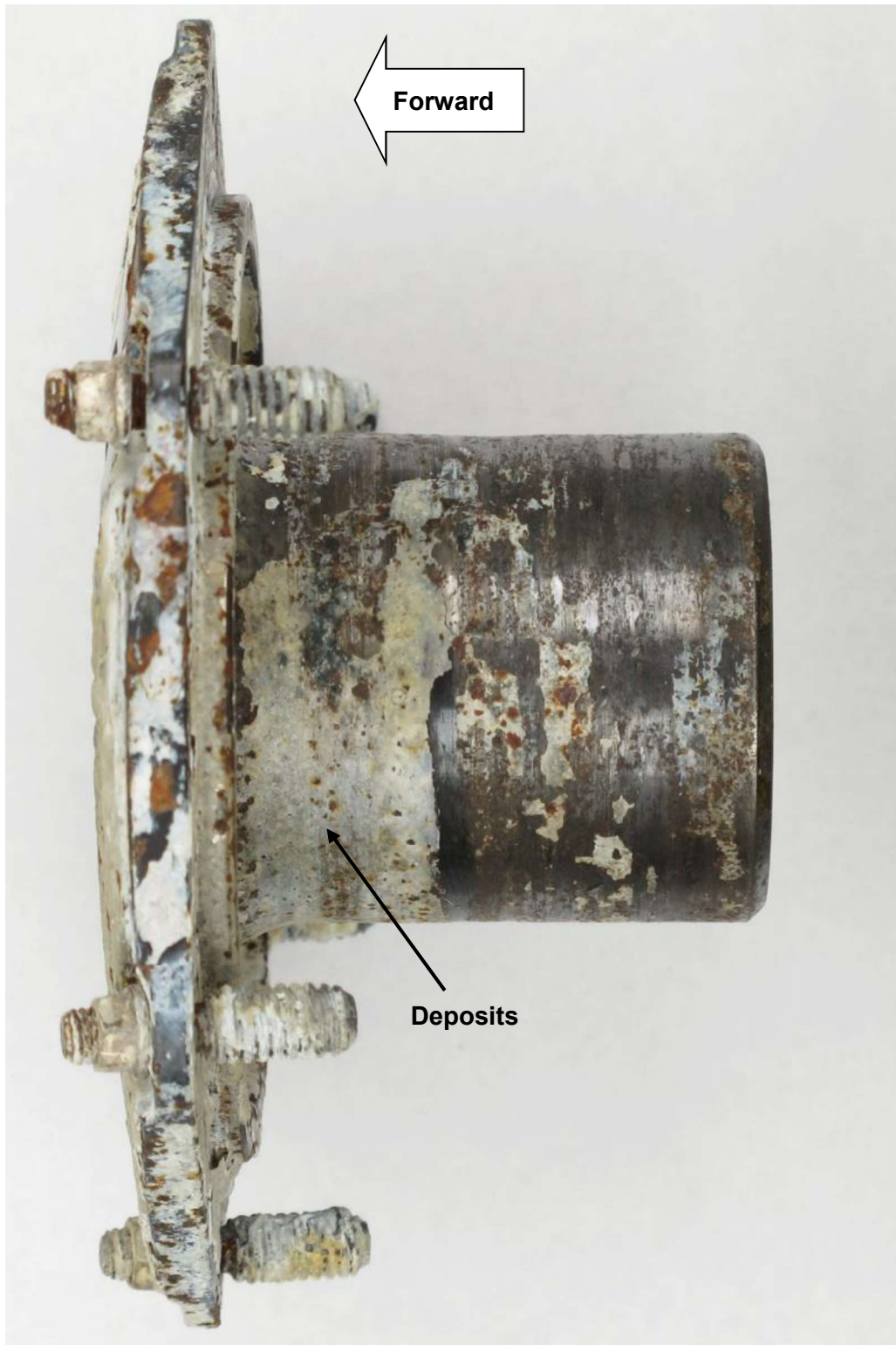


Figure 46. General condition of the flanged No. 2.5 bearing support cage after cleaning.

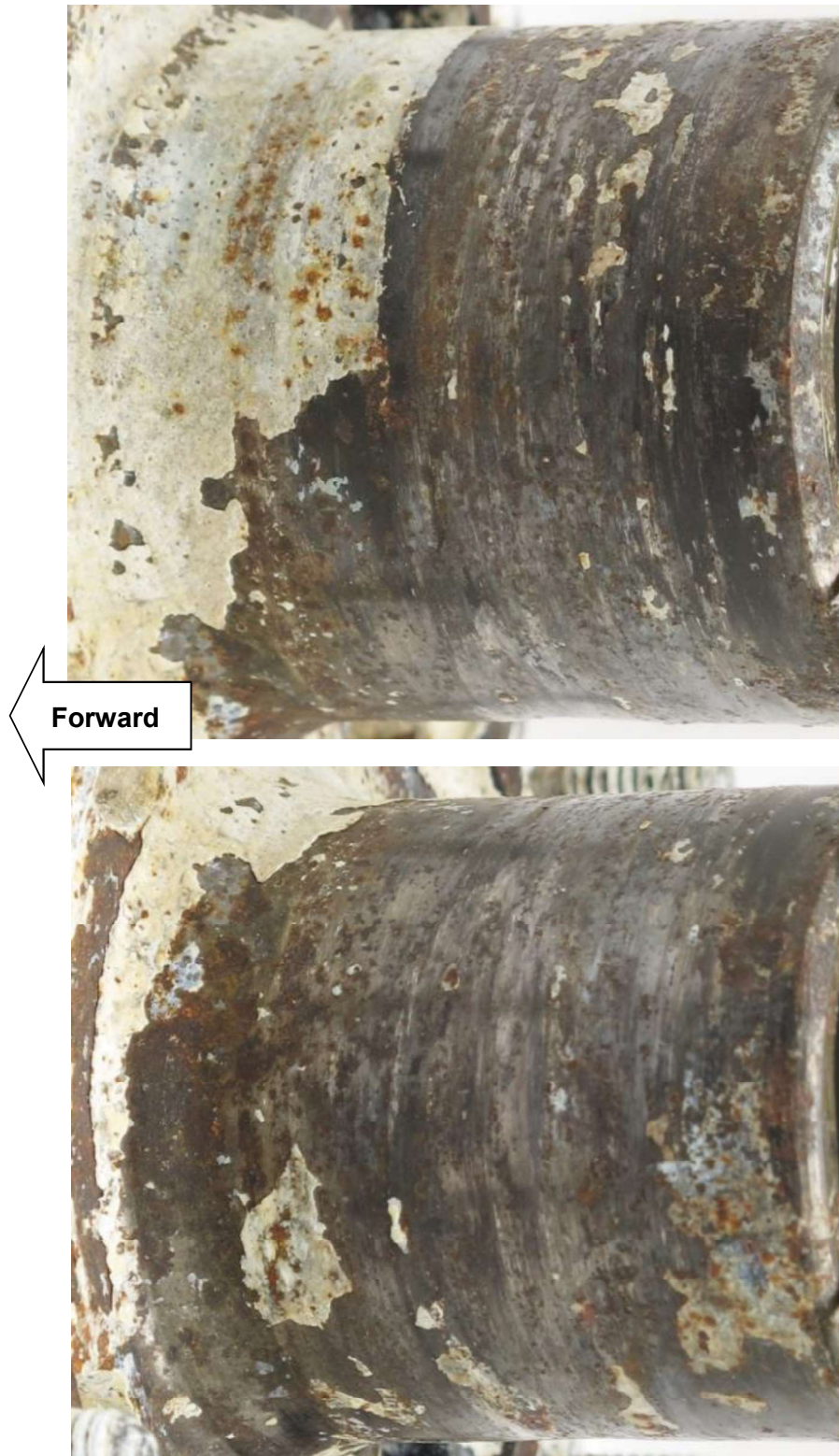


Figure 47. Detailed views of outer diameter of the flanged No. 2.5 bearing support cage, which exhibited circumferential rub. Each image shows the part rotated $\sim 90^\circ$ from the previous.

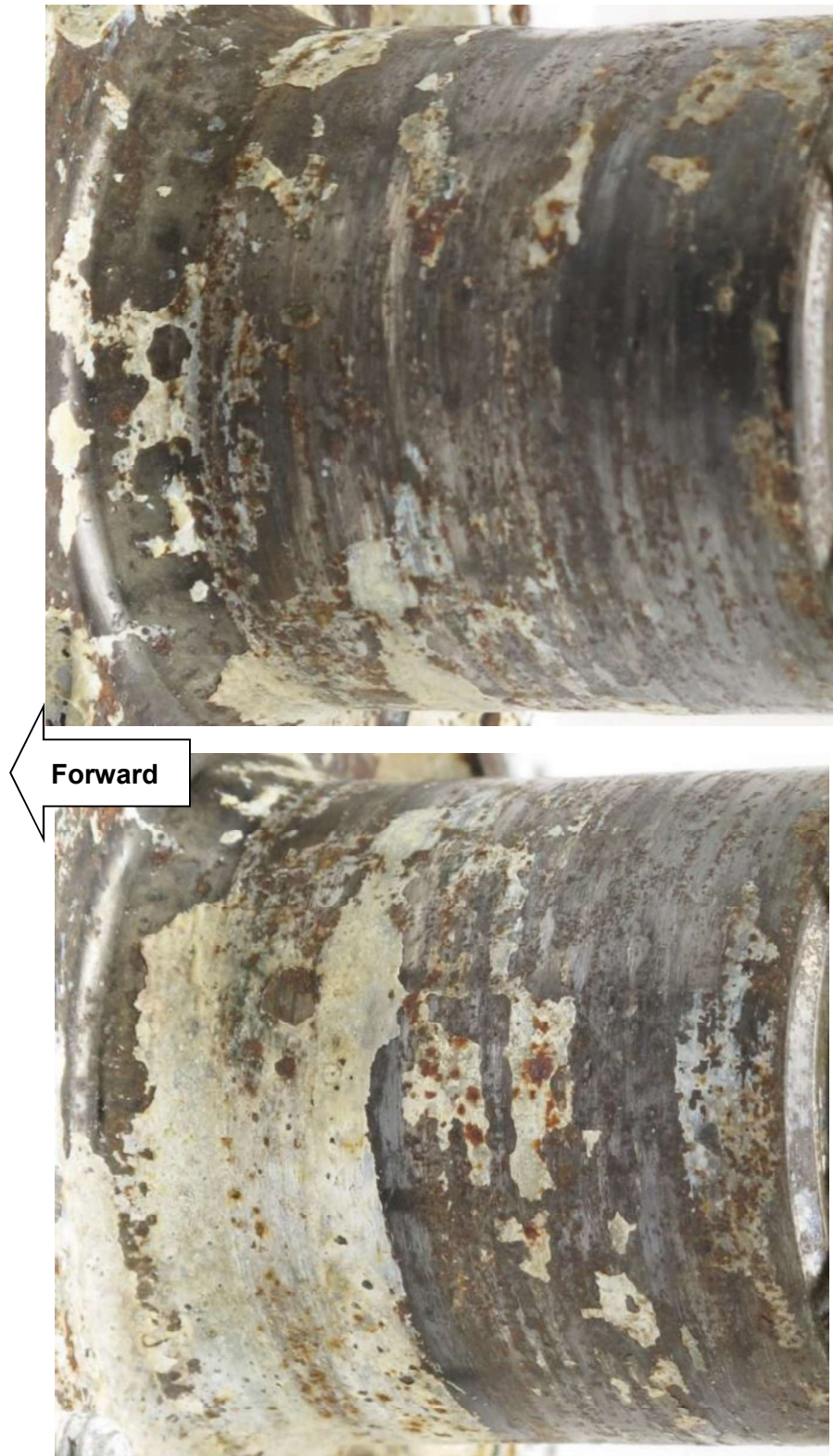
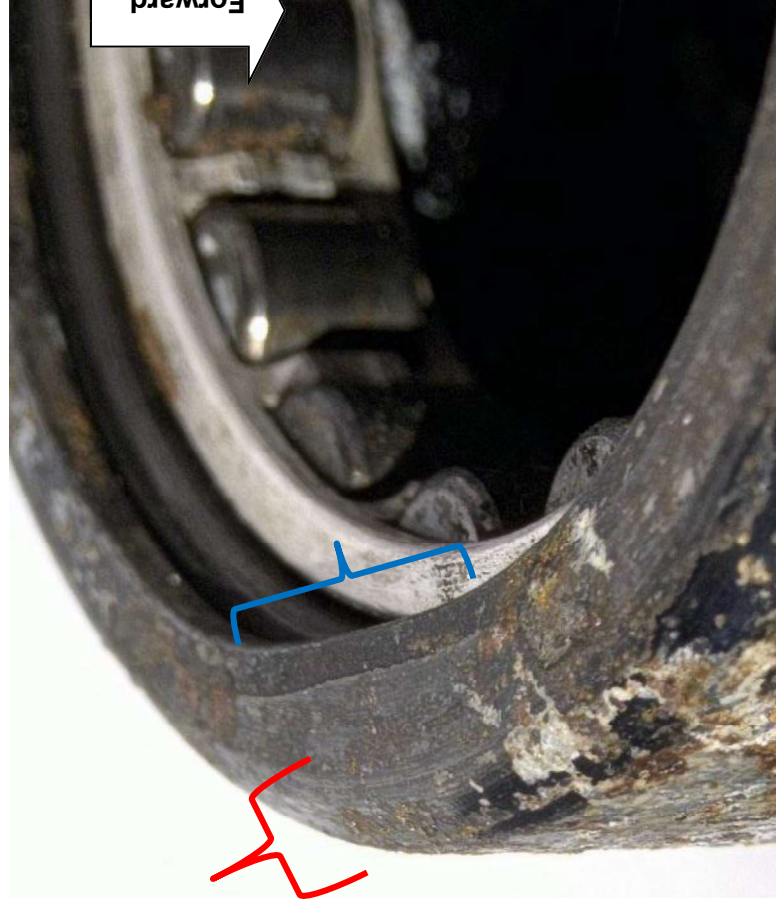
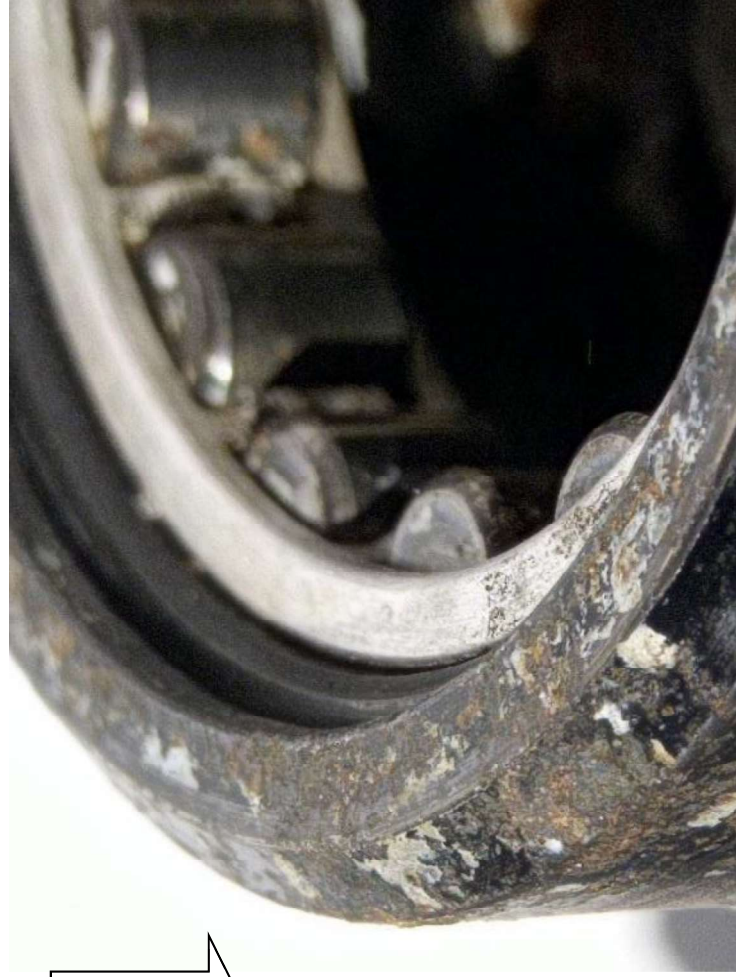


Figure 48. Detailed views of outer diameter of the flanged No. 2.5 bearing support cage, which exhibited circumferential rub. Each image shows the part rotated $\sim 90^\circ$ from the previous.



12:00 position



6:00 position

Figure 49. Detailed views of the aft face to outer diameter chamfer of the flanged No. 2.5 bearing support cage at two locations 180° apart. Circumferential rub (left, red brace) was observed at the same circumferential location at aft face deformation (blue brace, see following figure).



Figure 50. Aft looking forward (top) and inboard looking outboard (bottom) views of the aft face of the flanged No. 2.5 bearing support cage at the 12:00 position, which was deformed forward.

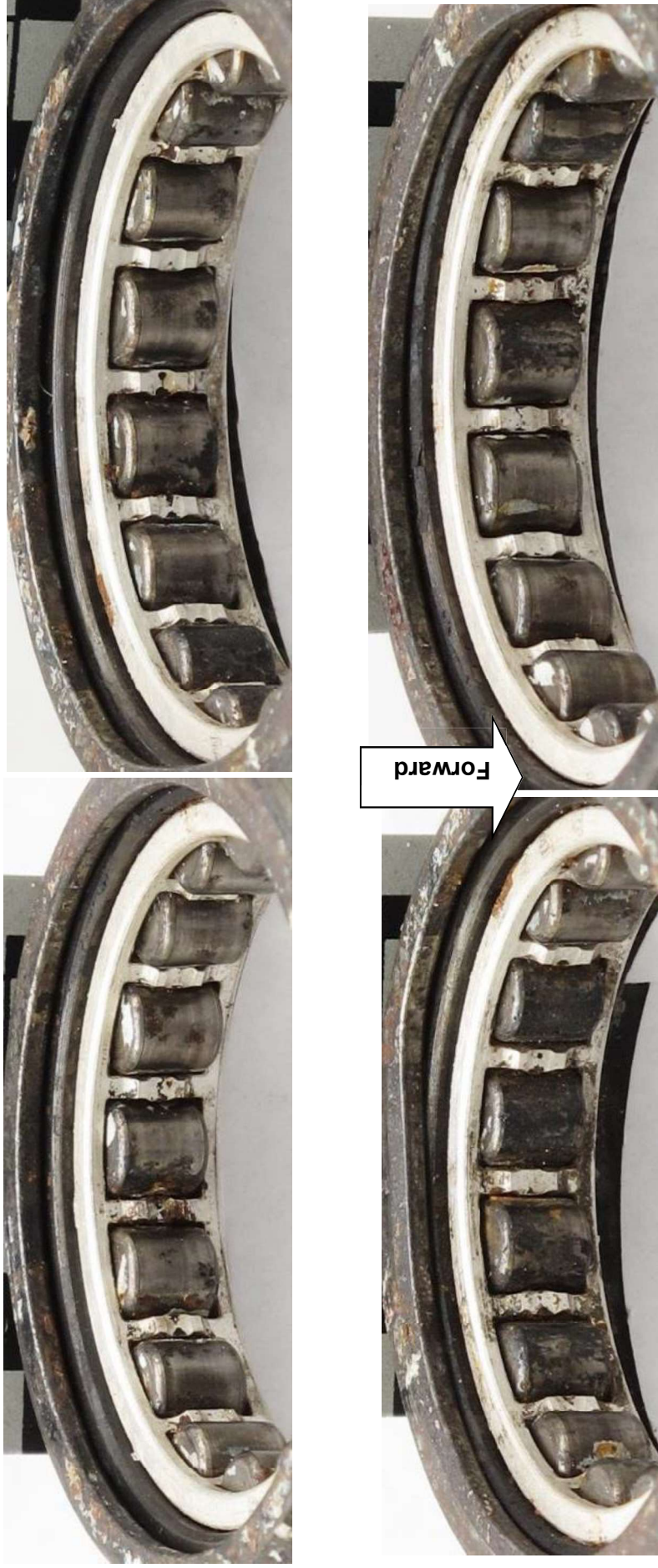


Figure 51. Detailed views of No. 2.5 bearing assembled in the flanged No. 2.5 bearing support cage. Each image shows the part rotated $\sim 90^\circ$ from the previous.

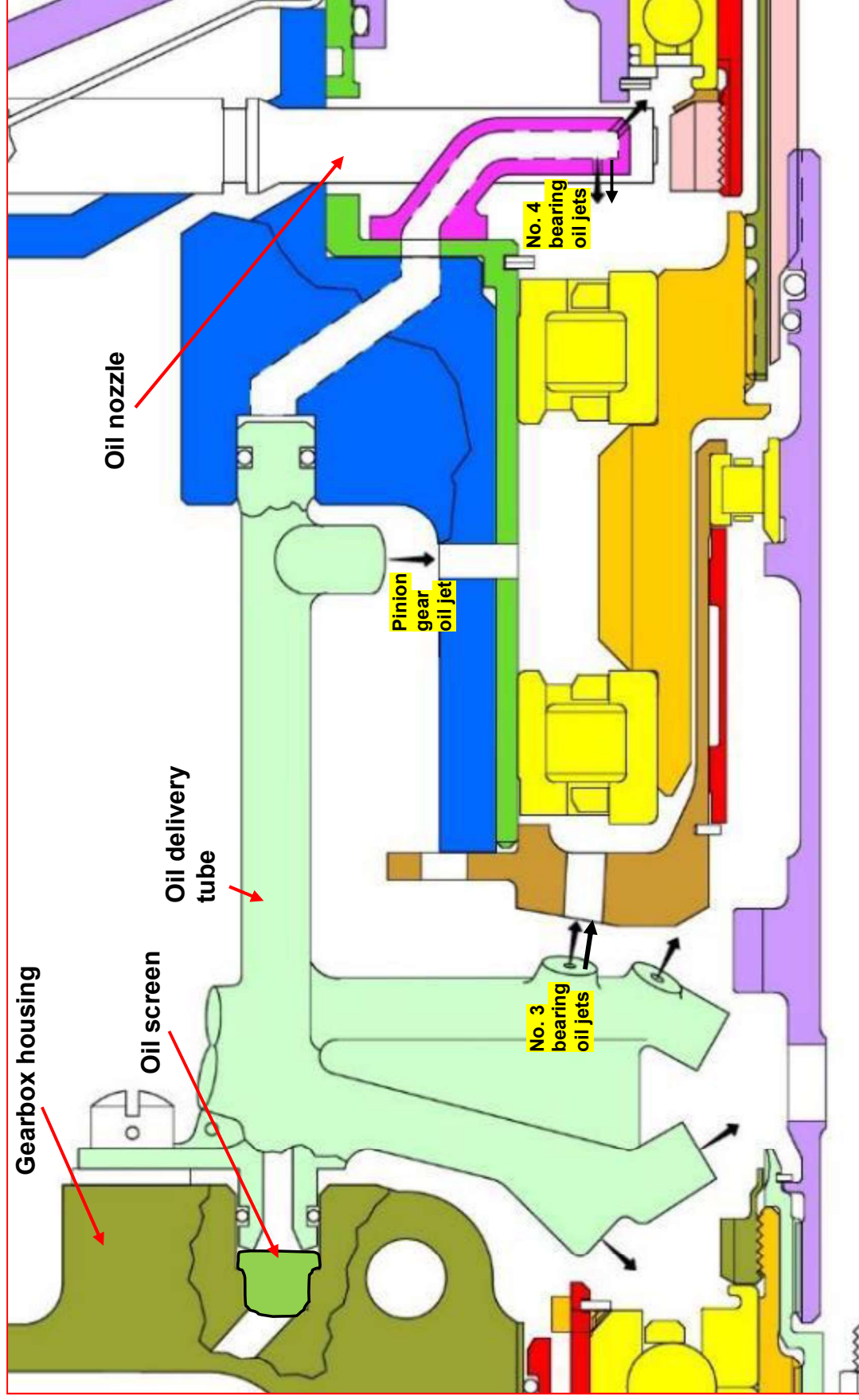


Figure 52. Partial cross section of the gear box, which highlights the oil delivery tube, oil nozzle, oil screen and gearbox housing. Schematic is not to scale and is shown for illustration purposes only.

Gearbox housing fragment

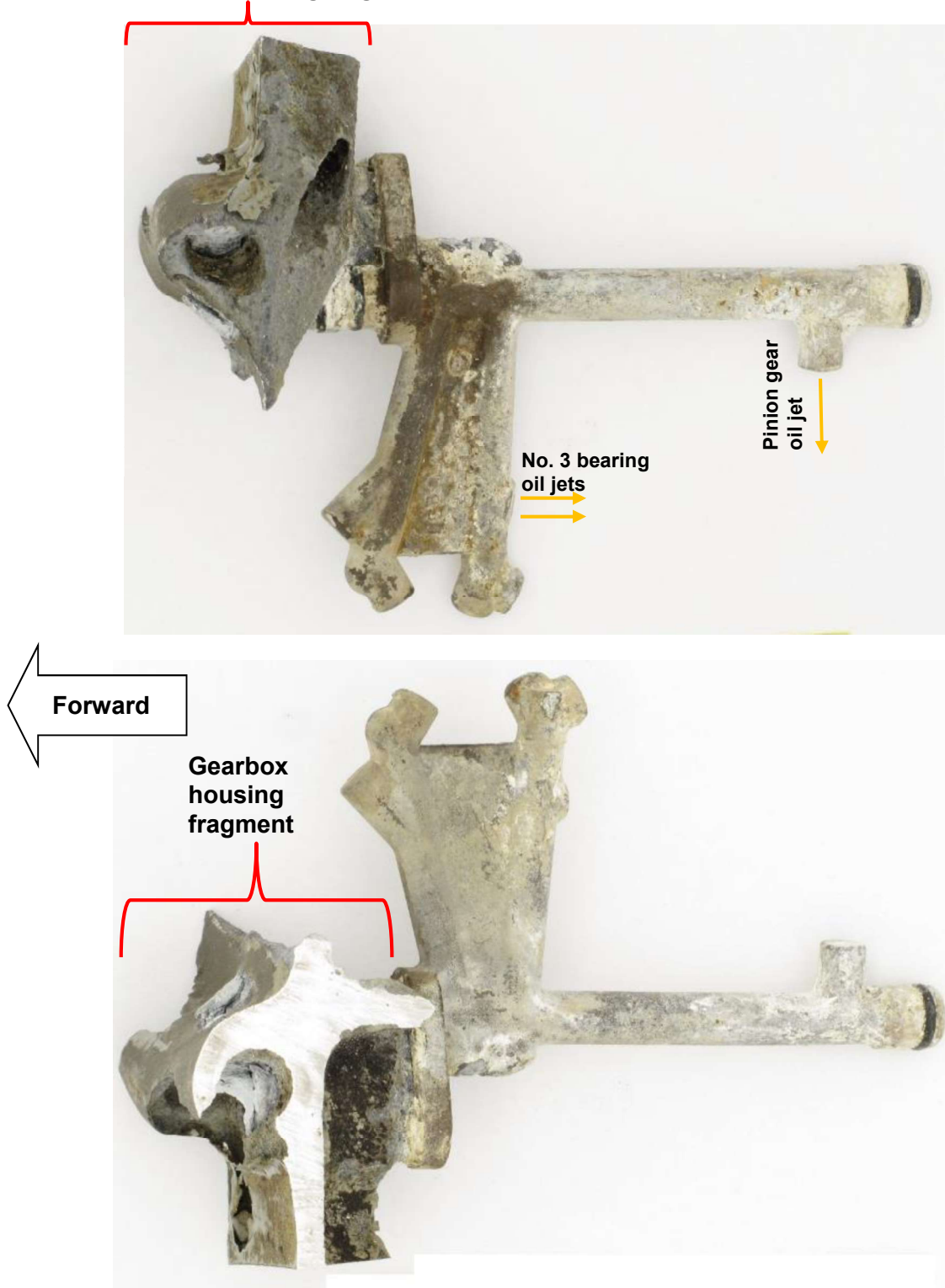


Figure 53. General condition of the left (top) and right (bottom) hand sides of the oil delivery tube.

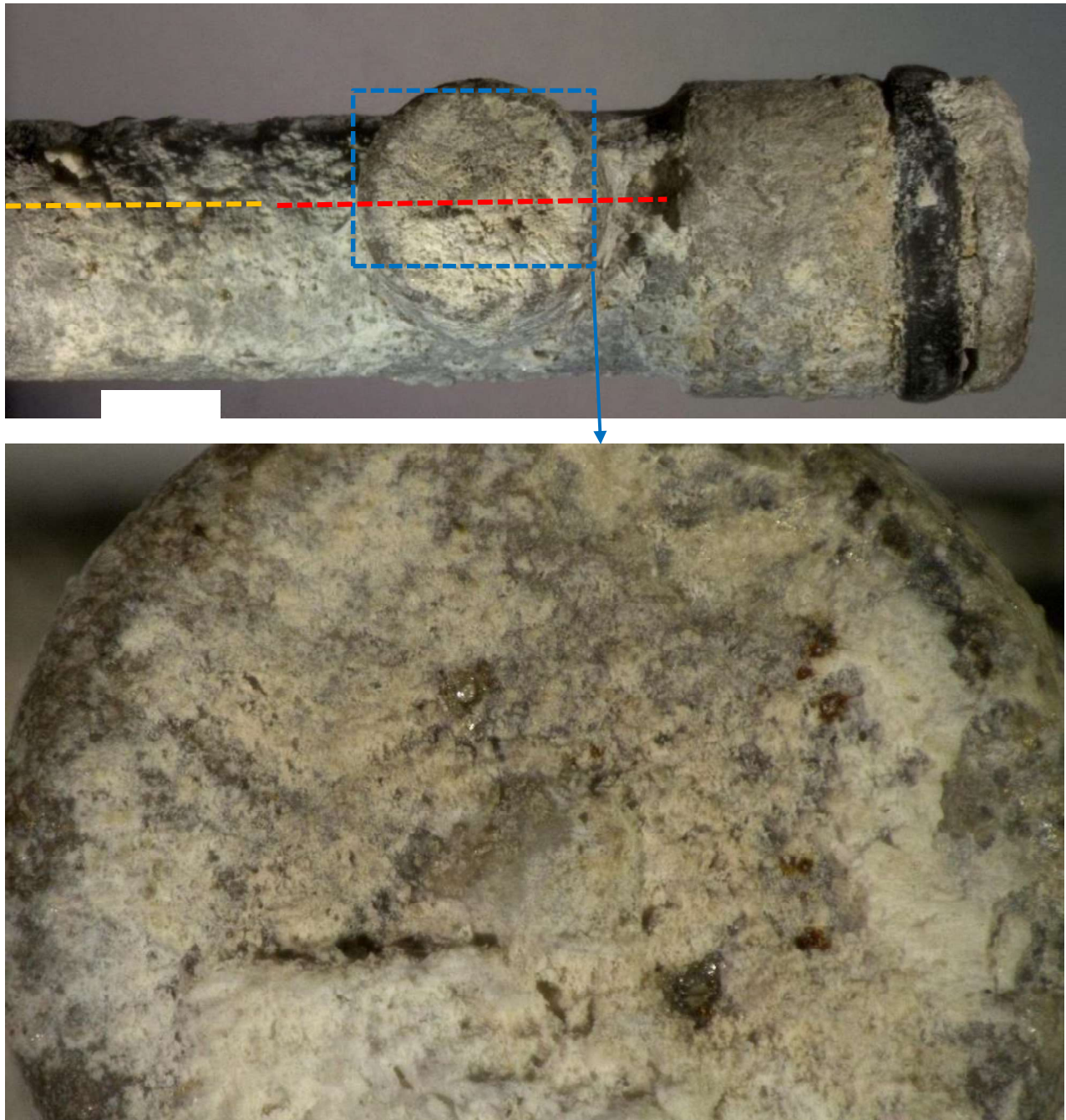


Figure 54. Detailed views of the pinion gear oil jet on the oil delivery tube, which was coated in deposits. The red and orange dashed lines mark the planes of metallographic evaluation (see Figure 61 and Figure 62, respectively).

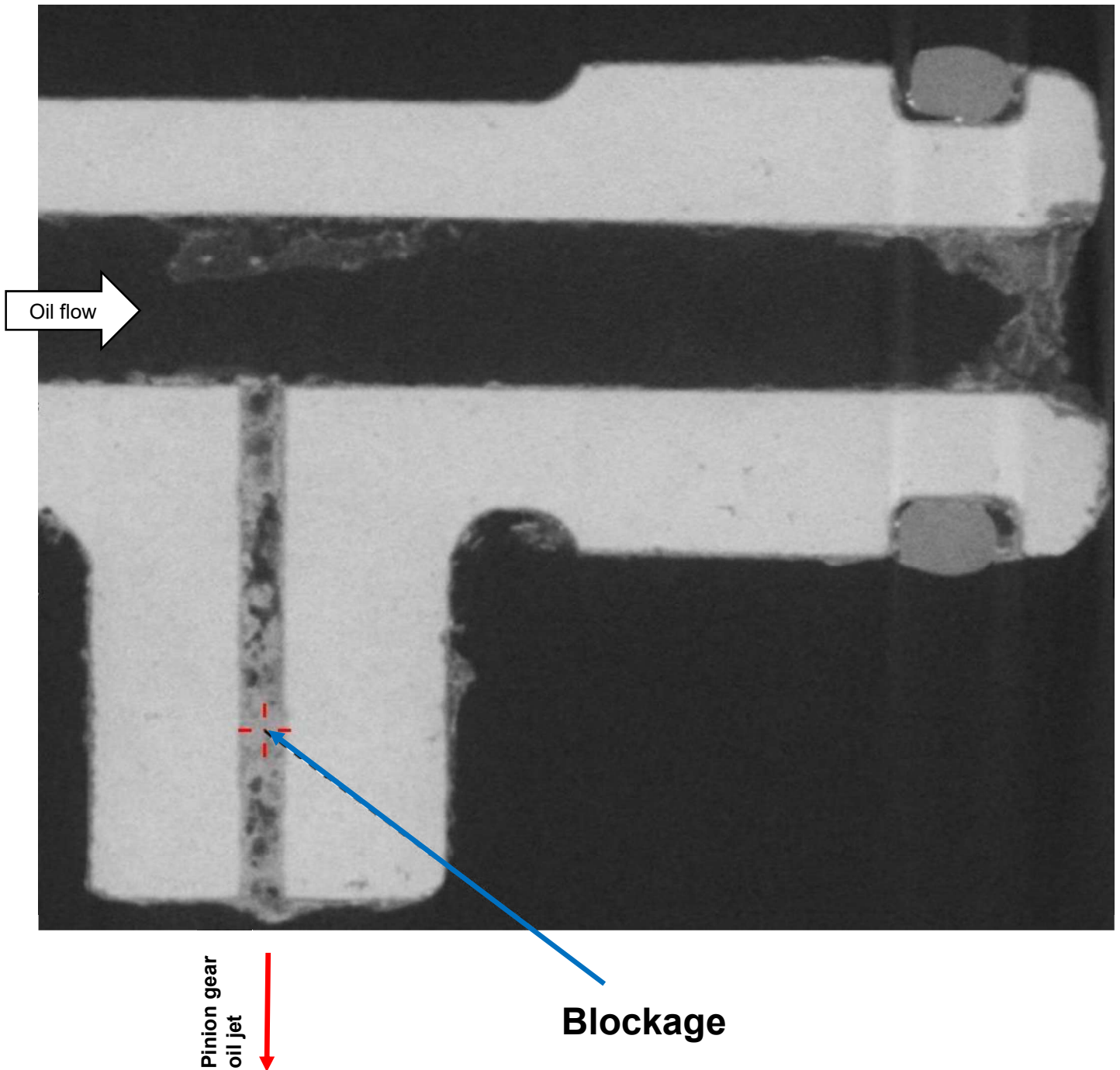


Figure 55. Detailed image of a CT cross section through the pinion gear oil jet on the oil delivery tube. The image was provided by an outside test facility.

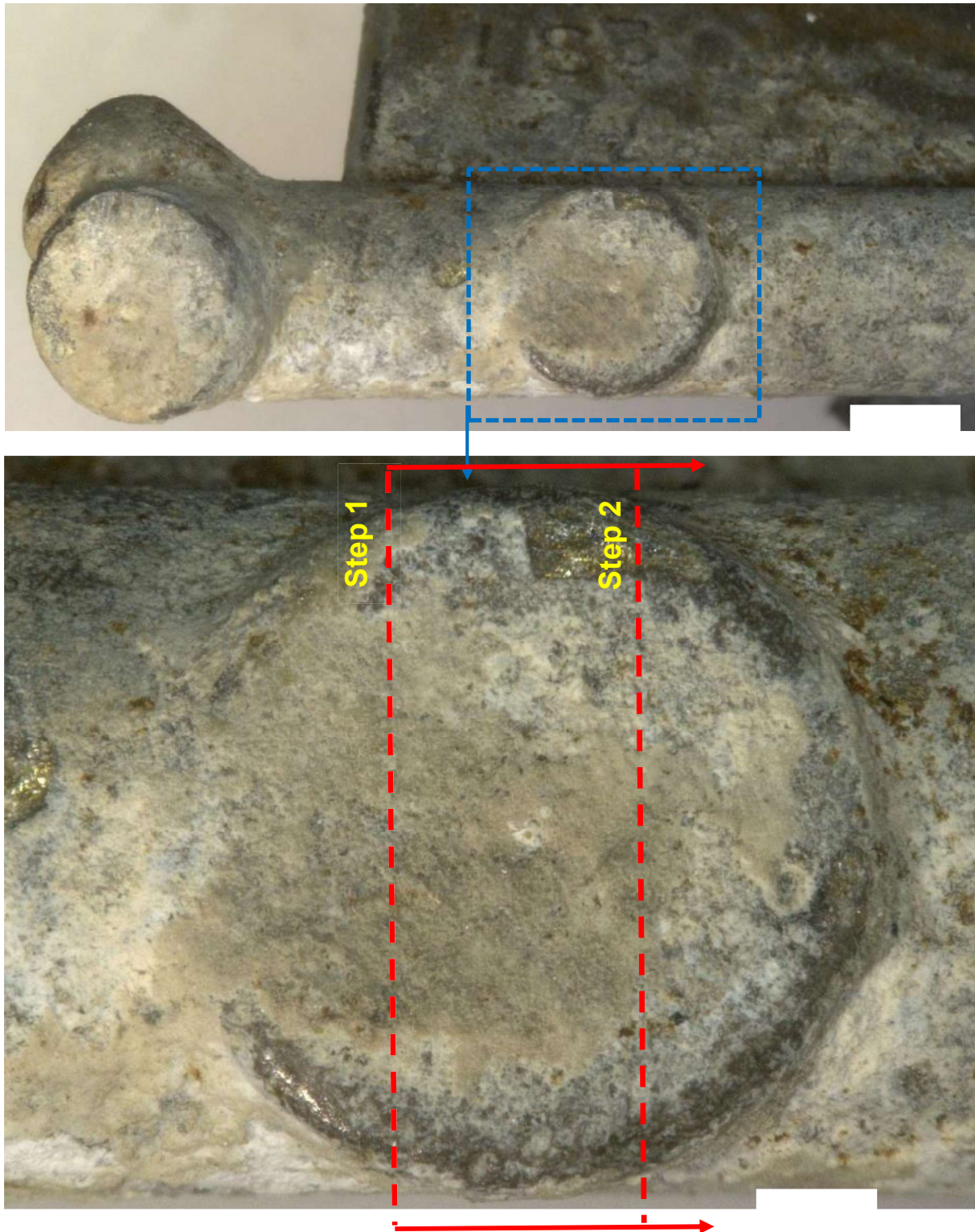


Figure 56. Detailed views of No. 3 bearing oil jets on the oil delivery tube, which were coated in deposits. The red dashed lines mark the planes of metallographic evaluation (see Figure 63 and Figure 64).

