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Palaeoenvironment and Volcanic Processes of the Wairēinga Falls Lava, Te Mata Quarry

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of the requirements for the degree

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Abstract

This study characterises the Wairēinga (Bridal Veil) Falls lava flow and reconstructs the palaeoenvironmental and volcanic history associated with this lava flow at Te Mata Quarry through integrated field observations and laboratory analyses.

Stratigraphic logging, petrographic analysis, grain-size analysis, X-ray fluorescence (XRF), X-ray diffraction (XRD), scanning electron microscopy (SEM), energy-dispersive spectroscopy (SEM-EDS), and portable XRF (pXRF) were used to investigate volcanic and sedimentary units exposed throughout the quarry.

The sedimentary sequence beneath the lava flow contains glauconite and abundant bioclastic material, indicating deposition in a shallow marine environment associated with the Oligocene Te Kuiti Group. In contrast, buried wood and coal horizons, and hyaloclastite beneath the basalt, which unconformably cross-cuts the Te Kuiti Group, demonstrate that a wet terrestrial valley had developed prior to lava emplacement in the late Pliocene/early Pleistocene.

The Wairēinga Falls lava flow was emplaced at approximately 2.57 Ma into this water-influenced palaeovalley. Hyaloclastite preserved along flow margins provides evidence of lava–water interaction, indicating that surface or near-surface water strongly influenced cooling and fragmentation during emplacement. Petrographic and geochemical analyses reveal a compositionally homogeneous basalt consistent with previous studies of the region. However, structural features including variable columnar joint spacing, multidirectional joint orientations, and rosette jointing suggest a complex emplacement history involving multiple flow units and the development of lava tubes, indicating spatial variability in emplacement processes despite a uniform magma composition.

The overlying Kauroa Ash sequence, particularly the T5 tephra, provides regional context and supports correlations with volcanic activity in the central North Island, including the Ongatiti Ignimbrite. Together, these findings place the lava flow and its emplacement environment in the Te Mata Quarry within the broader volcanic evolution of the Alexandra Volcanic Group, and improve understanding of lava emplacement processes, in a wet palaeoenvironment.

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Table of Contents

Abstract.....	2
Acknowledgements.....	3
Chapter 1: Introduction and Literature Review.....	11
1.1 Introduction.....	11
Thesis Outline	11
1.2 Regional Geology and Geomorphology.....	11
Stratigraphy of the Western Waikato	13
Volcanism across the Waikato Region.....	15
Local Geology associated with the Te Mata Quarry	16
1.3 Basalt lava Emplacement and Contact Features	16
Columnar Jointing	17
Peperite and Hyaloclastite	18
Charcoal Formation and Lava Flow	20
1.4 Study Aims	22
2 Chapter 2: Study Area and Methods	23
2.1 Content	23
Study Area	24
2.2 Methods	25
Field Descriptions and Sampling.....	25
Laser Particle Size Analysis	25
Thin Sections/Optical Microscopy	26
Stereo Microscopy	26
XRD Analysis.....	26
XRF Spectrometry	27
pXRF Spectrometry	28
SEM Imaging and EDS Analysis.....	28
3 Chapter 3: Results.....	30
Results	30
Field Observations	30
Laser Particle Size Analysis	41

Petrography	43
Basalt Geochemistry (XRF)	55
Cave Minerals	62
Clay and Hyaloclastite	73
Chapter 4: Discussion and Conclusions	89
Discussion.....	89
Sandstones and Siltstones – Oligocene Bedrock.....	90
Environment Before Lava Flow – Early Pleistocene.....	91
Implications.....	94
Limitations and Direction for Future Research.....	95
Conclusions	96
References	98
Appendices.....	103
Appendix A1.	103
Appendix A2.	105

List of Figures

Figure 1: Map of the Alexandra Volcanic Group and the surrounding terrain of the western Waikato. From Pittari et al. (2021).	23
Figure 2: Te Mata Quarry in relation to Wairēinga (Bridal Veil) Falls.	24
Figure 3: Locations of sample collection at Te Mata Quarry. Scale bar 60 m.	25
Figure 4: Quorum 150V ES plus (left) and Hitachi Regulus SU8230 FE-SEM (right).....	29
Figure 5: Sample S9 block mounted to stub with conductive tape.	29
Figure 6: Lower outcrop with white line showing the contact between the sediments (S1-S5) and the overlying basalt. Rosette jointing is partially visible in the right corner of the picture.	31
Figure 7: Stratigraphic log showing the sedimentary sequence of the sandstones and siltstones with basalt overlying.	32
Figure 8: Outcrop of samples S5-S8. Siltstone overlain by black organic-rich contact with a mantling iron pan.	33
Figure 9: Outcrop of samples S5-S8. Sample S5 is an olive-grey siltstone, S6 is a dark brown siltstone, S7 is a black biological contact and S8 is a bright orange iron pan.	33

Figure 10: Outcrop showing samples S9 and S10. Sample S9 is a hyaloclastite deposit with a fine white matrix and angular basalt fragments and S10 is a greyish yellow siltstone.	34
Figure 11: Charred root material found within the black contact (S7), as well as below in the siltstone (S6) with the iron pan (S8) overlying.	34
Figure 12: Charred wood remnants found within the basalt in the lower sector of the quarry. ...	35
Figure 13: Hyaloclastite deposit (S9) with large basalt fragments scattered throughout the fine white matrix.	35
Figure 14: Exterior of cave found within the basalt flow in the southeastern part of the quarry..	36
Figure 15: Interior panorama of cave, showing the massive sandstone unit (C3) and jigsaw breccia beneath the basalt.	36
Figure 16: Roof of cave, looking upwards, showing the dark woody material (C6) surrounded by crystal precipitates.	37
Figure 17: Crystals that were sampled in C1 and C5 (respectively) in place on the roof of the cave.	37
Figure 18: Columnar (left) and rosette (right) jointing showing the different patterns of jointing formed from the lava flows.	38
Figure 19: Outcrop of the Kauroa Ash and overlying Hamilton Ash on the western side of the quarry.	39
Figure 20: Red mottles (A and B), manganese specks (C), and T5 layer (D) from the Kauroa Ash.	39
Figure 21: Pebbles from the T5 ash layer. A) White veins present on the smooth rounded pebble. B) Rounded and angular pebbles with white and red mottling. C) Very smooth rounded pebble with red mottles on the surface.	40
Figure 22: Stratigraphic log showing the cover beds.	41
Figure 23: Photomicrographs of sandstone grains under plane-polarised (A-C) and cross-polarised (D-F) light. A) Sample S1. Shows the sorting and sizes of the grains. B) S2. Glauconite grains. C) C3. In the red circle shows a glauconite filled shell. D) C3. Quartz and plagioclase of varying shapes. E) S15. Ferromagnesian minerals in red circle. F) S1. Plagioclase displaying twinning with quartz surrounding.	44
Figure 24: Photomicrographs of siltstones in plane-polarised (left) and cross-polarised light (right). A/B) S11. Foraminifera surrounded by plagioclase, quartz, glauconite, and opaques. C/D) S12. Concentric layered inclusion around calcite groundmass with intruding quartz crystals. E/F) S13. Quartz and plagioclase surrounding bioclast. G/H) S14. Foraminifera (centre) surrounded by quartz, plagioclase, and opaques with a pink calcite groundmass.	45
Figure 25: Photomicrographs of minerals present within the basalt samples shown in plane-polarised (C and F) and cross-polarised (A, B, D, E, and G) light. A) B1. Olivine mineral in the centre (600 µm) surrounded by smaller olivine phenocrysts and a fine-grained groundmass. B) B1. Olivine phenocryst (~740 µm) showing embayment with small augite and plagioclase minerals present. C/D) B2. Large crustal xenolith with a ring around the exterior that is potentially altered glass. Small olivine and augite minerals are scattered about the xenolith. E) B2. Olivine phenocryst over 2 mm in length with smaller olivine phenocrysts surrounding. F) B3. Olivine under plane-polarised light with smaller olivine, augite, and plagioclase with a fine-grained groundmass. G) B4. Embayment present from an augite been resorbed.	46
Figure 26: Photomicrographs showing textures of the hyaloclastite in plane-polarised light. A) Colours range from light grey to very dark reddish brown/blackish brown. Small black specks	

can be seen scattered throughout the sample. B) Pale orange to very dark reddish brown. C) Pale yellow to black. D) Pale yellow to reddish brown. Small opaques are largely present in the groundmass of the dull orange sections.47

Figure 27: Photomicrographs of Kauroa Ash clasts in plane-polarised (left) and cross-polarised light (right). A/B) TR2. Groundmass has pinkish-orange clay-sized material when under plane-polarised light. C/D) TR2. In the centre of the image a large well-formed phenocryst is present surrounded by a light orange-pink clay-sized groundmass. E/F) TR1. Clay-sized dull pinkish-orange groundmass with yellow and brown material scattered throughout, a few opaques are seen but bubbles from glue are also present. In the upper centre there is an altered phenocryst. G/H) TA4. Groundmass clay-sized orangey-pink with darker brown and red material present, and opaques. I/J) TA2. Quartz rich with sizes varying. K/L) TA2. Large, weathered material with quartz rich groundmass.49

Figure 28: Stereomicroscopy of sample C1. A/B) 7x magnification. Elongate, translucent crystals within varying sizes of crystal material. C) 12.5x magnification. Long, elongate crystal which is in a fine matrix. D) 20x magnification. Wispy crystals in amongst larger crystals and material.50

Figure 29: Stereomicroscopy of sample C5. A/B) 7x magnification. C/D) 20x magnification. A) Clustered, radiating crystals with yellowish brown material on the surface of the crystals and a ~2 mm clast on the side. B) Clustered, radiating crystals with a yellow hue to them due to material present on the surface. C) Clustered blade-like, prismatic crystals. D) Clustered acicular and prismatic crystals with yellowish brown material on the crystal surfaces.51

Figure 30: Stereomicroscopy of sample C7. A/B) 7x magnification. C/D) 16x magnification. E) 25x magnification. A) Pale yellow fibrous crystals with yellowish brown material present on the surface. B) The crystal arrangement is very irregular with the pale yellow crystals not having very identifiable textures. C) Fibrous crystals surrounded by yellowish grey material. D) Prismatic and fibrous crystals of varying sizes with loose pale yellow aggregates around sample. E) Pale yellow/black aggregates and fibrous crystals.52

Figure 31: Stereomicroscopy of sample C2 at 7x magnification. A) The entire crystal piece surrounded by clay is ~20 mm. Within the crystal are small, potential, magnetite minerals. B) The clay is a pale yellow, encasing a large well-formed crystal with smaller crystals protruding from the clay. C) Pale yellow clay with prismatic crystals. D) The clay particles are all ~1 mm and range from a pale yellow to a brighter pale yellow, prismatic crystals are visible with small black specks scattered around.53

Figure 32: Stereomicroscopy of sample C4. A/B) 7x magnification. C/D) 16x magnification. E) 25x magnification. A) Pale to light yellow clay with small prismatic crystals and a 1 mm grey basalt fragment. B) Pale yellow clay encasing long fibrous crystals that fan out. C) Light yellow clay as well as a light grey mineral assemblage both having black specks scattered throughout, but a higher quantity in the grey. D) Long fibrous crystals interwoven with pale yellow clay collected on the surface. E) Pale to light yellow clay with small crystals present and a few small black specks.54

Figure 33: Stereomicroscopy of sample S9. A/B) 7x magnification. C) 16x magnification. D) 25x magnification. A) Combination of white, light grey, and light brown in the clays, small red and black material can be seen, as well as a piece of what appears to be a shiny metallic material. B) White/pale yellow and light grey with reddish brown mottles. C) Grey section of clay has visible porosity, and the white surrounding has light grey and red material scattered throughout.

D) Pale grey clay with small black specks and a shiny metallic material ~200 μm . A white clay around the grey clay also has small black specks as well as yellow-orange particles.	55
Figure 34: Harker Variation Diagram for major elements plotted against SiO_2 (wt.%).	61
Figure 35: Harker Variation Diagram of trace elements (Cr, Cl, and F) in ppm against SiO_2 (wt.%).	62
Figure 36: Weight percent (wt.%) of the most common elements present in the samples.	63
Figure 37: XRD analysis of sample C1 with alunogen peaks present.	63
Figure 38: XRD analysis of sample C5 with peaks of gypsum (blue) and natrojarosite (green). ...	64
Figure 39: SEM imaging using YAGBSE of sample C1 at 15kV. A) 200x magnification. Large platy morphologies dominant with a fine-grained matrix. B) 500x magnification. Well-defined prismatic crystal face amongst a continuous groundmass.....	64
Figure 40: SEM image of C1 showing locations where Spectrum 4-7 were taken.....	65
Figure 41: SEM image of C1 showing locations where Spectrum 8-12 were taken from.	65
Figure 42: SEM image of C1 showing locations where Spectrum 13-14 were taken from.	66
Figure 43: SEM imaging using YAGBSE for sample C5 at 15kV. A) 100x magnification. Well-defined prismatic crystals clustered together with some platy aspects and clay-like particles on the surface. B) 200x magnification. Long straight prismatic crystals with radiating crystals and clay-like particles. C) 500x magnification. Platy, sheet-like crystal habit coated with clay-like particles. D) 500x magnification. Platy crystal with particles on and in between the sheets.	67
Figure 44: SEM image of C5 showing locations where Spectrum 17-21 were taken from.	68
Figure 45: SEM image of C5 showing locations where Spectrum 22-25 were taken from.	68
Figure 46: SEM image of C5 showing locations where Spectrum 26-28 were taken from.	69
Figure 47: SEM imaging using YAGBSE of sample C7 at 15kV. A) 300x magnification. Densely packed cluster of acicular habits intertwined with platy grains. B) 350x magnification. Prismatic crystal surrounded by plates. C) 450x magnification. Prismatic and acicular crystals with flaky and platy grains. D) 450x magnification. Tight cluster of prismatic and acicular crystals that are surrounded by grains and sheets. E) 500x magnification. Densely clustered platy grains. F) 600x magnification. Cluster of tightly packed grains surrounded by plates.	70
Figure 48: SEM image of C7 showing locations where Spectrum 29-33 were taken from.	71
Figure 49: SEM image of C7 showing locations where Spectrum 34-35 were taken from.	71
Figure 50: SEM image of C7 showing locations where Spectrum 37-40 were taken from.	72
Figure 51: SEM image of C7 showing location where Spectrum 41 was taken from.	73
Figure 52: XRD of sample C2 showing jarosite (blue) and gypsum (green).	74
Figure 53: XRD of sample C4 displaying peaks consistent with anatase.	74
Figure 54: XRD analysis of grey S9 subsample with magnetite peaks.	75
Figure 55: XRD peaks of the white S9 subsample indicating olivine (blue) and anatase (green). 75	
Figure 56: SEM imaging using YAGBSE of sample C2 at 15kV. A) 200x magnification. A fine-grained granular matrix with a rough surface and pits that could be the result of minerals that have fallen out. B) 400x magnification. Fine-grained granular matrix with well-formed prismatic crystals and platy structures. C) 400x magnification. Rough surface texture with platy and prismatic crystals. D) 600x magnification. Surface texture is rough with pits and platy, sheet-like structures as well as crystals present.	76
Figure 57: SEM imaging using YAGBSE of sample C4 at 15kV. A) 250x magnification. Aggregates that are irregular and blocky with the surface having cracks and pits. B) 350x magnification. Rough surface showing pits where minerals might have once been. C) 350x magnification.	

