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Re: Analyses of lunar mission cuff checklist from Gene Cernan, Apollo 17
To: Mr. Roger Wagner
From: Prof. Dr. Stephen J. Mojzsis

Budapest, January 26, 2023

(CONFIDENTIAL REPORT)

Dear Mr. Wagner,

I am very pleased to provide you with my professional assessment of the "lunar mission **cuff checklist**" that you obtained from Cmdr. Gene Cernan (astronaut, Apollo 17), is now your personal property, and for which you wished me to examine for evidence of contamination from the Moon. Let me begin by stating that it was a pleasure for me to work with you and furthermore to consider how we could undertake detailed analyses of samples of adhered dust on certain pages of this item, which is of real historical and cultural significance.

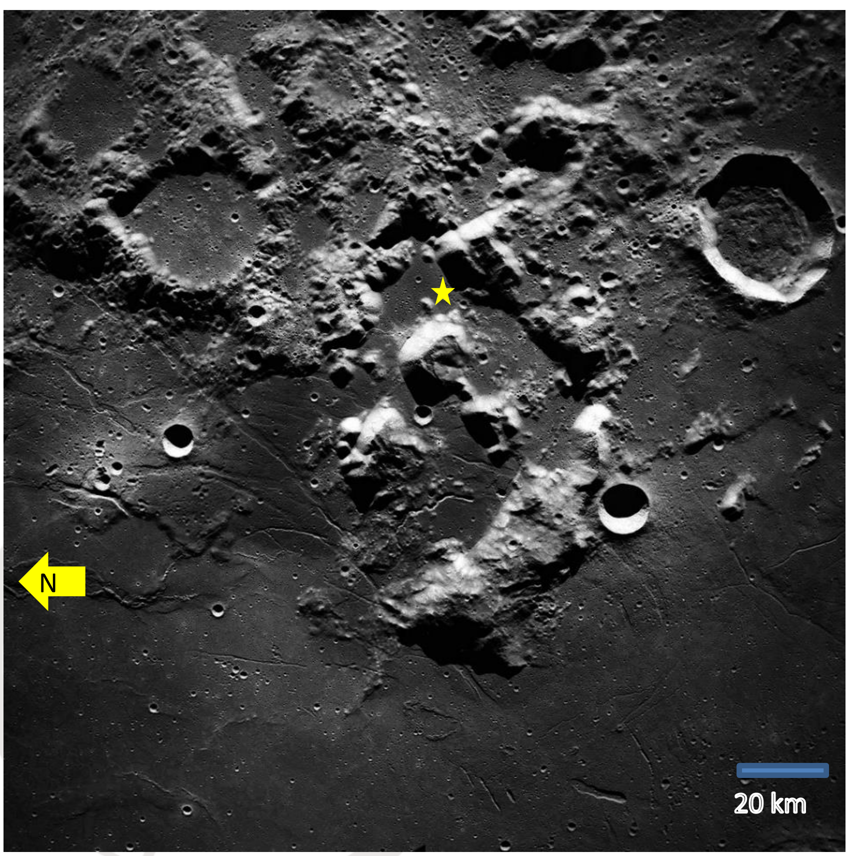
This **Report** is the product of those efforts and describes what I interpret to be material that is of lunar origin and thus confirms the provenance of this object as being an authentic item that was exposed to the Moon during one of the Extra-Vehicular Activities (EVA).

A **DRAFT of this Report** was previously provided of my investigations of these samples for comments. I acknowledge receipt of those comments and changes, and hereby present my final signed report.

Background to the work: Images of the item sent to me in advance by Mr. Roger Wagner via email and prior to the in-person analytical work showed what appeared to be a small spiral-bound notebook (or booklet) such as those used by the astronauts on the post-Apollo 13 missions to the Moon. Such Apollo cuff checklists were designed and manufactured at the NASA, Johnson Space Center (Houston, TX) and were intended to be worn on the wrist cap of an EVA glove, and were designed to withstand the harsh lunar environment. According to the information provided to me in the emails and in a ZOOM call, the cuff checklist was attributed by Mr. Wagner to Apollo 17 and specifically to Mission Commander Mr. Eugene Cernan. It contains instructions for lunar activities during the first traverse by the astronaut team on the surface (EVA 1). My research shows that the EVA 3 cuff checklist is now archived at the Smithsonian Air & Space Museum in Washington, D.C. I do not know the whereabouts of the EVA 2 cuff checklist. The Apollo 17 mission (December 7–19, 1972) was the last mission of NASA's Apollo program to the Moon, and thus the most recent time humans set foot on the Moon or for that matter, have traveled beyond low Earth orbit. The next Apollo-related mission was the so-called Apollo-Soyuz venture, which used spare equipment from the cancelled Apollo 18+ program and was limited to low Earth orbit. To confirm, this cuff checklist is labelled "EVA 1".

The cuff checklist was engineered to fit into an attachment band fastened in place on the astronaut's gloved arm with a velcro closure. It appears that these original parts are intact and still attached to the cuff checklist. Its spiral bound nature enabled the stiff pages to be turned even while wearing bulky extra-vehicular gloves, and to remain in place while operating other equipment. Records from NASA archives and the Smithsonian Institution curatorial facility also report that the booklet was constructed using "plasticized paper, paper, aluminum, and ink." More research shows that the "paper" is in fact a general term; the pages were actually composed of a stiff polymer coated with a high temperature plastic, and impregnated by black and sometimes red (probably carbon) ink with low thermal expansivity and other refractory properties appropriate for survival in the lunar environment. Hence, they are not paper *s.s.* in that they are not composed of processed plant material that would be at risk of damage in the near vacuum and extreme temperature conditions of the Moon's surface. The attachment bar of the booklet is composed of copper, and the attachment band is made of aluminum, Velcro, and nylon with some carbon components. All pieces of the item showed evidence of age (cracking, scratches, etc.). Visual inspection showed evidence of oxidation of Cu. Reported dimensions of the cuff checklist in *3-D, are: 17.8 x 8.9 x 7.6cm (7 x 3 1/2 x 3 in.). Thus, what was presented to me comported in all respects with these various reports, and thus provides important information about and support to, the provenance of the item.

The purpose of cuff checklists was to guide scientific investigations at every station on the Moon as well as the observations in between (*cf.* Lunar Surface Features, Vol. 1 *Nominal Plans*). Having a cuff checklist meant that various geological and other studies could be carried out with significant autonomy by the astronauts by following simple instructions prepared prior to the expedition by science team members on Earth. Instructions were included in abbreviated form into a cuff-checklist attached to the astronauts' spacesuit. Pre-Apollo 13 cuff checklists were sewn into the space suits, which means that at the least this particular item must post-date 1971. Radio waves travel at the speed of light; it takes 1.25 seconds to cover Earth-Moon distance. This is the reason that during the Apollo missions when Houston (Mission Control) said something, the response from the astronauts on the Moon arrived only after 2.5 seconds. Although this delay time is short, the efficacy of the missions required astronaut autonomy within reasonable safety parameters. Hence, the cuff checklist is an essential item to EVAs.



The Apollo 17 spacecraft landed in the Taurus–Littrow valley (**Figure 1)** on the lunar near side at the coordinates 20.0°N 31.0°E. The location is on on the southeastern edge of Mare Serenitatis (**Figure 2**) along mountain range formed between 3.8 and 3.9 billion years ago (Ga) associated with the pre-3.9 Ga Serenitatis Basin and its uplifts as part of the imposed ring structure.

Figure 1. *Landing site (star) and surrounding area, as imaged from the Apollo 17 command module, 1972 (NASA).*

Mr. Wagner's images, as well as personal inspection, indicated that some of the pages of the cuff checklist were variably contaminated by very fine (<2.5 micrometer; µm) dust. If this fine dust is of lunar origin, then it would have certain characteristics that could differentiate it from terrestrial contaminants. Two morphological features that are telling are: **Particle sizes and habit**. Lunar dust can be fine (2.5µm > D > 0.1µm) and ultra-fine (D < 0.1 µm). The granulometry of such fine samples can be determined using microscopic imaging methods. Most lunar dusts that have ever been examined show sub-angular to angular shapes with sharp edges. There are typically four shapes that predominate in lunar dust: (1) spherical; (2) angular blocks; (3) glassy shards; and, (4) irregular (ropey or holey). Sub-micrometer bubbles and cracks are also sometimes observed in lunar dust grains. It should be emphasized that the sharp edges of glass fragments is a characteristic morphological of nearly all lunar dust particles that are not melt spherules (see below). On Earth, hydration and weathering lead to rounding and breakdown of glassy shards. Not so on the Moon, which has almost no atmosphere and is extremely poor in volatiles such as water.

To study these samples at high resolution (because the dust grains are very small) and to simultaneously determine their composition(s), I used the FEI Field-emission Gun Environmental Scanning Electron Microscope (FEG-ESEM) at the Department of Nanomaterials at the University of California, San Diego (USA). In my analyses, I made use of Secondary Electron Microscopy (SEM), with Energy-dispersive X-Ray analyzer (EDX) and Back-scattered Electron (BSE) imaging. These methods are usually non-destructive, as each uses an electron beam focused on the sample surface to collect secondary electrons (SEM), back-scattered electrons (BSE) and resultant x-rays (EDX) with a suite of detectors. Unless the samples are very volatile, they should remain undamaged and unchanged from original composition. The laboratory work was performed over one full day (8 hours) with the instrument working optimally: This was enough time to facilitate studies of all of the samples at appropriate and equal detail to reach conclusions about provenance of the item.

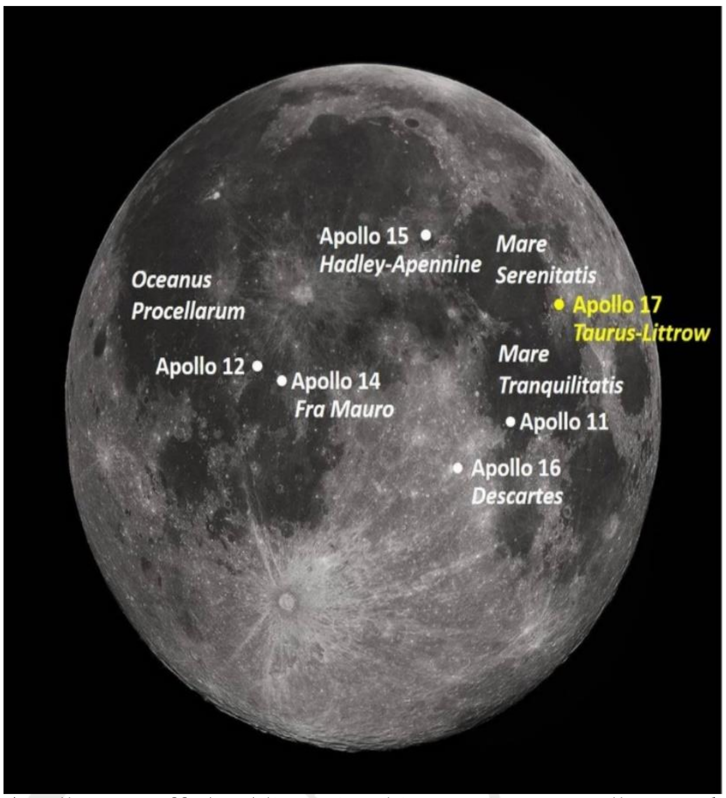


Figure 2. *The landing site selected for Apollo 17 was in the Taurus-Littrow Valley on the eastern rim of Mare Serenitatis (highlighted in yellow font). The two primary objectives were obtaining samples of highland material that were older than the Imbrium impact and investigating the possibility of young, explosive volcanism. Other Apollo sites are listed. (NASA).*

Visible details of the samples: In the laboratory, I was presented with the Apollo 17 cuff checklist. Visual inspection, as well as study under 50X magnification using a stereo-microscope, showed that multiple pages had varying amounts of what appeared to be fine dust adhered to them and some scuffing, smearing, and cracking of the pages that had dusty material contained therein. Other pages looked like they were essentially dust-free under normal optical microscopy. Care was taken to avoid handling the item very much, and latex gloves were used when it was required to do so. I do not know the curatorial history of this item. To recover the dust samples from the surfaces of the pages, I used double-sided sticky carbon/graphite tape that was pre-attached to conventional SEM aluminum stubs. That way, I was able to target specific regions of certain dusty pages and use the freshly exposed sticky side of the stub+tape to peel the surface.

Thirteen pages of the item were identified as promising targets for dust collection, and of these, six were earmarked for lifting off dusty material for imaging and chemical analysis. All sampling of the cuff checklist pages was done under the close supervision of Mr. Wagner. In some cases, noticeable differences were present on the pages after each peel, which I attributed to the effective removal of dust material from the plasticized pages. Consequently, from six pages, I created six mounted stub samples labeled 1-6 that were ready for the analysis. The fact that I used an FE-ESEM to analyze these samples meant that no further alterations whatsoever occurred to the original samples and that the dust material that I retrieved was left unaltered and uncoated (e.g. no conductive carbon or Au-Pd coatings were applied and thus the dust is pristine). The Al sample stubs are in the possession of Mr. Wagner.

Observations of the samples prior to introduction to the FEG-SEM: During visual initial inspection of the dust samples on the Al-stubs, I noticed that the carbon tape used to lift the surface material was slightly discolored. Otherwise, it was impossible to tell beforehand how effective the sampling was owing to the very fine nature of the dust.

First I discuss the mineralogy of the samples, their plausible relationship to the geology of the Moon, and then I will describe the overall outcomes of the investigations before concluding with my overall assessment and some musings about what future work could be performed on them.

MINERALOGY AND CHEMISTRY

The samples are all very similar to one another, with a coherent mineral composition and morphological structure of the grains, even if the abundances of the dust grains are different for different samples.

Similarities: The different sample stubs captured variable quantities of small grains ranging from fine dust-sized particles, to ultra-fine dust. These presented as a relatively narrow confine of shapes from lathe-like crystal or composite grain habits, to glassy and fractured (angular) fragments, spherules, and agglomerations. On each mount, there were areas where the grains were clumped up together as if they were previously electro-statically charged before becoming adhered to the tape. One of the sample studs showed small thread fragments of a contaminant with properties consistent with 'beta cloth' (https://en.wikipedia.org/wiki/Beta_cloth). It is worth mentioning that either because of where I sampled or owing to how the cuff checklist was stored for these many decades, there was very little contamination from terrestrial dirt. Terrestrial pollution is generally distinguishable from the samples of probably lunar origin based on composition, structure and superposition. Clays, salts and fibers are common terrestrial contaminants. None were seen in the sample peels.

Based on this background information provided to me, I paid special attention to mineralogical details of Apollo 17 dust and regolith samples as opposed to other (e.g earlier) lunar missions. Furthermore, as a specialist in lunar geology I was able to use my expertise to make sense of the information I obtained from these samples and to compare my results with prior reports prepared by NASA. For each of the samples described below, please refer to the extensive Appendix of this Report for the complete data used to reach the conclusions herein. References for the sources of technical information are available at request of the author.

GEOLOGY

Geology of the Apollo 17 landing site. Rocks from the floor of the Taurus-Littrow valley are mostly mare basalts. *Basalt* is a common igneous rock formed in terrestrial-type planets that forms from partial melting of a pre-existing rock from the mantle and consists primarily of the minerals plagioclase and pyroxene. It could be formed either from molten lava erupted at the surface or intruded into the crust at some depth while still molten. On the Moon, the mare basalts formed from material that melted at depths of at least 130 to 220 kilometers and then rose to the surface before solidifying, often by filling a lunar impact basin (see dark splotches in **Figure 2**, these are made from mare basalts). Geochronological analyses mostly by the $^{40-39}$Ar method, show that the Apollo 17 mare basalts generally formed between 3.7 and 3.8 billion years ago. It should be noted that this is the most common age assignment for a lunar basalt, but that this does not mean that volcanism ceased on the Moon by that time. Like the Apollo 11 basalts, the Apollo 17 basalts generally contain large amounts of the element titanium, which is contained in the mineral ilmenite ($FeTiO_3$). A few rare Apollo 17 basalts have very low titanium abundances, but high Ti is an expected signature of lunar material. Seismic and gravity observations indicate that the basalt layer is between 1.0 and 1.4 kilometers thick near the Apollo 17 landing site.

Mare basalts were emplaced as fluids (i.e. melt) that flowed easily across the Moon's surface and solidified under near-vacuum. Photographs taken from lunar orbit prior to the Apollo 17 mission were interpreted to show that some explosive volcanic activity had also occurred in this region, and there were some geologists who thought this activity might have occurred recently in lunar history. From orbit, the Apollo 15 crew (July 26 – August 7, 1971) observed several craters in this region surrounded by deposits of very dark material. These so-called “dark halo craters” were interpreted as volcanic cinder cones and were generally considered to be relatively young features, although some investigators pointed to features in the Apollo 15 photographs that indicated these deposits are actually very old. One of these craters, Shorty, was near the selected landing site and was another important objective of the mission. Finally, samples obtained from the floor of the valley would allow the age of the mare basalt material to be determined. Despite the narrowness of the valley and the high (1.5 to 2 kilometers) mountains on either side, Apollo 15 photography showed that the Lunar Module could land safely in this region. Moreover, the primary objectives of the mission could be achieved even if the Lunar Rover failed. One drawback of this landing site is that it is at the boundary between mare basalts and a basin rim, an environment very similar to that sampled by Apollo 15. Nevertheless, the other advantages of this site led to its selection as the Apollo 17 landing site. Thus, spectacularly, Shorty Crater (**Figure 3**) was explored to determine if it was a volcanic vent.

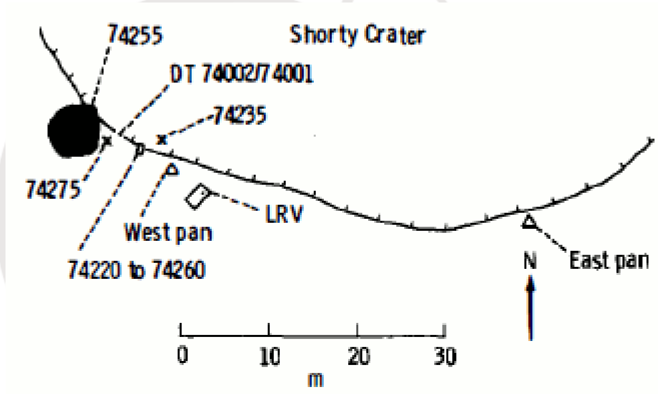


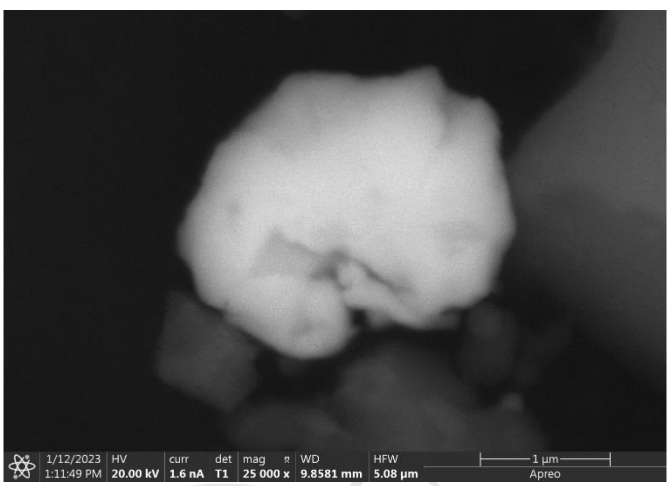
Figure 3. *Planimetric map of Station 4 including the rim of Shorty (NASA).*

Orange and black volcanic glass (the famous "orange soil"; https://curator.jsc.nasa.gov/lunar/lsc/74220.pdf) was found near the rim of Shorty Crater (**Figure 4**) and was confirmed to have formed in an explosive volcanic eruption prior to excavation by the impact. On Earth, such eruptions are sometimes called "fire fountains". It seems that the relationship between Shorty Crater and the volcanic glass is just coincidental because later analysis showed that the glass formed 3.64 billion years ago from material that melted about 400 kilometers below the surface. Shorty Crater turns out to be an ordinary impact crater, and the lack of degradation of its features indicates that the crater is much younger than the glass. The glass is exceedingly rich in volatile elements, which has led to a lot of discussion about the origin of this material as either indigenous to the Moon, or contamination from late accretion.

SAMPLES IN DETAIL

The most obvious feature shared by all six samples I studied is that dust particles are ubiquitous. This was a surprise at first, because I do not know anything about the archival history of this sample over the last 50 years. Judging from what I have seen, the sample (remarkably) was never cleaned and was kept in a quiet place for a long time. Also, in hindsight it made sense that fine dust of lunar origin should be very sticky: The Apollo 17 landing crew (Harrison Schmidt and Gene Cernan), reported that the air in their Lunar Module (LM), the *Challenger*, "…smelled like gun-powder." This comment came after the two had just returned from EVA 1 – with the cuff checklist under study herein – with exceedingly dusty spacesuits. Within the LM compartment, the dust became airborne and was breathed in by them. Later, Schmidt complained of congestion and fever, although his symptoms went away shortly thereafter.

Native metal grains



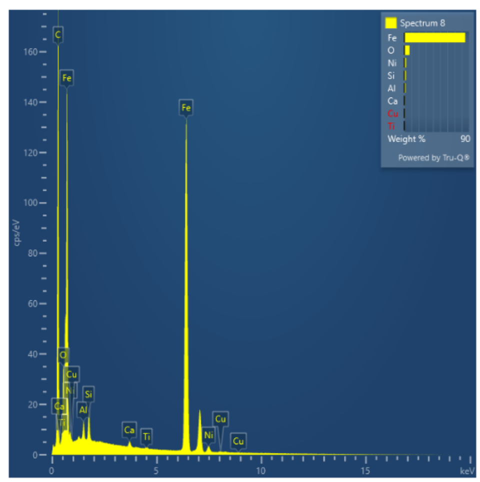
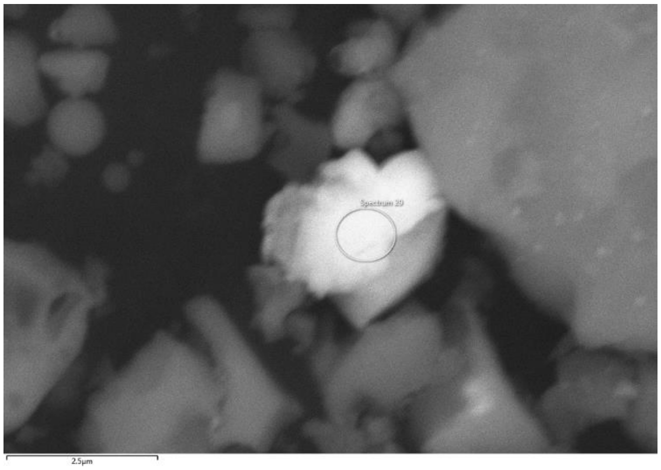
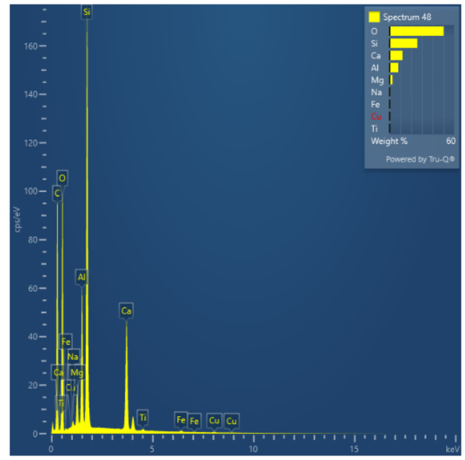


Figure S1_1 (above). This small (~2µm) grain of Fe(Ni) metal was the first high-contrast BSE material found in my survey in **specimen 1**. Based on its composition, it is mostly metal (Fe) with a small amount of Ni. Background carbon emissions and elements of other associated minerals provide C, Cu, Ti, Ca, Si, and Al peaks. It does not appear to be a terrestrial contaminant, and may be a small metallic fragment such as is sometimes found in lunar soils from extralunar (meteoritic) origin. The next example comes from **specimen 3 (Figure S3_4; next page)**, which shows another metallic grain with associated elemental spectra. Such materials are extremely rare on Earth and never found as dust grains (they become rapidly oxidized with water vapor).





Glass spherules. A "smoking gun" line of evidence for dust of lunar origin is the presence of small glassy spherules throughout the sampling. One of these is shown at left (**Figure S1_2**). Lunar glasses were found to be abundant in Apollo regolith samples and the dust that was sampled from the Moon. Glass droplets constitute about half of the fines in the Apollo regolith investigations. Varieties of impact glass include particles, surface coatings, and porous glassy aggregates. Some of the glass fragments are ropy or agglutinates. Unlike volcanic glasses that were produced in residual liquids at the end stages of crystallization of the lunar magma ocean, impact glasses are formed by melted impact ejecta during ballistic flight at temperatures upwards of 1,000 °C. They have a variety of distinct characteristics indicative of impact formation, including:

_ mineral or rock fragment inclusions, some of which may have been derived from the impacting meteorite;

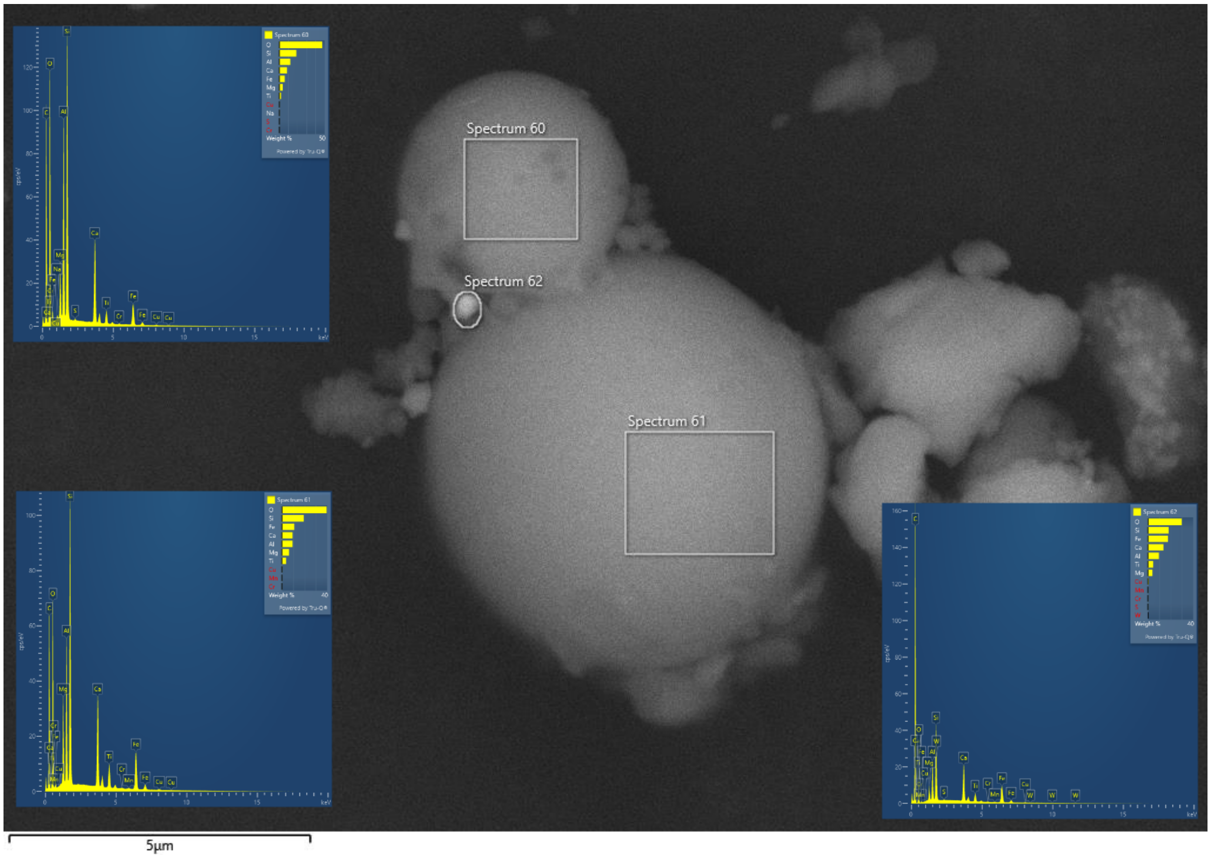
_ a single composition related to the mineral which melted upon impact;

_ flow features and/or shapes (e.g., dumbbell, teardrop, oblate spheroid, i.e., "splash-form" in the terrestrial literature) representative of rapid fusion and quenching; and/or

_ a coating of impact-induced "flour" that adhered to the outer surface when produced simultaneously with the glass in the impact. This "flour" can contain splattered droplets of nickel-iron, clinopyroxene, olivine, and troilite, among others.

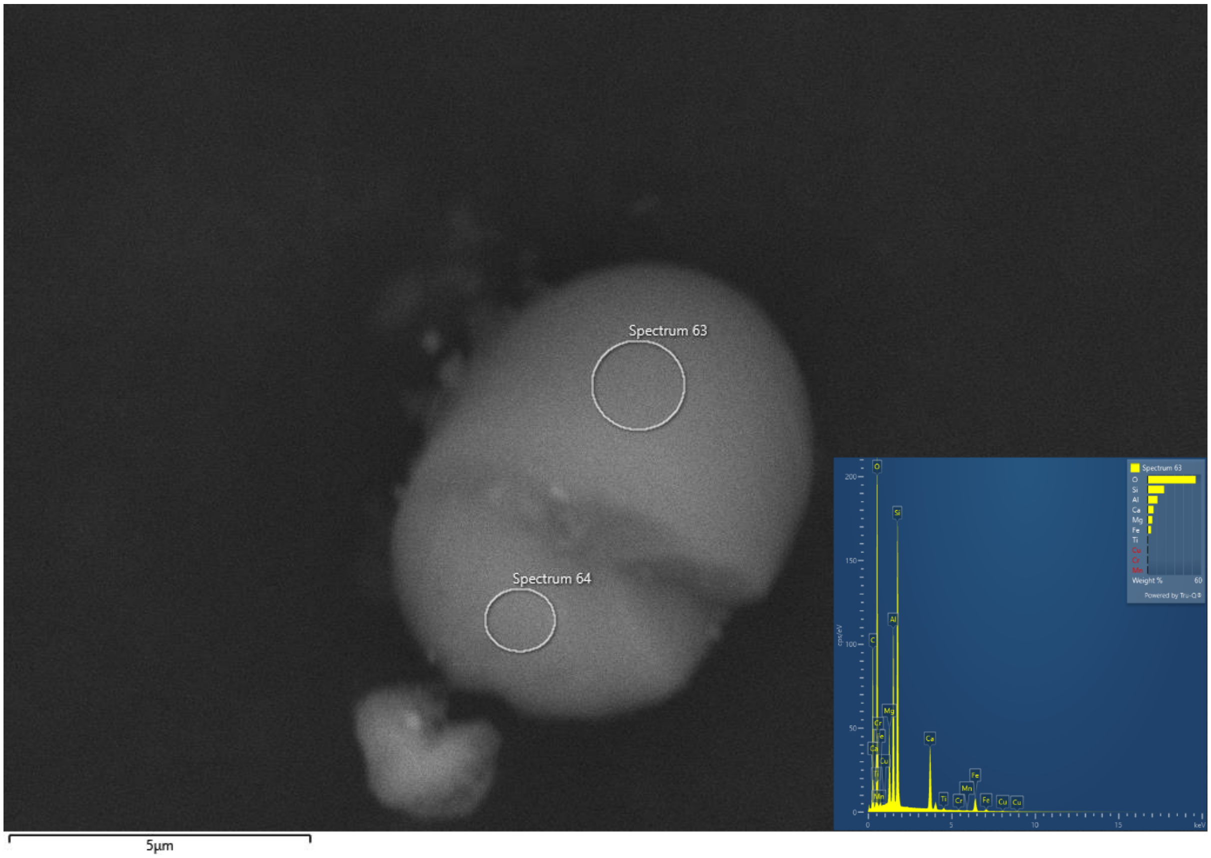
Because lunar impact glasses and glass spherules are abundant in the lunar regolith, hundreds of glass samples could be present in just a few grams of regolith. It turns out that impact glasses that are inclusion free and chemically homogenous like those found on the cuff checklist are also ideal probes for investigating the compositions of their source regions and for constraining the timing of impact events. The documented sizes of the smallest (dust-sized) pherules from directly sample lunar regolith (~1 μm) match that observed in the material examined herein and, thankfully, leave little room for contaminating material that would affect measurements of major and trace elements. It would require a great deal of analytical work to do such a study.

An example of a compound spherule is shown below (**Figure S4_9**).



The spectra from these spherules are consistent with glasses formed from Ca-Al-silicates (feldspars) rich also in Fe and Ti. These are typical lunar compositions. The representative spectra are shown as insets in this figure. Notice the small blob on the middle-right of the image, just above the spectrum? It is very similar to what have been dubbed "decorated spherules" such as those seen in other specimens of lunar dust that I have examined (e.g. Apollo 11). It is also evident from the above spectra that the two spherules in **Figure S4_9** have somewhat similar compositions, and the smaller one is different, reflecting the different presumably target rock compositions. (positions 60, 61, 62, respectively in the image).

An examples of spherules that fit into the category of quenching are shown next:



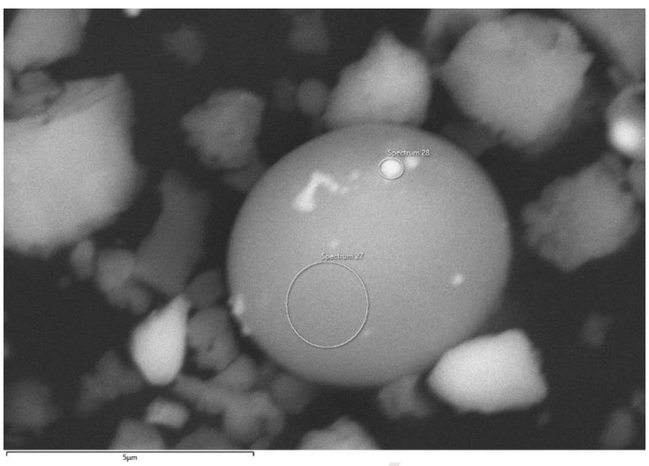


Figure S4_10 (above) is a partially broken (?) but certainly irregularly shaped spherule that is between oblate and dumbbell in shape. Spectra for this, shown as an inset, provide consistent whole rock compositions like that seen for other spherules from the Moon. **Figure S3_3** (at left) is a close-up of another "decorated" spherule, also with typical feldspathic rock composition, surround by rock and glass fragments.

Titanium-rich minerals. Common minerals of probable lunar origin include high-Ti pyroxene. As described in the Apollo 11 Lunar Sample Catalogue (LSC), Petrology section, page 6. This is a very common constituent of the fine material of Apollo 11. There are many examples of these grains in Sample 2, and what is striking about them is that they are very angular and appear to be unaltered. If these were Earth contaminants, the expectation is that they would show evidence of alteration (from hydration) and weathering due to erosional transport. Although it is not uncommon to find such minerals in certain areas on Earth (Hawai'I, Iceland), they would be very unusual elsewhere owing to the fact that such minerals at Earth's surface are relatively unstable in the presence of water. On the Moon, however, they are extremely common and formed from the breakup of rocks by energetic impacts associated with late accretion to the lunar surface.

Glass shards & Agglomerates. Most studies of lunar dusts have focused on impact glass spherules, but glass shards (i.e., angular fragments) are similarly abundant in the regolith samples and can provide additional information about both the composition and impact history of the Moon. With sizes as large as ~1 mm or more, these glass fragments probably started off as impact spherules but were then broken into shards over time, a result of high thermal stresses most likely caused by rapid quenching from hyper-liquidus temperatures that may have made them susceptible to comminution by subsequent impacts. Unlike glass shards, impact glass spherules are more likely to have compositions that are typical of the local regolith in which they were collected. Since lunar soils reflect the local geology of the areas in which they were formed, the observation that impact glass spherules have the local compositions means that they are more likely to be formed in small local impacts. Impact glass shards, on the other hand, are likely produced in large distant, potentially global, impact events (such as Serenitatis and Imbrium). Ejecta from these large-scale impacts effectively transport material from distant regions, and the glass shard compositions reflect this process. Examples of these are shown next:

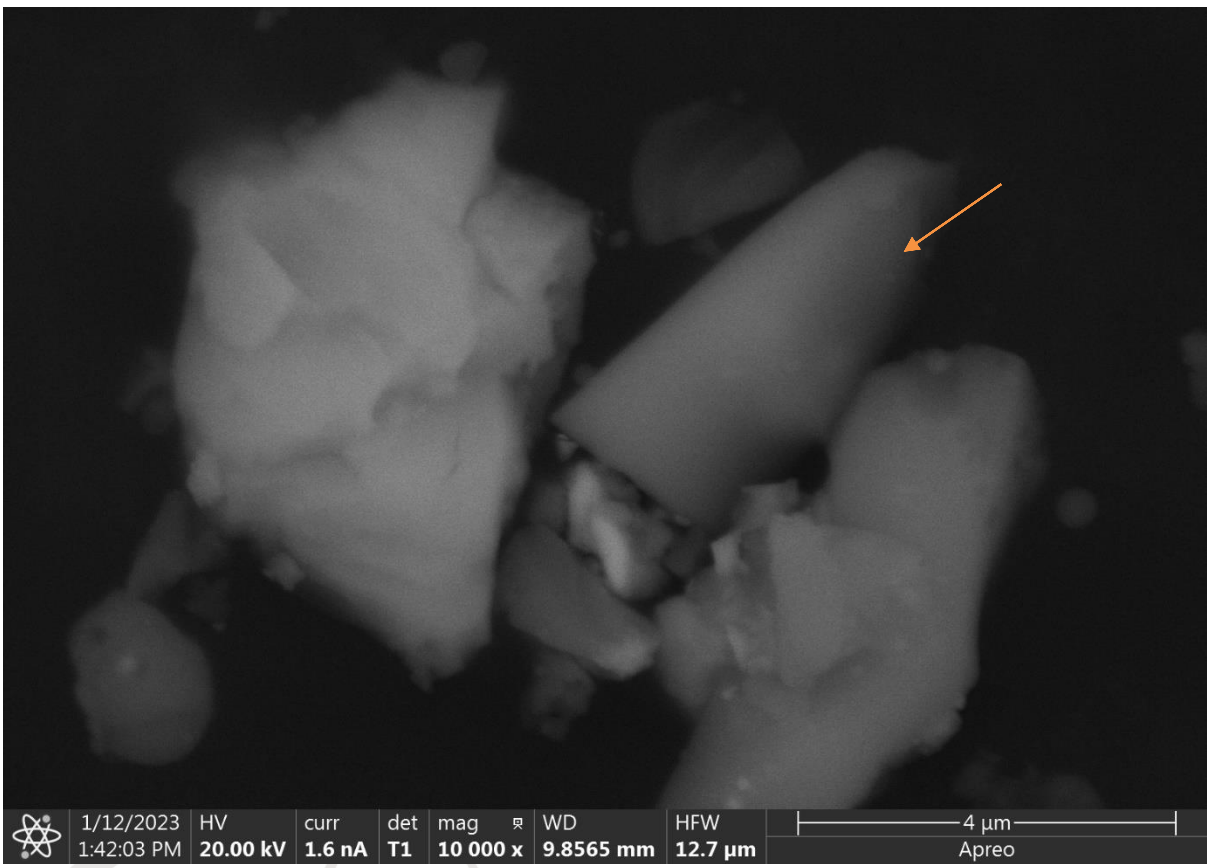
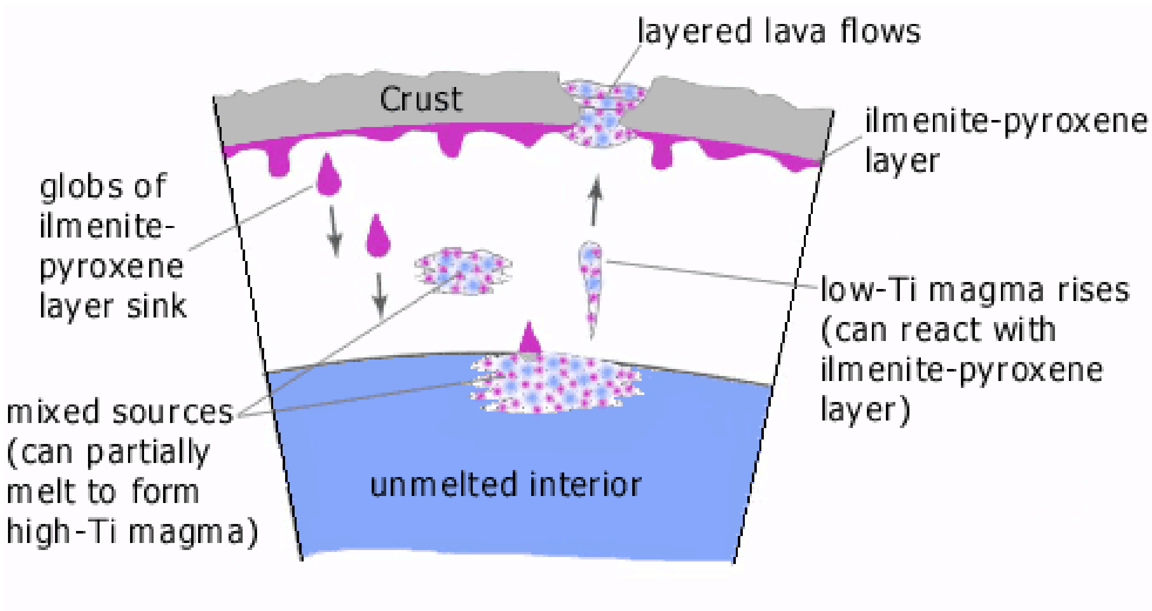


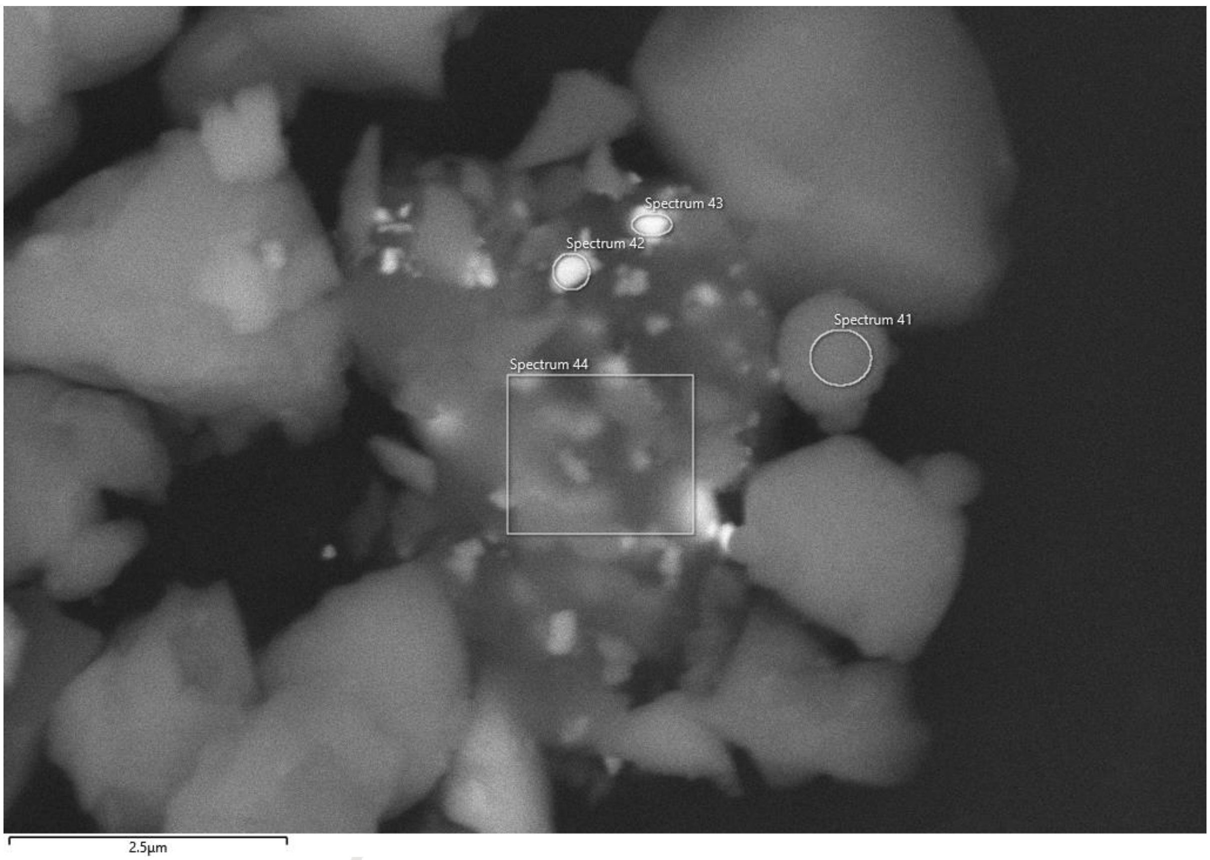
Figure S1_5_002 (above) shows a collection of interesting features. First, there is a small impact spherule on the lower left that connects to a rock fragment (higher contrast) with the composition and habit of Ti-rich pyroxene. A sharp-edged glass shard is indicated by the arrow.

Lunar volcanic minerals like pyroxene, and the volcanic (as opposed to impact-generated) glass deposits contain information about the composition of the Moon's interior and the melting processes that operated in it that helps us understand why rocks on the Moon can contain so much titanium. Indeed, some lunar glasses have unusually high amounts of titanium (expressed as titanium oxide, TiO2), up to about 16 wt%. All hypotheses for the formation of these high-titanium magmas make use of the presence of a titanium-rich layer deep in the Moon. This unusual layer was produced by the crystallization of a huge ocean of magma that surrounded the Moon at the time it formed. Ex-



periments indicate that this layer would consist mostly of ilmenite ($FeTiO_3$) and a variety of the mineral pyroxene that is rich in calcium. In one hypothesis the ilmenite-pyroxene layer sank and mixed (overturned thanks to density inversion) with low-titanium rocks inside the Moon. This produced a hybrid rock that later melted to form high-titanium magma. Here is a cartoon illustrating the process:

Figure S3_9 (below) shows a collection of spherules, shards and mineral fragments (mixture of pyroxene and feldspar, with some composite grains), surrounding an agglomerate grain (center). This is a fine example of a "ring" agglutinate that was formed by a single a micrometeor impact. There is a huge amount of energy associated with a micrometeor impact which can cause the underlying rock and regolith to melt. The reason for this is that the Moon is an airless body, and in the vicinity of Earth the impact velocities can approach 18 km/s. Some of the molten regolith then flows into the spaces between the surrounding lunar soil particles and as it cools it encases these particles in a vesicular glass matrix. The vesicles in the matrix may have formed by the evolution of solar wind implanted gases as the temperature rose which have then become trapped in the viscous melt. This is a fascinating discovery in the dust samples and certainly qualifies them to be suitable for research in the laboratory.



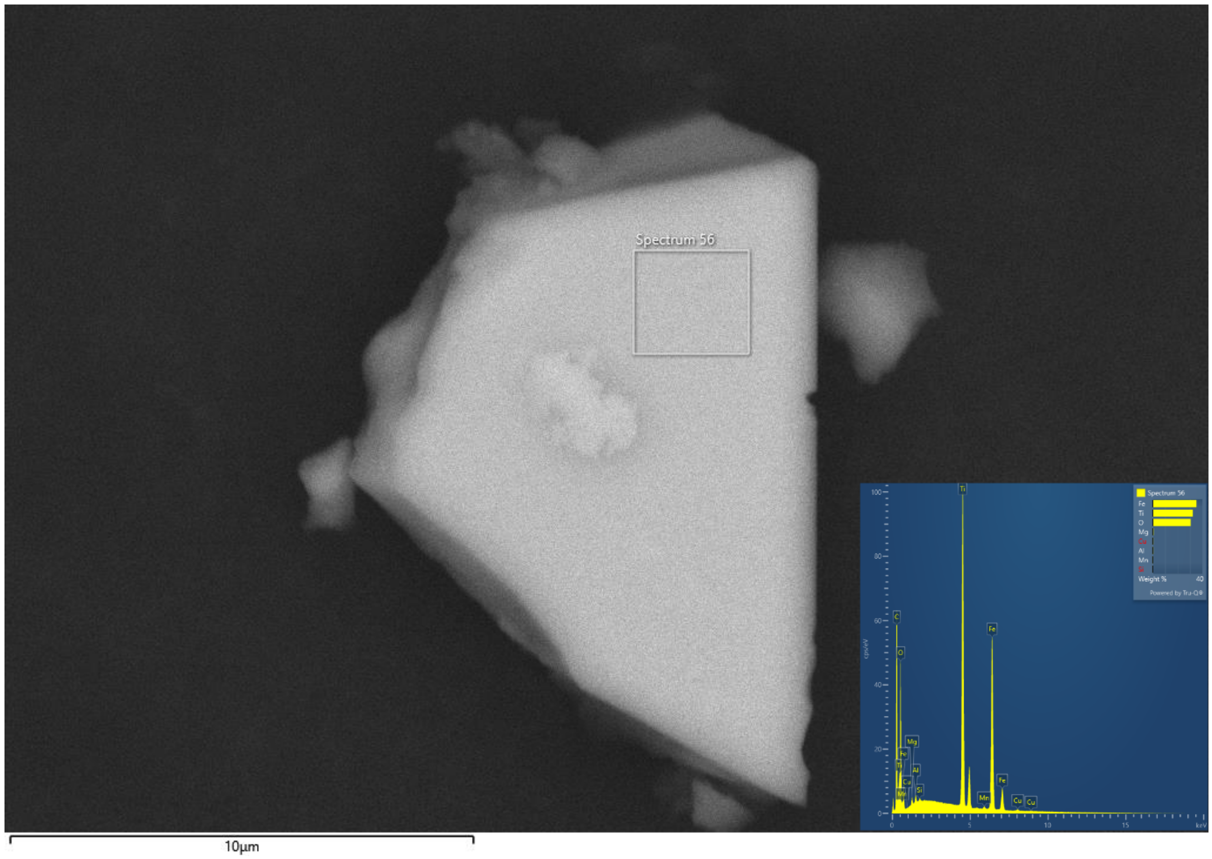


Figure S4_7 (above) is a beautiful example of a glass shard. Its x-ray spectral composition (inset) is a good match for ilmenite (Fe-Ti-oxide), a common mineral in lunar material.

CONCLUSIONS & POTENTIALS FOR THE FUTURE

Based on my analysis of the samples provided to me and the dust lift-off FESEM samples that I made from different surfaces of the item, coupled with my investigations of the literature as well as from long experience, I am able to come to the following conclusions.

1. It is my professional opinion that the "cuff checklist" owned by Mr. Roger Wagner and described as being from EVA-1 of the Apollo 17 mission to the Moon in 1972 is indeed consistent with descriptions of dusts and other samples reported in the Apollo 17 Lunar Sample Information Catalogue, as well as in other published reports of lunar material.
2. Furthermore, it is my professional opinion that the vast majority of the mineral grains that I studied from all of the samples prepared by me from the cuff checklist for analysis, are of lunar origin.

Hence, the EVA_1 Apollo 17 cuff checklist is an authentic item of extremely important historical significance, and of scientific value.

Furthermore, although the exact locations where the dust comes from in the area of the Apollo 17 mission may never be known, the fact that a combination of widespread and random sampling makes the lunar dusts sampled from this item powerful tools for geochemical and temporal explorations of lunar processes. With respect to the lunar impact spherules and glasses, not only do they provide important information about the timing of the Moon's impact flux, but they also provide important information about their provenance(s) somewhere on the Moon. As mentioned in this report, lunar impact glasses (both shards and spherules) are abundant in the regolith, which explains how and why I found so many on the cuff checklist. If future work was performed on these samples, one idea would be to explore the range in compositions of the different fragments and glasses to figure out whether or not they indicates that multiple regolith lithologies were sampled. All in all, such data provide useful information with which we can investigate the Moon's geological characteristics and evolution over time, including that of areas not directly sampled by past, current, or future planned missions.

Additional studies such as these will only increase the value of the data gleaned from lunar impact glasses. Compositions coupled with ages (e.g. from the U-Th/He method) could help to constrain the impact flux, especially in recent times, and reconcile these impact formation ages with other data sets will help us better understand the evolution of the asteroid belt.

Impact glasses sampled from depth may also provide useful information about the rate of impact gardening from the long-term mixing of the uppermost layers of the Moon from small impacts, the extent of sampling bias in the Apollo scoop samplings, and the nature of the solar wind (from the evolution of solar wind implantation into these materials) over time. If they possess a magnetic signature, the impact glasses can shed light on theoretical studies that predict they should record a magnetic signature of the impact event. Finally, the studies of lunar impact glasses lay the groundwork for extracting useful and important information from glass samples collected on other planetary bodies such as Mars, and potentially Mercury and the asteroids.

Included with this report are the raw data and images from the work performed as an Appendix.

Please do not hesitate to contact me if you have further questions (smojzsis@gmail.com).