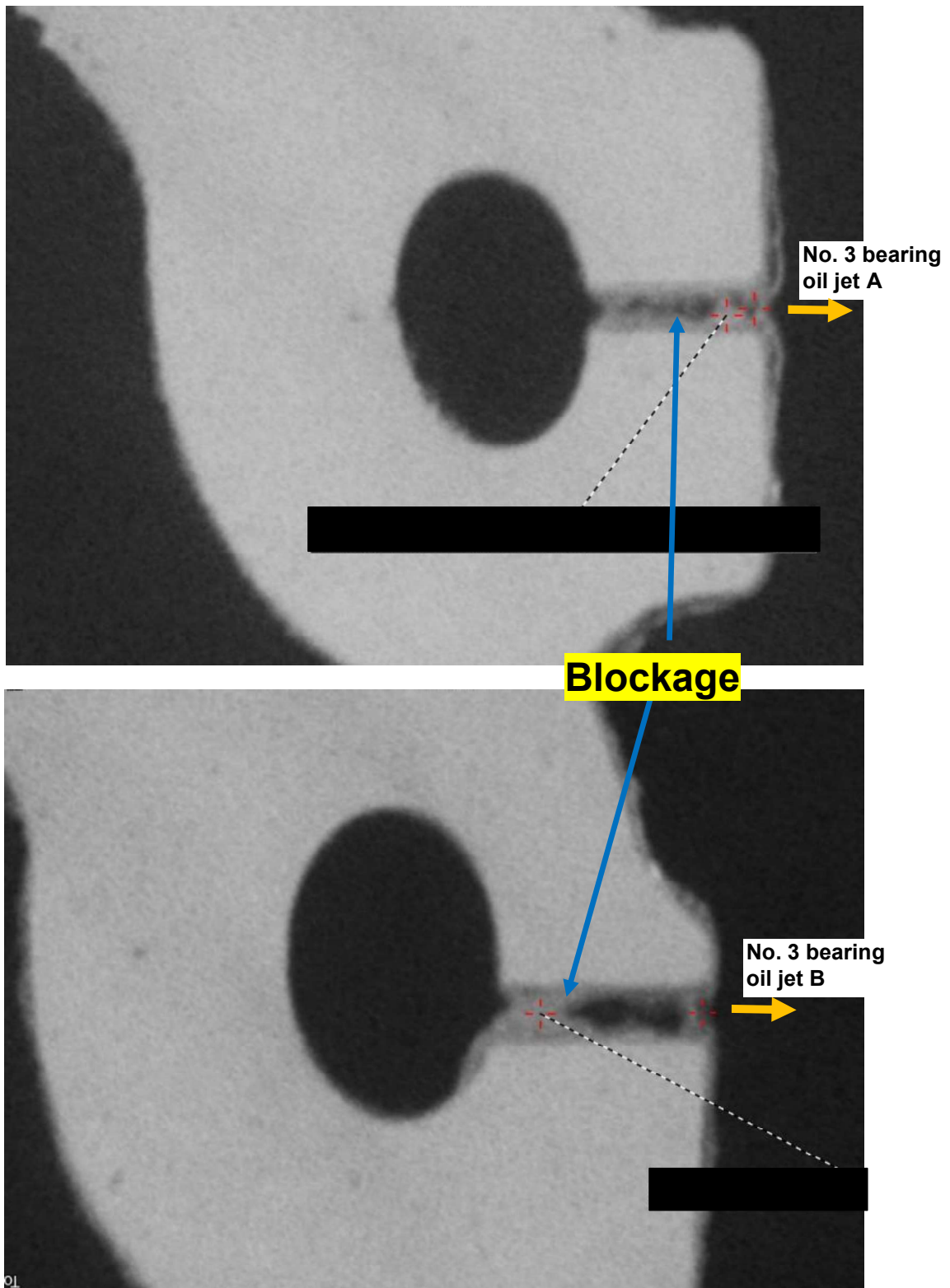


Figure 57. Detailed images of CT cross sections through No. 3 bearing oil jets A (top) and B (bottom) on the oil delivery tube. The images were provided by an outside test facility.

Gearbox housing fragment

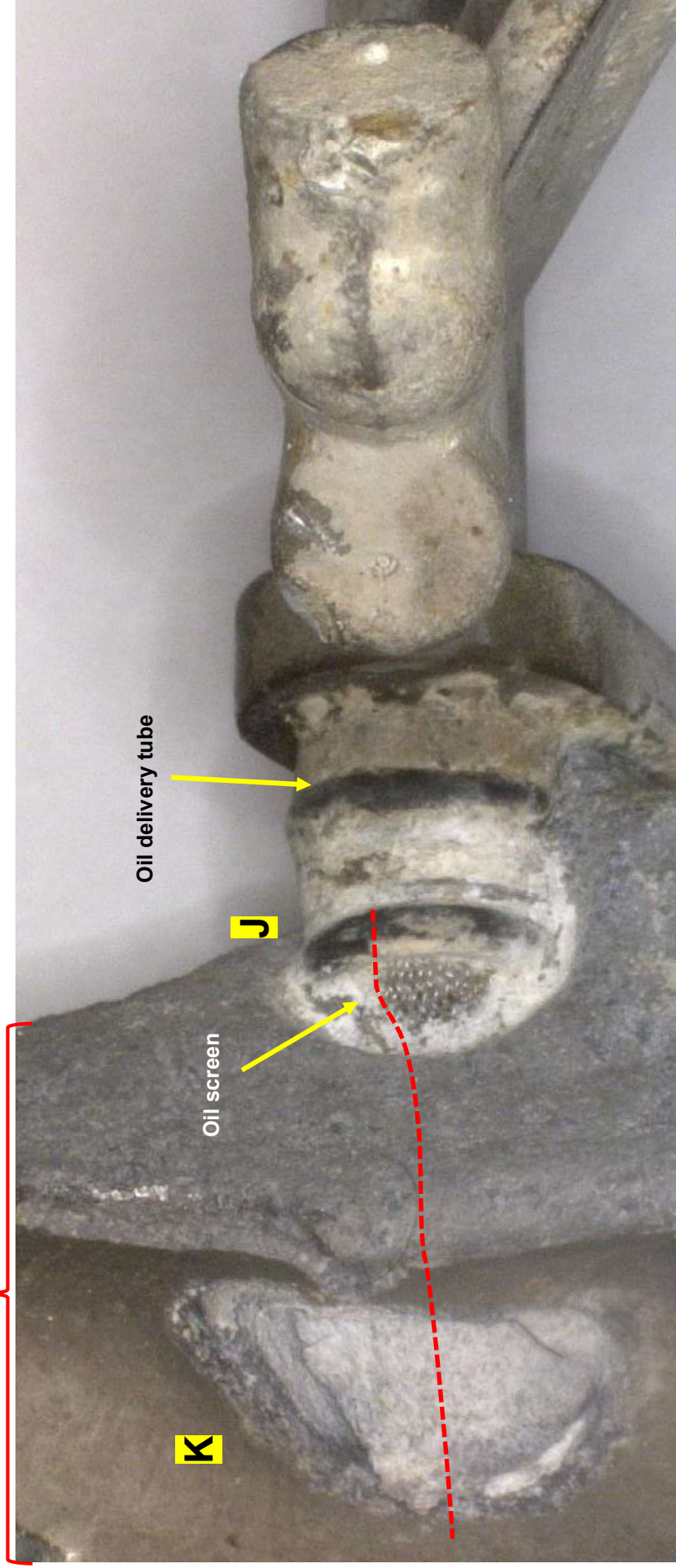


Figure 58. Detailed view of the oil delivery tube and oil screen assembled in a gearbox fragment. Locations J and K are shown in more detail in the following figure. The red dashed line marks the plane of metallographic evaluation (see Figure 65).



Figure 59. Detailed views of the oil screen and a blocked passage of the gearbox housing (see locations J and K in the previous figure, respectively).



Gearbox housing

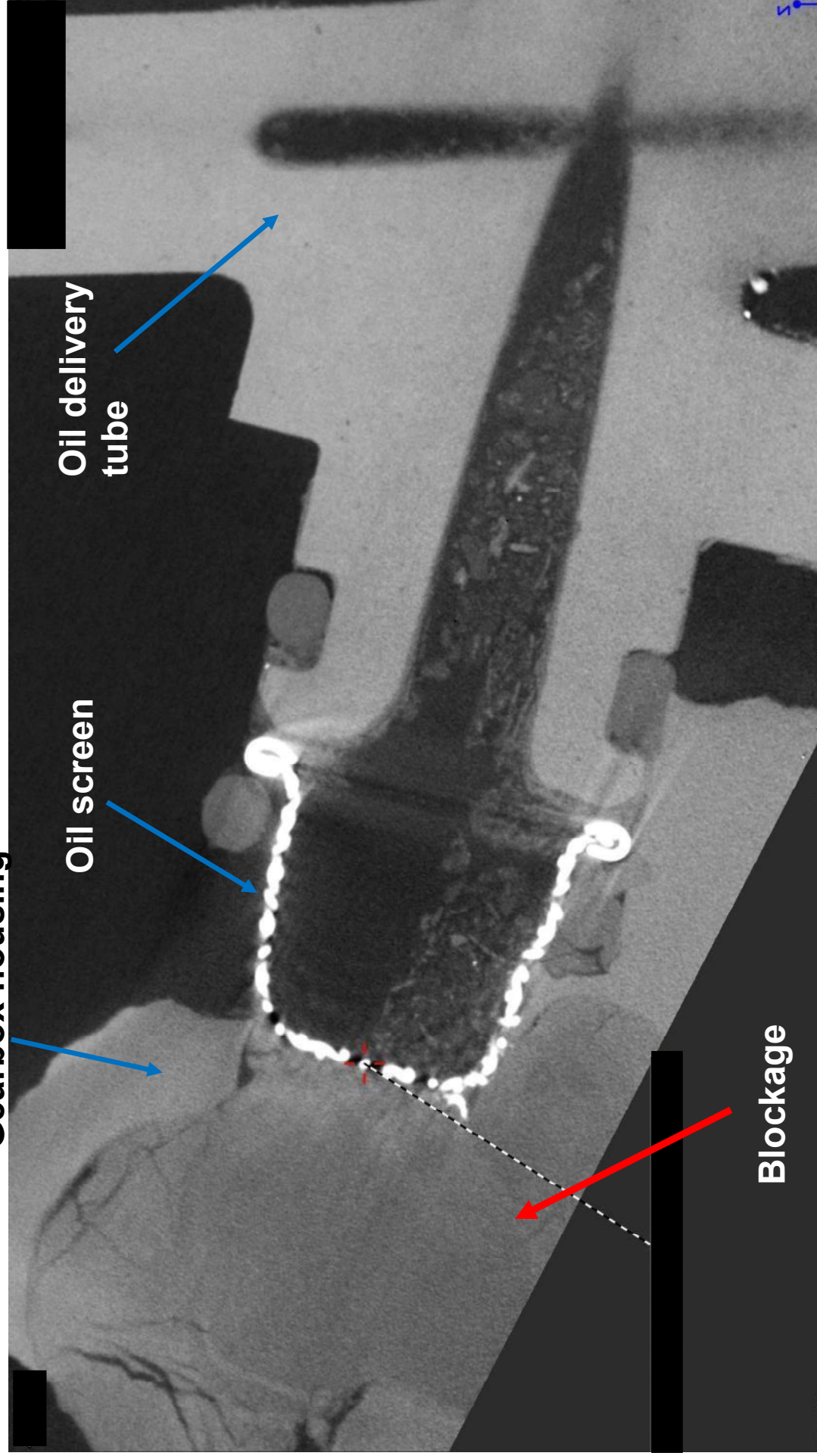


Figure 60. Detailed image of a CT cross section through oil delivery tube and oil screen assembled in a gearbox fragment. The image was provided by an outside test facility.

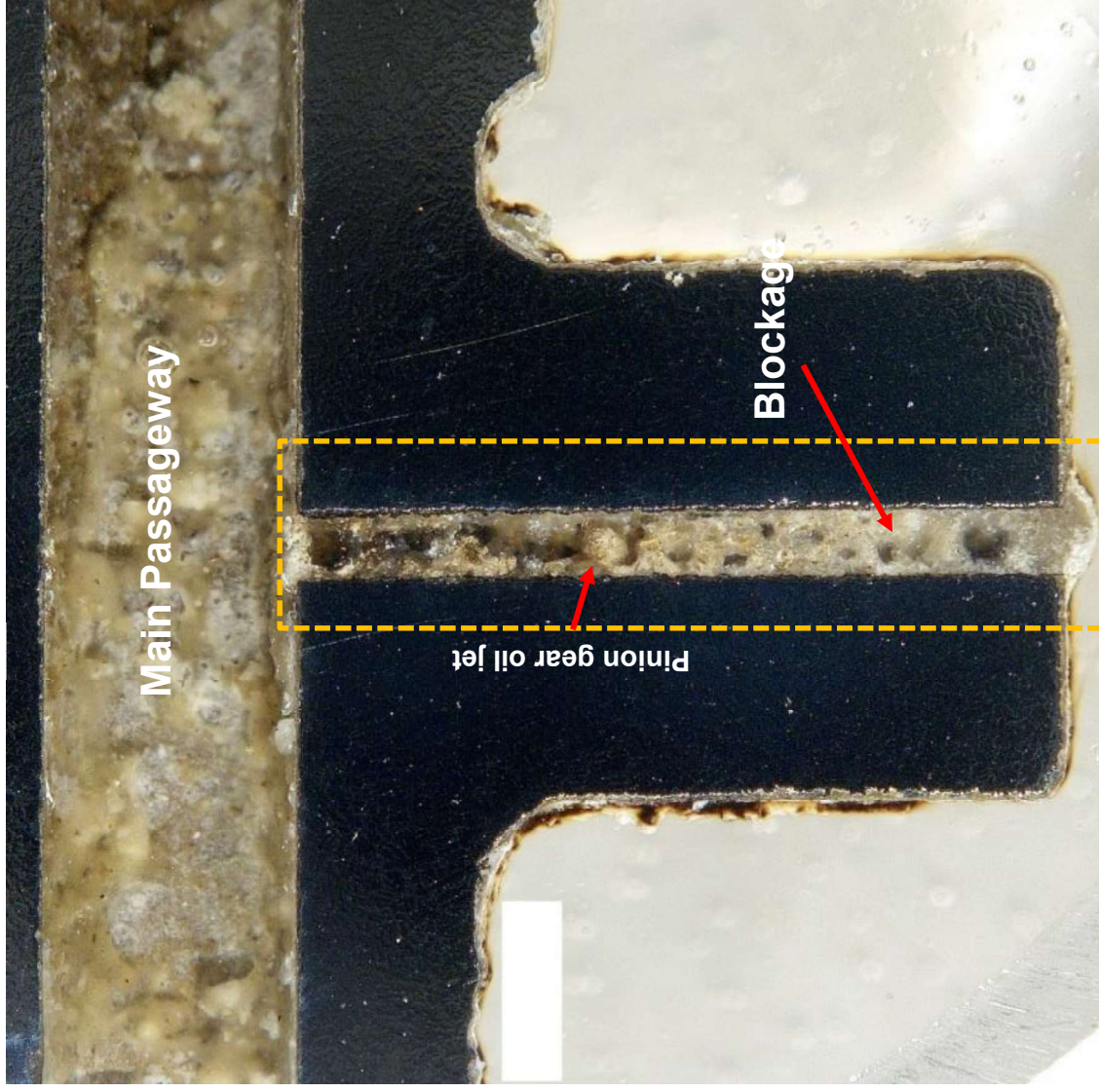


Figure 61. Metallographic section through the oil delivery tube (see the red dashed line in Figure 54). Orange boxed area is shown in more detail in the Figure 84.

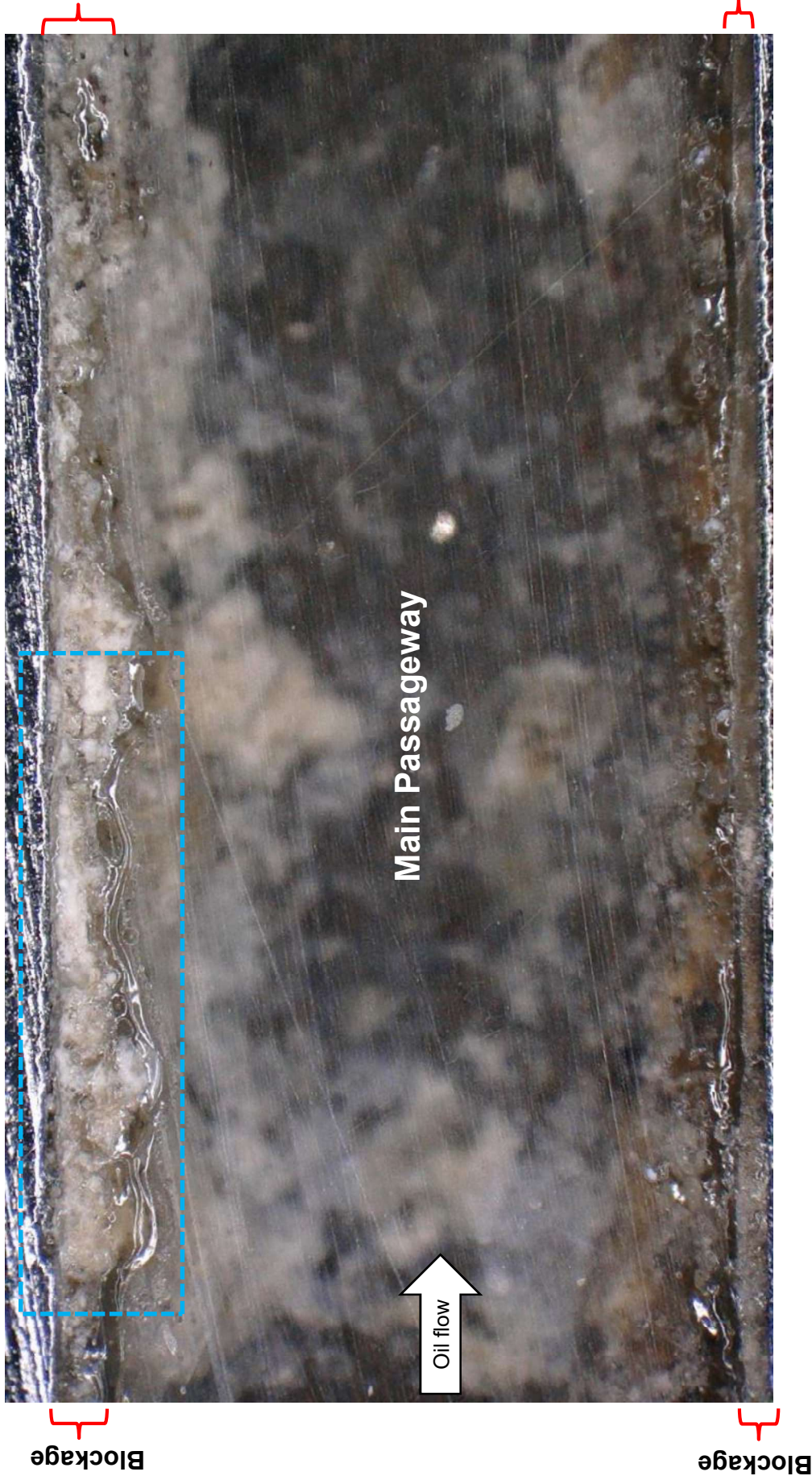


Figure 62. Metallographic section through the oil delivery tube (see the orange dashed line in Figure 54). Blue boxed area is shown in more detail in the Figure 89.

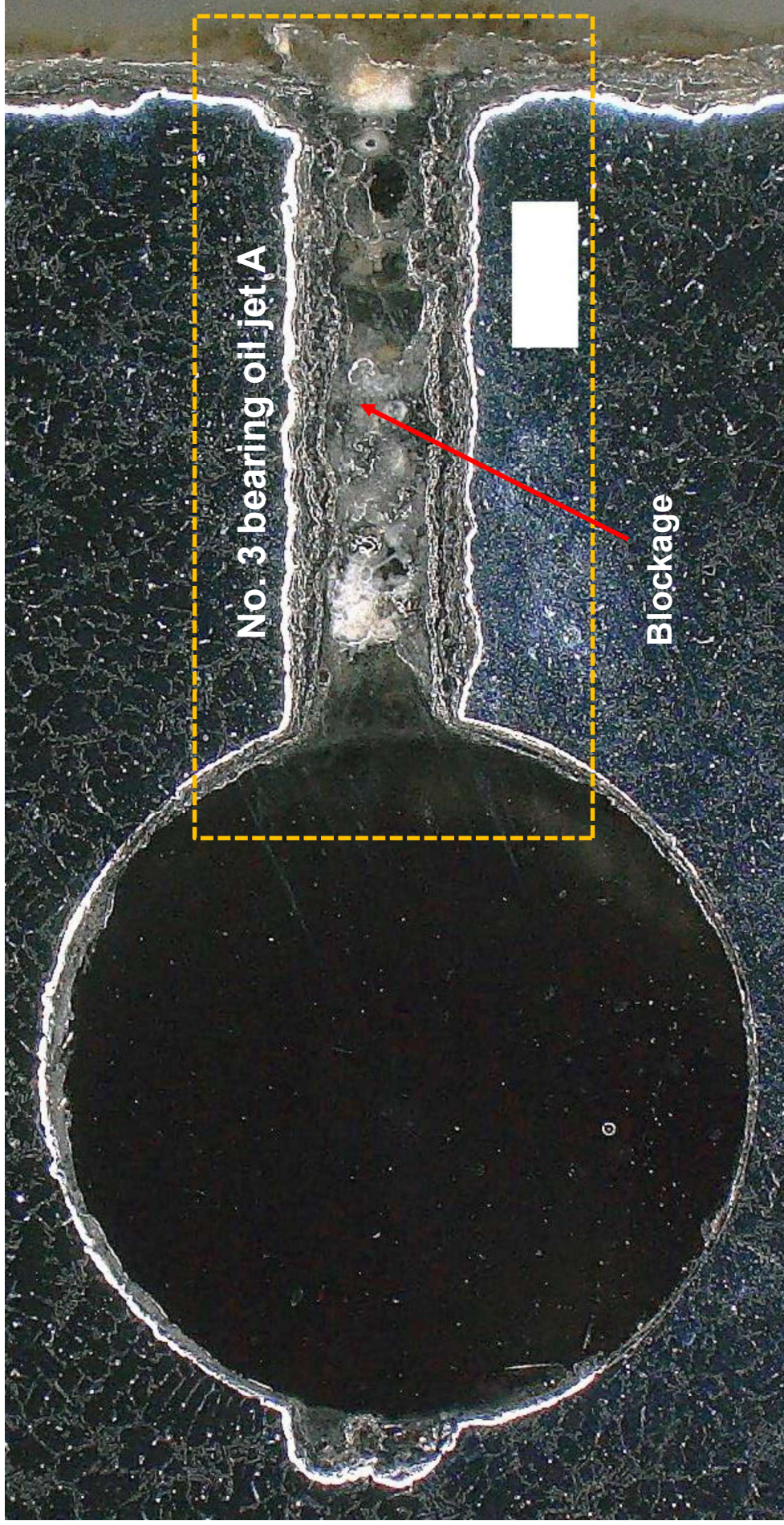


Figure 63. Metallographic section through the oil delivery tube (see the red dashed line at step 1 in Figure 56). Orange boxed area is shown in more detail in Figure 92.

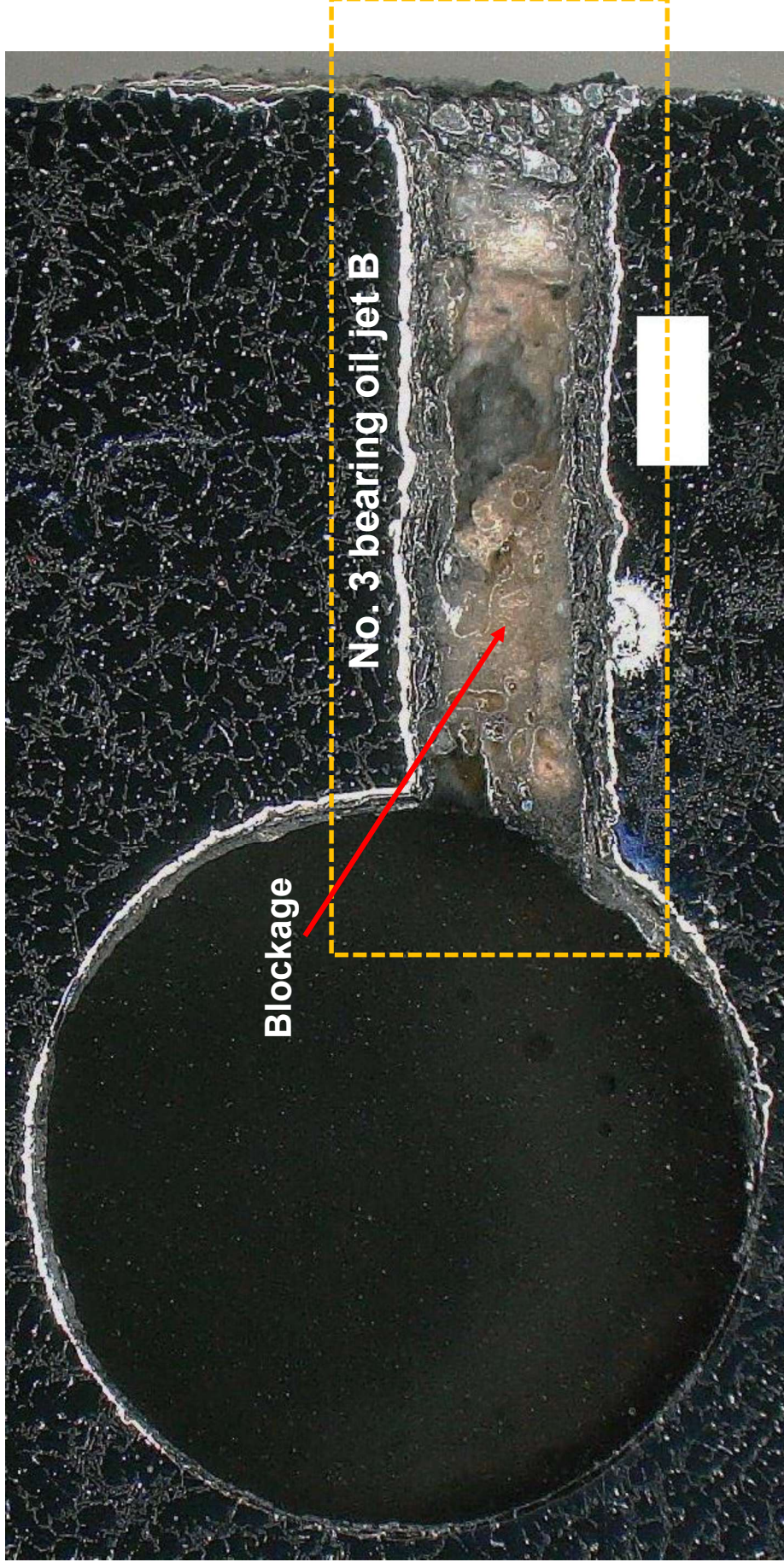


Figure 64. Metallographic section through the oil delivery tube (see the red dashed line at step 2 in Figure 56). Orange boxed area is shown in more detail in Figure 97.



Figure 65. Metallographic section through the gearbox housing and oil screen (see the red dashed line in Figure 58).

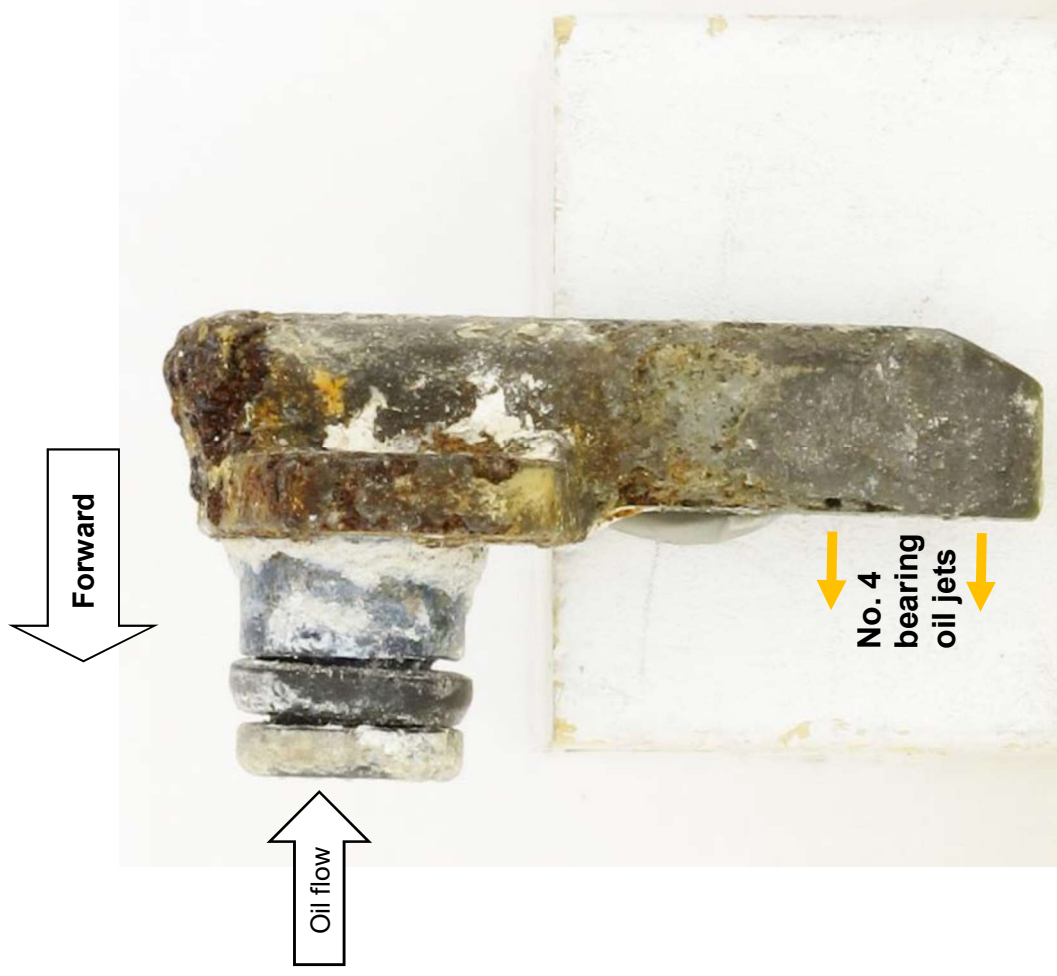


Figure 66. Radial (left) and forward looking aft (right) sides of the pinion gear oil nozzle. Red boxed area is shown in more detail in the following figure.

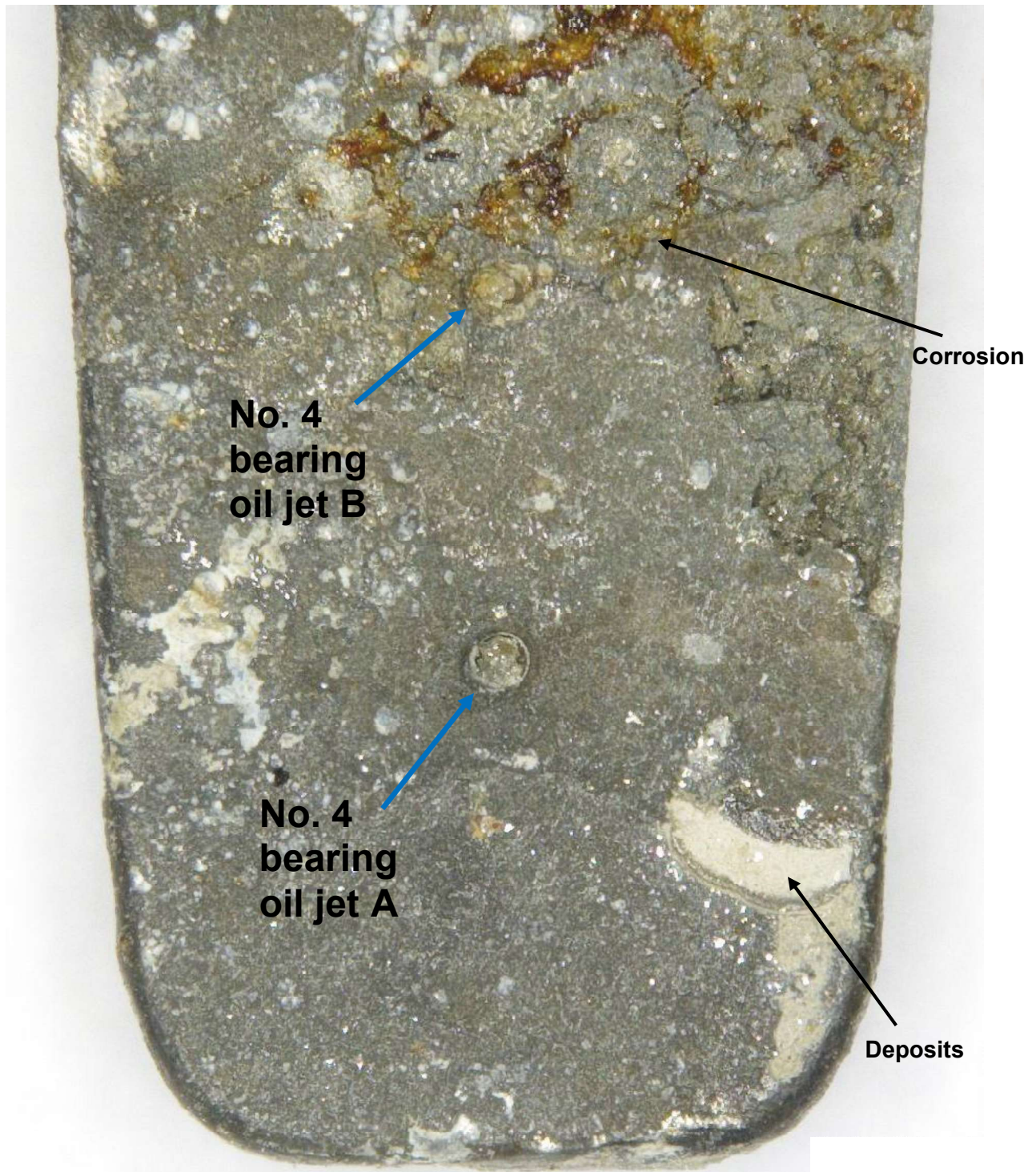


Figure 67. Detailed forward looking aft view (red boxed area in previous figure) of the pinion gear oil nozzle.

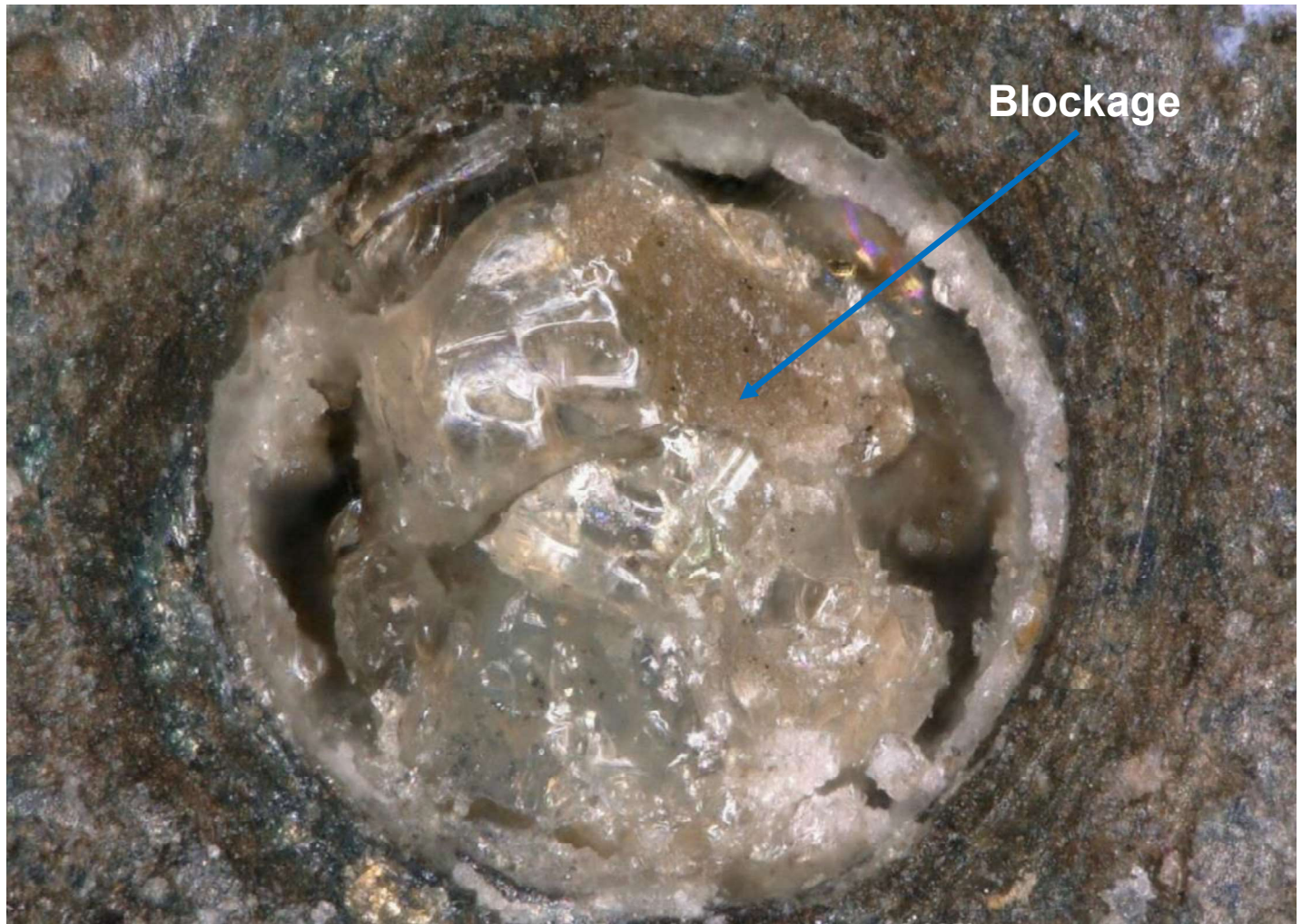


Figure 68. Detailed view of No. 4 bearing oil jet A on the pinion gear oil nozzle, which exhibited blockage.