Cracks and pit can be seen on the surface of the aggregate. D) 600x magnification. Very fine-grained aggregates with blocky textures, pits and cracks can also be seen on the rough surface of the particles.....	77
Figure 58: SEM imaging using YAGBSE of sample S9 under 15kV. A) 100x magnification. Smooth very fine-grained granular surface making a large, aggregated particle. B) 300x magnification. Highly porous, fine-grained matrix with pitted internal surfaces. C) 800x magnification. Surface textures are rough with pitting occurring alongside blocky and plate-like textures. D) 1.50k x magnification. The round particle is very smooth with small particles coating the outside. The aggregates around the spherical particle are rough.	78
Figure 59: SEM image of S9 showing location where Spectrum 1 was taken from.	79
Figure 60: SEM image of S9 showing locations where Spectrum 2-3 were taken from.	79
Figure 61: SEM imagery of the white section of the sample S9 block at 400x magnification under YAGBSE at 20kV. Very smooth surface that show minimal mineral assemblages.	81
Figure 62: SEM imagery of the element maps from S9 block.	82
Figure 63: SEM imaging of grey section of sample S9 block at 600x magnification under YAGBSE at 20kV. The exterior is smooth with rough internal surfaces and edges. There are minerals on and in the surface of the block as well as pits.	83
Figure 64: SEM imaging of element maps of sample S9 block.	84
Figure 65: SEM imaging of the surface of the sample S9 block at 120x magnification under YAGBSE at 20kV. Lower half, grey clast of hyaloclastite with abundant Fe-rich minerals and relict textures of a typical intergranular groundmass of a basalt. Upper half, white clay matrix of hyaloclastite.....	85
Figure 66: SEM imaging of element maps from Figure 65.....	86
Figure 67: SEM imaging of sample S9 block for elemental mapping at 250x magnification under YAGBSE at 20kV.....	87
Figure 68: SEM element maps showing element distribution from Figure 67.....	88

List of Tables

Table 1: Table showing the key distribution statistics for particle sizes.	42
Table 2: Table of key particle size distribution data from the 2023 pilot study.	43
Table 3: Whole rock geochemical analysis using XRF of the basalt (B1-B6) samples.....	56
Table 4: Elemental composition (wt.%) of SEM-EDS of C1 site.....	65
Table 5: Elemental composition (wt.%) of SEM-EDS of C1 site.....	65
Table 6: Elemental composition (wt.%) of SEM-EDS of C1 site.....	66
Table 7: Elemental composition (wt.%) of SEM-EDS of C5 site.....	68
Table 8: Elemental composition (wt.%) of SEM-EDS of C5 site.....	68
Table 9: Elemental composition (wt.%) of SEM-EDS of C5 site.....	69
Table 10: Elemental composition (wt.%) of SEM-EDS of C7 site.....	71
Table 11: Elemental composition (wt.%) of SEM-EDS of C7 site.....	72
Table 12: Elemental composition (wt.%) of SEM-EDS of C7 site.....	72
Table 13: Elemental composition (wt.%) of SEM-EDS of C7 site.....	73
Table 14: Elemental composition (wt.%) of SEM-EDS of S9 site.	79
Table 15: Elemental composition (wt.%) of SEM-EDS of S9 site.	80
Table 16: Elemental composition (wt.%) of SEM-EDS from S9 block site with standard deviation.	82
Table 17: Elemental composition (wt.%) of SEM-EDS from S9 block site with standard deviation.	84
Table 18: Elemental composition (wt.%) of SEM-EDS from S9 block site with standard deviation.	86
Table 19: Elemental composition (wt.%) of SEM-EDS from S9 block site with standard deviation.	88

Chapter 1: Introduction and Literature Review

1.1 Introduction

The Alexandra Volcanic Group (AVG) is an extinct volcanic field located in the western part of New Zealand's North Island that was active in the Early Pleistocene, between 2.74 and 1.6 Ma (Briggs, 1983) and encompasses composite cones such as Karioi, Pirongia, Kakepuku, Te Kawa, and Tokanui (Edbrooke et al., 1994; McLeod et al., 2024). The AVG is the largest basaltic volcanic field which produced about 55 km³ of volcanic material that spread over an area of 1100 km² from at least 120 vents of mainly basaltic material (Briggs, 1983; Briggs et al., 1989; McLeod et al., 2024). Specifically, this study looks at the palaeoenvironmental and volcanic history related to a volcanic eruption during the early Pleistocene period, the deposits of which are now exposed at Te Mata Quarry, which is within the AVG. The site was chosen as the study area as it has yet to be examined in detail and the exposure of the lava and its underlying geology provides an opportunity to reconstruct the palaeoenvironmental conditions and emplacement of the lava in a valley. Within this study, the geology was examined through outcrop observations and stratigraphic logs; samples were examined in thin section and detailed mineralogy further analysed by Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD). Additionally, the geochemistry of the basalt was characterised by X-Ray Fluorescence (XRF) spectroscopy.

Thesis Outline

This thesis is organised into four chapters, with the first consisting of a general introduction and review of previous literature concerning the study area and surrounding geological history. Chapter two contains details of the study area, and a methodology overview. Chapter three contains the results. Finally, chapter four includes the discussion and conclusion as well as acknowledging limitations and directions for future research.

1.2 Regional Geology and Geomorphology

The North Island of New Zealand is on the Australian Plate that overrides the subducting Pacific Plate, causing the subduction related volcanism that is seen throughout the North Island (Edbrooke, 2005). The Waikato region is on the active western side of the Australian-Pacific plate boundary, to the northwest of the active Taupō Volcanic Zone (TVZ), which marks the onshore extension of the Tonga-Kermadec Arc (Briggs et al., 1989; Goles et al., 1996;

McLeod, 2020; Shane, 2000). Most of the Tonga-Kermadec Arc consists of basaltic volcanoes that have risen through the thin basaltic oceanic crust of the Pacific Plate (Briggs, 1983; Timm et al., 2019). An exception to this trend occurs where the arc extends into the thicker continental crust of Zealandia such as in the TVZ, where the basaltic magma interacts with large amounts of metasedimentary rocks such as greywacke, creating silica-rich rhyolites (Briggs, 1983; Timm et al., 2019).

Major geological processes shaping the modern Waikato landscape include late Cenozoic block faulting, Pliocene-Pleistocene basaltic volcanism, emplacement of ignimbrites and fall deposits from Quaternary volcanism, fluvial remobilisation of pyroclastic materials, and prolonged weathering and erosion (Edbrooke, 2005).

Beneath the Waikato region, the basement rocks consist primarily of greywacke and argillite. These are overlain by Tertiary Te Kuiti Group siltstones and sandstones, which form the dissected hills and ranges across the region. Overlying these older units are Quaternary ignimbrites and tephra deposits derived from eruptions in the TVZ, which blanket large areas of the Waikato landscape.

In the Hamilton lowlands, extensive plains are bordered by dissected hills and ranges mainly formed on Mesozoic basement rocks with a thin cover of Tertiary sedimentary rocks (Edbrooke, 2005). The dissected hills and ranges extending inland from the coast north of Awakino to the Waipa Basin and Hamilton lowlands are formed on basement greywacke and argillite of the Murihiku Supergroup, with a discontinuous and generally thin cover of Te Kuiti Group sedimentary rocks. The Herangi Range in the south is the highest basement range, reaching 800 m (Edbrooke, 2005).

The back-arc zone lies beyond the volcanic arc, with both tectonic extension and scattered intraplate basaltic volcanism occurring in this zone. The physical causes of the back-arc volcanism appear to be related to magma rising along the distal edge of the Pacific Plate (Briggs et al., 1989; McLeod et al., 2022). Back-arc volcanism resulted in the number of geological features throughout the Waikato region. The rocks of the Orangiwhao Intrusive group are present south of the Kawhia Harbour (Edbrooke, 2005) and were emplaced during the Pliocene when magma cooled and solidified beneath the Earth's surface. The Late Pliocene-Early Pleistocene Alexandra Volcanic Group (AVG) lie to the north of Kawhia and comprises a chain of stratovolcanoes and their associated basalts (Edbrooke, 2005). Intraplate volcanism initially present in the AVG subsequently migrated northward in the active Auckland Volcanic

Field (AVF) and two fields in Northland. The AVG includes notable composite cones such as Pirongia and Karioi, which exhibit radial dissection due to prolonged erosion of their flanks. Gannet Island, located to the west of Aotea Harbour, is the eroded remnant of an isolated Pleistocene basaltic volcano (Briggs et al., 1997).

The largest tectonic feature of the western Waikato is the extensional depression of the Hamilton Basin, lying parallel to the Hauraki Rift, another notable graben structure, within the back-arc zone of the western North Island. Large volumes of ignimbrites, sediment, and tephra-fall deposits from Quaternary volcanic events, have infilled the Hamilton Basin (Kitchen, 2021; Selby & Lowe, 1992). The region also features distinctive Quaternary dune sands along the west coast and drowned harbours such as Raglan, Aotea, and Kawhia, which reflect ongoing subsidence and sea-level change as a result of Holocene sea-level rise (Edbrooke, 2005). The sands form barriers to the entries to Aotea and Kawhia Harbours but rise to heights reaching 150 m north of Marokopa and extend as far as 5 km inland. Beneath these Quaternary deposits lies a complex sequence of older sedimentary and volcanic rocks that record the long geological evolution of the Waikato region.

Stratigraphy of the Western Waikato

In the areas of the western North Island, the crust is ~25 km thick with the upper 10 km being formed by the Mesozoic age Murihiku Terrane sedimentary rocks (McLeod et al., 2024). The composition of the lower crust and underlying lithospheric mantle remains uncertain and poorly understood, with xenoliths carried to the surface providing the only evidence. The Murihiku Terrane is the oldest identified ‘basement’ strata of the Karioi area, consisting of volcanoclastic sandstones and siltstones with conglomerates and frequent tuff layers. It was formed at the eastern edge of Gondwana about 90 Ma before being separated from it in the late Cretaceous following continental rifting and was submerged during the late Cretaceous and early Miocene.

The Murihiku Terrane rocks are grouped together into the Murihiku Supergroup and are subdivided into six groups based on their fossil content and lithology. The six groups are described by Edbrooke (2005) as the Late Triassic rocks of the Newcastle Group, Early Jurassic rocks of the Newcastle Group, Early to Middle Jurassic Rengarenga Group, Middle to Late Jurassic Kirikiri Group, Late Jurassic Apotu Group, and the latest Jurassic Huriwai Group.

The offshore Taranaki Fault is the Murihiku Terrane’s western boundary within the Waikato geological area, whilst the Waipa Fault Zone forms its eastern boundary (Edbrooke,

2005). To the north and south of Kawhia Harbour, the Murihiku Terrane forms a prominent mountain range which extends in the east to the Hakarimata Range anticline at Ngāruawāhia (Edbrooke et al., 1994). Uplifted Murihiku greywacke forms the majority of the steep forested terrain west of Mt Pirongia (McLeod, 2020).

Overlying the Murihiku Terrane is the Te Kuiti Group, a widespread feature in the geology of the northwestern North Island, extending from Northland to the King Country (Edbrooke, 2005). The Te Kuiti Group are the oldest Tertiary rocks present in the onshore part of the Waikato geological map (Edbrooke, 2005). Across much of the western Waikato, the Te Kuiti Group represents a Late Eocene-Oligocene cover sequence (Matheson, 1981), and was deposited during a period of late Palaeogene tectonic quiescence (Edbrooke, 2005), with deposition finishing by the early Miocene (McLeod et al., 2024). The Te Kuiti Group is predominantly a transgressive basal sequence of coal measures that are overlain by marginal marine to outer shelf deposits (Edbrooke, 2005). It is up to 500 m thick to the north of Pirongia, where it is dominated by siltstone to mudstone, whilst in the south, there are sandstone-dominated sequences occurring in the much thinner deposits seen locally. Limestones are present throughout the Te Kuiti Group but are present in thicker deposits in the south of the Waikato region (Edbrooke, 2005).