Sincerely yours,

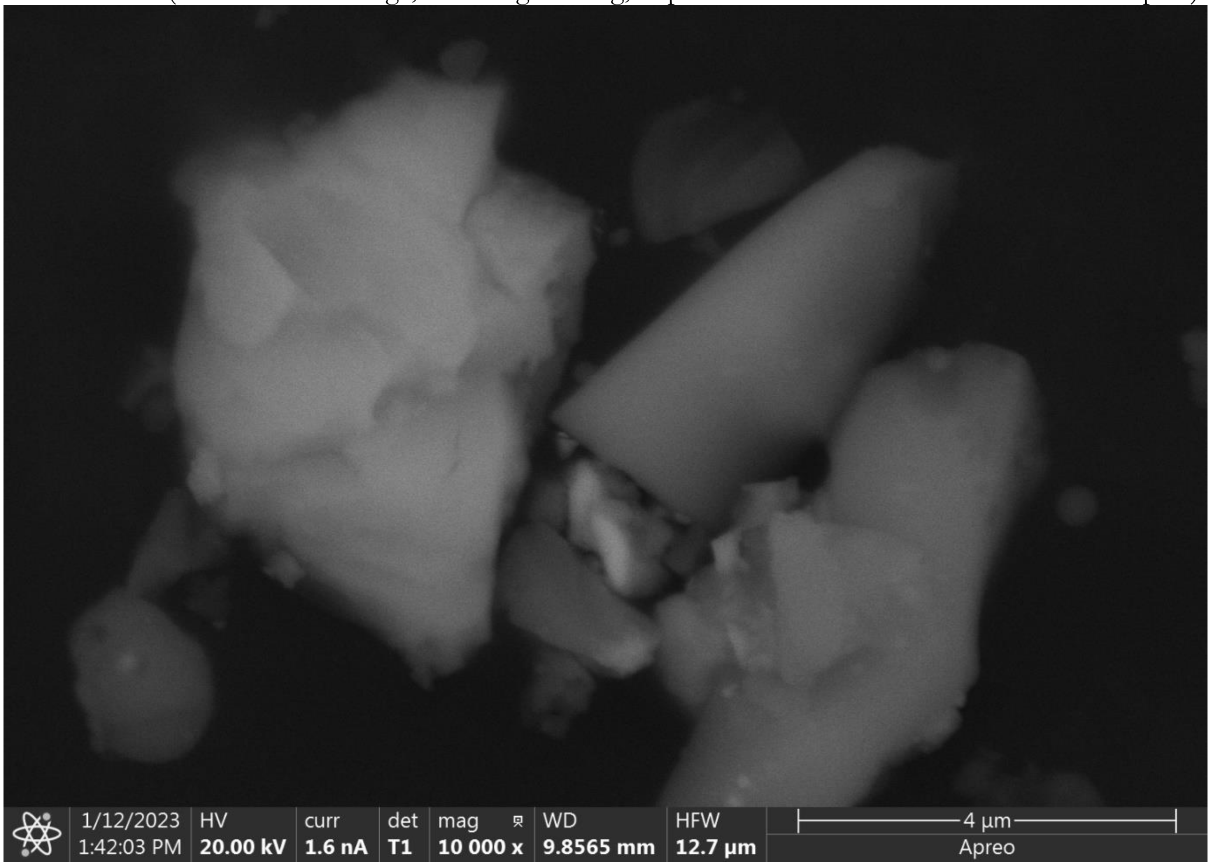
Prof. Dr. Stephen James Mojzsis

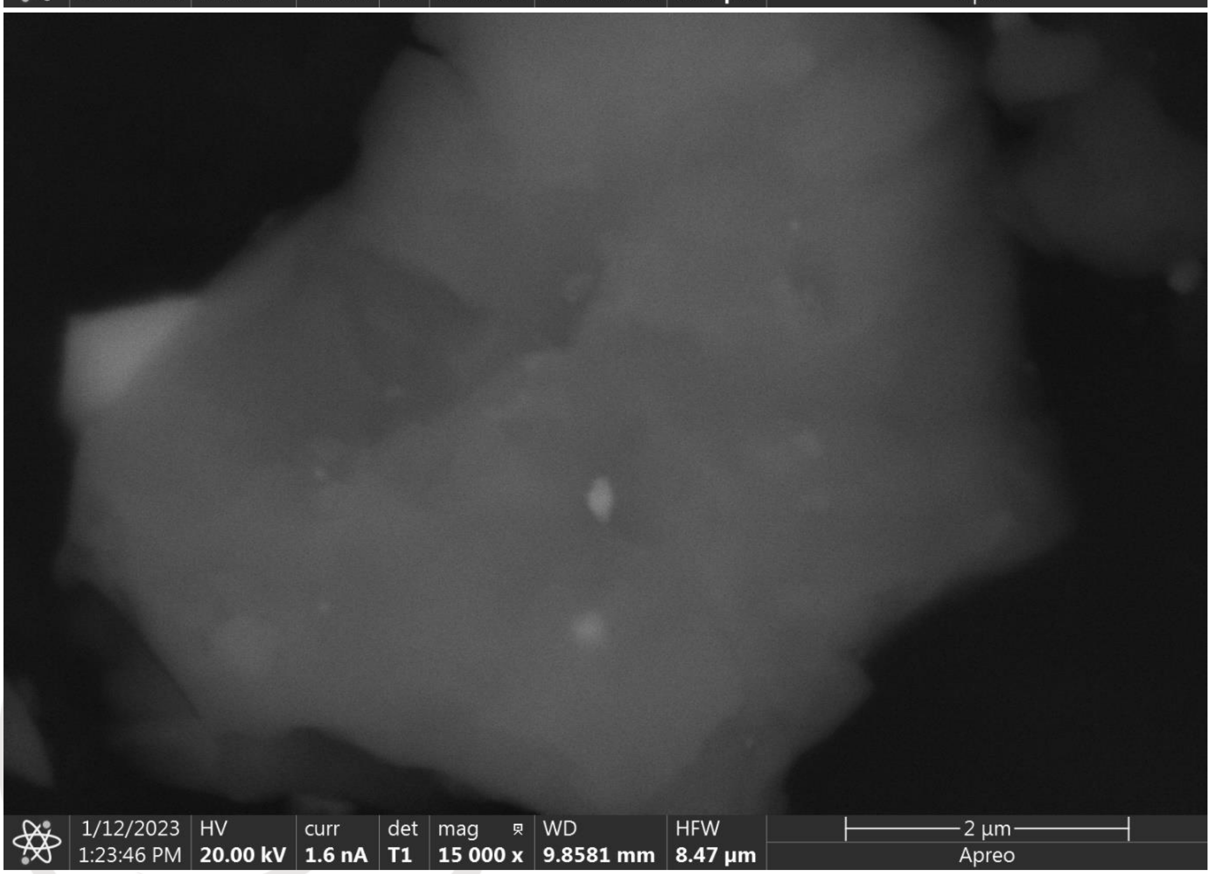
MTA, FRSC, FRAS, FGS

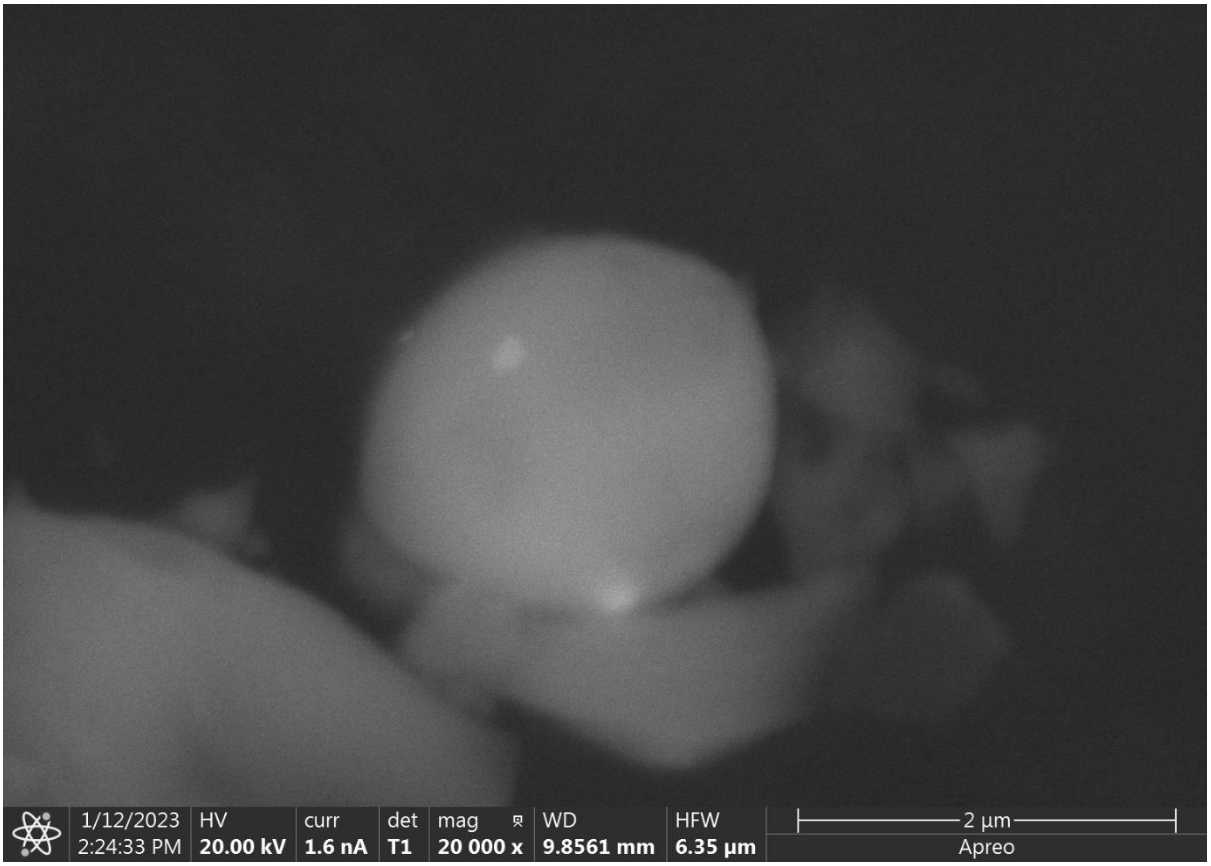
Research Professor and Senior Advisor
Director, Origins Research Institute
Research Centre for Astronomy & Earth Sciences

Professor of Geological Sciences (em.), University of Colorado at Boulder, USA
Guest Professor, Eötvös Loránd University of Science (ELTE), Budapest, Hungary
Ida Pfeiffer Professor and Senior Research Fellow, University of Vienna, Austria
A.v.Humboldt Research Professor, University of Jena, Germany

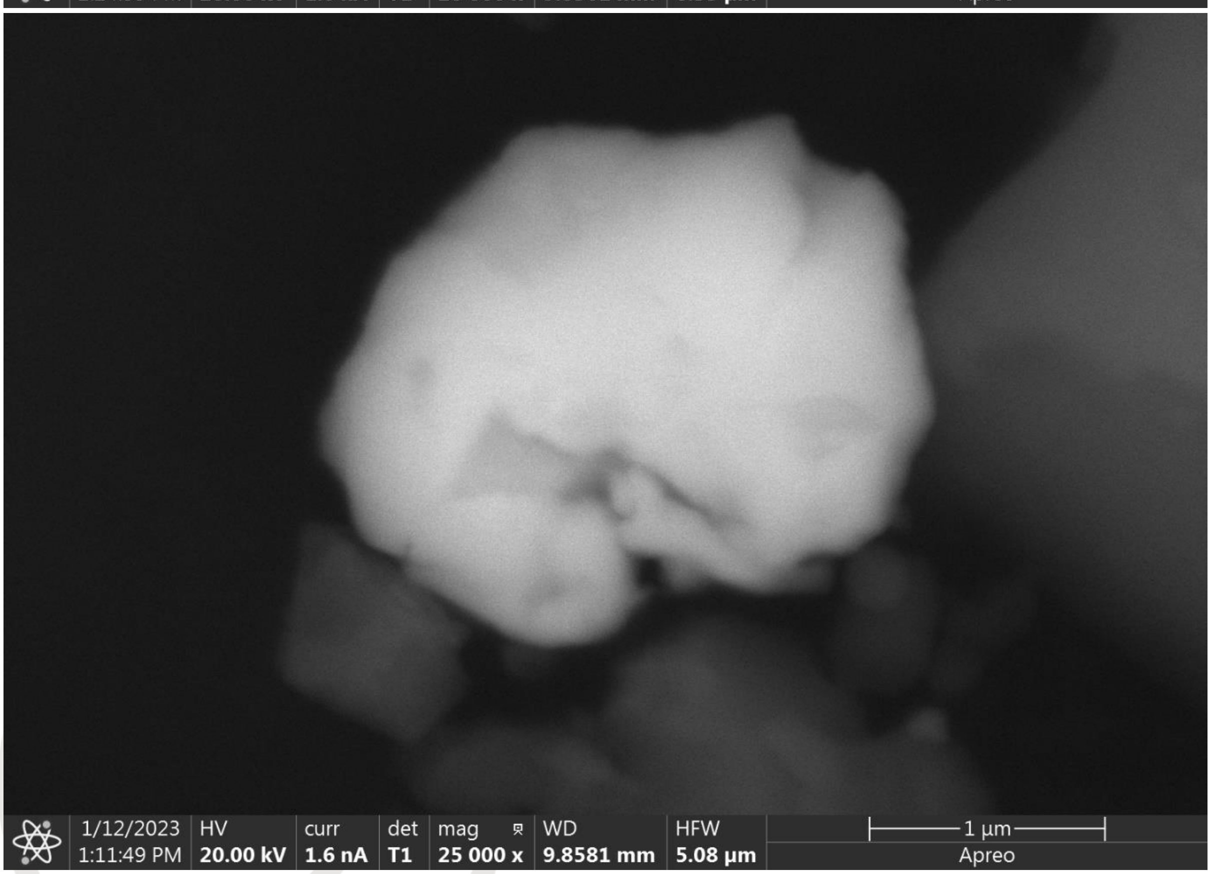
APPENDIX (details of each image, including labeling, as provided in the electronic annex to this report).







1/12/2023
2:24:33 PM
HV
20.00 kV
curr
1.6 nA
det
T1
mag
20 000 x
WD
9.8561 mm
HFW
6.35 µm
2 µm
Apreo



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det
T1
mag
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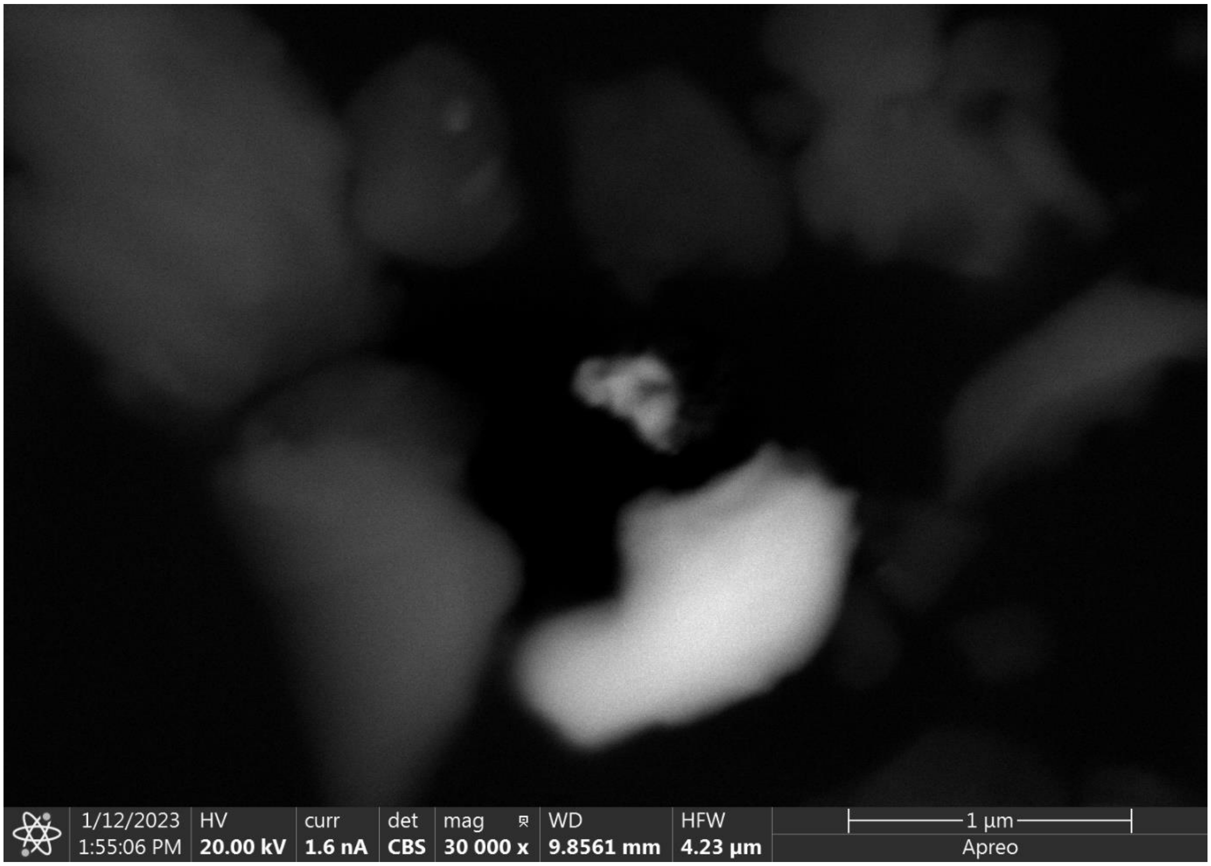
5.08 µm
1 µm
Apreo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det
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mag
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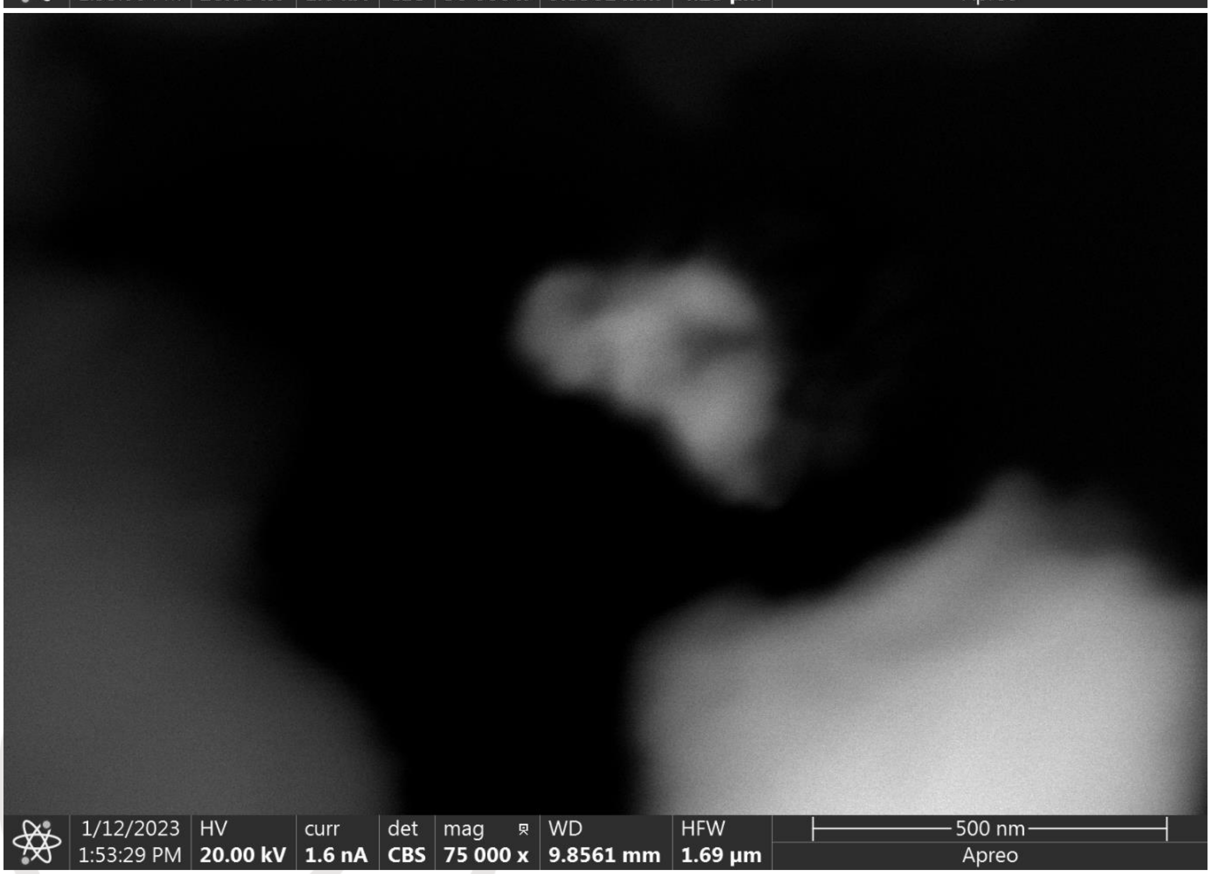
4.23 µm
1 µm
Apreo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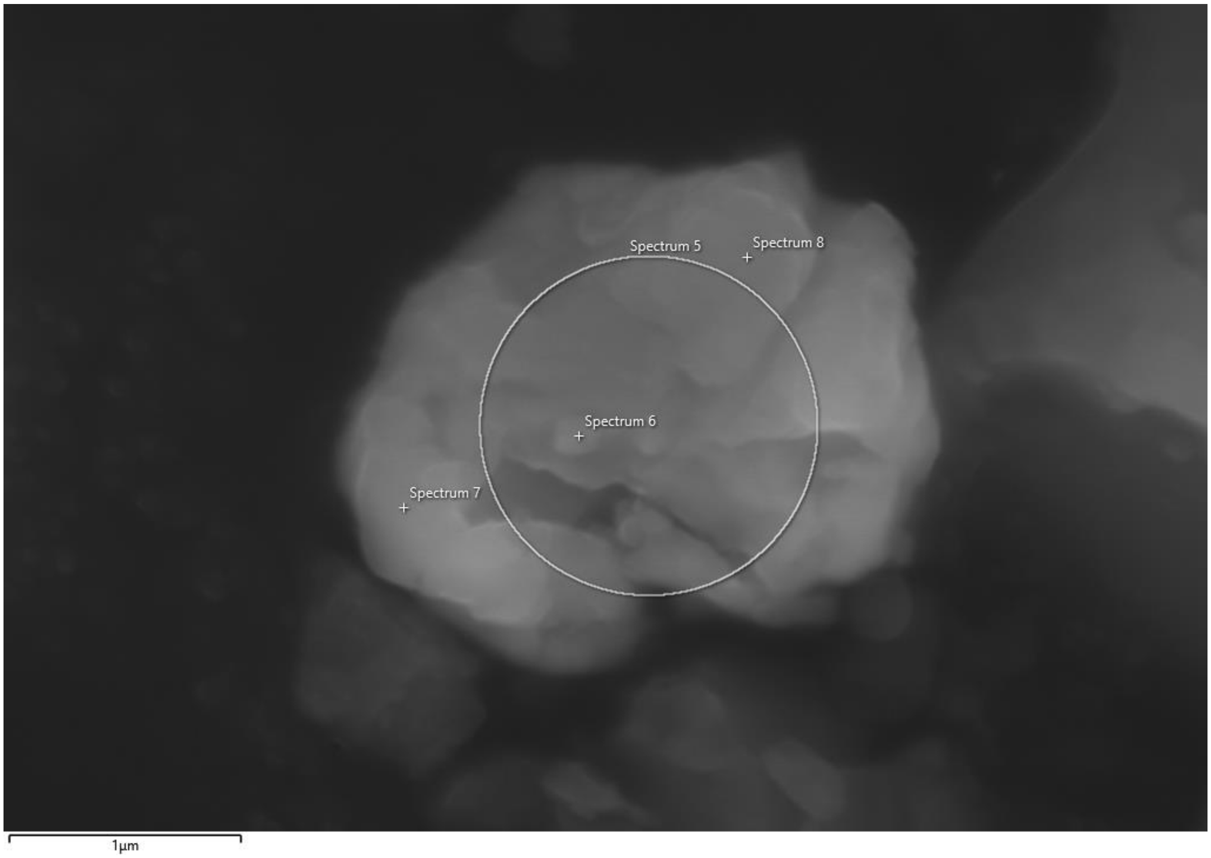
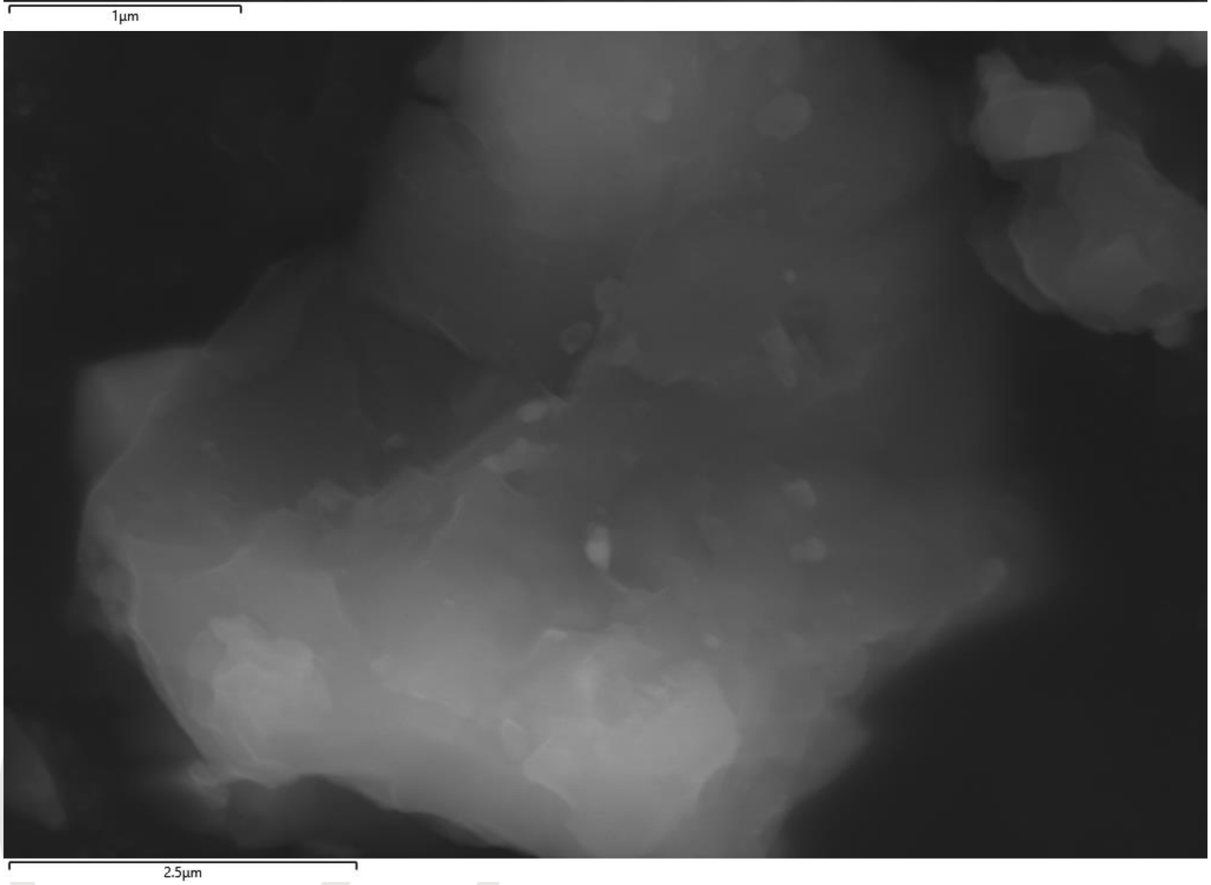
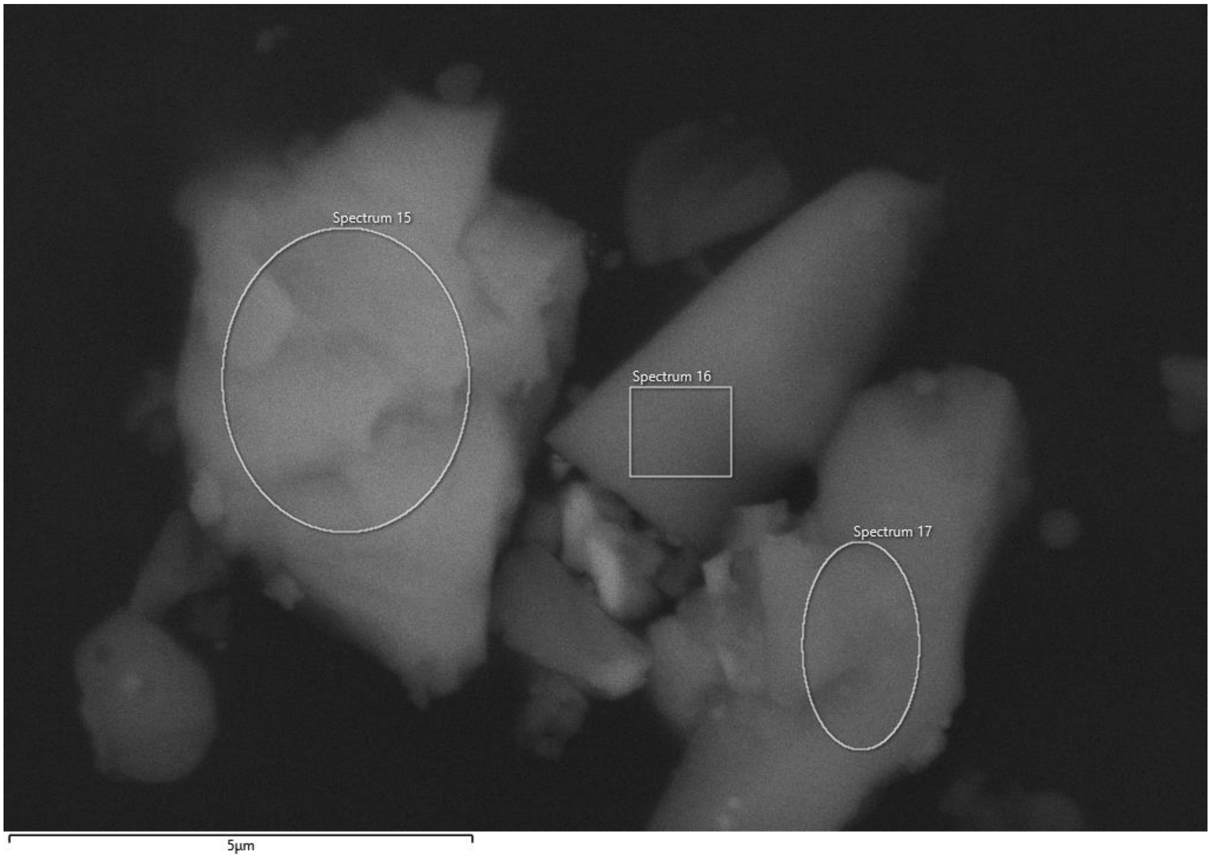
500 nm
Apreo


Spectrum 5
Spectrum 8
Spectrum 6
Spectrum 7
1µm


2.5µm


Spectrum 9
Spectrum 10
Spectrum 11
Spectrum 12
2.5µm


Spectrum 13
Spectrum 14
2.5µm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Spectrum 16
Spectrum 17
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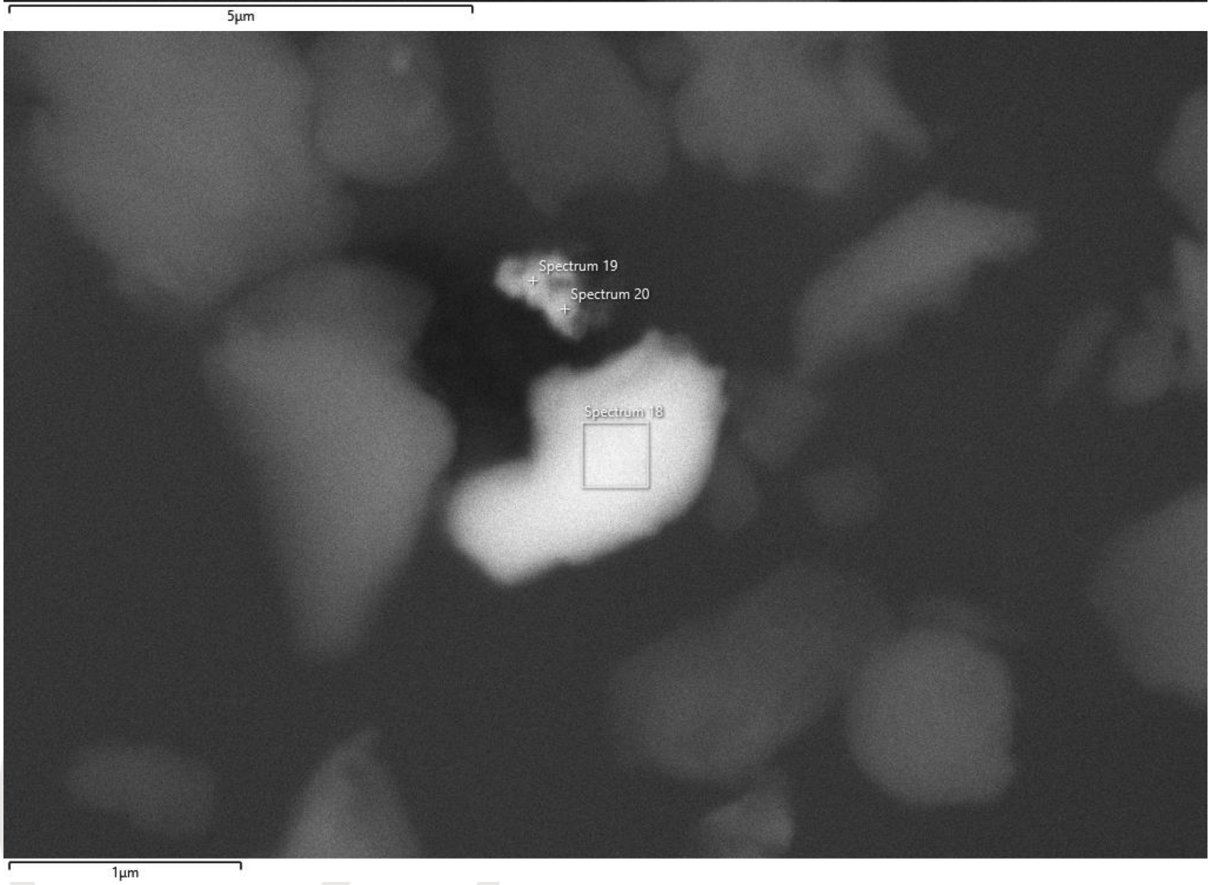
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Spectrum 20
Spectrum 18
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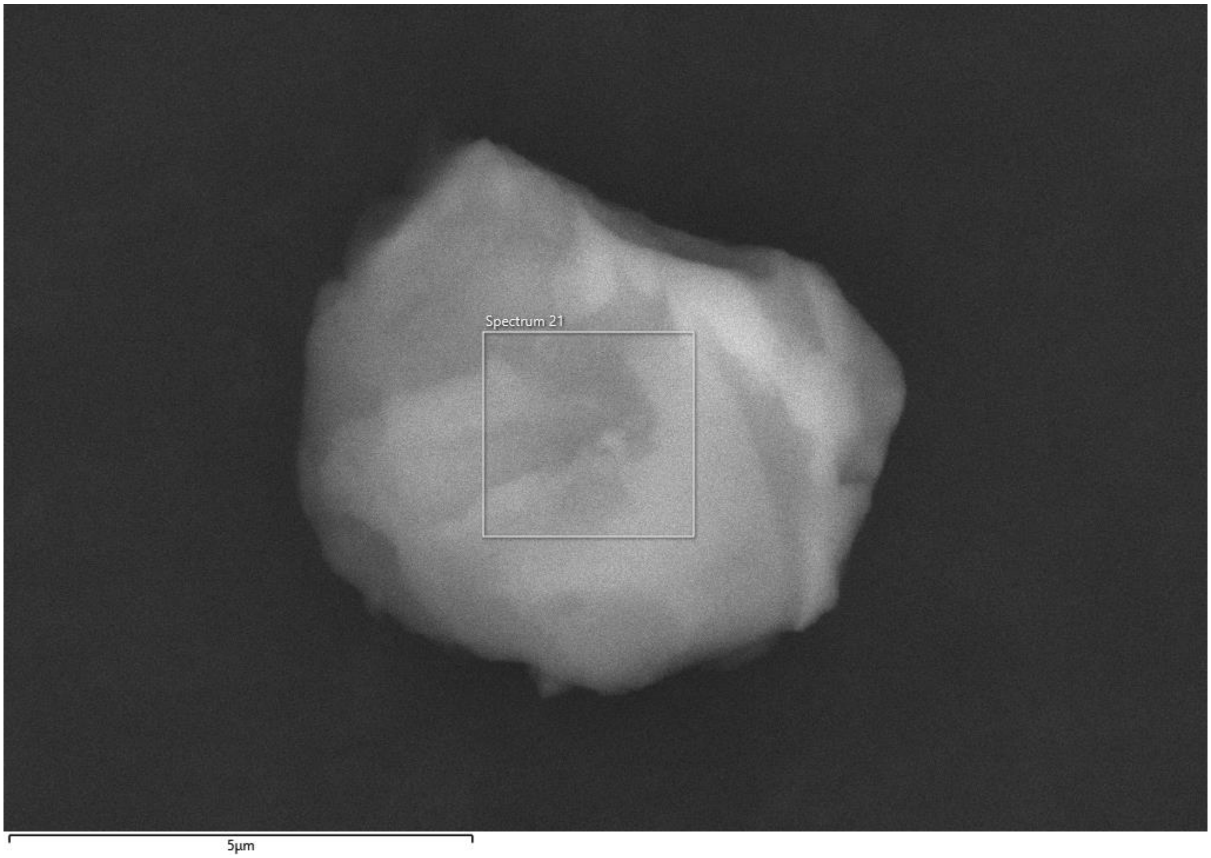
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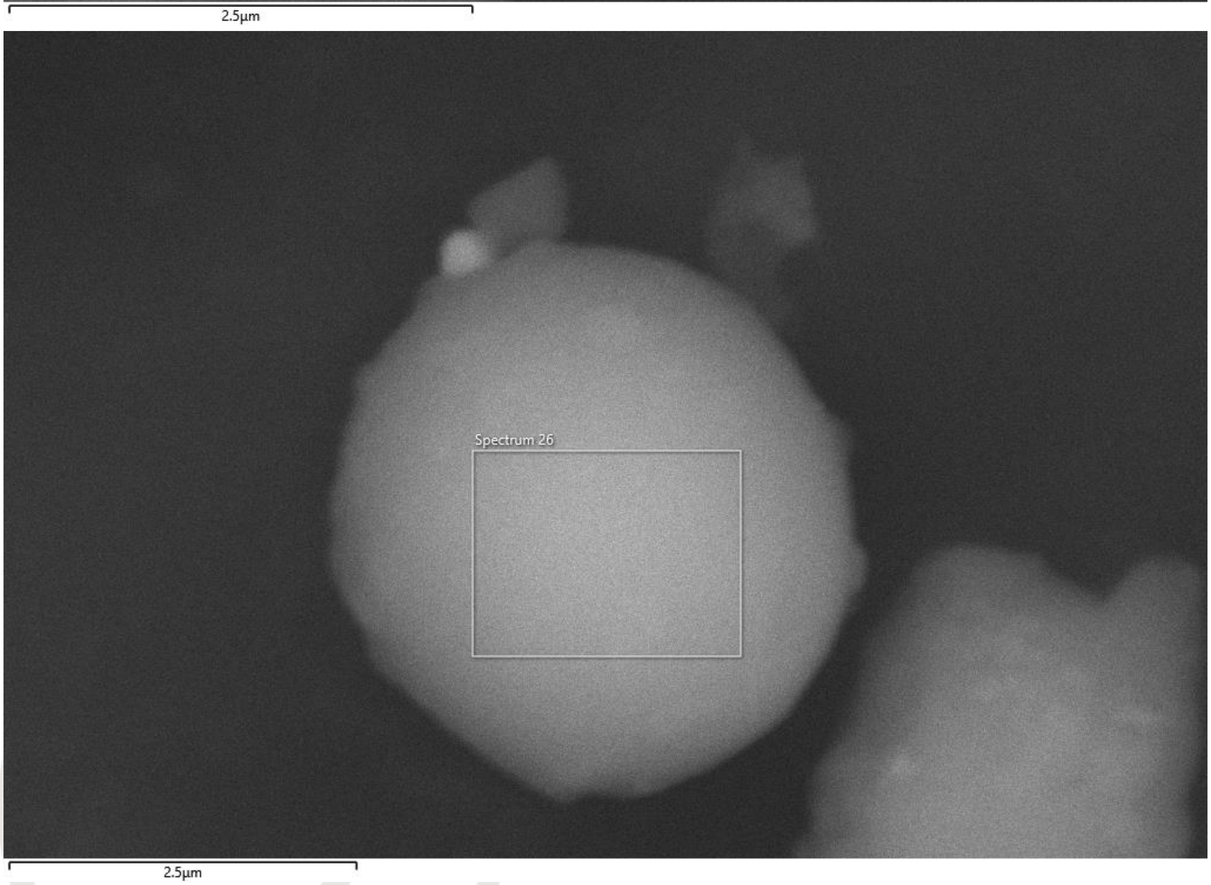
Spectrum 22
5µm


Spectrum 25
Spectrum 23
Spectrum 24
2.5µm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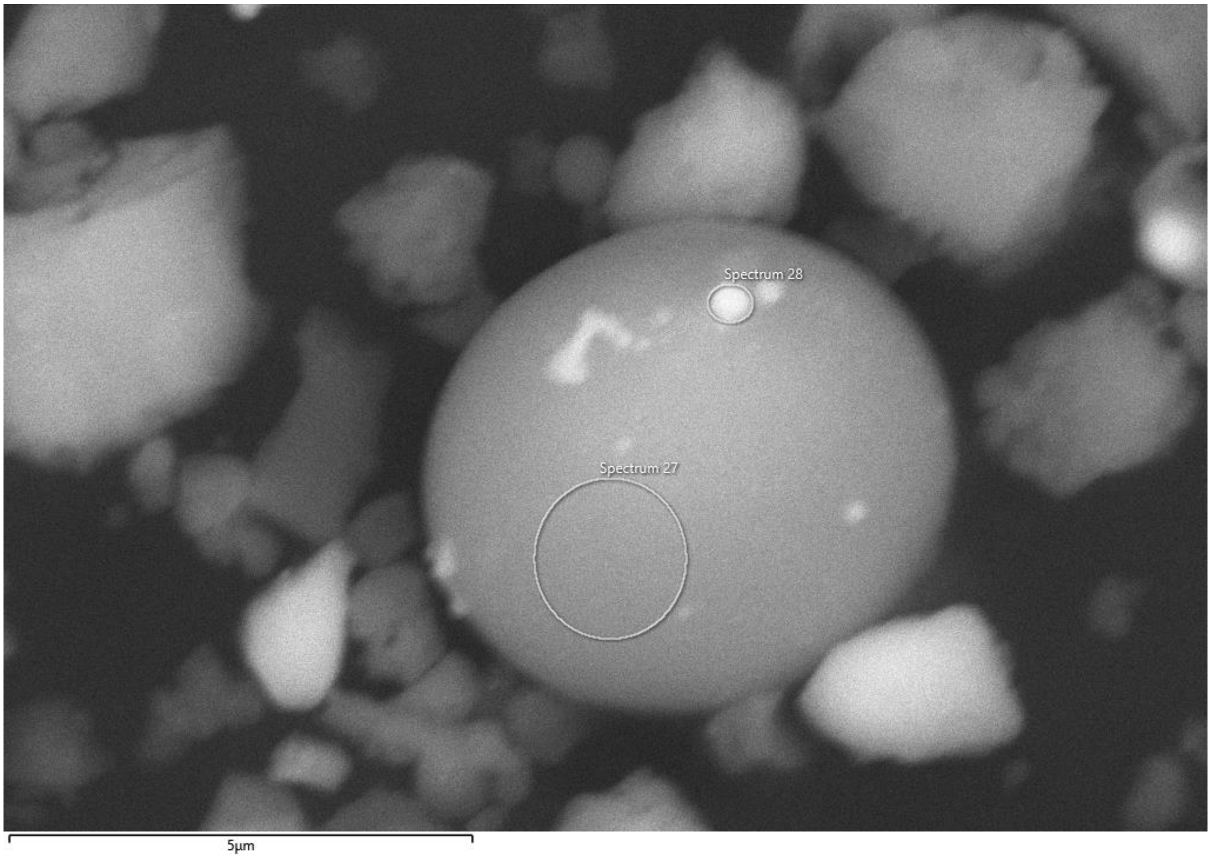
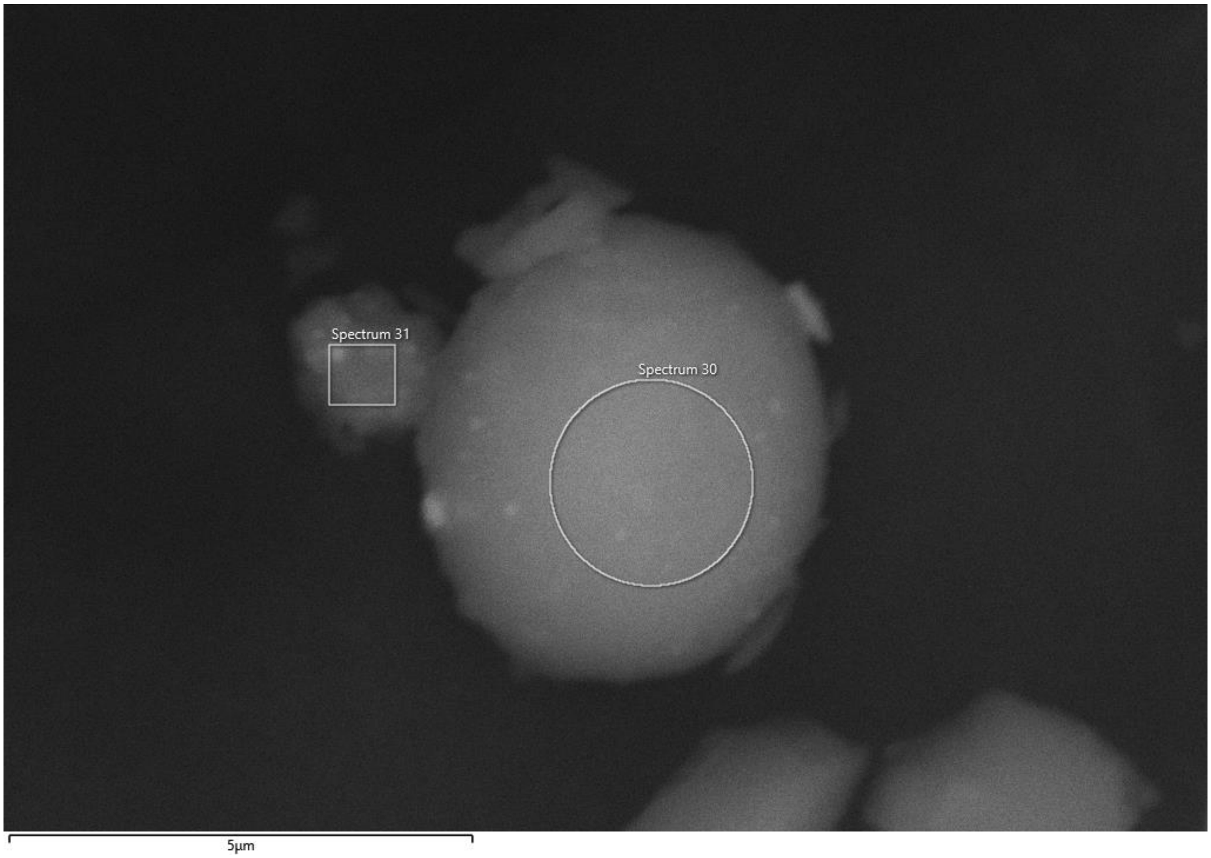

Spectrum 28
Spectrum 27
5µm


Spectrum 29
2.5µm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Spectrum 30
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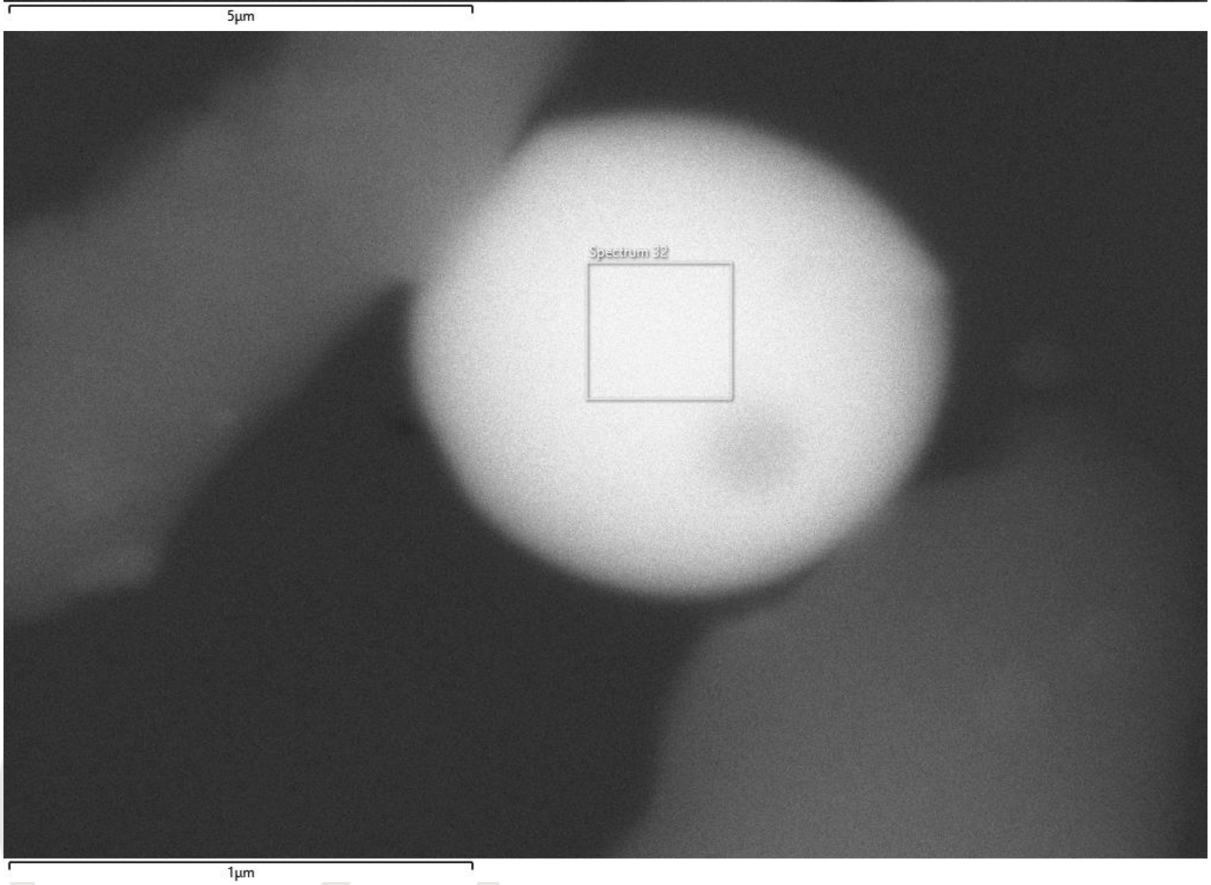
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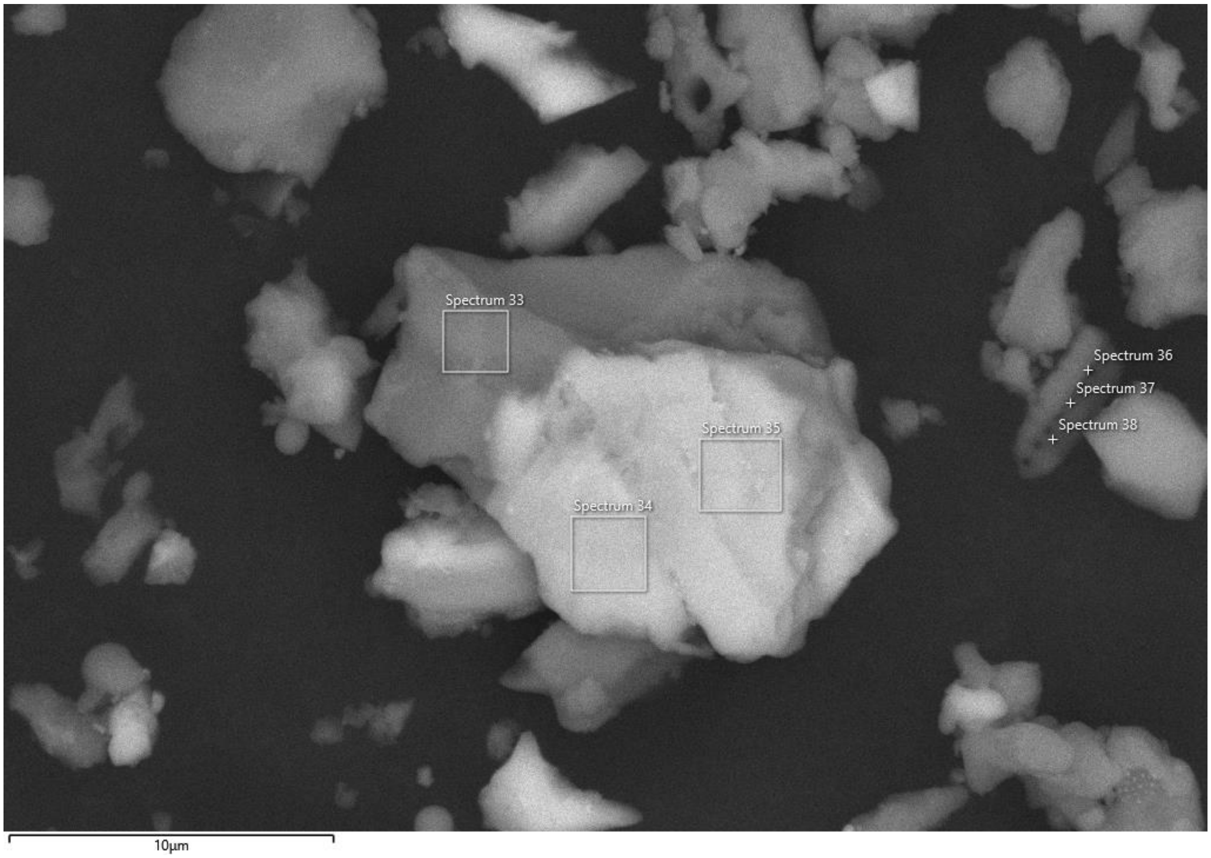
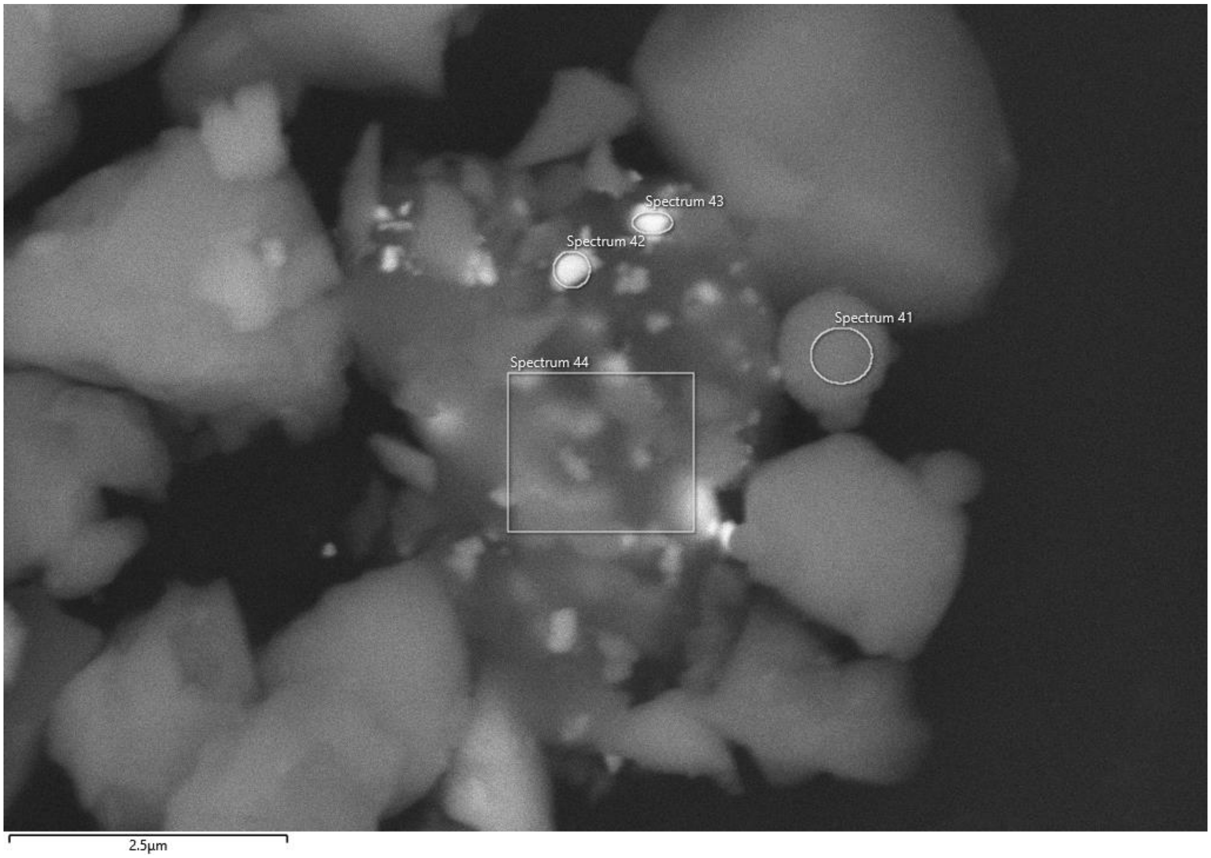