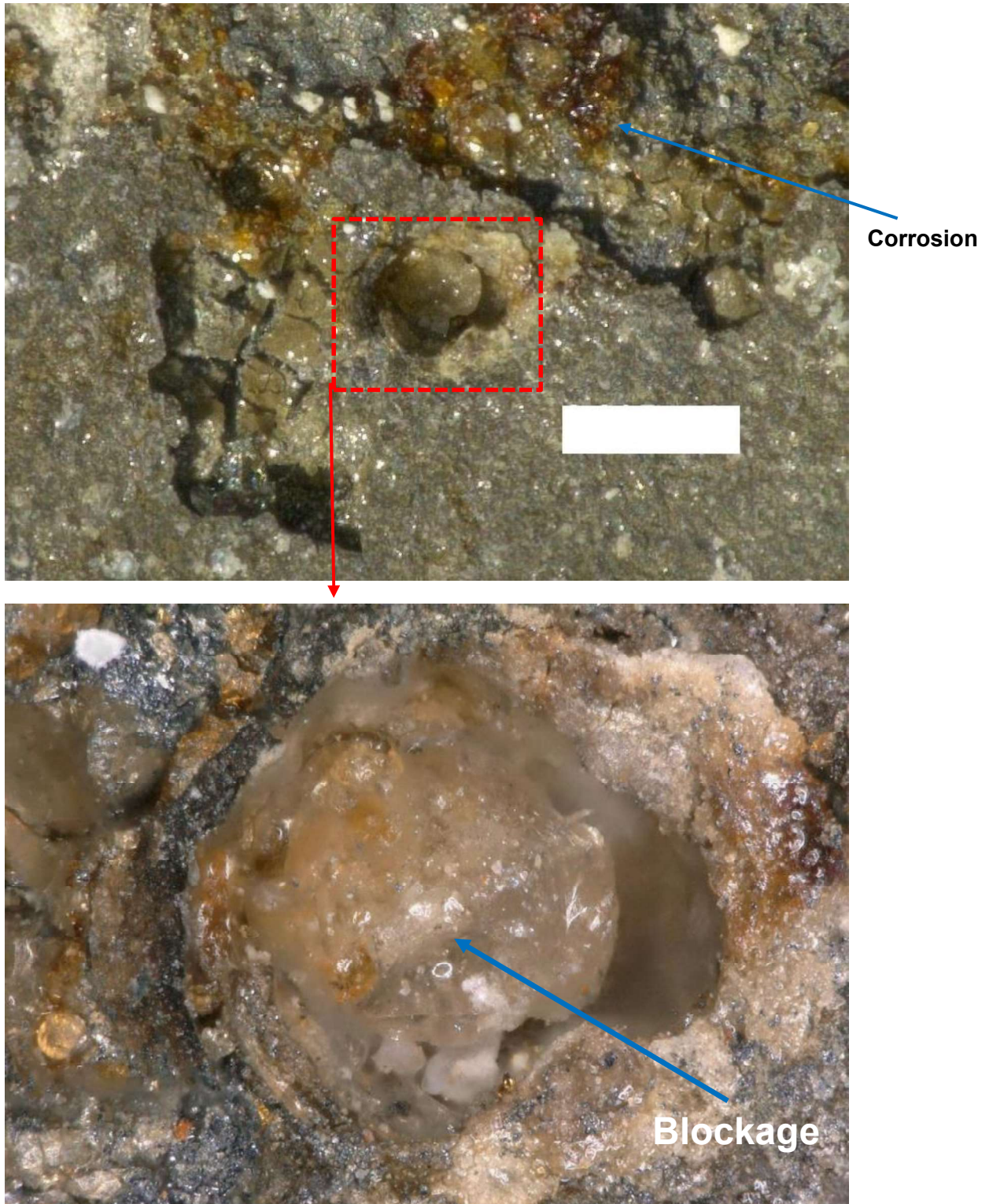


Figure 69. Detailed views of No. 4 bearing oil jet B on the pinion gear oil nozzle, which exhibited blockage.

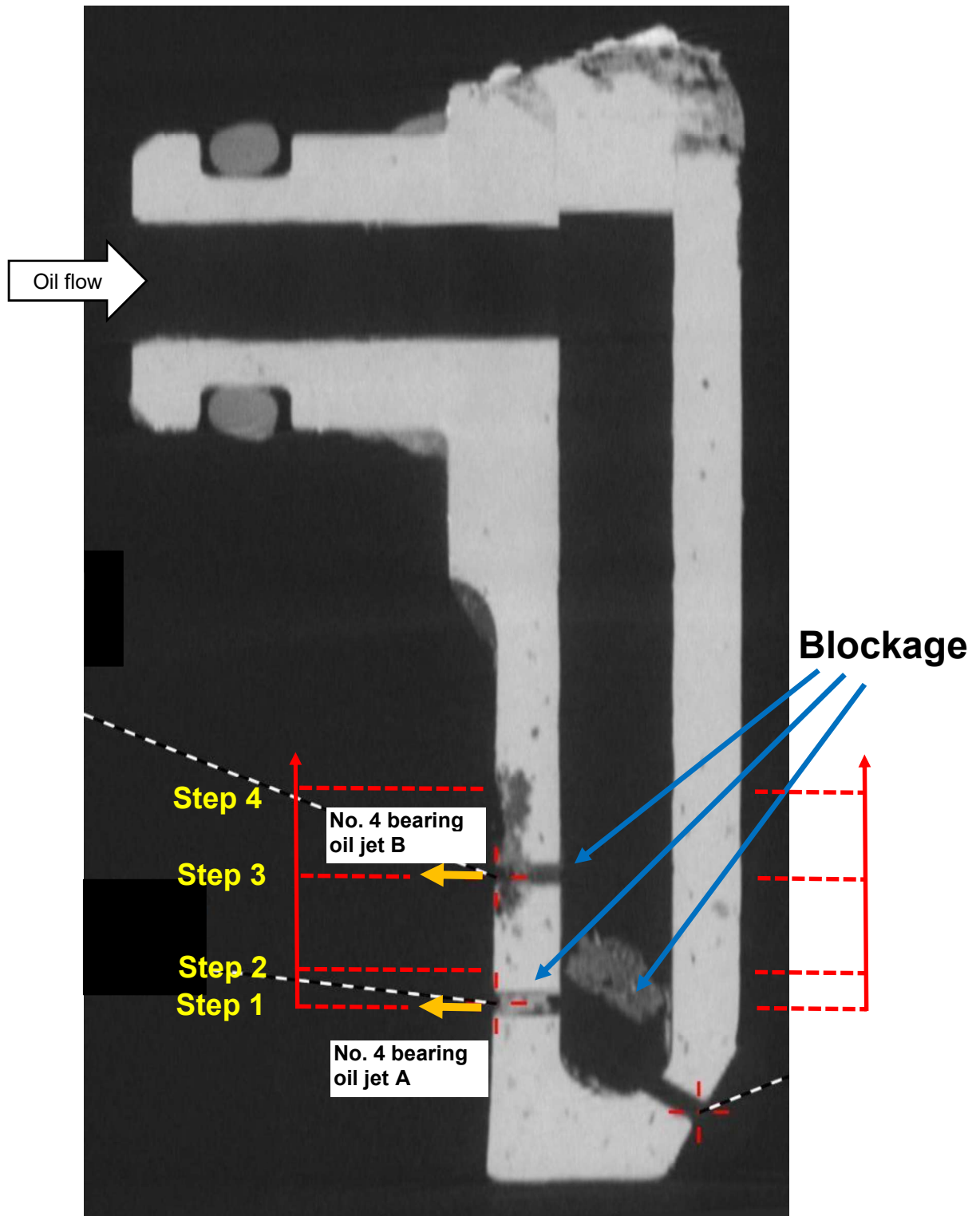


Figure 70. Detailed image of a CT cross section through the pinion bearing oil nozzle. The red dashed lines mark the planes of metallographic evaluation (see Figure 71, Figure 72, and Figure 73). Image was provided by an outside test facility.

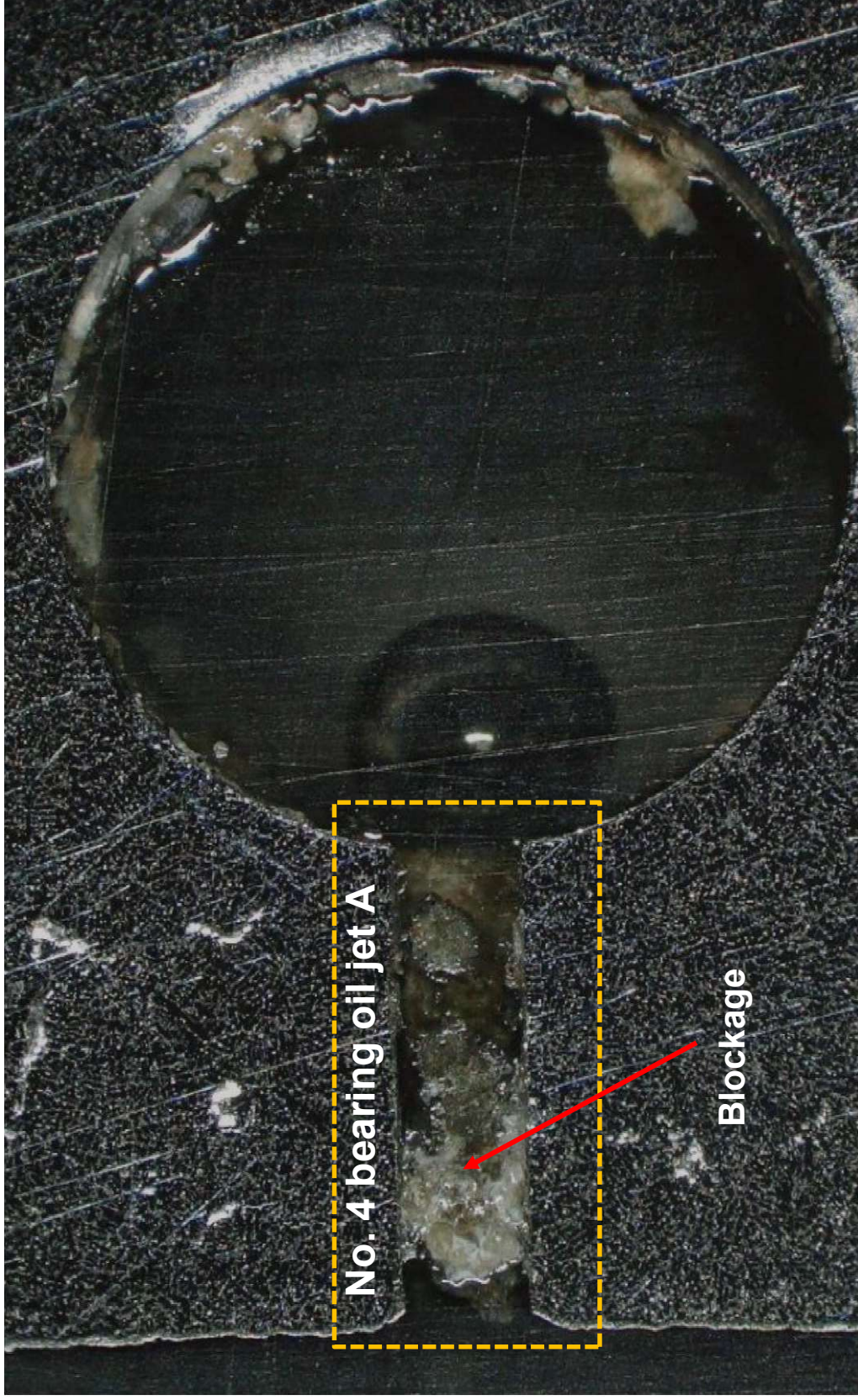


Figure 71. Metallographic section through the oil nozzle (see the red dashed line at step 1 in Figure 70). Orange boxed area is shown in more detail in Figure 108.

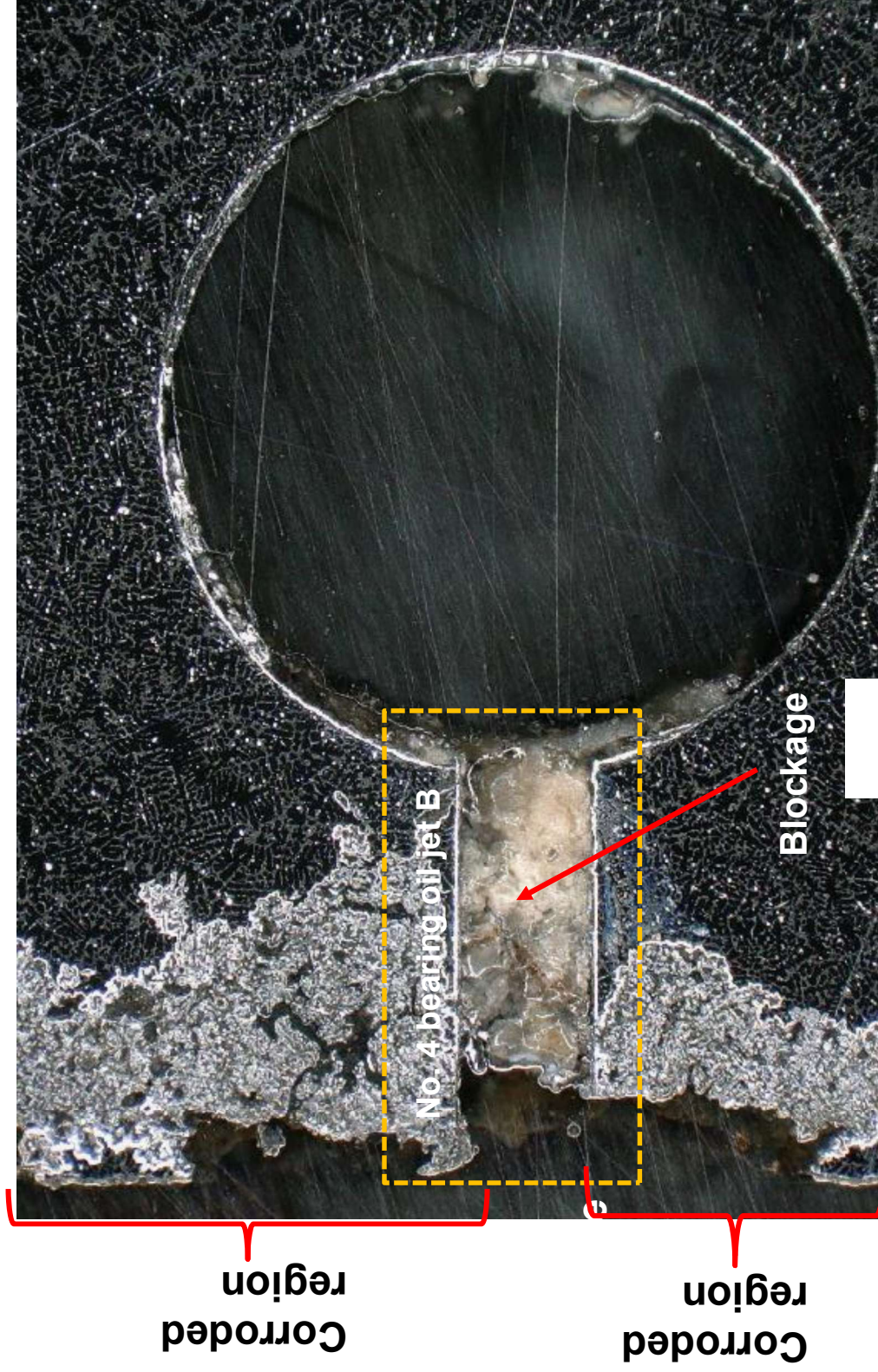


Figure 72. Metallographic section through the oil nozzle (see the red dashed line at step 3 in Figure 70). Orange boxed area is shown in more detail in Figure 114.

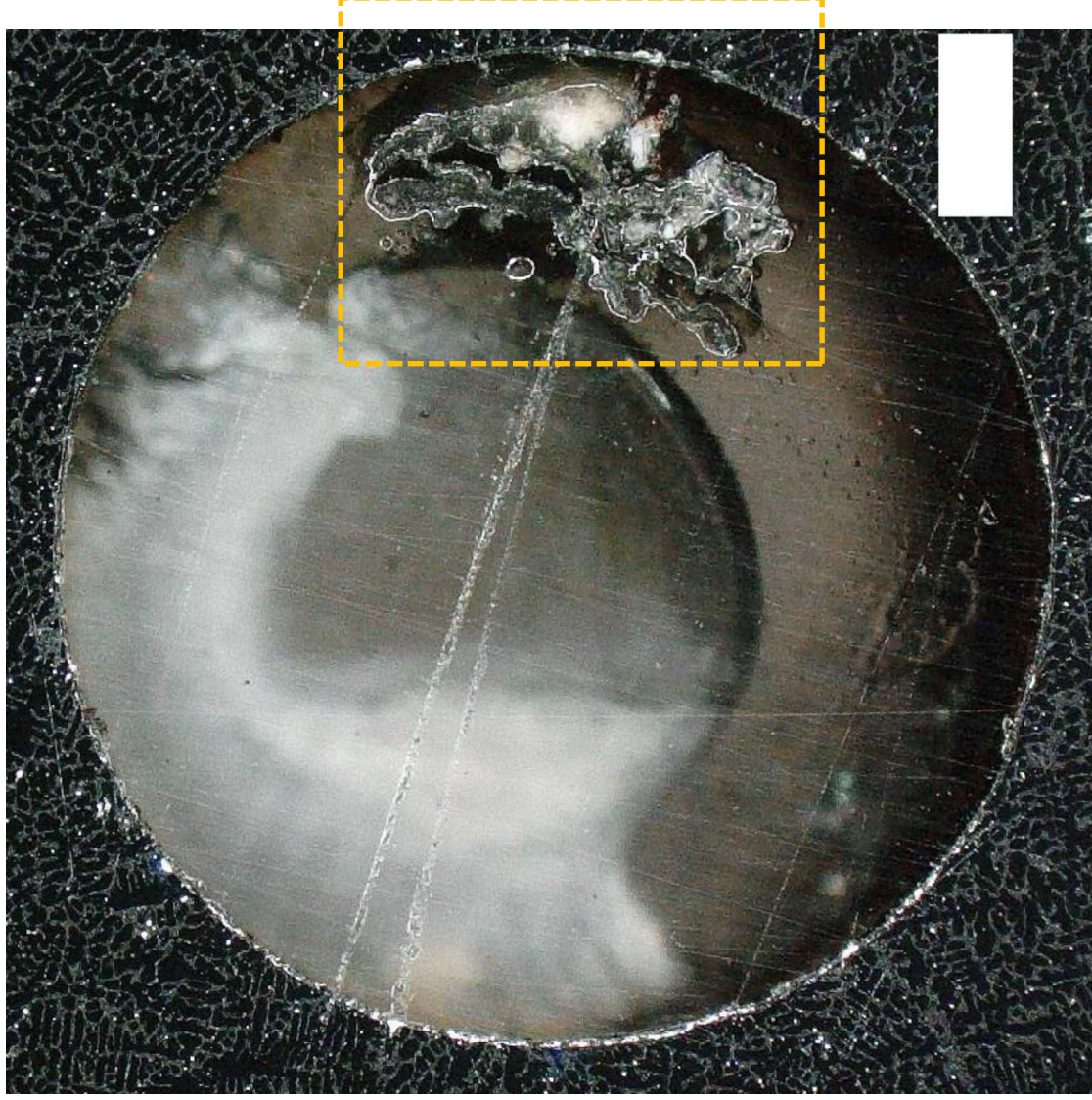


Figure 73. Metallographic section through the oil nozzle (see the red dashed line at step 4 in Figure 70), which exhibited debris. Orange boxed area is shown in more detail in Figure 120.



Figure 74. General condition of the forward (top) and aft (bottom) sides of the No. 4 bearing retaining ring.

Deposits



Figure 75. Detailed views of the tabs on the forward (top) and aft (bottom) sides of the No. 4 bearing retaining ring.

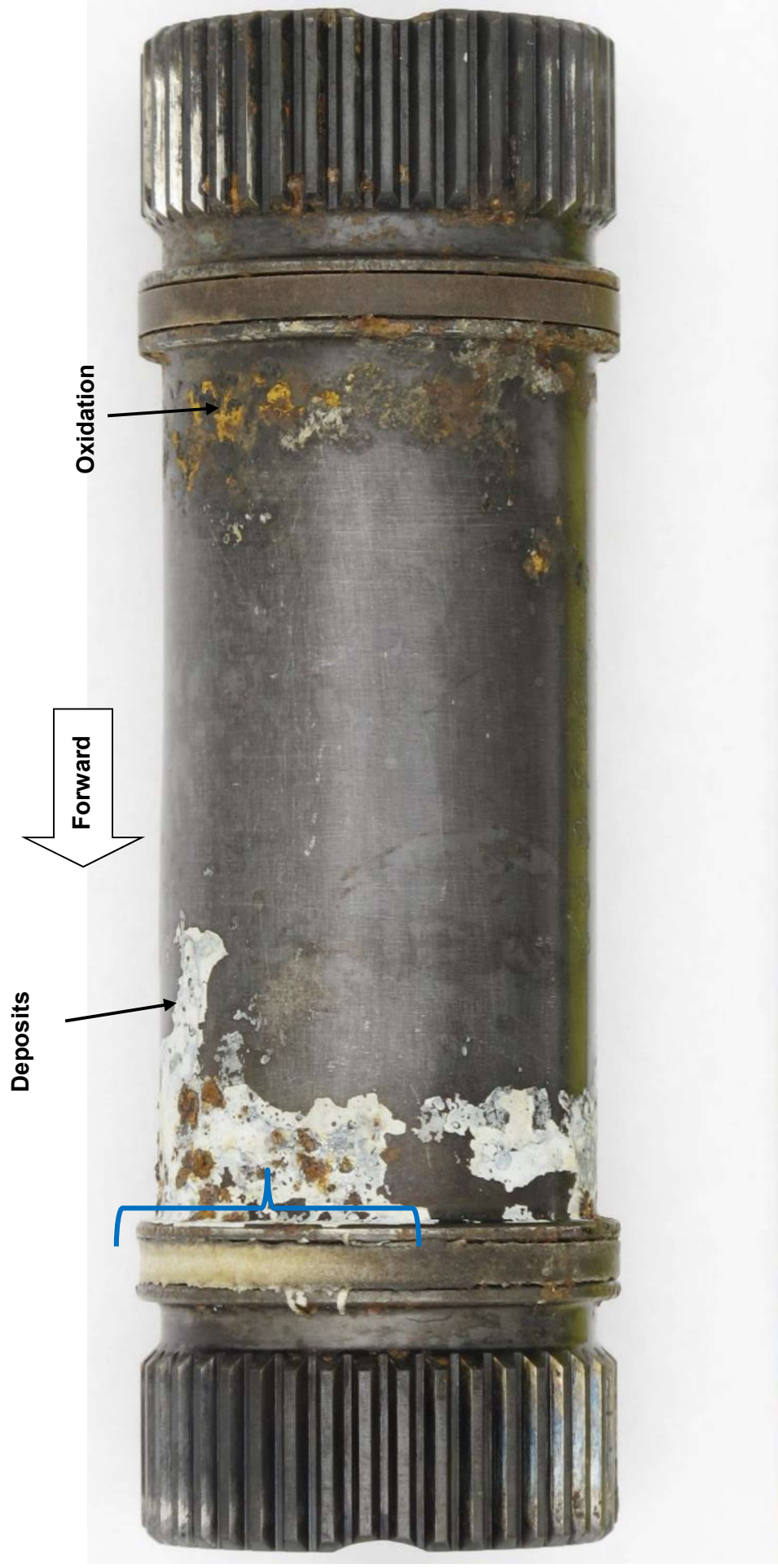


Figure 76. General condition of the turbine shaft to pinion coupling after cleaning. Blue brace marks evidence of thermal distress on the ring seal.

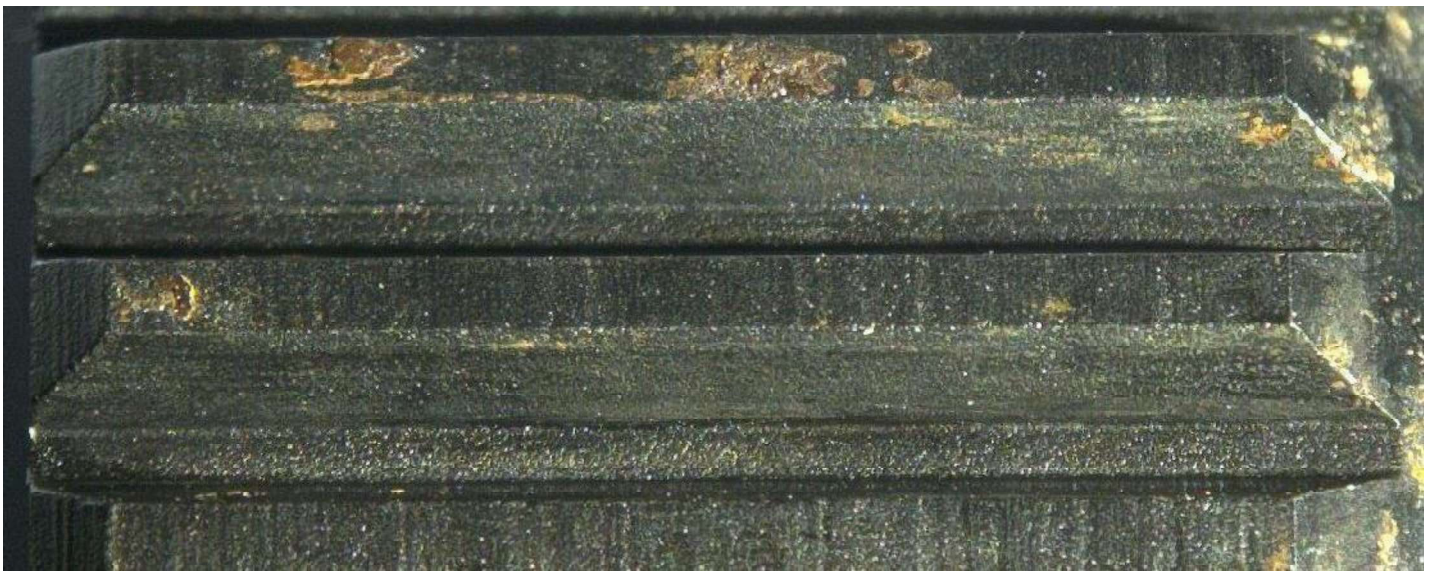
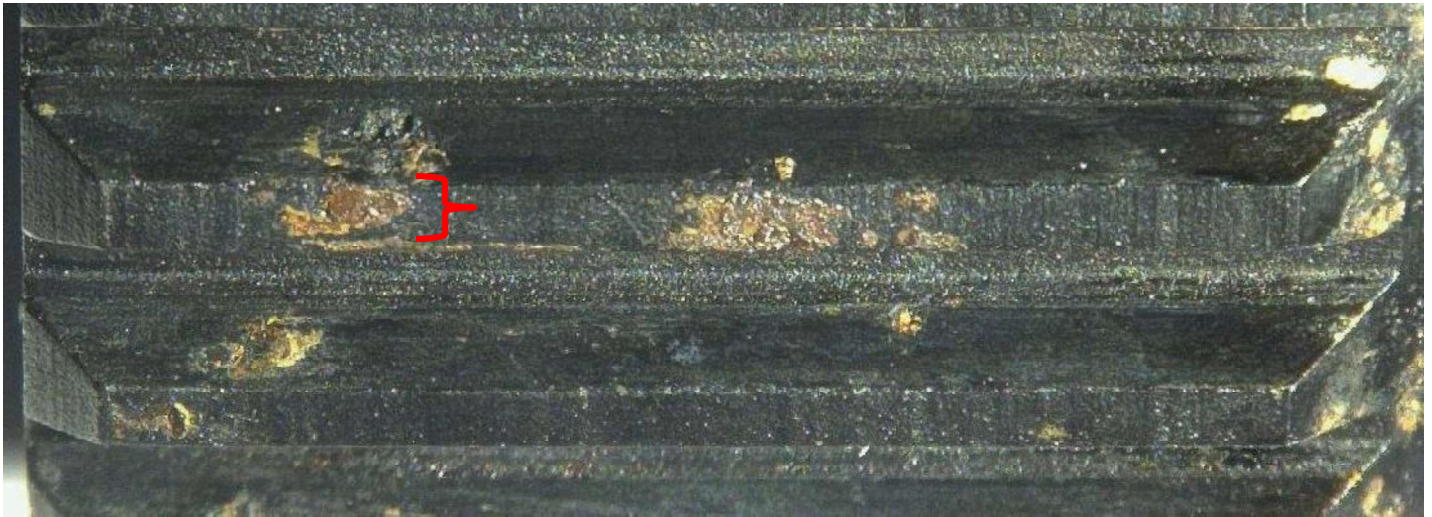


Figure 77. Detailed views of the loaded (top) and unloaded (bottom) flanks of the forward splines on the turbine shaft to pinion coupling. Red brace marks a region on the loaded flank on one spline where material fractured away.

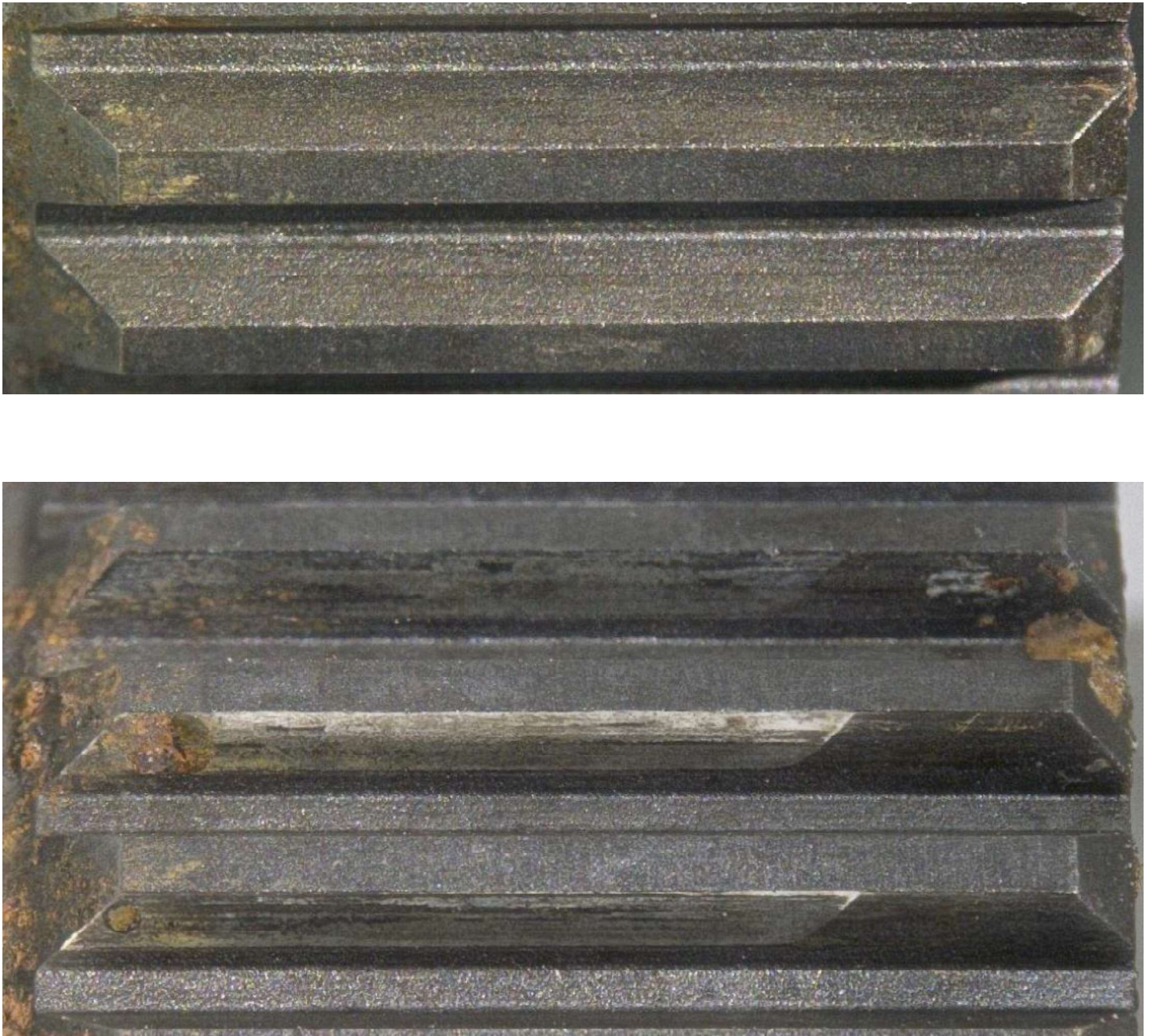


Figure 78. Detailed views of the loaded (bottom) and unloaded (top) flanks of the aft splines on the turbine shaft to pinion coupling.



Figure 79. General condition of the helical power takeoff gearshaft assembly after cleaning.

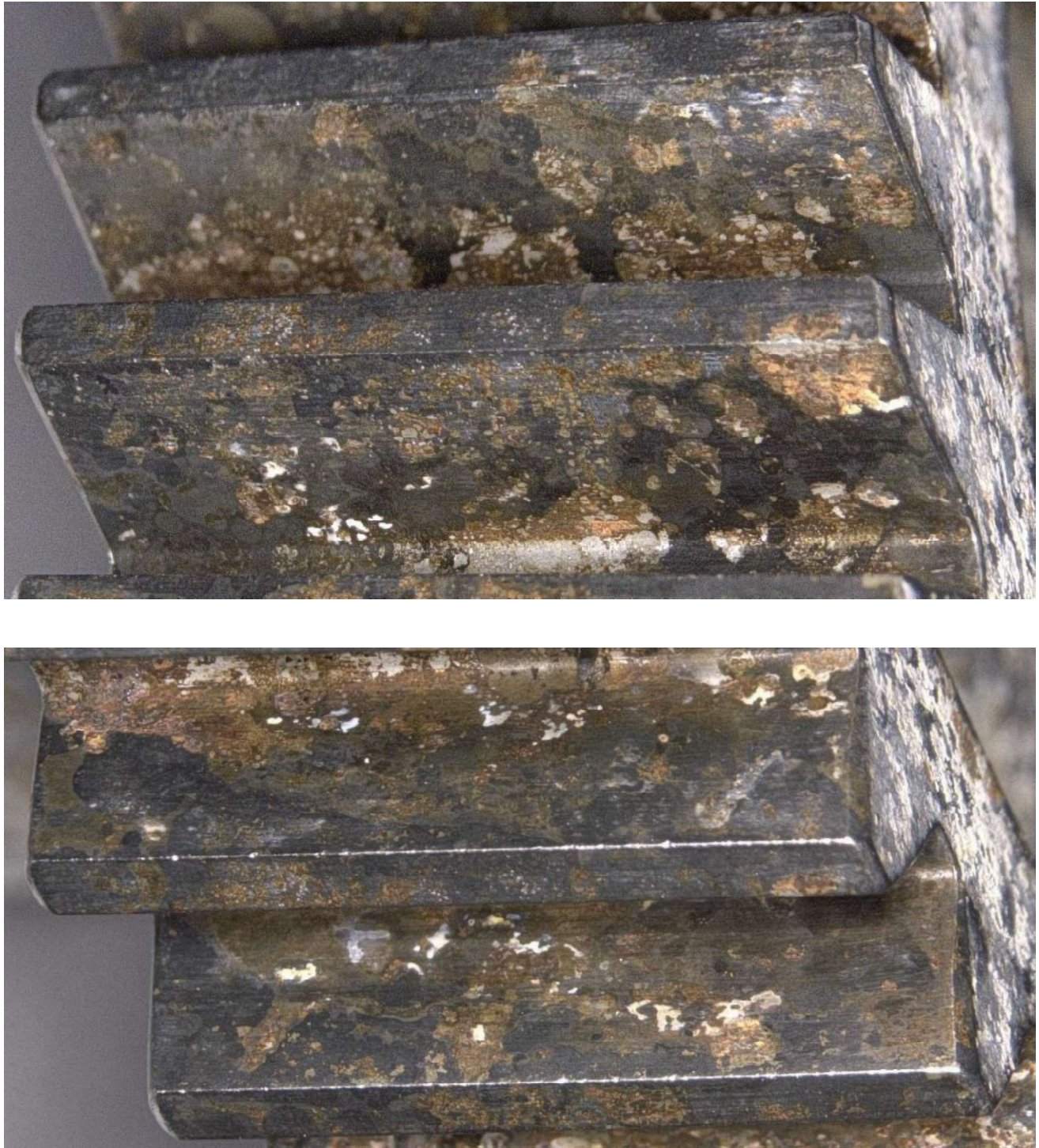


Figure 80. Detailed views of the driven (top) and coast (bottom) flanks of the larger diameter gear teeth on the helical power takeoff gearshaft.



Figure 81. General condition of the pressure oil filter (top) and CEFA oil filter bowl (bottom).



Figure 82. General condition of the CEFA oil filter (top) and debris collected from CEFA oil filter prior to arrival to the laboratory (bottom).

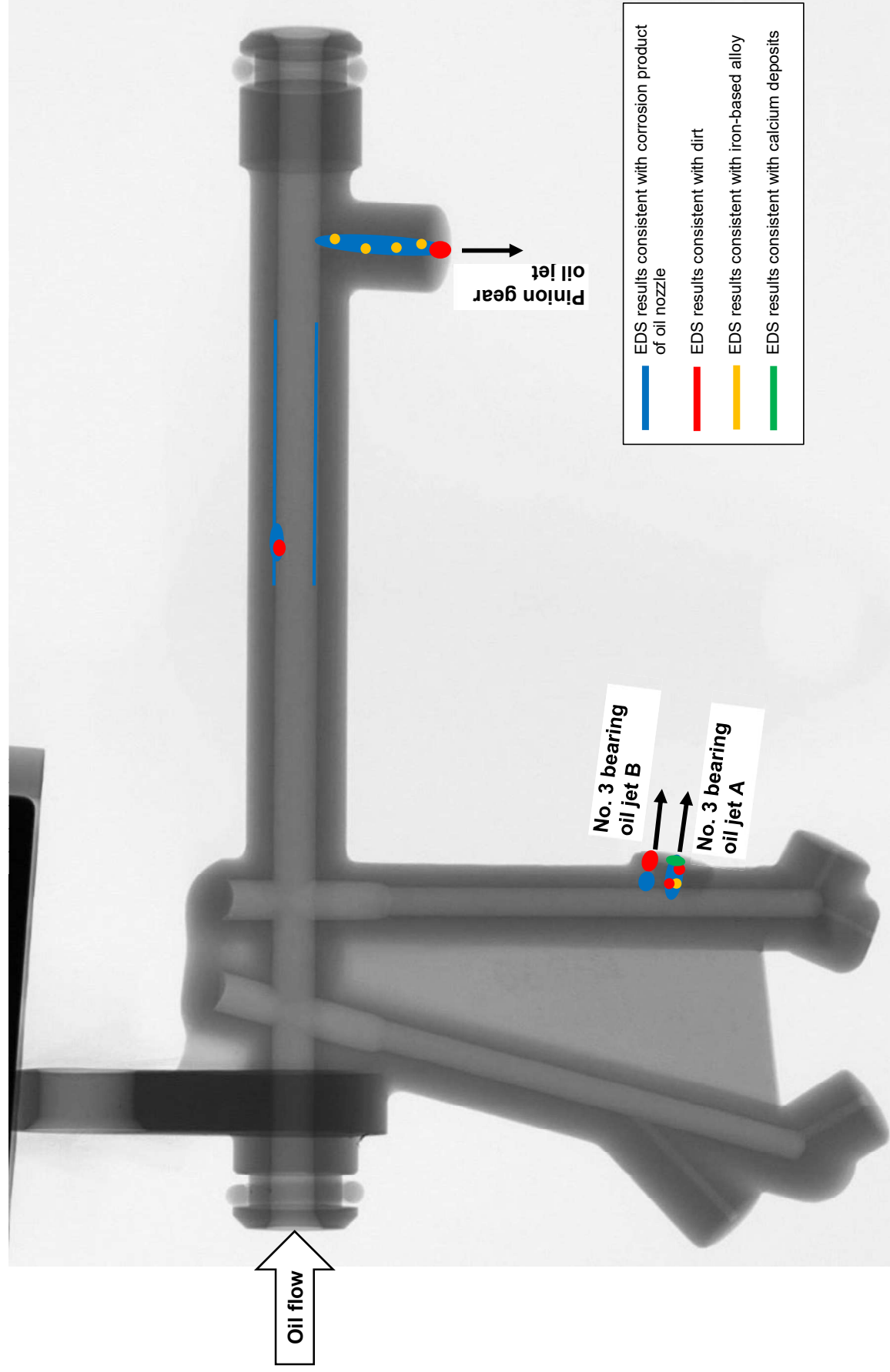


Figure 83. Color map of the EDS results for the blockage material in the oil jets and main passageway of the oil delivery tube.