The Early Oligocene Glen Massey Formation is deposited predominantly in shallow-marine shelf environments (Kamp et al., 2014a). Tripathi (2008) states that the Glen Massey Formation members are typically as follows: the Elgood Limestone Member is the basal unit which comprises a flaggy bioclastic limestone; the middle unit of Dunphail Siltstone Member is made up of massive calcareous siltstone, and the uppermost member of the Glen Massey Formation is the silty fine sandstone of Ahirau Sandstone Member (Tripathi, 2008).

The Late Oligocene Aotea Formation has a more complex depositional history and reflects significant tectonic reorganisation within the basin (Kamp et al., 2014b). Kamp et al. (2014b) states that the Aotea Formation has four facies associations; limestone (Waimai Limestone Member), calcareous sandstone (Hauturu Sandstone Member, Kihī Sandstone Member), calcareous siltstone (Patikirau Siltstone Member), and chemogenic facies (upper parts of Kihī Sandstone Member, Patikirau Siltstone Member, and Waimai Limestone Member).

By the late Pliocene/early Pleistocene volcanism and associated sedimentation became the dominant geological process influencing the Waikato region. Much of the Waikato is mantled by a thin layer of composite ash beds, derived mainly from eruptions in the TVZ but

also related to activity from the Coromandel Volcanic Zone (CVZ) and from Taranaki (Edbrooke, 2005). Prior to the Quaternary period all the rhyolitic volcanism was focused within the CVZ beginning from ~10 Ma (Adams et al., 1994). In contrast, Quaternary ignimbrites and tephra deposits have blanketed the North Island of New Zealand with deposits that originated primarily from the caldera-forming eruptions in the TVZ (Edbrooke, 2005). These ignimbrite deposits are particularly prominent in the east of the Waikato (Edbrooke, 2005). The Quaternary sequences of New Zealand and the surrounding ~1000 km have been consistently shown to be rich with silicic tephra beds having been erupted from the TVZ in the central North Island (Adams et al., 1994; Prentice, 2017).

There is little evidence of major faulting episodes in the middle Waikato Basin since the late Tertiary; however, the influence of Quaternary tectonism is recorded by at least 400 m of vertical movement along the Hauraki Fault, which marks the eastern margin of the Hauraki Plains and the uplifted Kaimai Range between 0.84 and 0.14 Ma BP (Selby & Lowe, 1992).

Volcanism across the Waikato Region

In the North Island there are New Zealand Quaternary sequences that include silicic tephra beds that have been erupted from both the CVZ and TVZ (Horrocks, 2000). Just before (Pliocene Epoch of the Neogene period) and during the Quaternary period, successive eruptions from the TVZ and CVZ deposited numerous airfall tephra layers and ignimbrite sheets across the Waikato region. These were emplaced during periods of basin infilling by fluvial, lacustrine, and volcanic materials, followed by erosion to form the hilly terrain seen today (Selby & Lowe, 1992). Volumetrically, most tephra had erupted from the rhyolitic calderas of the TVZ, but ash layers derived from the andesitic stratovolcanoes of the Tongariro and Egmont Volcanic Centres, and from the offshore volcano Mayor Island, have also been identified (Lowe, 1988; Selby & Lowe, 1992).

The Kauroa Ash Beds, first proposed by Ward (1967) and further described by Horrocks (2000), represent an early series of widespread rhyolitic eruptions. Many of the tephra beds have been correlated to the TVZ, but some older ones may be CVZ (Selby & Lowe, 1992).

The AVG in the western North Island is an extinct basaltic volcanic field that is part of an extensive volcanic system in the South Pacific (McLeod et al., 2024), and was active during the Early Pleistocene from 2.74-1.6 Ma (McLeod, 2020; McLeod et al., 2024). The AVG is the largest basaltic field (1100 km²) in the North Island and erupted approximately 55 km³ of predominantly

basaltic material from at least 120 vents during its active period (Briggs, 1983; McLeod, 2020; McLeod et al., 2024).

The major cones of the AVG extend over 60 km along the Alexandra Volcanic Lineament (AVL) in a SE to NW direction from Tokanui to Mt Karioi. The AVL strikes perpendicular to the Hikurangi subduction zone and is the only confirmed example of a cross-arc volcanic chain found onshore in New Zealand. Between there lie the numerous smaller peaks of the Okete Volcanic Formation (OVF) (McLeod et al., 2024).

A defining feature of the AVG is the eruption of both arc and intraplate basalts in close spatial and temporal association (McLeod et al., 2024). This is a globally rare phenomenon, only found at a few other sites such as the Cascades Arc in western North America. The arc basalts originate from subduction zones and predominate in the eastern half of the field. Intraplate basalts are widespread in the western half of the field, comprising all of the OVF and more than half of the Karioi Volcanic Formation (KVF) and typically are the result of non-subduction tectonic setting (McLeod et al., 2024).

Local Geology associated with the Te Mata Quarry

The Te Mata Quarry, located in the Raglan area, ~700 m East from Wairēinga (Bridal Veil) Falls, reveals a palaeovalley that was filled approximately 2.57 million years ago (Stipp, 1968) by the Wairēinga Falls basaltic lava flow originating from ~2 km west of the quarry at Kaitai Hill (McLeod et al., 2024). Buried beneath the basalt layer, are preserved logs and branches.

Two of the Te Kuiti Group formations are present in and adjacent to the study area. As described by McLeod et al. (2024) the Glen Massey Formation makes up the sandstone found at the base of Wairēinga Falls and the lower part of the Aotea Formation is well exposed at Te Mata Quarry below the basalt.

1.3 Basalt lava Emplacement and Contact Features

Basaltic lava flows have significantly influenced Earth's geological past, appearing in a variety of settings. Lava flow emplacement is the process by which molten rock flows onto the Earth's surface and subsequently cools and solidifies, forming various geological structures (Hetényi et al., 2012; Recchuiti et al., 2025). This process is fundamentally governed by the physical properties of the magma (primarily its chemistry and viscosity), as well as environmental conditions (such as surrounding lithology and water availability) and the rate of effusion (Goehring & Morris, 2008; Hetényi et al., 2012; Recchuiti et al., 2025). The geology of

the environment influences the style of emplacement and the resulting geometry (Hetényi et al., 2012), whilst chemistry acts as a major determinant of the mechanical and thermal properties of the lava. Felsic lava flows are more viscous than the relatively more fluid basaltic mafic flows. This means that felsic lava flows are thicker and cover a smaller area than mafic basaltic flows of the same volume (Hetényi et al., 2012).

The cooling and solidification of these basaltic flows are driven by three main heat loss mechanisms that allow lavas to cool: radiative, convective, and conductive (Recchuiti et al., 2025). The environment dictates the boundary conditions at the flow surfaces, influencing the heat-transfer rate (DeGraff et al., 1989). While conductive heat transfer is a primary factor, water infiltrating along joints can significantly enhance cooling via convection (DeGraff et al., 1989). Interaction with external water, either during or after emplacement, is a fundamental process that leads to specific geological deposits and alterations (Phillips et al., 2013).

Columnar Jointing

As basalt cools, it often develops characteristic joint patterns known as columnar jointing. These are networks of interconnected tension fractures that divide the solidifying mass into long prismatic units, or columns, often exhibiting hexagonal symmetry (Aydin & DeGraff, 1988; DeGraff & Aydin, 1987; Spry, 1962). The columnar joints may range from several millimetres to hundreds of metres in diameter. Jointing starts when the temperatures of the lavas fall below the glass transition temperature, which for basalts is around 750 °C, allowing for the accumulation of thermal stress (Goehring & Morris, 2008; Phillips et al., 2013).

The initiation of columnar jointing begins at the exterior surfaces of a lava flow margin or any cooling surface, such as the exposed surface of a flood basalt flow or lava lake. From these margins, the process advances inward toward the core of the lava body as cooling progresses (Goehring & Morris, 2008). This mechanism allows columnar jointing to commence simultaneously at both the upper and lower crusts of a solidifying lava flow, with columns growing toward each other. Variations in the spacing and form of joints result in the development of horizontal tiers within the flow (DeGraff et al., 1989).

The columnar joints extend methodically from the flow margins into the interior of the cooling lava. The presence of chisel-like markings called striae on the column faces marks discrete phases of extension during joint formation (DeGraff & Aydin, 1987; Goehring & Morris, 2005; Phillips et al., 2013). The relationship between column width and stria size is proportional, and both are inversely related to the cooling rate: slower cooling produces wider,

more robust columns, while faster cooling results in narrower columns (Goehring & Morris, 2008; Hetényi et al., 2012).

The rheological properties of lava, which are influenced by temperature and the cooling history, play a substantial role in determining column morphology (Goehring & Morris, 2008). Environmental factors, particularly the geometry of the emplacement setting, affect column stoutness: constrained environments tend to yield stouter columns due to limited space, while in unconstrained flows, magma chemistry becomes the dominant influence, with felsic lavas typically forming thicker columns (Hetényi et al., 2012).

Columnar joints within basaltic flows can be classified by their joint spacing and arrangement into two main types: colonnades and entablatures. Colonnades consist of organised patterns of regular, coarser, stout columns, whereas entablatures comprise a more irregular assembly of thinner columns, which often curve, fan, or terminate against one another (DeGraff et al., 1989; Hetényi et al., 2012; Phillips et al., 2013; Sánchez et al., 2025). In flows where both column types are present, entablatures are always situated in the upper portions and may alternate with colonnades (DeGraff et al., 1989; Hetényi et al., 2012). Colonnades are usually found in the lower sections of the flow, with the junctions between the two column types lying well below the flow's midpoint. This arrangement reflects the comparatively rapid cooling of entablatures versus the slower cooling experienced by colonnades (DeGraff et al., 1989).

The interaction of magma and lava with their environment, including surrounding rock types and especially external water, either during or after emplacement, is a significant geological process. This interaction leads to distinctive deposits and changes in the composition of the magma (Phillips et al., 2013).

Peperite and Hyaloclastite

Hyaloclastite is a volcanoclastic deposit that forms in situ via quench fragmentation of magma during rapid cooling in the presence of water. This process is driven by thermal stress that is generated as the outer margins of magma cools and contracts, which results in brittle fracture of volcanic glass leading to the formation of clasts (Cas et al., 2024; van Otterloo et al., 2015). Hyaloclastite forms in a range of water influenced environments, including submarine, lacustrine, and subglacial, and is a key indicator of magma-water interaction. It commonly occurs in association with peperite, where increasing involvement of unconsolidated sediment

leads to a transition from quench-fragmented material to magma-sediment mingling (Martin & Németh, 2007; Skilling et al., 2002; White et al., 2000).

Peperite is formed when magma comes into contact with unconsolidated and wet sediments, which is a common occurrence in environments in which sedimentation occurs with volcanism (Doyle, 2000; Martin & Németh, 2007; White et al., 2000). These interactions can be seen particularly in submerged environments where large amounts of magma came from synvolcanic intrusions (Doyle, 2000). Several differing products may be produced due to these interactions, including intrusive pillows, effusive magma-sediment slurries and peperite. Peperite is defined by White et al. (2000) as a genetic term applied to rocks that essentially formed in situ by disintegration of magma that is intruding into and mingling with unconsolidated or poorly consolidated, typically wet sediment such as wet ash, mud, sand, or fine clastic deposits, and when no other term is applicable to the formation of these deposits (White et al., 2000). Molten rock may also come into contact with surface water bodies to form peperite. Magma, in the context of peperite formation, refers to any molten volcanoclastic deposit, whether effused as lava, intruded or fused from pyroclasts that mix with appropriate sediments (Skilling et al., 2002). This interaction of magma and wet sediment generates steam that fragments the magma and mixes the resultant volcanic particles (White et al., 2000).

Peperite domains vary greatly in size, from small pockets near contacts and other volcanic deposits to large bodies spanning several cubic kilometres (Skilling et al., 2002). They can be distinguished from other similar volcanoclastic rocks by features such as volume and geometry, spatial relationship to their parent intrusion or deposit, and their internal structure (Skilling et al., 2002). Peperite generally has contacts that are discordant to the stratification present in the host sediment. Juvenile peperite clasts are usually found near the margins of the volcanic intrusion/lava but may be widely dispersed within the sediment. Typically, peperite clasts are not bedded or laminated but can show a preferred orientation that differs from the host sediment (Skilling et al., 2002).

Busby-Spera & White (1987) established two types of peperite textures based on the predominant morphology of juvenile clasts: blocky (also termed hydroclastic) and fluidal (globular). Blocky clasts are described as angular, polyhedral, or tabular in shape. These clasts typically fit together tightly, resembling a puzzle, and their arrangement is indicative of in situ fragmentation within the host sediment (Busby-Spera & White, 1987; Doyle, 2000; Martin & Németh, 2007; Skilling et al., 2002). In contrast, fluidal or globular clasts display more rounded and irregular morphologies, which can range from amoeboid shapes to lobes, globules, thin

wisps, and tendrils. These fluidal clasts may connect through slender necks or be deformed around more rigid fragments within the deposit. The globular texture is characterised by centimetre- to metre-sized clasts exhibiting diverse and often intricate forms, including laminae and wisps. Such textures are similar to those produced in frozen fuel-coolant interactions (FCI), where sedimentary particles are incorporated into the clast as the magma cools rapidly (Busby-Spera & White, 1987; Doyle, 2000; Hooten & Ort, 2002; Martin & Németh, 2007; Skilling et al., 2002). Both blocky and fluidal clast types can coexist within the same peperite deposit, reflecting the variable mechanisms of magma-sediment interaction and fragmentation (Busby-Spera & White, 1987; Martin & Németh, 2007).