Spectrum 33
Spectrum 34
Spectrum 35
Spectrum 36
Spectrum 37
Spectrum 38
10µm


Spectrum 39
Spectrum 40
2.5µm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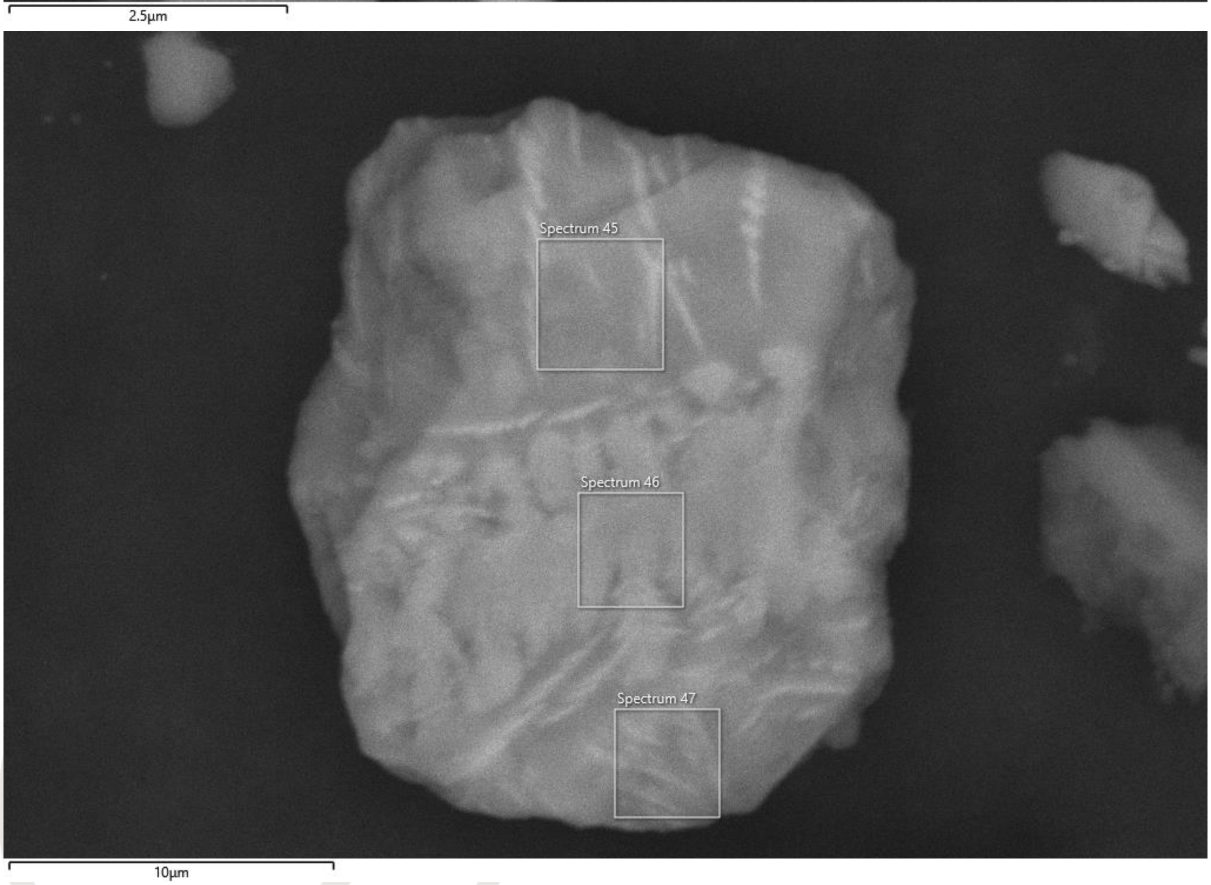
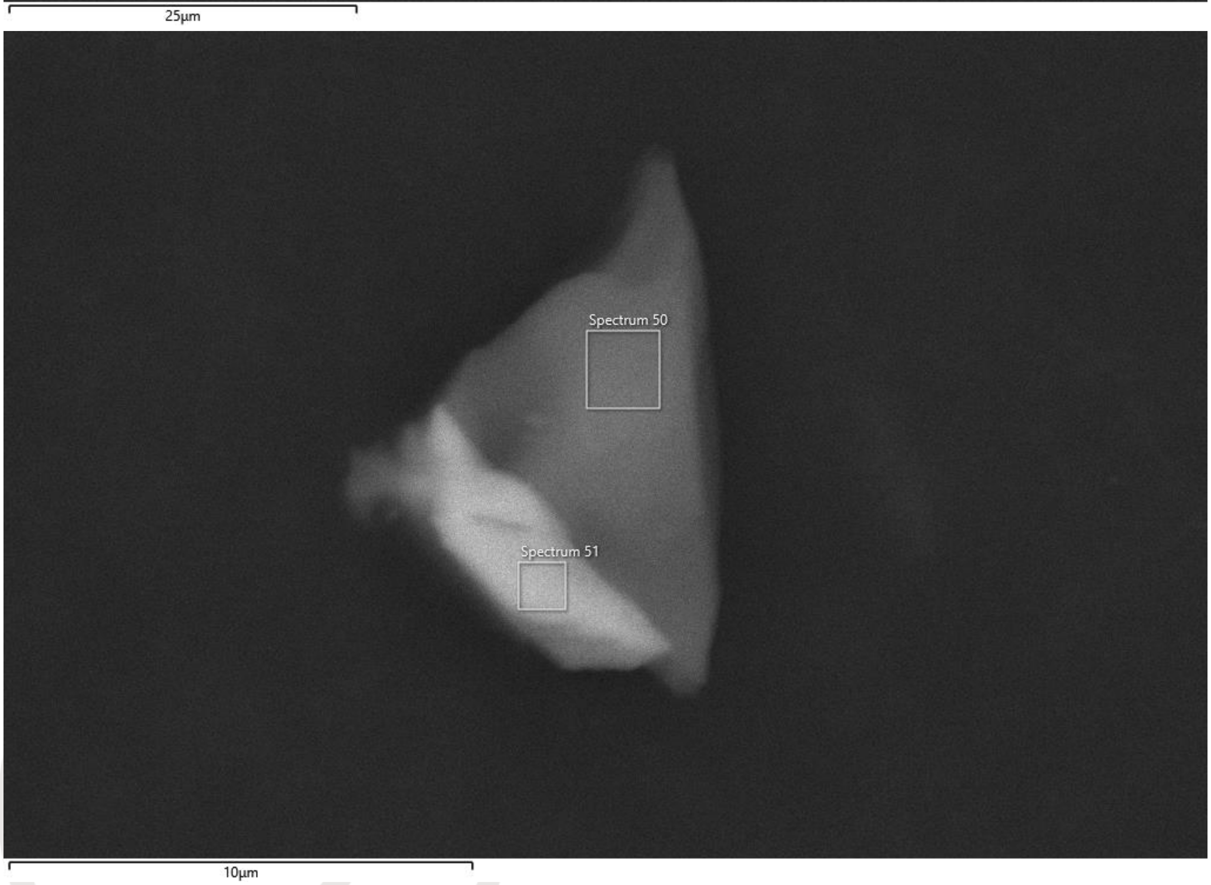
Spectrum 42
Spectrum 41
Spectrum 44
2.5µm


Spectrum 45
Spectrum 46
Spectrum 47
10µm


Spectrum 48
Spectrum 49
25µm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Spectrum 51
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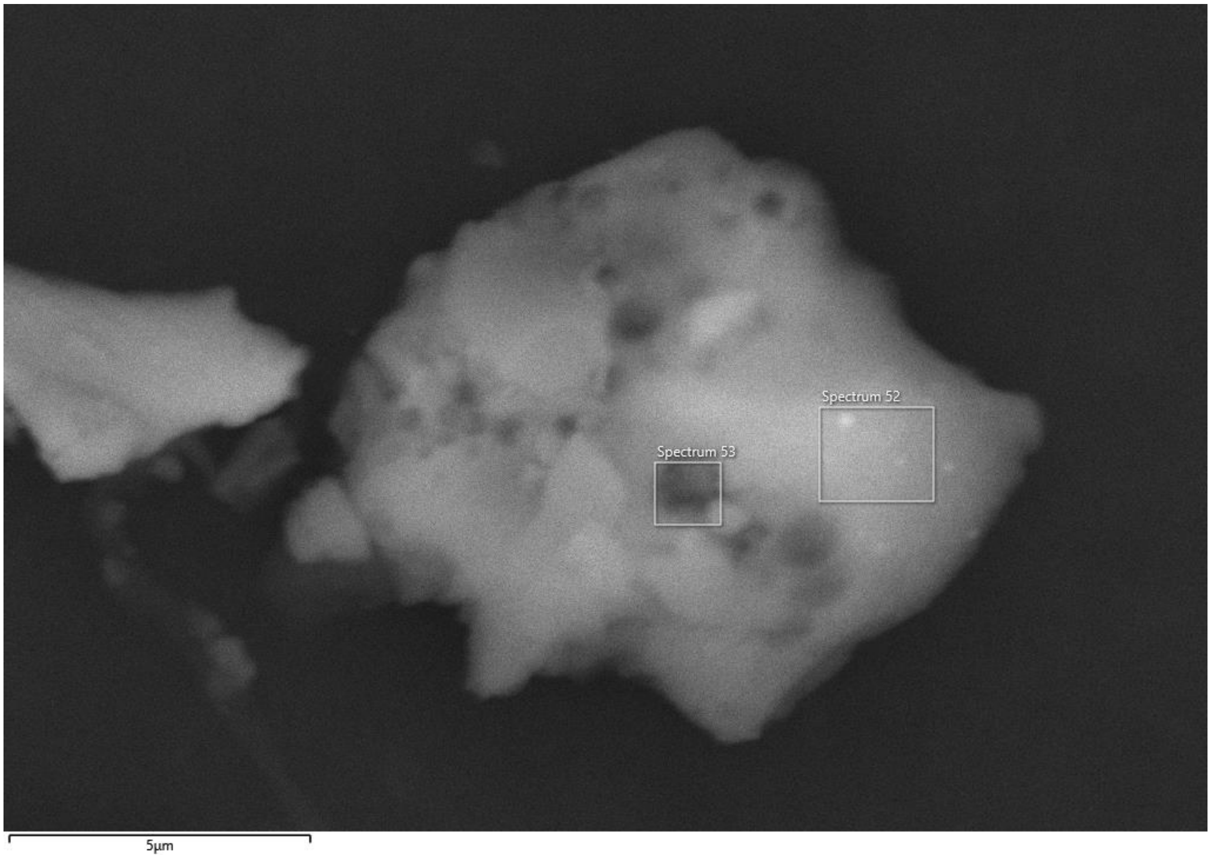
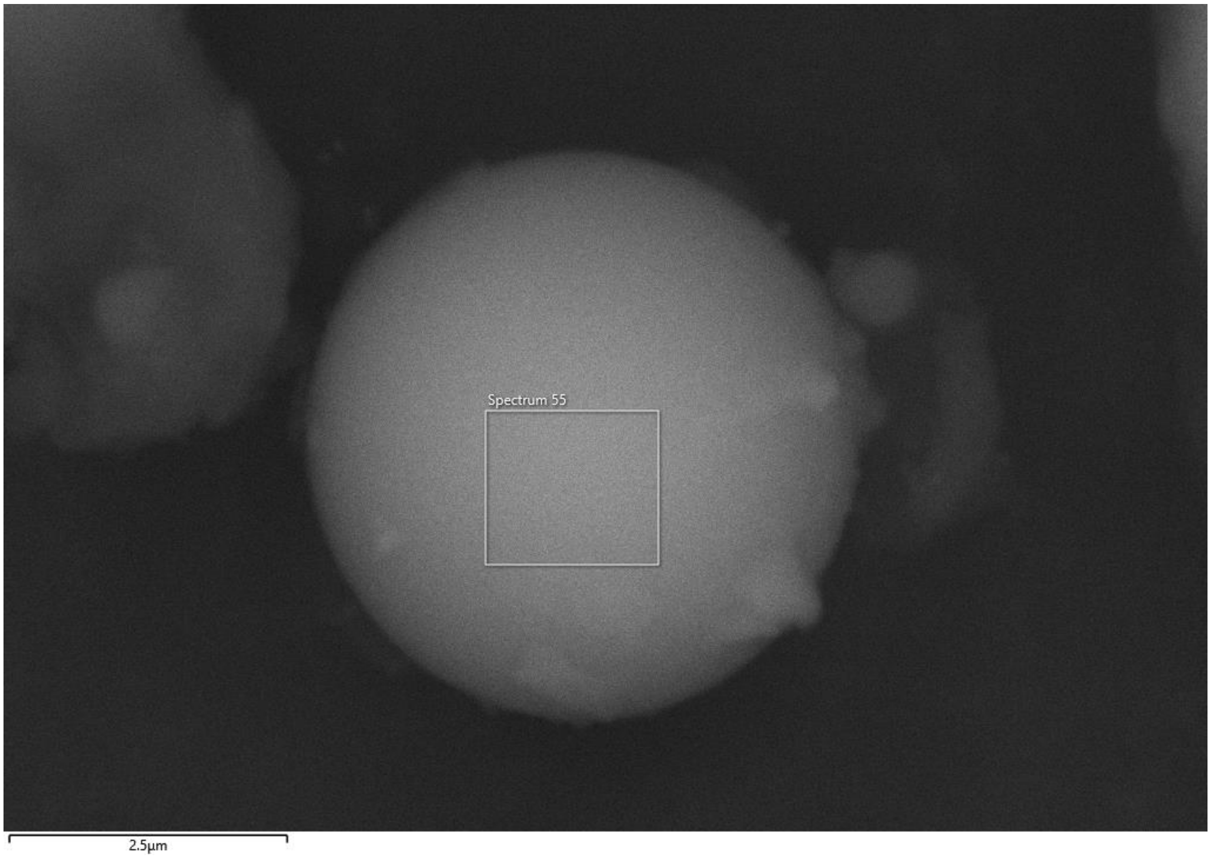

Spectrum 52
Spectrum 53
5μm


Spectrum 54
10μm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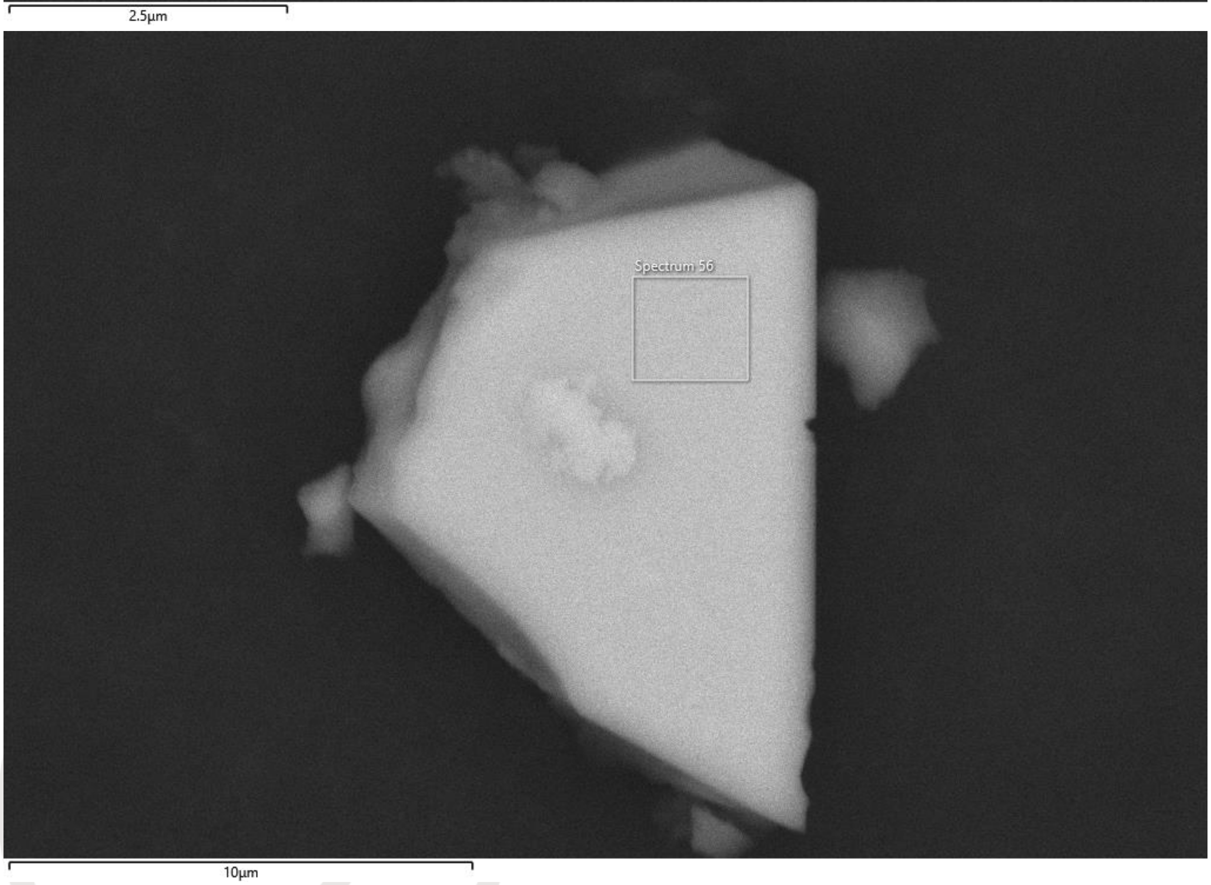
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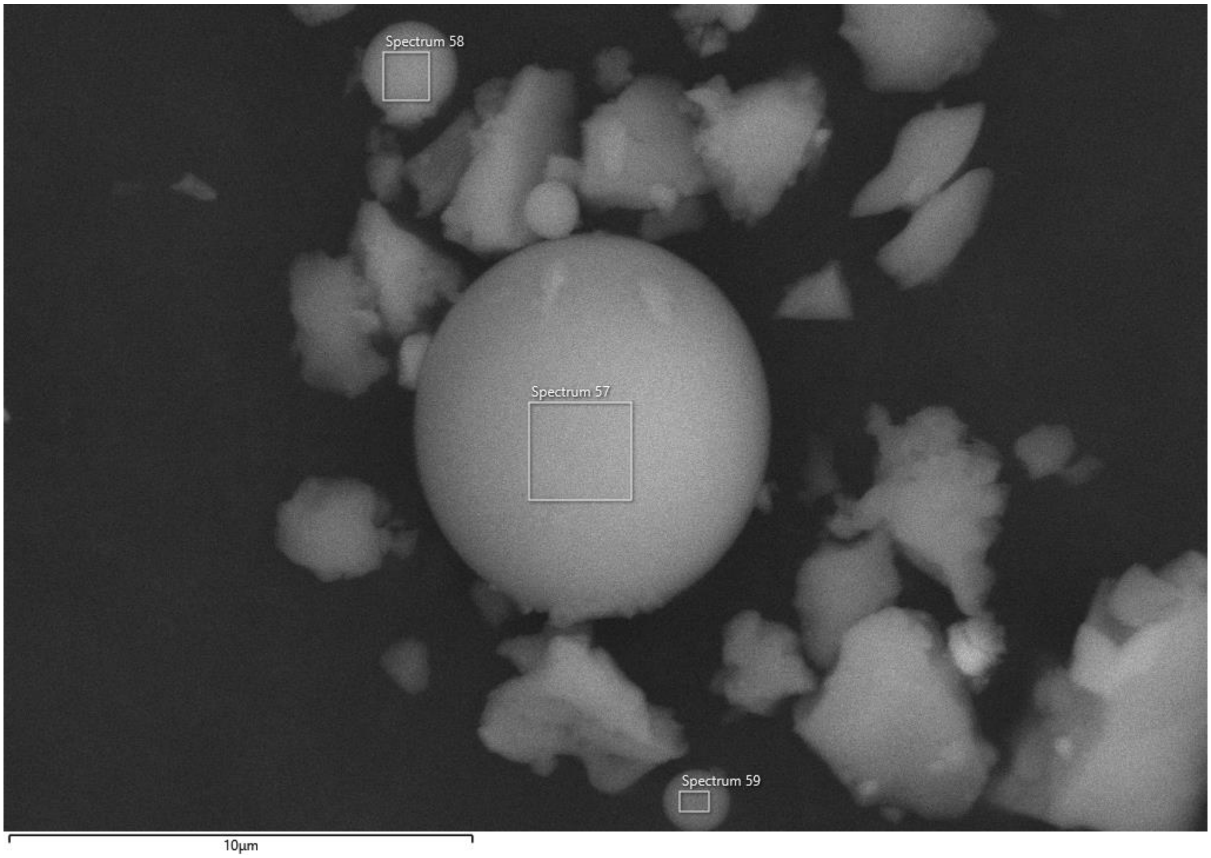
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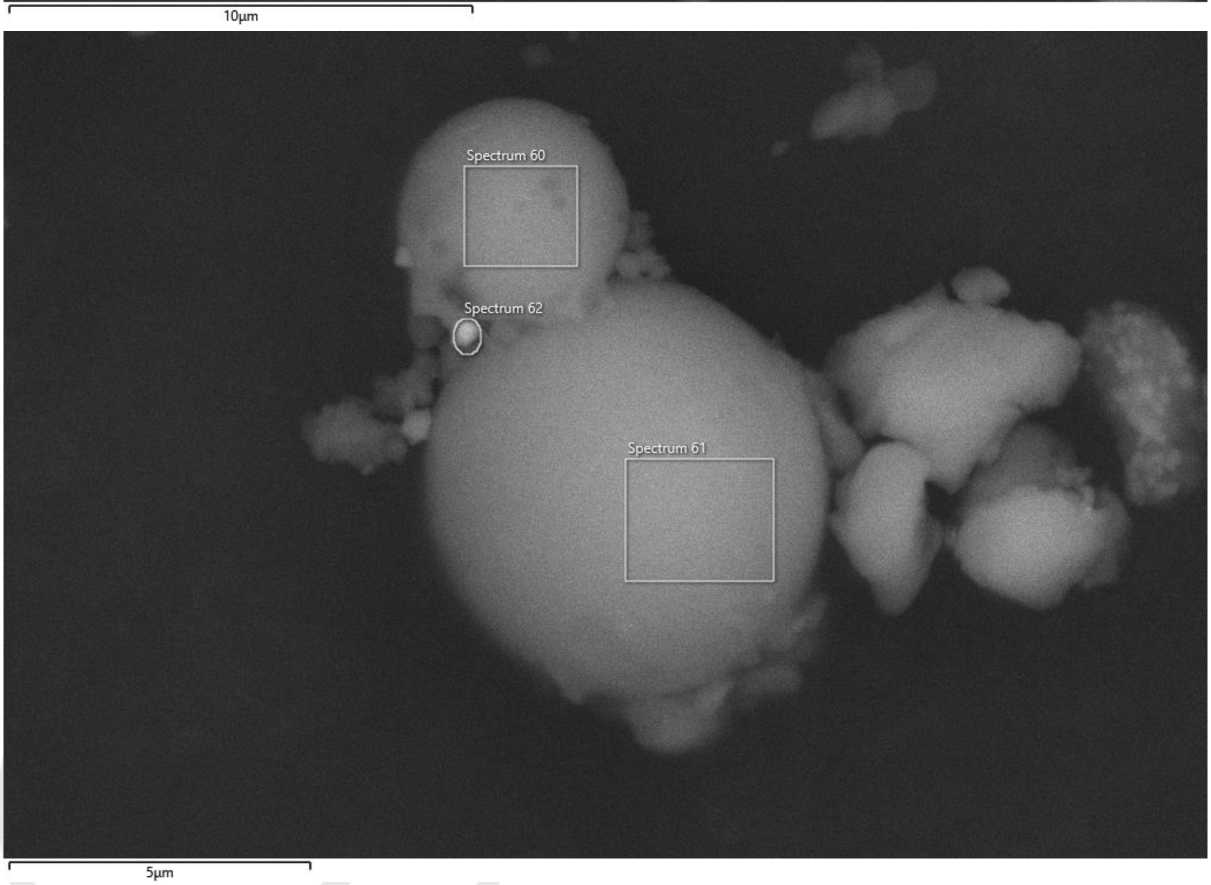
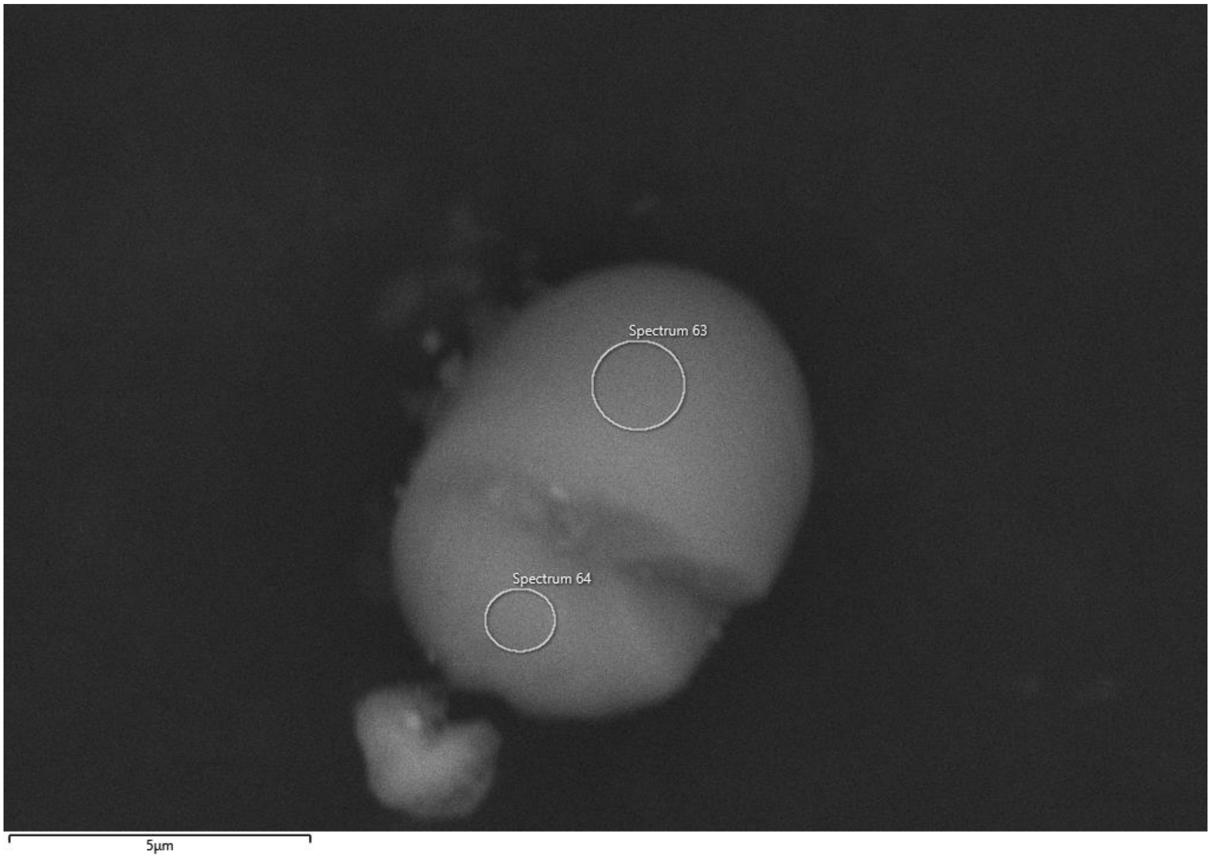
Spectrum 57
Spectrum 59
10µm


Spectrum 60
Spectrum 62
Spectrum 61
5µm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Spectrum 64
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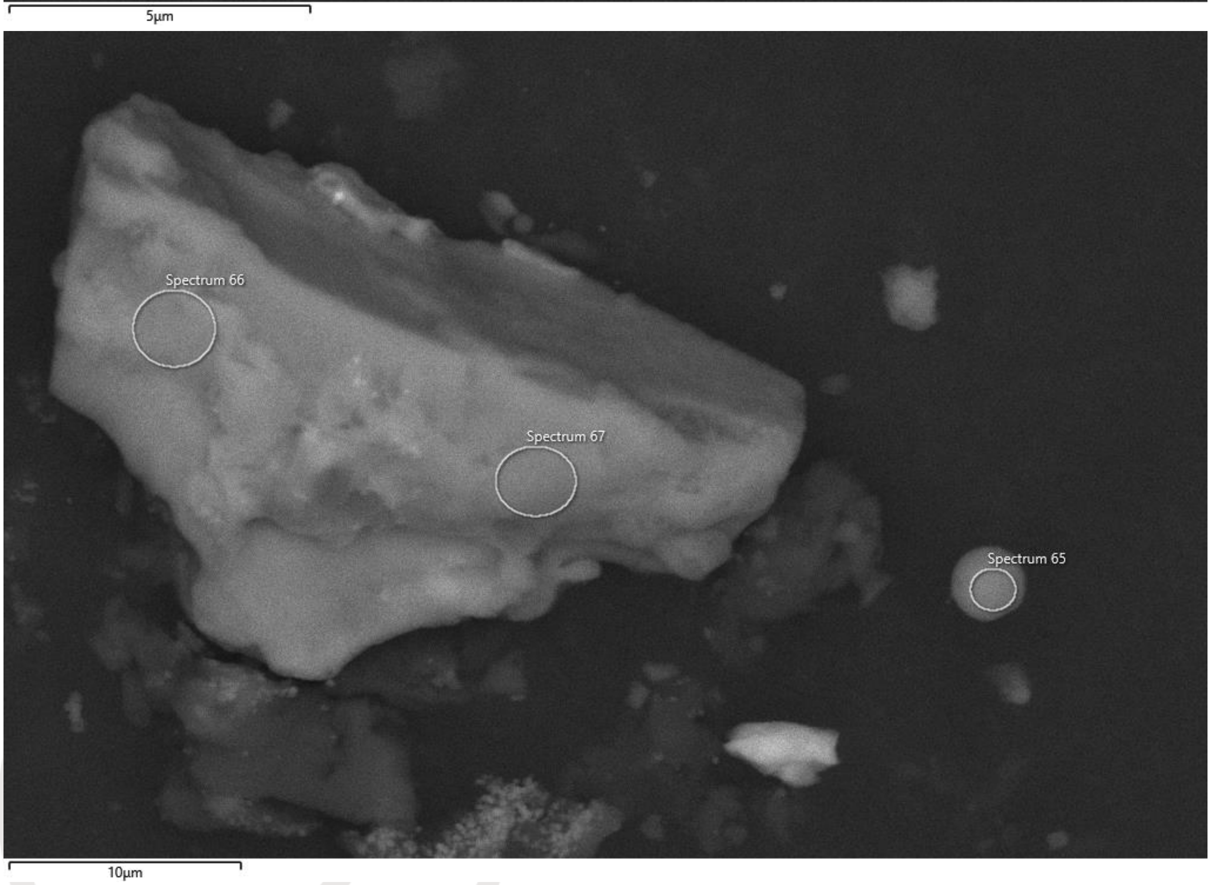
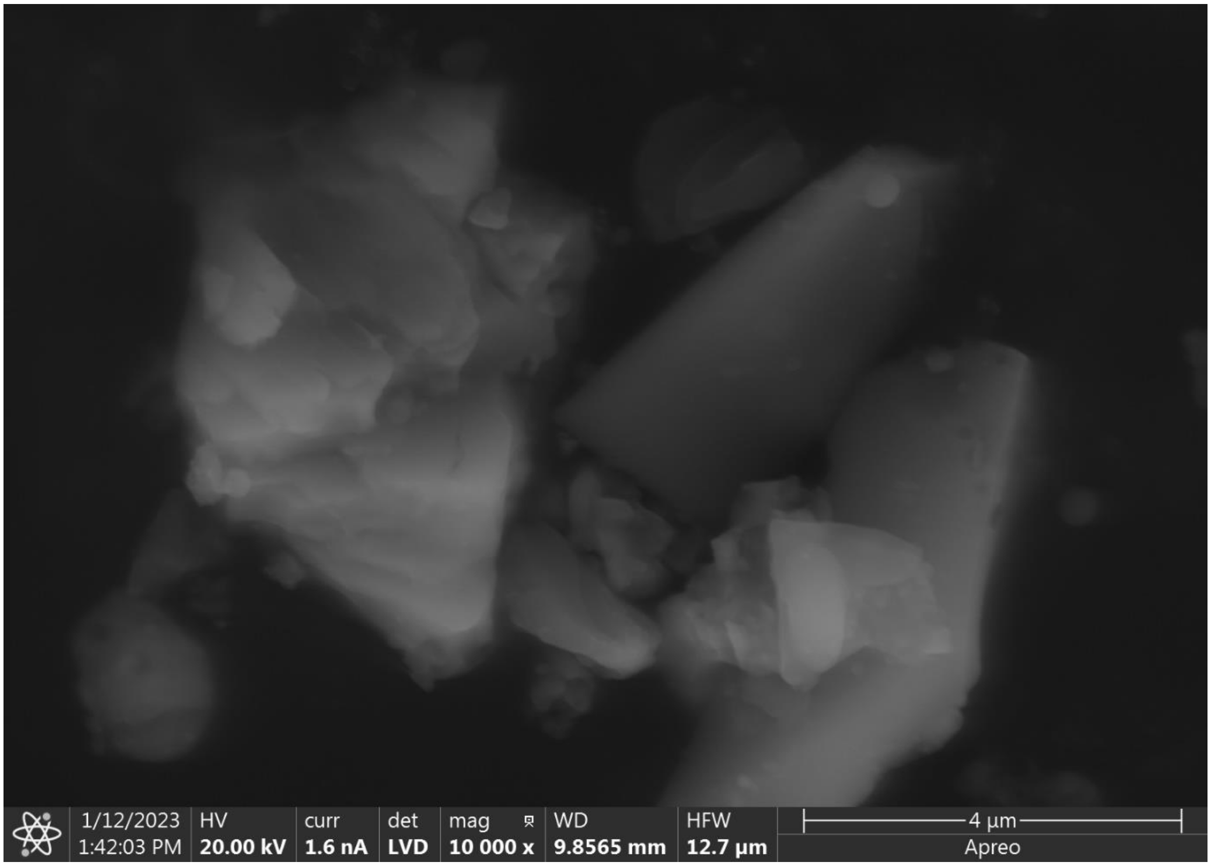

Spectrum 66
Spectrum 67
Spectrum 65
10µm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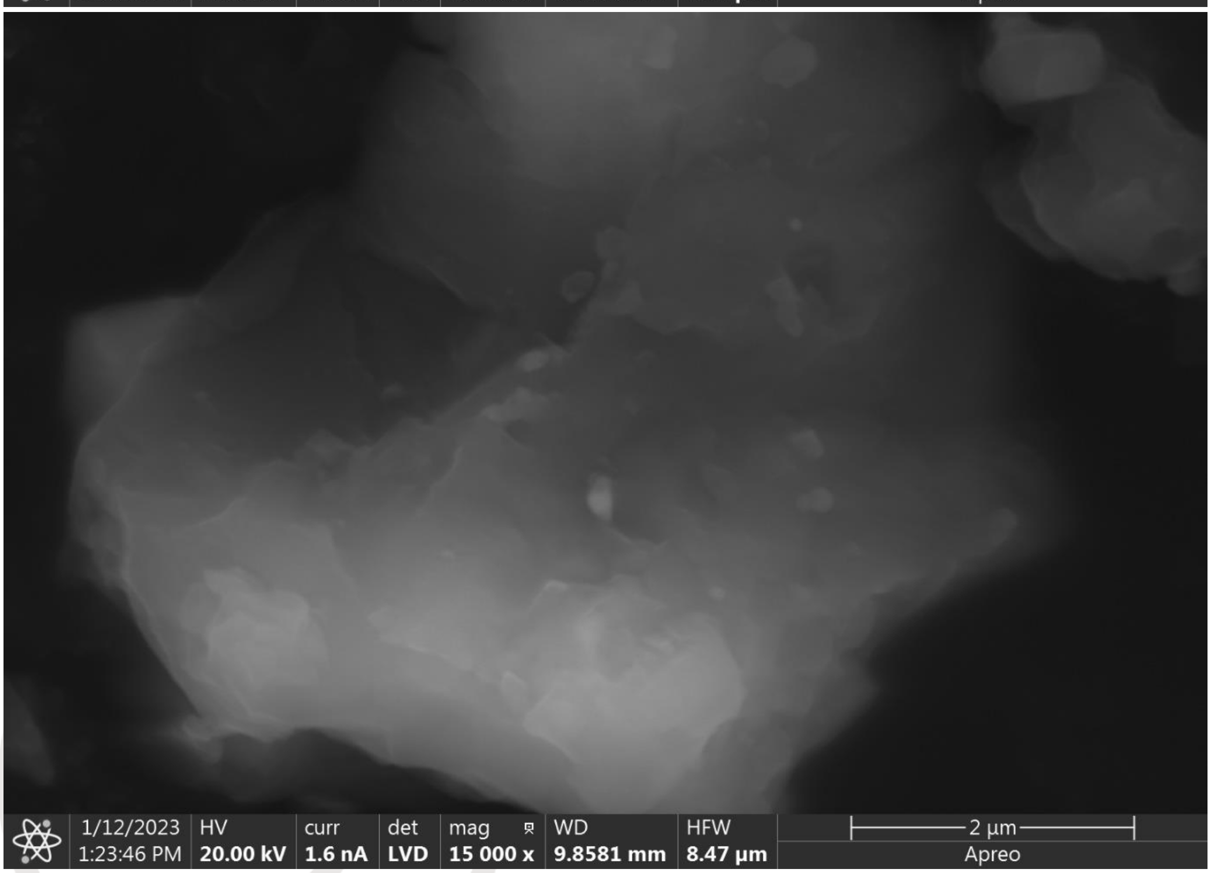
12.7 µm
4 µm
Apreo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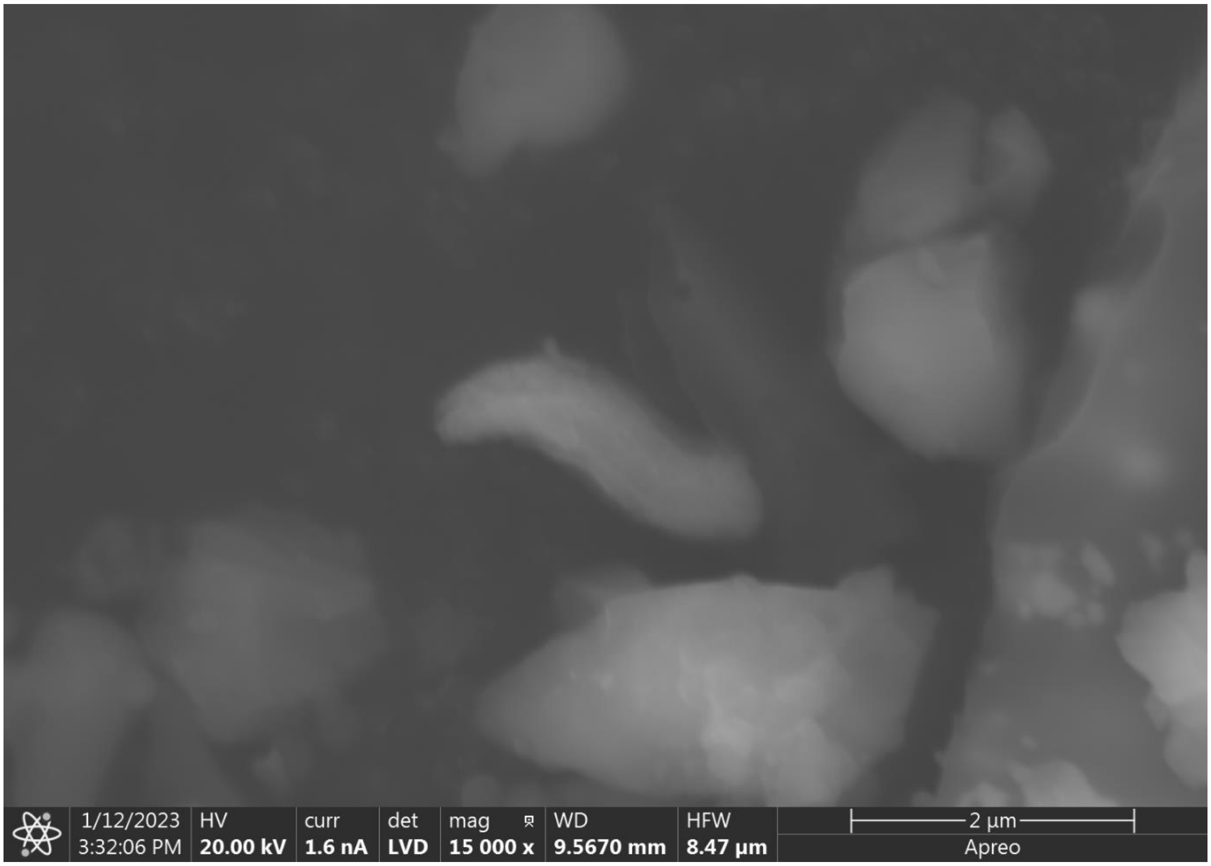
8.47 µm
2 µm
Apreo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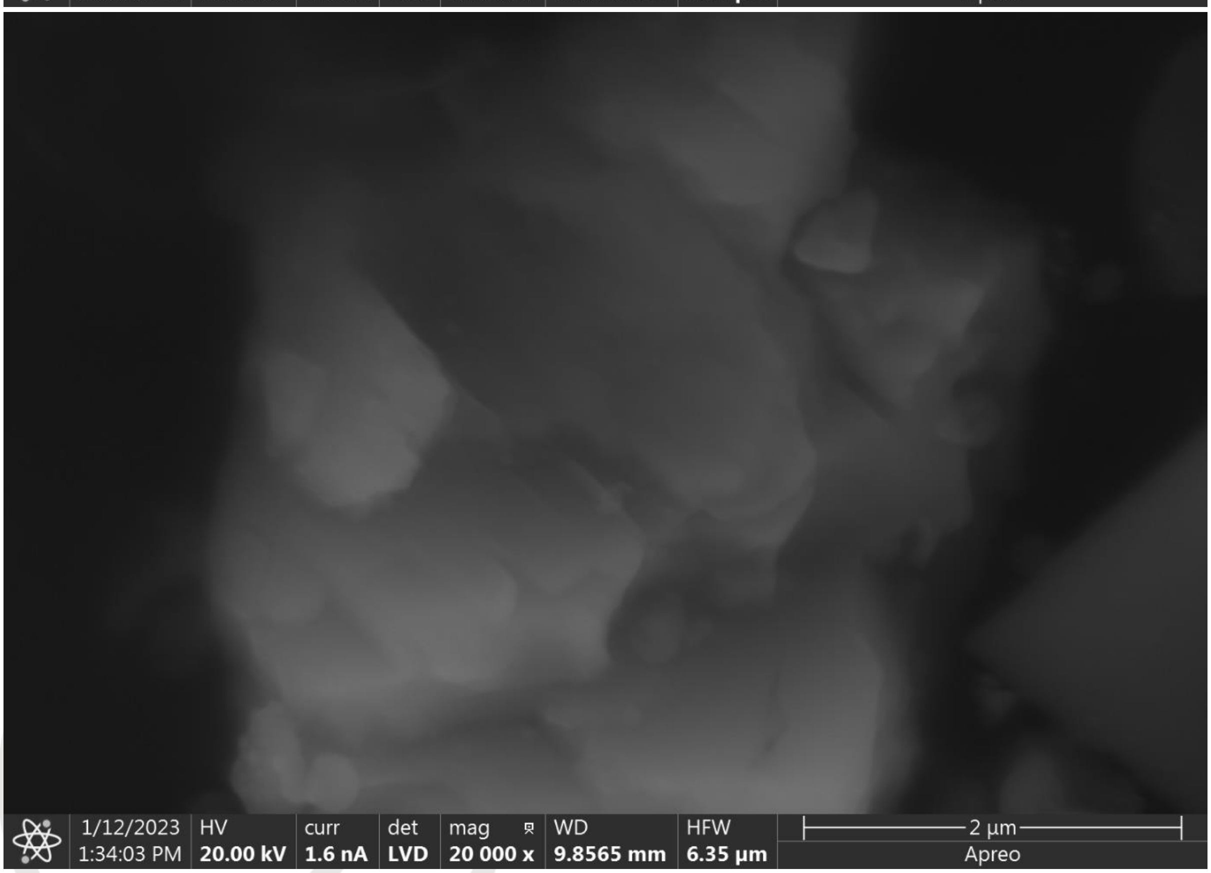
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det
LVD
mag
20 000 x
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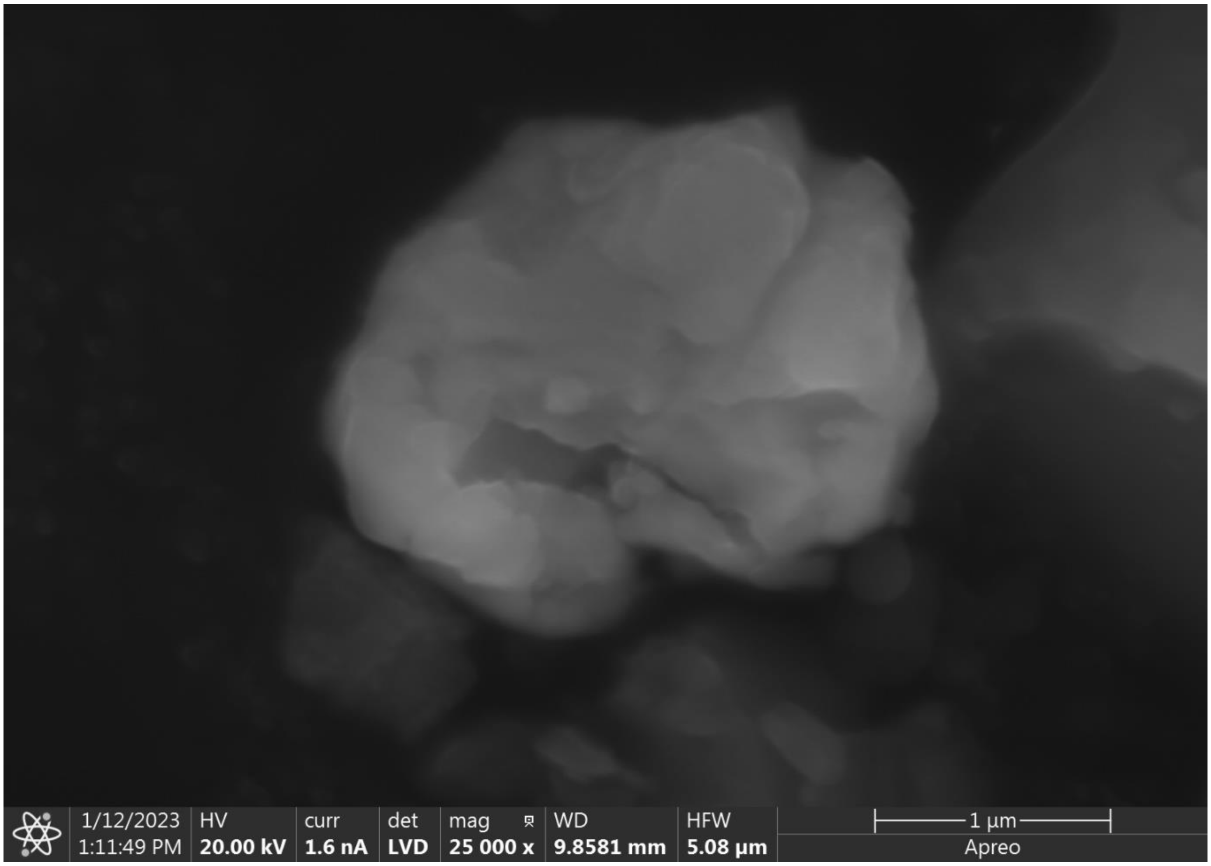
9.8565 mm
HFW
6.35 µm
2 µm
Apreo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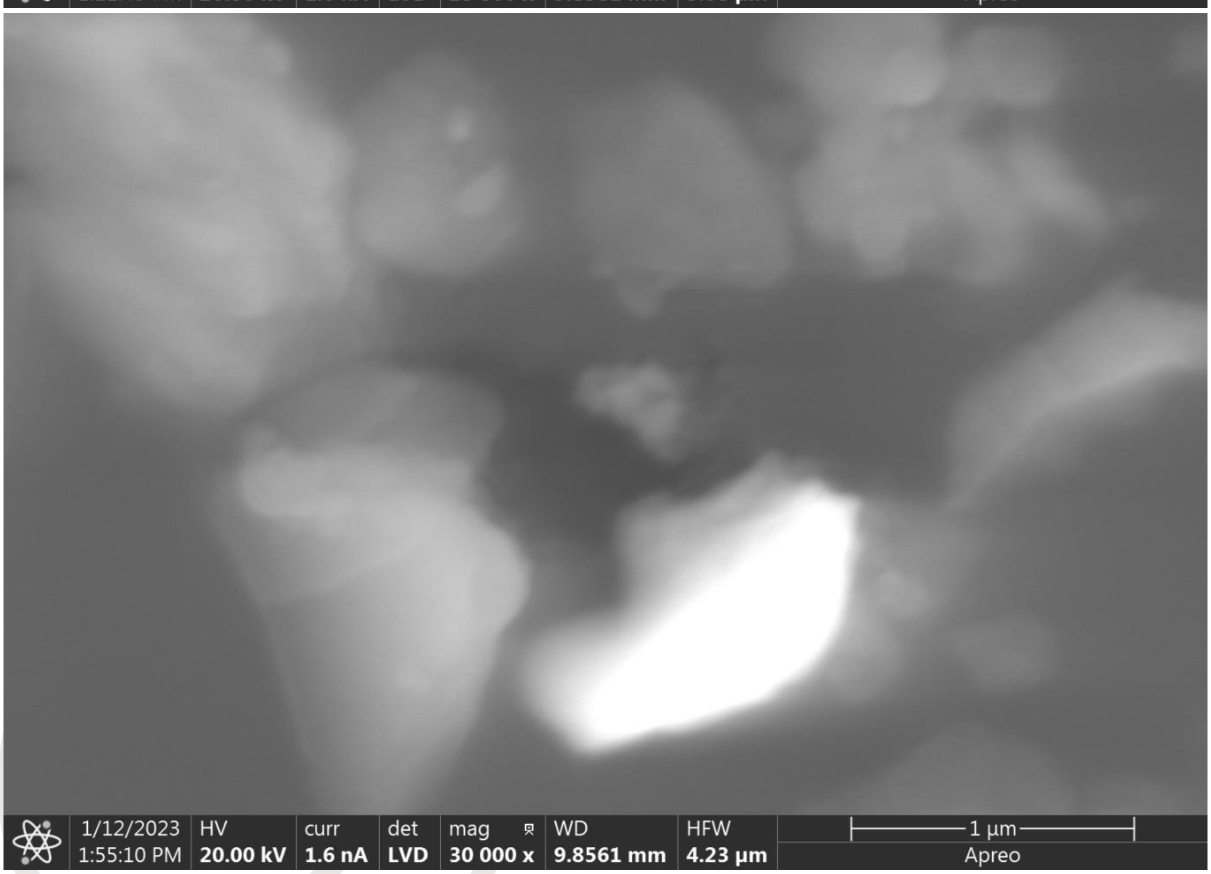
curr 1.6 nA
det LVD
mag 25 000 x
WD 9.8581 mm
HFW 5.08 µm
1 µm
Apreo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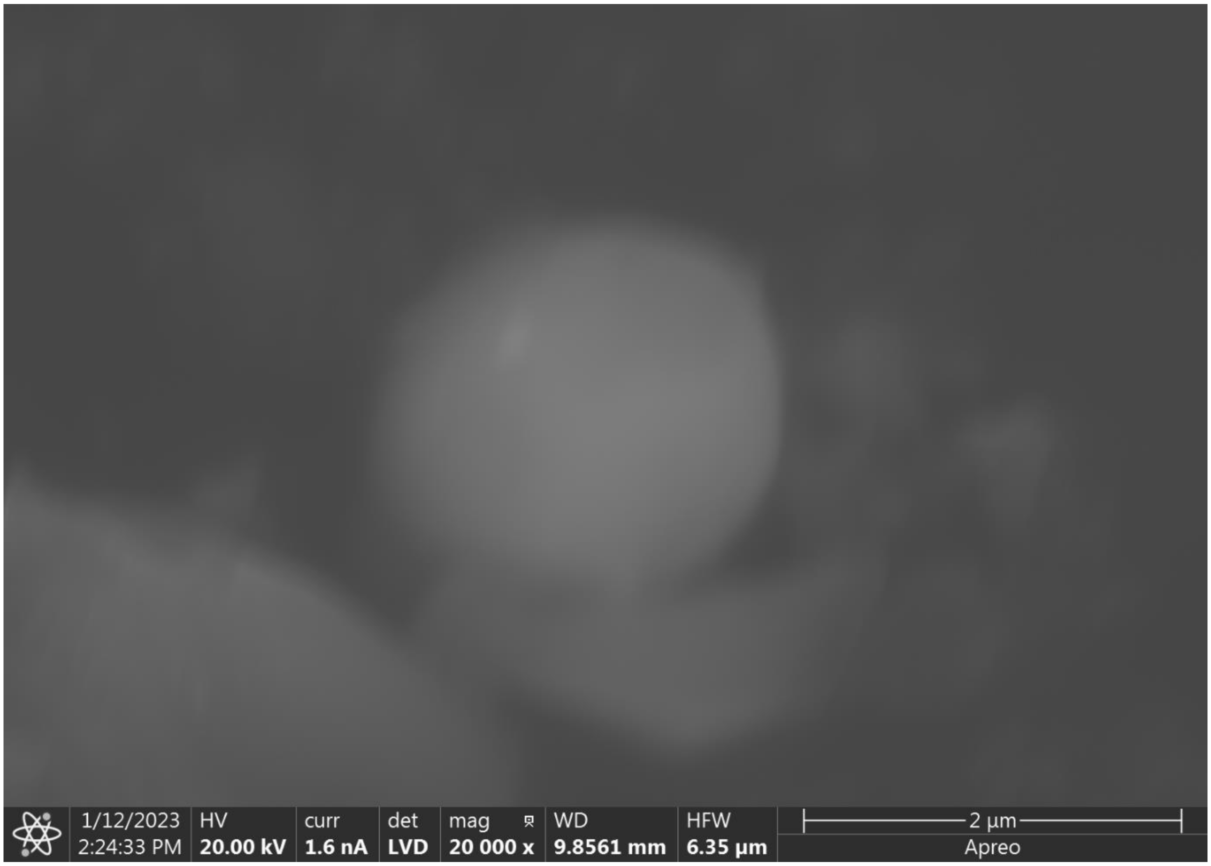
det LVD
mag 30 000 x
WD 9.8561 mm
HFW 4.23 µm
1 µm
Apreo