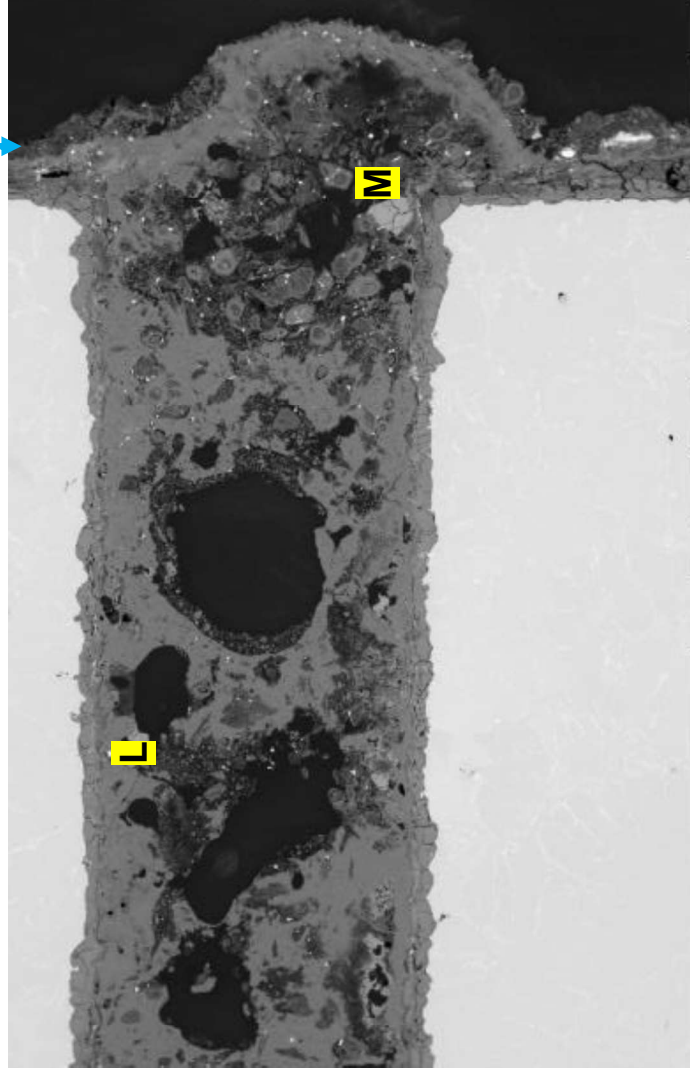


Figure 84. Optical (top) and backscattered electron SEM (bottom) images of the metallographic section through pinion gear oil jet of the oil delivery tube (see orange boxed area in Figure 61), which exhibited blockage. Locations L and M are shown in more detail in the following figure.

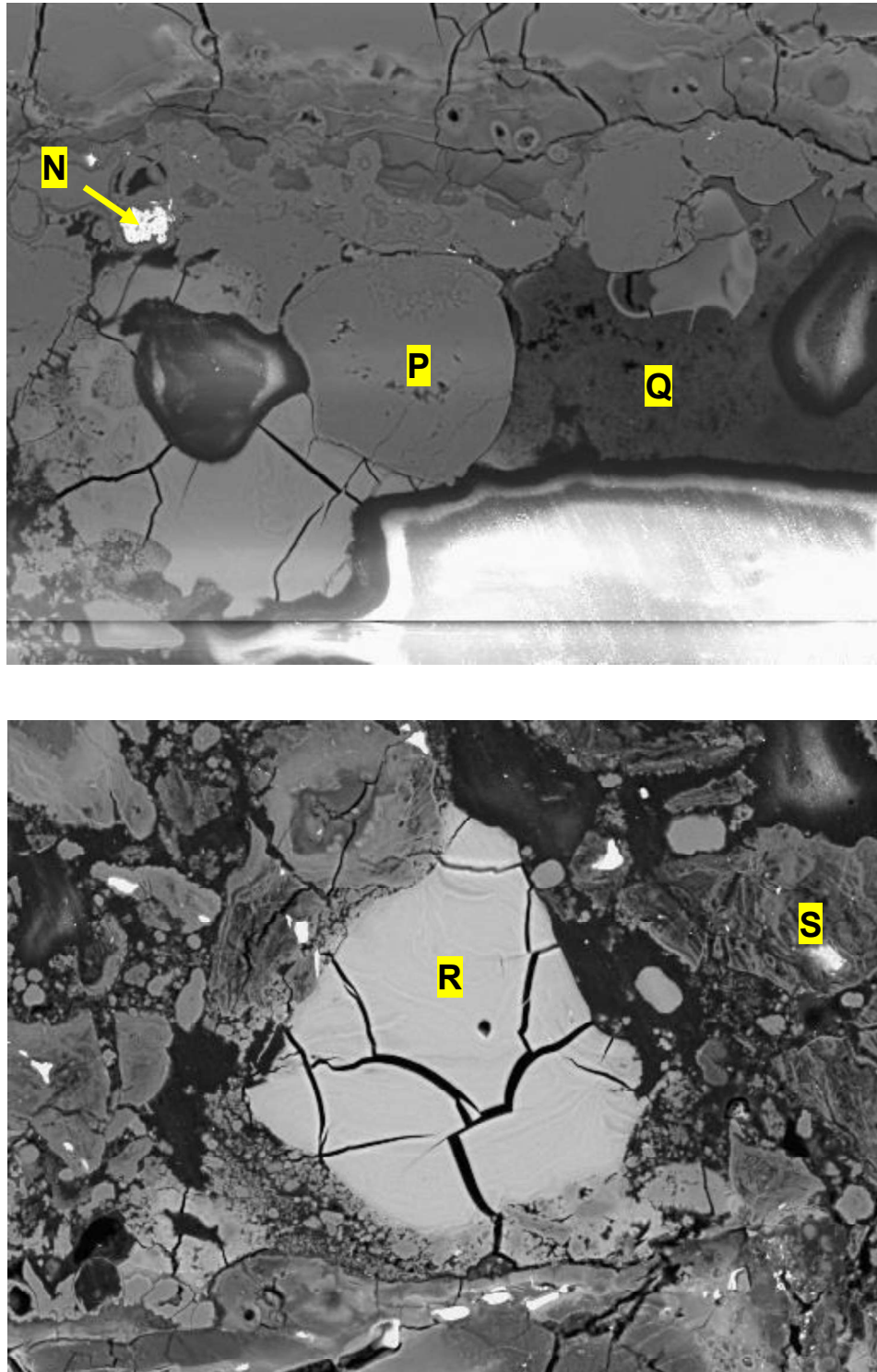


Figure 85. Backscattered electron SEM images of the blockage in pinion gear oil jet of the oil delivery tube. Top and bottom images are detailed views of locations L and M in previous figure, respectively. Semi-quantitative EDS results for blockage material at locations N through S are shown in more detail in Figure 86 through Figure 88.

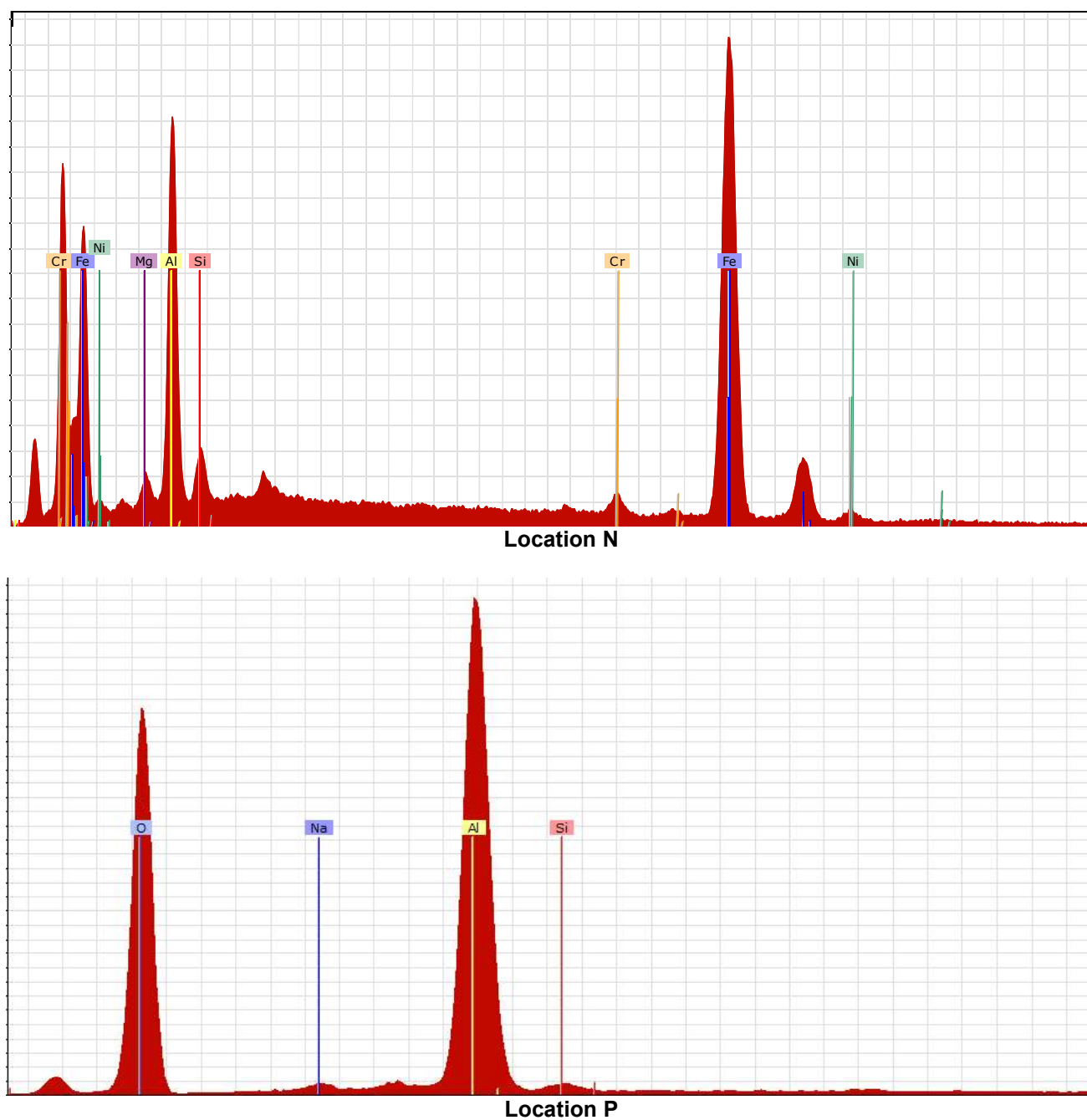


Figure 86. Semi-quantitative EDS results for blockage material at locations N and P in pinion gear oil jet of the oil delivery tube (see Figure 85). Location N exhibited concentrations of iron, aluminum, nickel, chromium, silicon, and magnesium. Location P exhibited concentrations of aluminum, oxygen, sodium, and silicon.

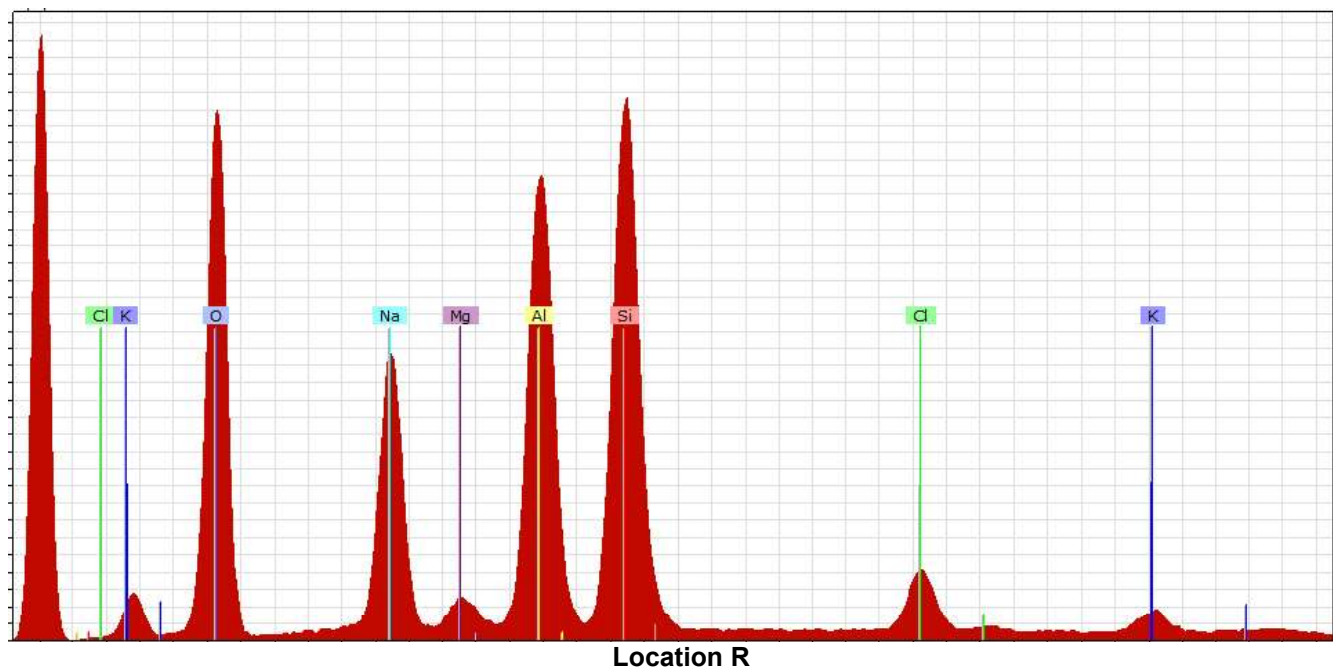
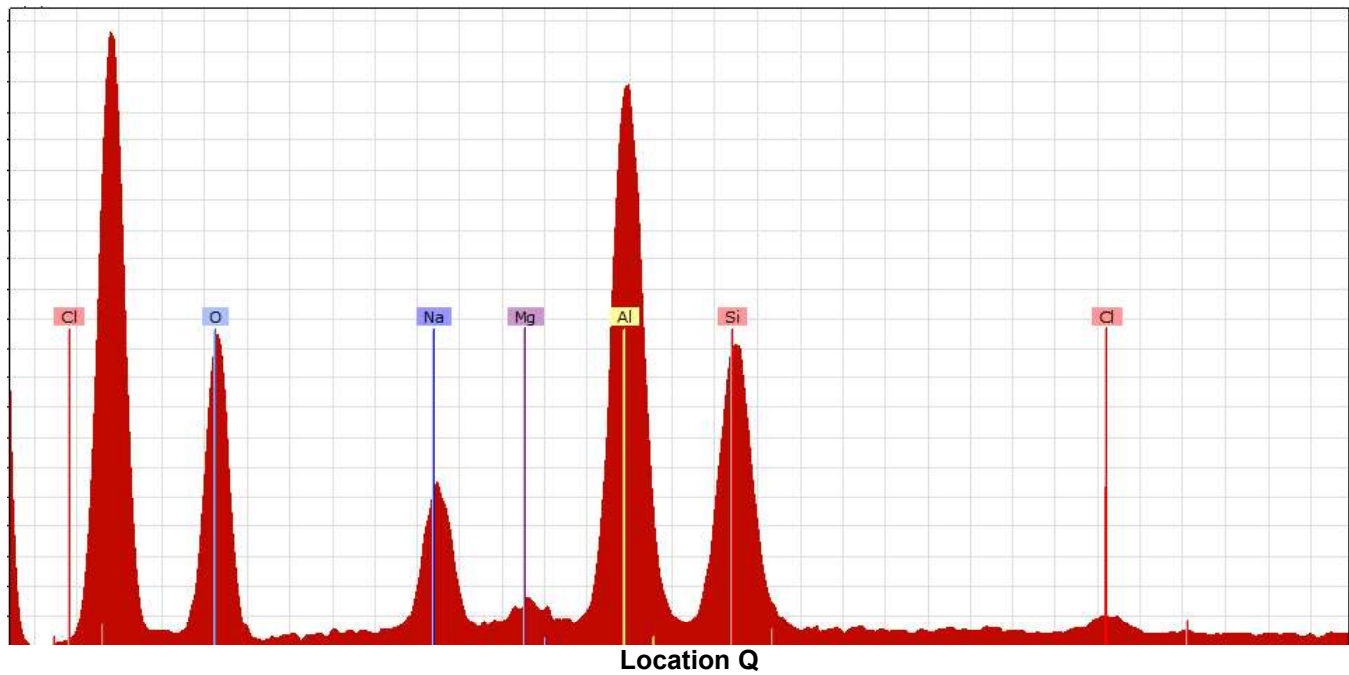


Figure 87. Semi-quantitative EDS results for blockage material at locations Q and R in pinion gear oil jet of the oil delivery tube (see Figure 85), which exhibited concentrations of silicon, aluminum, oxygen, sodium, chlorine, and magnesium.

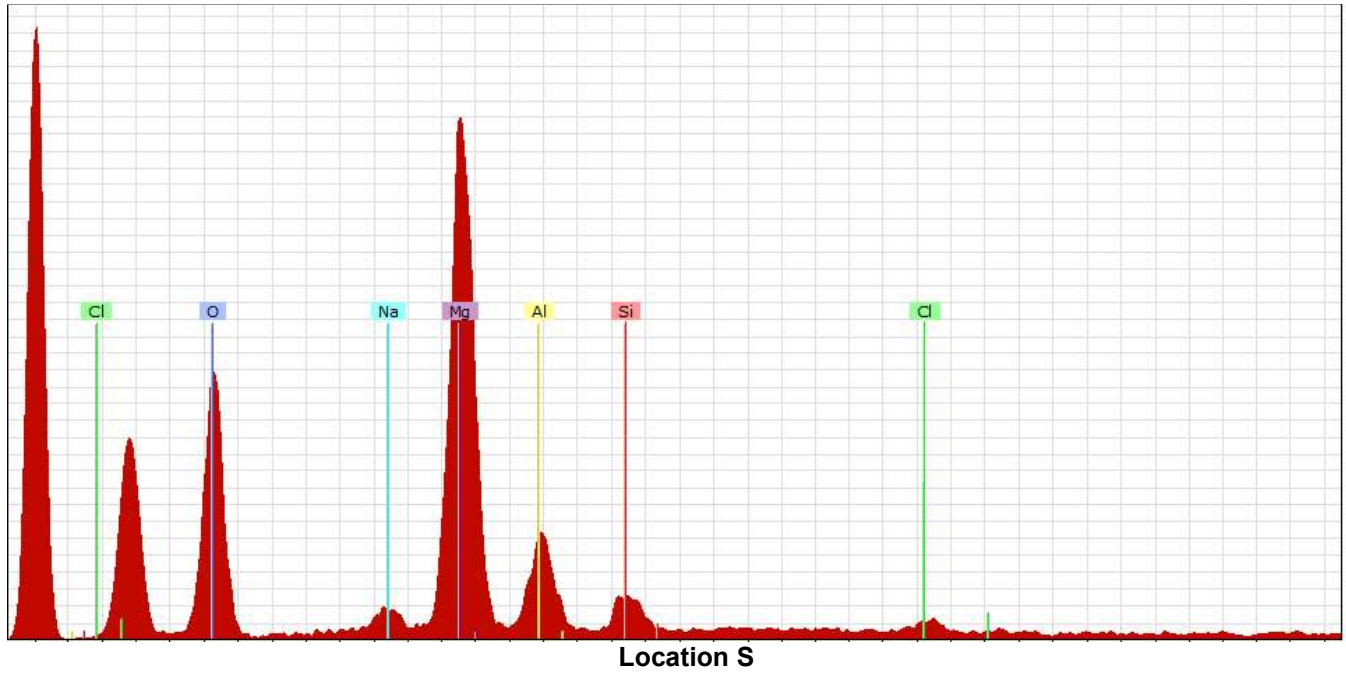


Figure 88. Semi-quantitative EDS results for blockage material at locations S in pinion gear oil jet of the oil delivery tube (see Figure 85), which exhibited concentrations of magnesium, oxygen, aluminum, silicon, and chlorine.

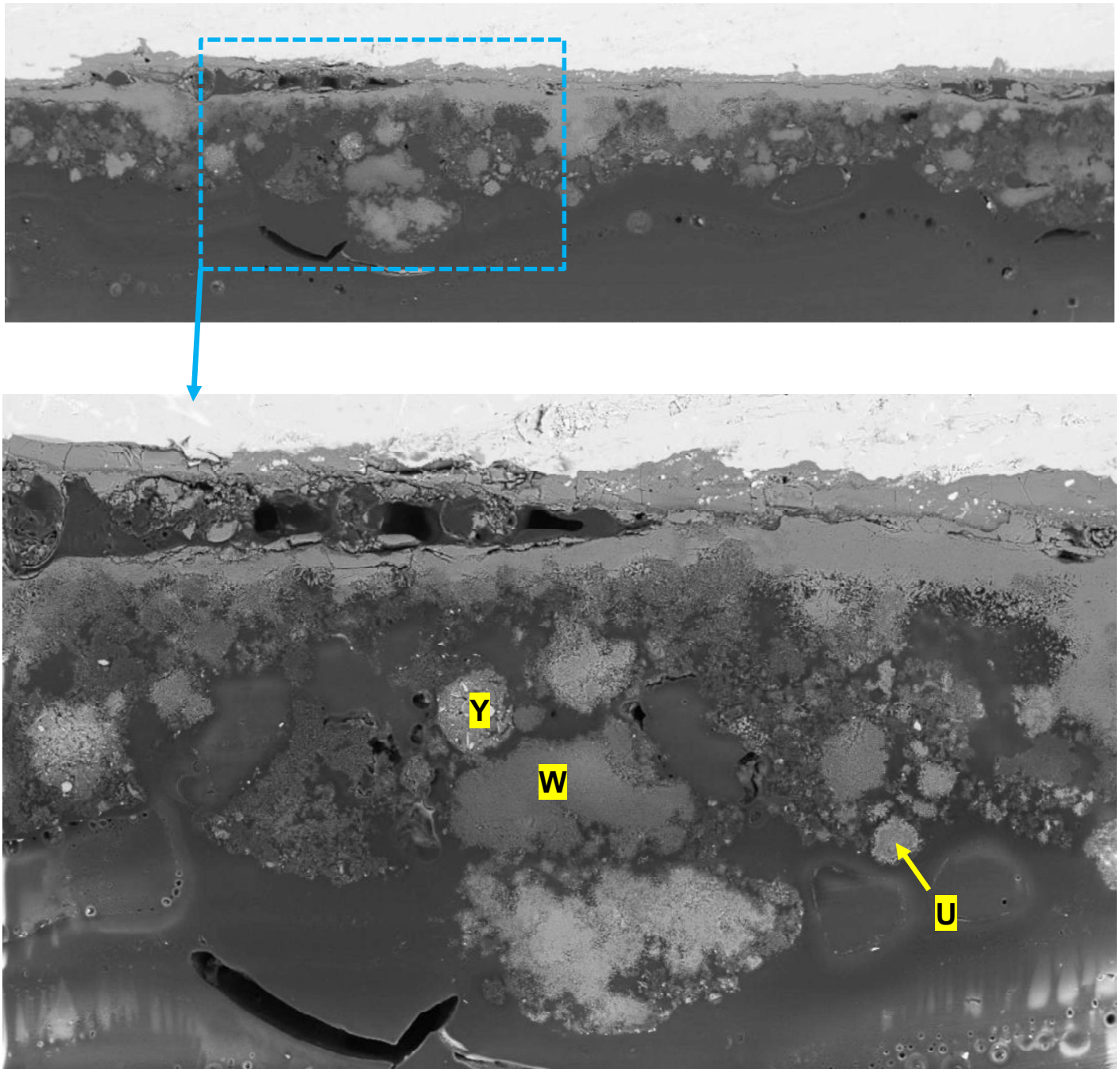


Figure 89. Backscattered electron SEM images of the metallographic section through the main passageway of the oil delivery tube (see blue boxed area in Figure 62), which exhibited blockage. Semi-quantitative EDS results for blockage material at locations U through Y are shown in more detail in Figure 90 and Figure 91.

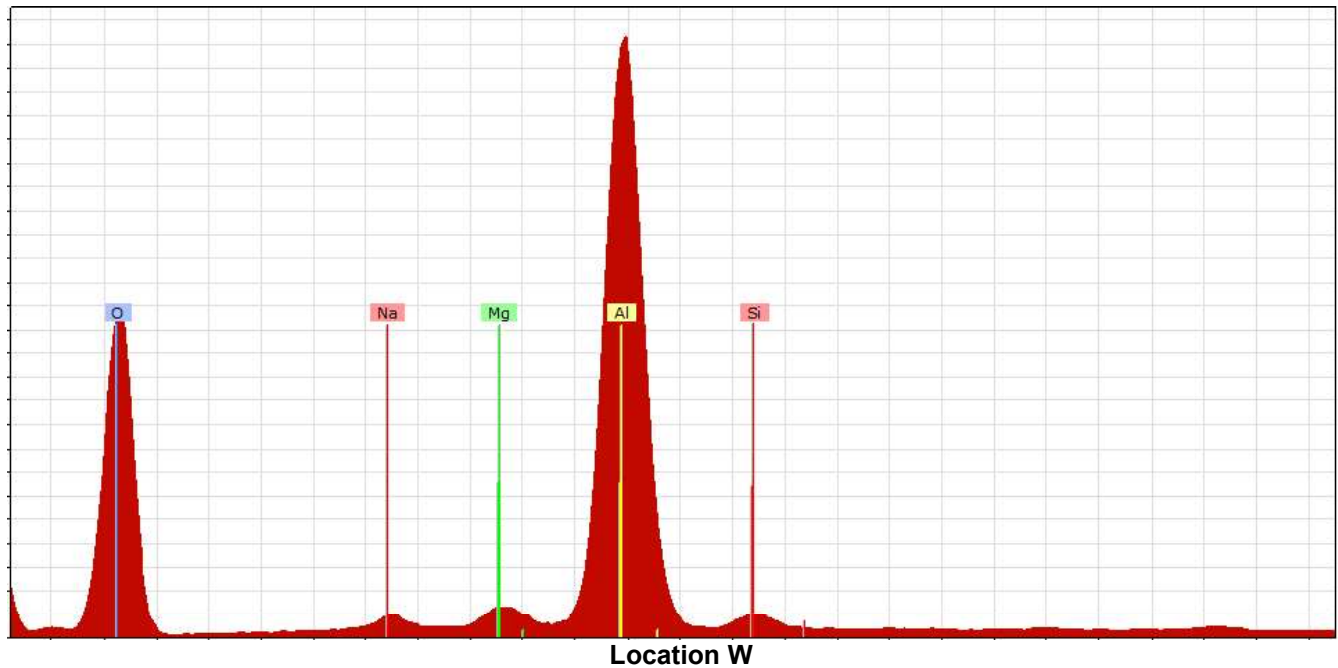
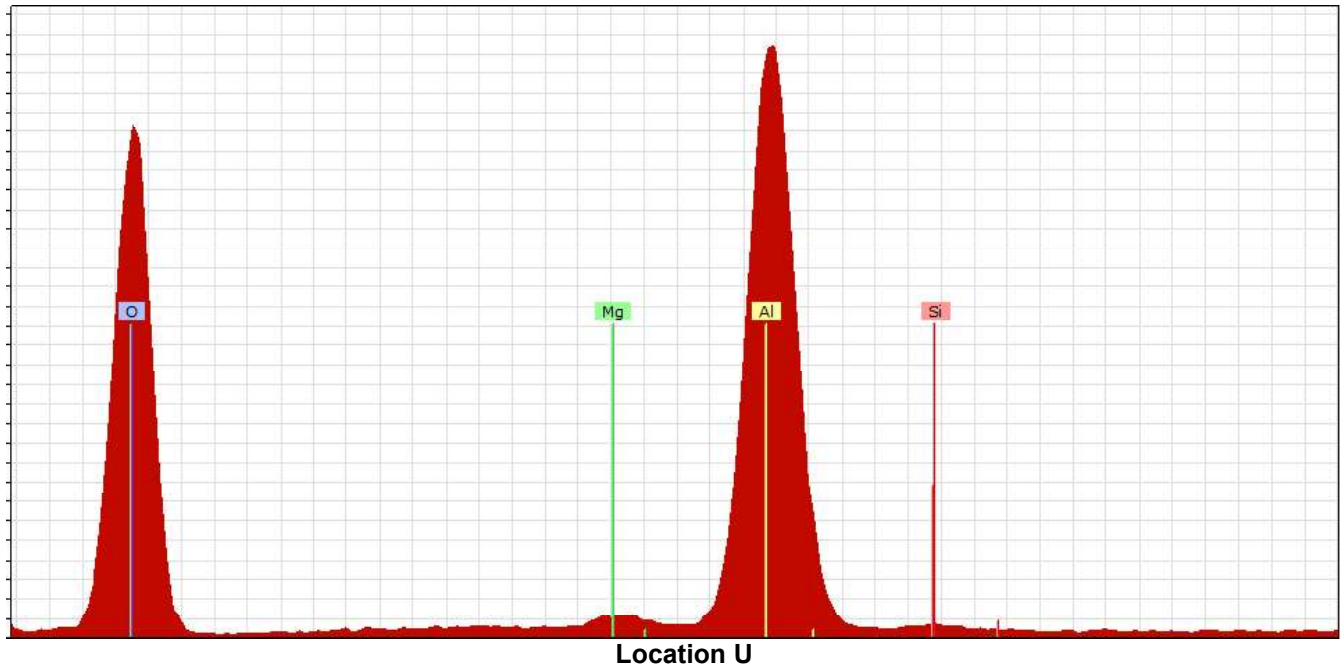


Figure 90. Semi-quantitative EDS results for blockage material at locations U and W in the main passageway of the oil delivery tube (see Figure 89). Location U exhibited concentrations of oxygen, aluminum, magnesium, and silicon. Location W exhibited concentrations of aluminum, oxygen, magnesium, silicon, and sodium.

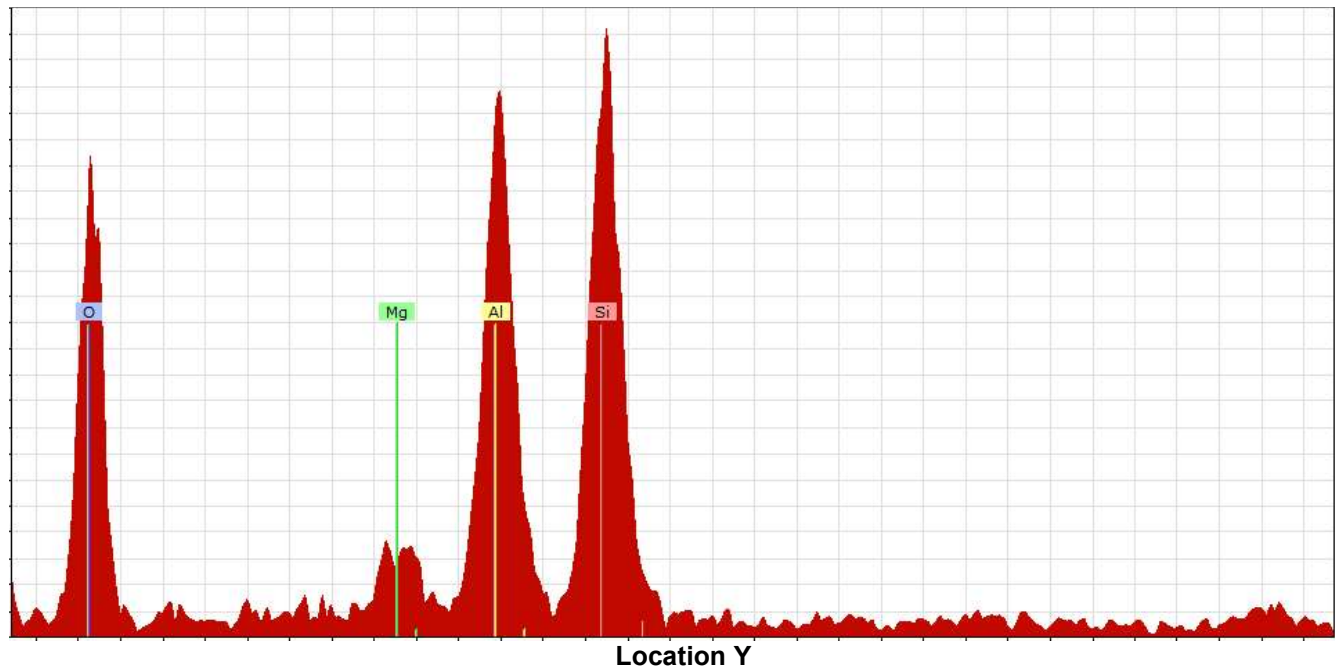


Figure 91. Semi-quantitative EDS results for blockage material at locations Y in the main passageway of the oil delivery tube (see Figure 89), which exhibited concentrations of oxygen, silicon, aluminum, and magnesium.

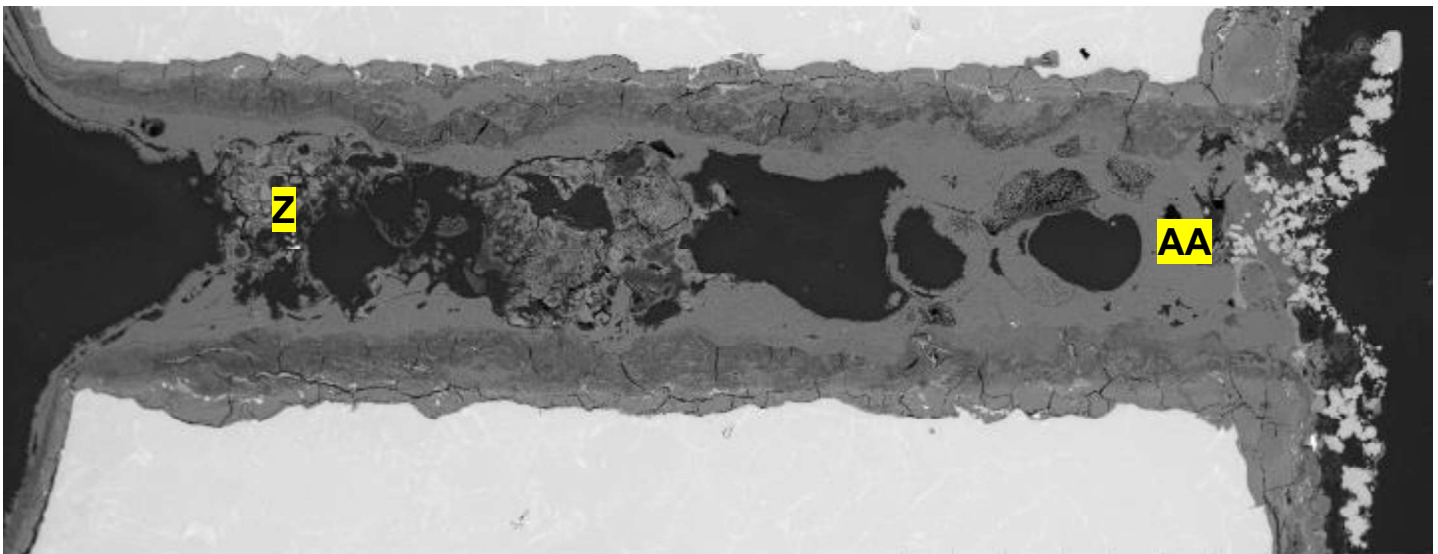
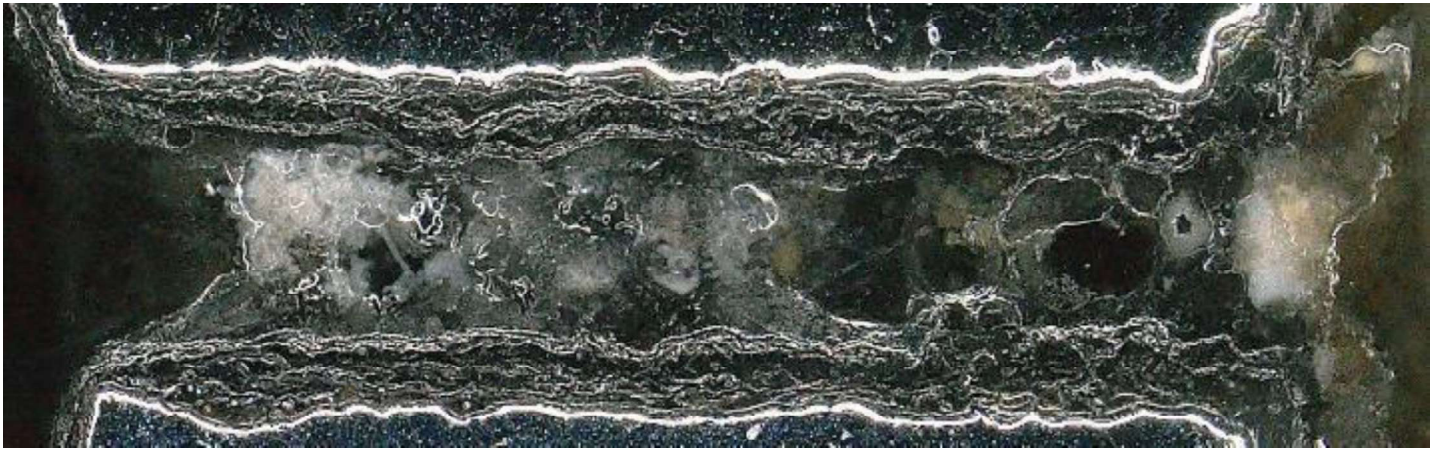


Figure 92. Optical (top) and backscattered electron SEM (bottom) images of the metallographic section through No. 3 bearing oil jet A of the oil delivery tube (see orange boxed area in Figure 63), which exhibited blockage. Locations Z and AA are shown in more detail in the following figure.