The study of peperite is important as it provides information on multiple aspects of a volcanic deposit, including the relative timing of magmatism and sedimentation, magma flow and fragmentation processes and host sediment rheology (White et al., 2000). The study of peperite provides field evidence for magma-water and magma-sediment interactions, including mixing processes that may precede FCI-type explosive eruptions. These insights enhance interpretations of intra-vent processes associated with Surtseyan and Taalian activity, assist in distinguishing lavas from sills, and inform palaeoenvironmental reconstructions by indicating contemporaneous sedimentation and magmatism (White et al., 2000).

Charcoal Formation and Lava Flow

Charcoal generally refers to the macroscopic material produced by the incomplete combustion of organic materials to produce carbon-rich (60-90%) compounds, which are often arranged in a highly condensed aromatic configuration, but the term can refer to any product along a combustion continuum from charred biomass to black carbon particles (Bird, 2006; Scott, 2010). Fossil charcoal is abundant in many sedimentary sequences, including volcanic rocks (Scott, 2010). Most of the charcoal found in the geological record derives from wood, with its open porous structure often being preserved despite the conversion of wood to charcoal (Bird, 2006). Charcoal may be rarely formed from the incomplete combustion of animals, especially invertebrates (Scott, 2010). Charcoal is predominantly the product of wildfires, although volcanic activity can also produce charcoal.

The process that underpins the formation and preservation of charcoal beneath basaltic lava flows is now better understood based on the work by Lockwood & Lipman (1980). Charcoal production is a rate-dependent process controlled primarily by temperature, the nature of the wood burned (density, water content, size, and form) and the associated thermal environment, including humidity, the rate and duration of heating and especially local oxygen supply and

concentrations. Charcoal will form whenever living woody material buried by advancing lava is raised to sufficiently high temperatures ($> 500\text{ }^{\circ}\text{C}$), but in the presence of abundant oxygen will continue to burn rapidly, forming ash and thus preventing preservation in the deposit. The critical factors for charcoal preservation are therefore temperatures not exceeding $500\text{ }^{\circ}\text{C}$ and/or more critically restricted oxygen supply (Scott, 2010). Generally, oxygen is derived directly from the atmosphere, but it can also come from porous soil, as soil oxygen levels are only slightly depleted compared to that of atmospheric oxygen.

In reduced oxygen situations, charcoal will be preserved, but if atmospheric oxygen circulates freely, charcoal is only preserved at lower temperatures, below the level needed for charcoal ignition or catalytic oxidation (Lockwood & Lipman, 1980). Pyroclastic flows and debris can suddenly entomb plant material, excluding oxygen. This anoxia means that despite temperatures that may reach $> 1000\text{ }^{\circ}\text{C}$, charcoalification may occur without combustion (Scott, 2010). These factors mean that carbonised wood, especially that derived from living plant roots, is commonly preserved under all parts of pahoehoe flows because of its exclusion from atmospheric oxygen (Lockwood & Lipman, 1980). Charcoal in these flows are generally derived from roots and rootlets, as smaller trees and shrubs are often completely burned to ash whilst large trees killed by lava are not carbonised due to insufficiently high temperatures being reached, combined with cooling by water evaporation, and so biologically decompose (Lockwood & Lipman, 1980). Charcoal formation from rootlets occurs at optimal depths of 2-20 cm below the base of the flow due to there being sufficient oxygen directly below the base to completely burn wood, whilst at greater depths, temperatures are insufficient to carbonise roots. A size gradient may also be seen across zones in charcoal formation, with thicker roots carbonised at the top and smaller roots at the lower zones, where larger roots remain uncarbonised (Lockwood & Lipman, 1980). Charcoal is, however, often formed under the margins of aa lava where temperatures often fall between $200\text{-}500\text{ }^{\circ}\text{C}$ (Lockwood & Lipman, 1980).

The rapid burial of charcoal and carbonised wood beneath lava deposits, combined with its inert nature and long-term environmental stability, leads to charcoal often being preserved within soils, allowing later analysis (Hudspeth et al., 2010), though some degradation via chemical oxidation does occur (Bird, 2006). The chemistry of charcoal is dependent on the conditions present at pyrolysis, with increases in carbon content and aromaticity seen with increasing temperature and variations in the degree of organised and non-organised components present within the charcoal, depending upon the chemical structure of the original

material (Bird, 2006). Carbon-rich, high-density charcoals formed from dense woody materials are the most resistant to chemical oxidation and best suited for radiocarbon dating purposes (Bird, 2006).

1.4 Study Aims

The primary aim of this study is to characterise the Wairēinga Falls lava flow, its emplacement, and the palaeoenvironment and volcanic history at Te Mata Quarry. This work is particularly important because the site has yet to be examined from a volcanological and palaeoenvironmental perspective. This will build upon the most recent work published on the geology of the Karioi area by (McLeod et al., 2024). This thesis will achieve this aim by accomplishing the following objectives:

1. Documenting the stratigraphy below and above Wairēinga Falls lava flow, the morphology of the lava, and the characteristics of its contacts at Te Mata Quarry.
2. Characterising the petrography and geochemistry of the Wairēinga Falls basalt.
3. Investigating the nature and distribution of hyaloclastite and joint patterns to understand magma-water interaction and cooling history, respectively.
4. Integrating findings within broader context of the Alexandra Volcanic Group and regional Quaternary stratigraphy.

Collectively, this project will focus on examining three key aspects of the quarry area:

1. The sedimentology of the underlying sediments.
2. The emplacement of the basaltic lava into the valley.
3. The geological history of the tephra-loess-palaeosol ash cover bed sequence.

By achieving these objectives, this study aims to enhance the existing knowledge of the regional volcanic history and improve the reconstruction of palaeoenvironmental conditions at the Te Mata Quarry site.

Chapter 2: Study Area and Methods

2.1 Content

The purpose of this chapter is to provide details about the study area, a detailed methodology of analysis undertaken and the results. The study was undertaken to investigate the Wairēinga Falls basaltic lava flow, how it was emplaced, and characterise the palaeoenvironment and volcanic history at Te Mata Quarry. Previous research on the general wider area has been undertaken and mapped, but no research has been solely focused on Te Mata Quarry.

The basalt of Te Mata Quarry originated from a vent at Kaitai Hill ~2 km west of the quarry (McLeod et al., 2024). Karioi is part of the larger Alexandra Volcanic Group, an extinct volcanic field that stretches from Karioi in the NW, through Pirongia and down to Tokanui towards the SE (Figure 1 from Pittari et al. (2021)).

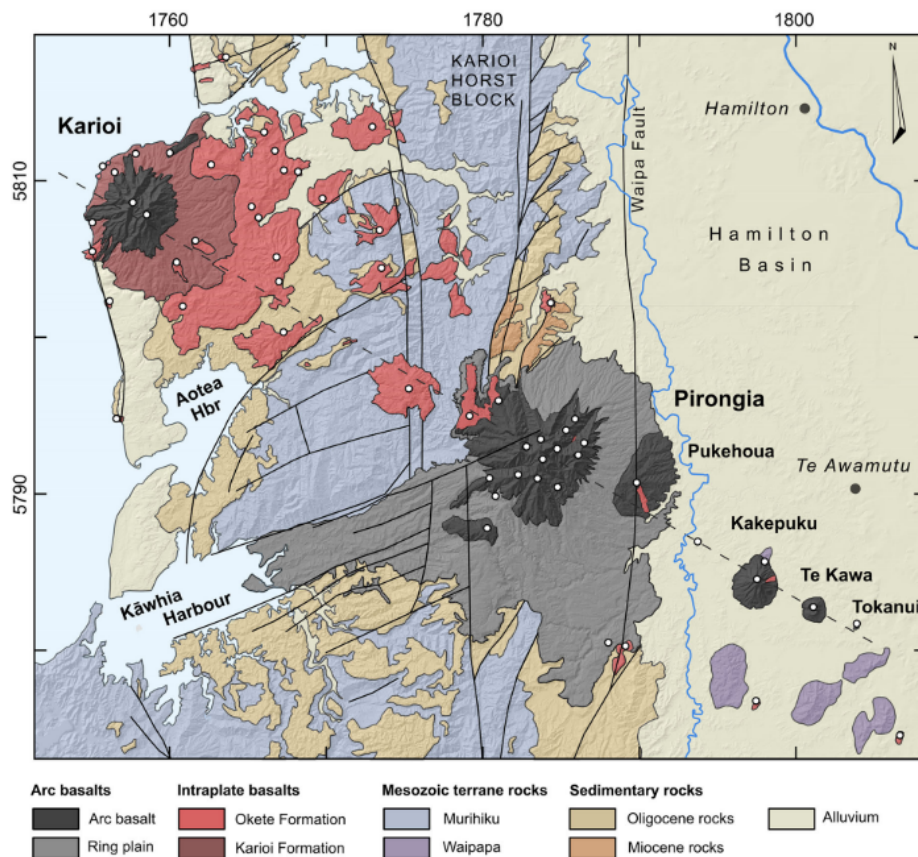


Figure 1: Map of the Alexandra Volcanic Group and the surrounding terrain of the western Waikato. From Pittari et al. (2021).

Study Area

Te Mata Quarry (Figure 2) is located ~700 m east of the Wairēinga (Bridal Veil) Falls, ~11 km south of the Raglan township, on the West coast of the North Island. Te Mata Quarry is an active basalt quarry from an Okete basaltic flow that ponded in a valley covering the sediment and underlying geology.

Majority of the sediments in the quarry are sandstones and siltstones underlying the basalt with the Kauroa Ash and Hamilton Ash beds mantling the basalt. Most of the sampling occurred in the western sectors of the quarry (Figure 3).



Figure 2: Te Mata Quarry in relation to Wairēinga (Bridal Veil) Falls.



Figure 3: Locations of sample collection at Te Mata Quarry. Scale bar 60 m.

2.2 Methods

Field Descriptions and Sampling

Majority of the fieldwork took place on the 13th of December 2024 and the 31st of March 2025, with some samples having been collected on the 17th of August 2023 as part of an undergraduate pilot study (Wilde, 2023, unpublished data). From the pilot study, ten different samples (S1 through S10) were collected and reused for this thesis with the addition of new samples which included all the B and C samples, as well as the tephra samples, and samples S11-S15. Samples were collected using a trowel, rock hammer, niwashi, before being put into labelled sample bags. The geology was documented using stratigraphic logs with descriptions focusing on appearance, texture, components, depositional structure, and contacts. Grain size was estimated visually and with reference to a grain size comparator chart, while a hand lens was used to assess mineral composition and sorting. Colour was recorded using the Munsell Soil Colour Chart; to further reduce subjectivity.

Laser Particle Size Analysis

Samples were analysed with the Mastersizer® laser diffraction particle size analyser to determine the grain size of samples C3, S11, S12, S13, S14, and S15. These analyses

complemented previous particle size analysis of samples S1-8 and S10 from the pilot study in 2023.

Each of the samples were mixed with a 10% Calgon solution to break up clay particles to allow for more accurate measurement of particle size distribution. The samples were broken up to remove any large clumps that would skew the results. The sample was then placed into the Malvern Mastersizer 3000 where the particle refractive index used was 1.500, the particle absorption index was 0.200 and the dispersion refractive index was 1.330 with the dispersant being water. The weighted residuals were all $< 1\%$ for all the runs.

Thin Sections/Optical Microscopy

Thin section analysis allowed for more detailed examination of individual grains and minerals than could be achieved through field analysis. This enabled volcanic textures and sedimentary textures to be described. Thin sections, therefore, complemented field descriptions by providing finer-scale data necessary for interpreting petrographic characterisation through optical microscopy. Thin section samples were examined using an Olympus BX51 microscope in both plane polarise light (PPL) and cross polarised light (XPL) to be able to identify and describe the minerals and textures present in the sample. Samples chosen for thin section analysis were sandstones (S1, S2, S15, and C3), siltstones (S5 and S11-S14) and hyaloclastite (S9), as well as all of the basalt (B1-B6) samples, and seven rounded and angular pebbles found within a significant tephra layer.

Stereo Microscopy

Several samples (S9, C1, C2, C4, C5, and C7) were examined under an Olympus SZX12 Stereo Microscope and images were obtained to examine the surface textures and particle morphologies. These samples were analysed in this way so that their surface textures in 3D were not destroyed (in the case of the crystalline material), or due to the sample texture (such as C2 and C4) being soft clays. Sample S9 was the only sample that has a corresponding thin section made and the decision to do both was to supplement what was found in thin section. To analyse each sample, a small subsample was placed in a petri dish under the stereo microscope where the surface textures were examined and images obtained.

XRD Analysis

Prior to analysis, samples were oven-dried overnight at 110 °C to remove moisture and subsequently crushed to a fine powder using a mortar and pestle. Bulk XRD was conducted to determine the overall mineral composition of the clay samples from the cave (C2 and C4) and

two samples from S9 with the grey and white parts separated for separate analysis (S9G and S9W respectively). Additionally, bulk XRD analysis was carried out on crystalline samples recovered from the cave beneath a section of basalt (samples C1, C5, and C7).

X-ray Diffraction (XRD) was employed as a non-destructive analytical technique to identify the mineralogical composition of selected samples. The XRD patterns were collected at the University of Auckland with a Rigaku Mini Flex II X-ray diffractometer using a standard Cu X-ray source with a $K\alpha_1$ wavelength of 1.5418 Å. Materials were scanned over a two-theta range of 5 - 90° with a 0.02° step size with a scan rate of 1.25°/min. XRD results were imported into HighScore Plus at the University of Waikato where peaks were identified and potential minerals assessed.

XRF Spectrometry

X-Ray Fluorescence (XRF) spectrometry is a destructive method of analysis used to determine the major and trace elemental composition of a bulk sample. XRF was used on the six basalt samples (B1 through to B6) to examine the major and trace elements found in the rocks. For each of the six samples, the whole rock sample had been broken up with a geological hammer, and the small pieces were collected and placed in an oven overnight at 110 °C. Once the moisture had been removed, they were crushed to a fine powder using a tungsten-carbide ring mill to ensure homogeneity.