1/12/2023
2:24:33 PM
HV
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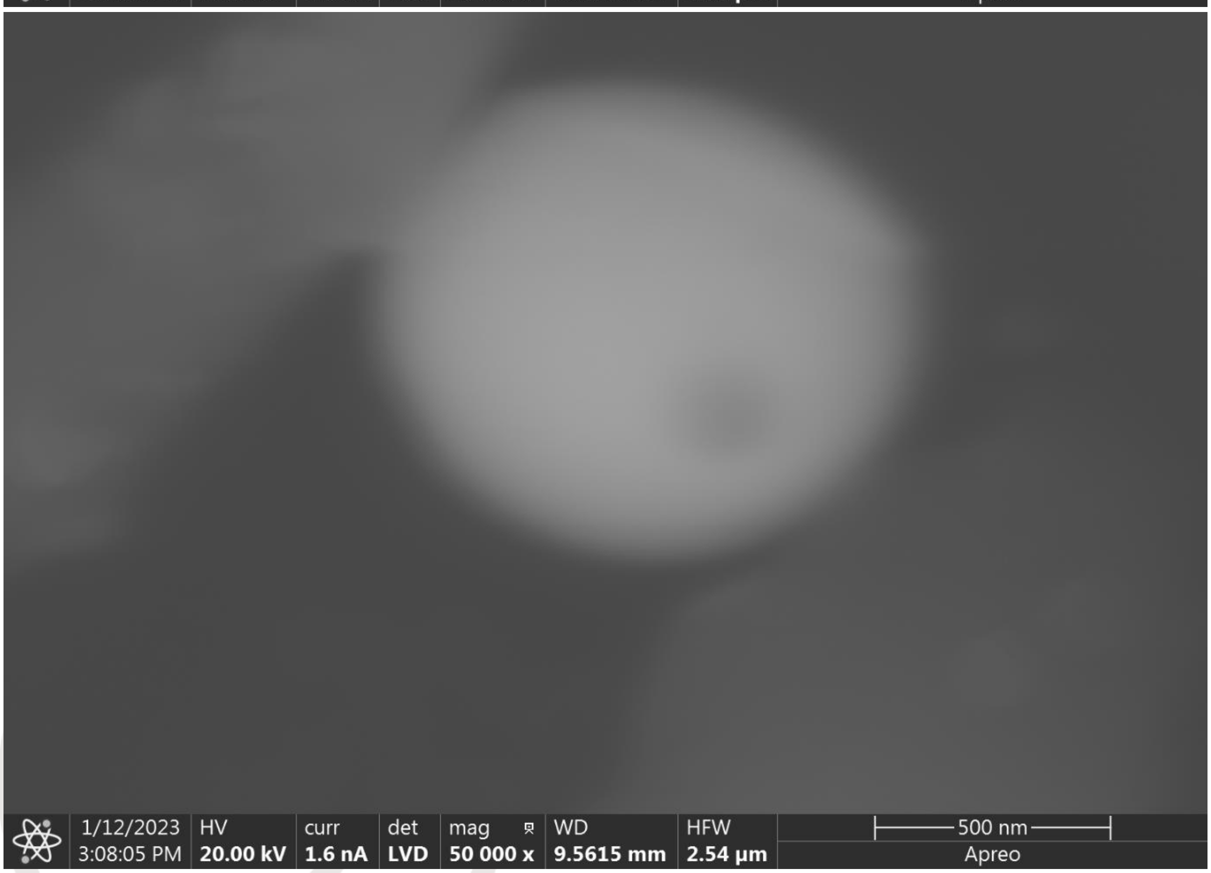
curr
1.6 nA
det
LVD
mag
20 000 x
WD
9.8561 mm
HFW
6.35 µm
2 µm
Apreo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det
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mag
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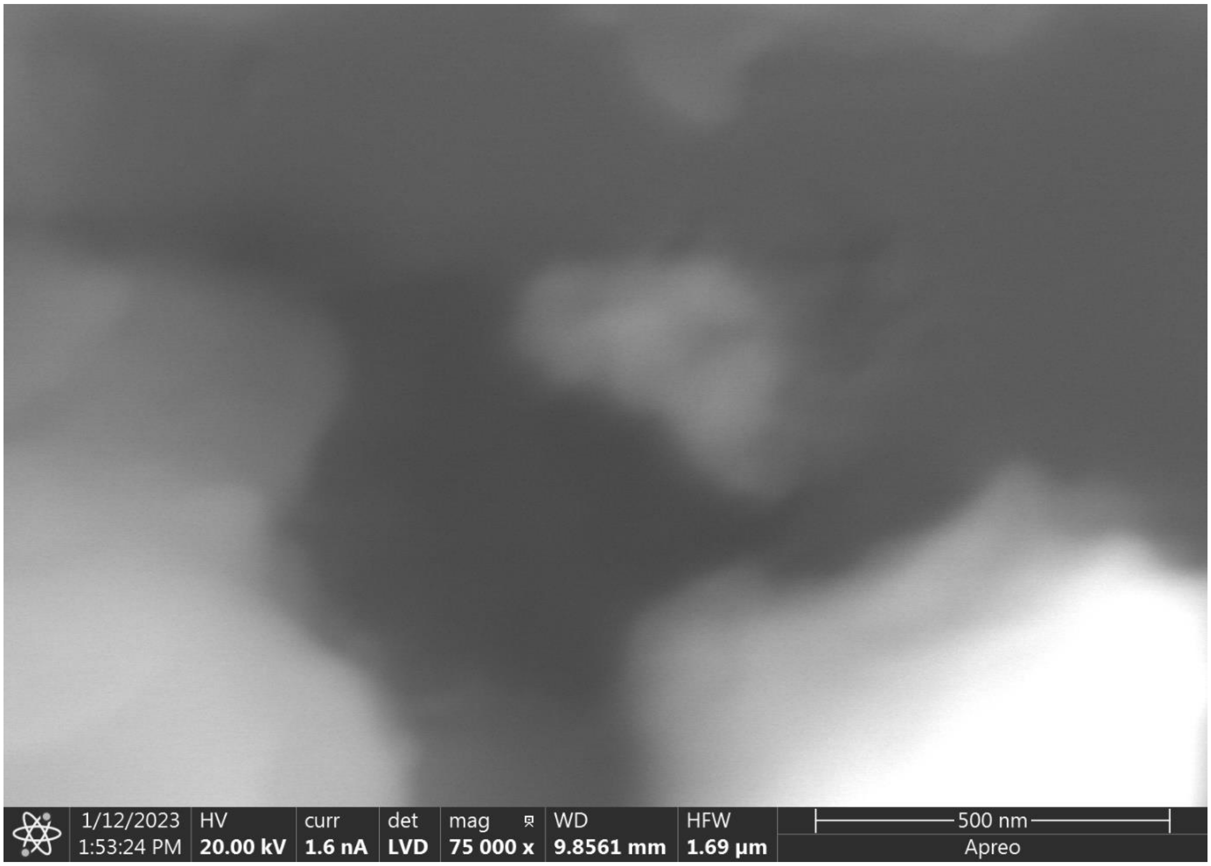
2.54 µm
500 nm
Apreo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HV
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curr
1.6 nA
det
LVD
mag
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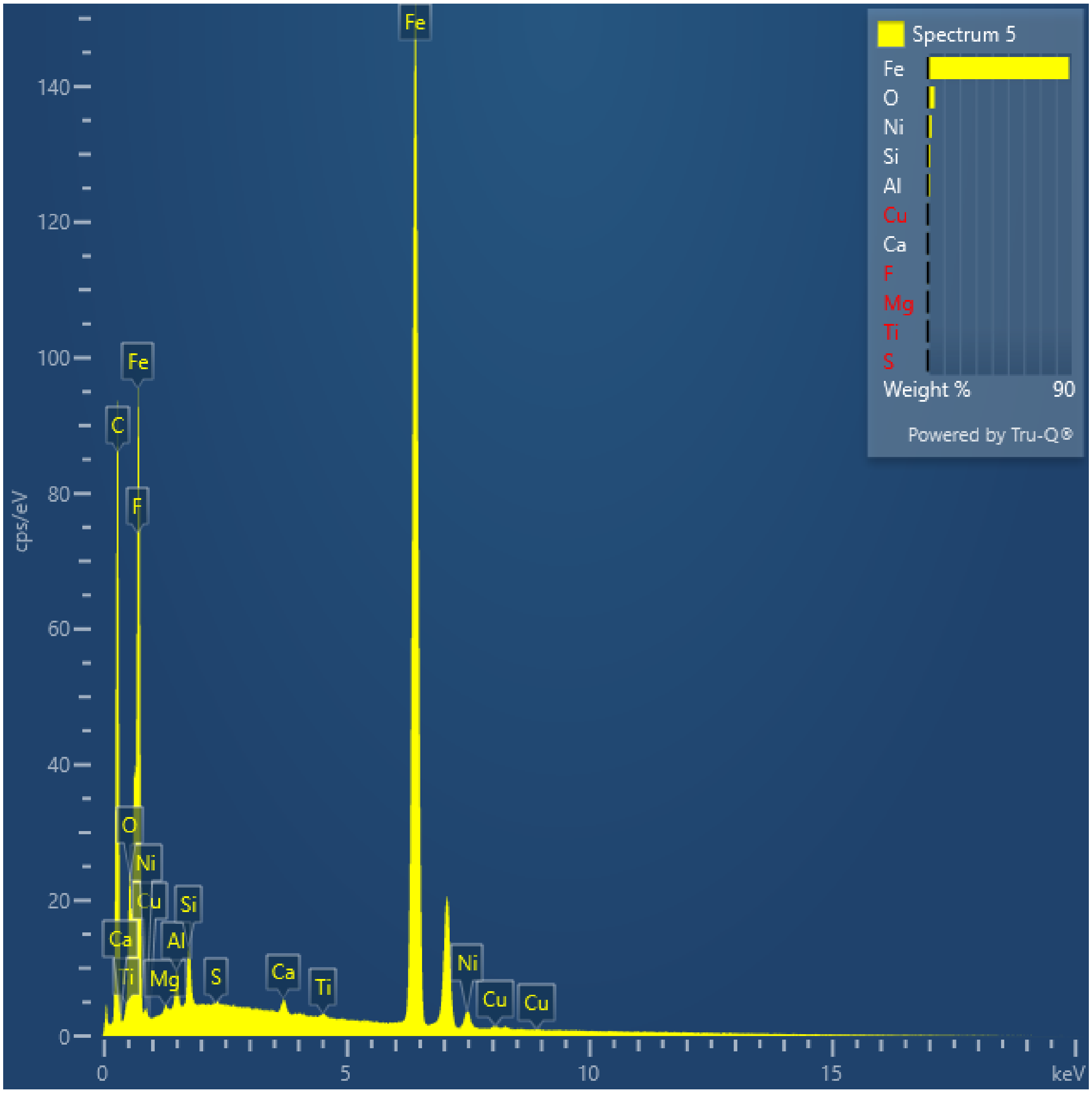
HFW
1.69 µm
500 nm
Apreo



Spectrum 5
Fe
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Ni
Si
Al
Cu
Ca
F
Mg
Ti
S
Weight %
90
Powered by Tru-Q®
cps/eV
140
120
100
80
60
40
20
0
Fe
Fe
C
F
O
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Mg
S
Ca
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Ni
Cu
Cu
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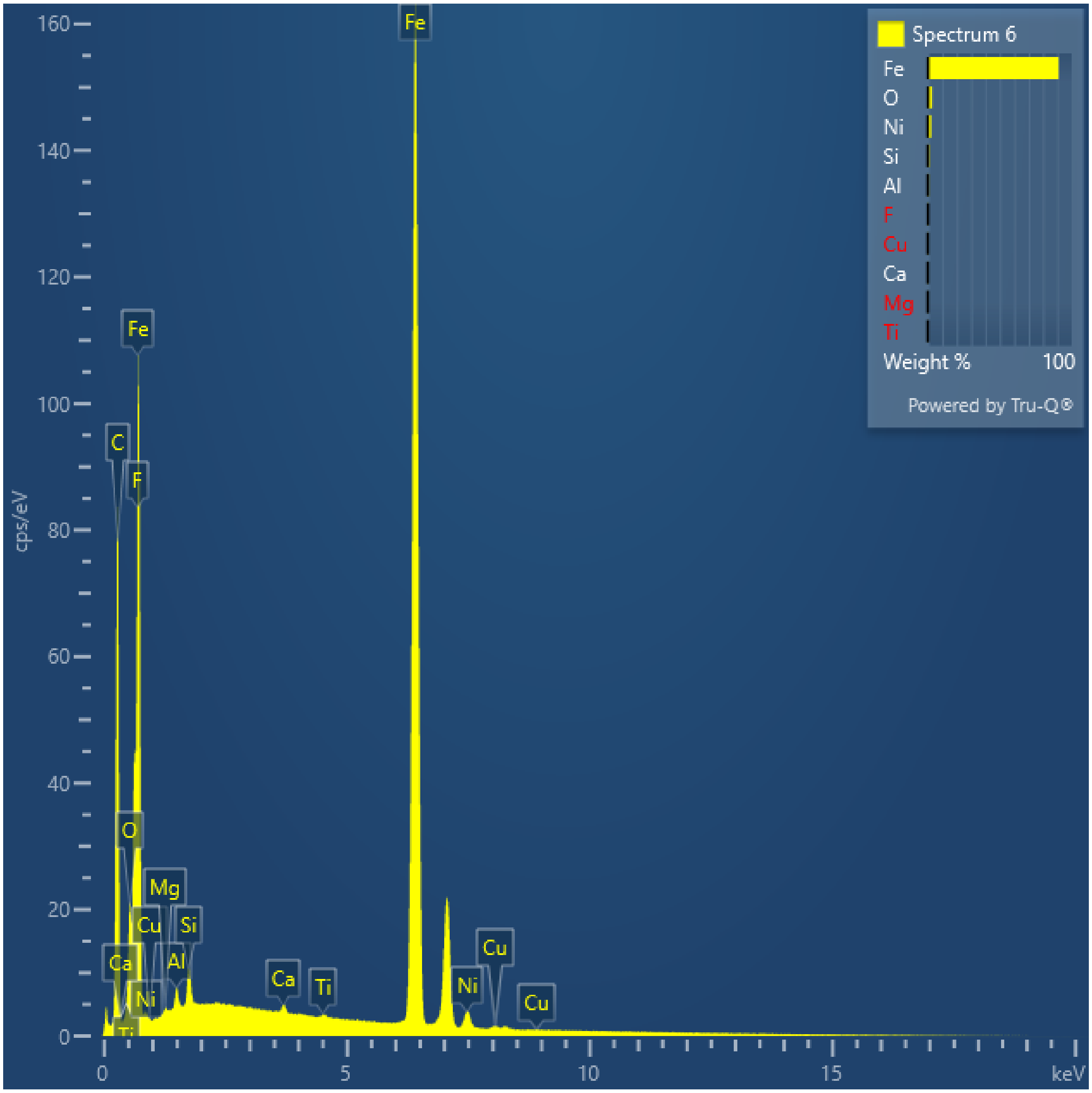
5
10
15
keV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Mg
Ti
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Powered by Tru-Q®
cps/eV
keV
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100
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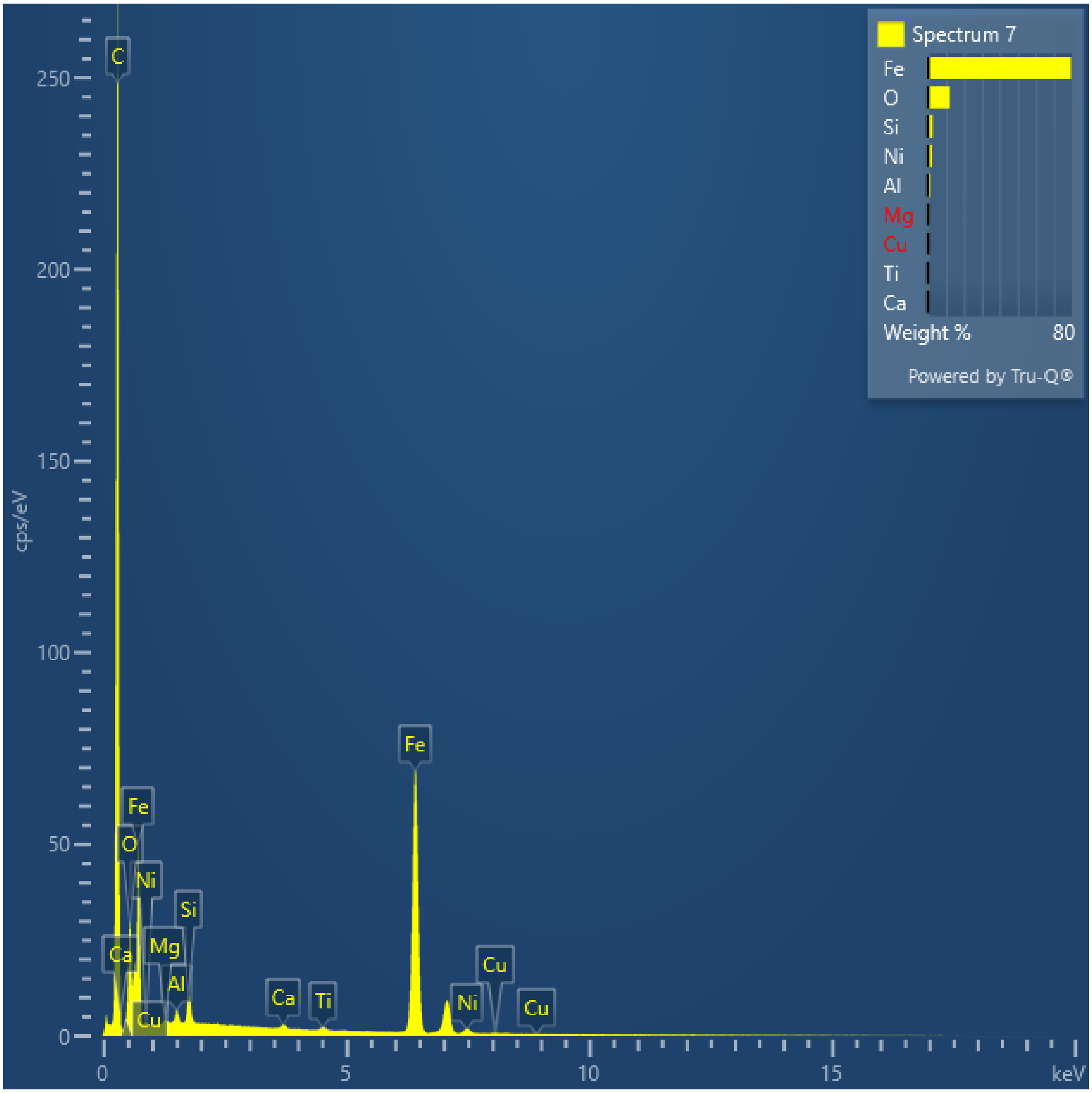
C
Al
Ca
Ti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Cu
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Powered by Tru-Q®
cps/eV
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100
50
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Cu
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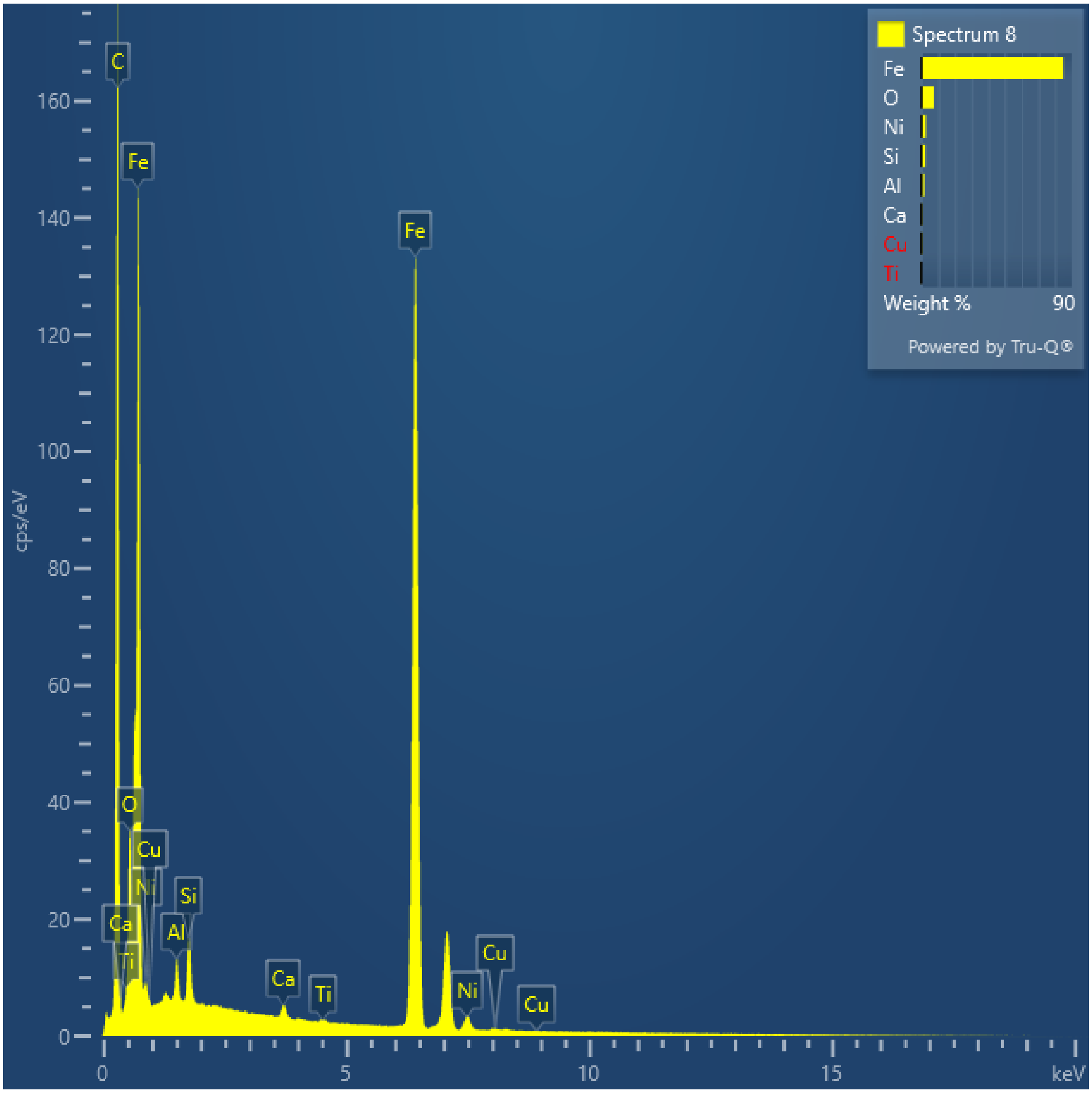
15
keV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Cu
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cps/eV
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80
60
40
20
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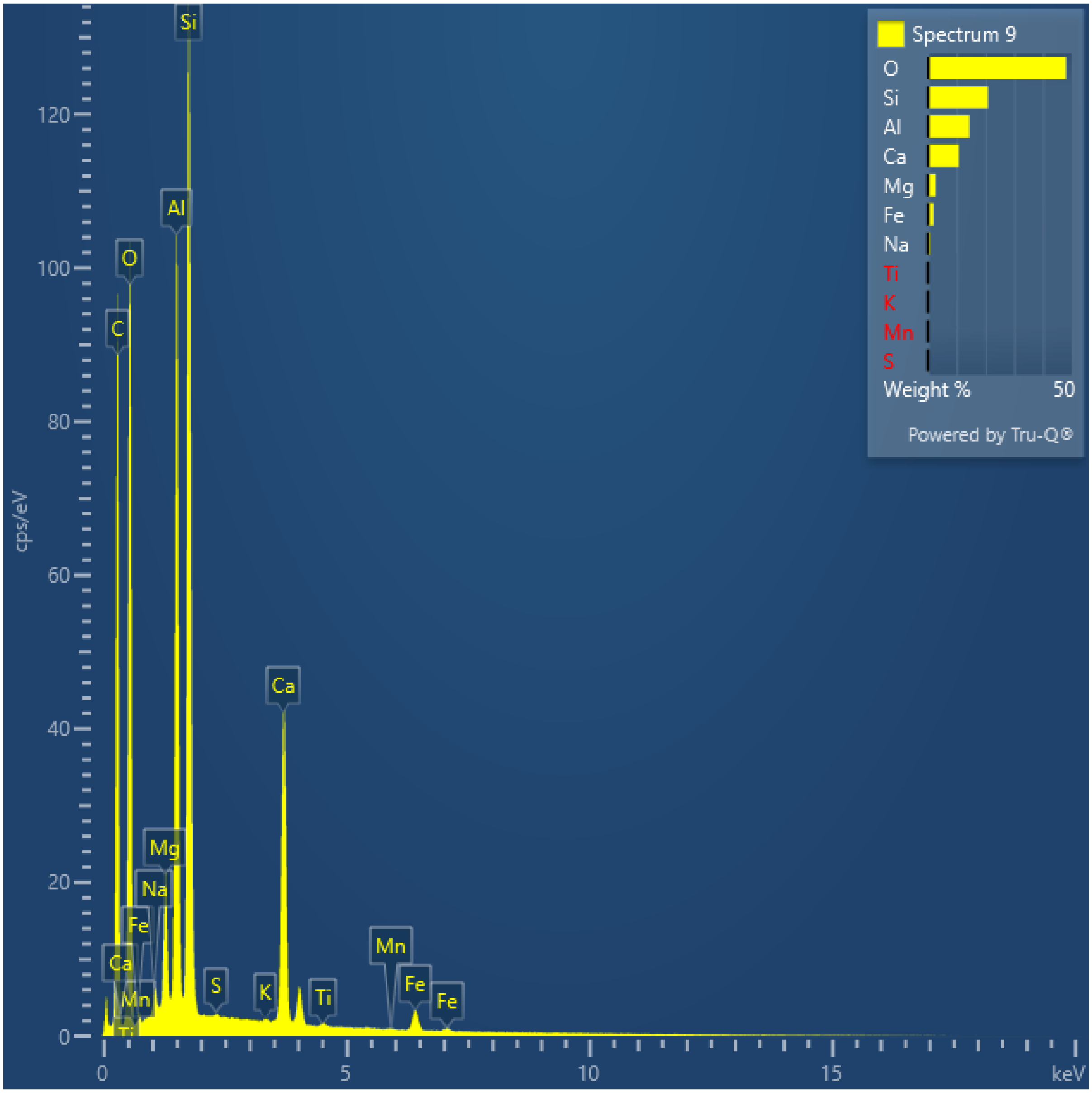
Fe
O
Cu
Ni
Si
Ca
Al
Ti
Ca
Ti
Cu
Ni
Cu
0
5
10
15
keV



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Ti
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Mn
S
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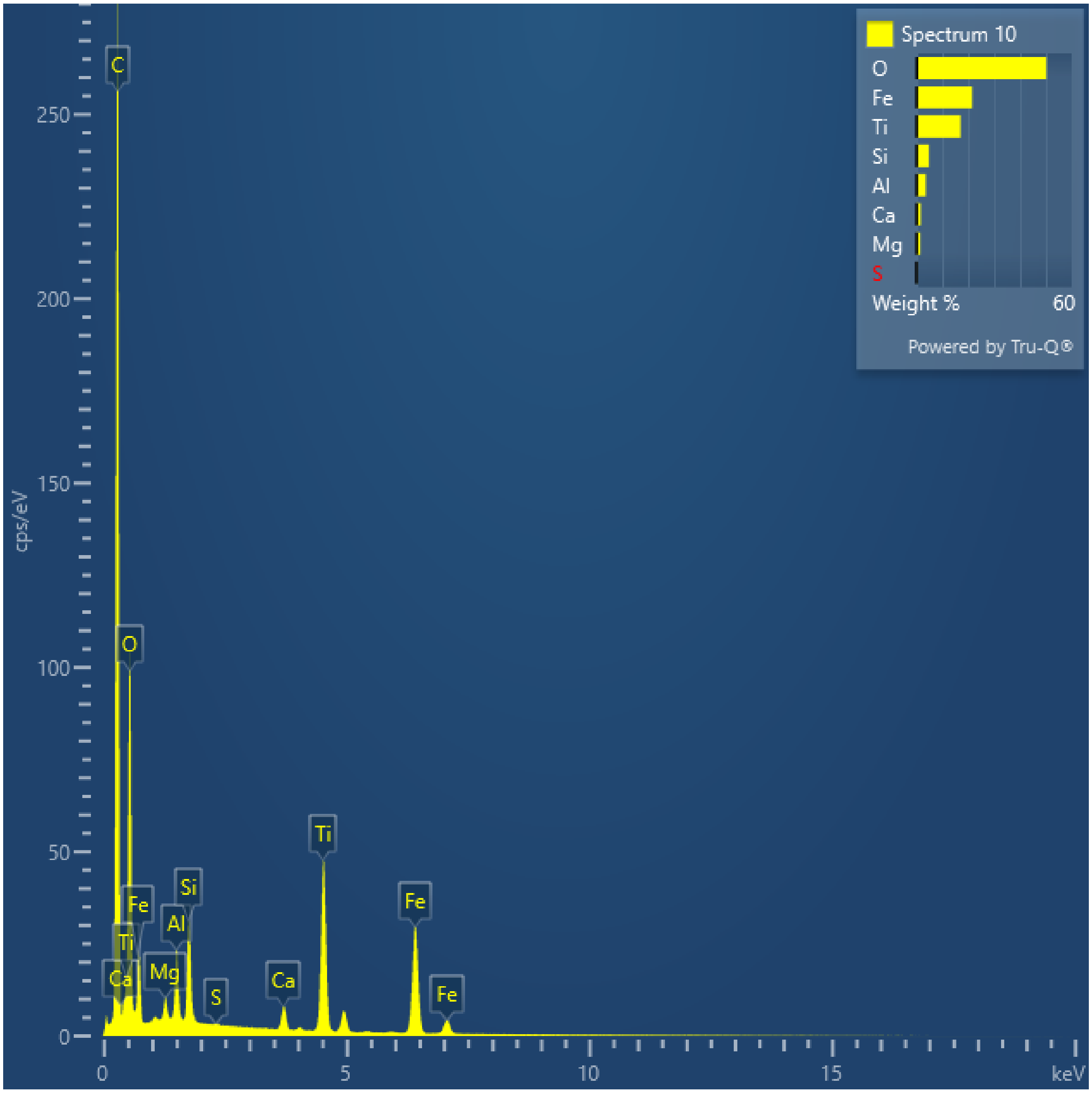
Powered by Tru-Q®
cps/eV
keV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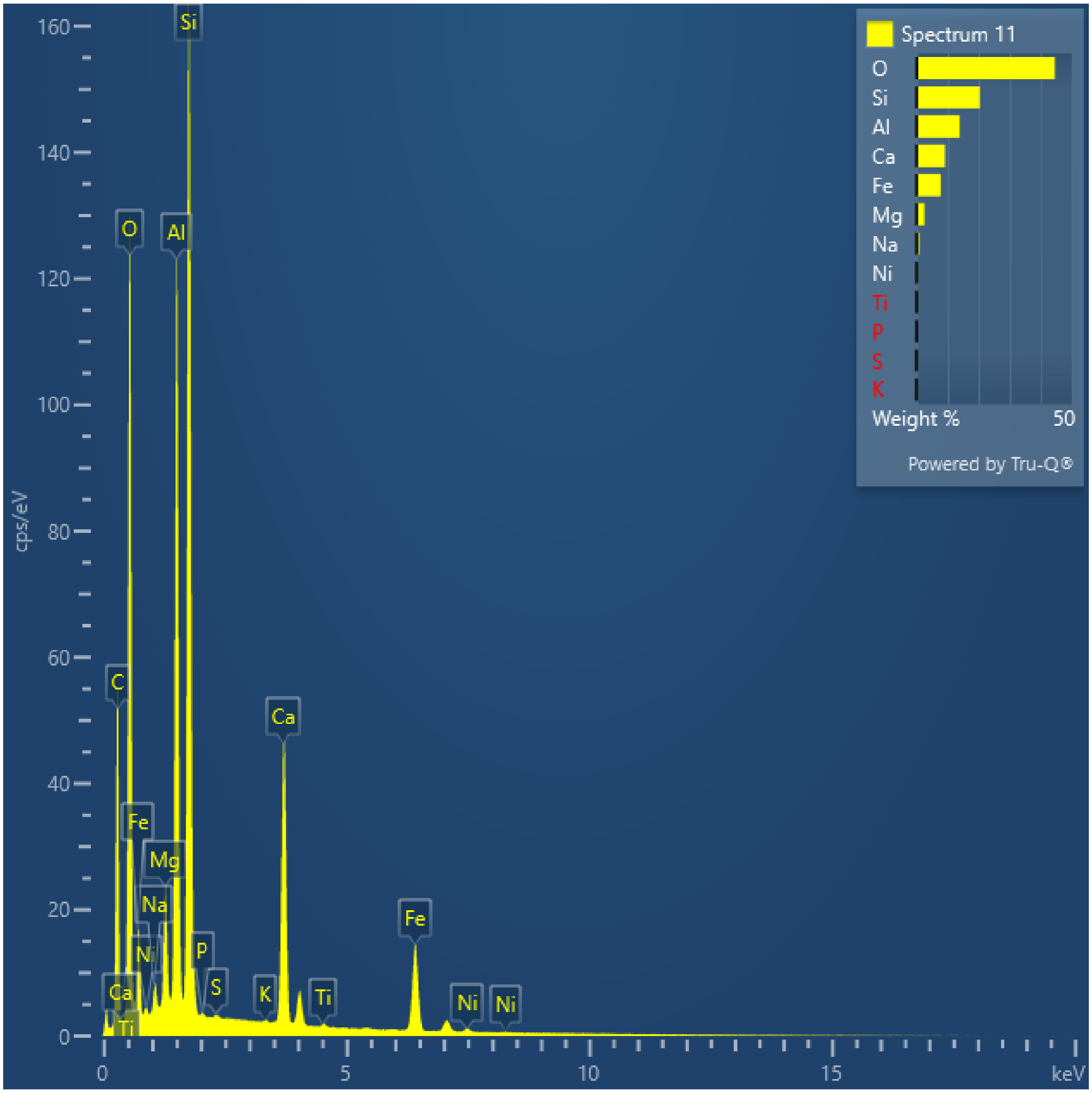
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Powered by Tru-Q®
cps/eV
keV
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Ni
P
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K
Ti
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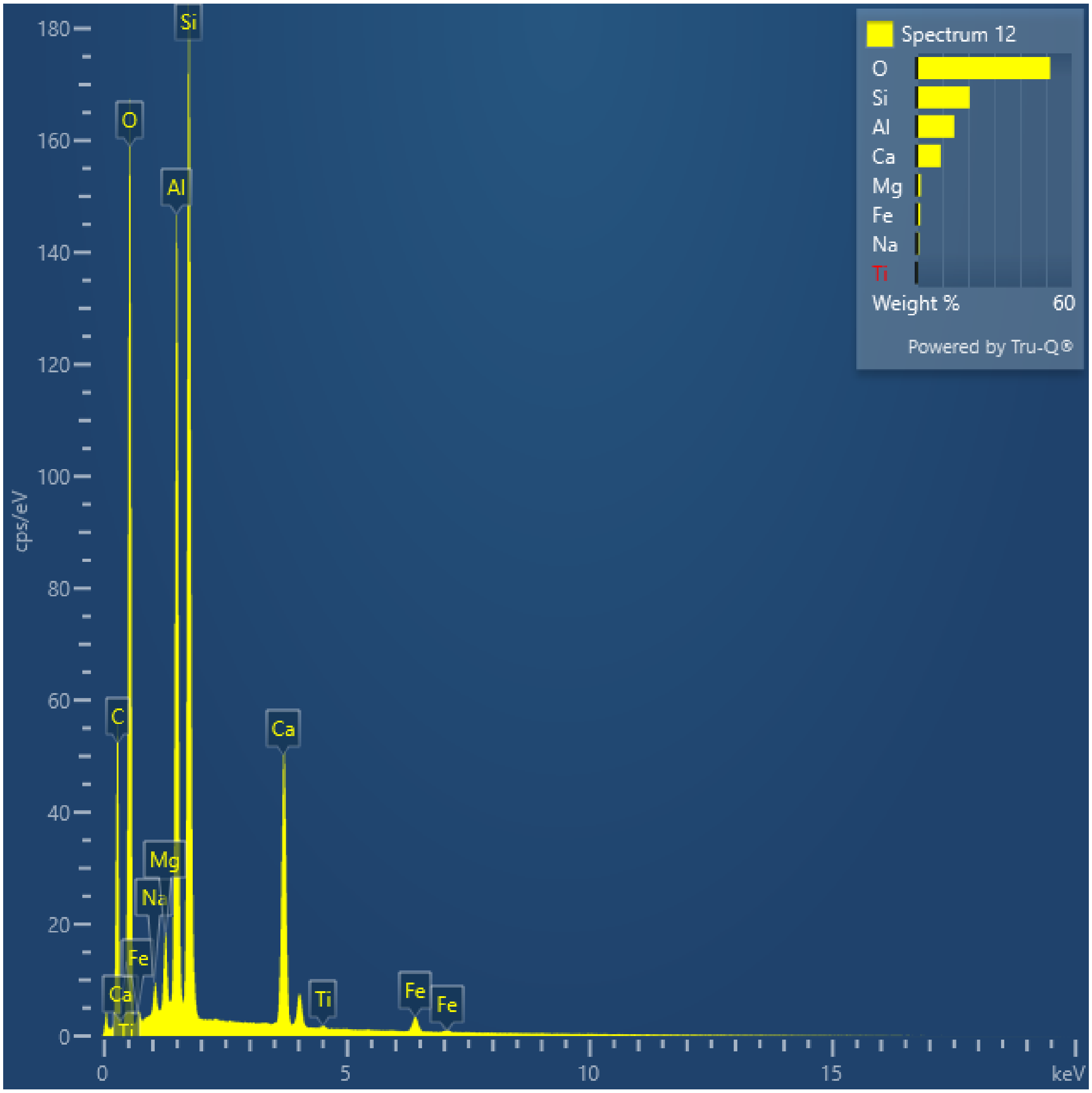
Ni
Ni



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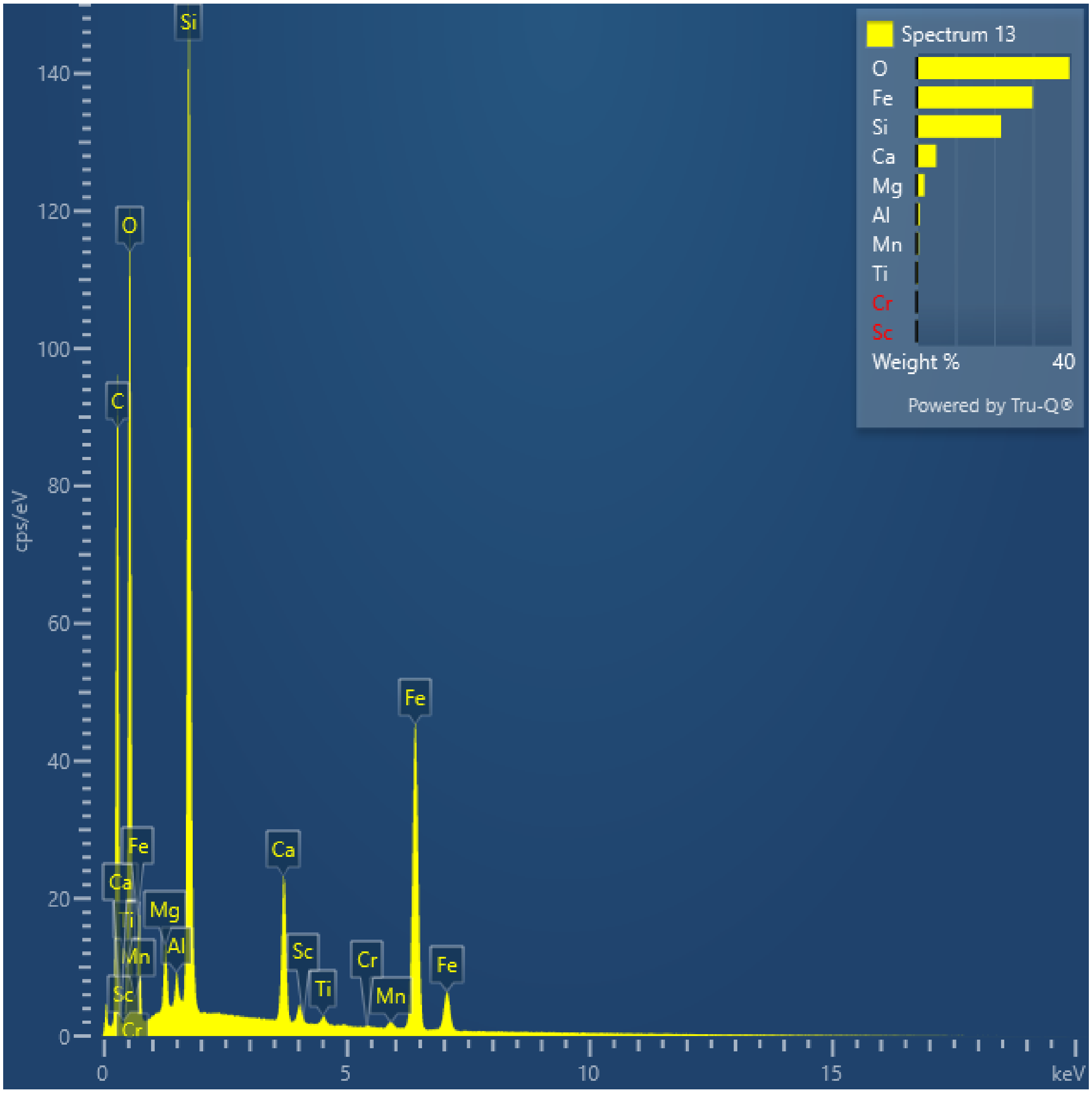
5
10
15
keV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cps/eV
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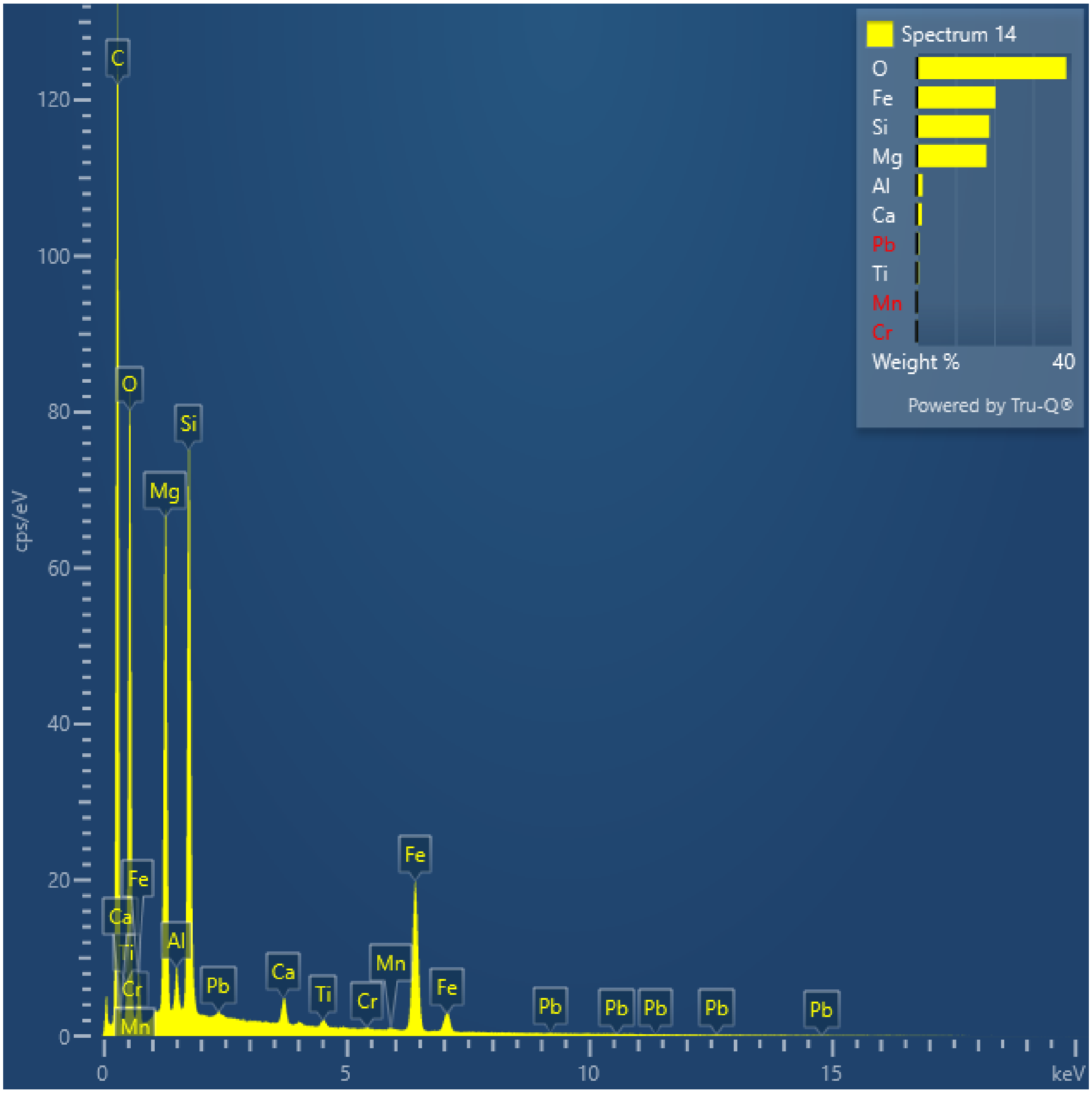
keV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Mn
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Weight %
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Powered by Tru-Q®
cps/eV
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60
40
20
0
C
O
Si
Mg
Fe
Ca
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Fe
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Pb
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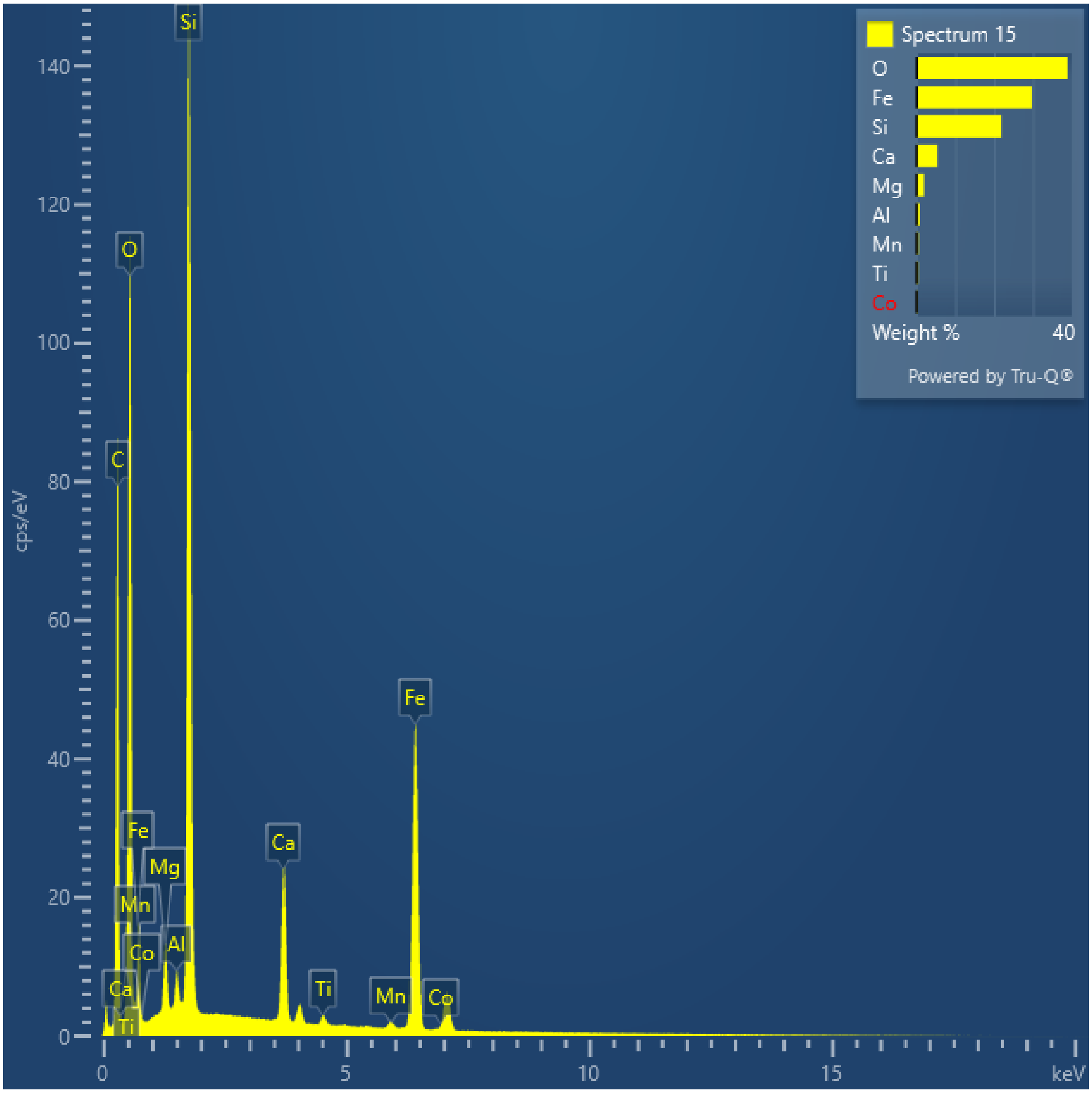
Pb
Pb
Pb
0
5
10
15
keV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Al
Mn
Ti
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cps/eV
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40
20
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5
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15
keV
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C
Fe
Mg
Mn
Al
Co
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Fe
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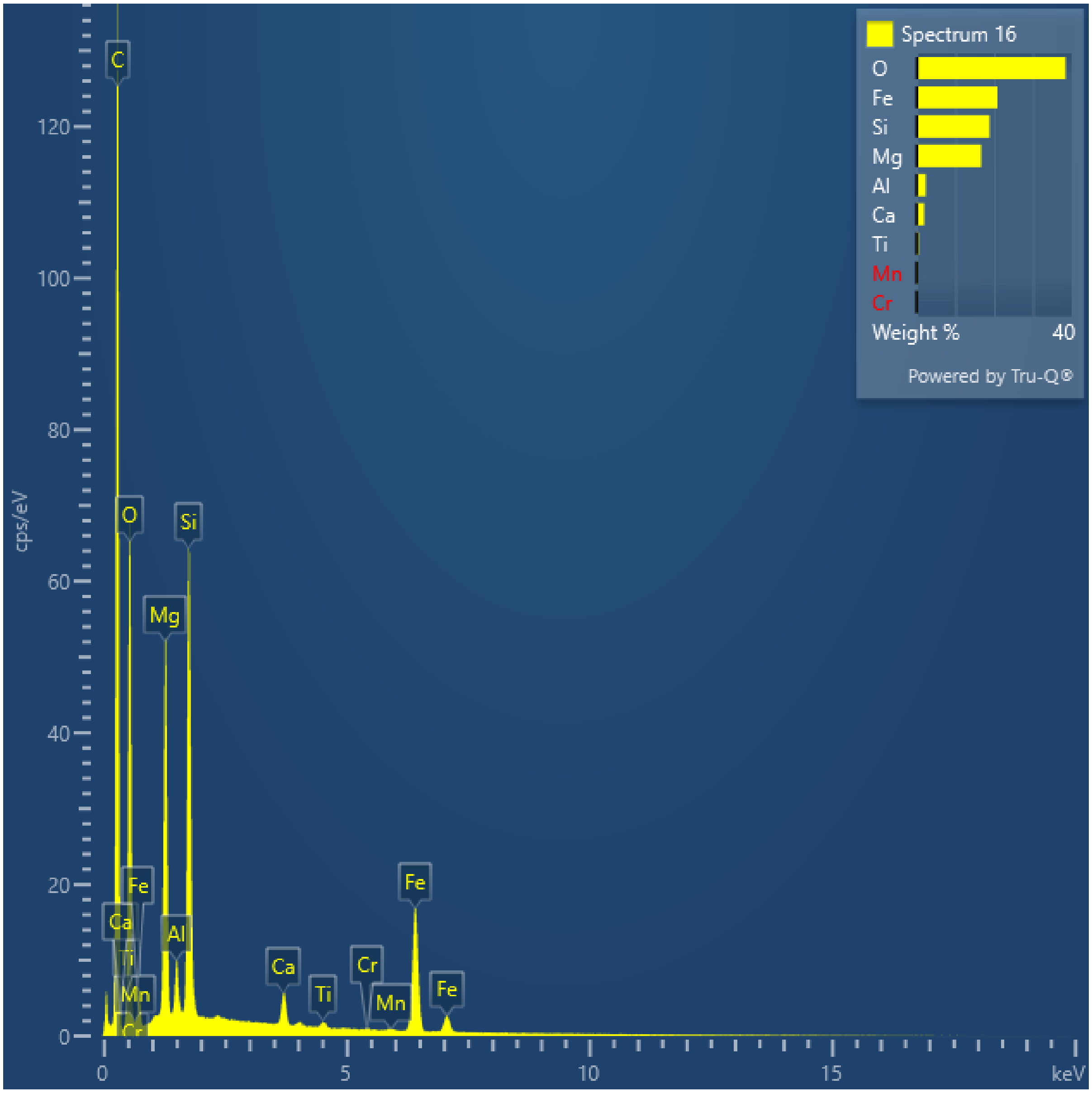
Mn
Co