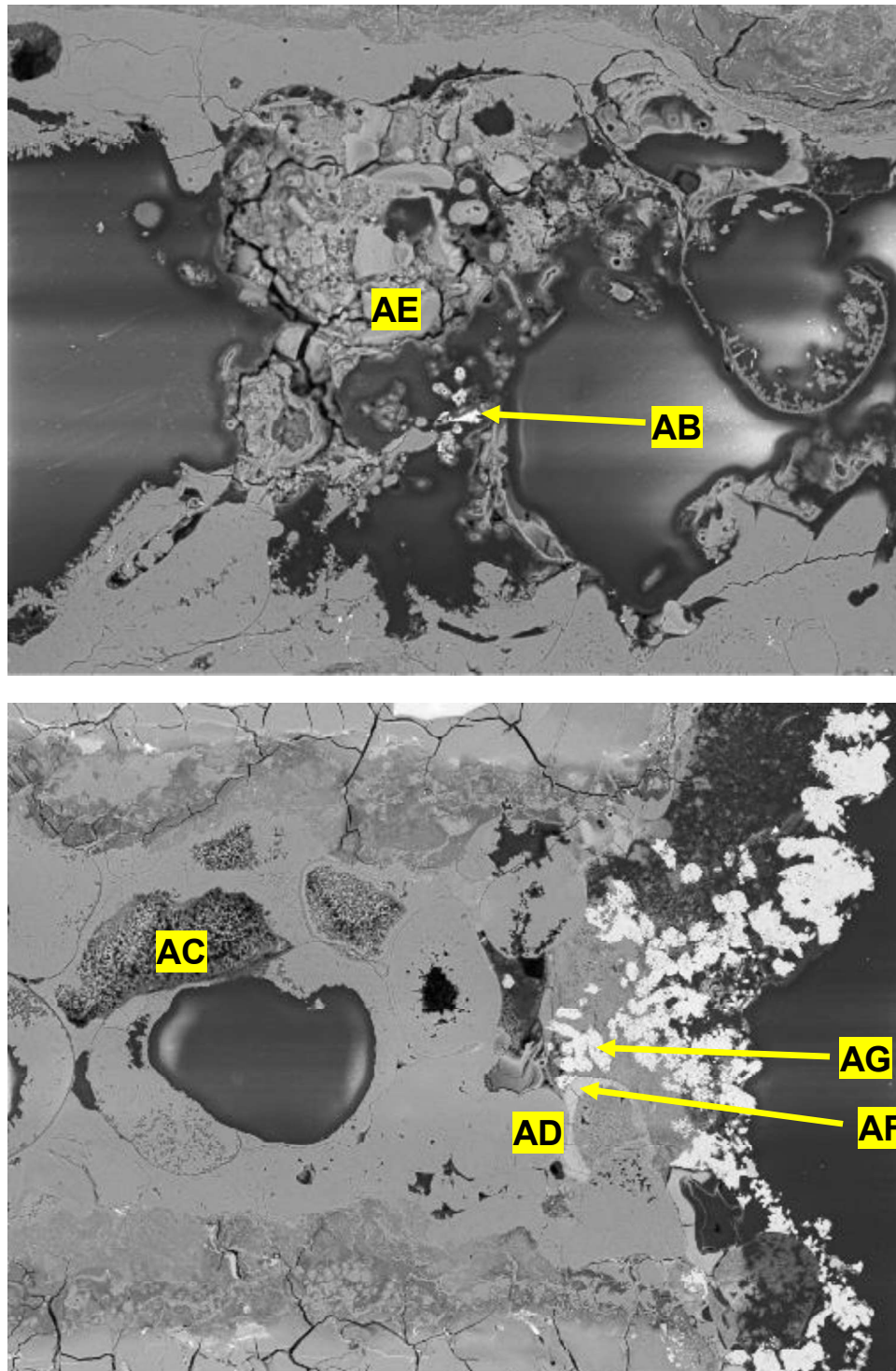


Figure 93. Backscattered electron SEM images of the blockage in No. 3 bearing oil jet A of the oil delivery tube. Top and bottom images are detailed views of locations Z and AA in previous figure, respectively. Semi-quantitative EDS results for blockage material at locations AB through AG are shown in more detail in Figure 94 and Figure 96.

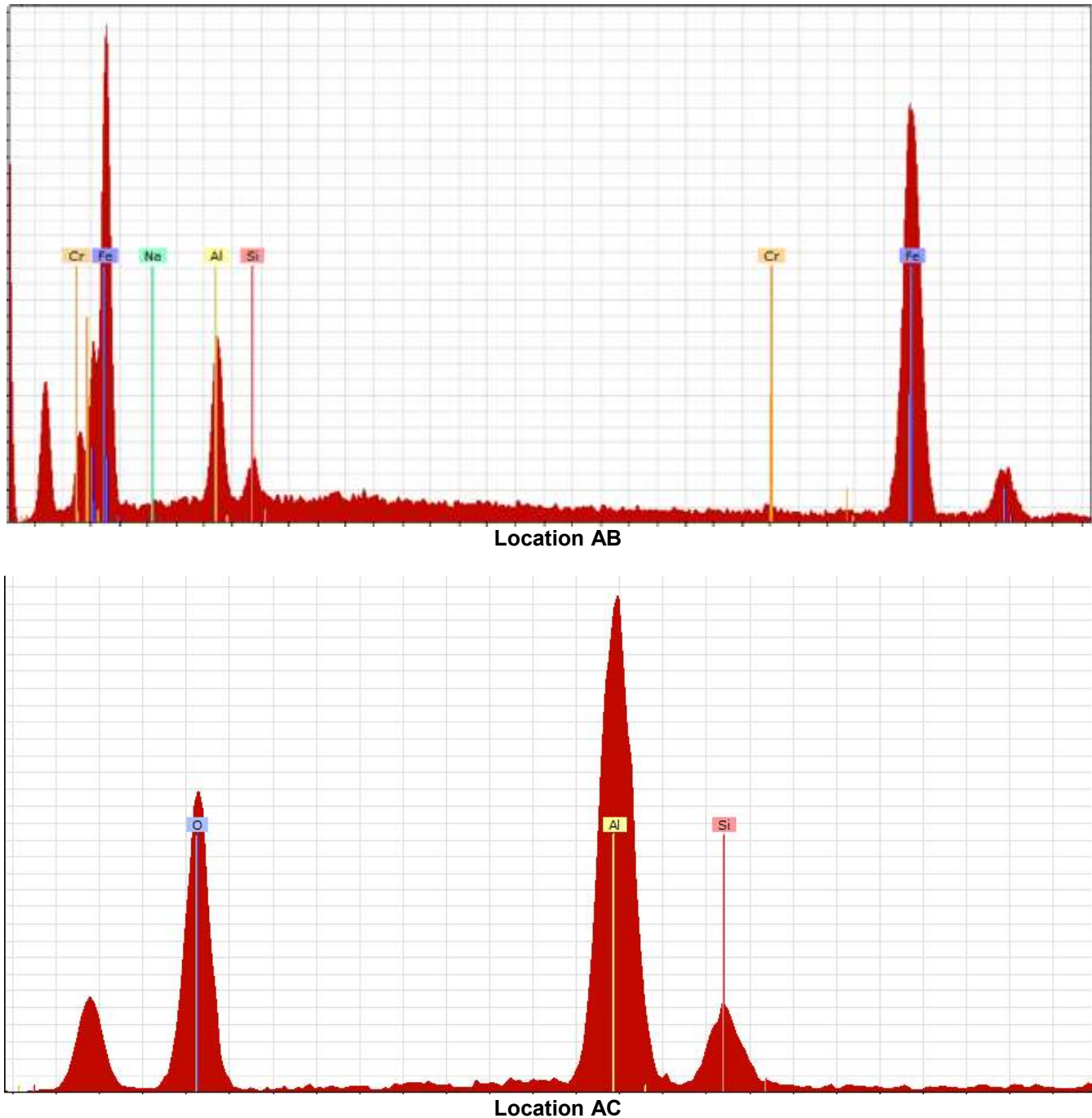


Figure 94. Semi-quantitative EDS results for blockage material at locations AB and AC in No. 3 bearing oil jet A of the oil delivery tube (see Figure 93). Location AB exhibited concentrations of iron, aluminum, silicon, chromium, and sodium. Location AC exhibited concentrations of aluminum, oxygen, and silicon.

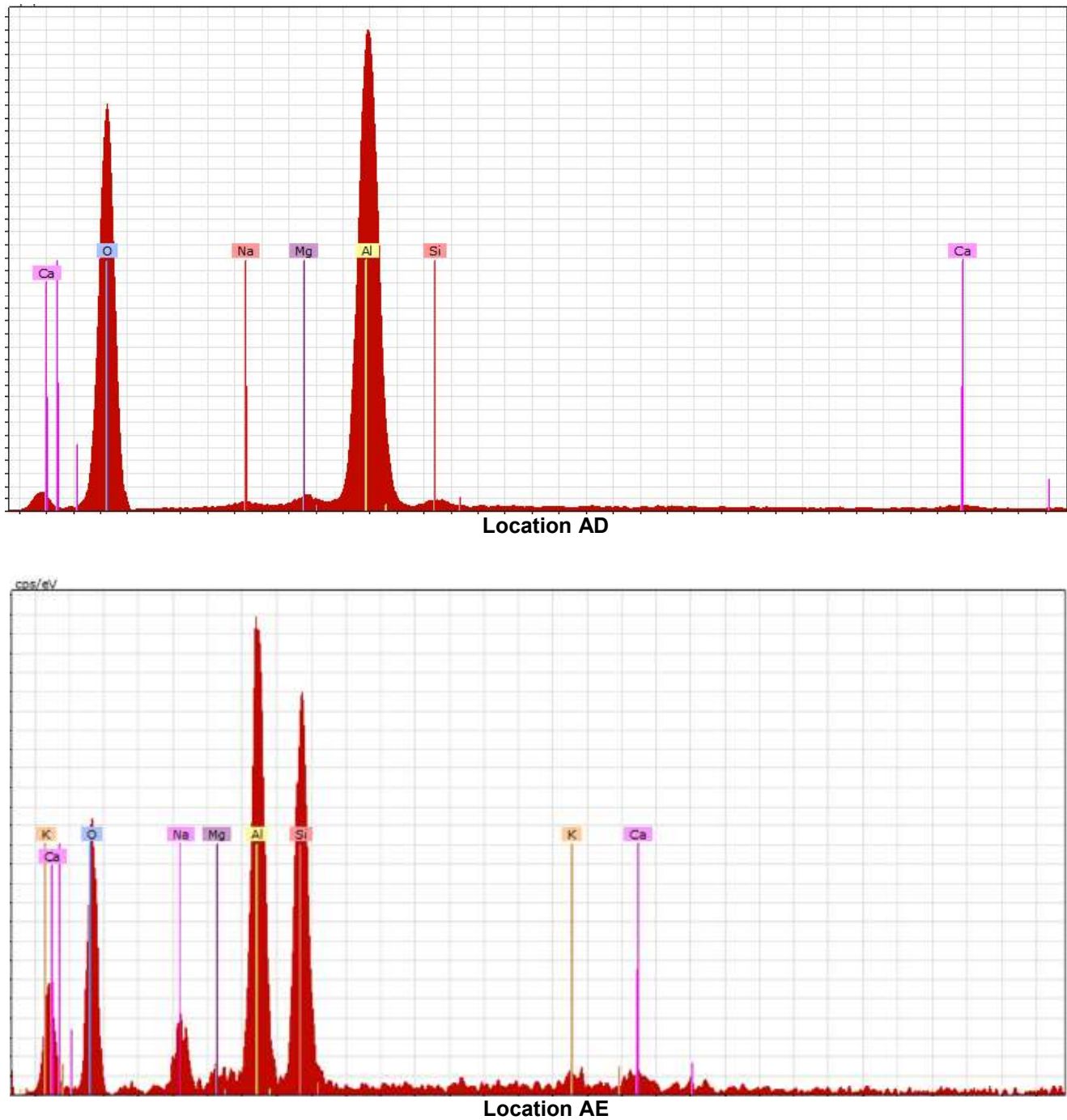


Figure 95. Semi-quantitative EDS results for blockage material at locations AD and AE in No. 3 bearing oil jet A of the oil delivery tube (see Figure 93). Location AD exhibited concentrations of aluminum, oxygen, and magnesium, calcium, sodium, and silicon. Location AE exhibited concentrations of silicon, aluminum, oxygen, calcium, sodium, magnesium, and potassium.

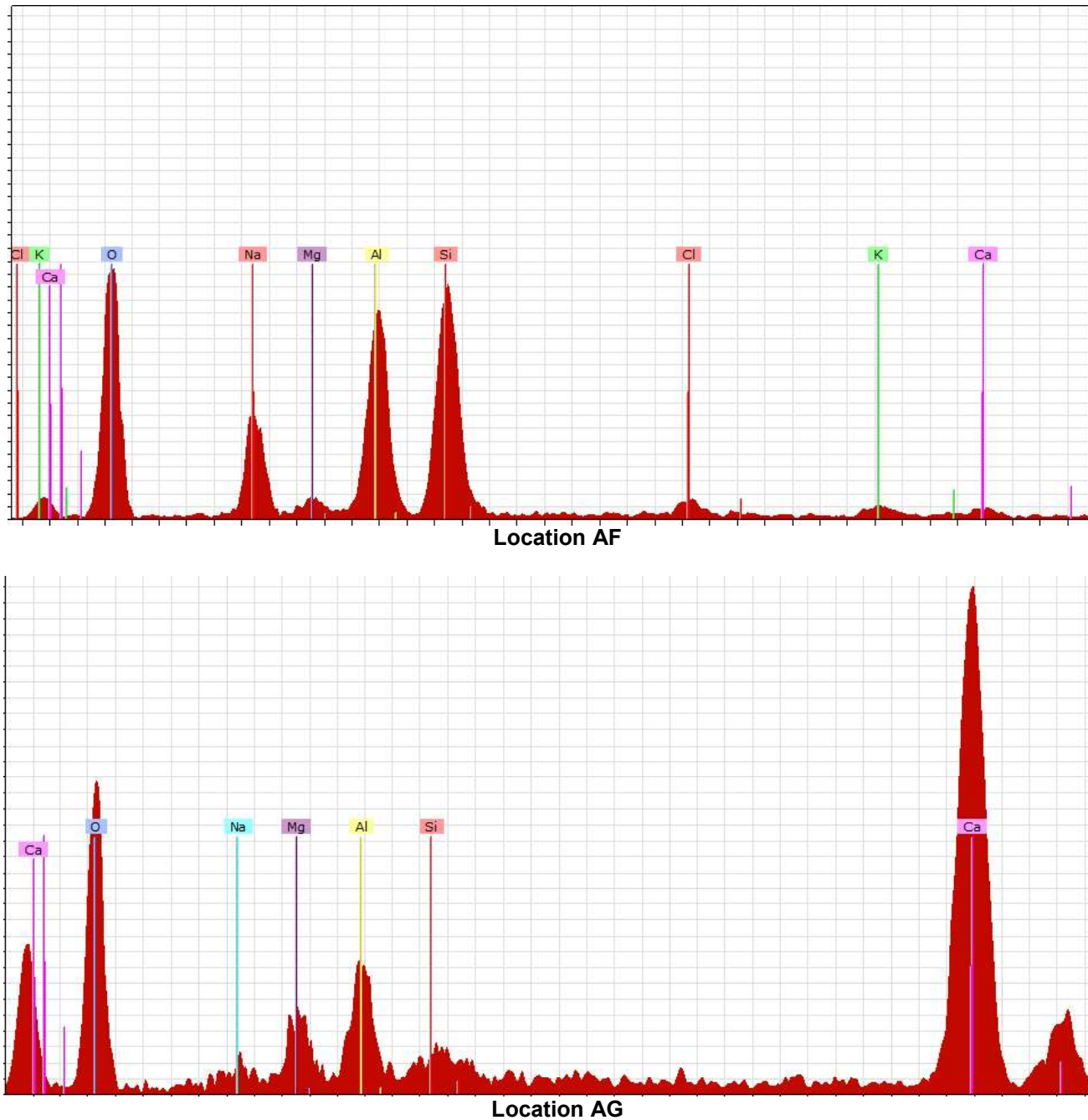


Figure 96. Semi-quantitative EDS results for blockage material at locations AF and AG in No. 3 bearing oil jet A of the oil delivery tube (see Figure 93). Location AF exhibited concentrations of silicon, aluminum, oxygen, magnesium, chlorine, potassium, and calcium. Location AG exhibited concentrations of calcium, oxygen, aluminum, magnesium, sodium, and silicon.

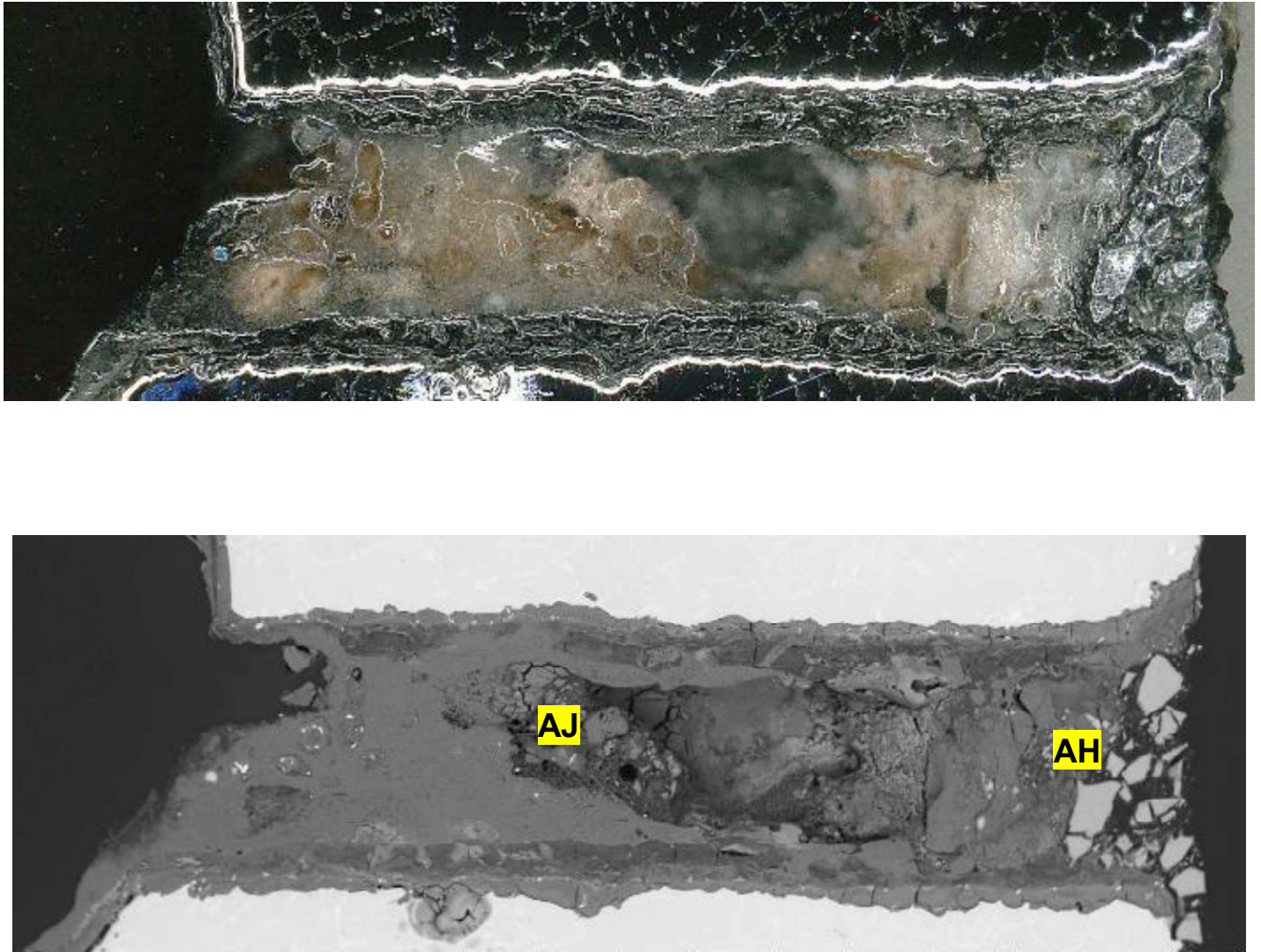


Figure 97. Optical (top) and backscattered electron SEM (bottom) images of the metallographic section through No. 3 bearing oil jet B of the oil delivery tube (see orange boxed area in Figure 64), which exhibited blockage. Locations AH and AJ are shown in more detail in the following figure.

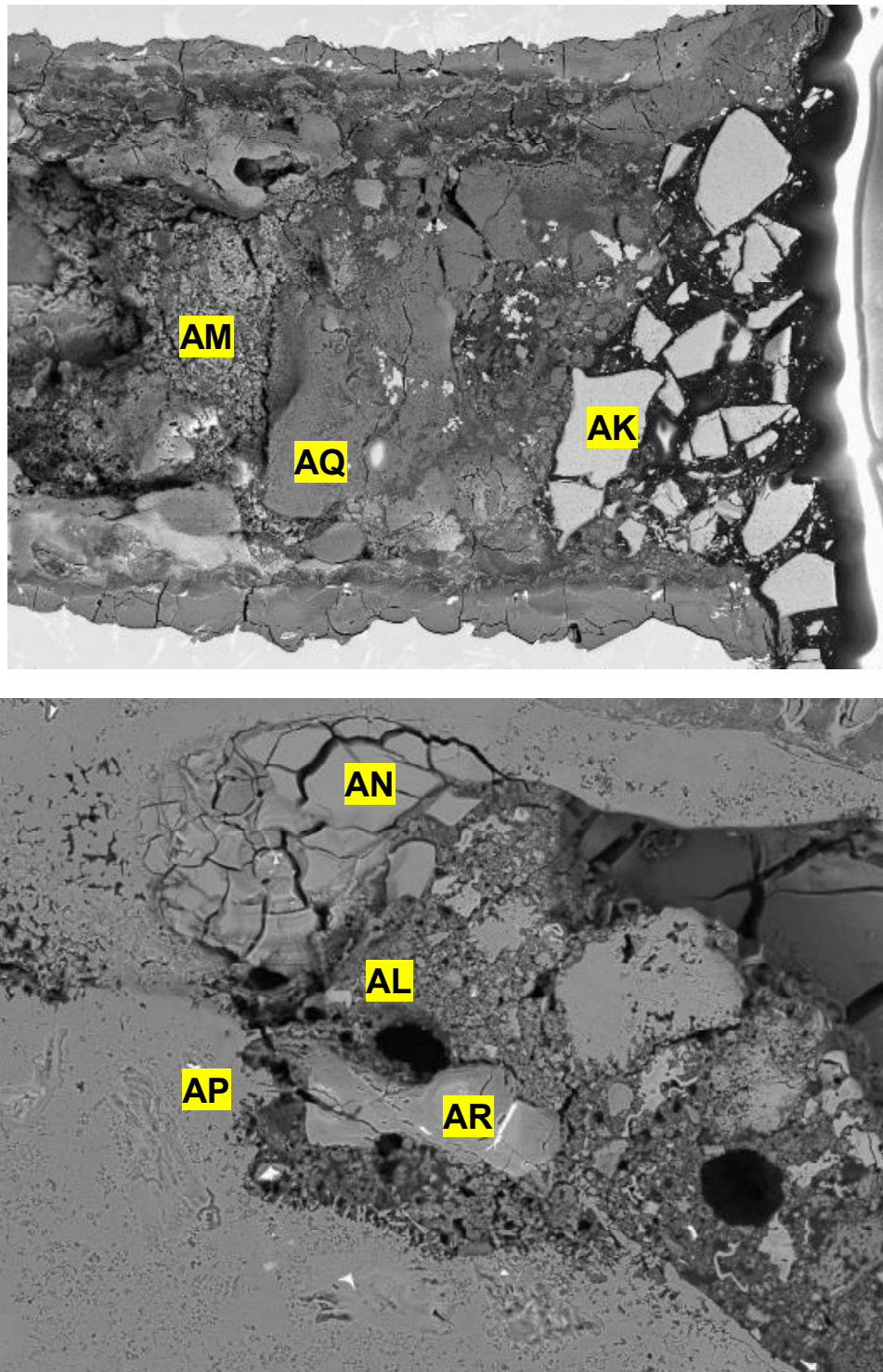


Figure 98. Backscattered electron SEM images of the blockage in No. 3 bearing oil jet B of the oil delivery tube. Top and bottom images are detailed views of locations AH and AJ in previous figure, respectively. Semi-quantitative EDS results for blockage material at locations AK through AR are shown in more detail in Figure 99 and Figure 102.

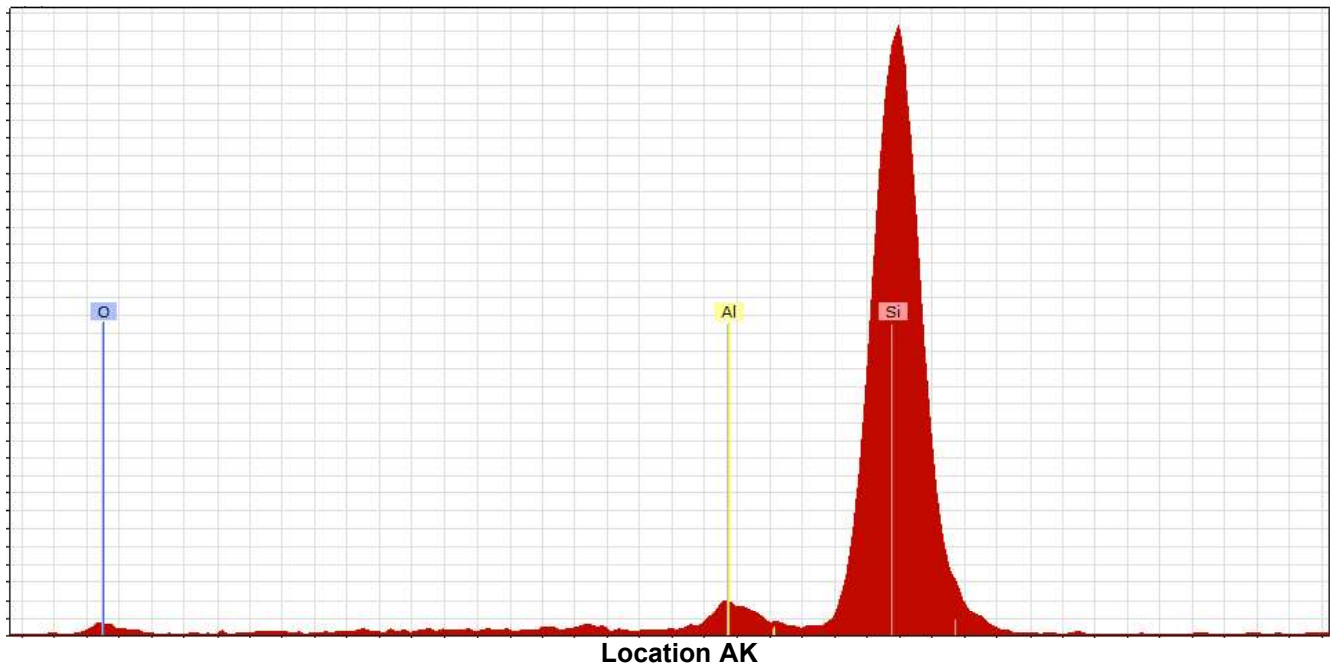
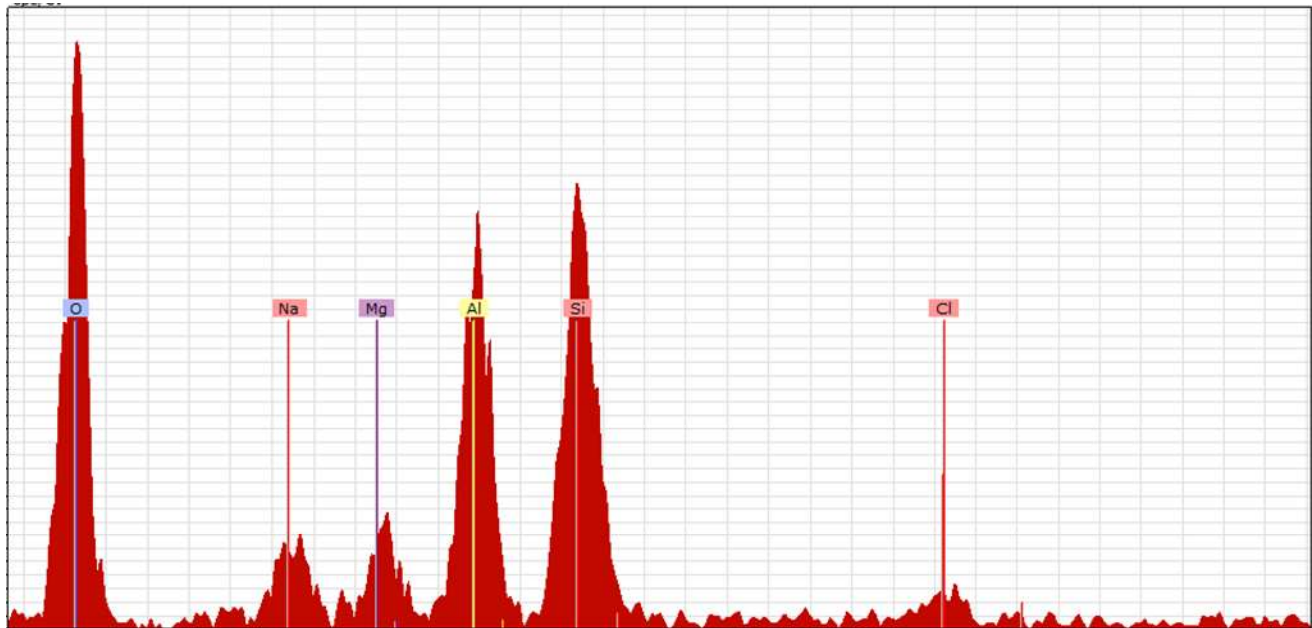
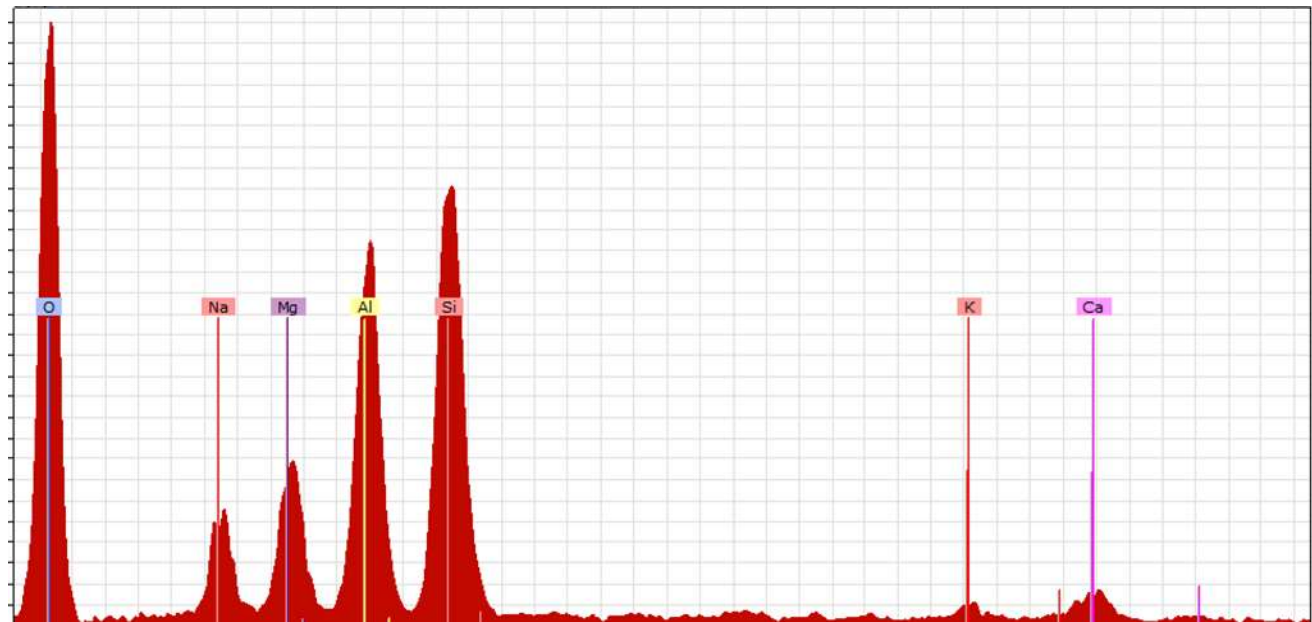


Figure 99. Semi-quantitative EDS results for blockage material at location AK in No. 3 bearing oil jet B of the oil delivery tube (see Figure 98), which exhibited concentrations of silicon, oxygen, and aluminum.

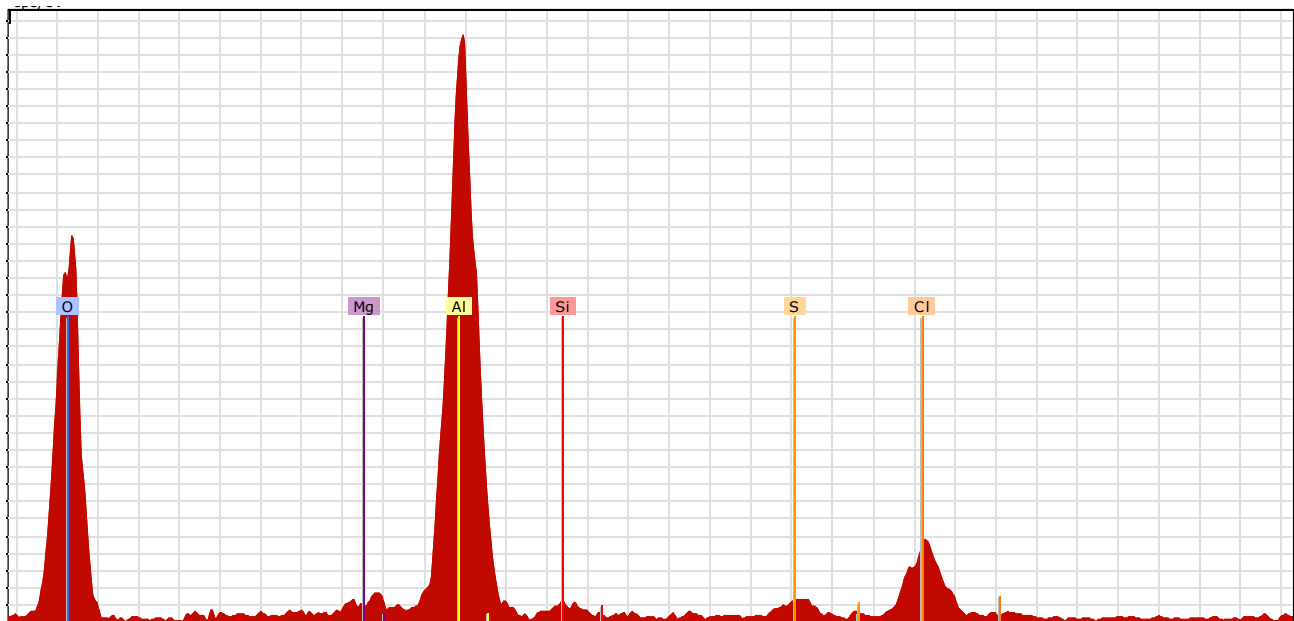


Location AL

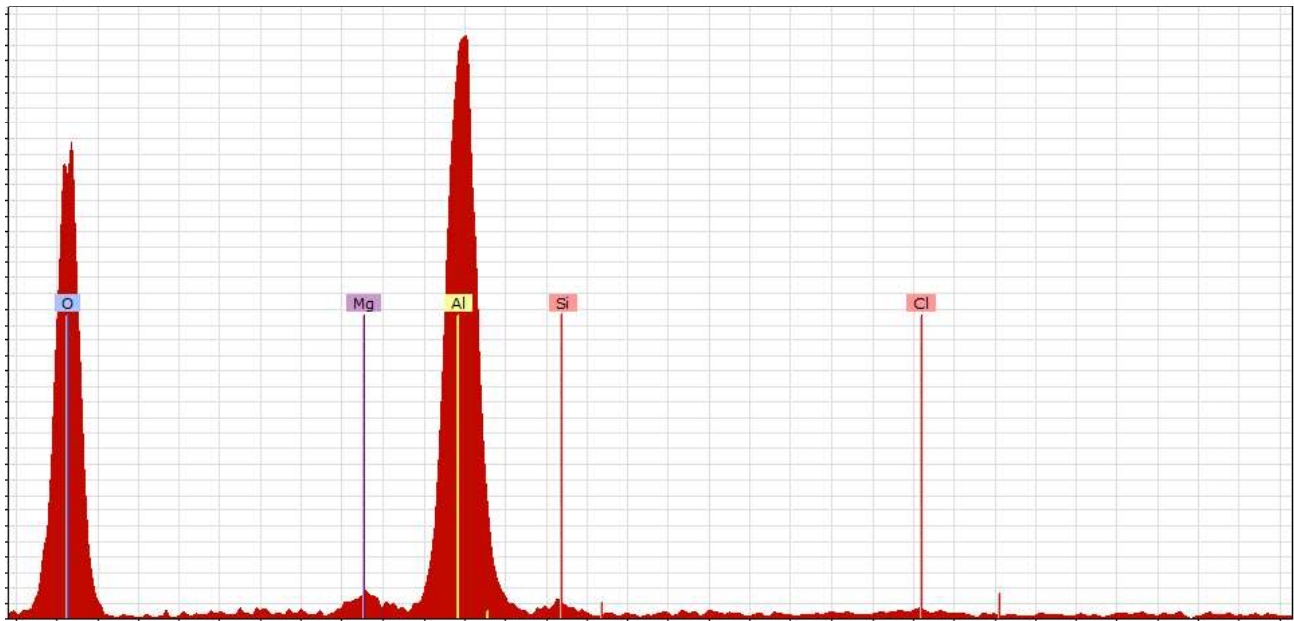


Location AM

Figure 100. Semi-quantitative EDS results for blockage material at locations AL and AM in No. 3 bearing oil jet B of the oil delivery tube (see Figure 98), which exhibited concentrations of silicon, aluminum, oxygen, magnesium, and calcium.



Location AN



Location AP

Figure 101. Semi-quantitative EDS results for blockage material at locations AN and AP in No. 3 bearing oil jet B of the oil delivery tube (see Figure 98), which exhibited concentrations of aluminum, oxygen, silicon, chlorine, and magnesium.