Major oxide element concentrations were determined using fused glass beads prepared from the powdered samples. For each bead analysis, 0.80 g ($\pm$ 0.0010 g) of sample powder was mixed with 8.00 g ($\pm$ 0.0015 g) of XRF Flux 12:22 (lithium tetraborate 35.3% : lithium metaborate 64.7%) and 0.1–0.2 g of ammonium iodide (NH_4I) as a releasing agent. The mixture was fused in the Claisse Neo Fluxer furnace at 1050 °C for approximately 30 minutes until fully melted and then cooled to form a homogenous glass disc suitable for analysis.

Trace element concentrations were determined using pressed powder pellets. Approximately 7.8–8.0 g of powdered sample was homogenised with ~20 drops (~0.8 g) of a polyvinyl alcohol (PVA) binding solution, placed into an aluminium cap, and compacted using a hydraulic press to produce a stable pellet. The pellets were then dried in an oven at ~70 °C for at least two hours to remove residual moisture and binding solution.

Analyses were performed using the Bruker S8 Tiger (WSD) spectrometer. The fused glass beads were used to obtain accurate measurements of major element oxides, while the pressed pellets provided quantitative data on trace elements. Coupled together, these

methods provided comprehensive data to assess the geochemical composition and variation within samples.

The Loss on Ignition (LOI) for each sample was calculated by igniting 1-2 g of sample at 1100 °C for 1 hour and taking the loss/gain in weight as a percentage. The LOI was calculated using the formula:

$$LOI = 100 - \left(\left(\frac{DW_{1100}}{DW_{110}} \right) * 100 \right)$$

Where LOI represents the loss in weight as a percentage after combustion at 1100 °C. DW_{110} represents the dry weight before combustion and DW_{1100} represents the sample after it had been heated to 1100 °C.

pXRF Spectrometry

Portable X-Ray Fluorescence (pXRF) spectrometry is a non-destructive portable method (with no preparation time needed) of analysis in which the pXRF instrument (Delta Olympus Handheld XRF) was held up to the surface of the sample and analysed on “Geochem” mode which gave the concentration, in percentage or ppm, of the elements present in the samples. The pXRF was used on the tops of samples C1, C5, and then the top and bottom of sample C7.

This method was chosen over XRF due to its non-destructive nature. XRF analysis requires a significant amount of sample to be crushed, whereas pXRF works by laser without destruction allowing the samples to be used for further analyses.

SEM Imaging and EDS Analysis

Scanning Electron Microscope (SEM) using a back-scattered electron (BSE) detector was used for imaging the three crystalline samples from the wall/roof of the cave: C1, C5, and C7, and the clay samples S9, C2, and C4. Energy Dispersive Spectroscopy (EDS) analysis was then run on samples C1, C5, C7, and S9 to obtain semi-quantitative elemental data. Further to these tests, a polished block of sample S9 was also used and run using SEM BSE and Energy Dispersive Spectroscopy (EDS) analysis.

The instrument used for SEM was the Hitachi Regulus SU8230 FE-SEM (Figure 4). The samples analysed were C1, C2, C4, C5, C7, and S9. Before analysis, the samples were air dried over the weekend to remove moisture. To prepare for the samples, double sided conductive carbon tape was attached to a stub so the samples would stick, then these were placed into the Quorum 150V ES plus (Figure 4) where the samples were coated in 5 nm of platinum.



Figure 4: Quorum 150V ES plus (left) and Hitachi Regulus SU8230 FE-SEM (right).

For the S9 block (Figure 5), the sample surface was smoothed using the Struers Labopol 25 first with SiC-Paper with a grit of 500 and then with SiC-Paper grit 1200 to remove any saw marks that were created during thin section preparation and to ensure a flat surface. It was then polished using the Buehler Metaserv Grinder Polisher to smooth and level the surface of the sample before being dried and mounted to the stub with conductive tape before being coated in platinum in the Quorum 150V ES plus.

The reason for the EDS analysis of the polished block was to be able to generate element maps to see the textures that otherwise would not have been distinguishable/present in the thin section of said sample. It also allows for a contrast to be seen in terms of texture and chemical composition.

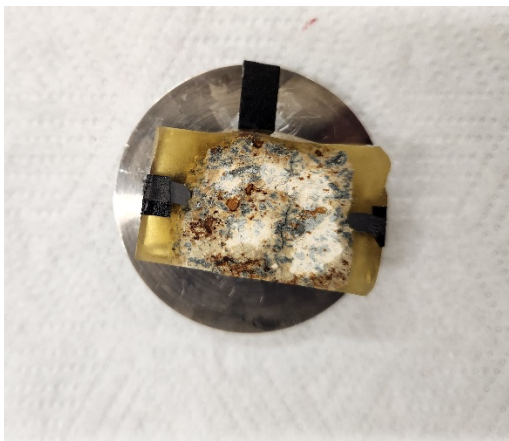


Figure 5: Sample S9 block mounted to stub with conductive tape.

Chapter 3: Results

Results

Field Observations

Sedimentary Sequence

Figure 6 shows the lowermost bench in the quarry where the lower 4 m of the sedimentary sequence outcrops and the contact with the overlying basalt can be seen. To the right of the outcrop rosette jointing can be seen.

The sedimentary sequence (~36 m thick) (Figure 7) is composed of a basal fine-grained sandstone unit (S1), which is described as olive-yellow in colour, quartz-rich, well sorted, and relatively angular. The upper metre of this unit exhibits bright reddish-brown banding and iron bands. This is overlain by a bright orange, medium- to coarse-grained sandstone (S2) with blue-grey bands of silt. The sandstone unit (Figure 7) is overall 2 m thick. The next unit begins with a sandy siltstone (S3) of a greyish olive colour, with occasional wood fragments present. Above that is a greyish olive siltstone (S4) that has bright orange clods scattered sporadically throughout the unit and grades up to an olive grey siltstone (S5) and dark brown siltstone (S6), before reaching the top of the lower bench outcrop. Above the quarry bench the siltstone continues grading from greyish yellow (S10) to light bluey grey (S11-S14). The lower sandstone also occurs further to the east of the quarry where it is ~8 m thick (S15) and to the southeast of the quarry within the lower half of the cave (C3).

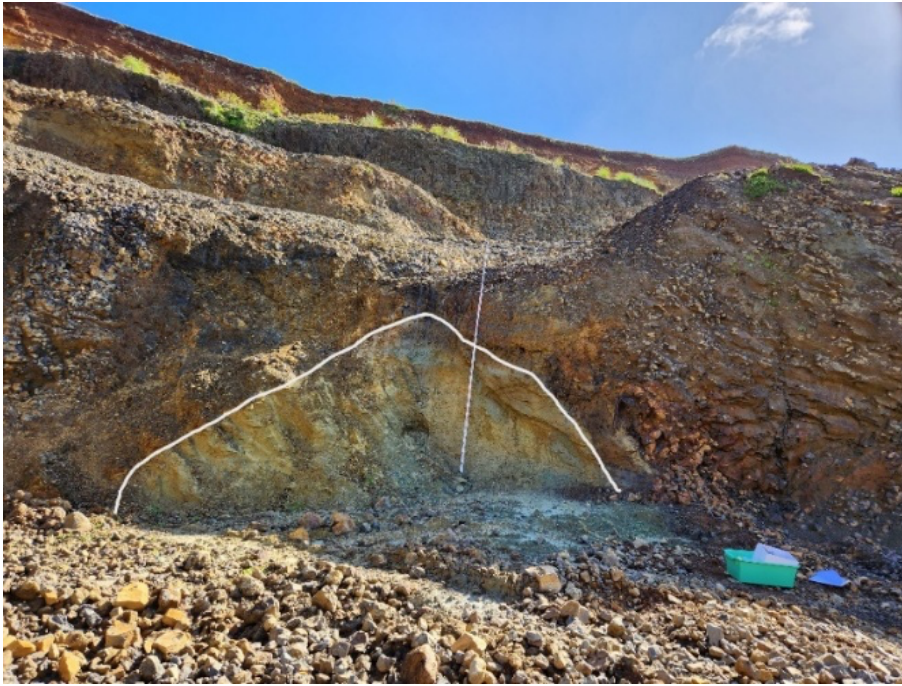


Figure 6: Lower outcrop with white line showing the contact between the sediments (S1-S5) and the overlying basalt. Rosette jointing is partially visible in the right corner of the picture.

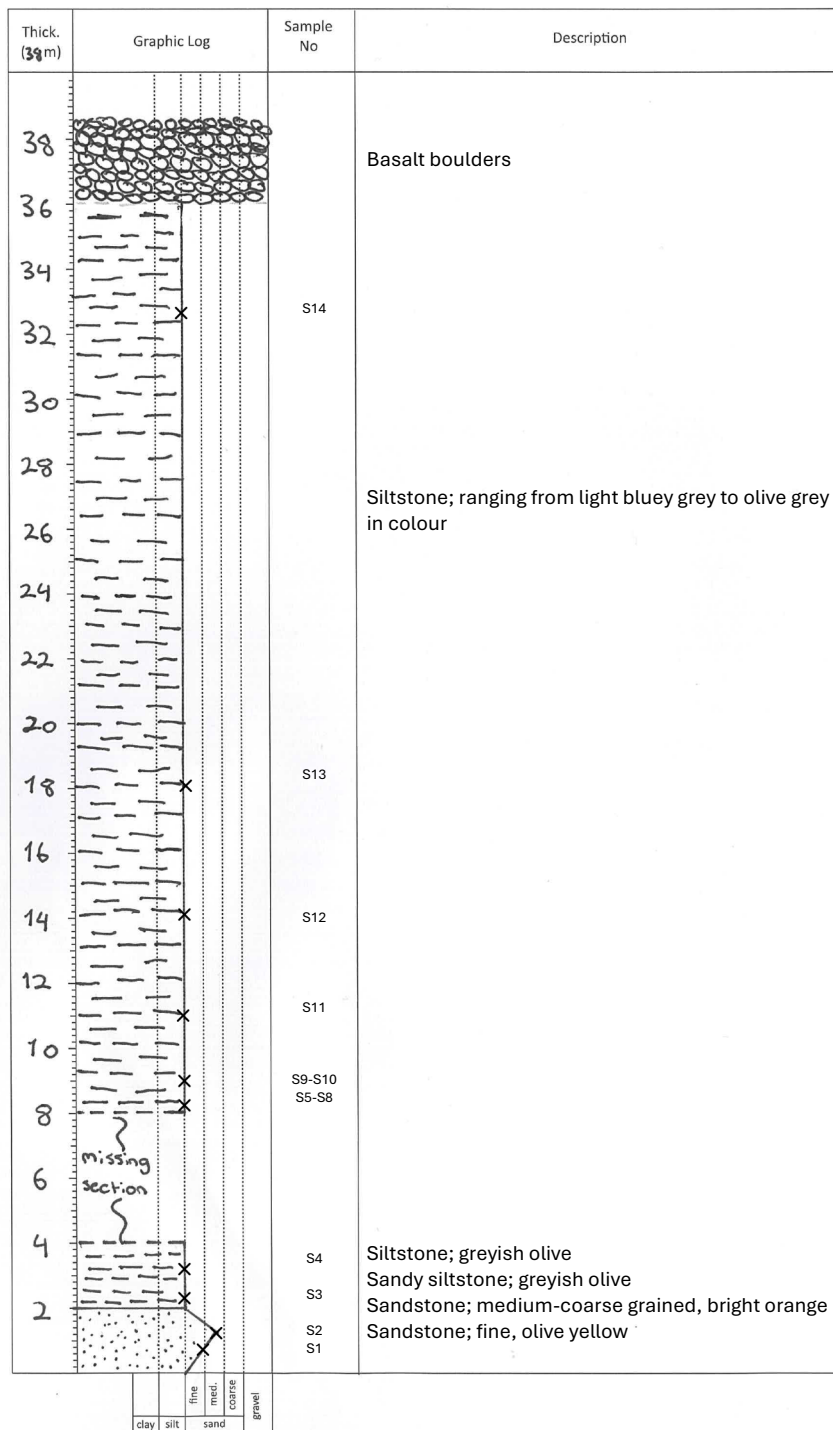


Figure 7: Stratigraphic log showing the sedimentary sequence of the sandstones and siltstones with basalt overlying.

Contact between Sediment and Basalt

The contact with the basalt crosscuts the entire sedimentary sequence as the palaeovalley into which the basalt flow has cut through both the siltstone and sandstone. The contact zone consists of a black organic-rich band (S7), bright orange iron pan (S8), and hyaloclastite (S9) (Figures 8-13).

At the contact examined between the sediments and basalt there is the presence of organic materials of black ‘coal-like’ material ~5 cm thick (S7) as well as the remains of what appear to be roots as seen in Figure 11. In the lower section there are large pieces of charred wooden material that appear to be the remains of trees (Figure 12) that were engulfed when the lava flowed over the valley.



Figure 8: Outcrop of samples S5-S8. Siltstone overlain by black organic-rich contact with a mantling iron pan.



Figure 9: Outcrop of samples S5-S8. Sample S5 is an olive-grey siltstone, S6 is a dark brown siltstone, S7 is a black biological contact and S8 is a bright orange iron pan.



Figure 10: Outcrop showing samples S9 and S10. Sample S9 is a hyaloclastite deposit with a fine white matrix and angular basalt fragments and S10 is a greyish yellow siltstone.



Figure 11: Charred root material found within the black contact (S7), as well as below in the siltstone (S6) with the iron pan (S8) overlying.



Figure 12: Charred wood remnants found within the basalt in the lower sector of the quarry.