Spectrum 16
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Mn
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Weight %
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cps/eV
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80
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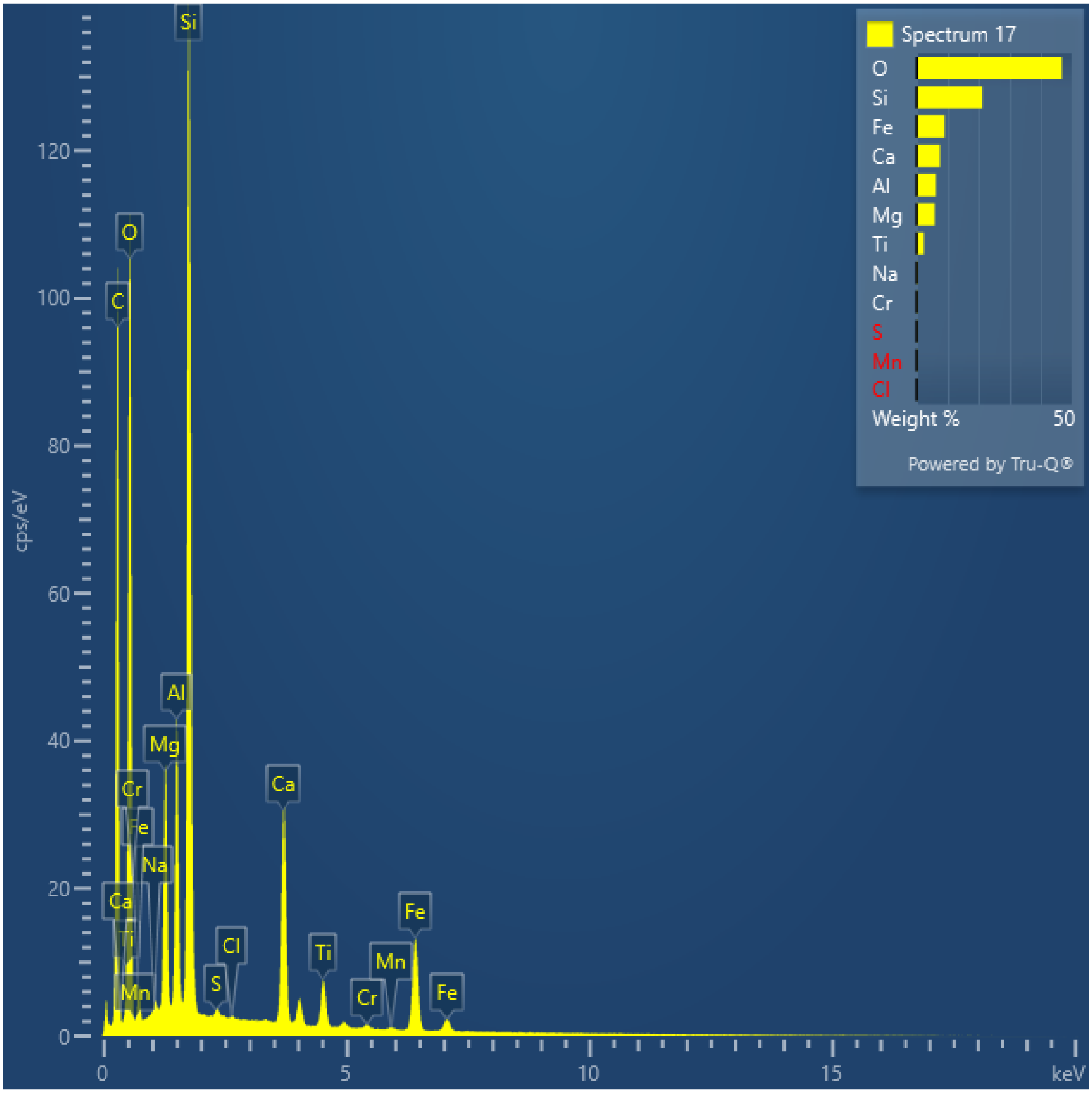
15
keV


Spectrum 17
O
Si
Fe
Ca
Al
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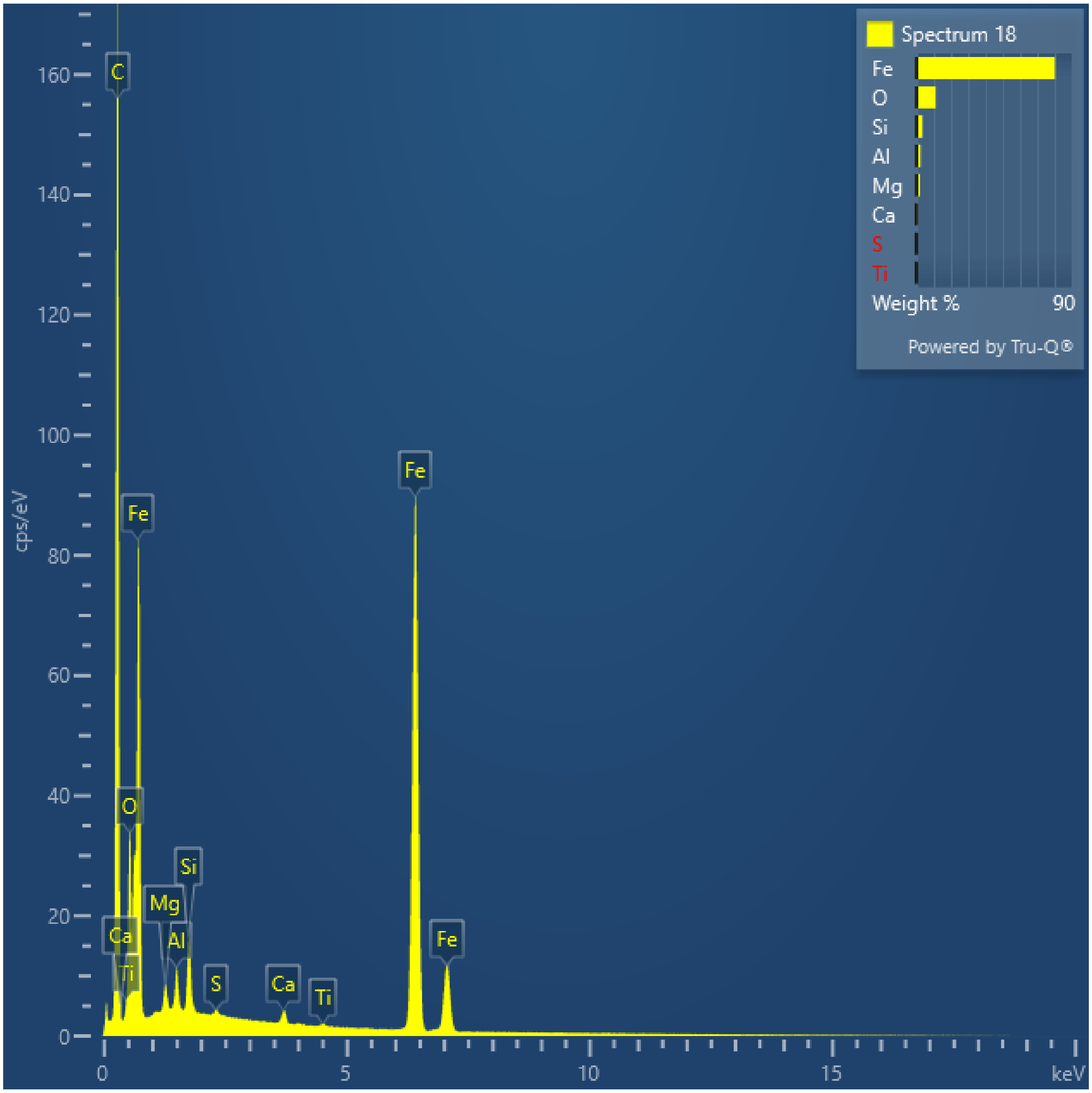
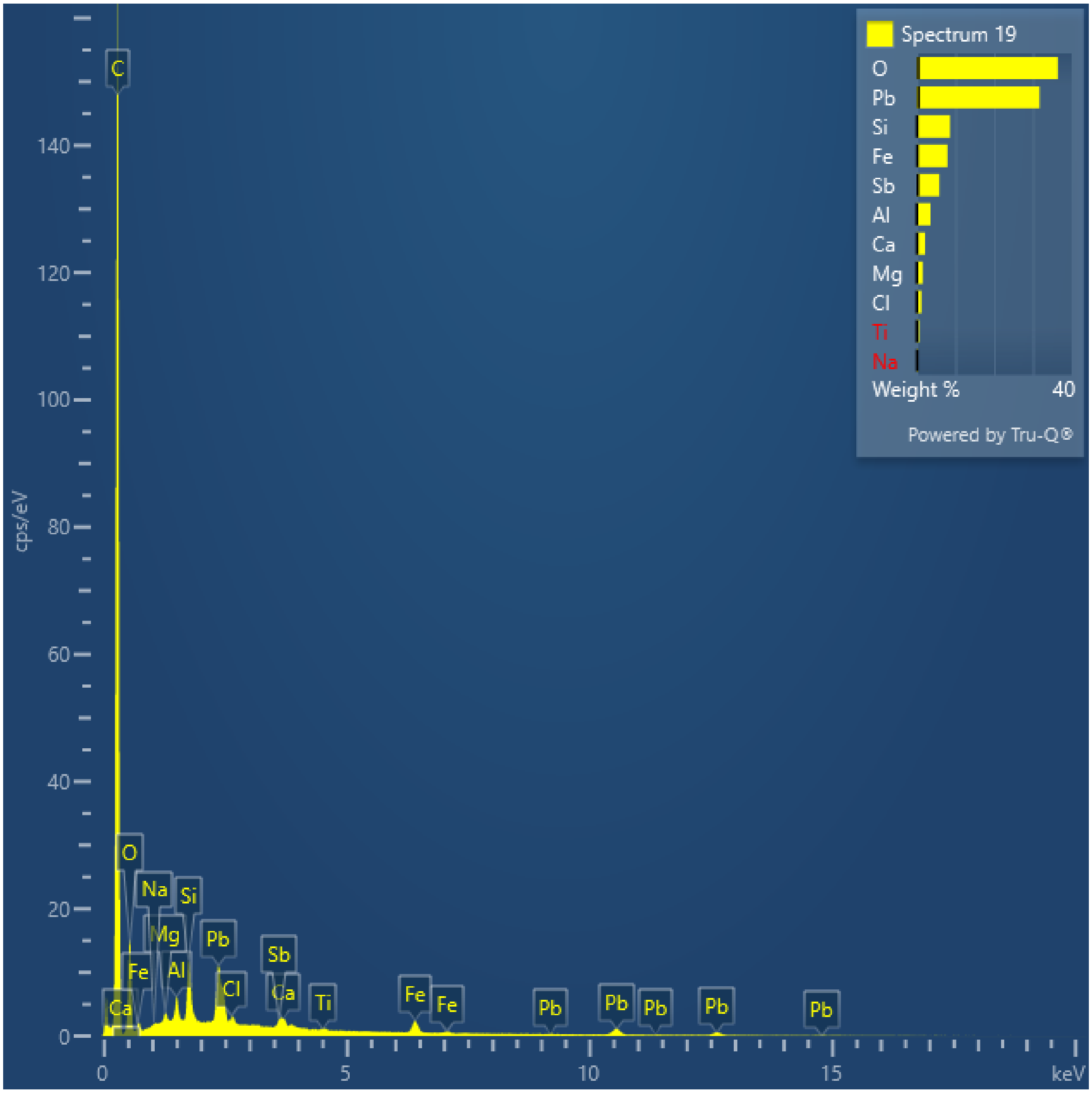
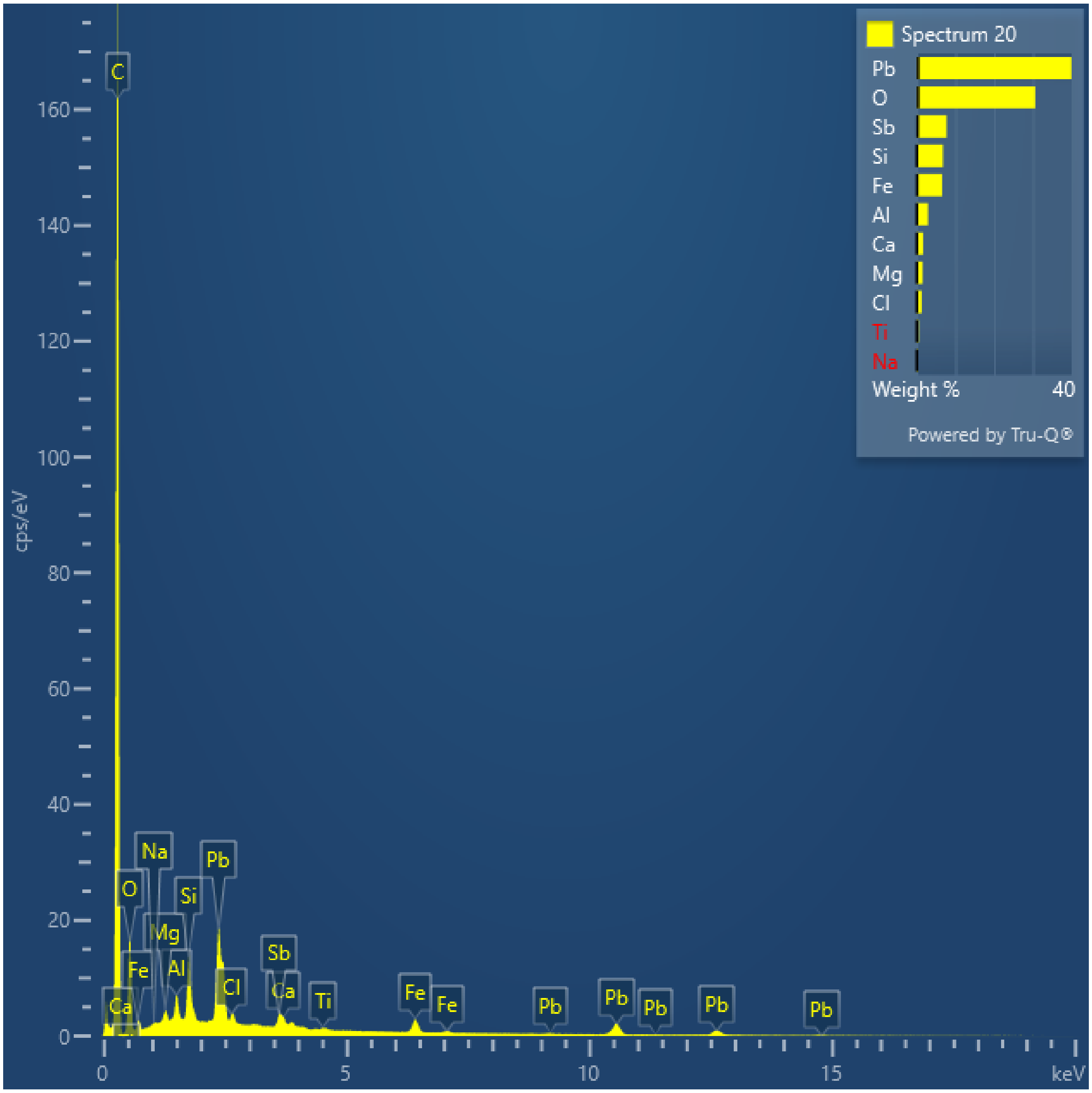
Ti
Na
Cr
S
Mn
Cl
Weight %
50
Powered by Tru-Q®
cps/eV
keV
C
Cr
Fe
Na
Ca
Ti
Mn
S
Cl
Ti
Mn
Cr
Fe
Fe

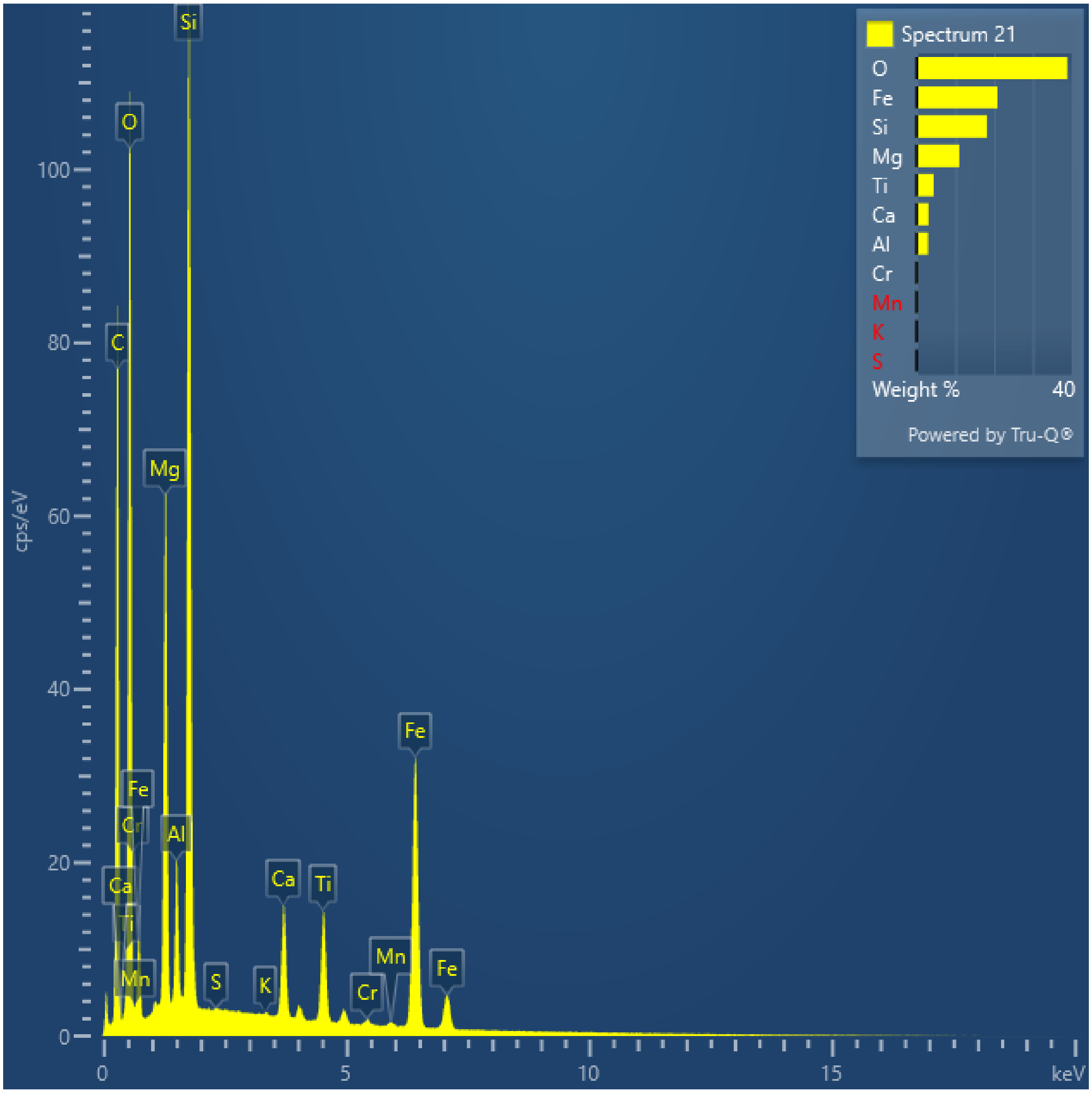


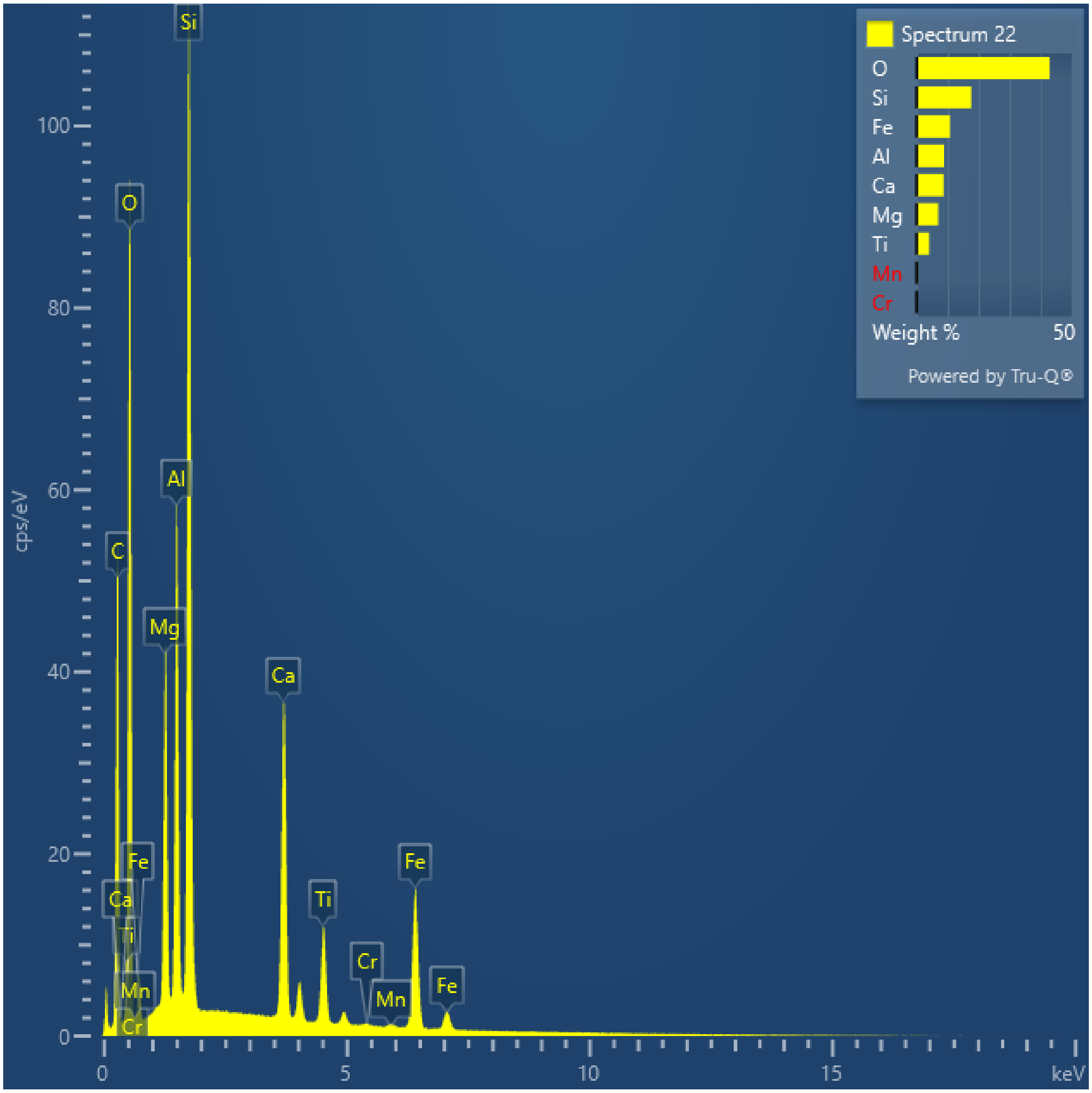
Spectrum 18
Fe
O
Si
Al
Mg
Ca
S
Ti
Weight %
90
Powered by Tru-Q®
cps/eV
160
140
120
100
80
60
40
20
0
C
Fe
O
Si
Mg
Ca
Al
Ti
S
Ca
Ti
Fe
Fe
0
5
10
15
keV



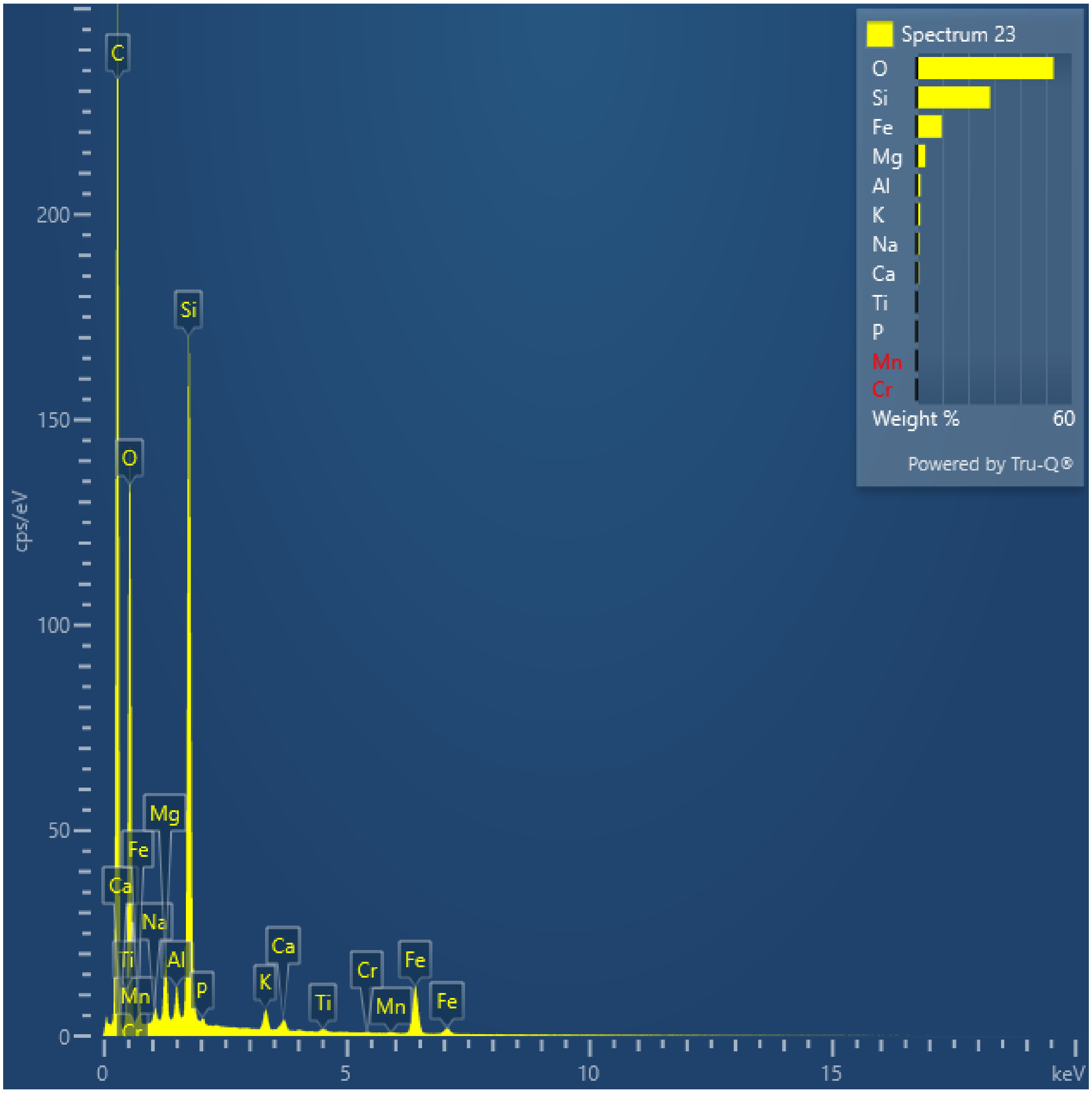
Spectrum 19
O
Pb
Si
Fe
Sb
Al
Ca
Mg
Cl
Ti
Na
Weight %
40
Powered by Tru-Q®
cps/eV
140
120
100
80
60
40
20
0
C
O
Na
Si
Mg
Pb
Fe
Al
Cl
Sb
Ca
Ti
Fe
Fe
Pb
Pb
Pb
Pb
Pb
0
5
10
15
keV

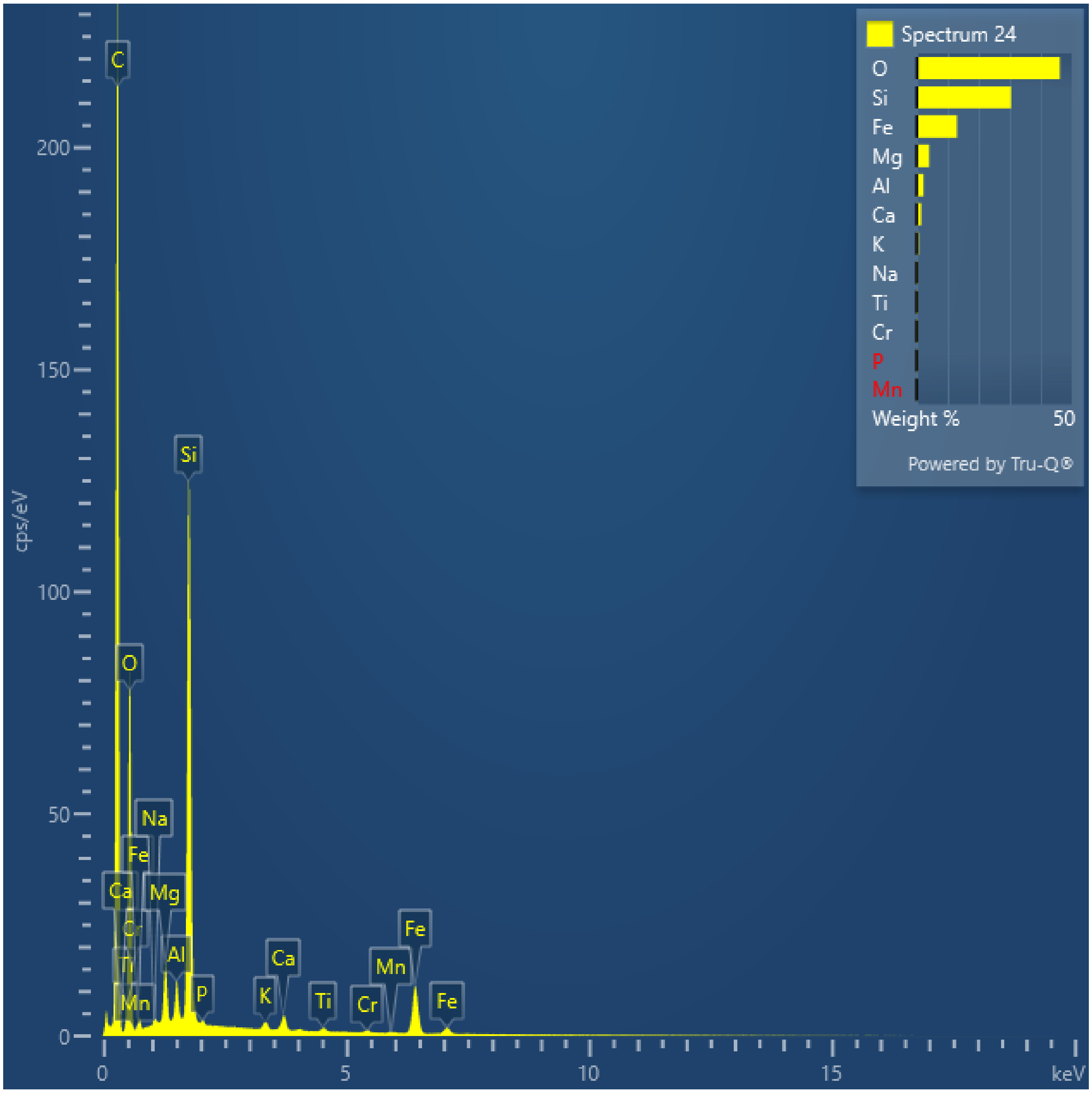

Spectrum 20
Pb
O
Sb
Si
Fe
Al
Ca
Mg
Cl
Ti
Na
Weight %
40
Powered by Tru-Q®
cps/eV
keV
C
Na
Pb
O
Si
Mg
Fe
Al
Cl
Ca
Sb
Ca
Ti
Fe
Fe
Pb
Pb
Pb
Pb
Pb

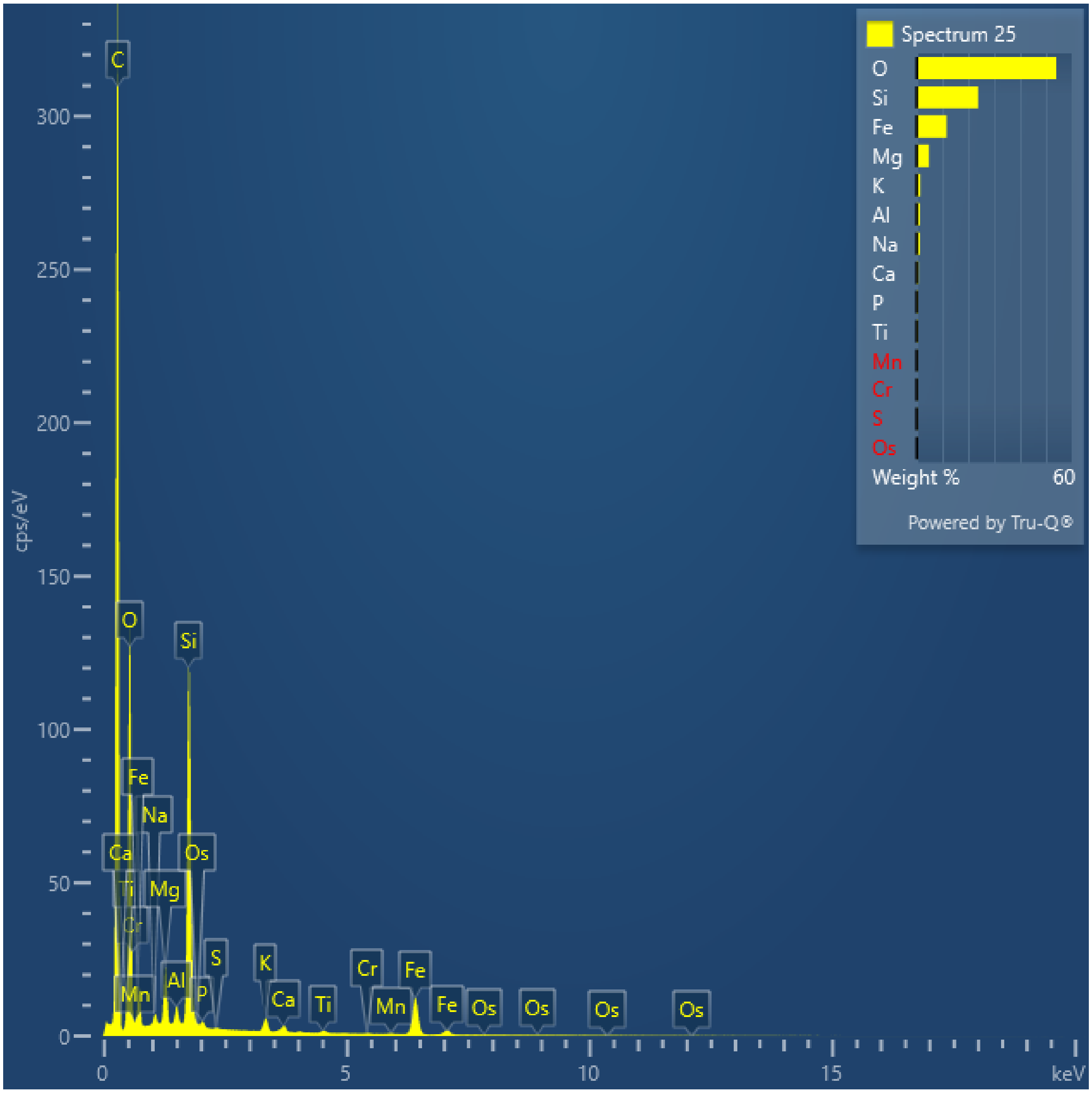

Spectrum 21
O
Fe
Si
Mg
Ti
Ca
Al
Cr
Mn
K
S
Weight %
40
Powered by Tru-Q®
cps/eV
keV
Si
O
C
Mg
Fe
Cr
Al
Ca
Ti
Mn
S
K
Ca
Ti
Fe
Mn
Cr
Fe
0
20
40
60
80
100
0
5
10
15



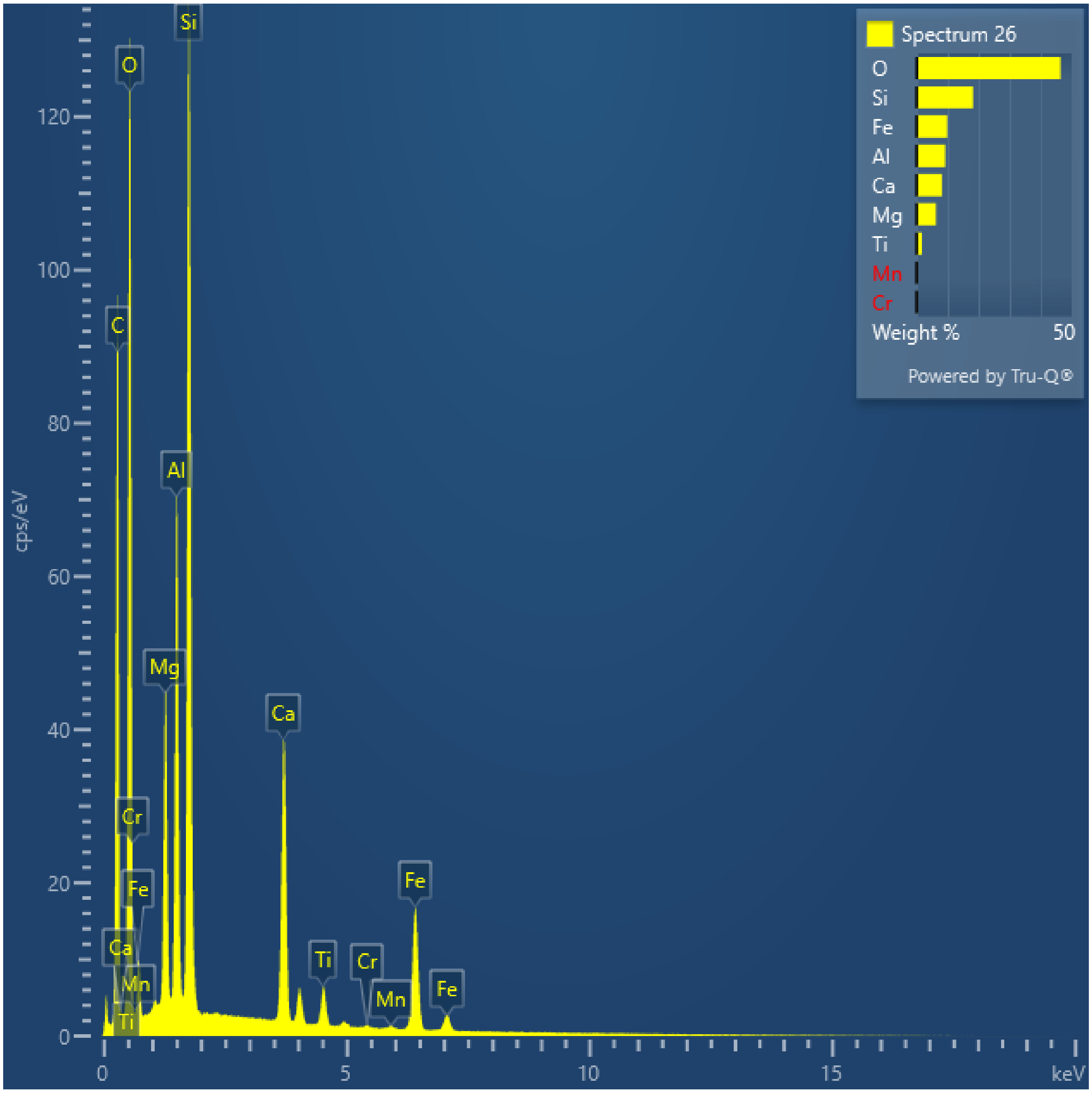
Spectrum 22
O
Si
Fe
Al
Ca
Mg
Ti
Mn
Cr
Weight %
50
Powered by Tru-Q®
cps/eV
100
80
60
40
20
0
Si
O
Al
C
Mg
Ca
Fe
Ca
Ti
Mn
Cr
Ti
Cr
Mn
Fe
Fe
0
5
10
15
keV

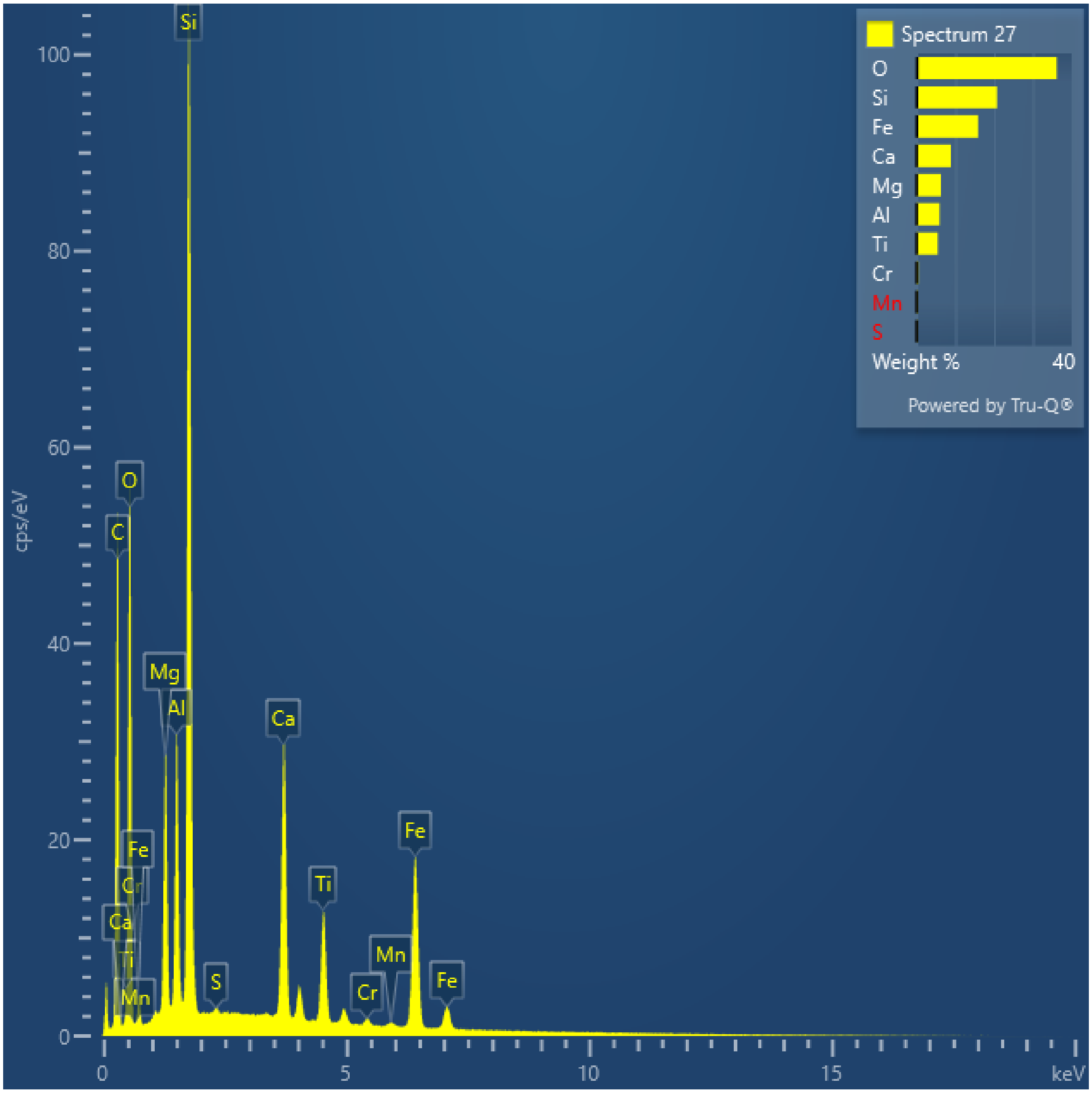

Spectrum 23
O
Si
Fe
Mg
Al
K
Na
Ca
Ti
P
Mn
Cr
Weight %
60
Powered by Tru-Q®
cps/eV
0
50
100
150
200
0
5
10
15
keV
C
O
Si
Mg
Fe
Ca
Na
Ti
Al
Mn
P
Cr
K
Ca
Ti
Cr
Mn
Fe
Fe


Spectrum 24
O
Si
Fe
Mg
Al
Ca
K
Na
Ti
Cr
P
Mn
Weight %
50
Powered by Tru-Q®
cps/eV
200
150
100
50
0
C
Si
O
Na
Fe
Ca
Mg
Cr
Ti
Al
Mn
P
K
Ca
Ti
Cr
Mn
Fe
Fe
0
5
10
15
keV



Spectrum 25
O
Si
Fe
Mg
K
Al
Na
Ca
P
Ti
Mn
Cr
S
Os
Weight %
60
Powered by Tru-Q®
cps/eV
keV


Spectrum 26
O
Si
Fe
Al
Ca
Mg
Ti
Mn
Cr
Weight %
50
Powered by Tru-Q®
cps/eV
0
20
40
60
80
100
120
keV
5
10
15
C
O
Si
Al
Mg
Ca
Cr
Fe
Ca
Mn
Ti
Ti
Cr
Mn
Fe
Fe