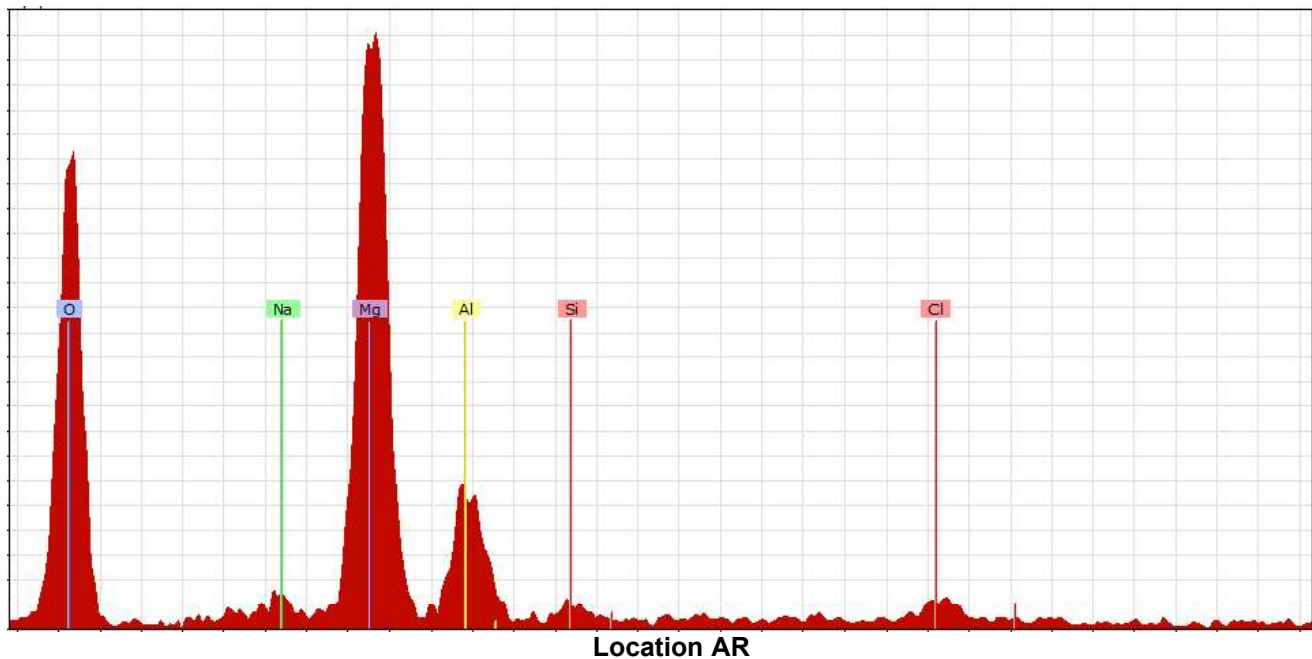
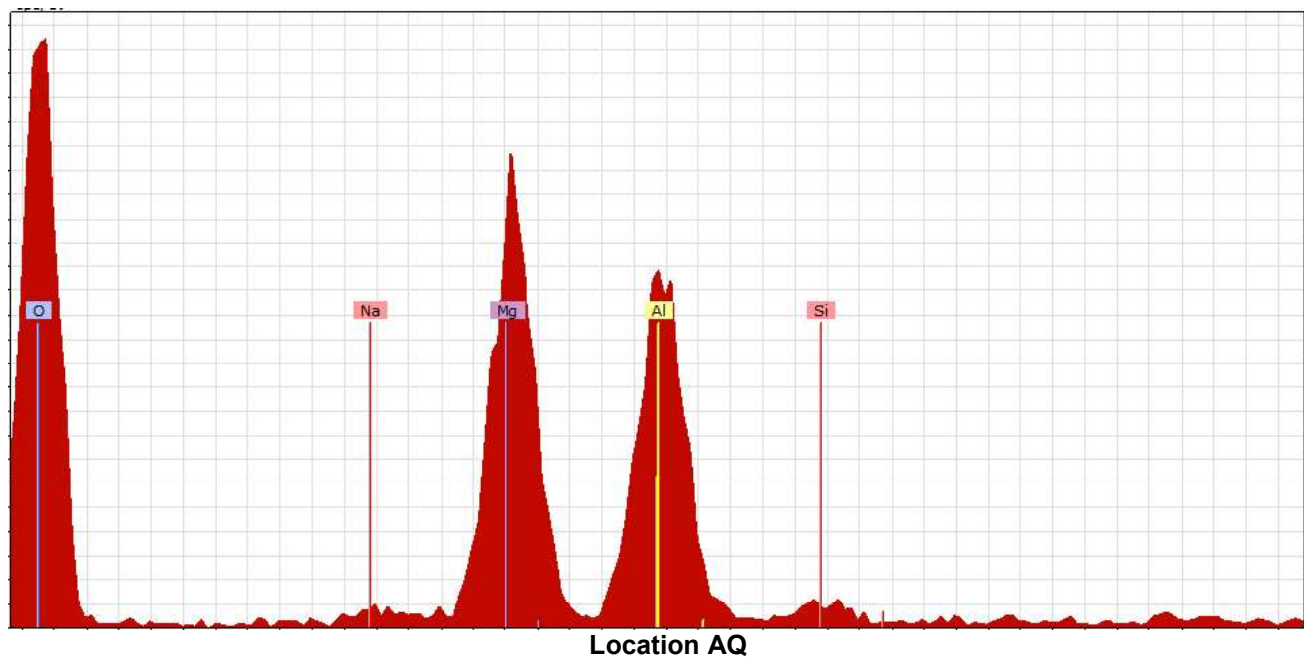


Figure 102. Semi-quantitative EDS results for blockage material at locations AQ and AR in No. 3 bearing oil jet B of the oil delivery tube (see Figure 98), which exhibited concentrations of magnesium, oxygen, aluminum, silicon, and sodium.

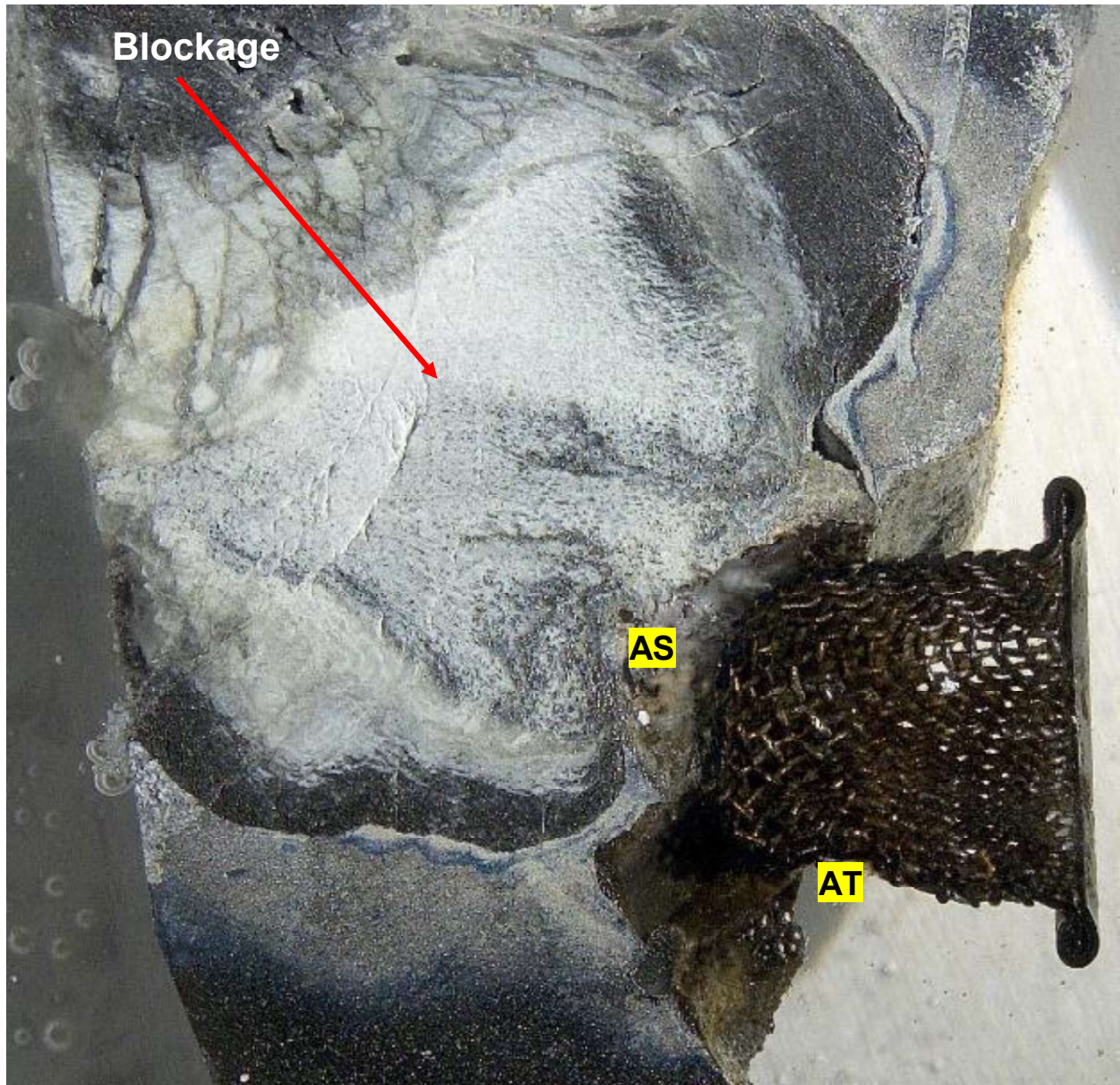


Figure 103. Metallographic section through the gearbox housing and oil screen (see the red dashed line in Figure 58). Locations AS and AT are shown in more detail in the following figure.

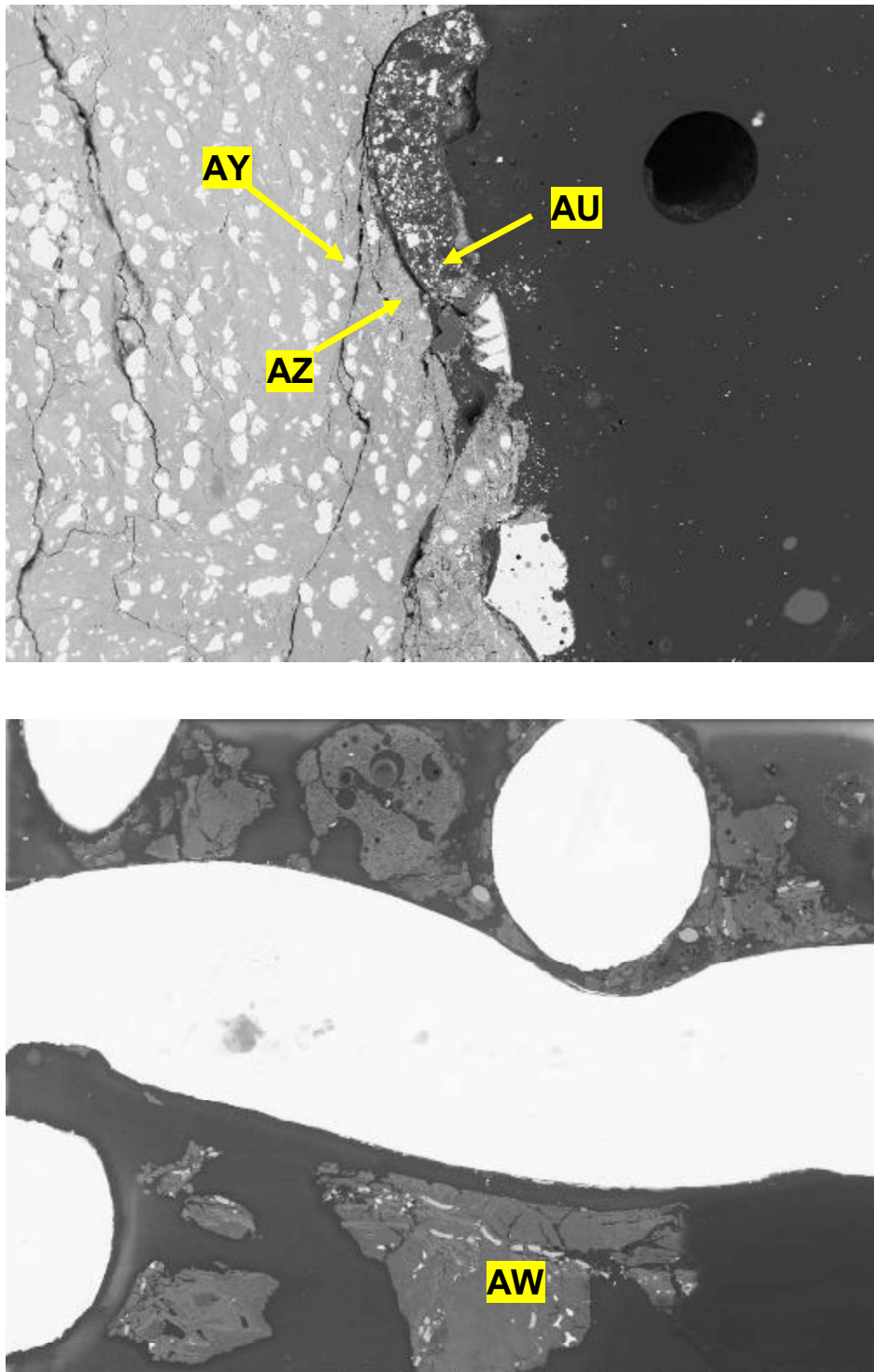


Figure 104. Backscattered electron SEM images of the blockage in the gearbox housing (top) and oil screen (bottom). Top and bottom images are detailed views of locations AS and AT in previous figure, respectively. Semi-quantitative EDS results for blockage material at locations AU through AZ are shown in more detail in Figure 105 and Figure 106.

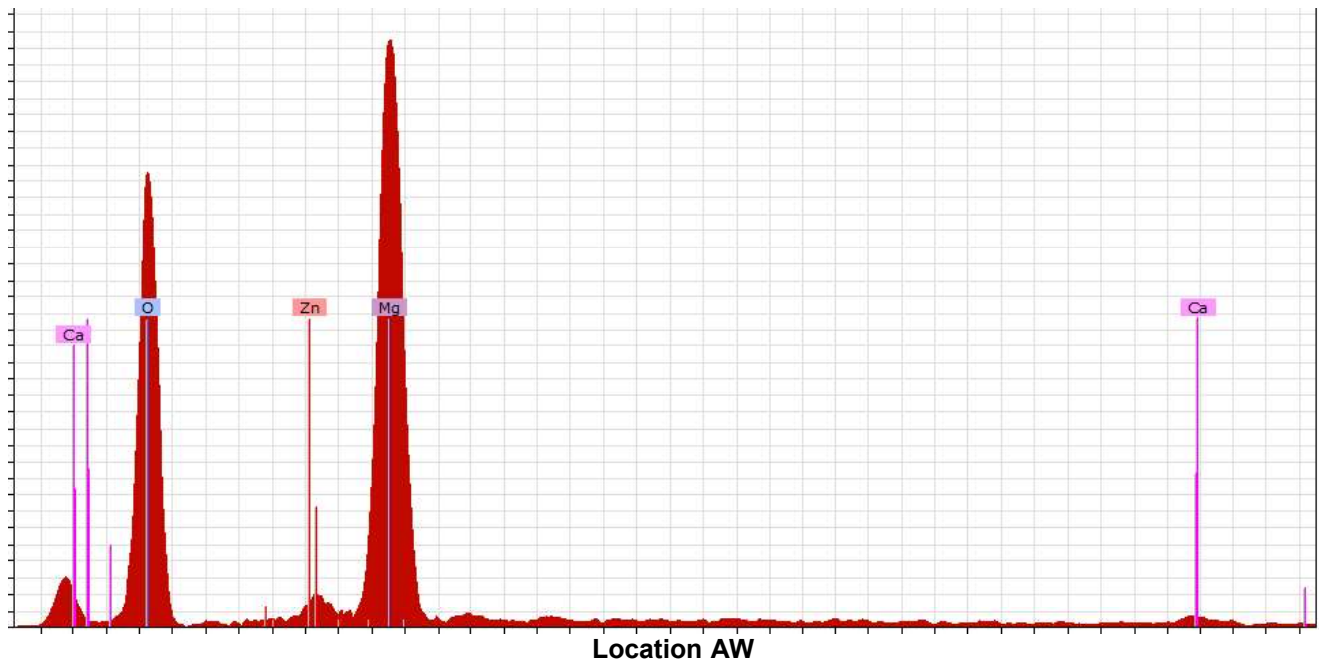
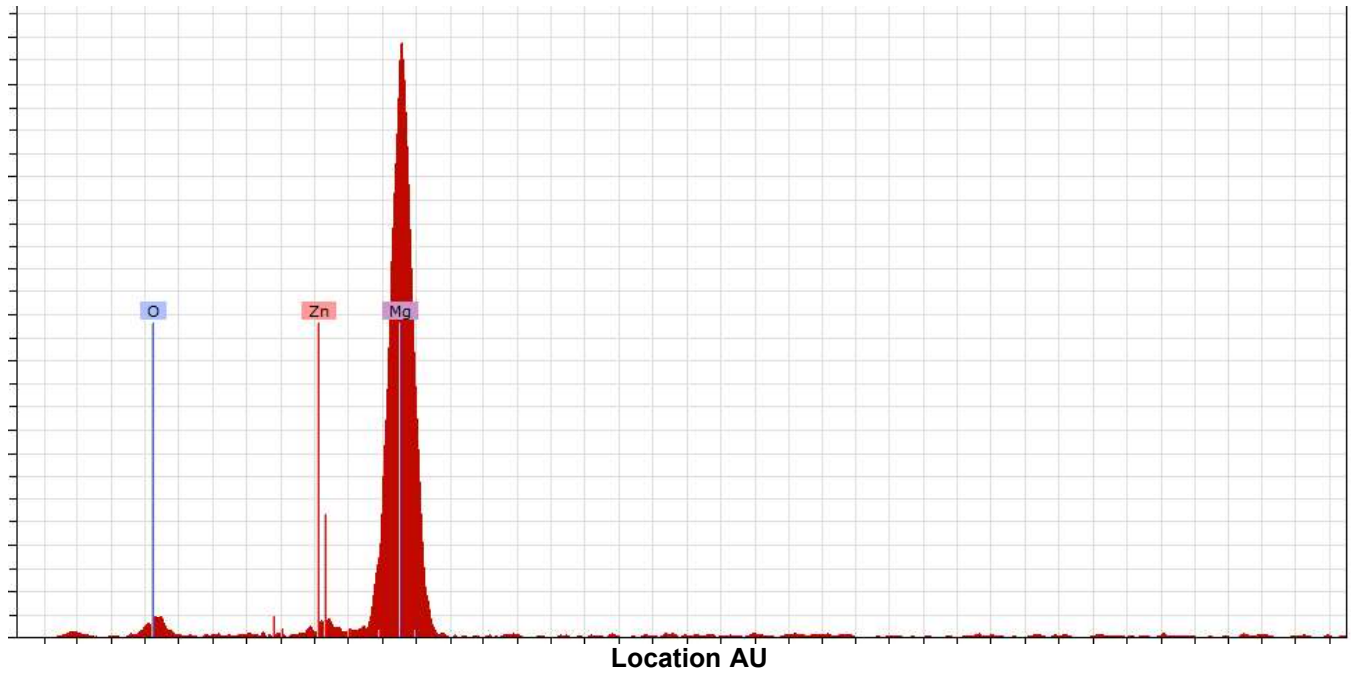


Figure 105. Semi-quantitative EDS results for blockage material at locations AU and AW in the gearbox housing (see Figure 104), which exhibited concentrations of magnesium, oxygen, and zinc.

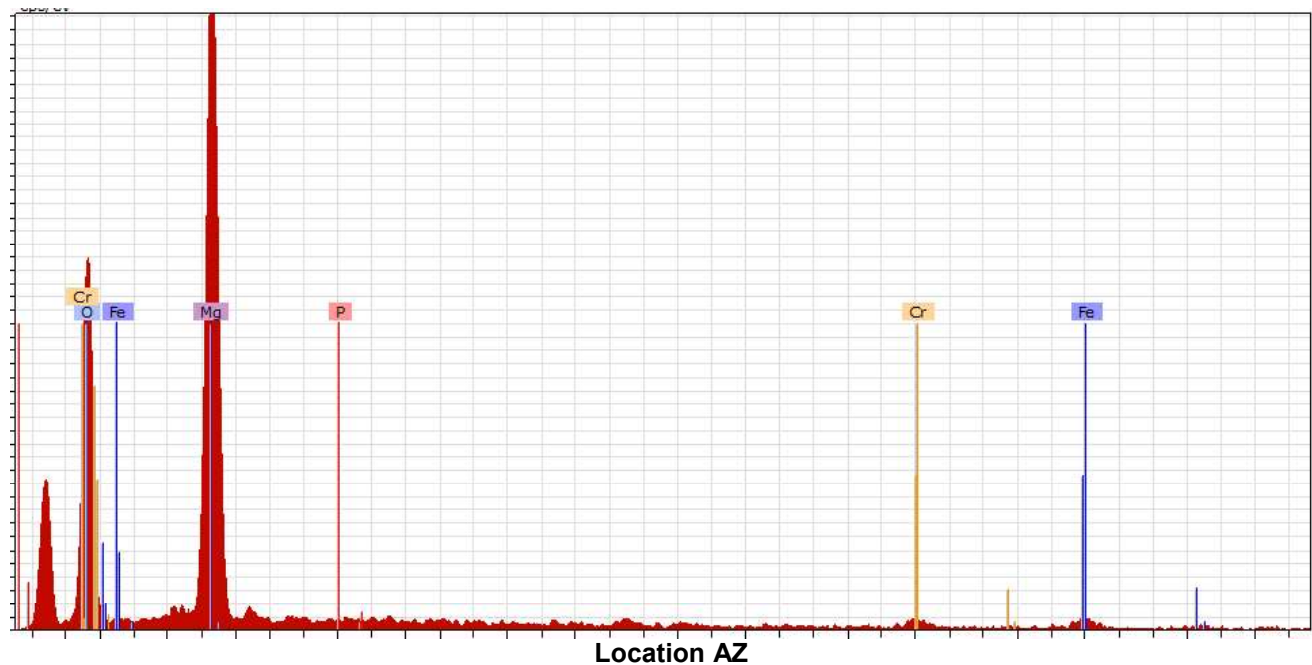
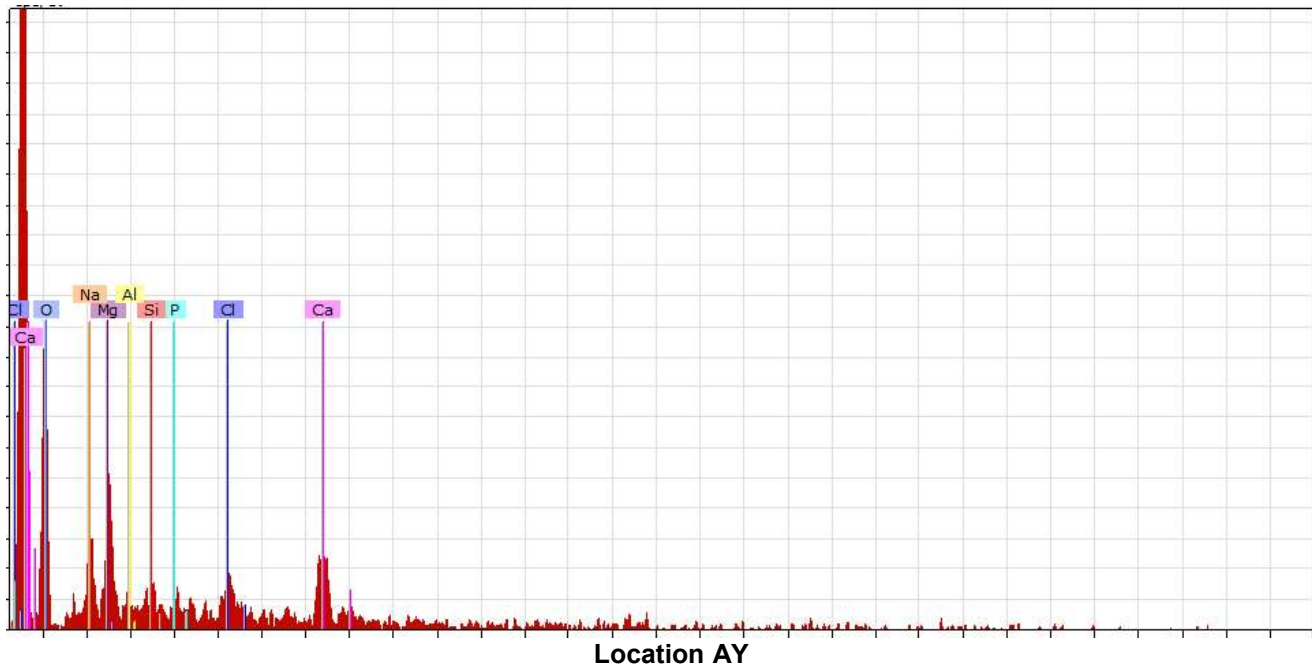


Figure 106. Semi-quantitative EDS results for blockage material at locations AY and AZ in the gearbox housing and oil screen (see Figure 104). Location AY exhibited concentrations of magnesium, oxygen, calcium, silicon, sodium, and aluminum. Location AZ exhibited concentrations of magnesium, oxygen, iron, and chromium.

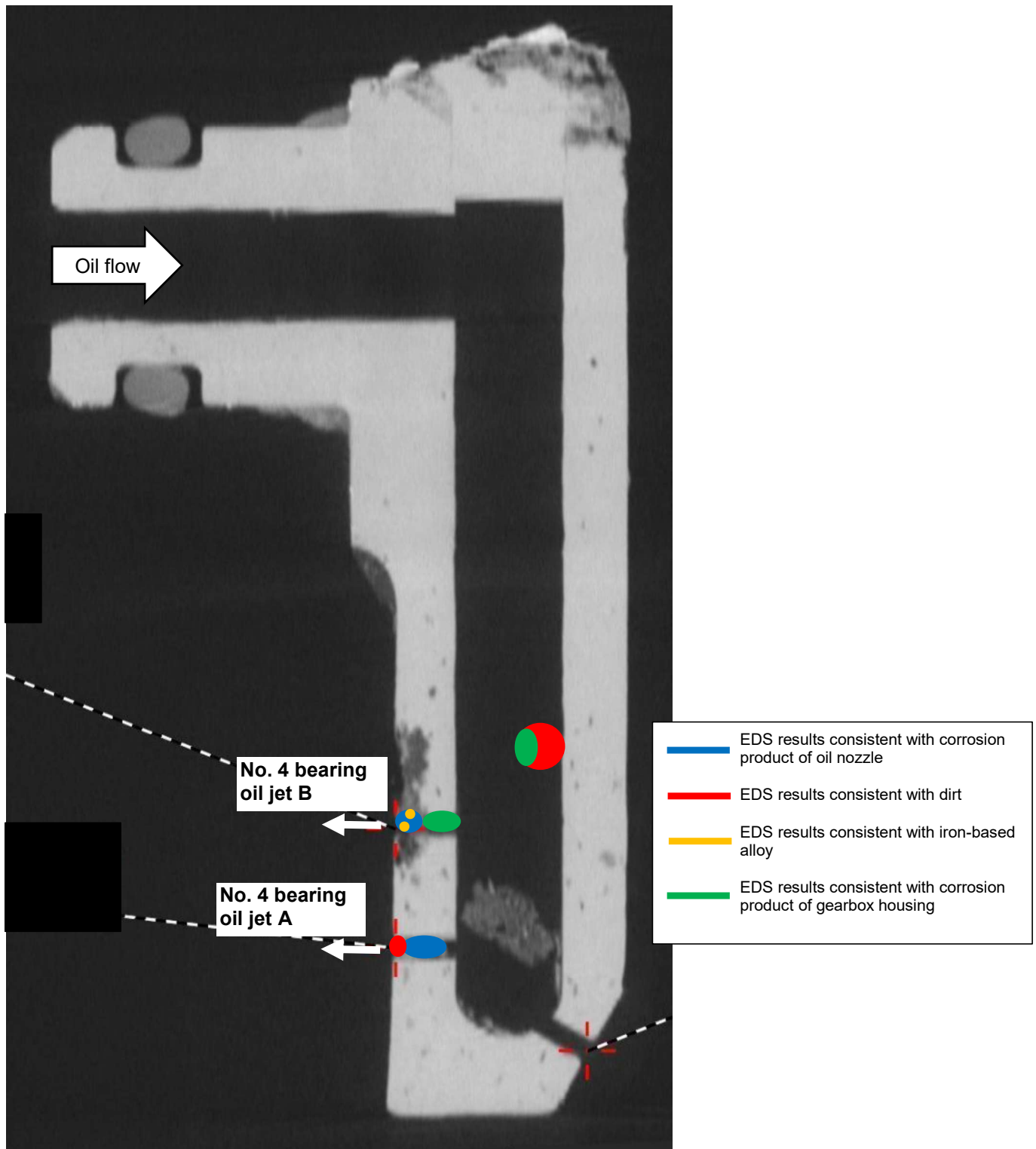


Figure 107. Color map of the EDS results for the blockage material in the oil jets and main passageway of the pinion bearing oil nozzle.

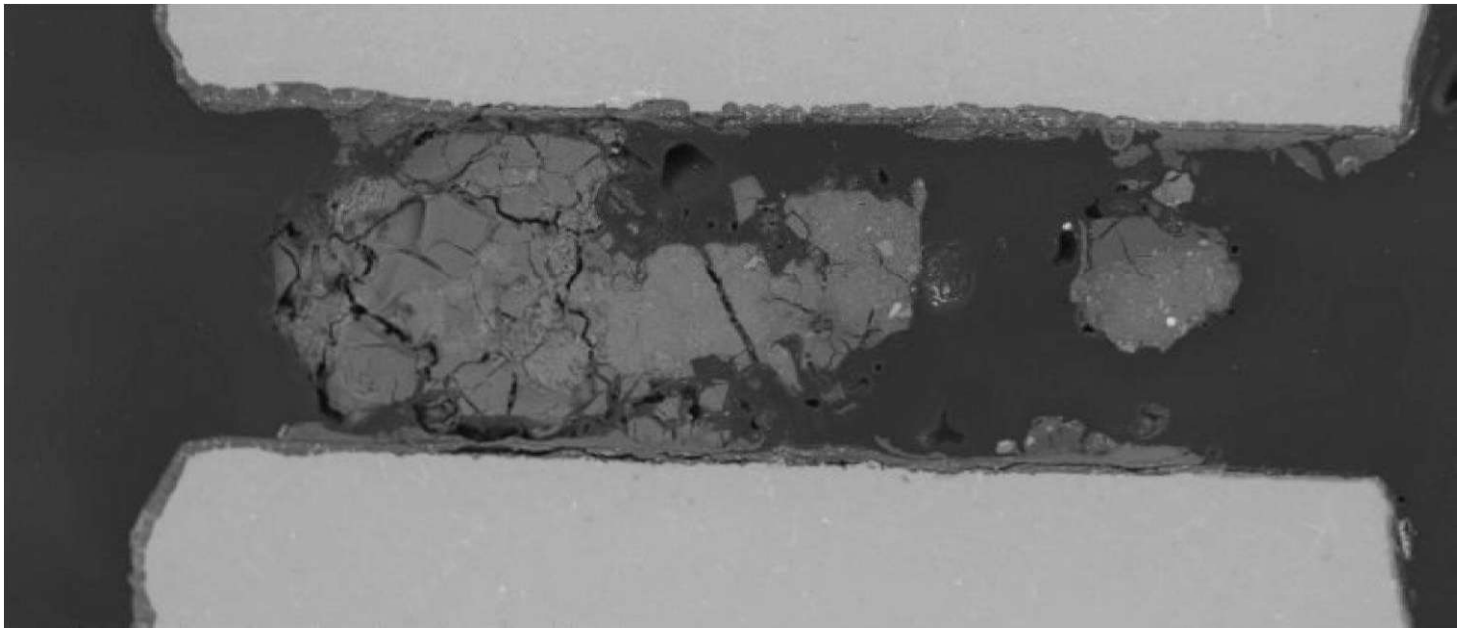
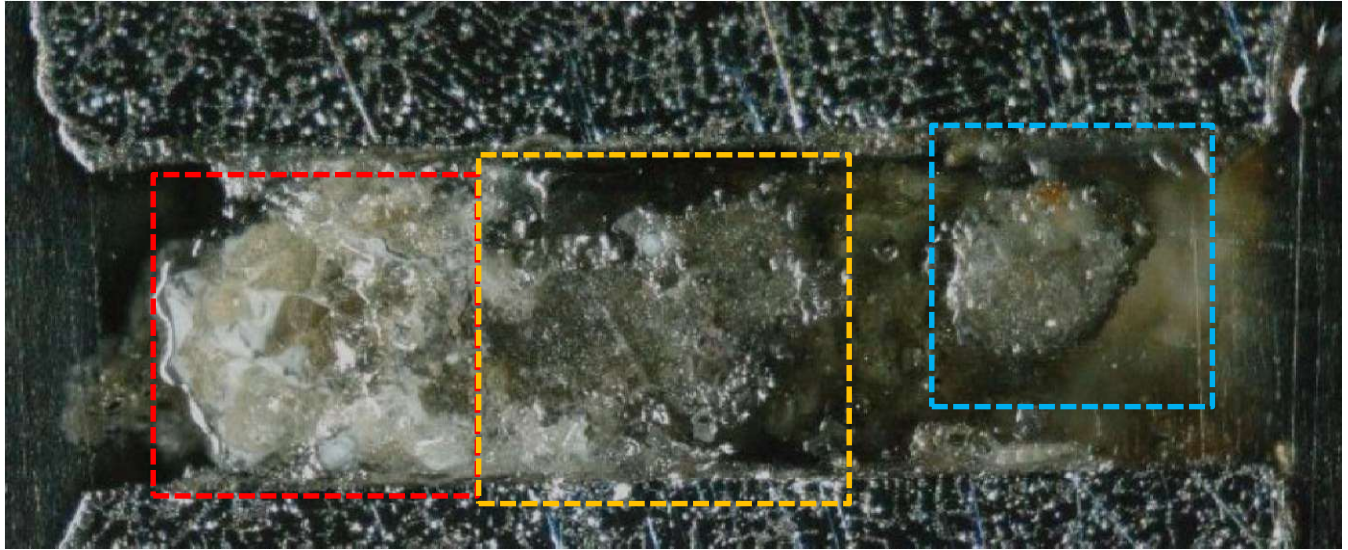


Figure 108. Optical (top) and backscattered scanning electron microscope (bottom) images of the metallographic section through No. 4 bearing oil jet A of the oil nozzle (see orange boxed area in Figure 71), which exhibited blockage. The red, orange, and blue boxed areas are shown in more detail in Figure 109 and Figure 110.

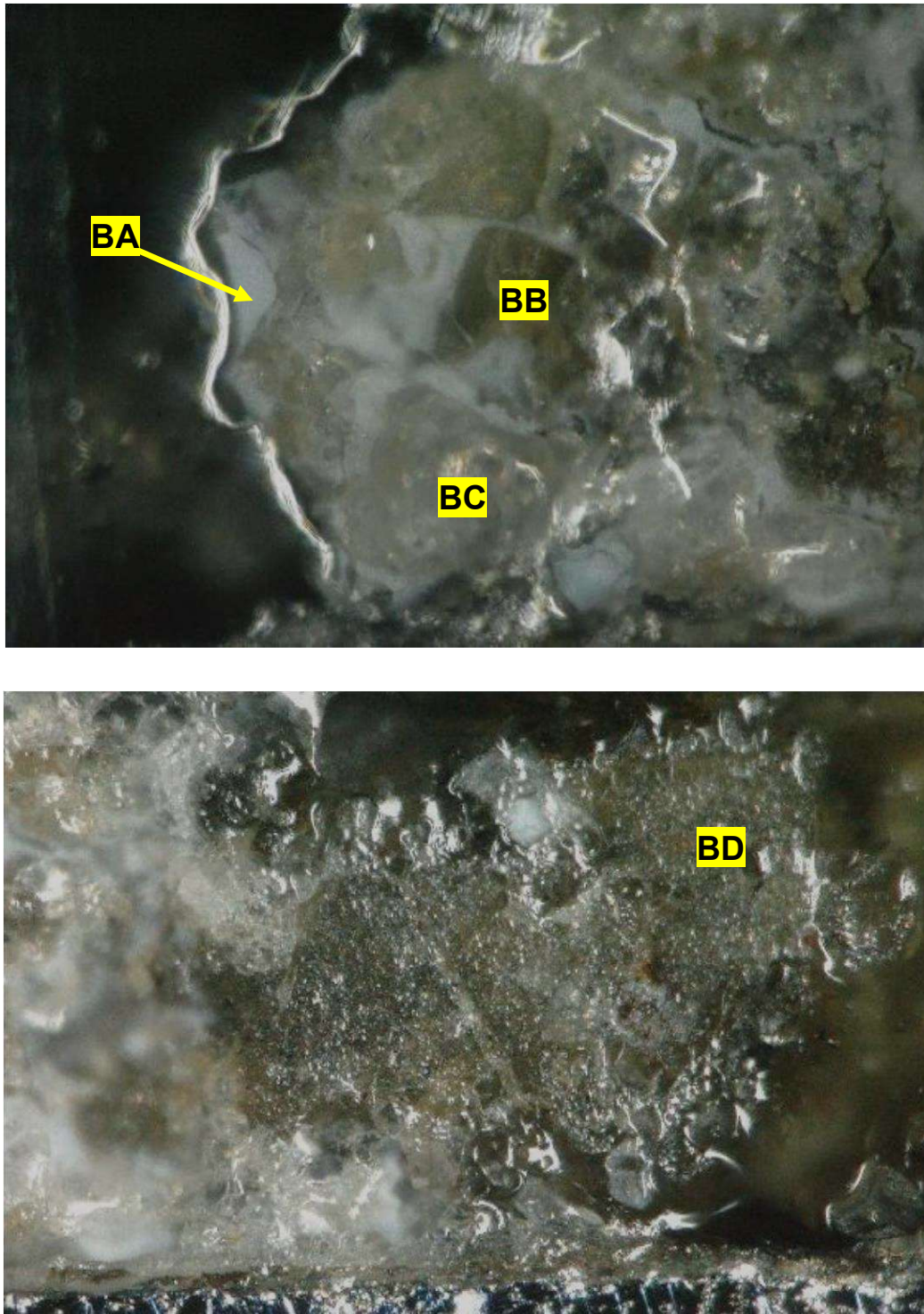


Figure 109. Detailed views of the blockage in No. 4 bearing oil jet A of the oil nozzle. Top and bottom images are detailed views of the red and yellow boxed areas in previous figure, respectively. Semi-quantitative EDS results for blockage material at locations BA through BD are shown in more detail in Figure 111 and Figure 112.

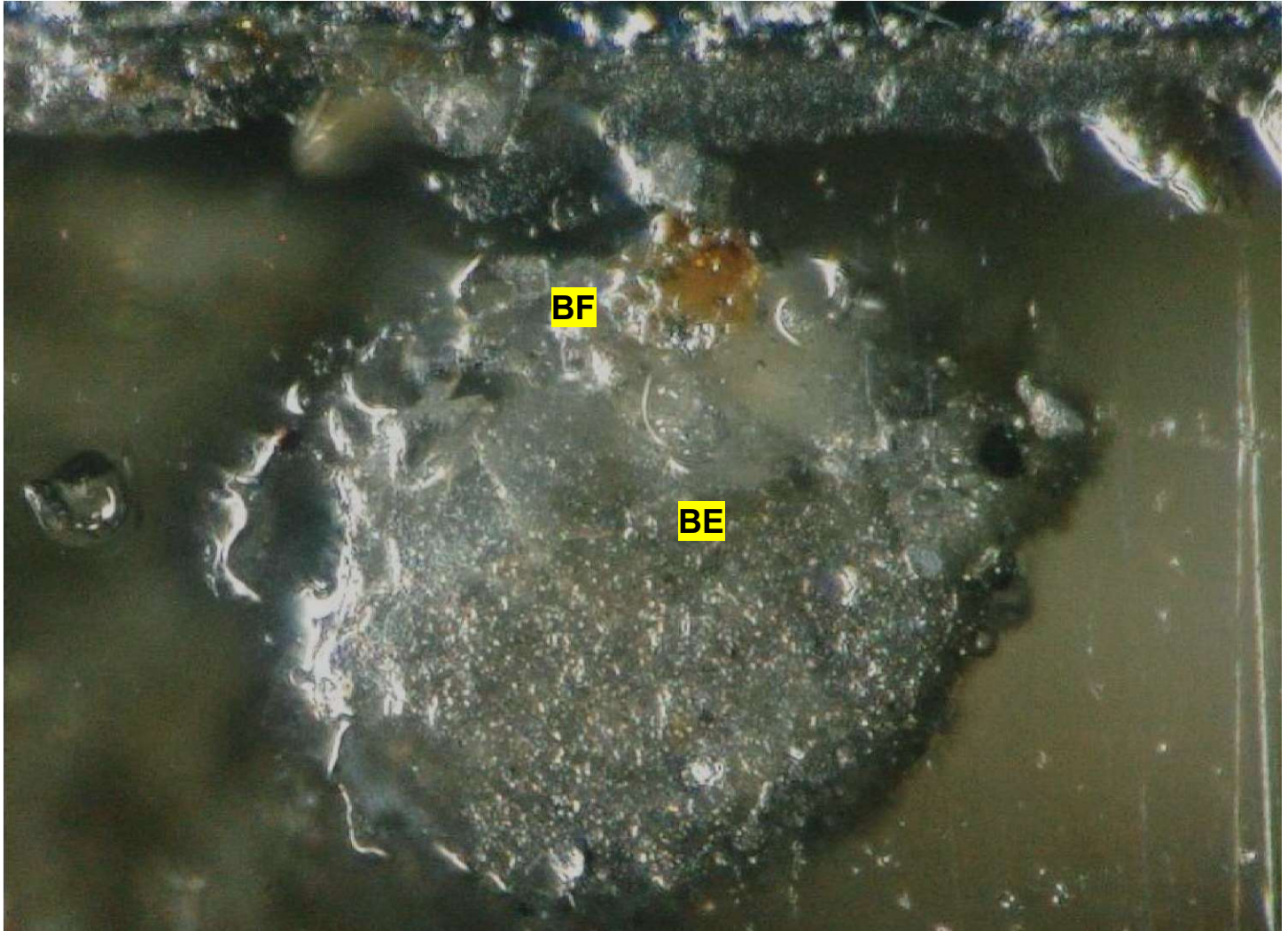


Figure 110. Detailed view of the blockage in No. 4 bearing oil jet A of the oil nozzle (blue boxed area in Figure 108). Semi-quantitative EDS results for blockage material at locations BE and BF are shown in more detail in Figure 113.