The hyaloclastite of sample S9 (Figure 13) was described in the field as a fine breccia with a fine, white matrix, and approximately 40% of angular basalt fragments with sizes ranging from 2-10 mm and some large fragments up to 10 cm present within it.



Figure 13: Hyaloclastite deposit (S9) with large basalt fragments scattered throughout the fine white matrix.

On the southeastern side of the quarry (Figure 3), a cave with small exterior (Figure 14) led into an approximately 1.6 m thick and 3 m wide opening. Within the cave, many different textures and structures were present. The lower section of the cave wall is a massive sandstone (C3) that was collected from below the basalt. The upper section of the cave wall, above a thick red boundary, is a jigsaw breccia of white clay clasts (C2 and C4); there was a reddish-brown matrix between the breccia clasts (Figure 15). From the clay samples, C2 is pale yellow with

crystals scattered throughout and C4 is greyish yellow with sparce basalt fragments of various sizes present.

On the roof of the cave surrounded by crystal precipitates is wood (C6) (Figure 16), which is also associated with the breccia. Immediately above the breccia is the basalt. On the roof of the cave crystal precipitates were found and collected (C1 and C5). Sample C1 has a yellow surface and a pale cream interior with very fine grains, and C5 is brittle and has large visible cream/beige crystals (Figure 17). Crystalline material was found at the entrance to the cave, sample C7 is pale pink/orange and very fibrous in texture, in addition to being hard but brittle and a massive indistinguishable structure.



Figure 14: Exterior of cave found within the basalt flow in the southeastern part of the quarry.

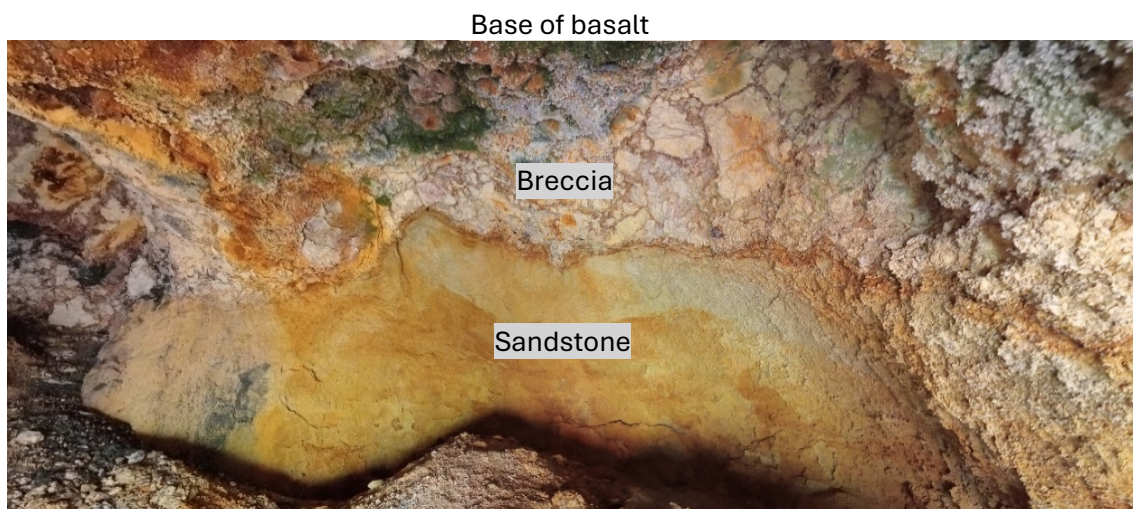


Figure 15: Interior panorama of cave, showing the massive sandstone unit (C3) and jigsaw breccia beneath the basalt.



Figure 16: Roof of cave, looking upwards, showing the dark woody material (C6) surrounded by crystal precipitates.



Figure 17: Crystals that were sampled in C1 and C5 (respectively) in place on the roof of the cave.

Basalt

Throughout the quarry a range of features can be seen in the basalt including multiple flow units, jointing patterns, and the infilling of the pre-existing valley as the basaltic lavas flowed and cooled over the sediments and organic matter. The contact between lava flow units is sharp, indicating that no significant time breaks occurred between eruption events. The jointing orientations, widths, and the patterns vary around the quarry, which can be seen in Figure 18 with the blocky, prismatic columnar jointing of the upper sector and rosette jointing in the lower sector, where the columns and thus joints emanate out from the central point of the flow.

All the jointing that was observed in the lower sector of the quarry appears to be curved and irregular, whereas the joints in the upper sector, in general, are straighter and blockier. The

curved and irregular jointing is likely due to the flow being restricted and confined by the walls of the valley.



Figure 18: Columnar (left) and rosette (right) jointing showing the different patterns of jointing formed from the lava flows.

All the basalt samples show very similar results in terms of their descriptions. The samples are dark grey basalts with olivine phenocrysts abundant throughout the lava flow. The fresh surfaces are light to dark grey, while the weathered surfaces have a reddish-brown appearance due to oxidation. The samples have pale green-yellowish olivine phenocrysts visible with aggregates of smaller crystals reaching up to 20 mm in length, but majority being < 2 mm in length. Small feldspars are present throughout hand samples when seen with a hand lens.

Cover Beds

On the western edge of the quarry the cover beds of the Kauroa Ash and Hamilton Ash formations were measured at least ~10.7 m thick; an additional few metres representing the lowermost part of this sequence in direct contact with the top of the basalt were obscured by a terrace of quarry tailings (Figure 19). The Kauroa Ash tended to be lighter in colour than that of the overlying Hamilton Ash, however, both have a mostly bright brown to reddish orange appearance. There are a lot of red mottles present in the outcrop as well as specks of what appeared to be manganese as seen in Figure 20.

From the outcrop of the ash beds the lowest visible unit is a pale-yellow clay with red/orange veins present (T3), that becomes yellow orange (T4) with a gradation in colour over 20 cm, it then grades into a pebble gravel with a pale-yellow clay matrix that has round ‘pumice-like’ pebbles and other lithics scattered throughout (T5). This unit then transition into reddish

orange clays (T6 and T7), bright yellowish brown (T8), before becoming light yellow orange, bright yellowish brown and orange layers with red mottles (T9). The next three units are all clays that are orange (T10 and T12) or light yellow orange (T11), then grades into a bright yellowish brown, fine gravelly clay (T13 and T15), and brown clay (T14).



Figure 19: Outcrop of the Kauroa Ash and overlying Hamilton Ash on the western side of the quarry.

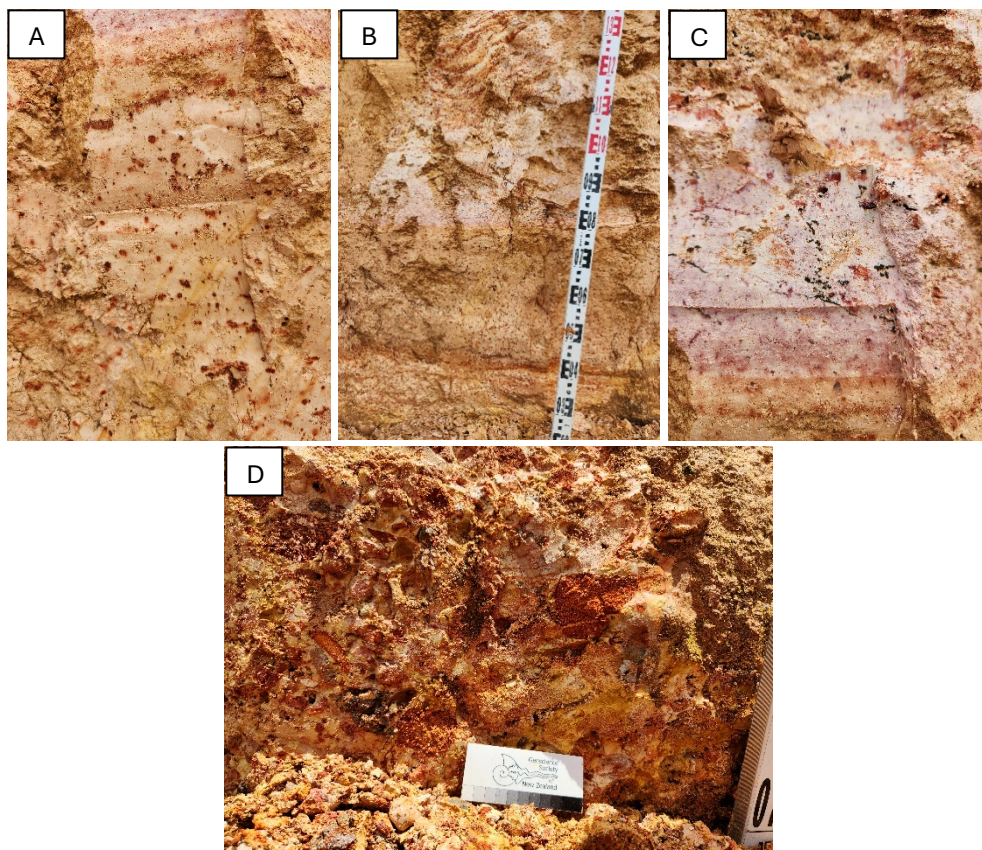


Figure 20: Red mottles (A and B), manganese specks (C), and T5 layer (D) from the Kauroa Ash.

The grain sizes present within the beds ranged from clay to fine gravelly clay. The samples taken from the cover bed outcrop were identified in the field as clay except pebble-sized clasts were selected in sample T5. Due to the uniqueness of the T5 layer in the lower

section of the Kauroa Ash sequence, additional attention was given to its description and sampling. The T5 layer is ~1 m thick with gradation over 20 cm, with ~35% of the layer made up of pebbles (Figure 20). The pebbles are mostly sub-rounded with sizes ranging from 20 to 60 mm. The pebbles vary in colour from pale grey/white to a rust red. The samples are mostly fine-grained and aphanitic, with vesicular textures and a chalky feel. There were white veins in some of the samples, but these were not further tested to determine the composition. Several of the pebbles were very light and vesicular which could indicate pumice that has undergone alteration. Sample T5 included pebbles present of differing sizes and variation in shape, texture, and colour (Figure 21).

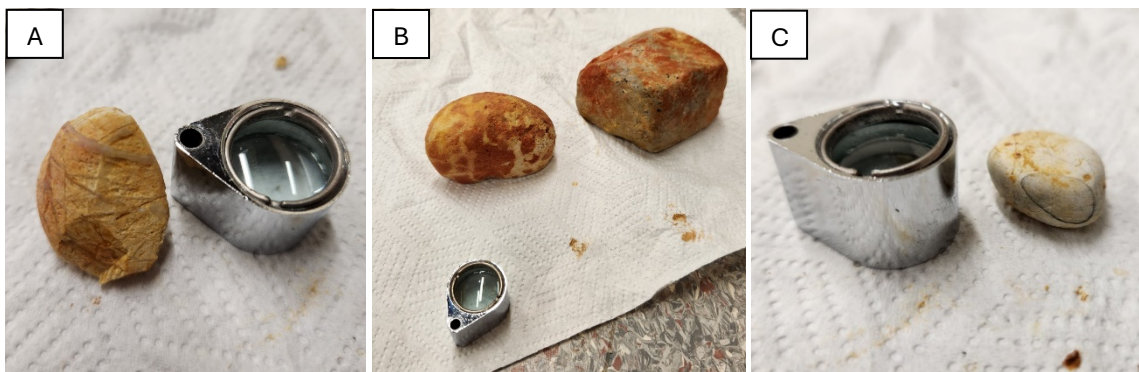


Figure 21: Pebbles from the T5 ash layer. A) White veins present on the smooth rounded pebble. B) Rounded and angular pebbles with white and red mottling. C) Very smooth rounded pebble with red mottles on the surface.

values, as well as the highest mode (259 μm). In contrast, samples S12 – S14 contain the finest overall particles with the D_{10} values between 2.35 – 3.31 μm . Sample (C3) was comparatively coarser as it taken from the sandstone unit, on the opposite side of the quarry, whereas the finer samples (S11-S14) were taken from siltstone units.

Based on these values, it places C3 as a fine sand, S15 as a very fine sand, S12 as a medium silt, and samples S11, S13, and S14 are all coarse silts.

The span, representing polydispersity, is also significantly varied among samples. The narrowest distributions were observed in C3 (span = 2.50) and S15 (span = 2.93). The broadest distribution occurred in S12 (4.67) and S13 (5.10), indicating a significant proportion of both fine and coarse grains within these samples.

Statistical distribution parameters support these observations. Samples S13 and S14 exhibited high kurtosis and positive skewness, reflecting long-tailed distributions with an extended coarse-particle fraction. In contrast, C3, S11, and S15 displayed low kurtosis and only moderate skewness, suggesting more symmetric, moderately dispersed distributions within these samples.

Mode values were generally consistent with each of the samples D_{50} value but shifted toward the coarser end of the size spectrum. For example, S13 has a median of 33.8 μm , but a mode at 67.8 μm , while C3 shows a median of 158 μm and a mode of 259 μm , providing further evidence of the presence of coarse components. Laser obscuration values range from 12.11% (S14) to 22.98% (S12). Higher obscuration indicates more particles blocking the laser beam, which can correlate with higher particle concentration or larger particle sizes.

Table 2 shows the key distribution statistics that were examined in the pilot study (Wilde, 2023, unpublished data).

Table 1: Table showing the key distribution statistics for particle sizes.