Spectrum 27
O
Si
Fe
Ca
Mg
Al
Ti
Cr
Mn
S
Weight %
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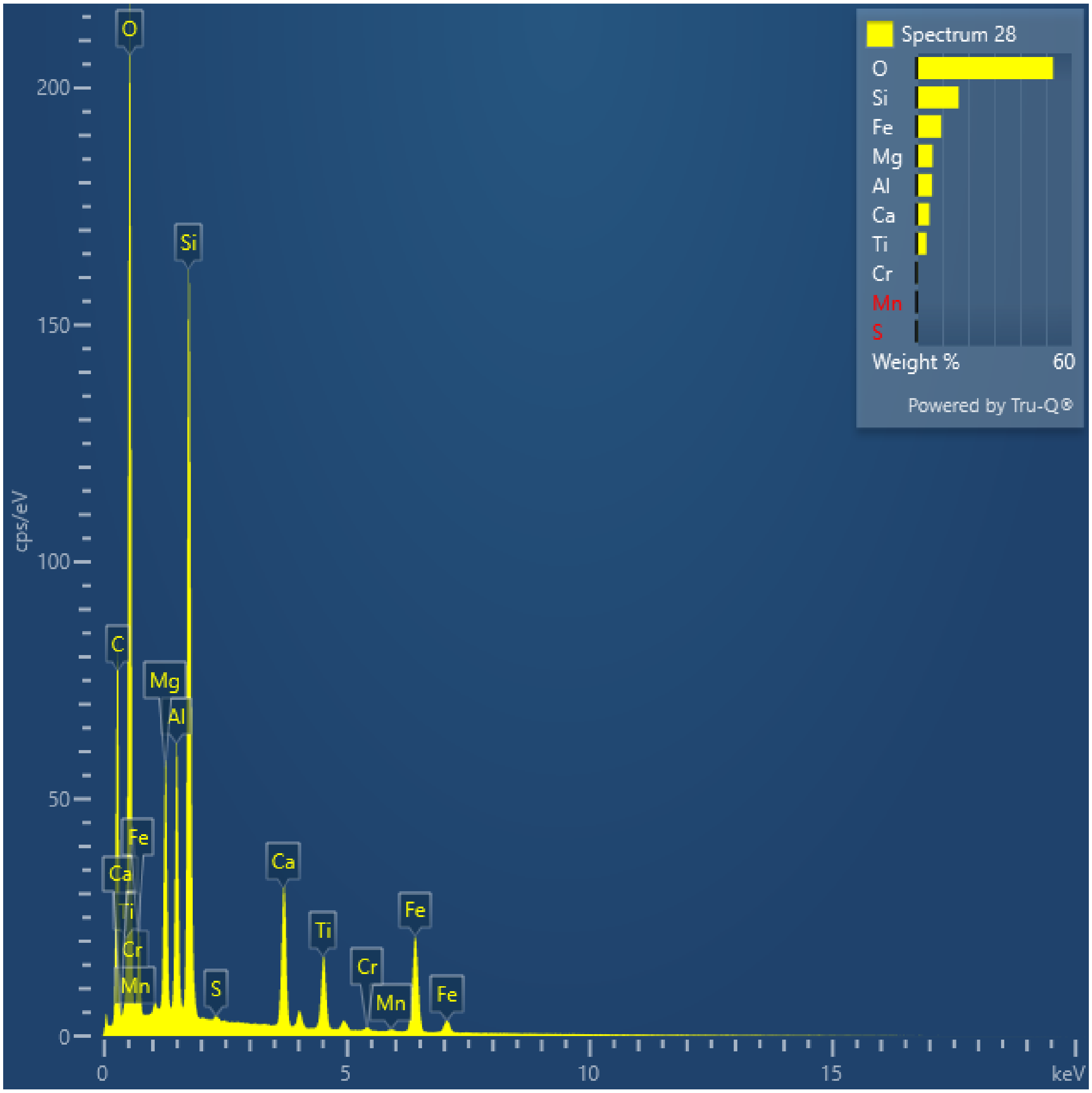
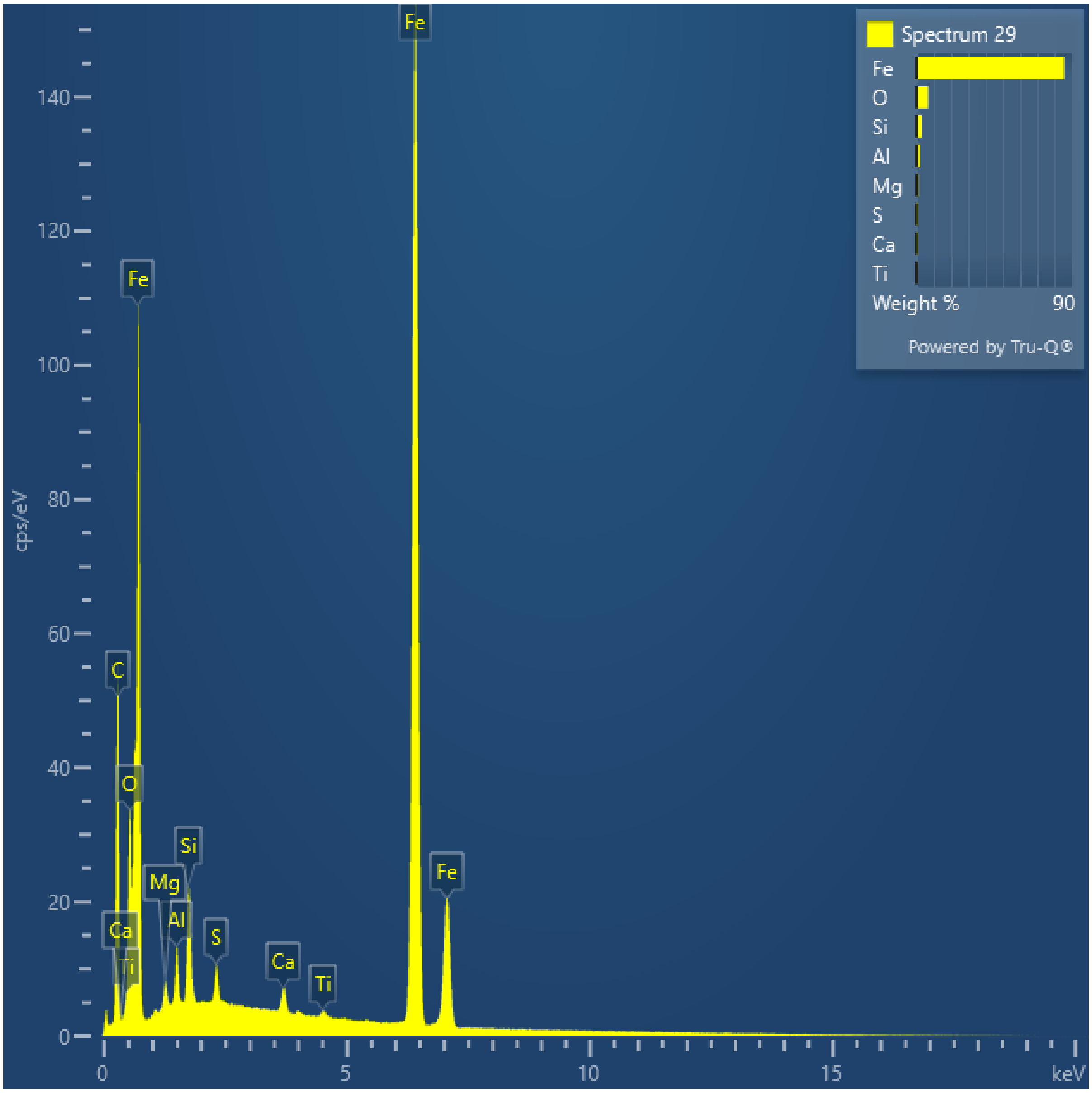
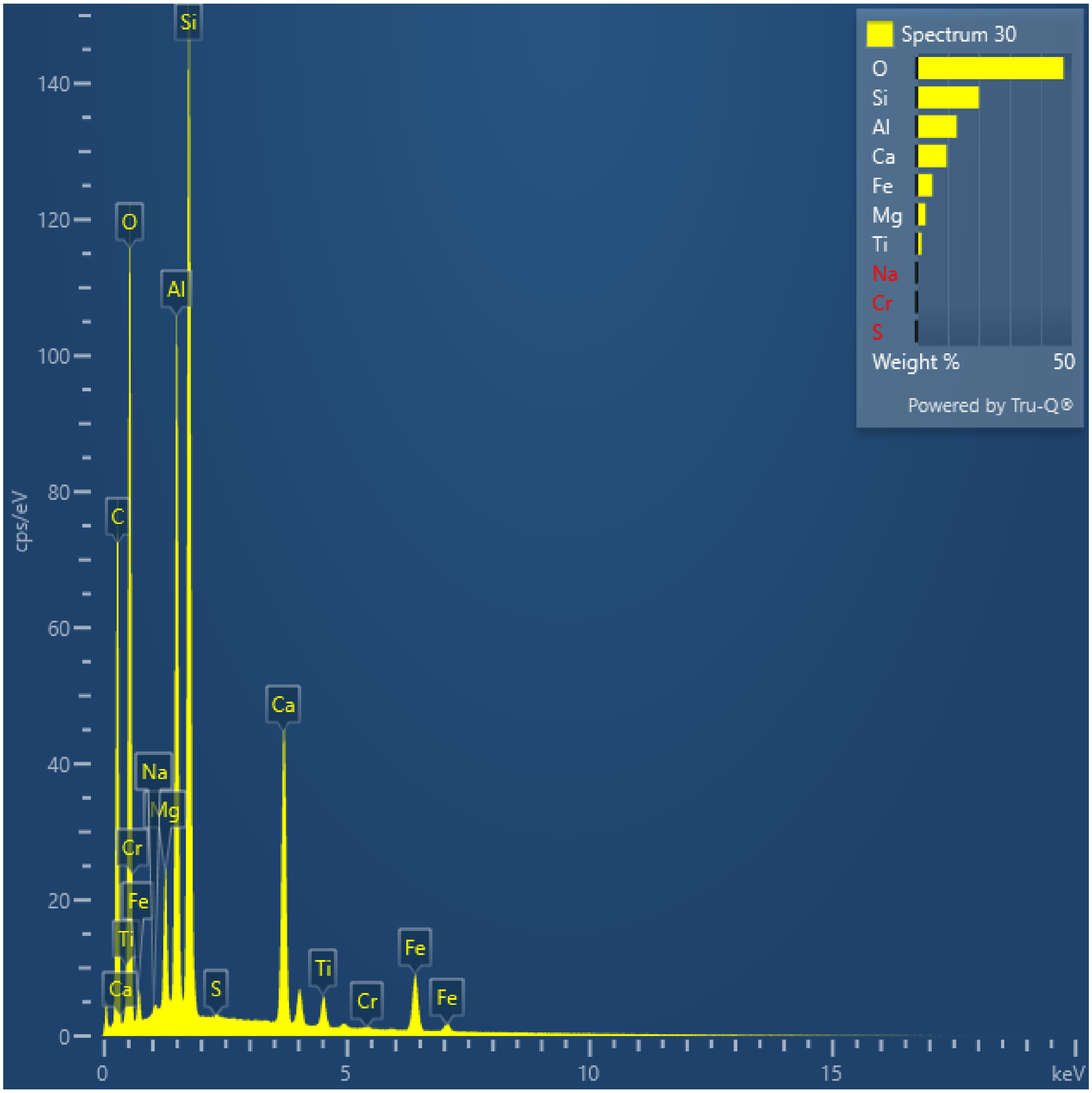
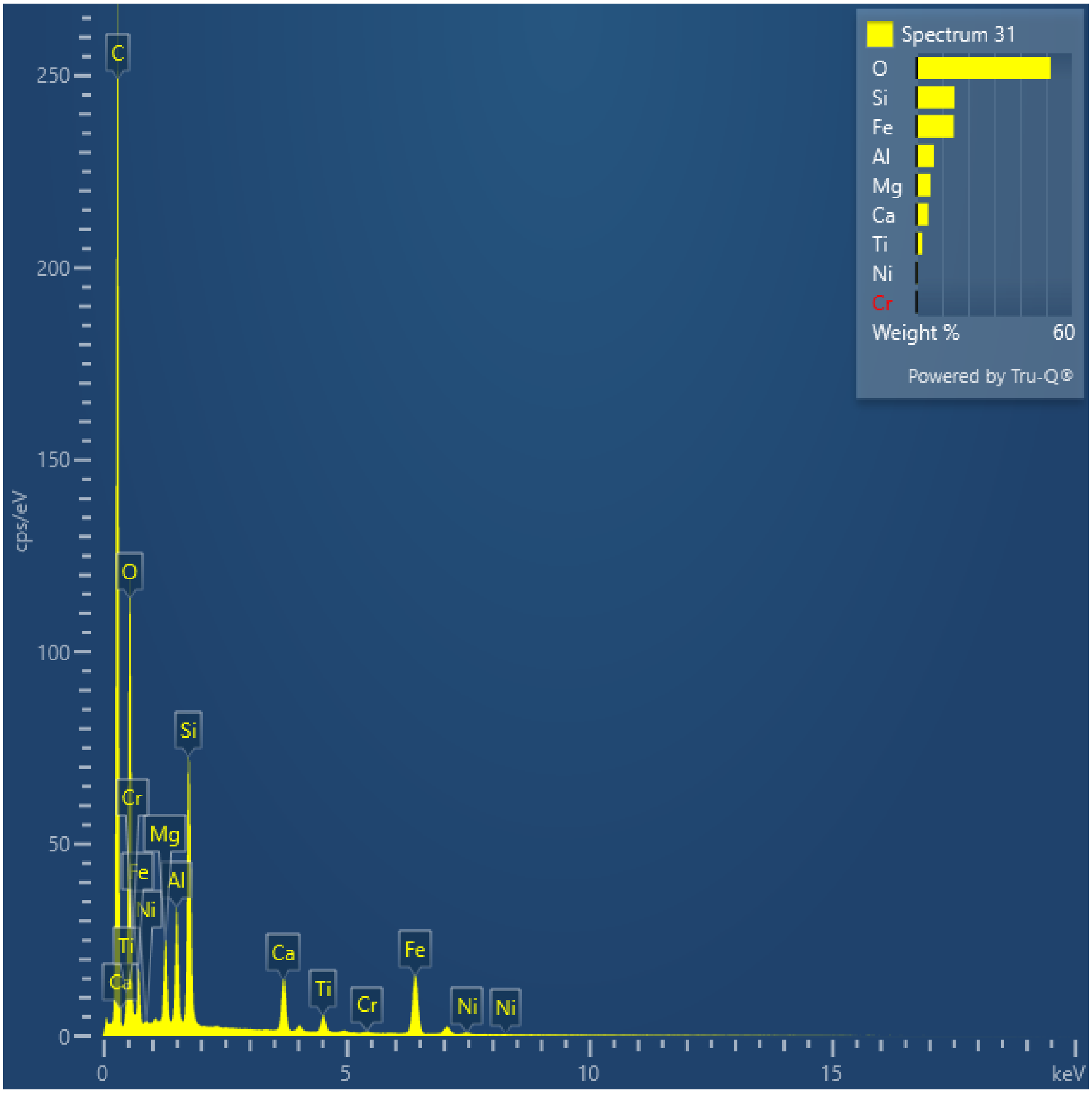
Powered by Tru-Q®
cps/eV
keV

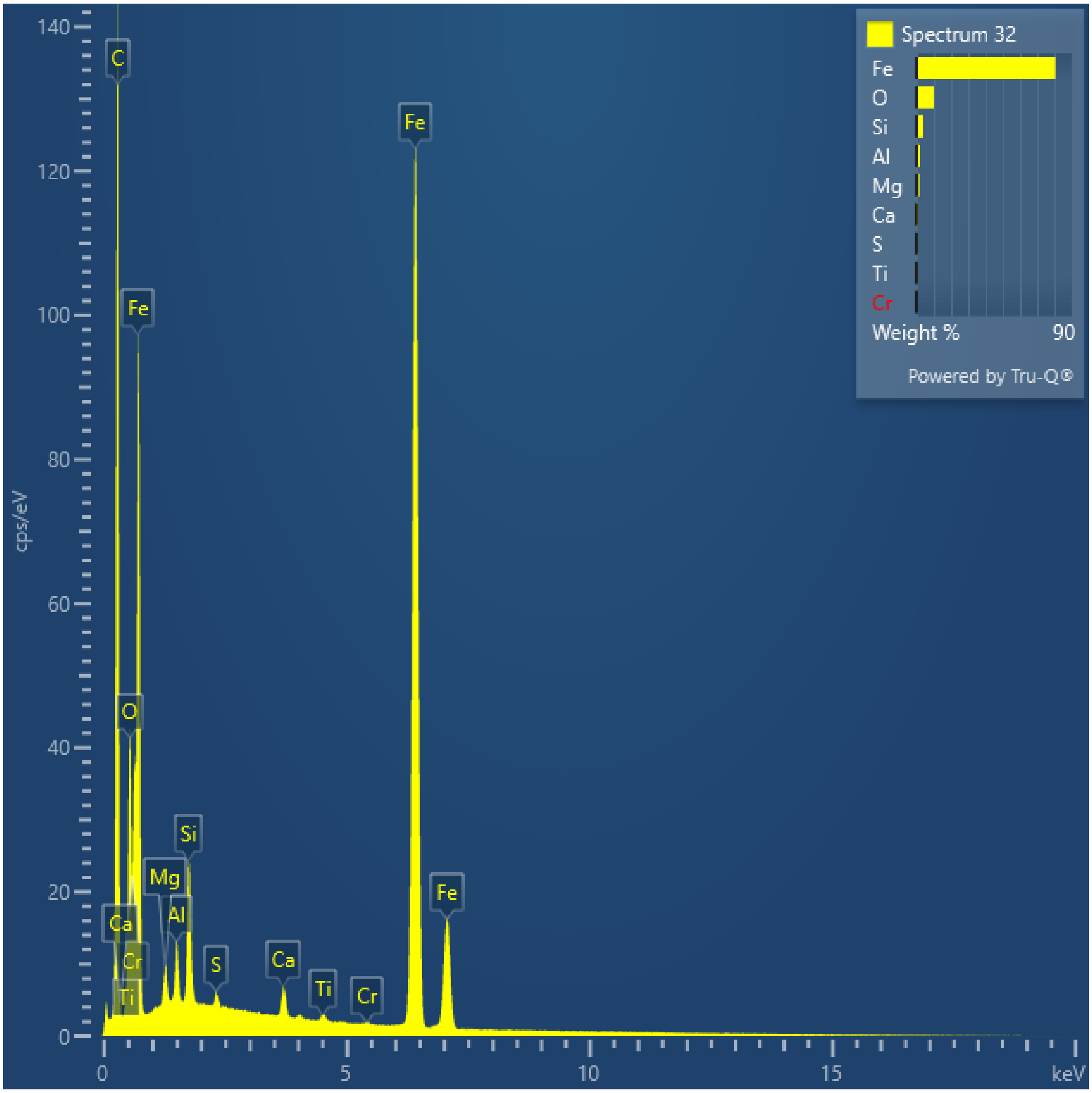

Spectrum 28
O
Si
Fe
Mg
Al
Ca
Ti
Cr
Mn
S
Weight %
60
Powered by Tru-Q®
cps/eV
0
50
100
150
200
0
5
10
15
keV
O
Si
C
Mg
Al
Fe
Ca
Ti
Cr
Mn
S
Ca
Ti
Fe
Cr
Mn
Fe


Spectrum 29
Fe
O
Si
Al
Mg
S
Ca
Ti
Weight %
90
Powered by Tru-Q®
cps/eV
0
20
40
60
80
100
120
140
5
10
15
keV
Fe
Fe
C
O
Si
Mg
Al
S
Ca
Ti
Ca
Ti
Fe


Spectrum 30
O
Si
Al
Ca
Fe
Mg
Ti
Na
Cr
S
Weight %
50
Powered by Tru-Q®
cps/eV
140
120
100
80
60
40
20
0
Si
O
Al
C
Ca
Na
Mg
Cr
Fe
Ti
Ca
S
Ti
Fe
Cr
Fe
0
5
10
15
keV



Spectrum 31
O
Si
Fe
Al
Mg
Ca
Ti
Ni
Cr
Weight %
60
Powered by Tru-Q®
cps/eV
keV
C
O
Si
Cr
Mg
Fe
Al
Ni
Ti
Ca



Spectrum 32
Fe
O
Si
Al
Mg
Ca
S
Ti
Cr
Weight %
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Powered by Tru-Q®
cps/eV
keV
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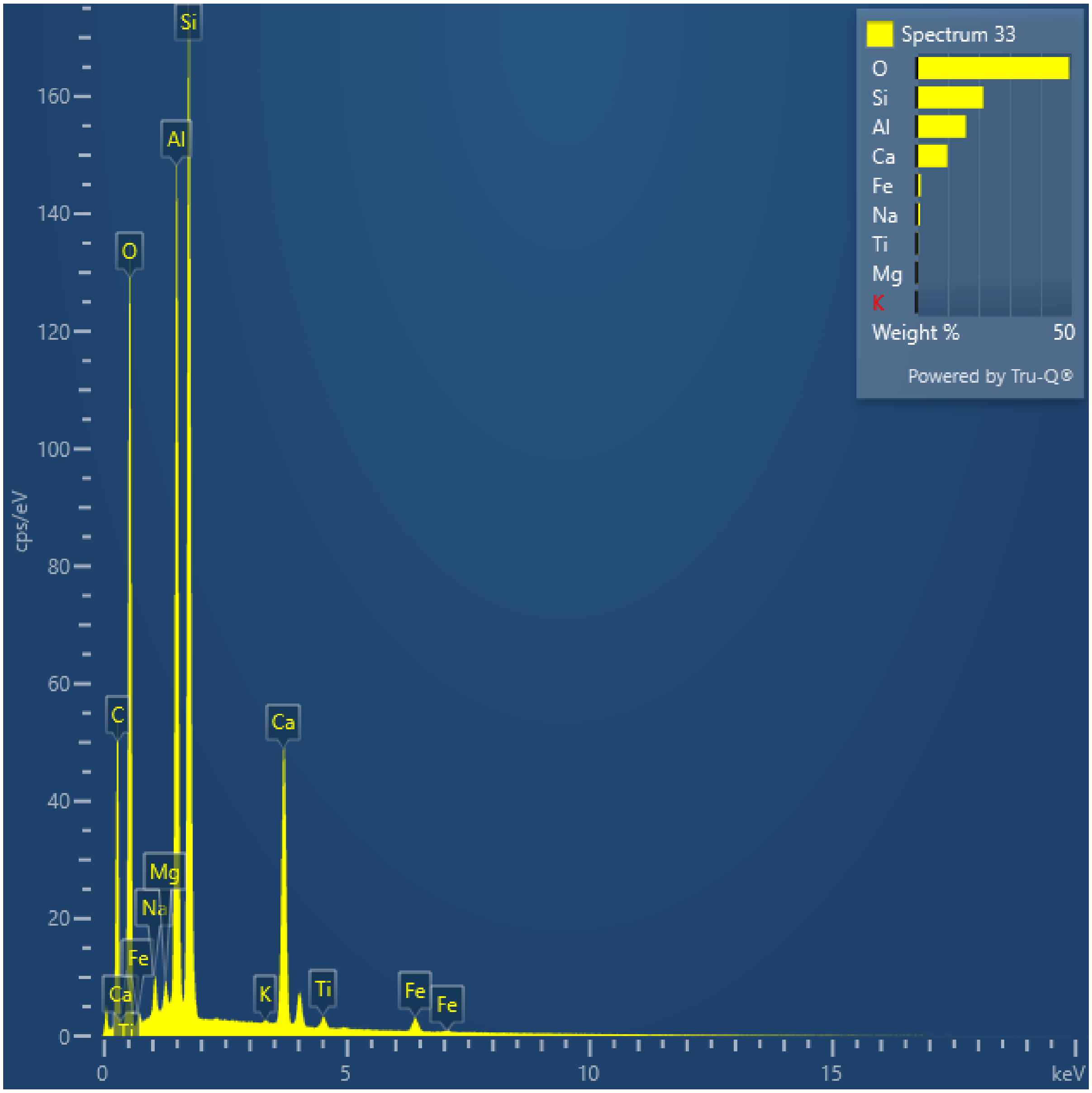
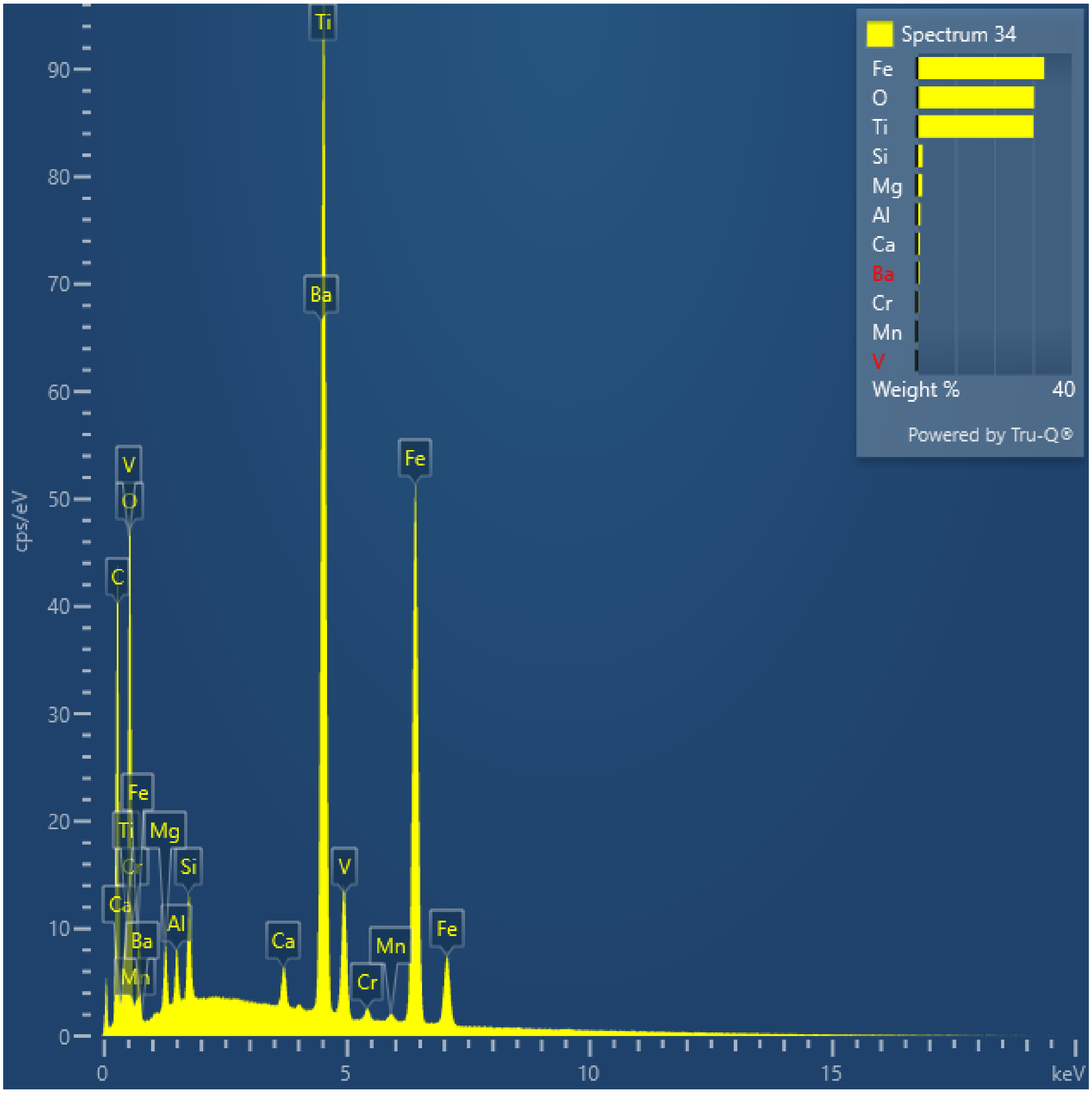
Si
Mg
Al
Ca
Cr
Ti
S


Spectrum 33
O
Si
Al
Ca
Fe
Na
Ti
Mg
K
Weight %
50
Powered by Tru-Q®
cps/eV
160
140
120
100
80
60
40
20
0
0
5
10
15
keV
Si
Al
O
C
Ca
Mg
Na
Fe
Ca
Ti
K
Ti
Fe
Fe


Spectrum 34
Fe
O
Ti
Si
Mg
Al
Ca
Ba
Cr
Mn
V
Weight %
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Powered by Tru-Q®
cps/eV
keV
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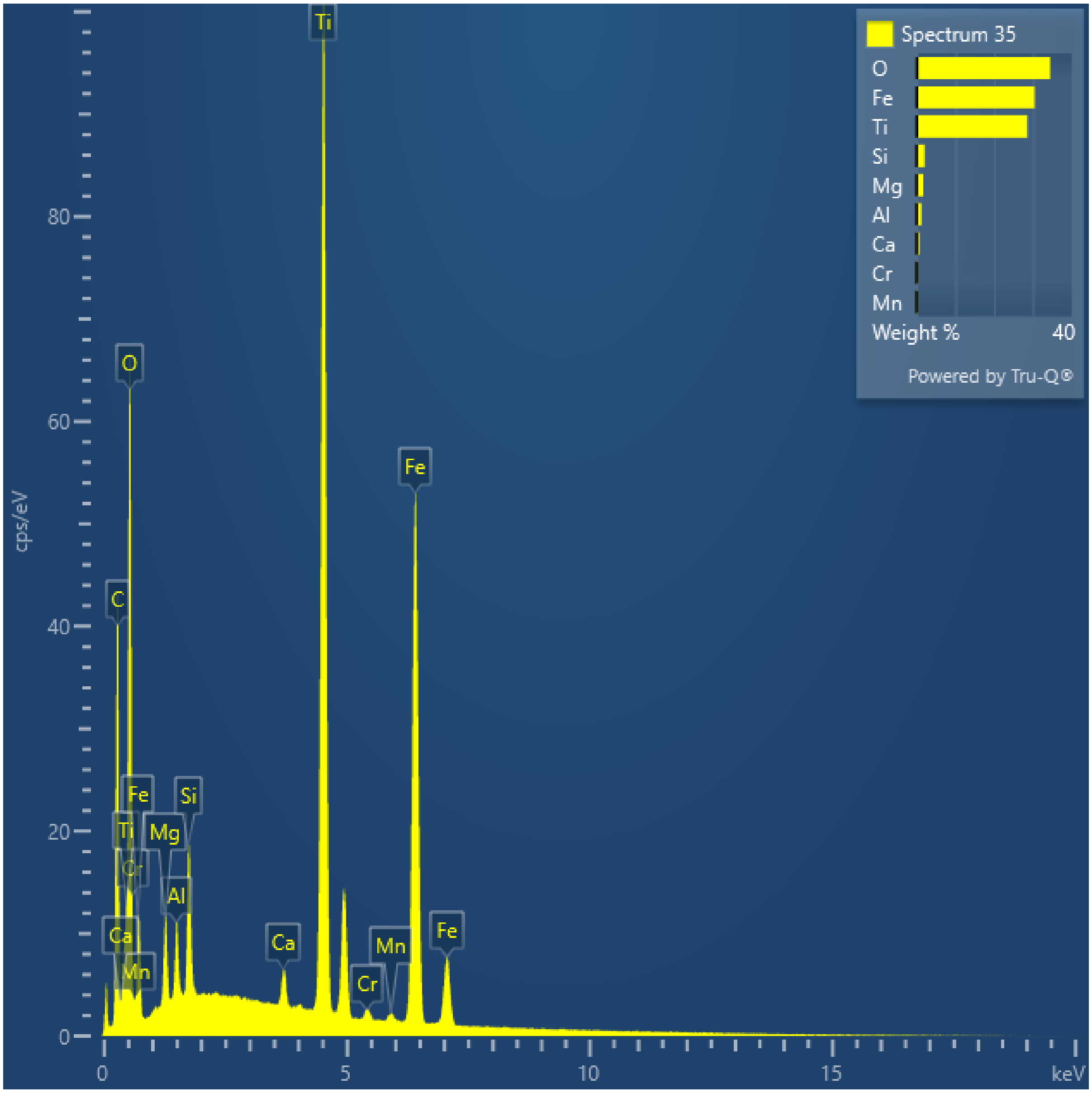
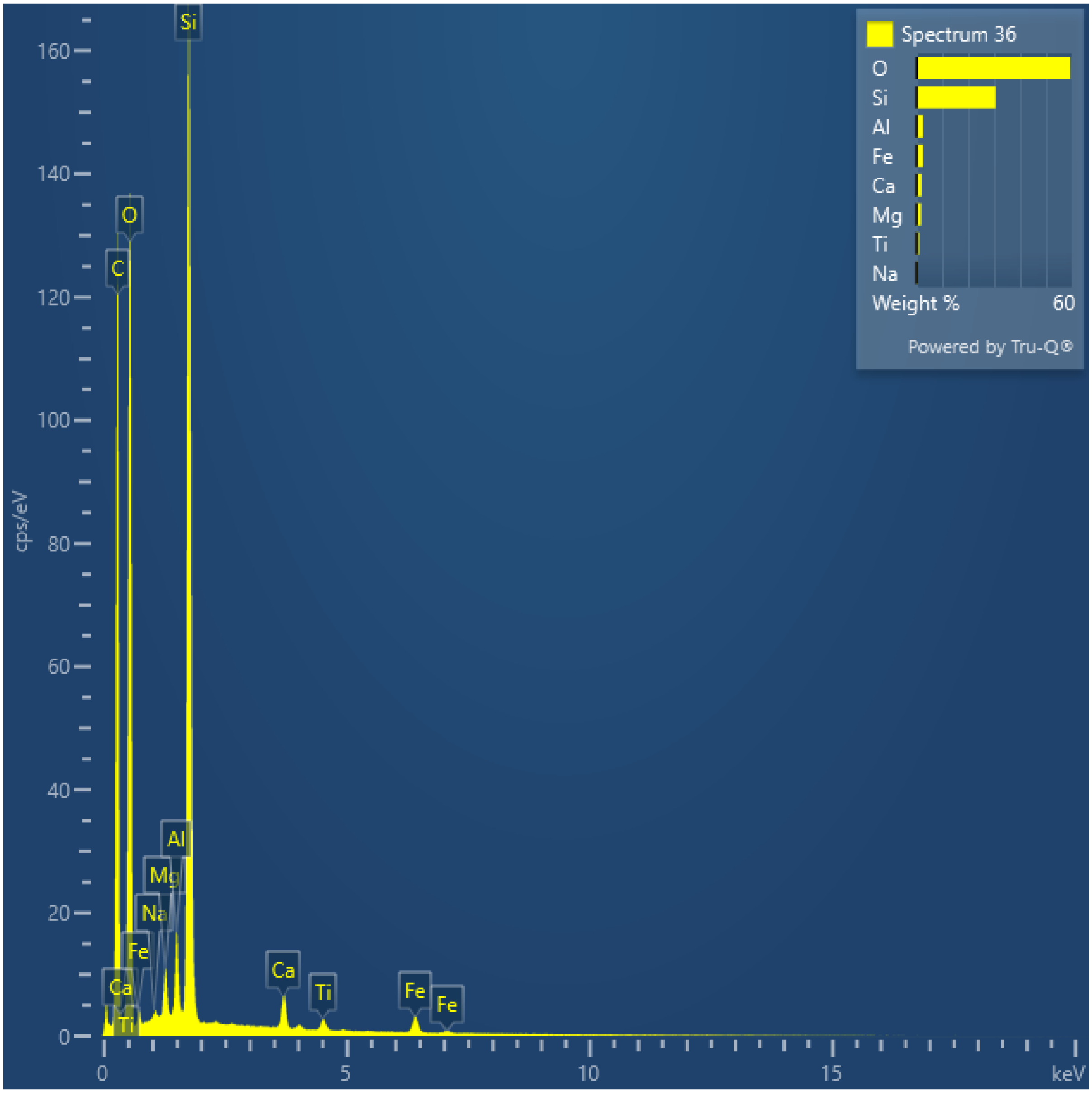
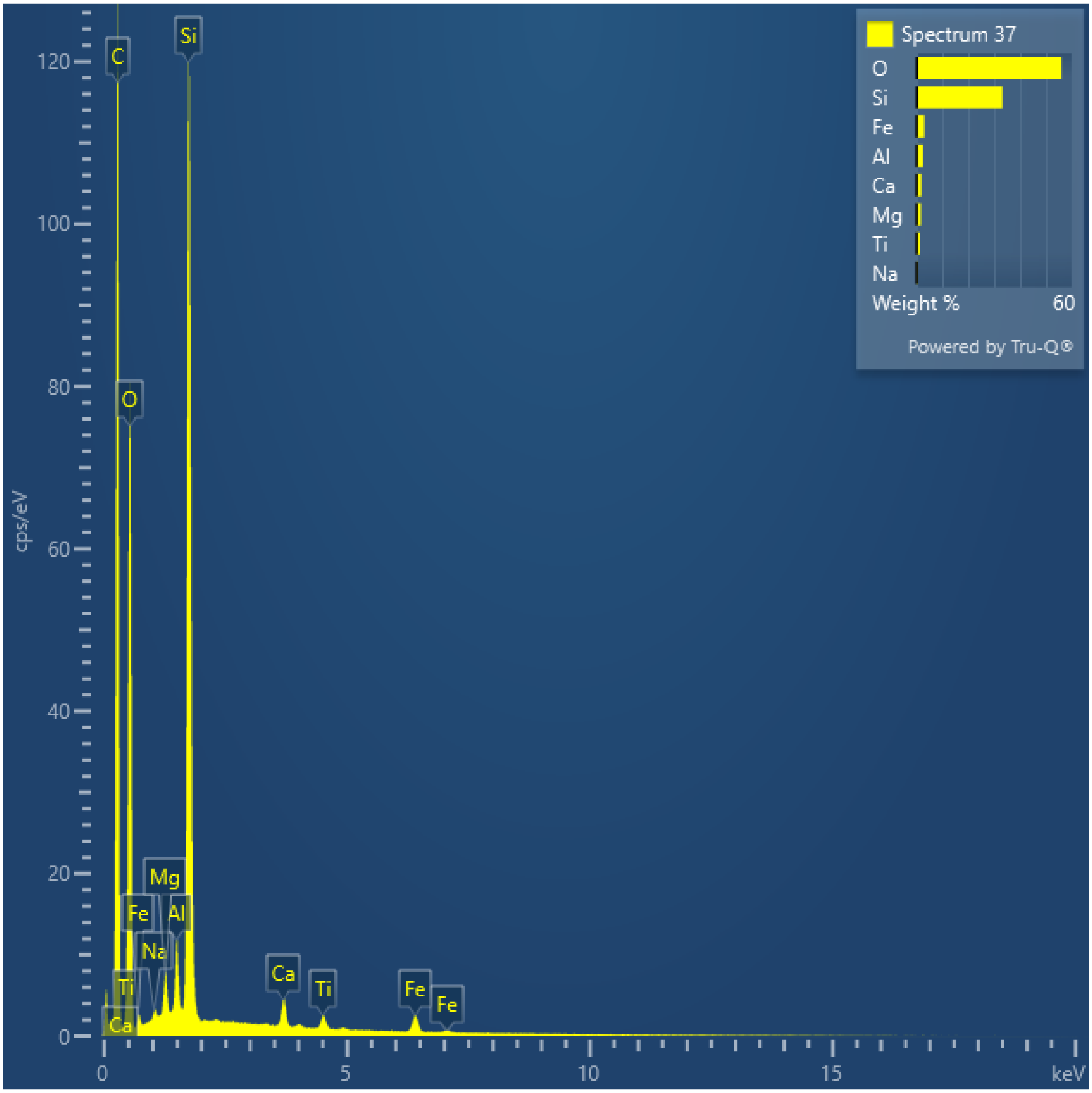
5
10
15
10
20
30
40
50
60
70
80
90


Spectrum 35
O
Fe
Ti
Si
Mg
Al
Ca
Cr
Mn
Weight %
40
Powered by Tru-Q®
cps/eV
0
20
40
60
80
5
10
15
keV
Ti
O
Fe
C
Fe
Si
Ti
Mg
Cr
Al
Ca
Mn
Ca
Mn
Cr
Fe


Spectrum 36
O
Si
Al
Fe
Ca
Mg
Ti
Na
Weight %
60
Powered by Tru-Q®
cps/eV
160
140
120
100
80
60
40
20
0
Si
O
C
Al
Mg
Na
Fe
Ca
Ti
Ca
Ti
Fe
Fe
0
5
10
15
keV


Spectrum 37
O
Si
Fe
Al
Ca
Mg
Ti
Na
Weight %
60
Powered by Tru-Q®
cps/eV
120
100
80
60
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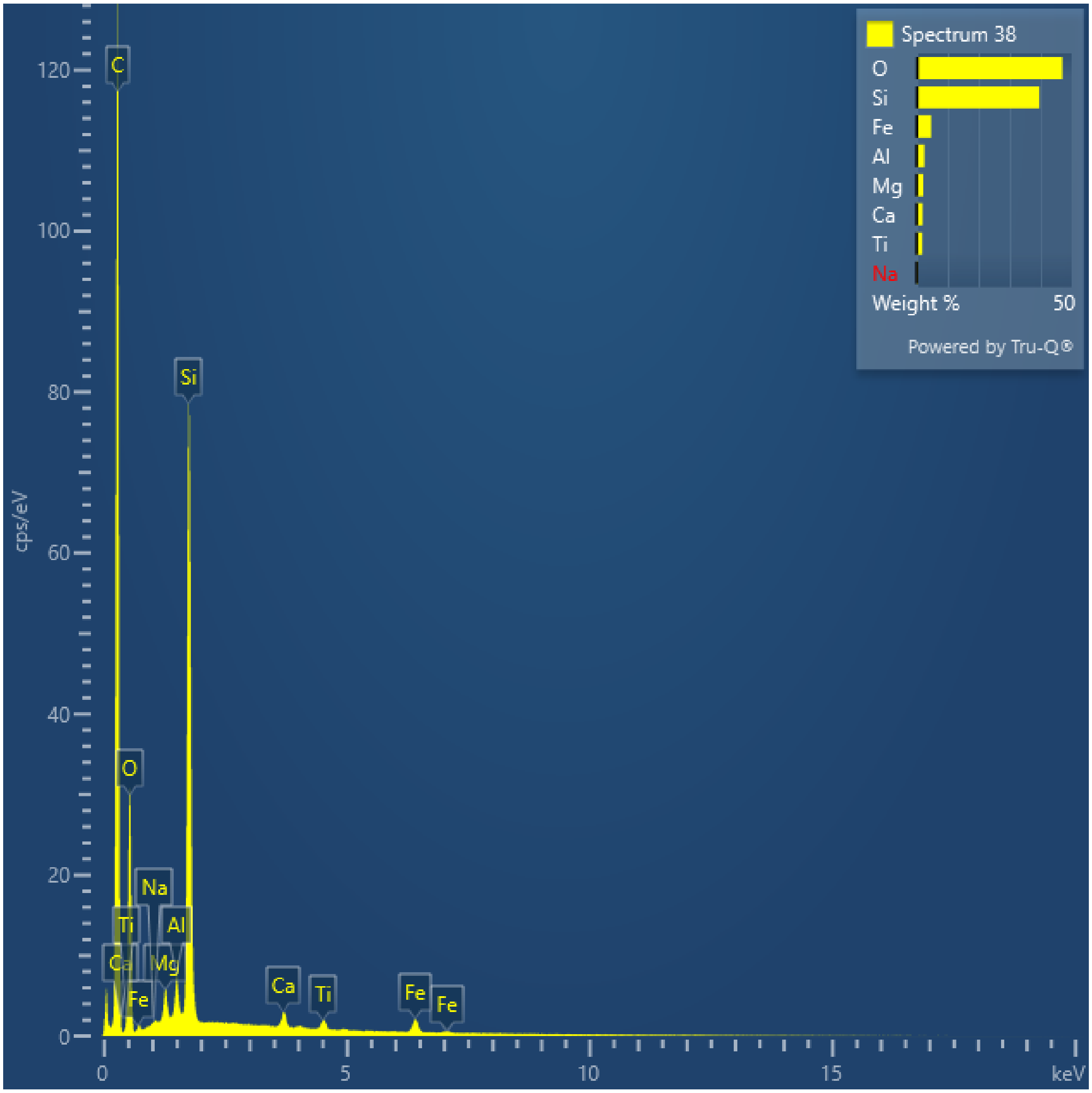
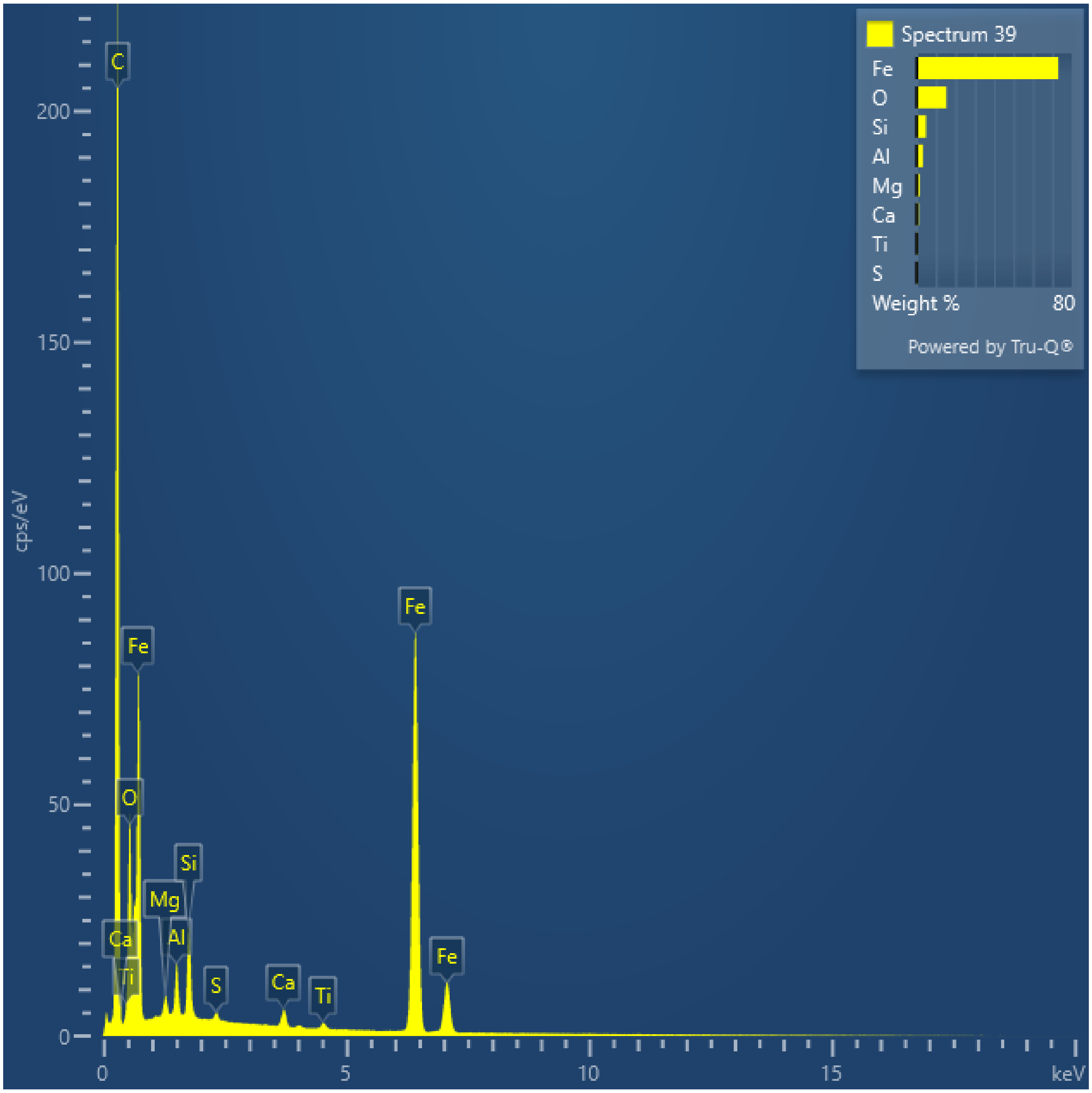
C
Si
O
Mg
Fe
Al
Na
Ti
Ca
Ca
Ti
Fe
Fe
0
5
10
15
keV


Spectrum 38
O
Si
Fe
Al
Mg
Ca
Ti
Na
Weight %
50
Powered by Tru-Q®
cps/eV
120
100
80
60
40
20
0
C
Si
O
Na
Ti
Al
Ca
Mg
Fe
Ca
Ti
Fe
Fe
0
5
10
15
keV


Spectrum 39
Fe
O
Si
Al
Mg
Ca
Ti
S
Weight %
80
Powered by Tru-Q®
cps/eV
200
150
100
50
0
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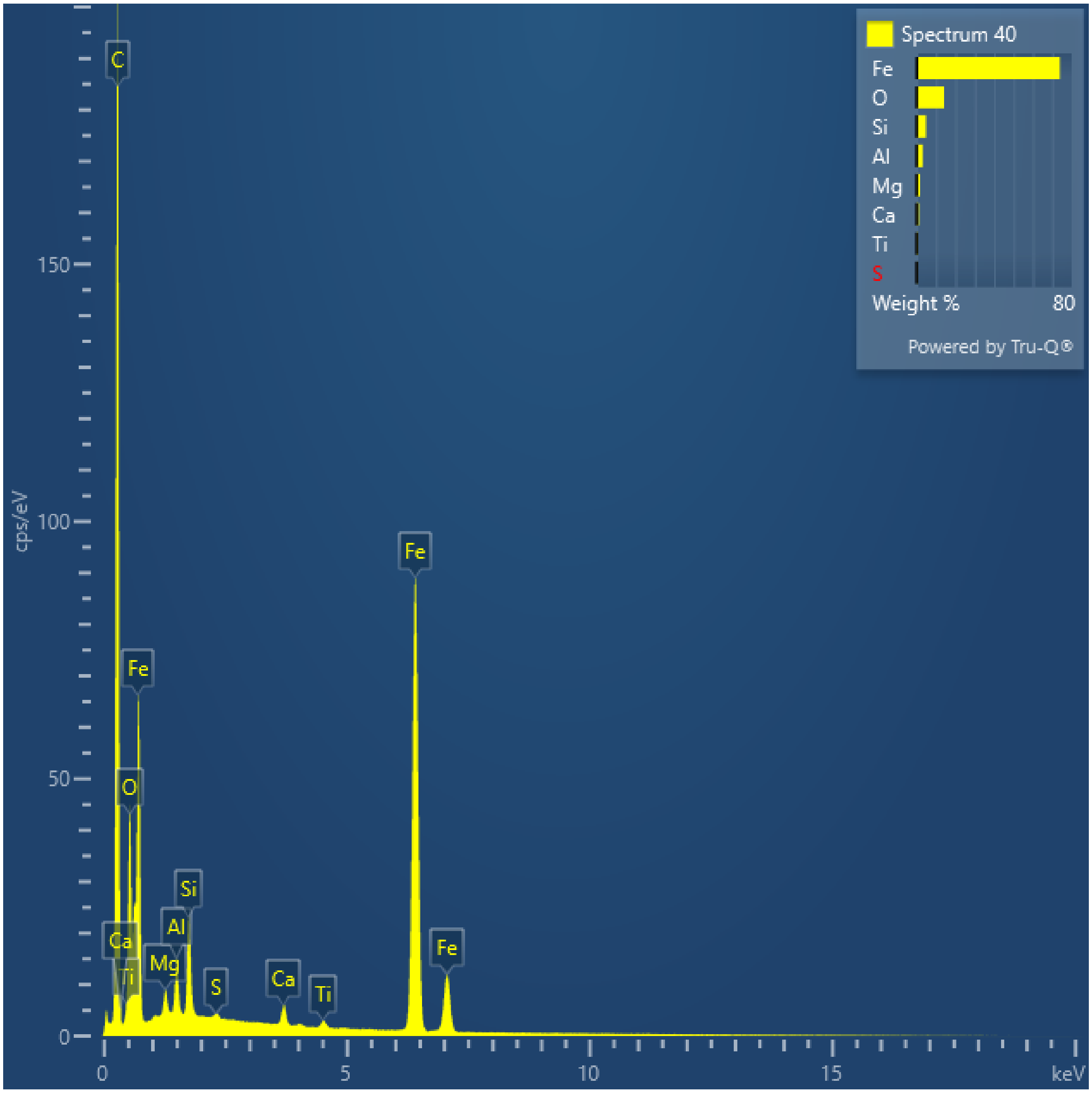
Fe
O
Si
Mg
Ca
Al
Ti
S
Ca
Ti
Fe
Fe
0
5
10
15
keV