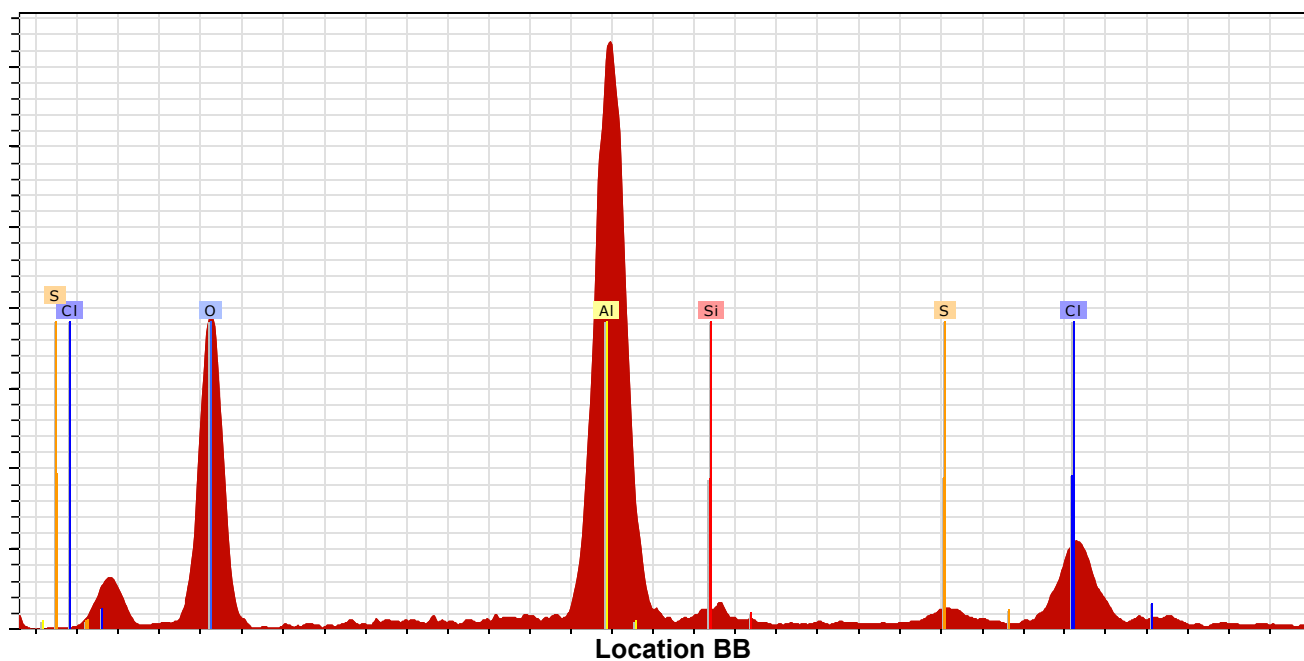
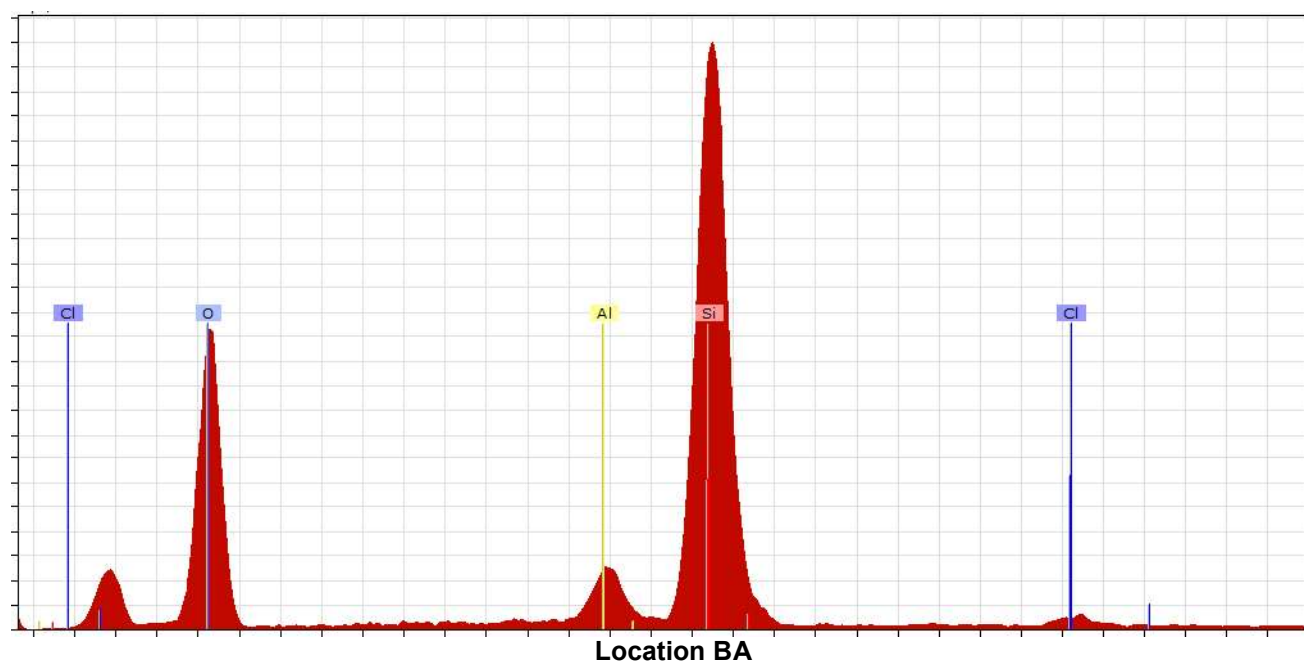


Figure 111. Semi-quantitative EDS results for blockage material at locations BA and BB in No. 4 bearing oil jet A of the oil nozzle (see Figure 109). Location AU exhibited concentrations of silicon, aluminum, and chlorine. Location AW exhibited concentrations of aluminum, silicon, oxygen, sulphur, and chlorine.

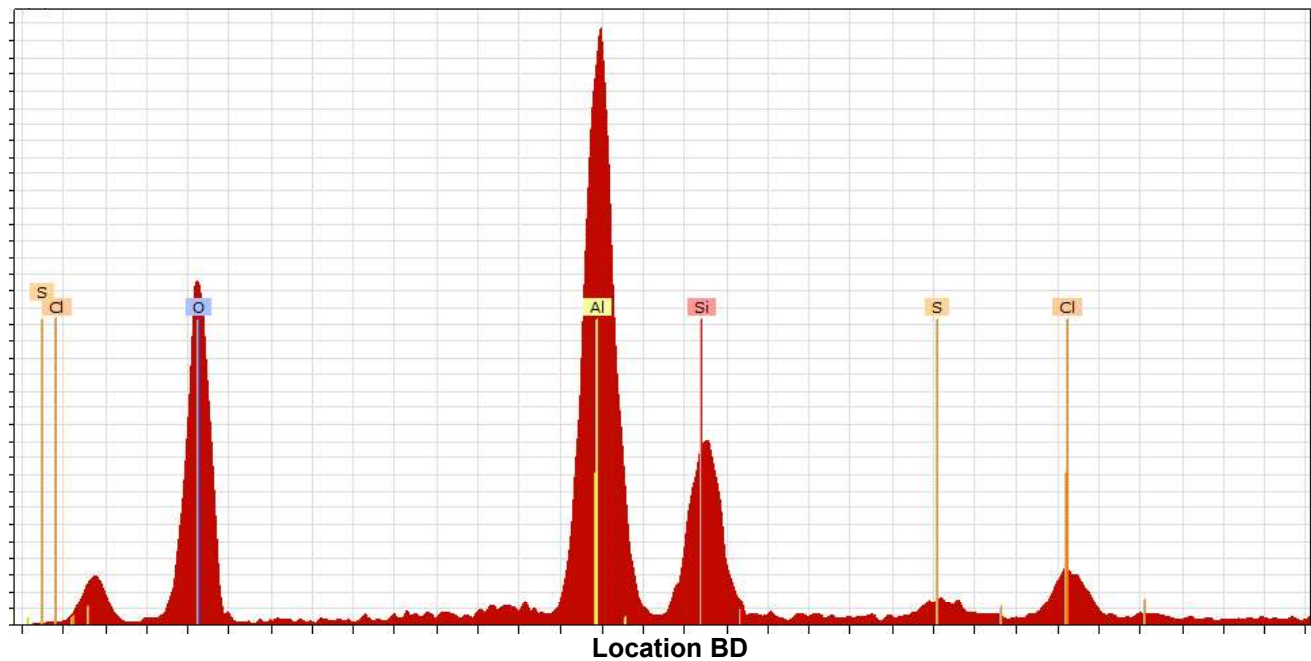
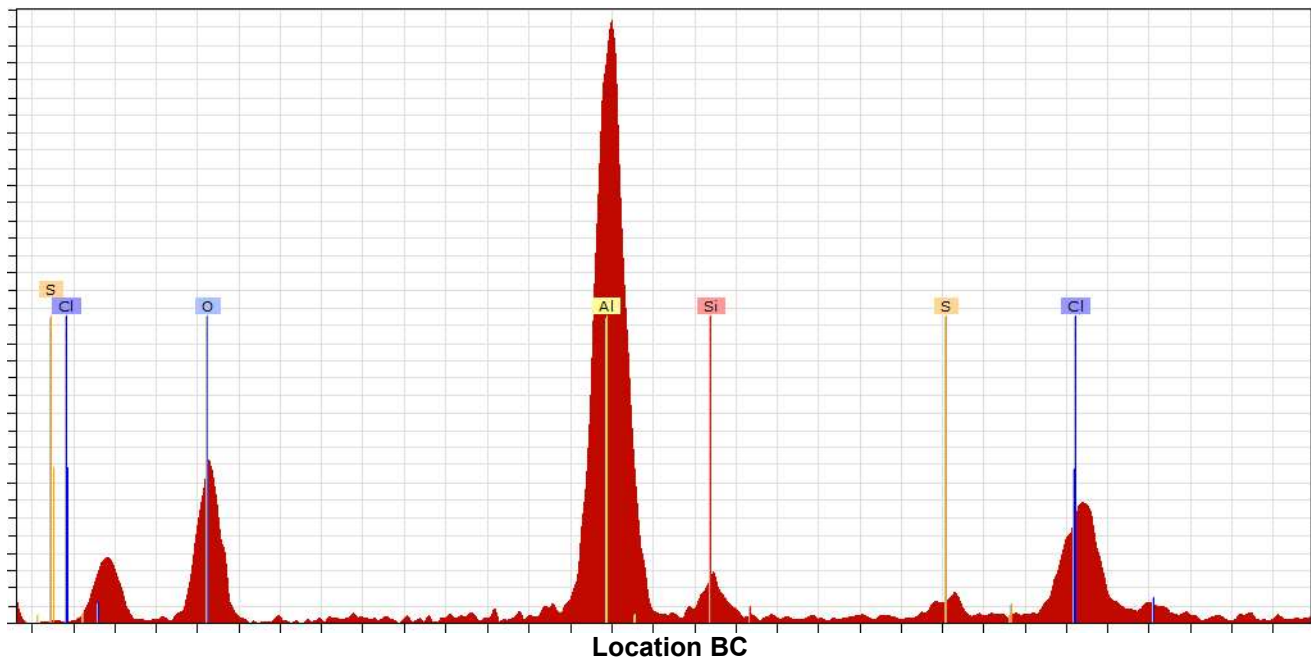


Figure 112. Semi-quantitative EDS results for blockage material at locations BC and BD in No. 4 bearing oil jet A of the oil nozzle (see Figure 109), which exhibited concentrations of aluminum, silicon, oxygen, sulphur, and chlorine.

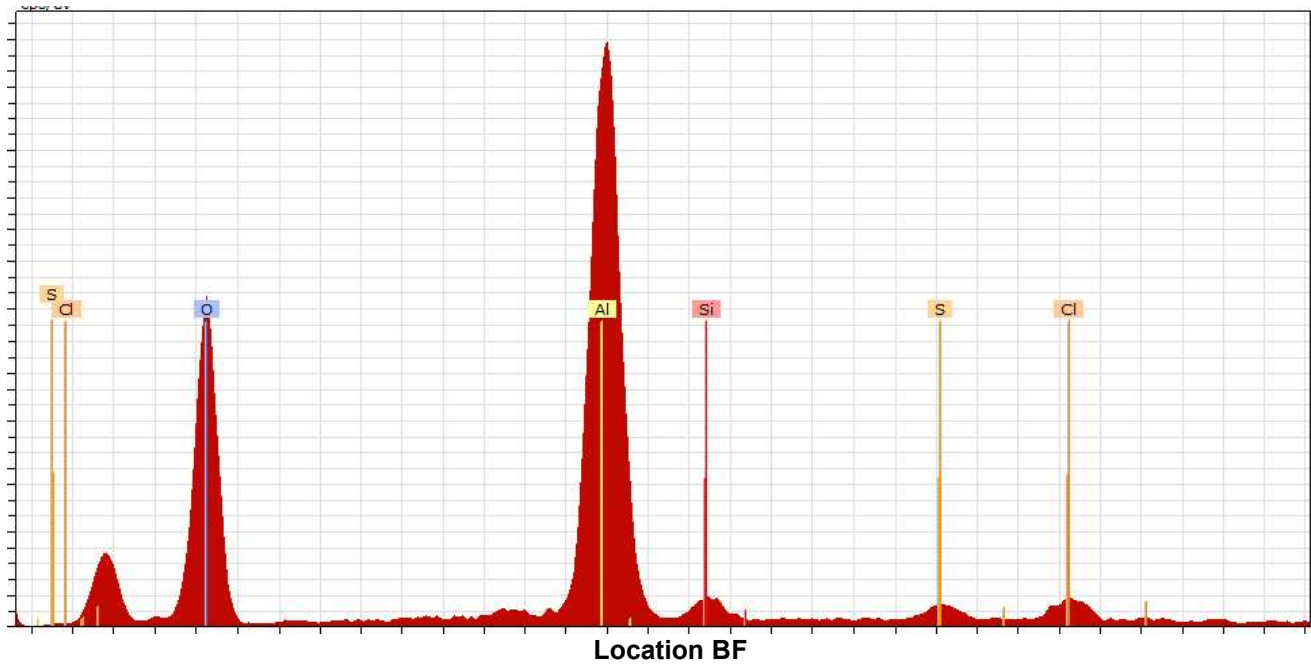
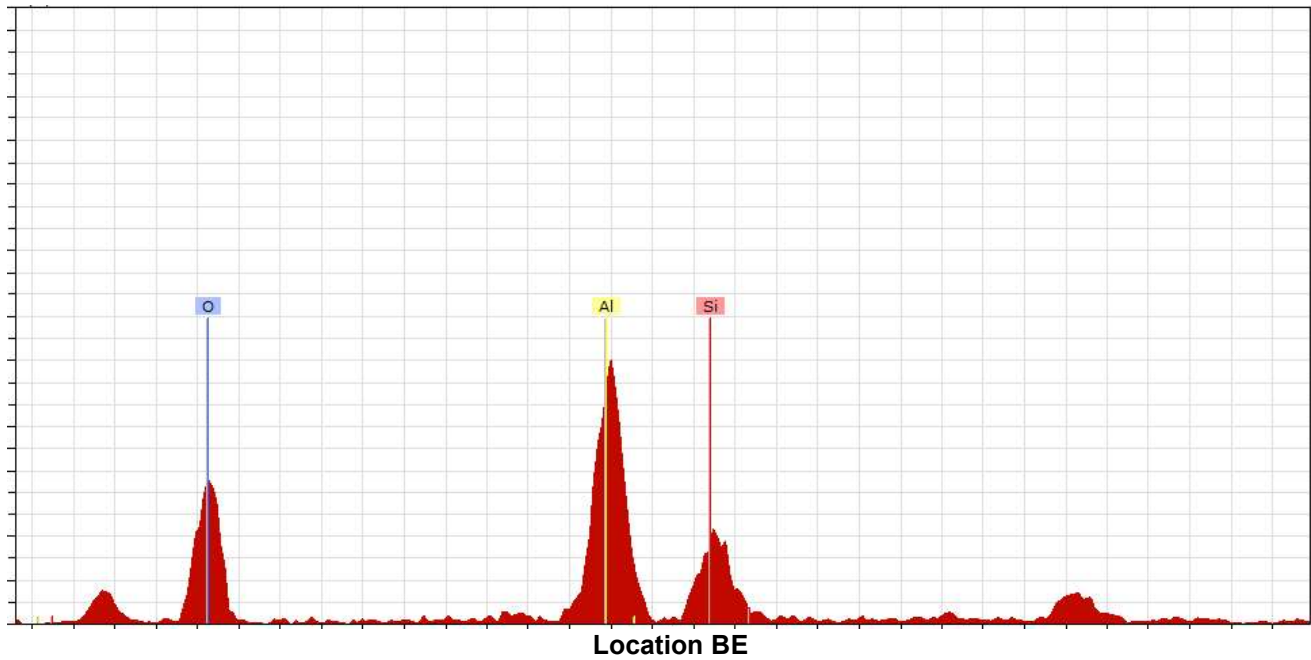


Figure 113. Semi-quantitative EDS results for blockage material at locations BE and BF in No. 4 bearing oil jet A of the oil nozzle (see Figure 110), which exhibited concentrations of aluminum, silicon, and oxygen.

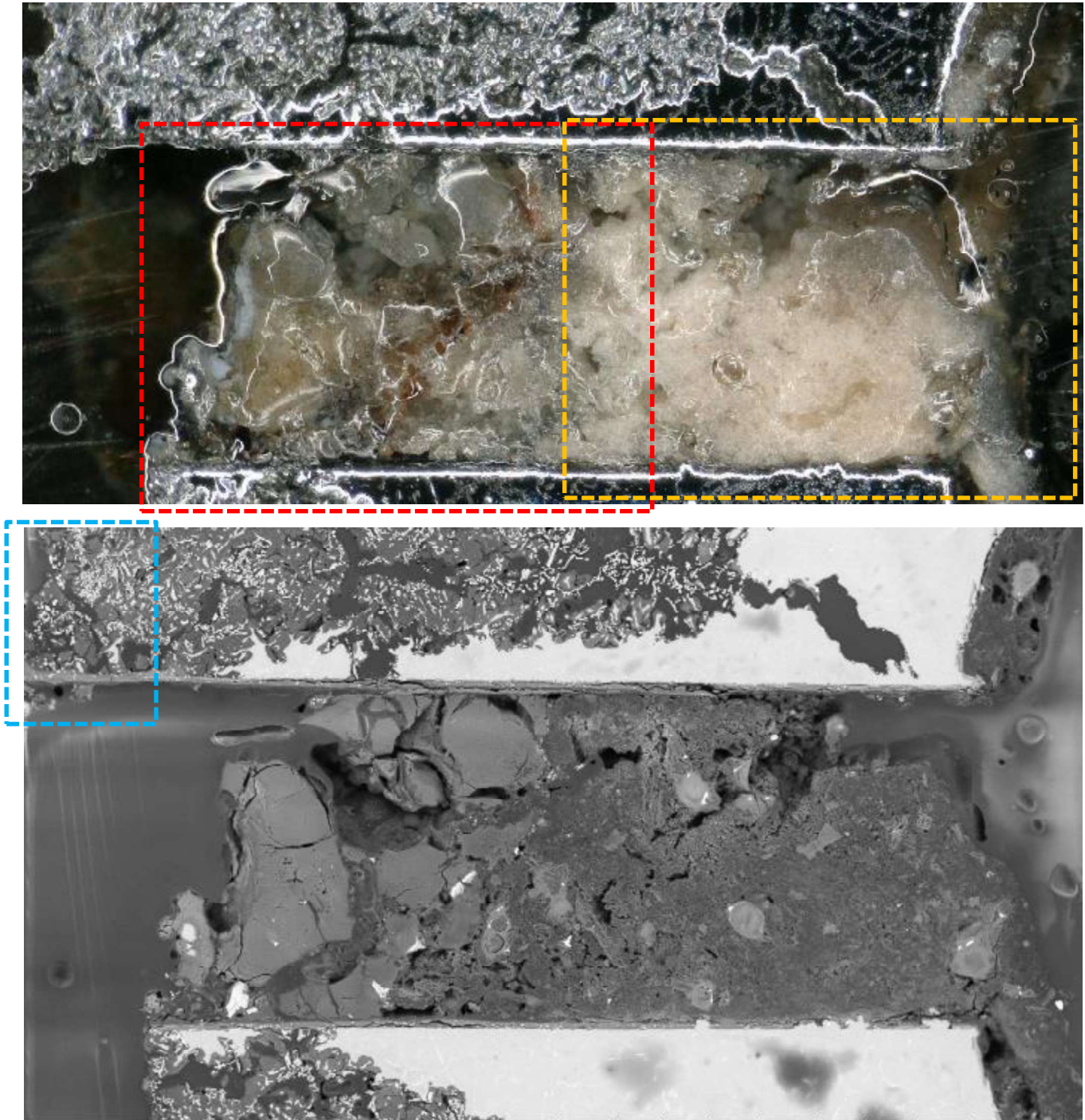


Figure 114. Optical (top) and backscattered scanning electron microscope (bottom) images of the metallographic section through No. 4 bearing oil jet B of the oil nozzle (see orange boxed area in Figure 72), which exhibited blockage. The red, orange, and blue boxed areas are shown in more detail in Figure 115 and Figure 116.

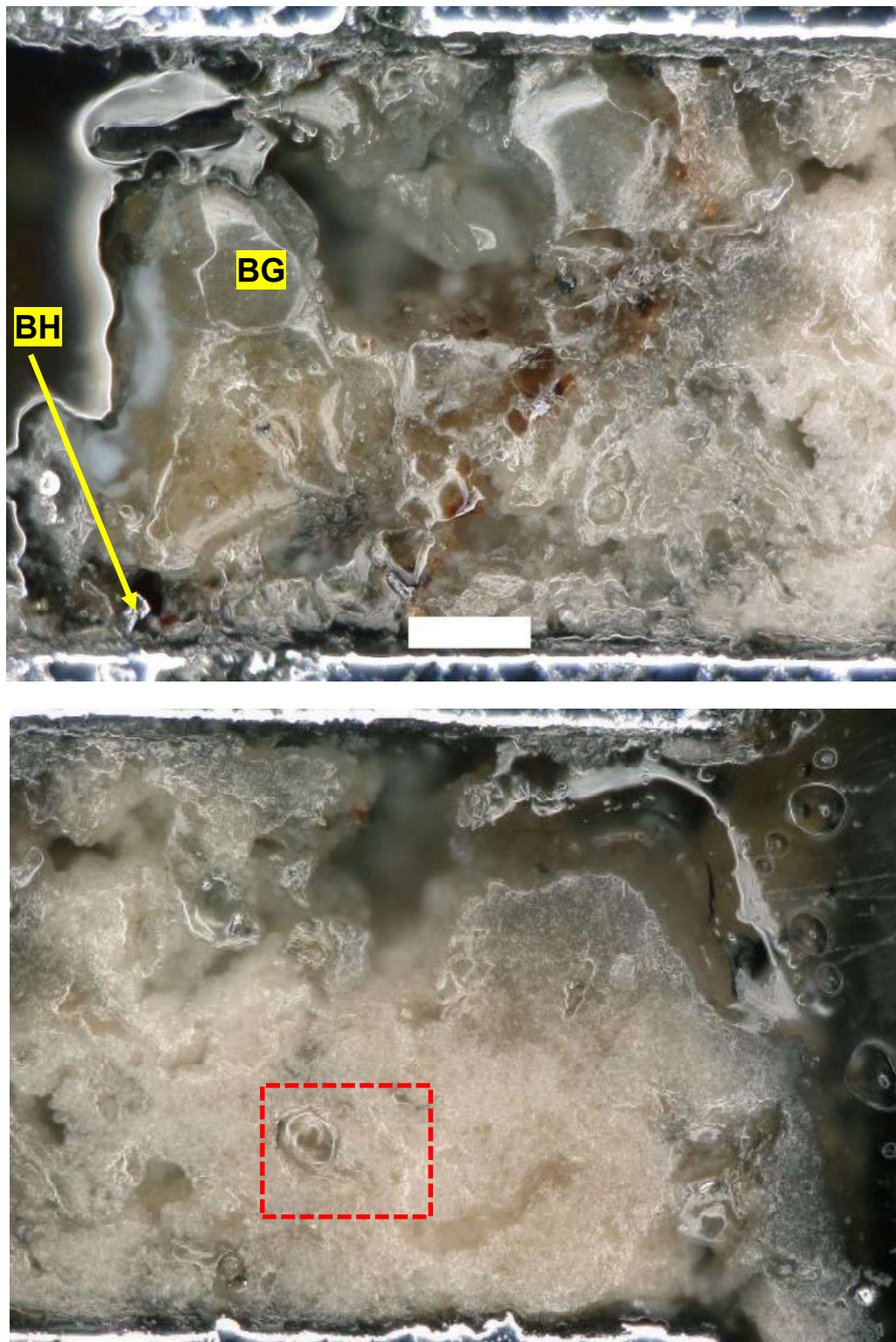


Figure 115. Detailed views of the blockage in No. 4 bearing oil jet B of the oil nozzle. Top and bottom images are detailed views of the red and orange boxed areas in previous figure, respectively. Semi-quantitative EDS results for blockage material at locations BG and BH are shown in more detail in Figure 117. The red boxed area is shown in more detail in the following figure.

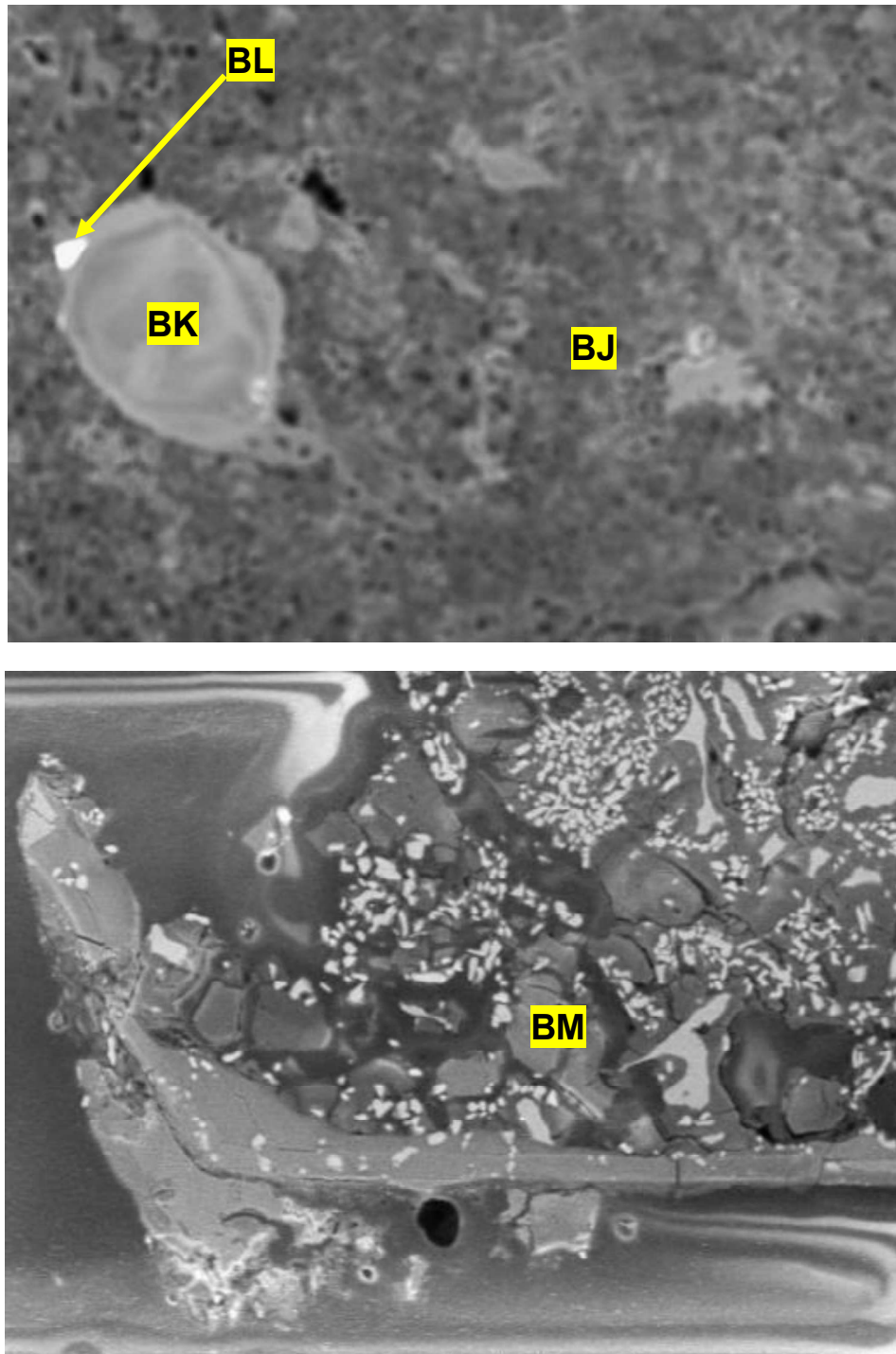


Figure 116. Backscattered scanning electron microscope images of the blockage in No. 4 bearing oil jet B of the oil nozzle (top image, see red boxed area in the previous figure) and corrosion in the base material adjacent to hole (bottom image, see blue boxed area in Figure 114). Semi-quantitative EDS results for material at locations BJ through BM are shown in more detail in Figure 118 and Figure 119.

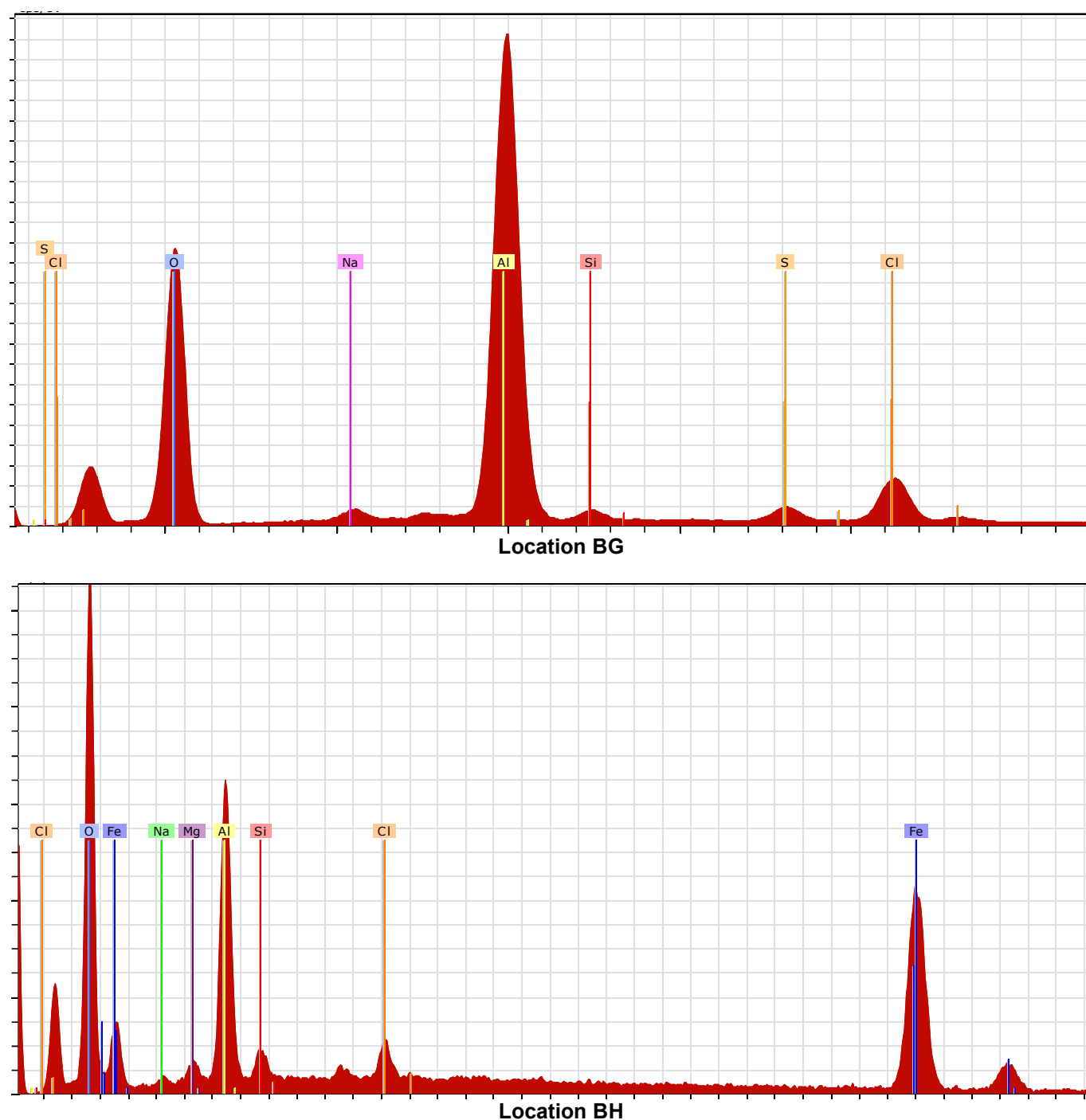


Figure 117. Semi-quantitative EDS results for blockage material at locations BG and BH in No. 4 bearing oil jet B of the oil nozzle (see Figure 115). The blockage at location BG exhibited concentrations of aluminum, oxygen, chlorine, sodium, sulphur, and silicon. The blockage at location BH exhibited concentrations of iron, oxygen, aluminum, silicon, magnesium, and chlorine.

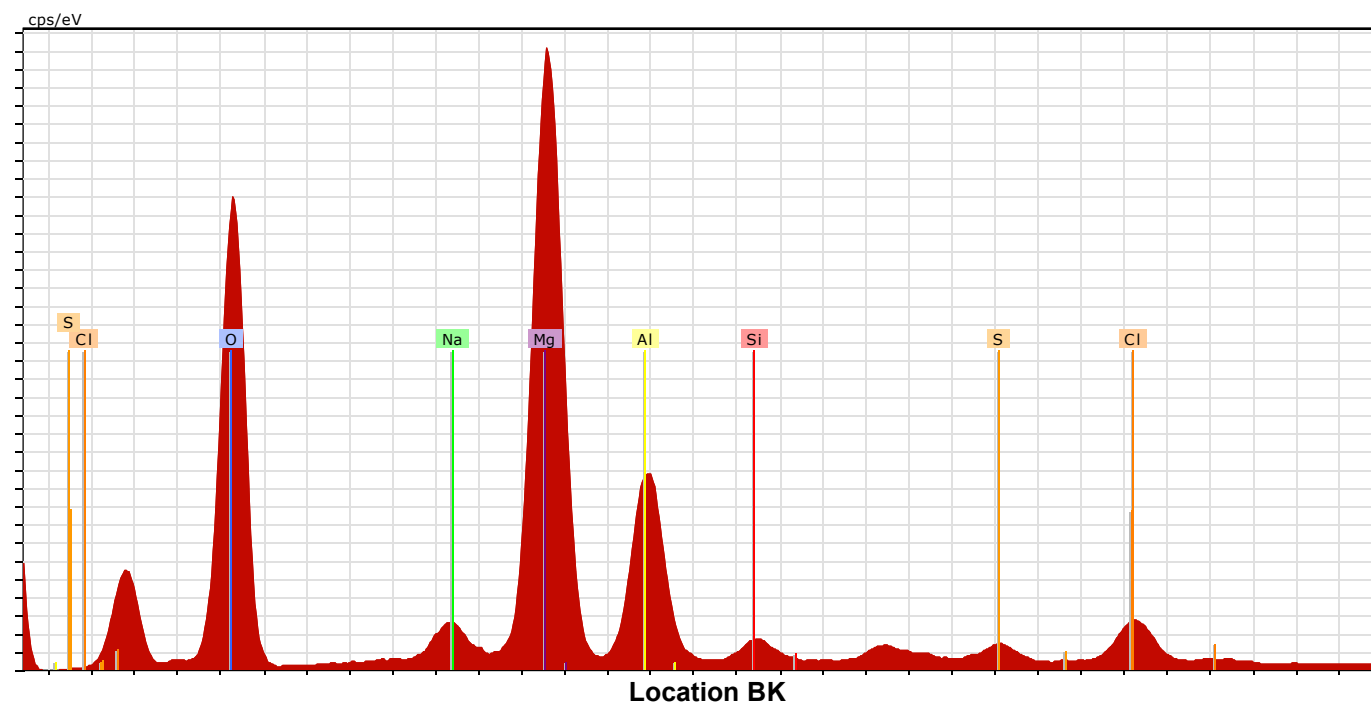
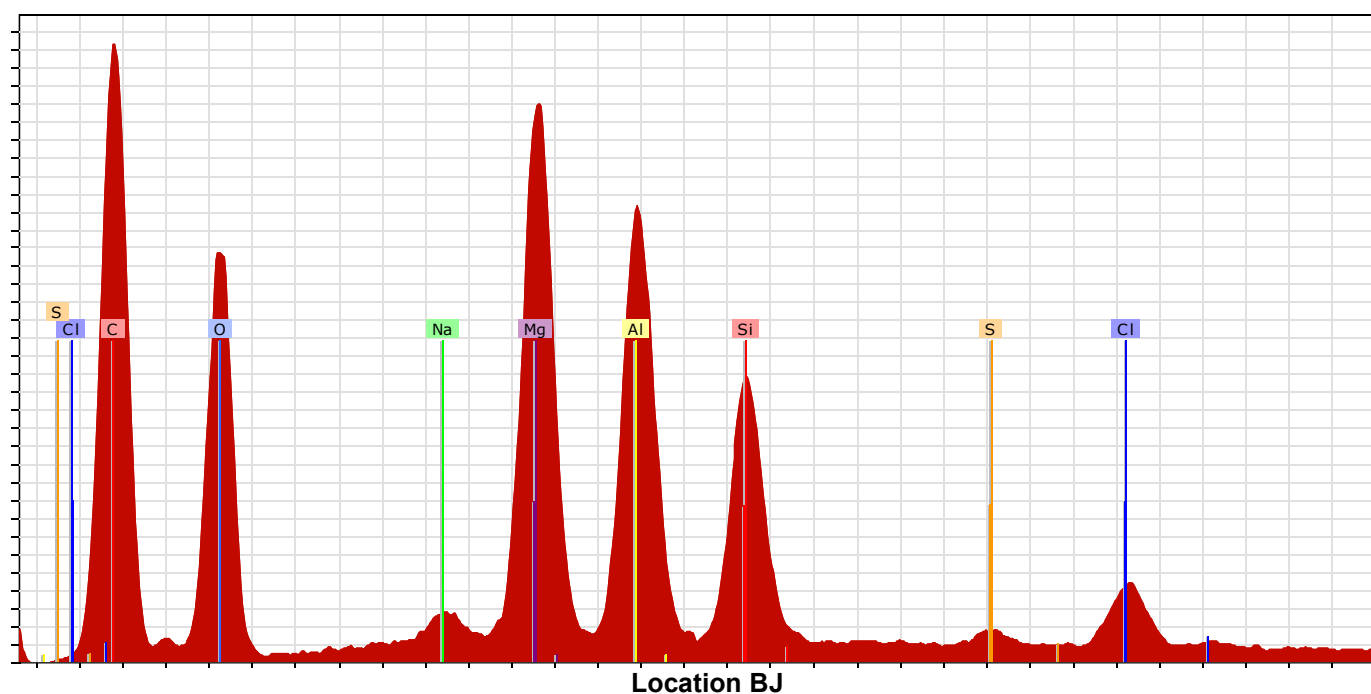


Figure 118. Semi-quantitative EDS results for blockage material at locations BJ and BK in No. 4 bearing oil jet B of the oil nozzle (see Figure 116), which exhibited concentrations of magnesium, oxygen, aluminum, sulphur, chlorine, and silicon.