Sample	D_{10} (μm)	D_{50} (μm)	D_{90} (μm)	Mean $D[4,3]$ (μm)	$D[3,2]$ (μm)	Mode (μm)	Span	Kurtosis	Skewness
C3	14.8	158	409	187	20.4	259	2.502	0.117	0.846
S11	4.02	58.3	185	78.3	10.3	110	3.104	0.994	1.168
S12	3.09	26.4	127	48.9	7.79	77	4.671	3.483	1.794
S13	3.31	33.8	175	79.9	8.48	67.8	5.097	16.295	3.711
S14	2.35	34	127	54.3	6.87	71.4	3.665	8.016	2.416
S15	10.2	89.1	271	118	18.9	177	2.927	0.569	1.055

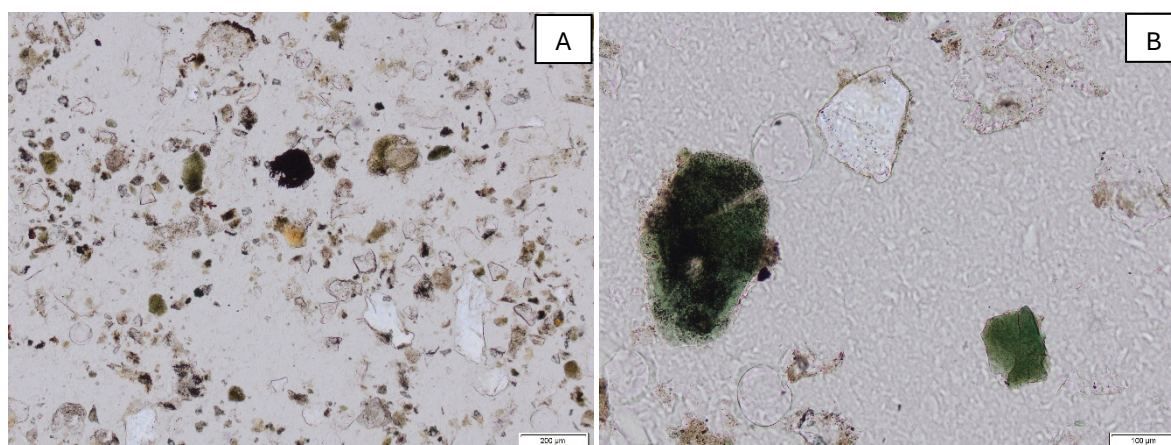
Table 2: Table of key particle size distribution data from the 2023 pilot study.

Sample	D ₁₀ (μm)	D ₅₀ (μm)	D ₉₀ (μm)	Mean D[4,3] (μm)	D[3,2] (μm)	Mode (μm)	Span	Kurtosis	Skewness
S1	6.64	98	260	116	15.1	174	2.583	-0.047	0.81
S2	2.75	44.2	209	80.4	7.77	159	4.663	0.221	1.052
S3	2.23	28.4	177	60.2	6.22	40.2	6.165	2.313	1.678
S4	4.67	73.9	1550	471	12.5	56	20.887	2.427	1.741
S5	1.86	23.8	113	44.2	5.5	73.7	4.669	5.434	1.975
S6	2.09	27.5	144	69	5.97	66.4	5.147	27.201	4.714
S7	5.43	72	1040	314	14.1	91.7	14.394	6.048	2.358
S8	7.53	122	1400	486	16.6	1010	11.415	2.075	1.543
S10	1.99	25.4	117	47.8	5.74	68.6	4.515	13.354	3.005

Petrography

Description of Sandstones and Siltstones

The sandstones are poorly sorted with most of the grains being angular to subangular, with large quantities of plagioclase which display albite twinning, as well as subangular to subrounded quartz grains. There is glauconite present in all samples with some large grains up to 200 μm as seen in Figure 23B, as well as sample C3 having a glauconite filled shell (Figure 23C). Opaque minerals occur with variable abundance throughout all samples.



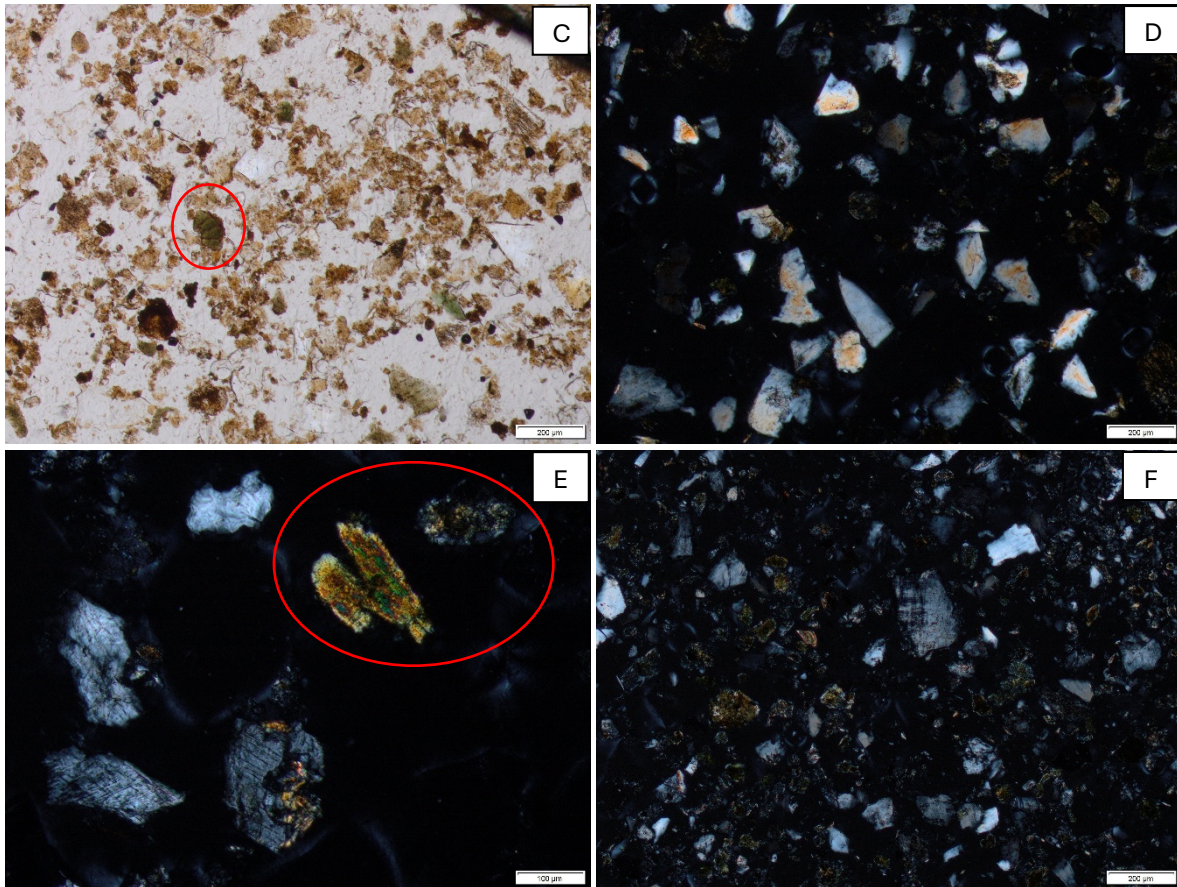
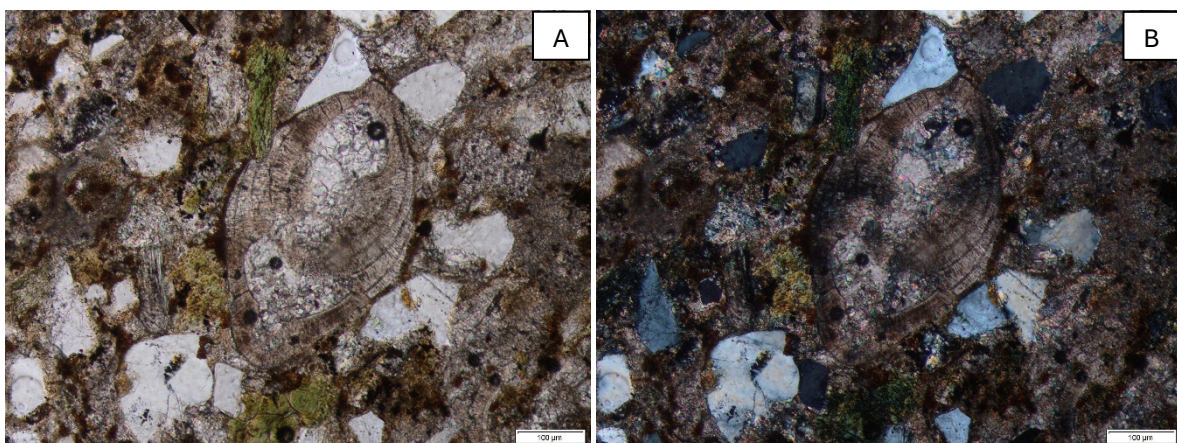


Figure 23: Photomicrographs of sandstone grains under plane-polarised (A-C) and cross-polarised (D-F) light. A) Sample S1. Shows the sorting and sizes of the grains. B) S2. Glauconite grains. C) C3. In the red circle shows a glauconite filled shell. D) C3. Quartz and plagioclase of varying shapes. E) S15. Ferromagnesian minerals in red circle. F) S1. Plagioclase displaying twinning with quartz surrounding.

Within the thin sections of the siltstones (Figure 24), there is poorly sorted, subangular to subrounded quartz, angular to subangular plagioclase, and glauconite grains as well as opaques of variable abundance and sizes set into a very fine pinkish groundmass likely to be calcite. There is an abundance of shells of various shapes and sizes throughout all samples. Concentric layered inclusion around calcite with intruding quartz crystals is seen in Figure 24C, D.



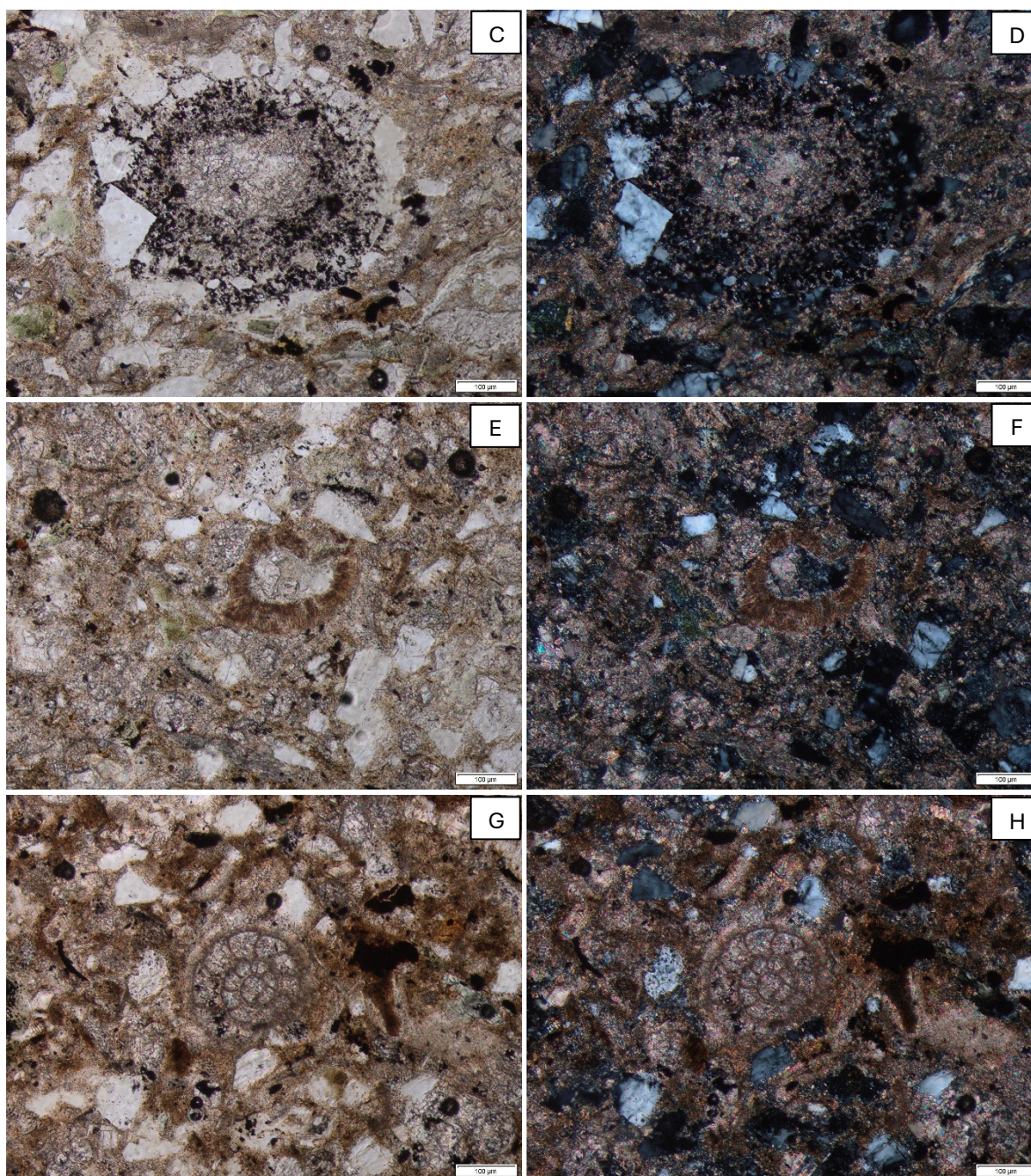


Figure 24: Photomicrographs of siltstones in plane-polarised (left) and cross-polarised light (right). A/B) S11. Foraminifera surrounded by plagioclase, quartz, glauconite, and opaques. C/D) S12. Concentric layered inclusion around calcite groundmass with intruding quartz crystals. E/F) S13. Quartz and plagioclase surrounding bioclast. G/H) S14. Foraminifera (centre) surrounded by quartz, plagioclase, and opaques with a pink calcite groundmass.