Spectrum 40
Fe
O
Si
Al
Mg
Ca
Ti
S
Weight %
80
Powered by Tru-Q®
cps/eV
150
100
50
0
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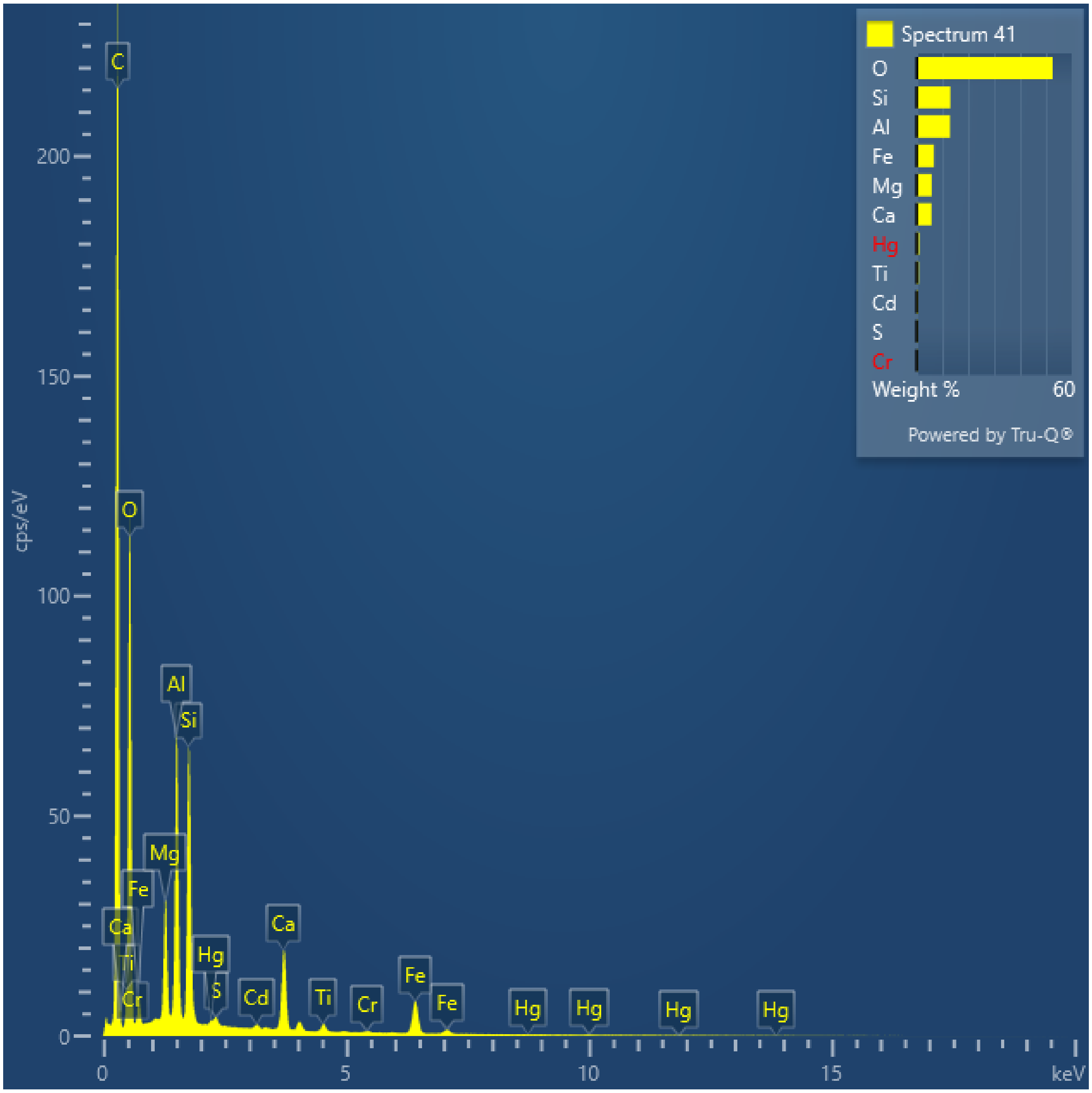
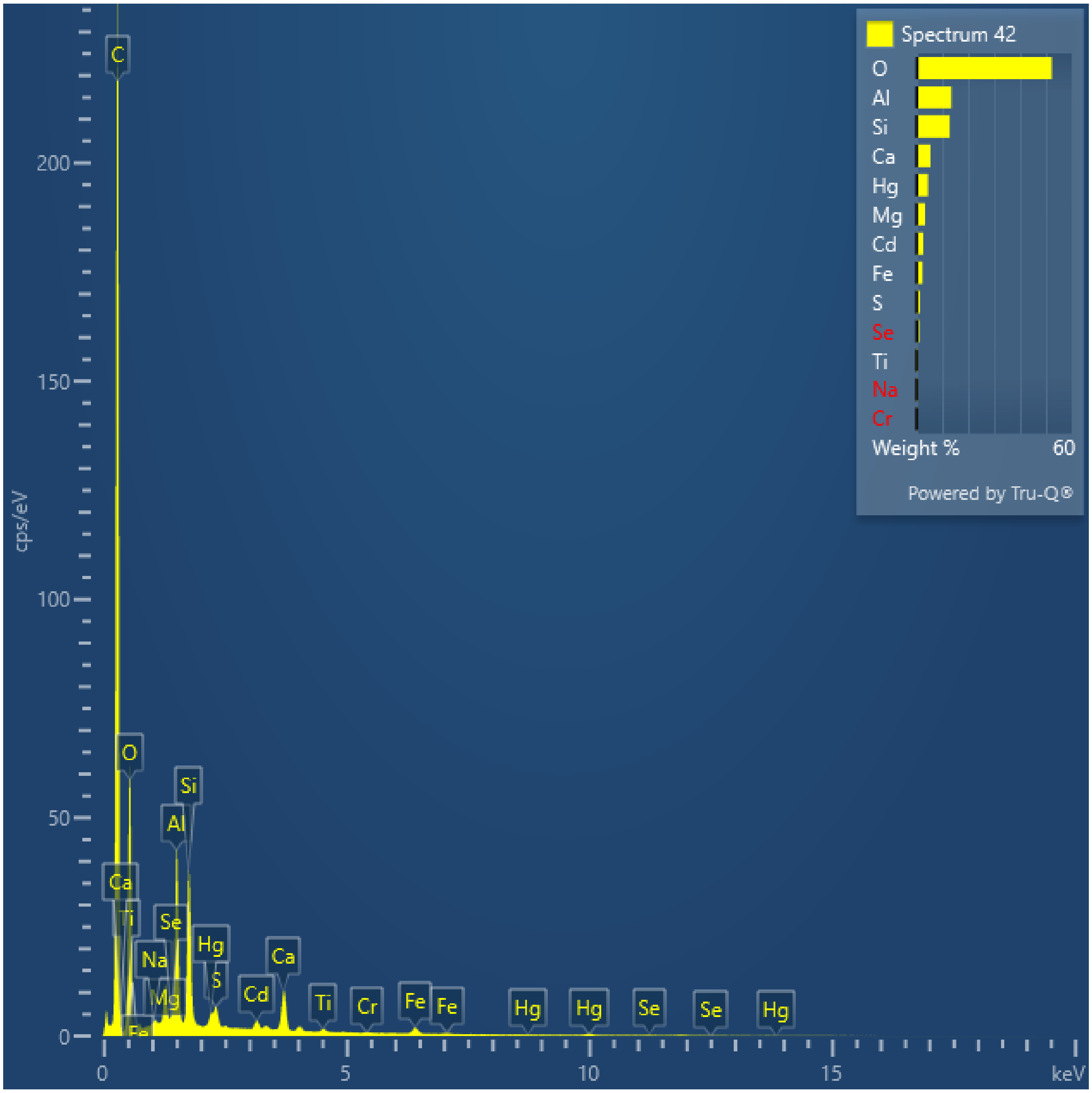
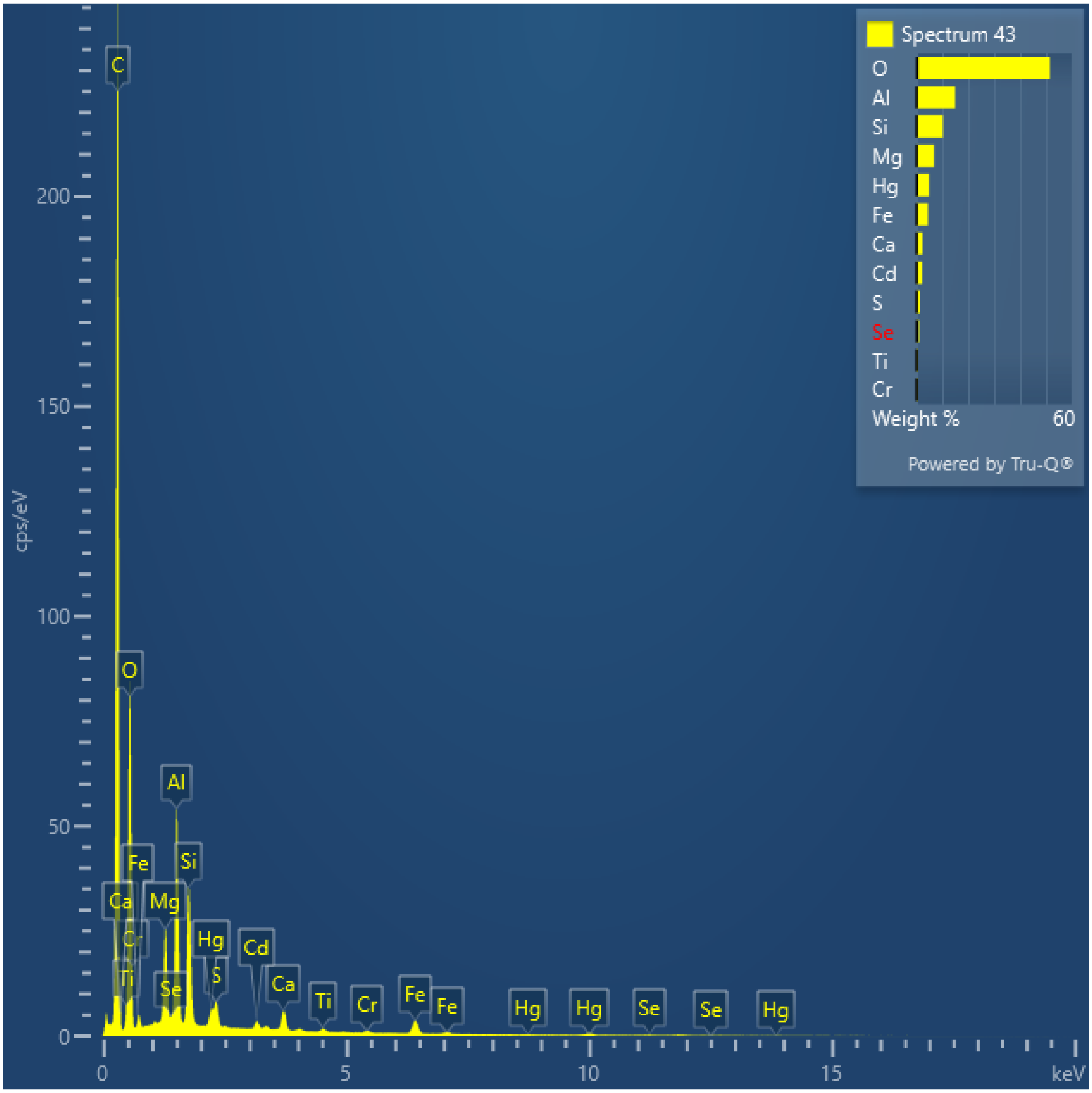
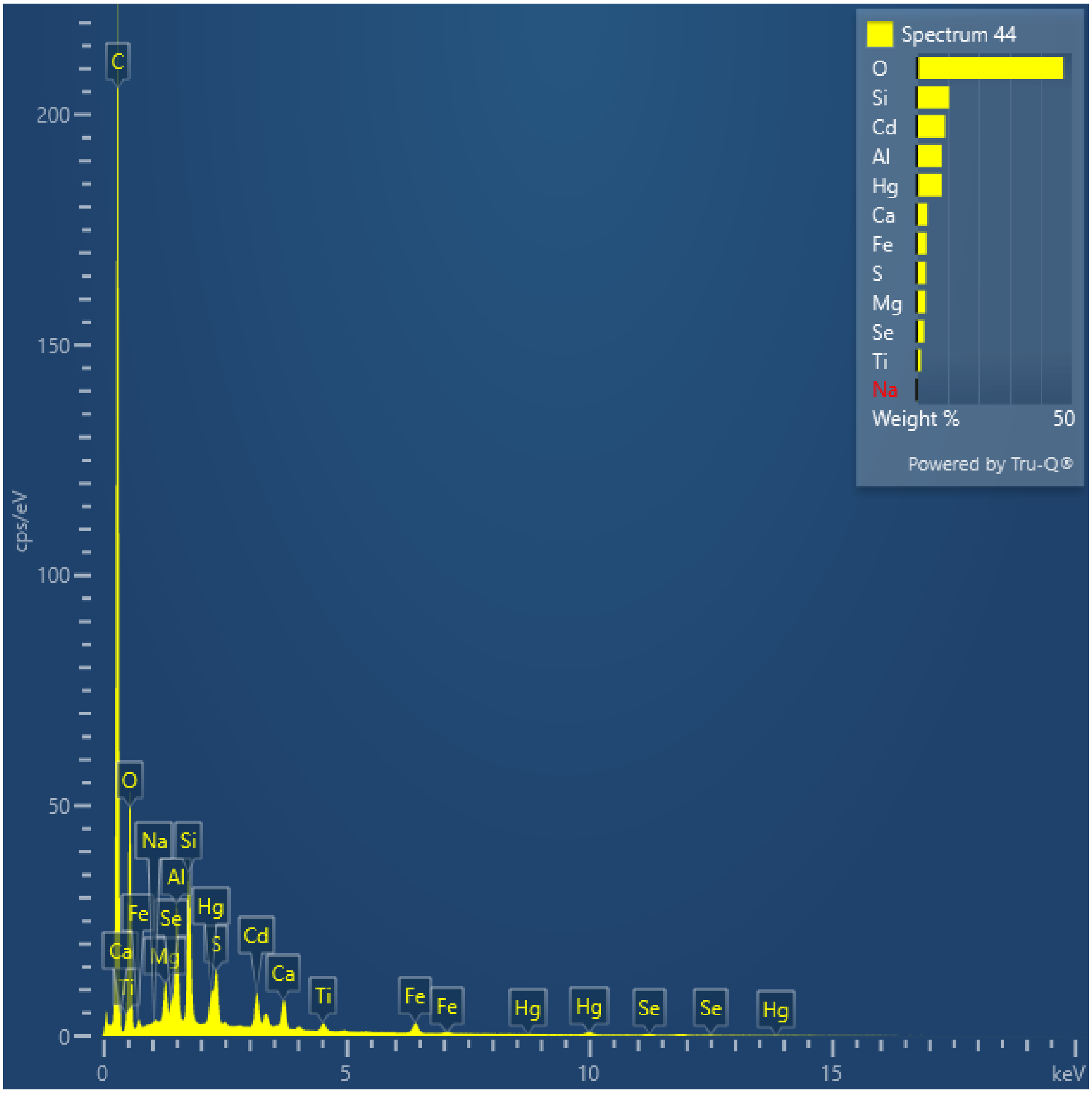
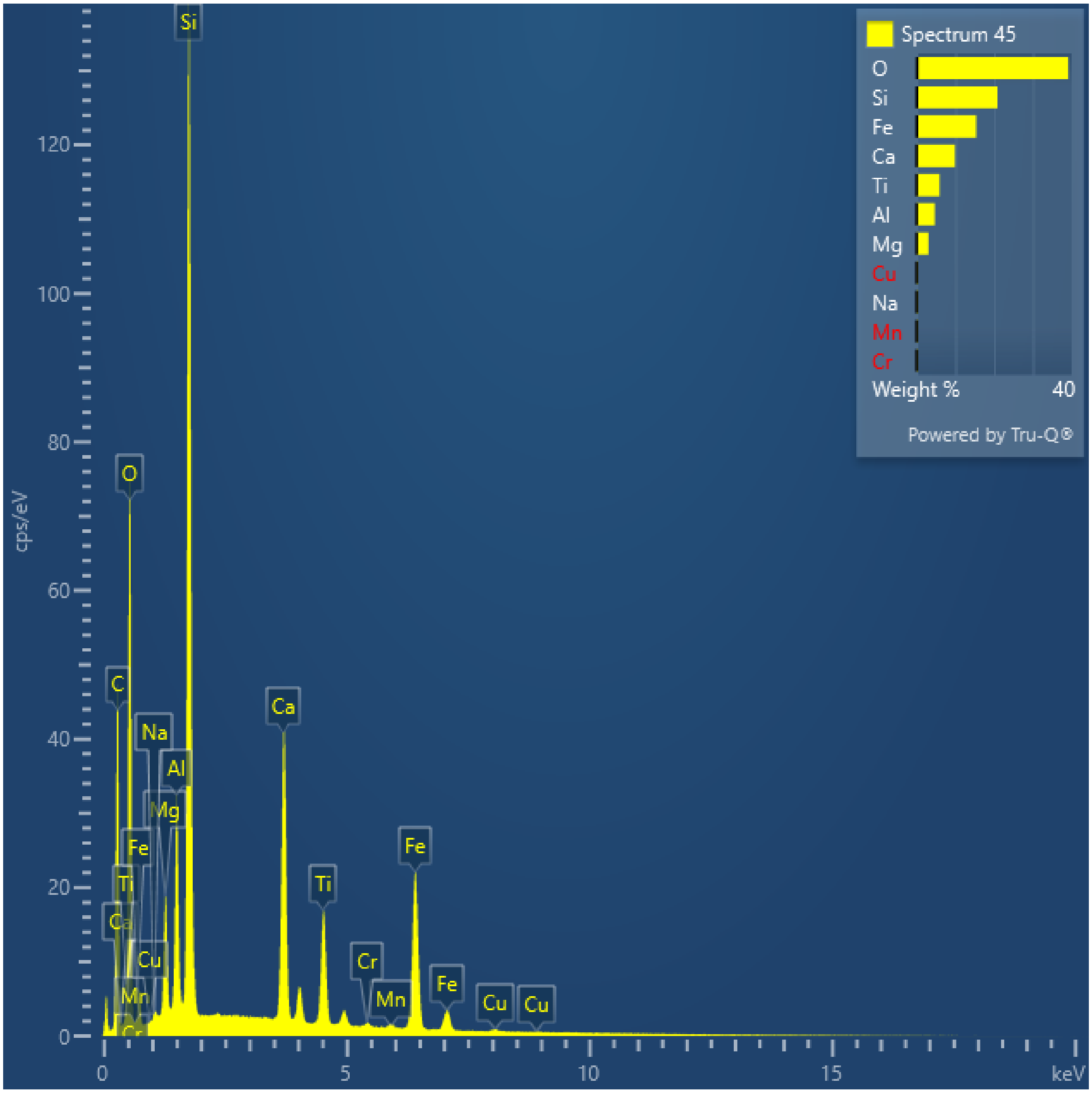
Fe
O
Si
Al
Ca
Ti
Mg
S
Ca
Ti
Fe
Fe
0
5
10
15
keV

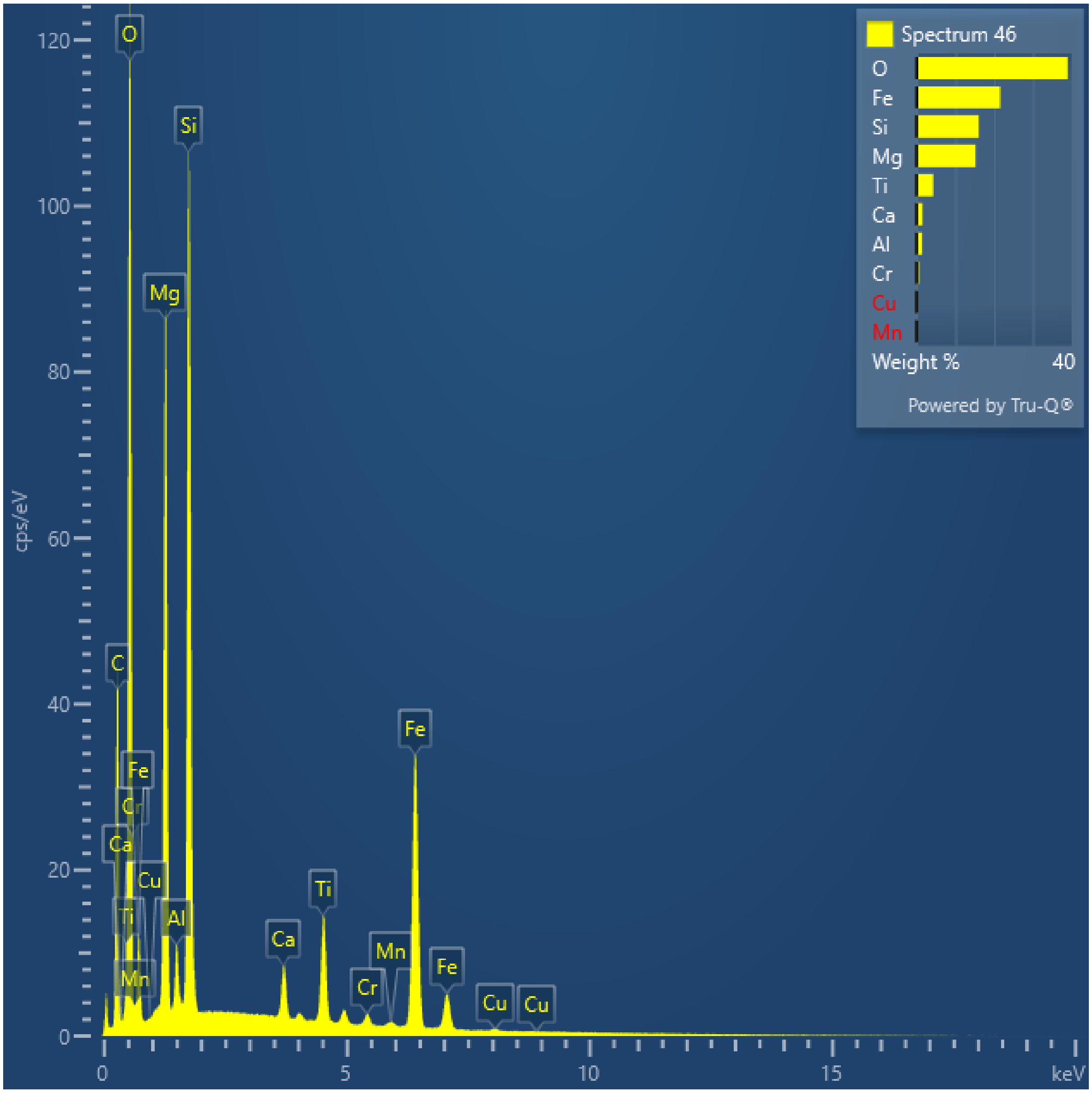

Spectrum 41
O
Si
Al
Fe
Mg
Ca
Hg
Ti
Cd
S
Cr
Weight %
60
Powered by Tru-Q®
cps/eV
200
150
100
50
0
5
10
15
keV
C
O
Al
Si
Mg
Fe
Ca
Ti
Cr
Hg
S
Cd
Ca
Ti
Cr
Fe
Fe
Hg
Hg
Hg
Hg

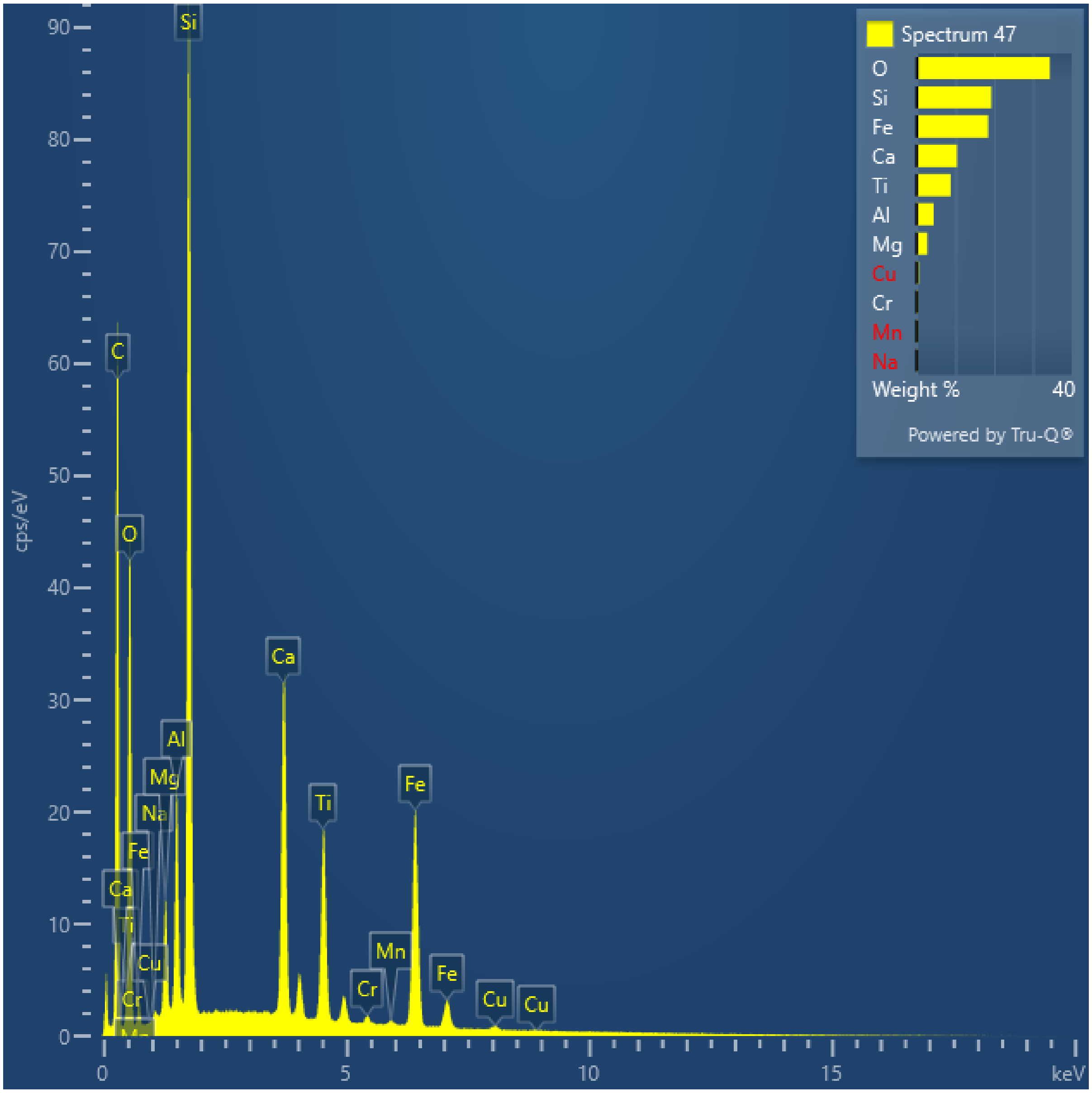

Spectrum 42
O
Al
Si
Ca
Hg
Mg
Cd
Fe
S
Se
Ti
Na
Cr
Weight %
60
Powered by Tru-Q®
cps/eV
0
50
100
150
200
keV
0
5
10
15
C
O
Si
Al
Ca
Ti
Se
Na
Mg
Hg
S
Cd
Ca
Ti
Cr
Fe
Fe
Hg
Hg
Se
Se
Hg


Spectrum 43
O
Al
Si
Mg
Hg
Fe
Ca
Cd
S
Se
Ti
Cr
Weight %
60
Powered by Tru-Q®
cps/eV
0
50
100
150
200
5
10
15
keV
C
O
Al
Fe
Si
Ca
Mg
Cr
Hg
Cd
Ti
Se
S
Ca
Ti
Cr
Fe
Fe
Hg
Hg
Se
Se
Hg

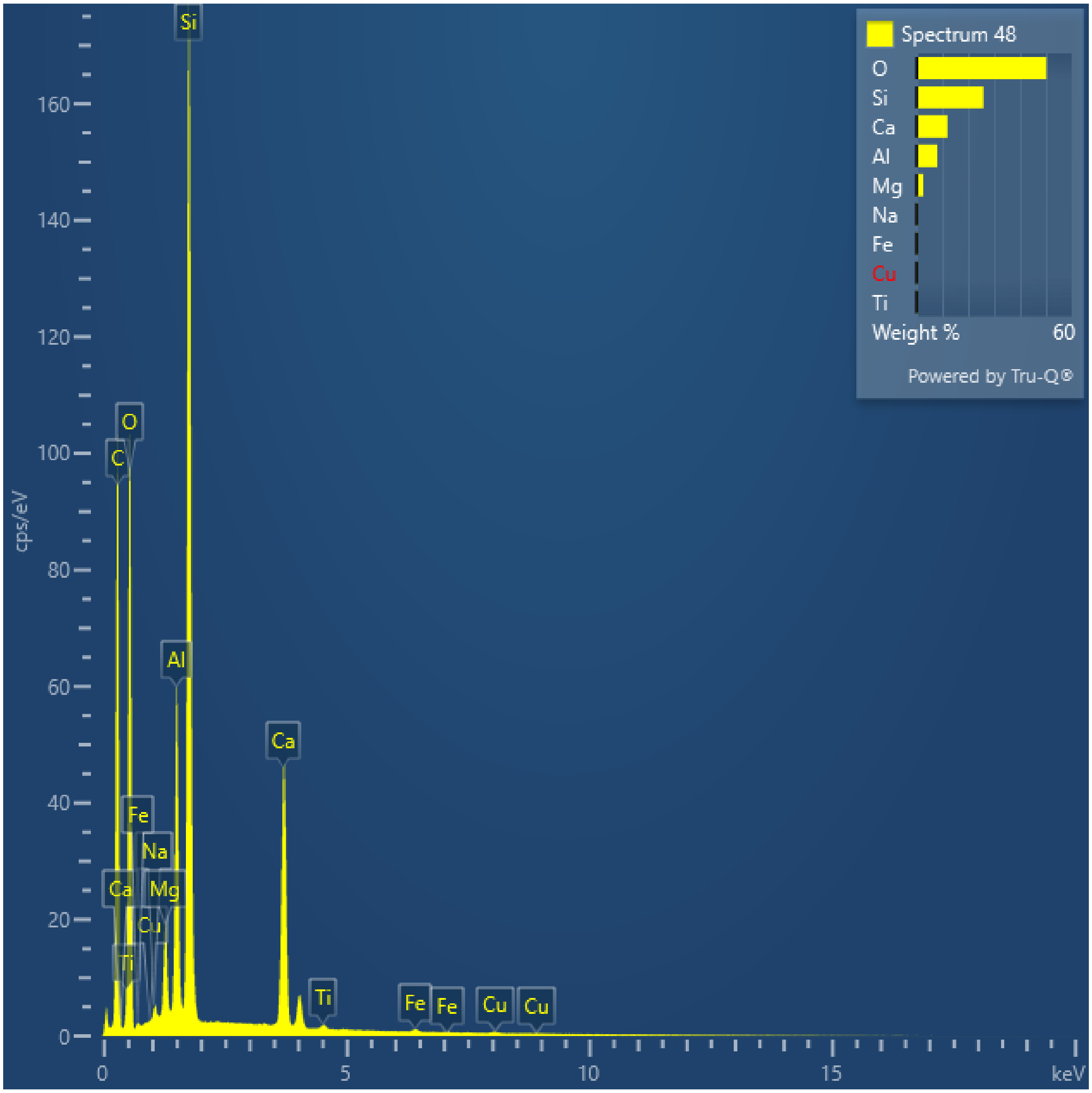

Spectrum 44
O
Si
Cd
Al
Hg
Ca
Fe
S
Mg
Se
Ti
Na
Weight %
50
Powered by Tru-Q®
cps/eV
keV
C
O
Na
Si
Al
Fe
Se
Hg
Ca
Mg
S
Cd
Ti

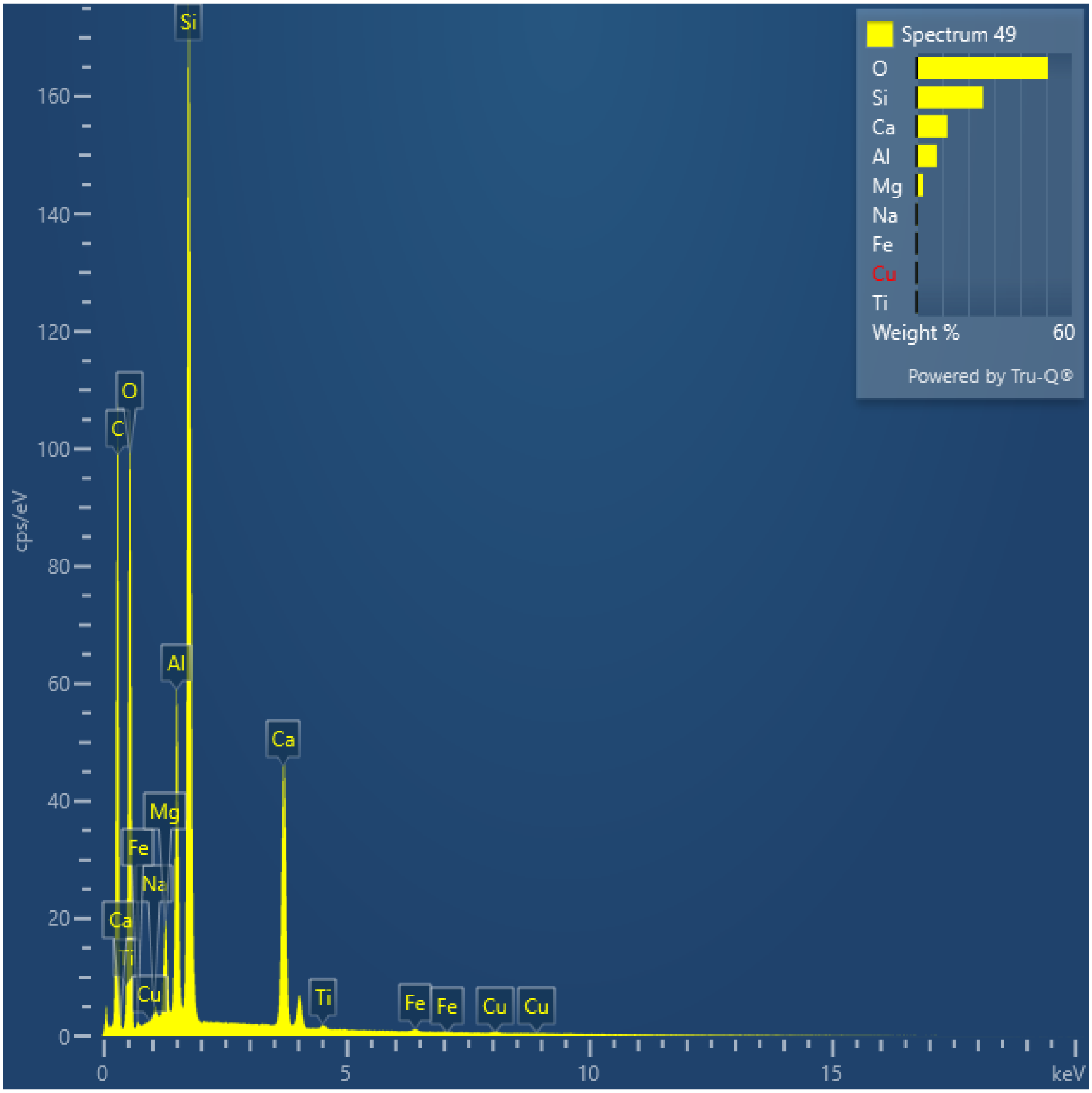

Spectrum 45
O
Si
Fe
Ca
Ti
Al
Mg
Cu
Na
Mn
Cr
Weight %
40
Powered by Tru-Q®
cps/eV
keV
Si
O
C
Na
Al
Mg
Fe
Ti
Ca
Cu
Mn
Ca
Ti
Cr
Mn
Fe
Fe
Cu
Cu


Spectrum 46
O
Fe
Si
Mg
Ti
Ca
Al
Cr
Cu
Mn
Weight %
40
Powered by Tru-Q®
cps/eV
keV
0
20
40
60
80
100
120
5
10
15
C
Cu
Ti
Mn
Fe
Cr



Spectrum 47
O
Si
Fe
Ca
Ti
Al
Mg
Cu
Cr
Mn
Na
Weight %
40
Powered by Tru-Q®
cps/eV
keV


Spectrum 48
O
Si
Ca
Al
Mg
Na
Fe
Cu
Ti
Weight %
60
Powered by Tru-Q®
cps/eV
keV
Si
O
C
Al
Ca
Fe
Na
Ca
Mg
Cu
Ti
Ti
Fe
Fe
Cu
Cu


Spectrum 49
O
Si
Ca
Al
Mg
Na
Fe
Cu
Ti
Weight %
60
Powered by Tru-Q®
cps/eV
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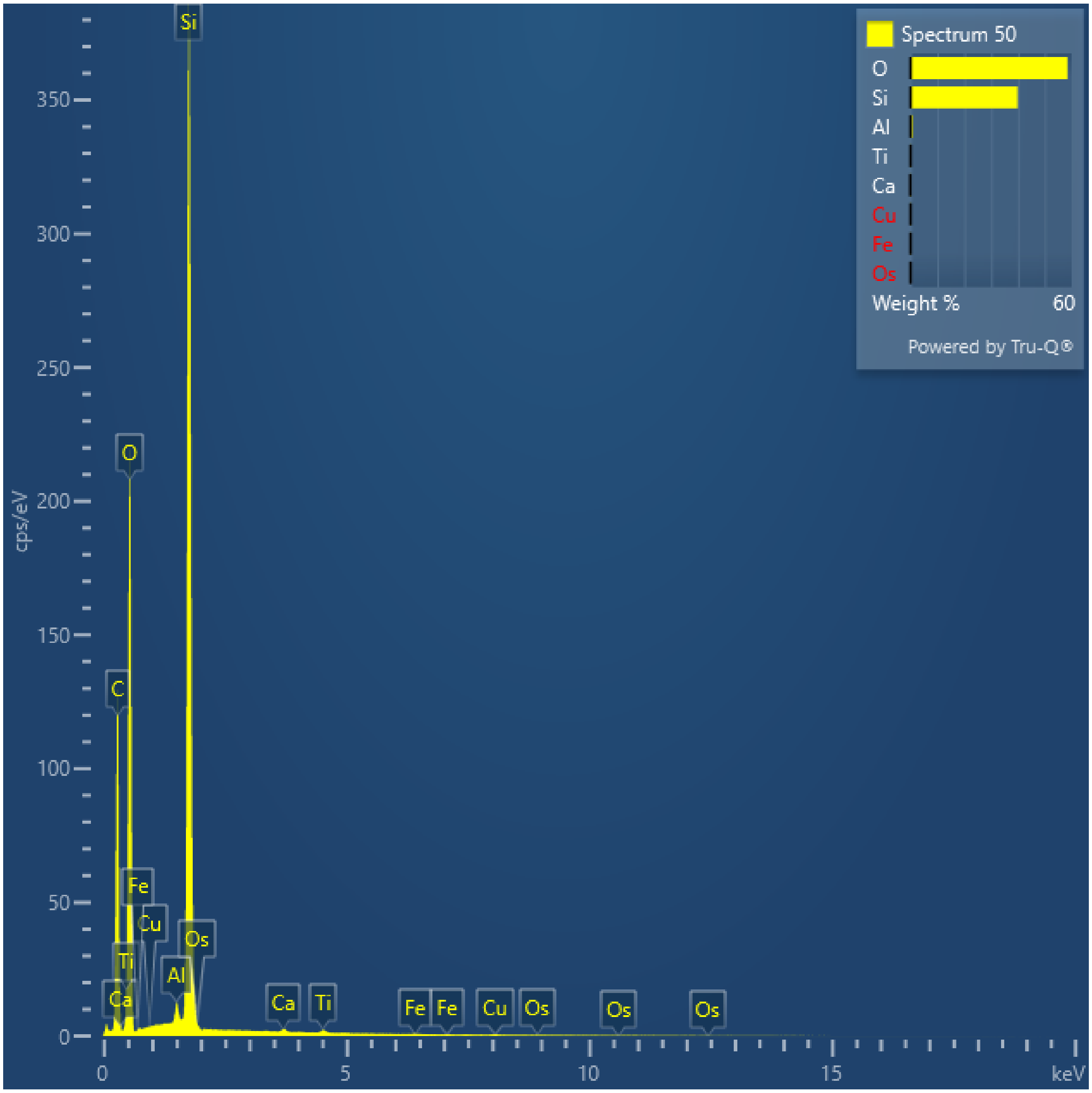
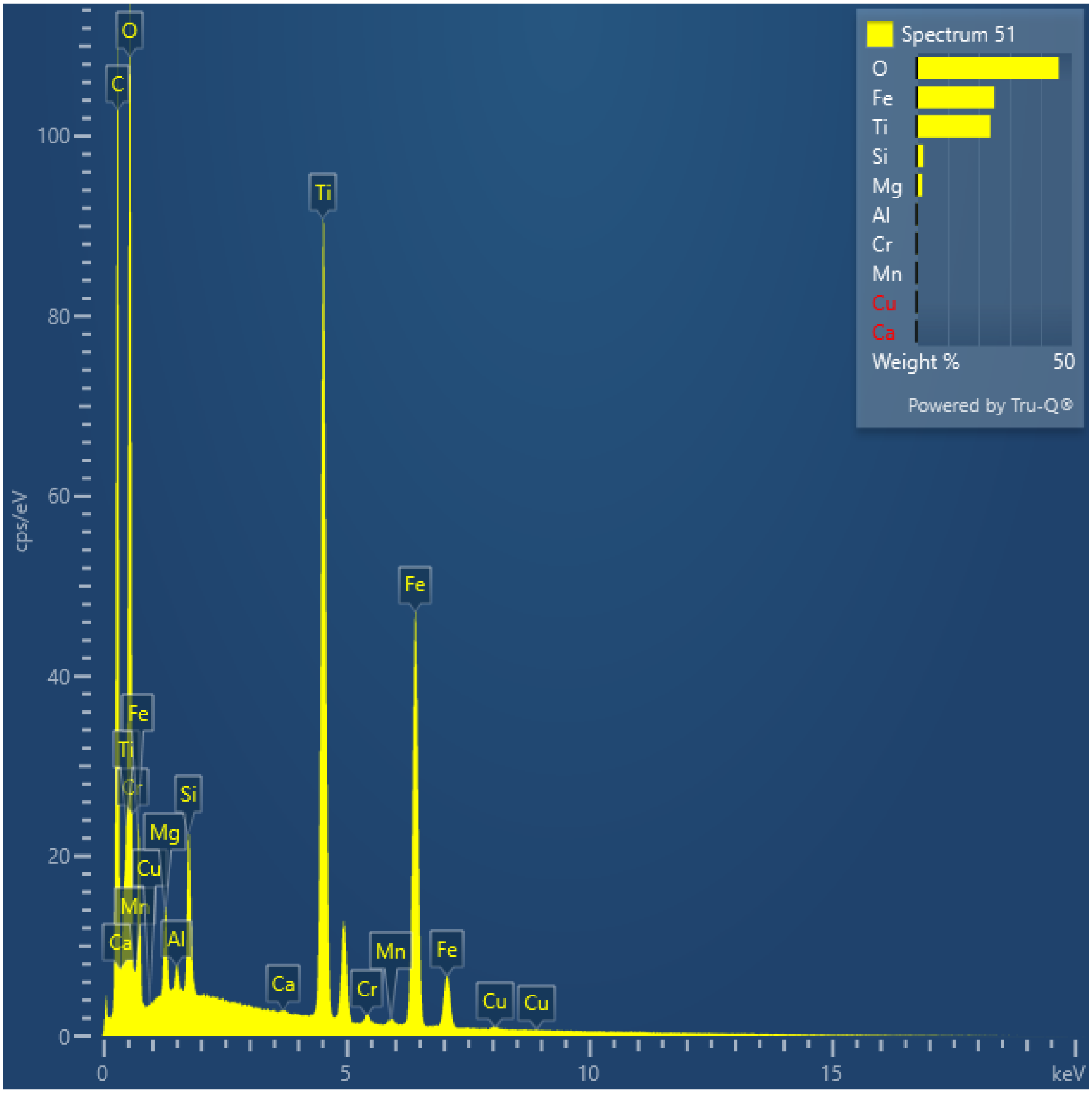
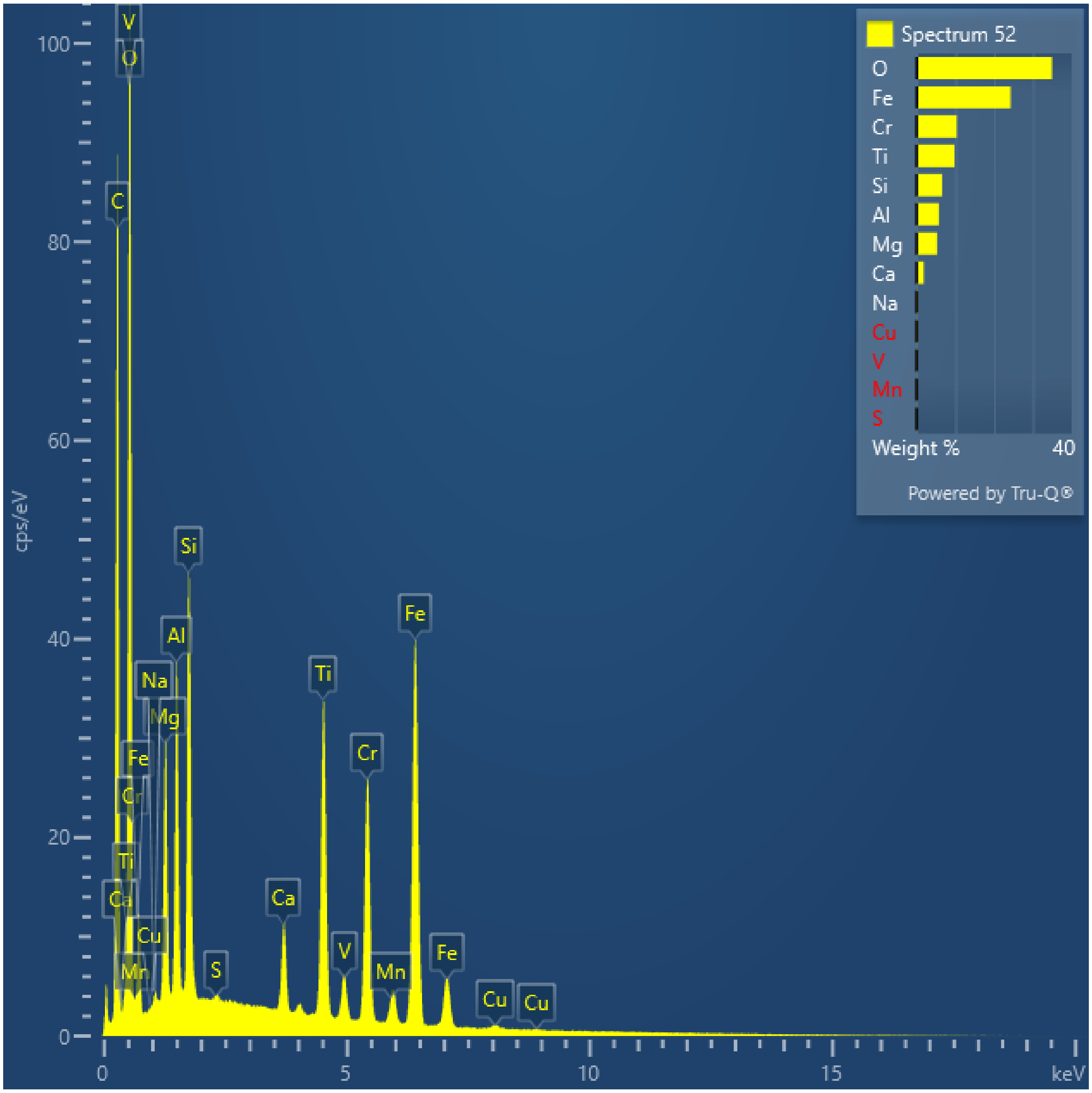
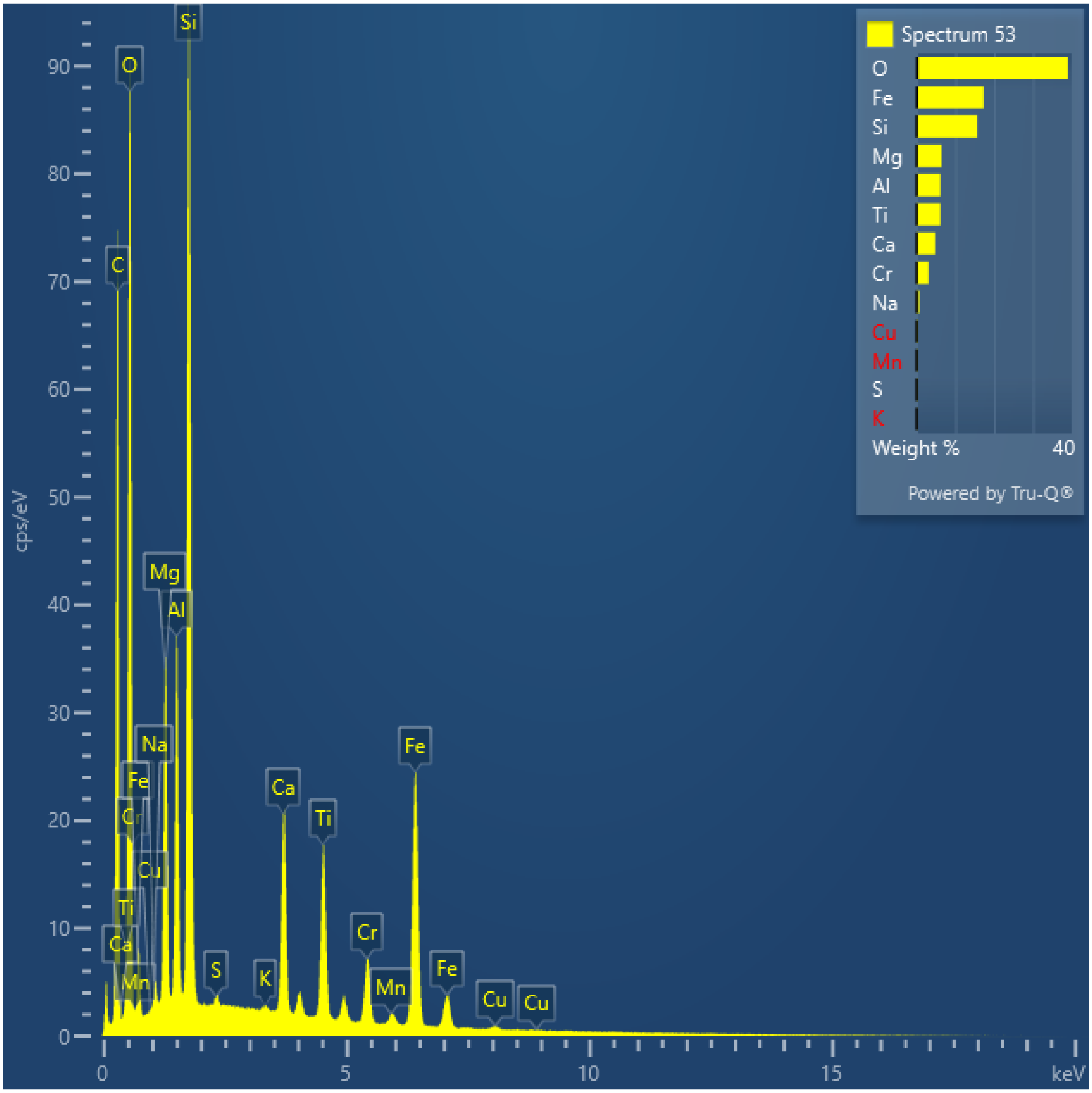
140
120
100
80
60
40
20
0
Si
O
C
Al
Ca
Mg
Fe
Na
Ca
Ti
Cu
Ti
Fe
Fe
Cu
Cu
0
5
10
15
keV

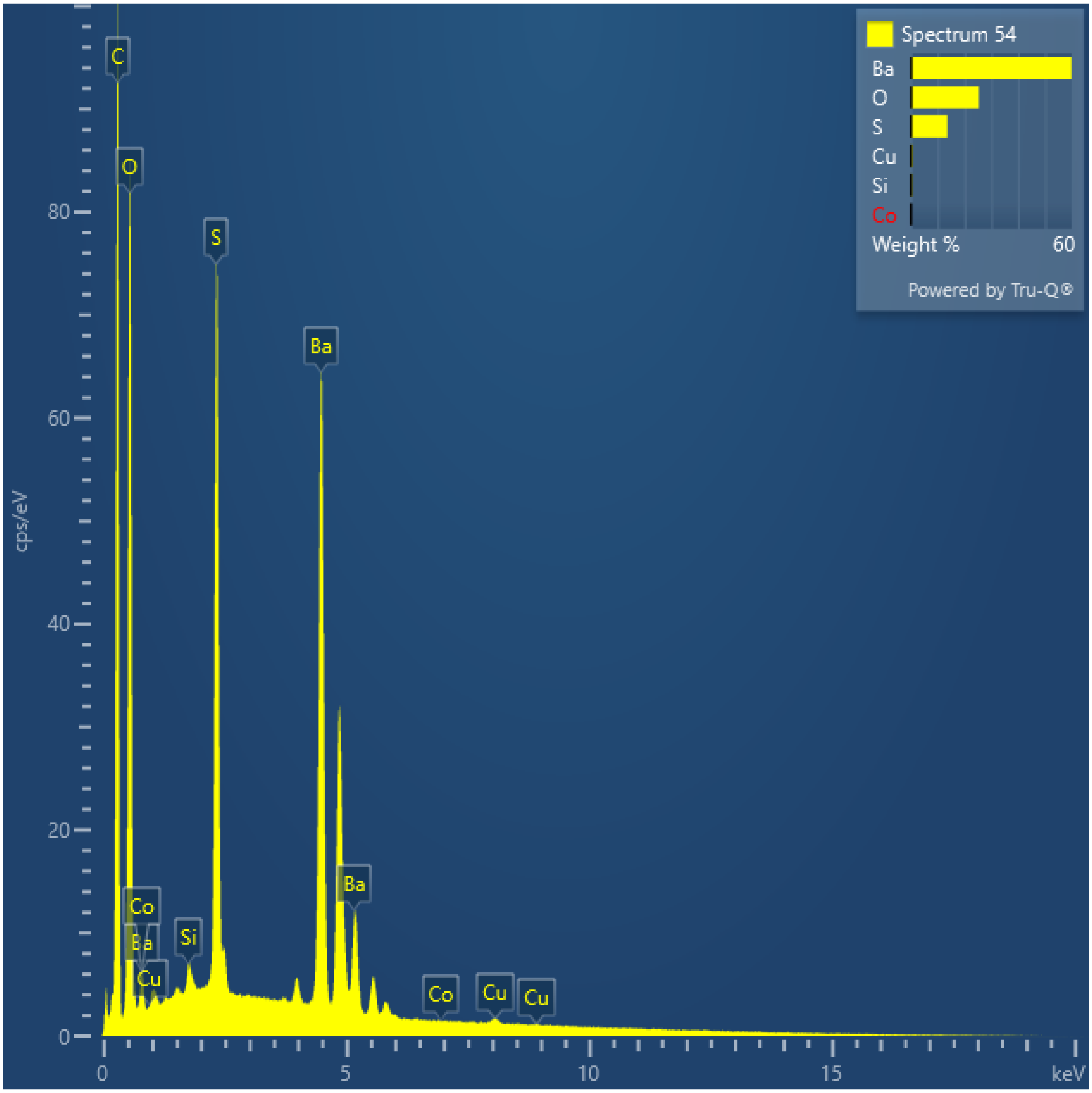

Spectrum 50
O
Si
Al
Ti
Ca
Cu
Fe
Os
Weight %
60
Powered by Tru-Q®
cps/eV
350
300
250
200
150
100
50
0
Si
O
C
Fe
Cu
Ti
Ca
Al
Os
Ca
Ti
Fe
Fe
Cu
Os
Os
Os
0
5
10
15
keV


Spectrum 51
O
Fe
Ti
Si
Mg
Al
Cr
Mn
Cu
Ca
Weight %
50
Powered by Tru-Q®
cps/eV
keV
O
C
Ti
Fe
Fe
Ti
Cr
Si
Mg
Cu
Mn
Ca
Al
Ca
Cr
Mn
Fe
Cu
Cu