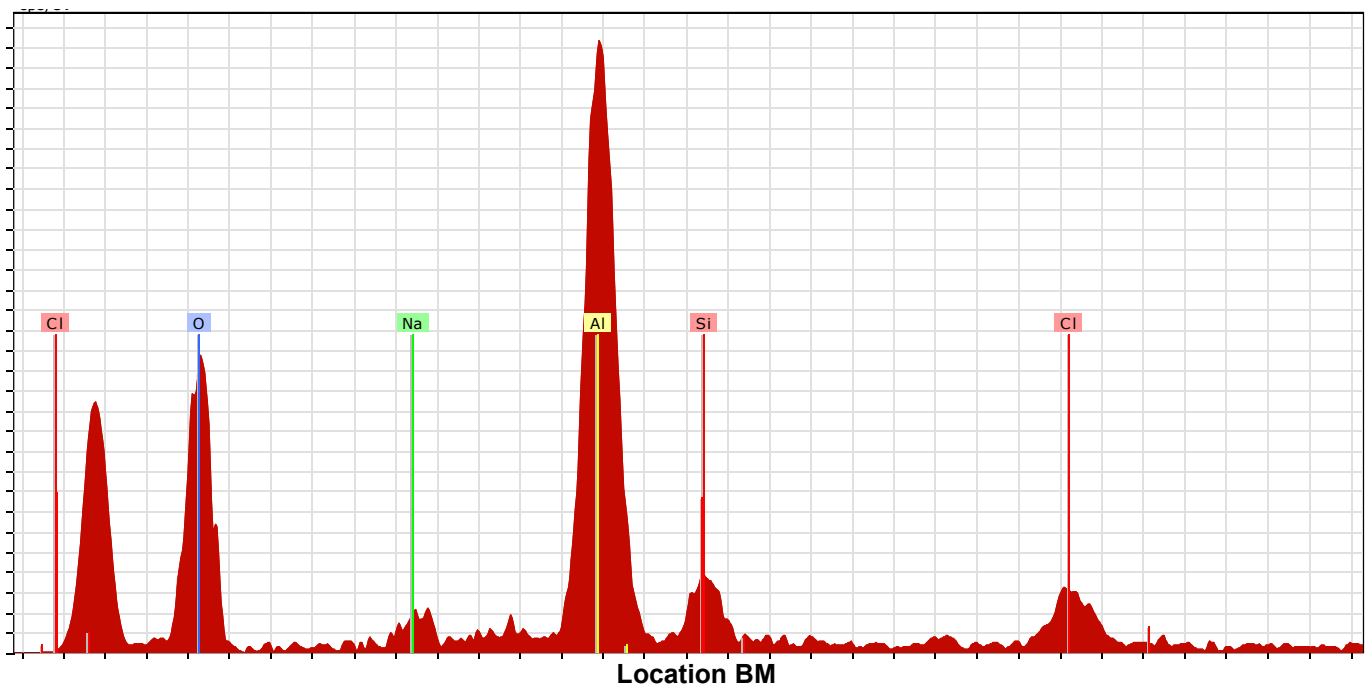
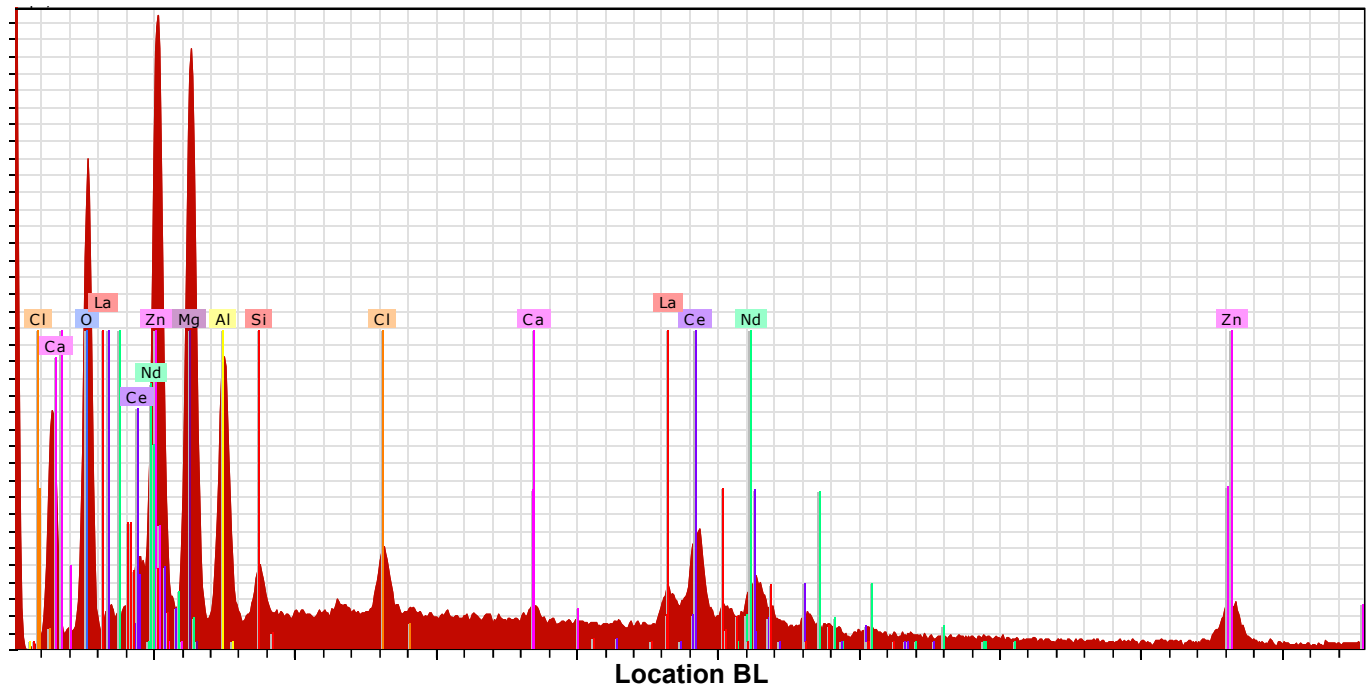


Figure 119. Semi-quantitative EDS results for blockage material at locations BL and BM in No. 4 bearing oil jet B of the oil nozzle (see Figure 116). The blockage at location BL exhibited concentrations of magnesium, oxygen, zinc, aluminum, rare earth metals, chlorine, and silicon. The corroded base material at location BM exhibited concentrations of aluminum, oxygen, chlorine, silicon, and sodium.

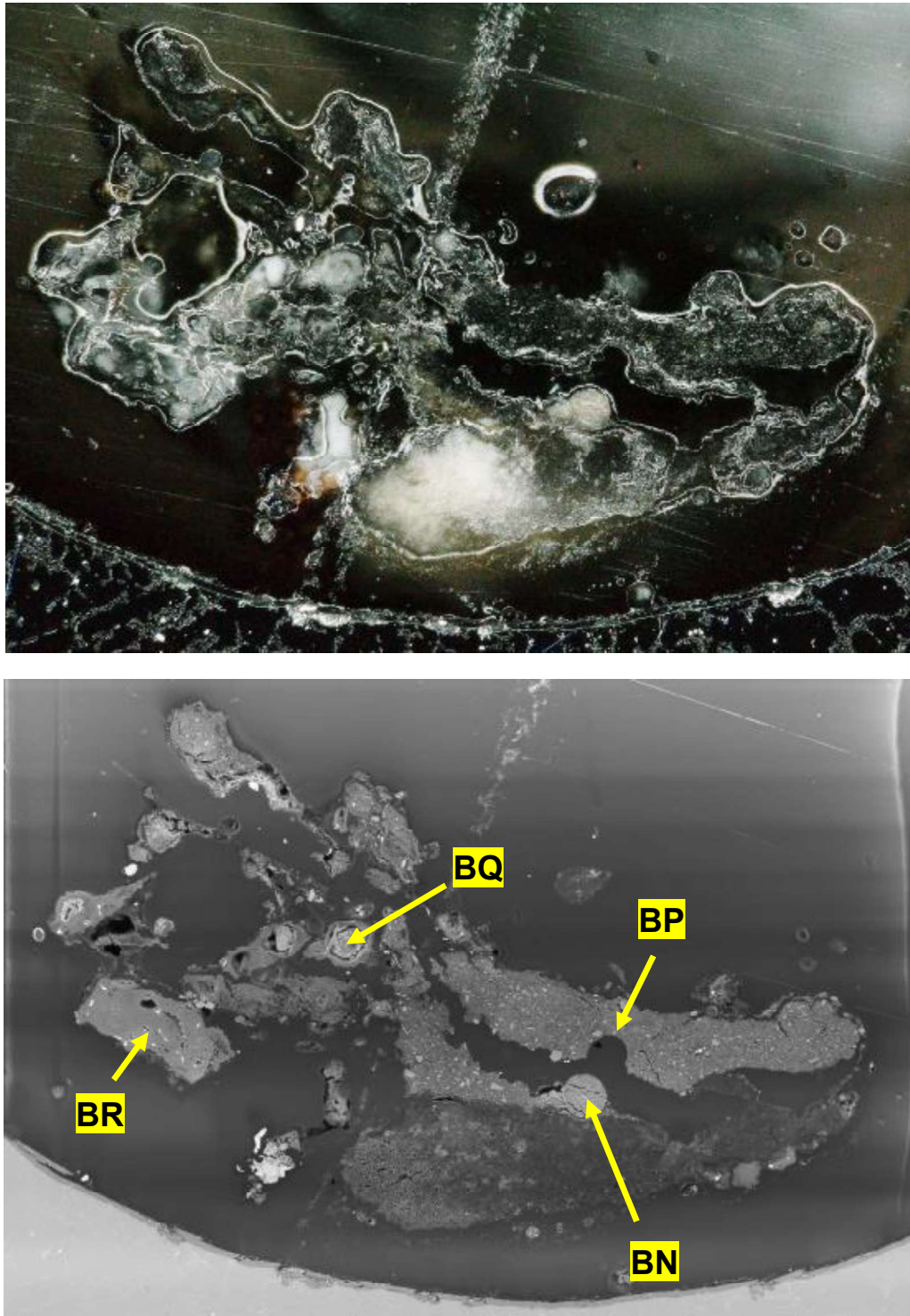


Figure 120. Optical (top) and backscattered electron SEM (bottom) images of the metallographic section through debris in the oil nozzle main passage (see orange boxed area in Figure 73). locations BN through BR are shown in more detail in the following figures.

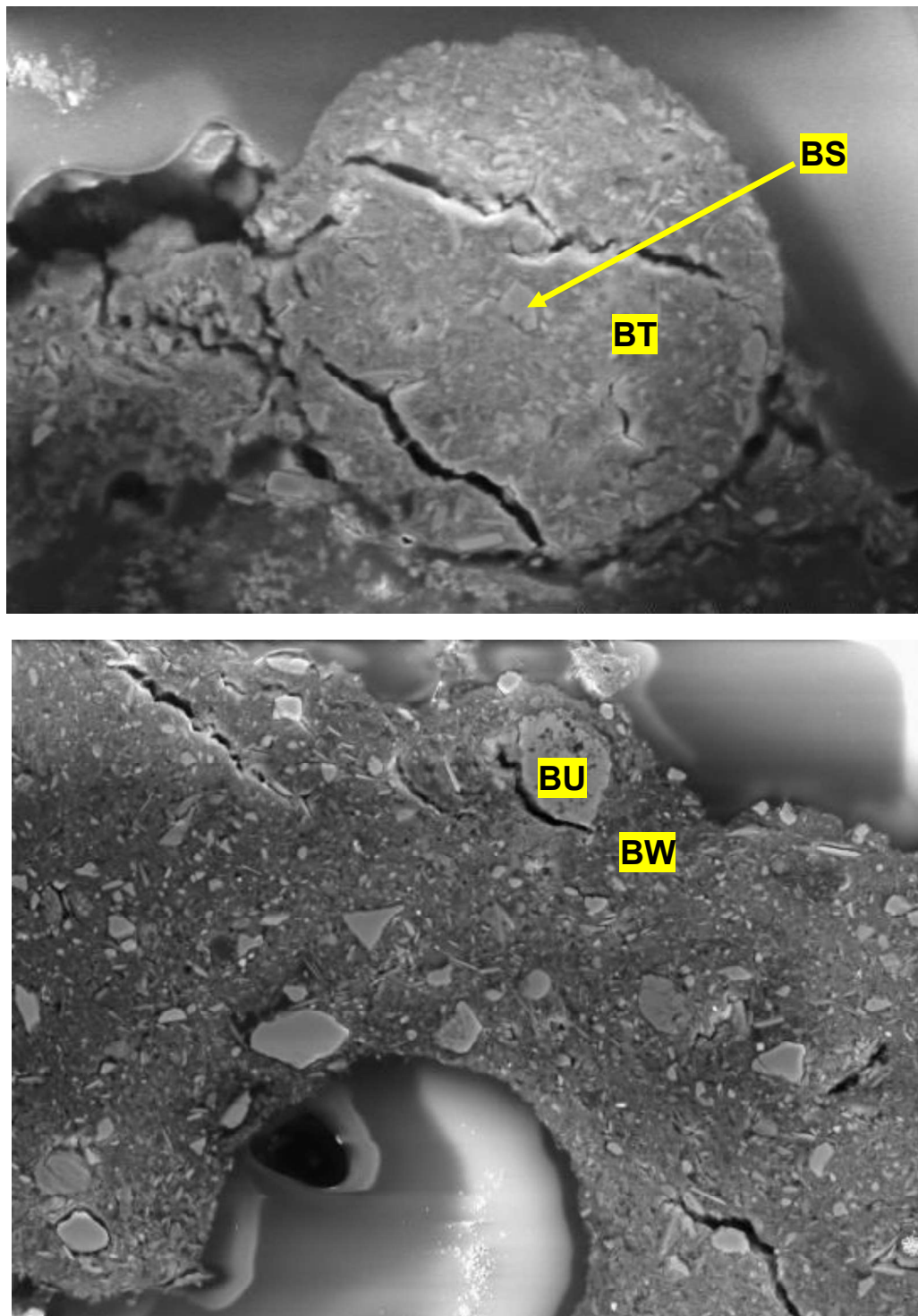


Figure 121. Backscattered electron SEM images of debris in the oil nozzle main passage. Top and bottom images are detailed views of locations BN and BP in previous figure, respectively. Semi-quantitative EDS results for debris material at locations BS through BW are shown in more detail in Figure 124 and Figure 125.

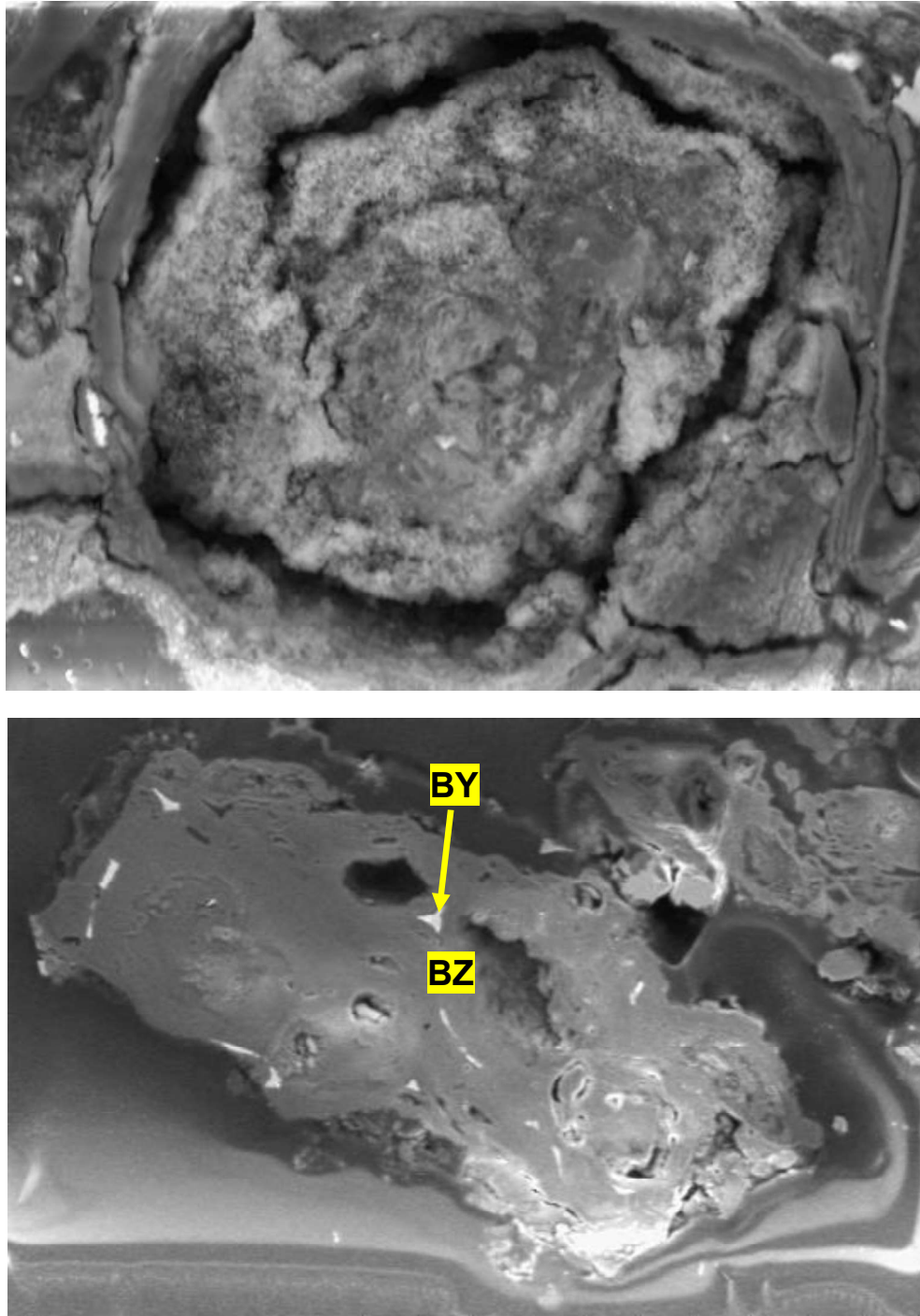


Figure 122. Backscattered electron SEM images of debris in the oil nozzle main passage. Top and bottom images are detailed views of locations BQ and BR in Figure 120, respectively. Semi-quantitative EDS results for debris material at locations BQ, BY, and BZ are shown in more detail in Figure 123 and Figure 126.

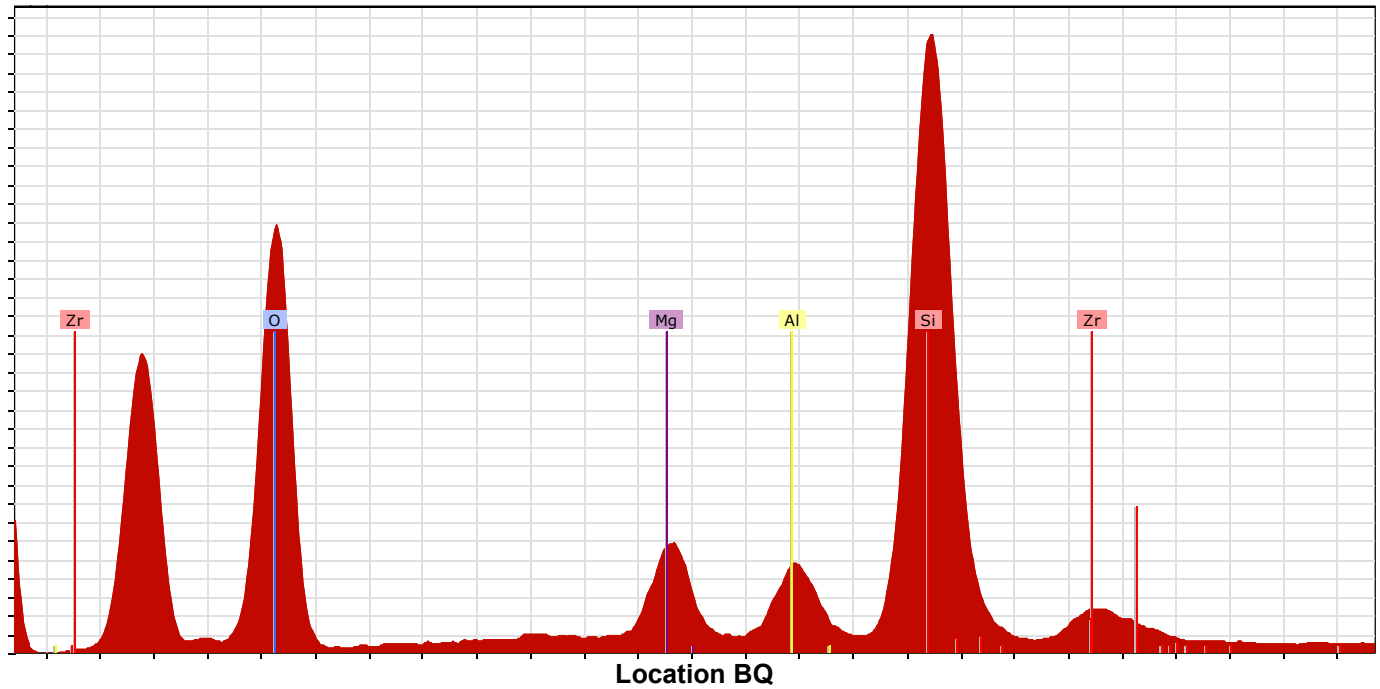


Figure 123. Semi-quantitative EDS results for debris at location BQ in the main passageway of the oil nozzle (see Figure 122), which exhibited higher concentrations of silicon, magnesium, aluminum, zirconium, and oxygen.

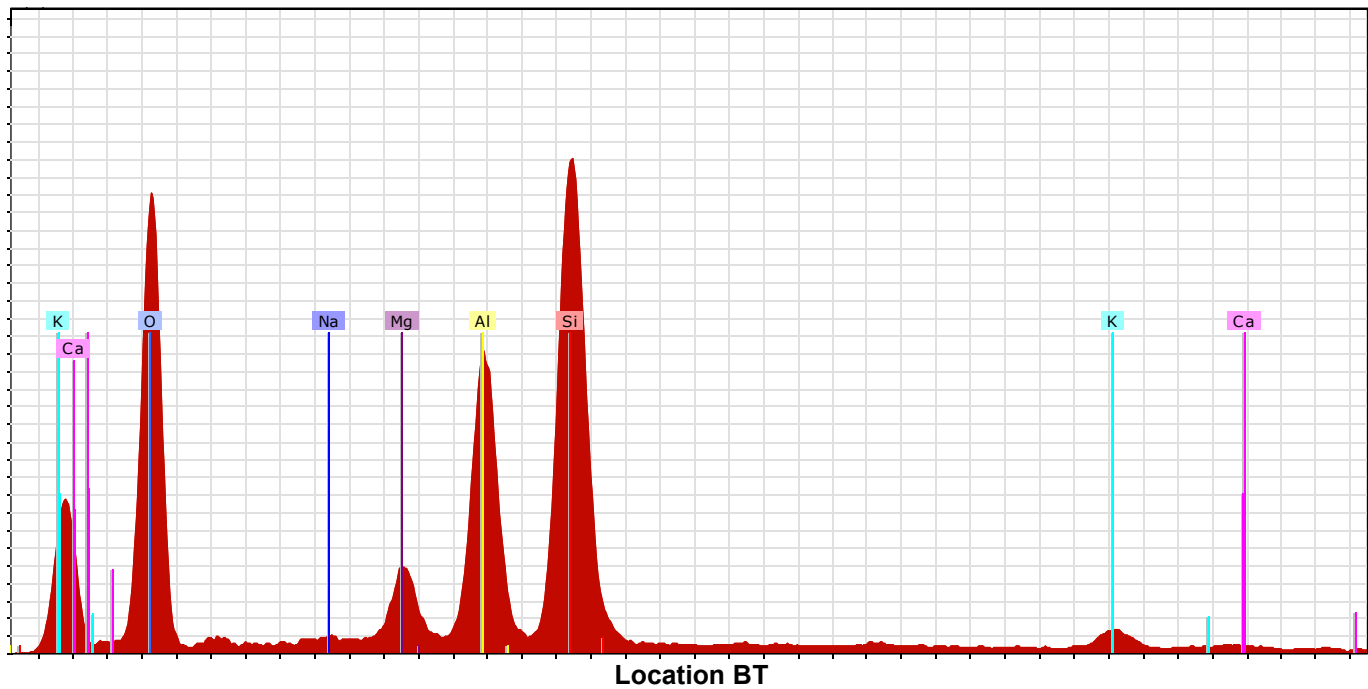
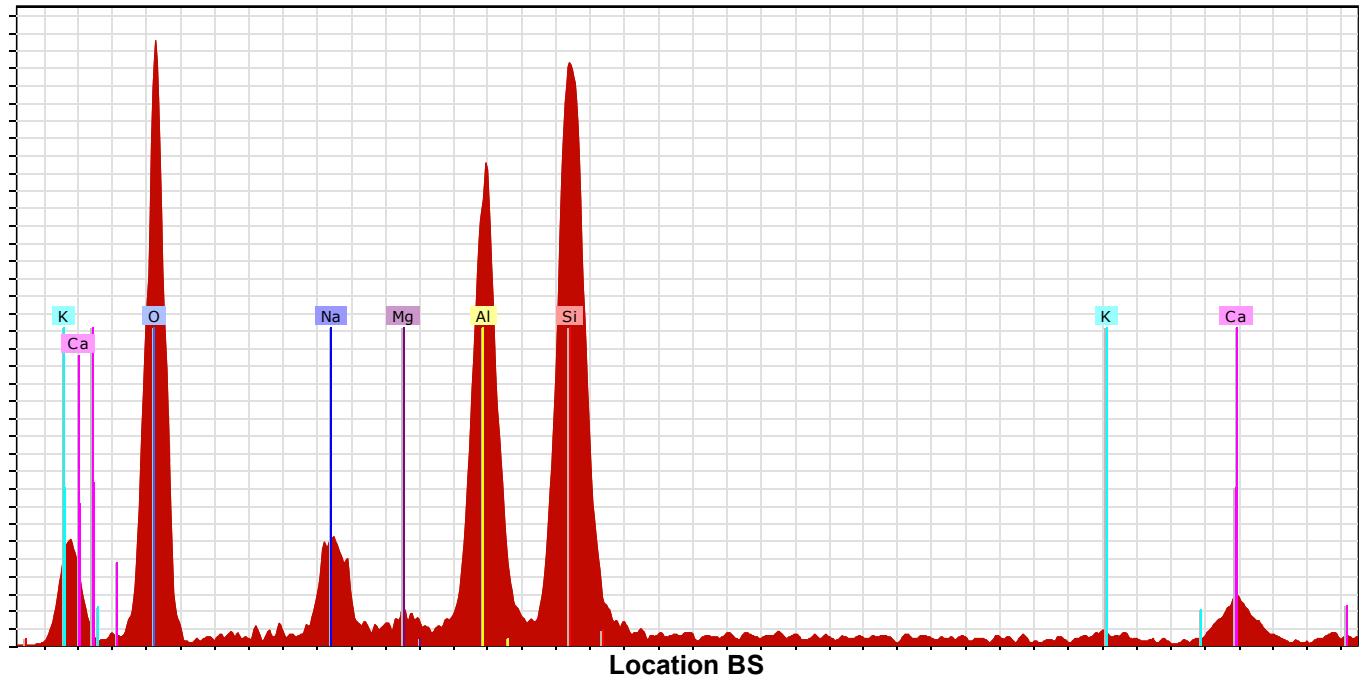


Figure 124. Semi-quantitative EDS results for debris at locations BS and BT in the main passageway of the oil nozzle (see Figure 121). Location BS exhibited higher concentrations of silicon, aluminum, calcium, magnesium, sodium, potassium, and oxygen. Location BT exhibited higher concentrations of silicon, aluminum, magnesium, sodium, potassium, and oxygen.

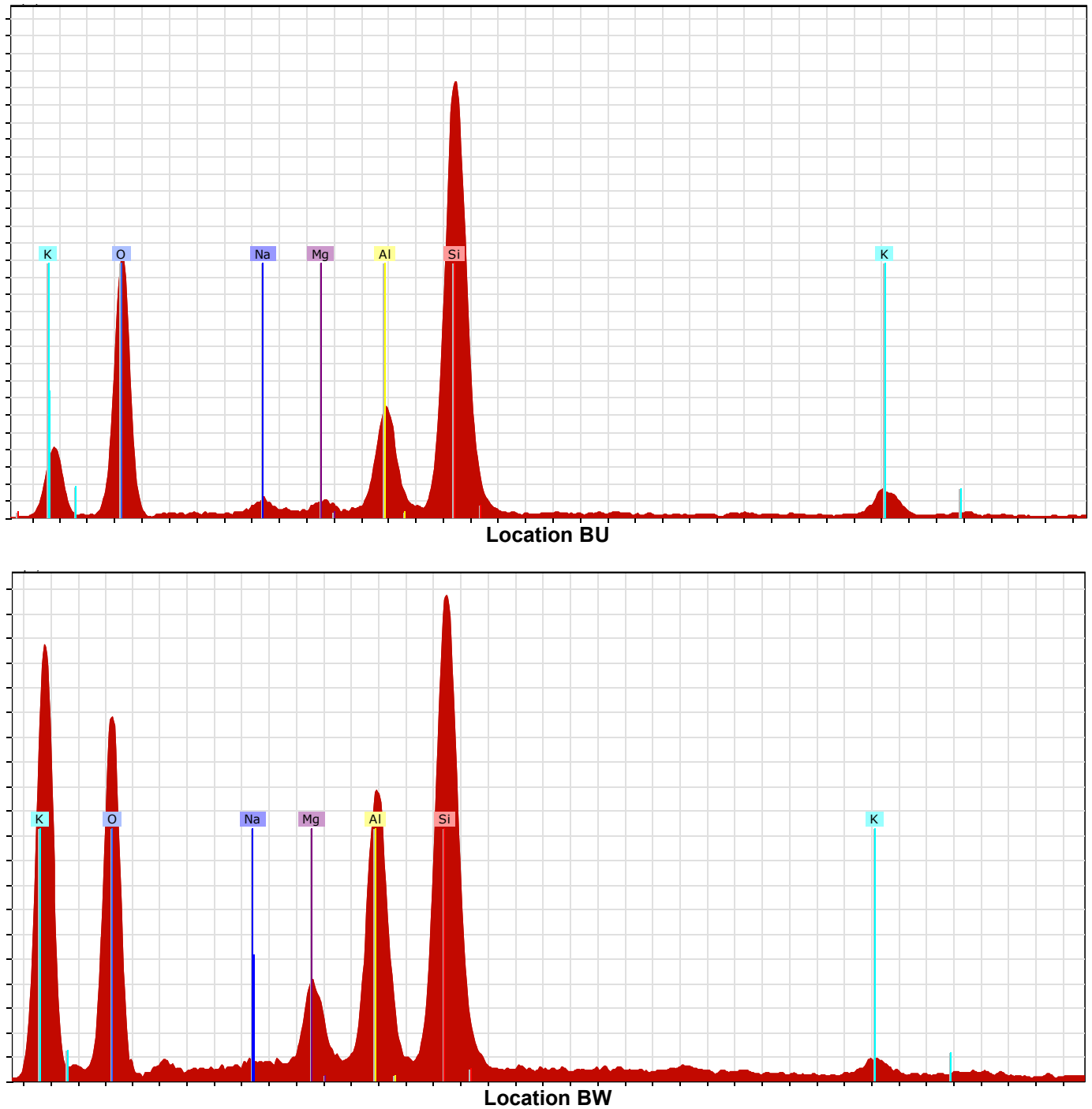


Figure 125. Semi-quantitative EDS results for debris at locations BU and BW in the main passageway of the oil nozzle (see Figure 121), which exhibited higher concentrations of silicon, aluminum, magnesium, sodium, potassium, and oxygen.

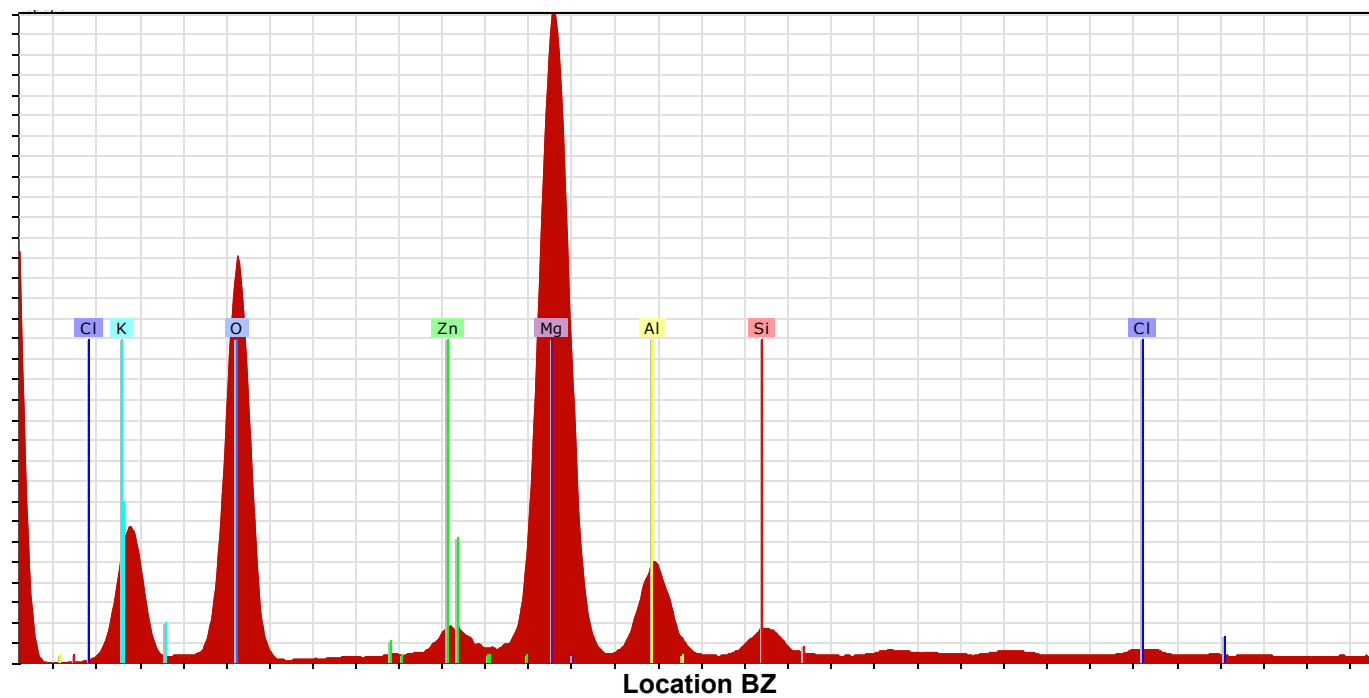
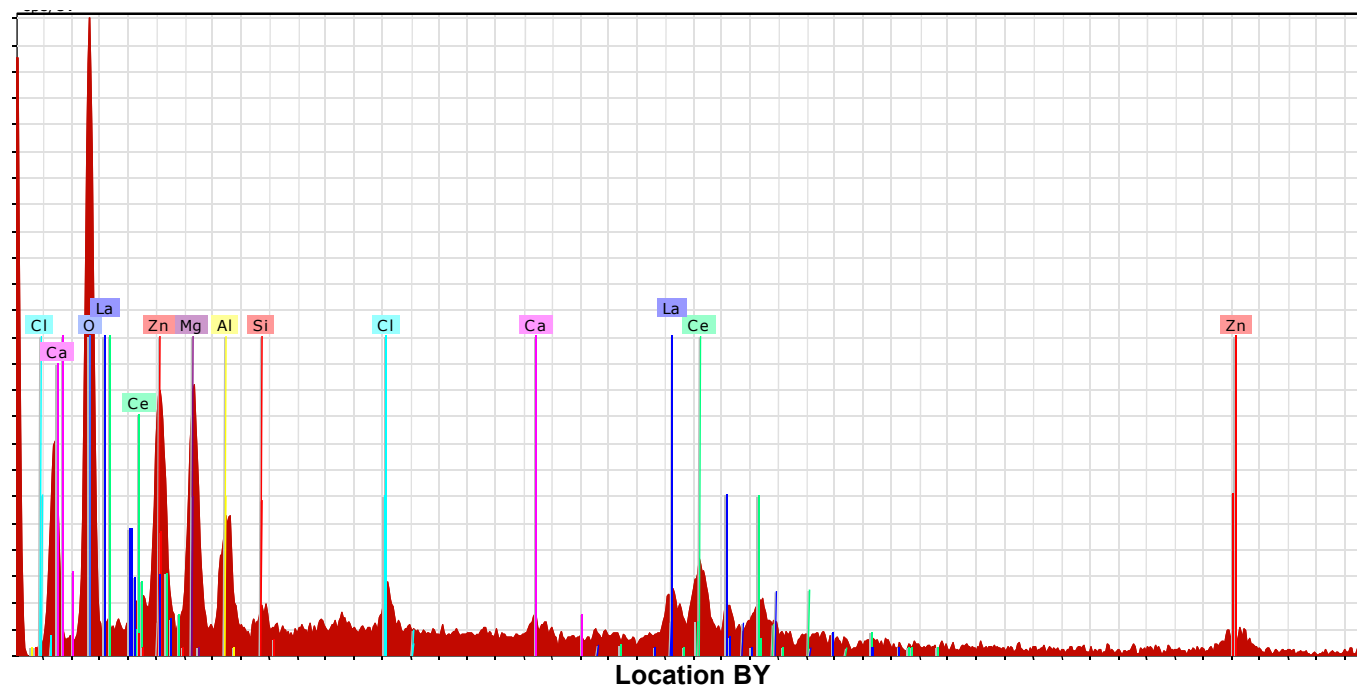


Figure 126. Semi-quantitative EDS results for debris at locations BY and BZ in the main passageway of the oil nozzle (see Figure 122). Location BY exhibited higher concentrations of magnesium, zinc, rare earth metals, aluminum, and oxygen. Location BZ exhibited higher concentrations of magnesium, aluminum, zinc, silicon, chlorine, and oxygen.