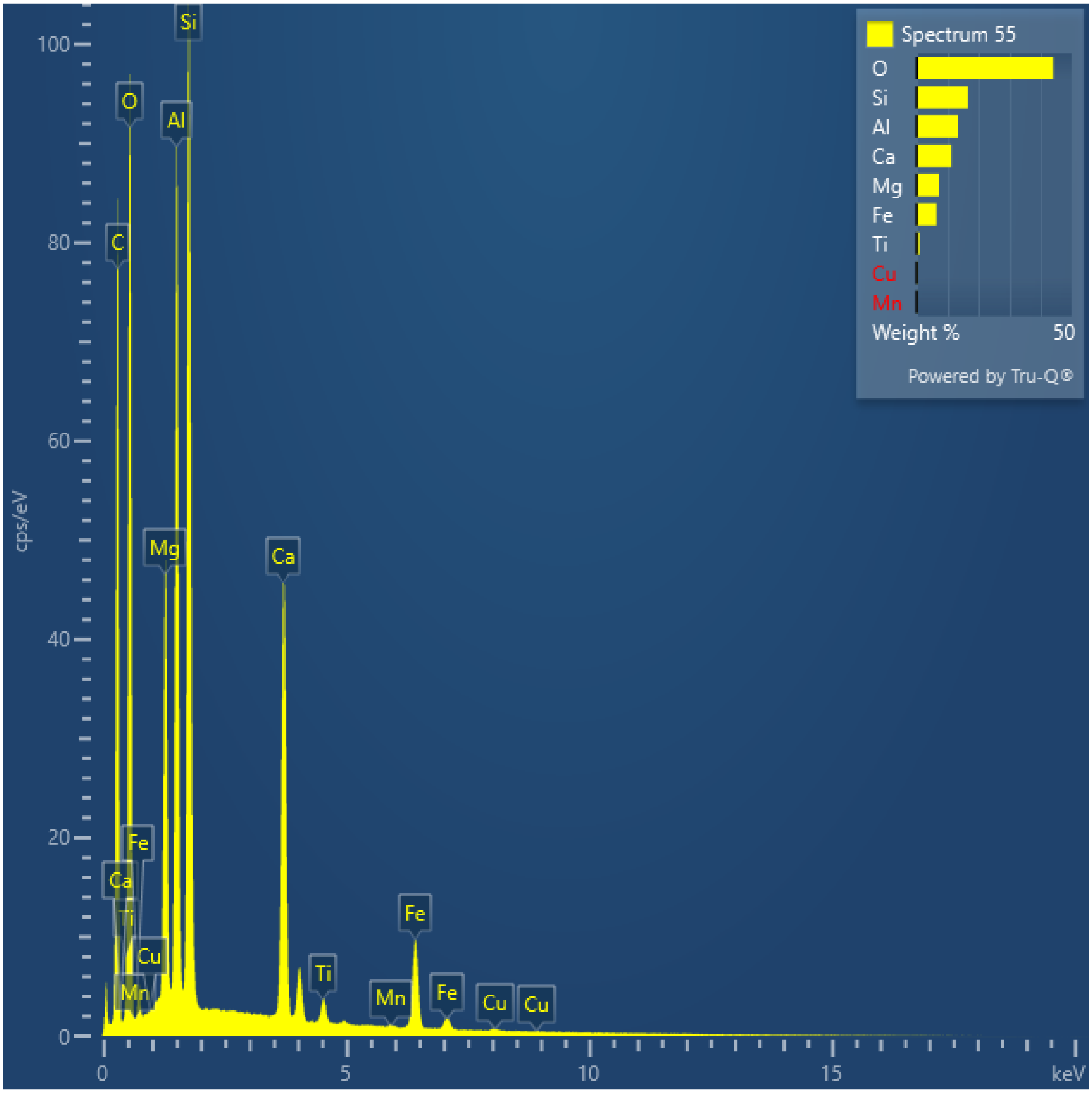

Spectrum 52
O
Fe
Cr
Ti
Si
Al
Mg
Ca
Na
Cu
V
Mn
S
Weight %
40
Powered by Tru-Q®
cps/eV
keV
0
20
40
60
80
100
5
10
15

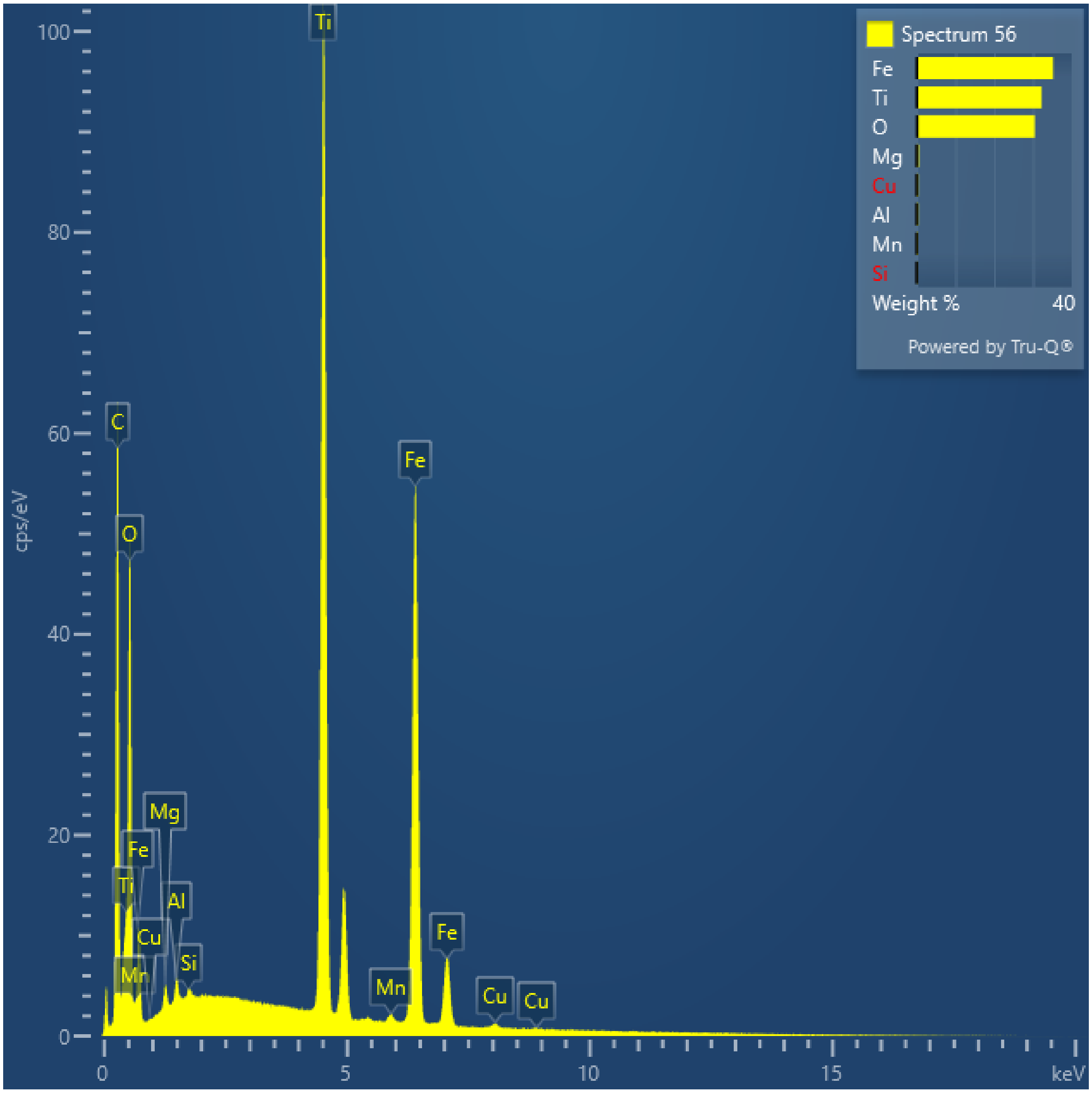


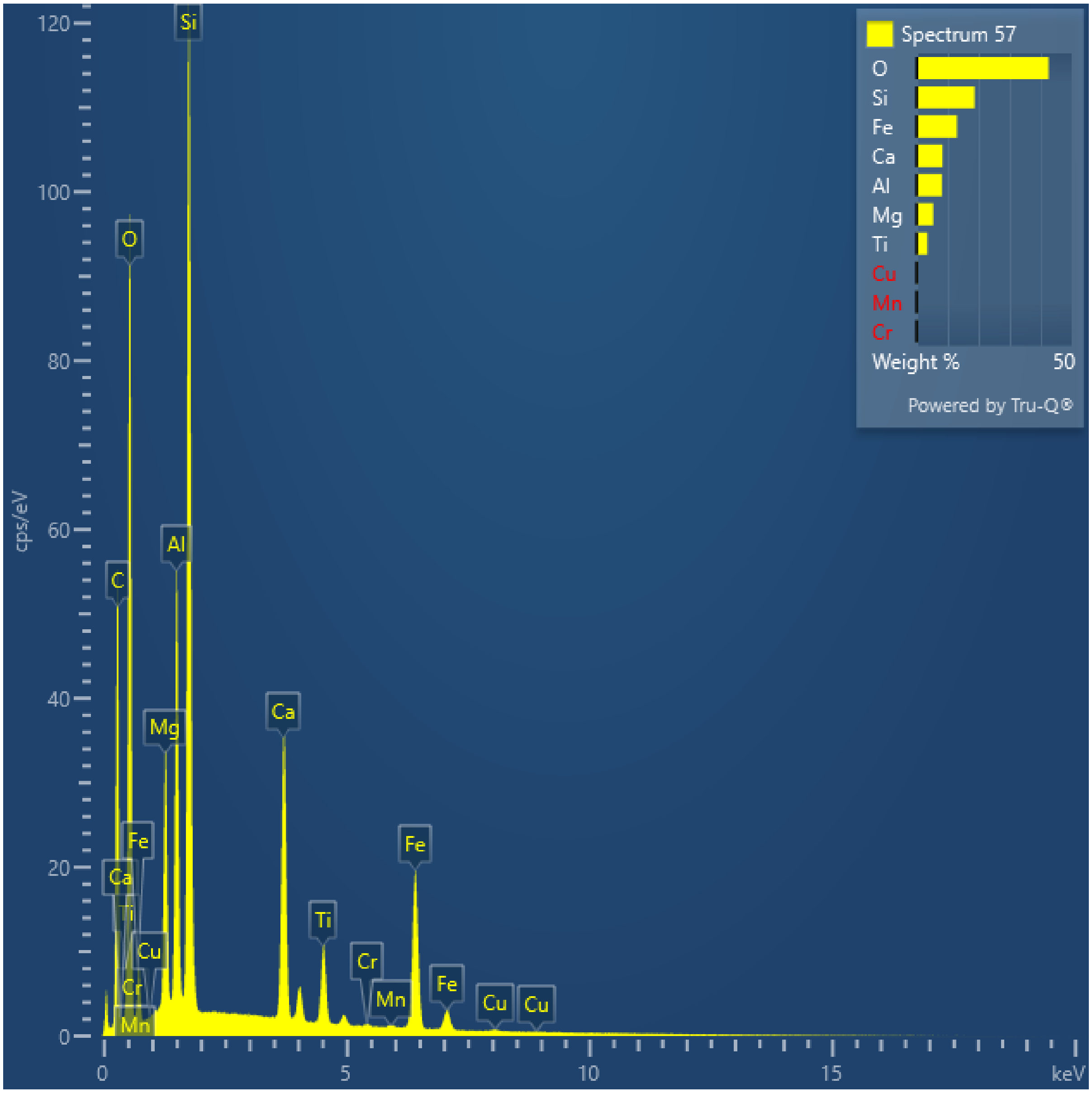
Spectrum 53
O
Fe
Si
Mg
Al
Ti
Ca
Cr
Na
Cu
Mn
S
K
Weight %
40
Powered by Tru-Q®
cps/eV
keV

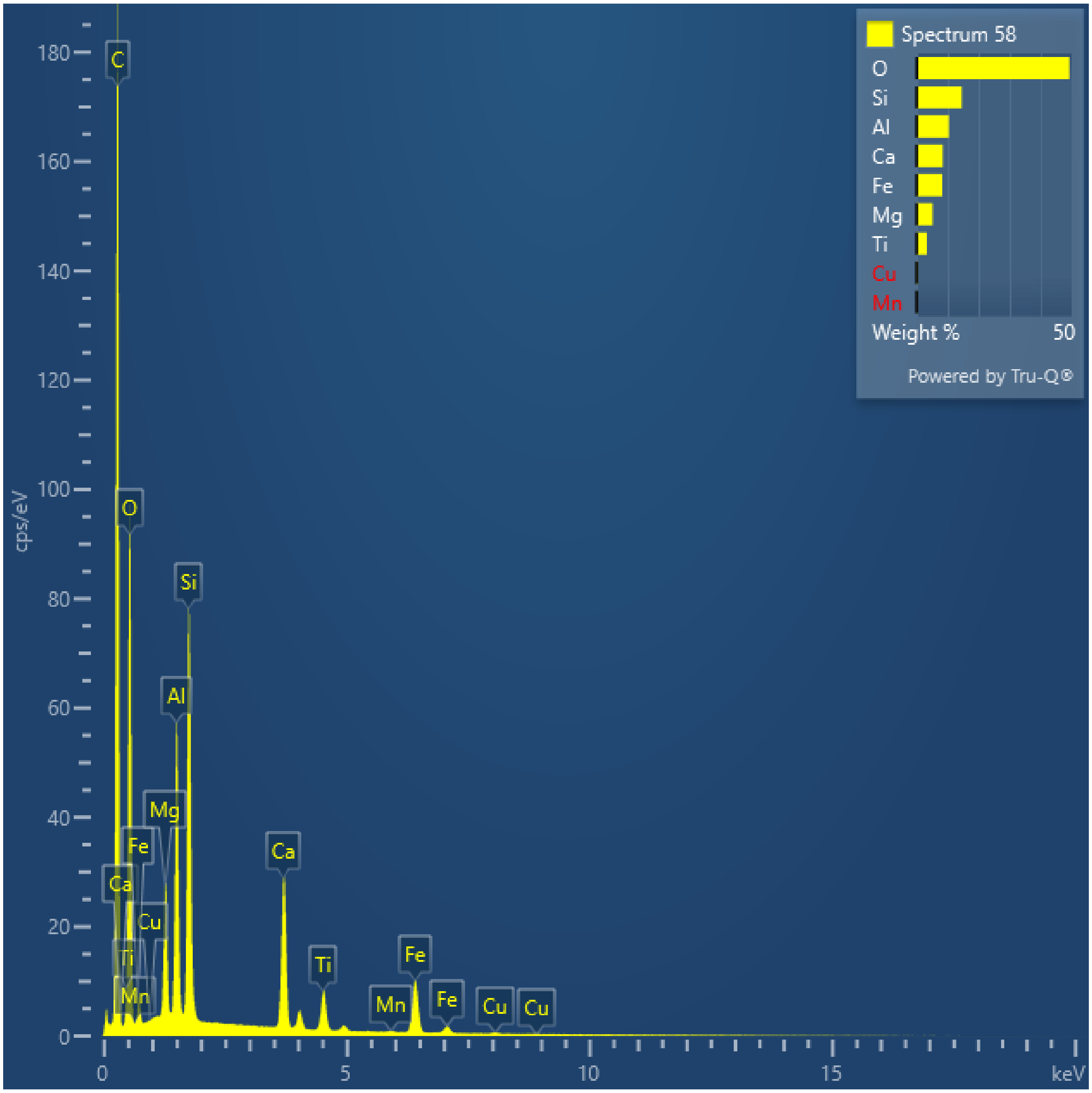


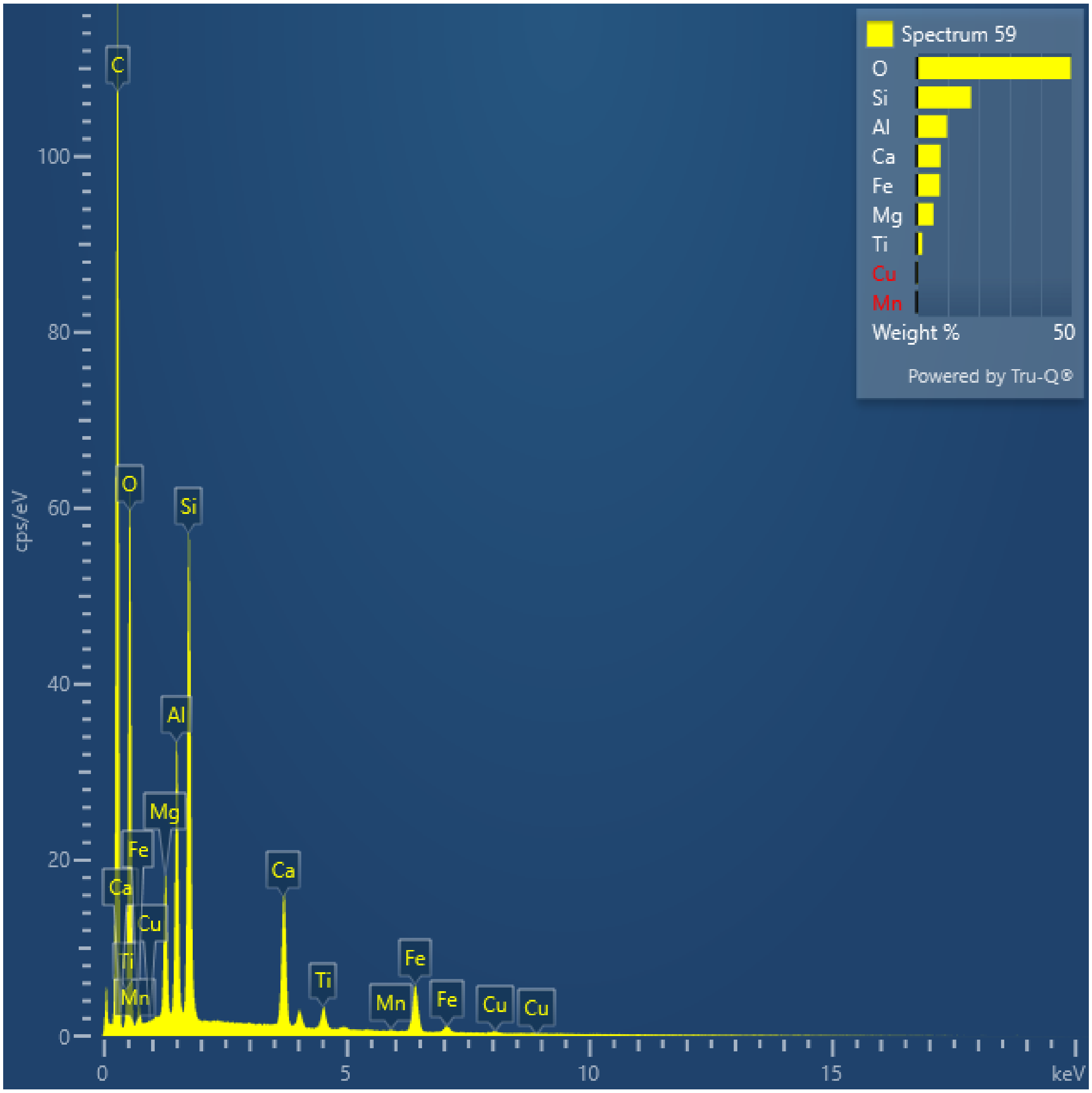
Spectrum 54
Ba
O
S
Cu
Si
Co
Weight %
60
Powered by Tru-Q®
cps/eV
80
60
40
20
0
C
O
S
Ba
Ba
Co
Ba
Cu
Si
Co
Cu
Cu
0
5
10
15
keV

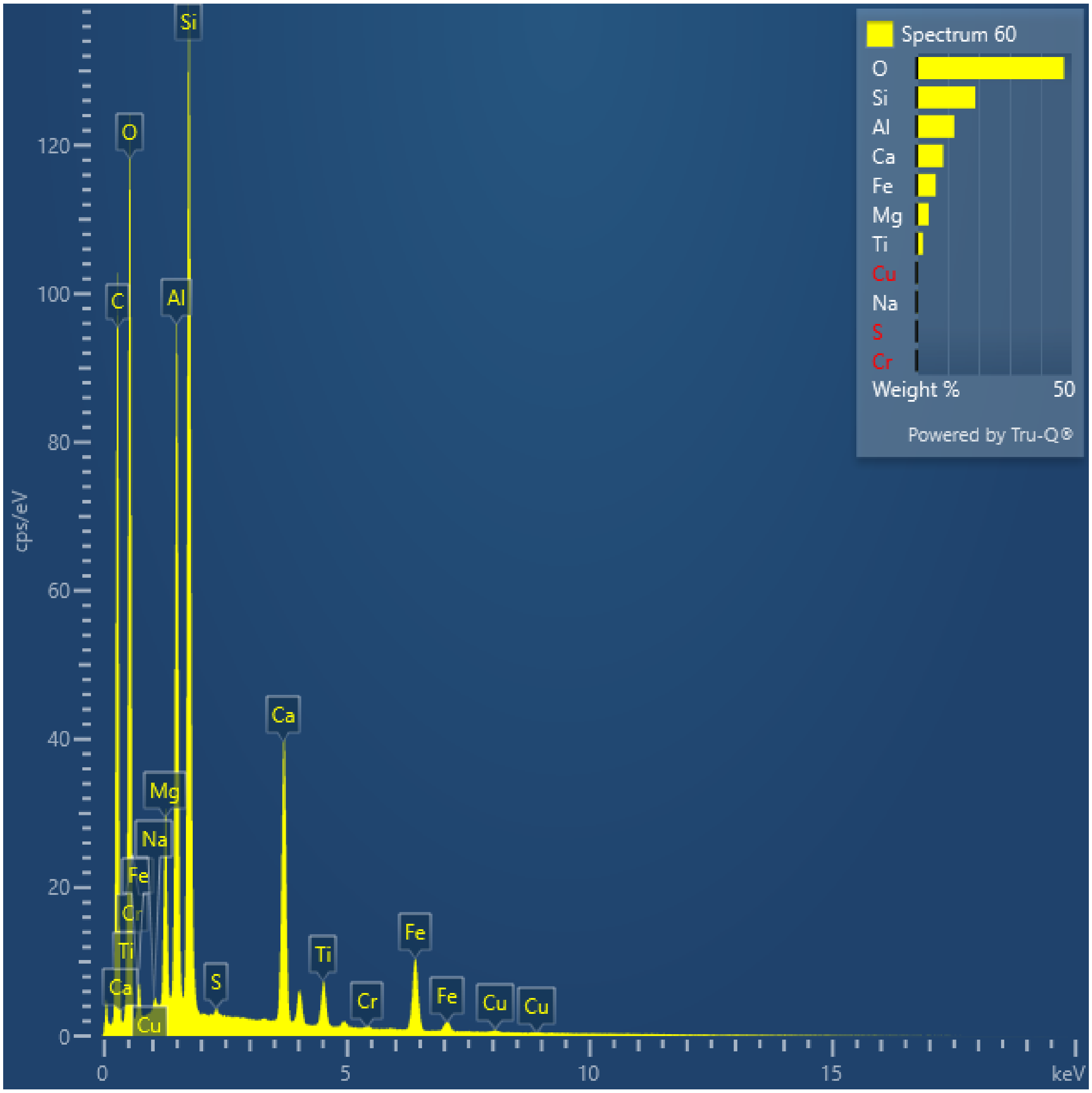

Spectrum 55
O
Si
Al
Ca
Mg
Fe
Ti
Cu
Mn
Weight %
50
Powered by Tru-Q®
cps/eV
100
80
60
40
20
0
5
10
15
keV
Si
O
Al
C
Mg
Ca
Fe
Ca
Ti
Cu
Mn
Fe
Ti
Mn
Fe
Cu
Cu

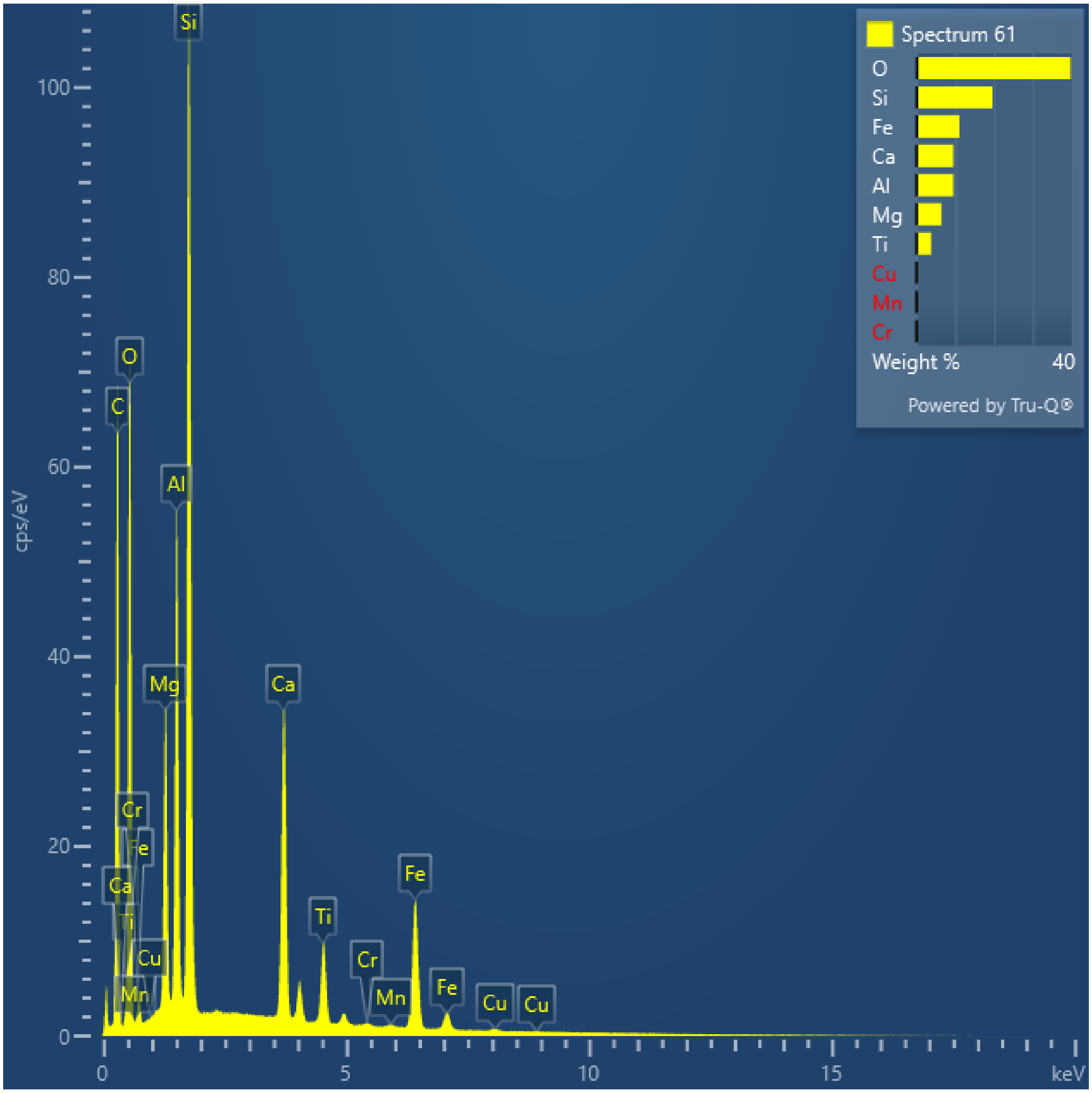

Spectrum 56
Fe
Ti
O
Mg
Cu
Al
Mn
Si
Weight %
40
Powered by Tru-Q®
cps/eV
100
80
60
40
20
0
0
5
10
15
keV
Ti
C
O
Fe
Mg
Fe
Ti
Al
Cu
Si
Mn
Fe
Mn
Cu
Cu


Spectrum 57
O
Si
Fe
Ca
Al
Mg
Ti
Cu
Mn
Cr
Weight %
50
Powered by Tru-Q®
cps/eV
keV
Si
O
Al
C
Mg
Ca
Fe
Ti
Cr
Mn
Cu

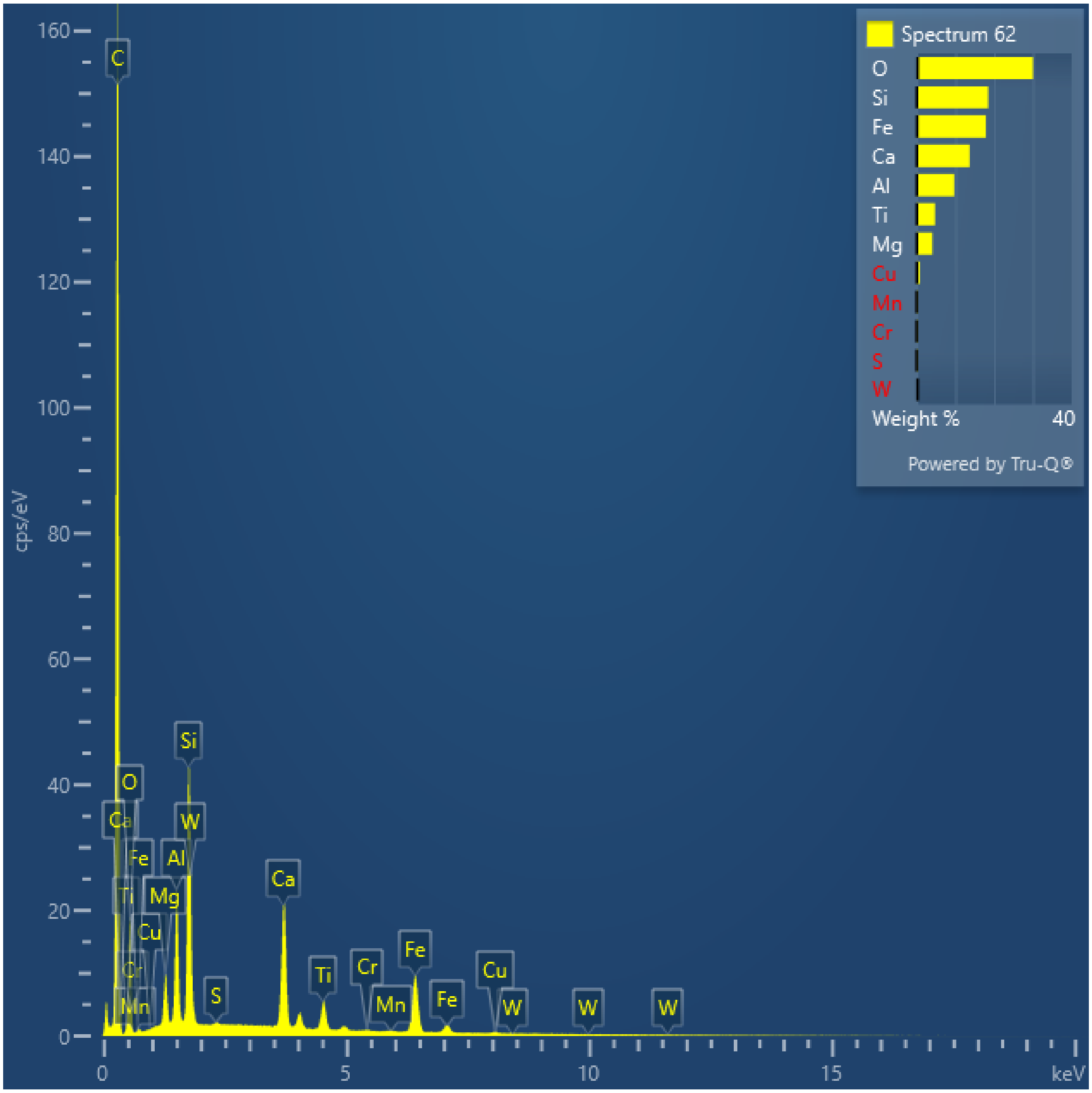

Spectrum 58
O
Si
Al
Ca
Fe
Mg
Ti
Cu
Mn
Weight %
50
Powered by Tru-Q®
cps/eV
keV
C
O
Si
Al
Mg
Fe
Ca
Cu
Ti
Mn


Spectrum 59
O
Si
Al
Ca
Fe
Mg
Ti
Cu
Mn
Weight %
50
Powered by Tru-Q®
cps/eV
100
80
60
40
20
0
C
O
Si
Al
Mg
Fe
Ca
Cu
Ti
Mn
Ca
Ti
Fe
Mn
Fe
Cu
Cu
0
5
10
15
keV

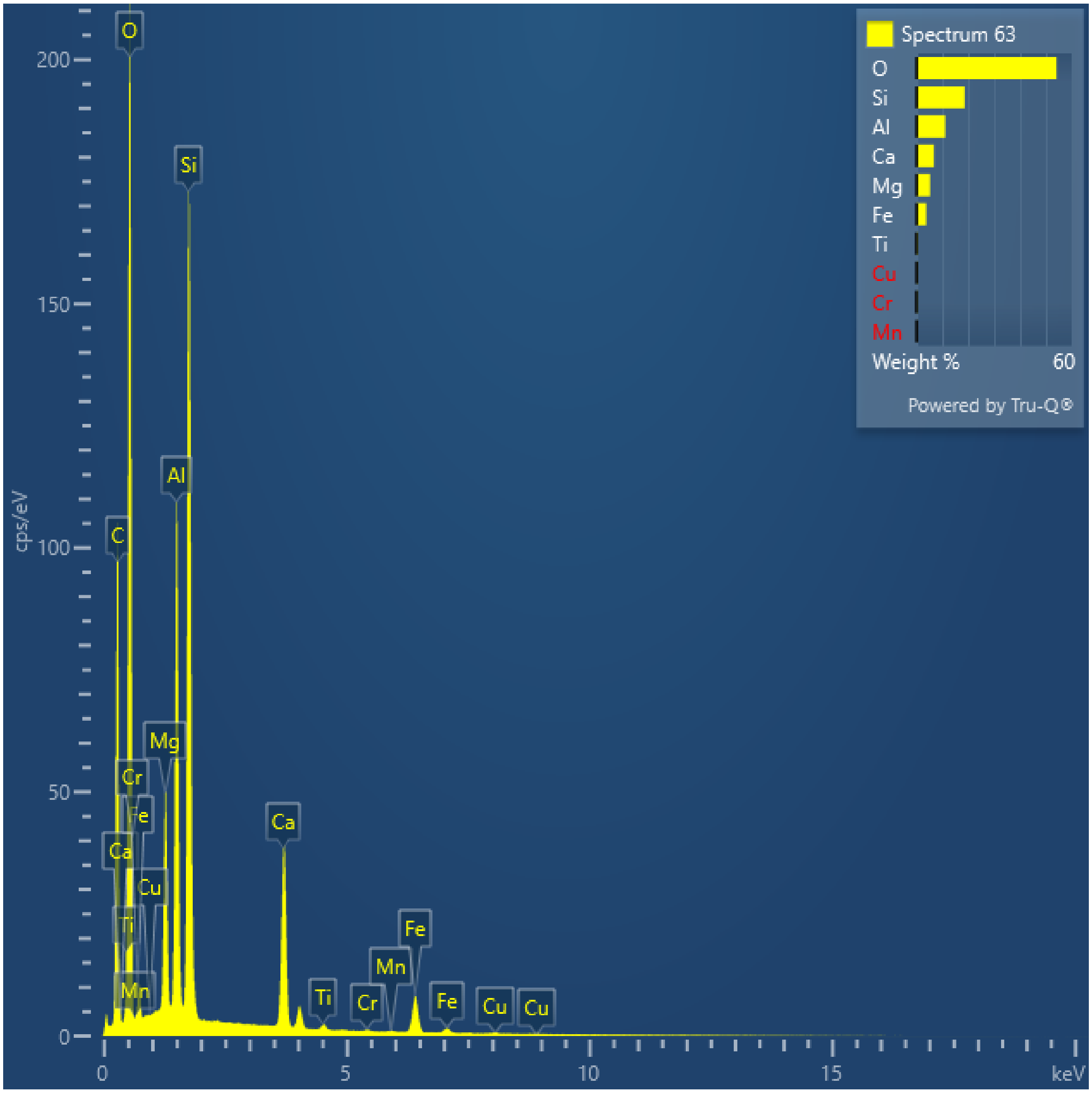

Spectrum 60
O
Si
Al
Ca
Fe
Mg
Ti
Cu
Na
S
Cr
Weight %
50
Powered by Tru-Q®
cps/eV
120
100
80
60
40
20
0
5
10
15
keV
Si
O
C
Al
Ca
Mg
Na
Fe
Cr
Ti
Ca
Cu
S
Ti
Cr
Fe
Fe
Cu
Cu

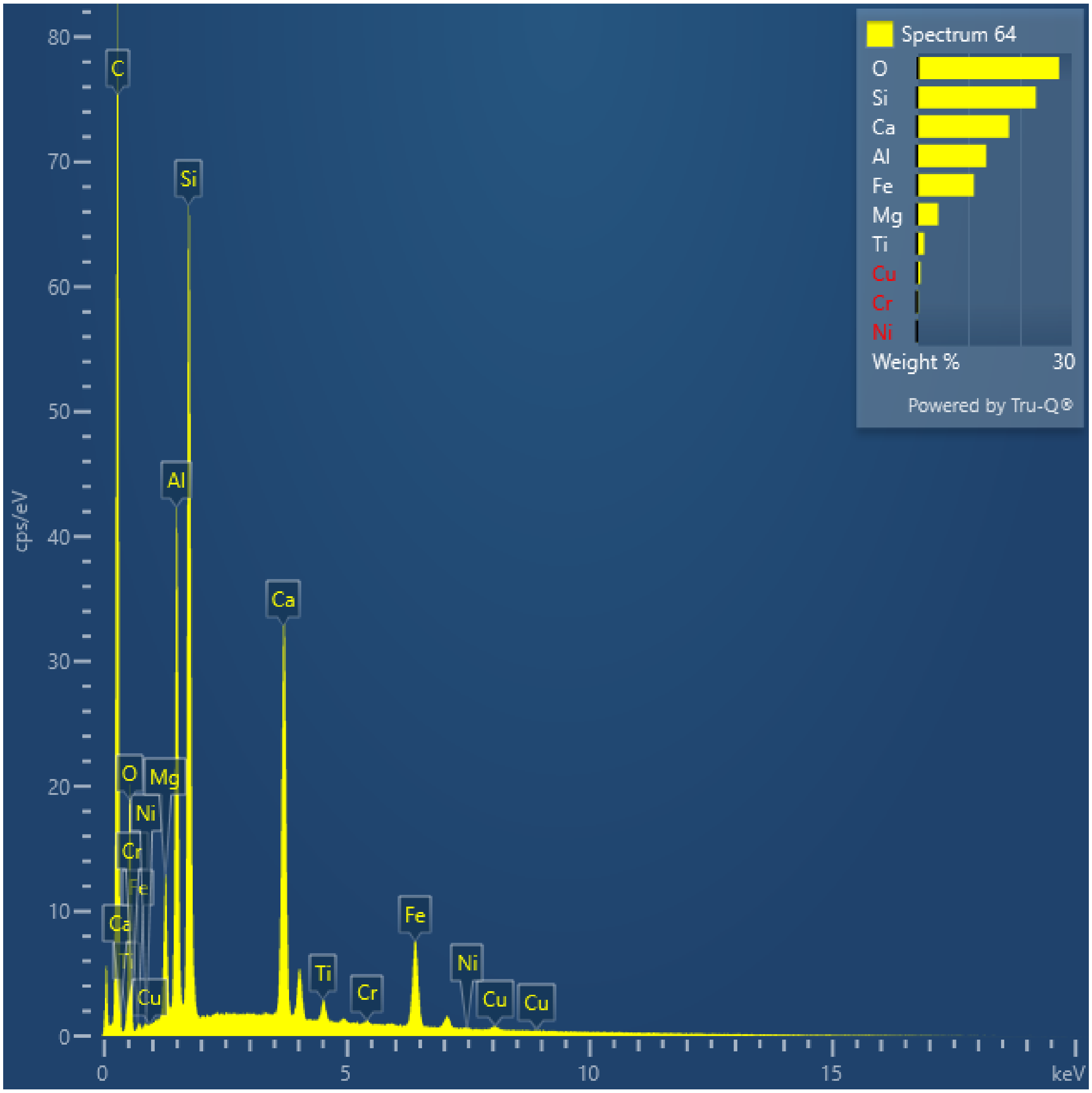


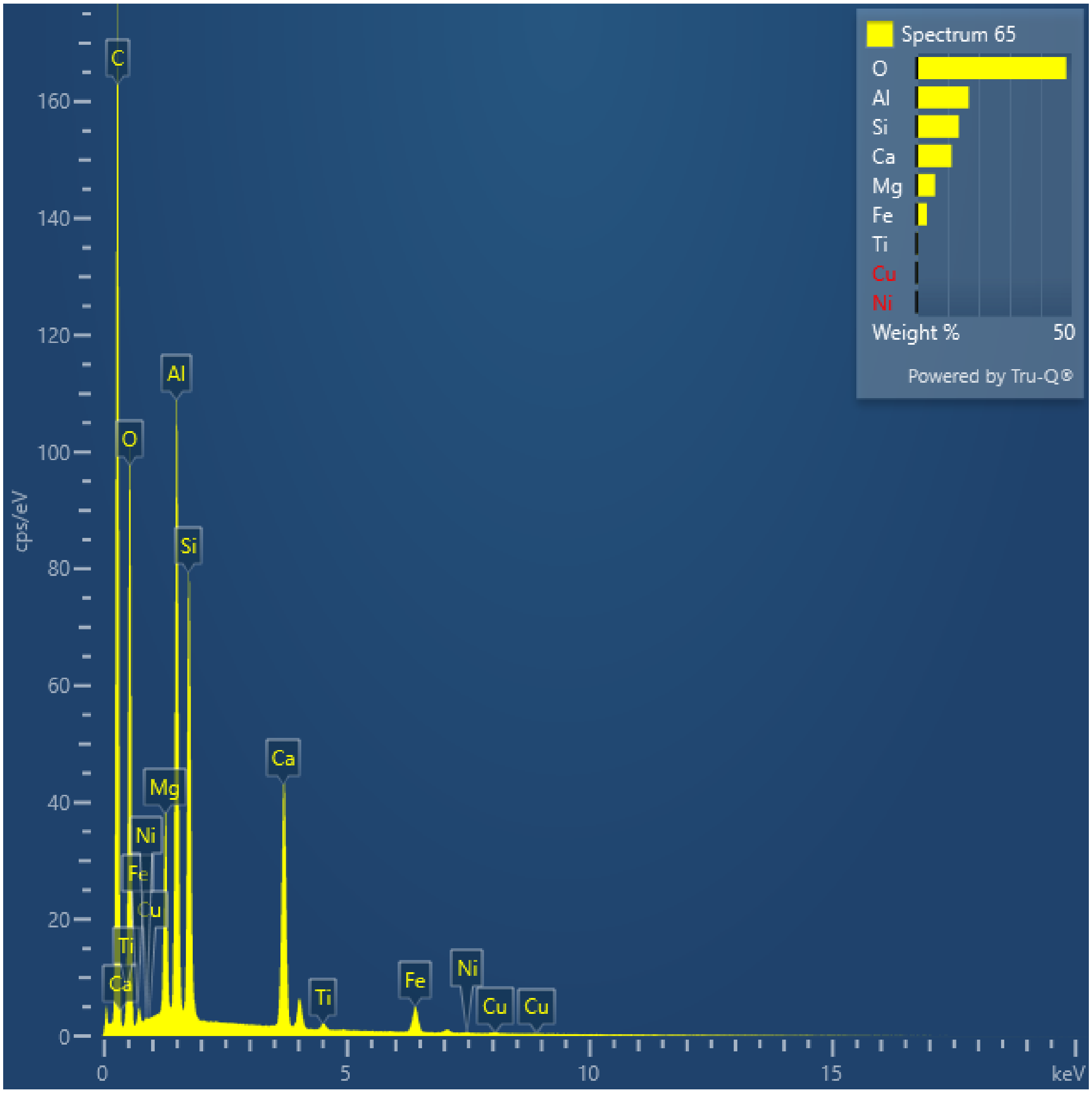
Spectrum 61
O
Si
Fe
Ca
Al
Mg
Ti
Cu
Mn
Cr
Weight %
40
Powered by Tru-Q®
cps/eV
100
80
60
40
20
0
0
5
10
15
keV
Si
O
C
Al
Mg
Ca
Cr
Fe
Ca
Ti
Cu
Mn
Fe
Ti
Cr
Mn
Fe
Cu
Cu

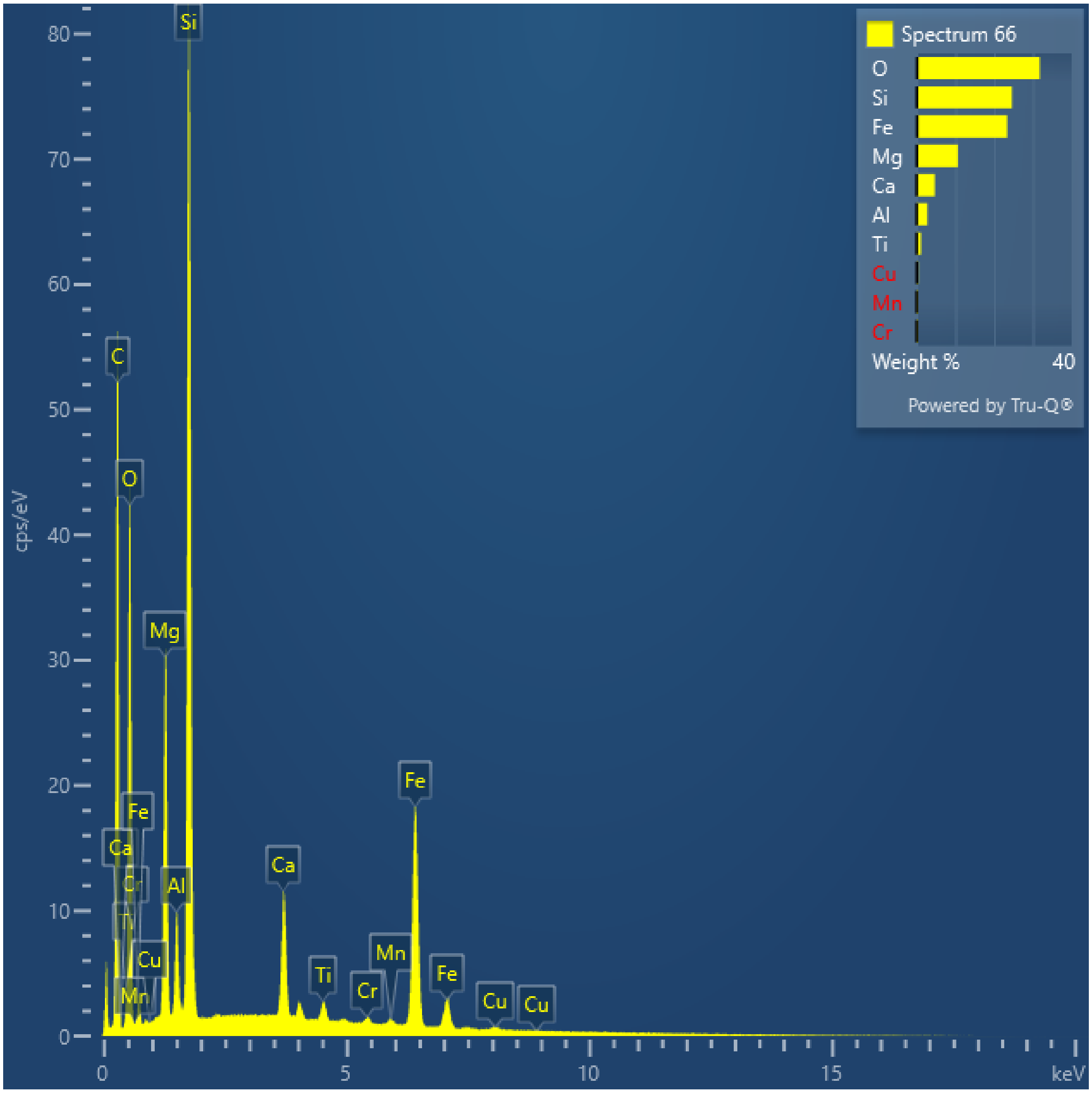


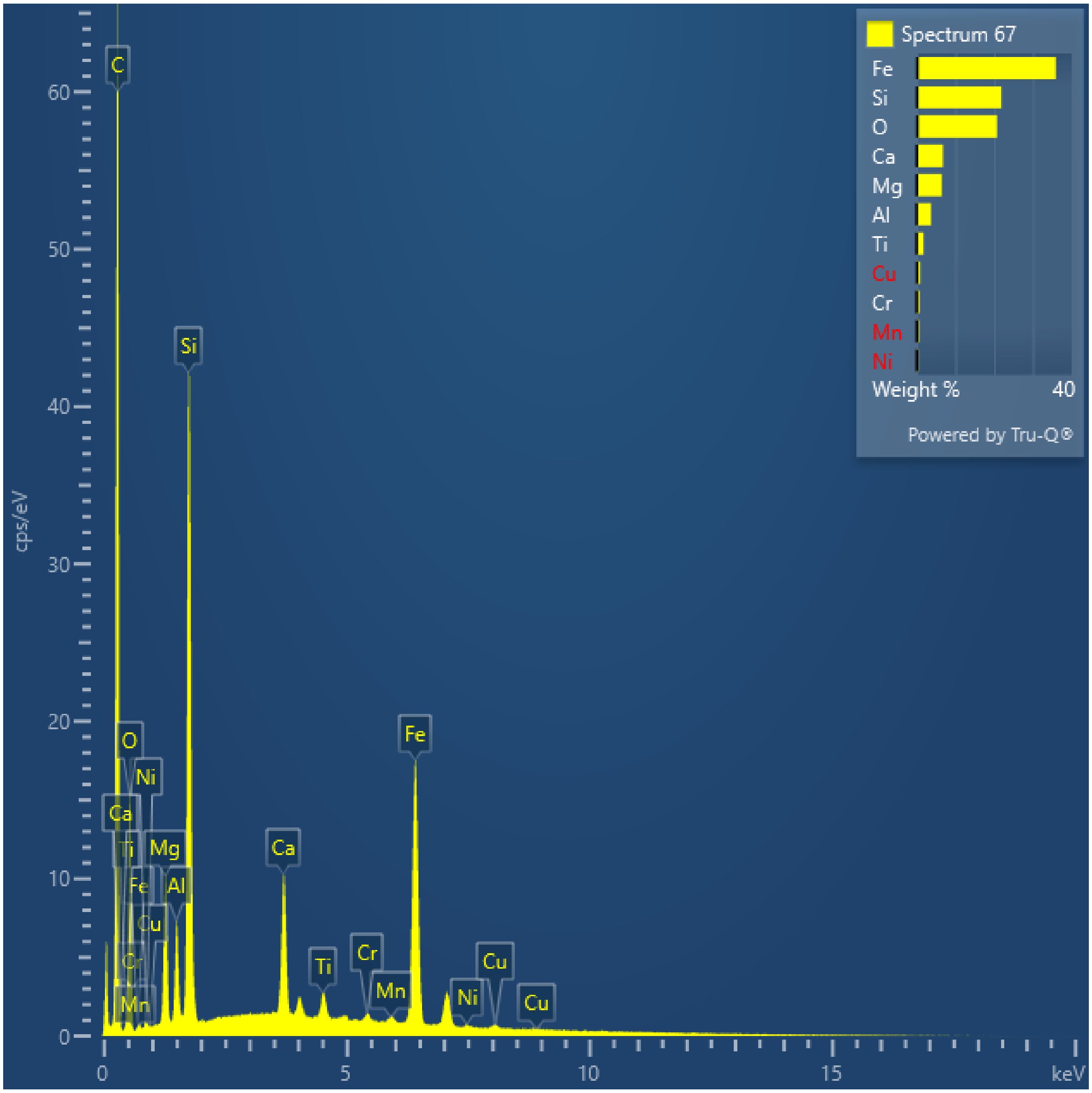
Spectrum 62
O
Si
Fe
Ca
Al
Ti
Mg
Cu
Mn
Cr
S
W
Weight %
40
Powered by Tru-Q®
cps/eV
160
140
120
100
80
60
40
20
0
0
5
10
15
keV
C
Si
O
Ca
W
Fe
Al
Ti
Mg
Cu
Cr
Mn
S
Ca
Ti
Cr
Mn
Fe
Fe
Cu
W
W
W


Spectrum 63
O
Si
Al
Ca
Mg
Fe
Ti
Cu
Cr
Mn
Weight %
60
Powered by Tru-Q®
cps/eV
200
150
100
50
0
5
10
15
keV
O
Si
Al
C
Mg
Cr
Fe
Ca
Cu
Ti
Mn
Ca
Ti
Cr
Mn
Fe
Fe
Cu
Cu


Spectrum 64
O
Si
Ca
Al
Fe
Mg
Ti
Cu
Cr
Ni
Weight %
30
Powered by Tru-Q®
cps/eV
keV
C
Si
Al
Ca
O
Mg
Ni
Cr
Fe
Ca
Cu
Ti
Cr
Fe
Ni
Cu
Cu


Spectrum 65
O
Al
Si
Ca
Mg
Fe
Ti
Cu
Ni
Weight %
50
Powered by Tru-Q®
cps/eV
0
20
40
60
80
100
120
140
160
C
O
Al
Si
Mg
Ni
Fe
Cu
Ti
Ca
Ca
Ti
Fe
Ni
Cu
Cu
0
5
10
15
keV


Spectrum 66
O
Si
Fe
Mg
Ca
Al
Ti
Cu
Mn
Cr
Weight %
40
Powered by Tru-Q®
cps/eV
keV
C
O
Si
Mg
Fe
Ca
Cr
Al
Ti
Cu
Mn
Ca
Ti
Cr
Mn
Fe
Fe
Cu
Cu


Spectrum 67
Fe
Si
O
Ca
Mg
Al
Ti
Cu
Cr
Mn
Ni
Weight %
40
Powered by Tru-Q®
cps/eV
keV
C
Si
O
Ni
Ca
Ti
Mg
Fe
Al
Cu
Cr
Mn
Ca
Fe
Ti
Cr
Mn
Cu
Ni
Cu