Description of Basalt

The thin sections taken from the six basalts collected show overall hypocrySTALLINE, fine-grained, porphyritic basalt containing prominent euhedral to subhedral olivine phenocrysts > 2 mm with plagioclase phenocrysts and small augites and opaques, and a very fine-grained dark microclitic groundmass. Some phenocrysts have been partially resorbed showing embayments and others contain inclusions or both. In sample B2 a large crustal xenolith over 2 mm was found with a ring around it that could be altered glass (Figure 25C, D).

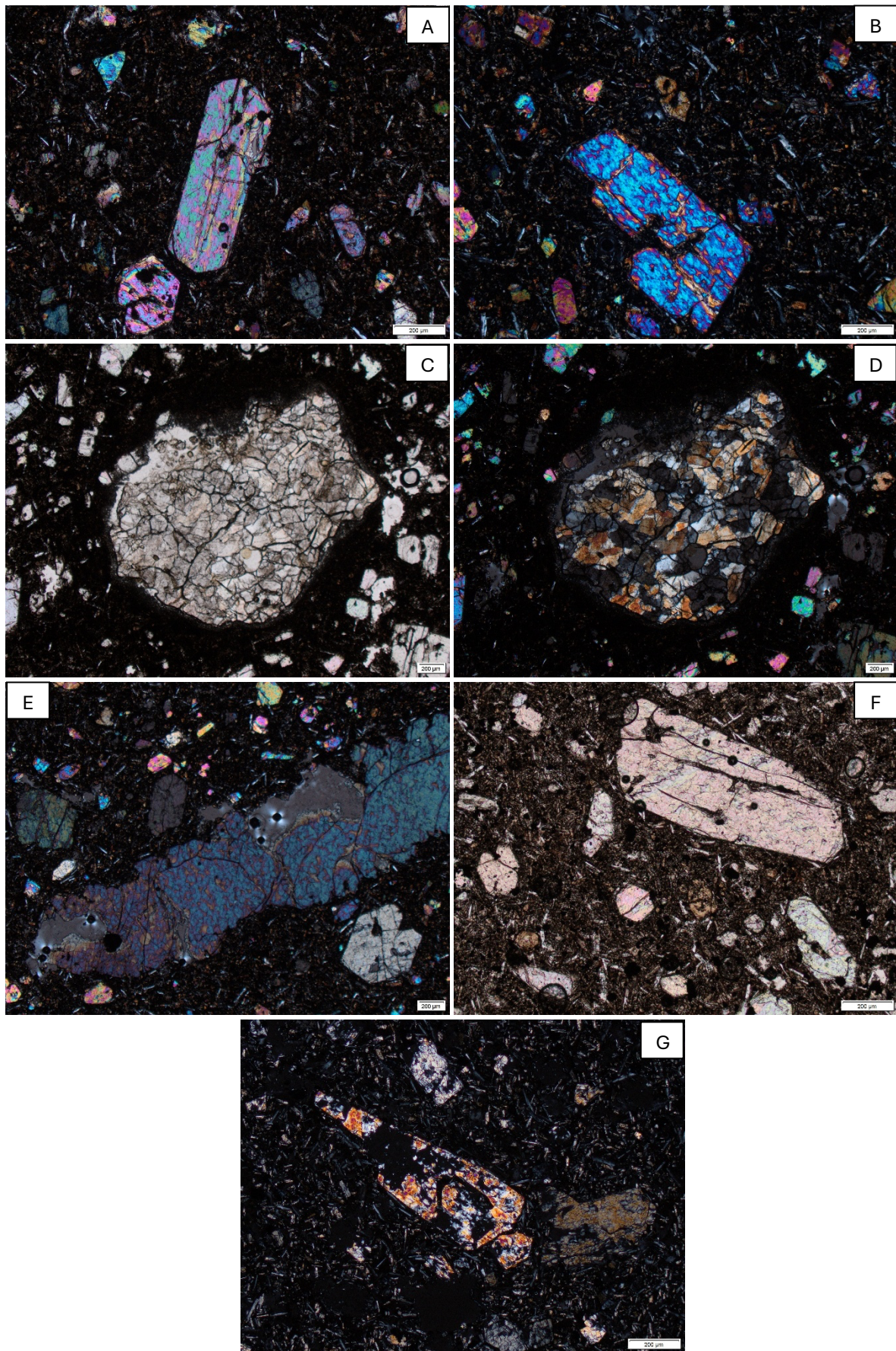


Figure 25: Photomicrographs of minerals present within the basalt samples shown in plane-polarised (C and F) and cross-polarised (A, B, D, E, and G) light. A) B1. Olivine mineral in the centre (600 μm) surrounded by smaller olivine

phenocrysts and a fine-grained groundmass. B) B1. Olivine phenocryst (~740 μm) showing embayment with small augite and plagioclase minerals present. C/D) B2. Large crustal xenolith with a ring around the exterior that is potentially altered glass. Small olivine and augite minerals are scattered about the xenolith. E) B2. Olivine phenocryst over 2 mm in length with smaller olivine phenocrysts surrounding. F) B3. Olivine under plane-polarised light with smaller olivine, augite, and plagioclase with a fine-grained groundmass. G) B4. Embayment present from an augite been resorbed.

Description of Hyaloclastite Microtexture

The microtexture of the clay matrix and basalt-like clasts were studied in a thin section of sample S9. There are defined areas of differing colours and textures throughout the thin section in PPL (Figure 26), however, it proved considerably difficult to visualise anything under XPL, due to amorphous clay present, which is notably more prominent in the grey sections. The dominant mineral seen is quartz, however, structure and textural details are difficult to determine. The sample has magnetite microphenocrysts and a very-fine crystalline groundmass. There is some resorption of minerals that has occurred throughout the sample. There is not a lot of uniformity across the slide/sample, regarding texture, colour, and arrangement of minerals and grains.

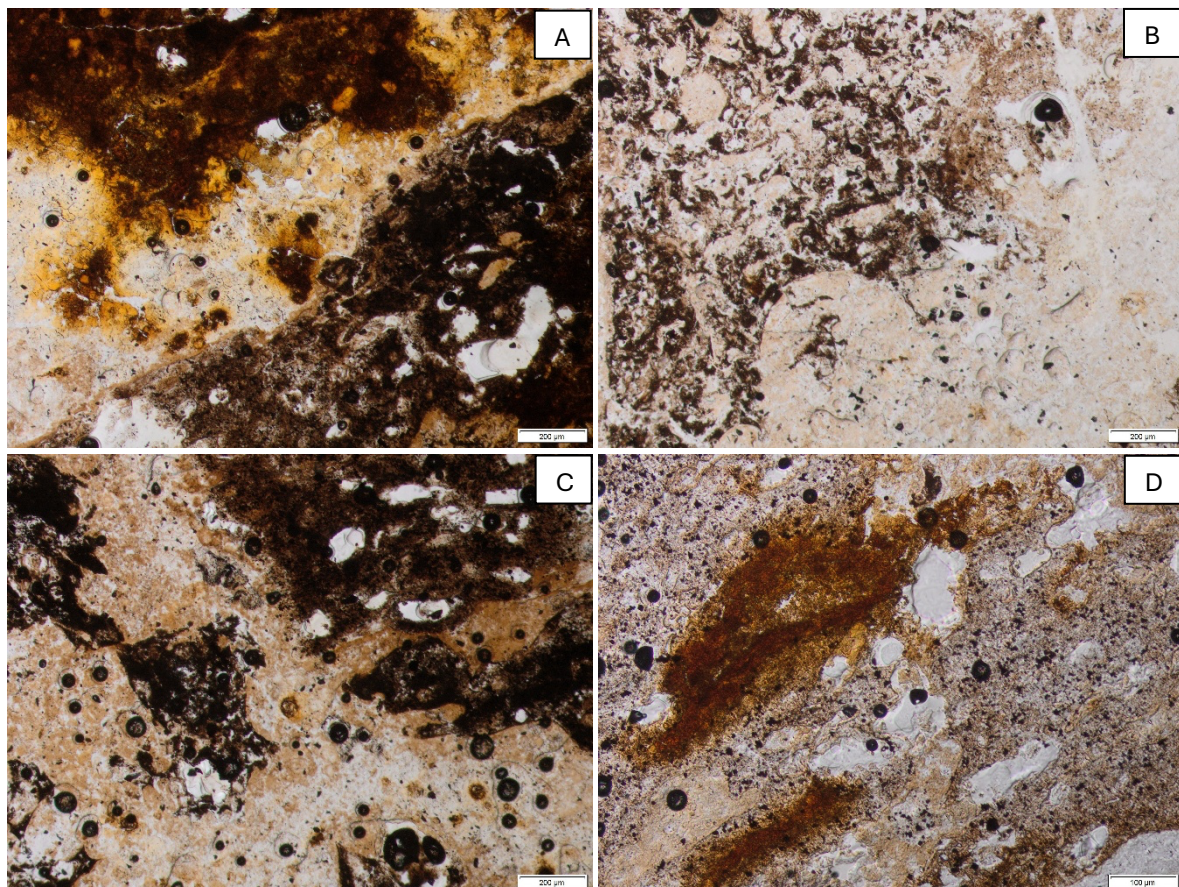
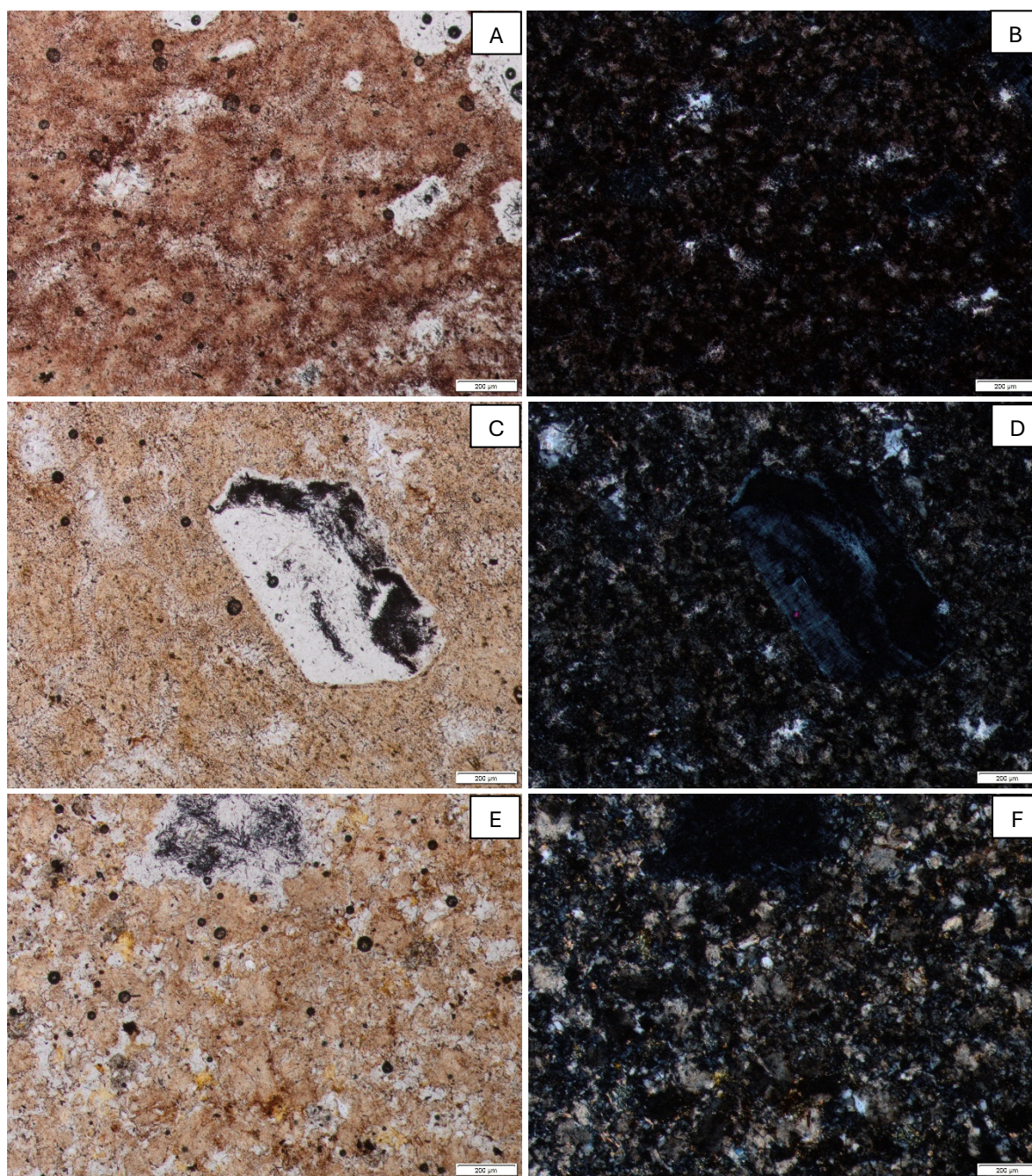


Figure 26: Photomicrographs showing textures of the hyaloclastite in plane-polarised light. A) Colours range from light grey to very dark reddish brown/blackish brown. Small black specks can be seen scattered throughout the sample. B) Pale orange to very dark reddish brown. C) Pale yellow to black. D) Pale yellow to reddish brown. Small opaques are largely present in the groundmass of the dull orange sections.

Description of pebbles from Kauroa Ash layer

The pebbles from the Kauroa Ash layer, T5, were divided based on the roundness or angular nature of the samples. From the rounded clasts (Figure 27A-F), the thin sections under PPL showed dull/earthy brown and red to pink-orange colours with clay sized groundmass, a few opaques and isotropic minerals as well as phenocrysts with alteration. The angular clasts (Figure 27G-L) were mostly quartz rich with some weathering occurring throughout. Under PPL the colours range from colourless to deep red/brown. Altered phenocrysts can be seen as well as opaques and isotropic minerals.



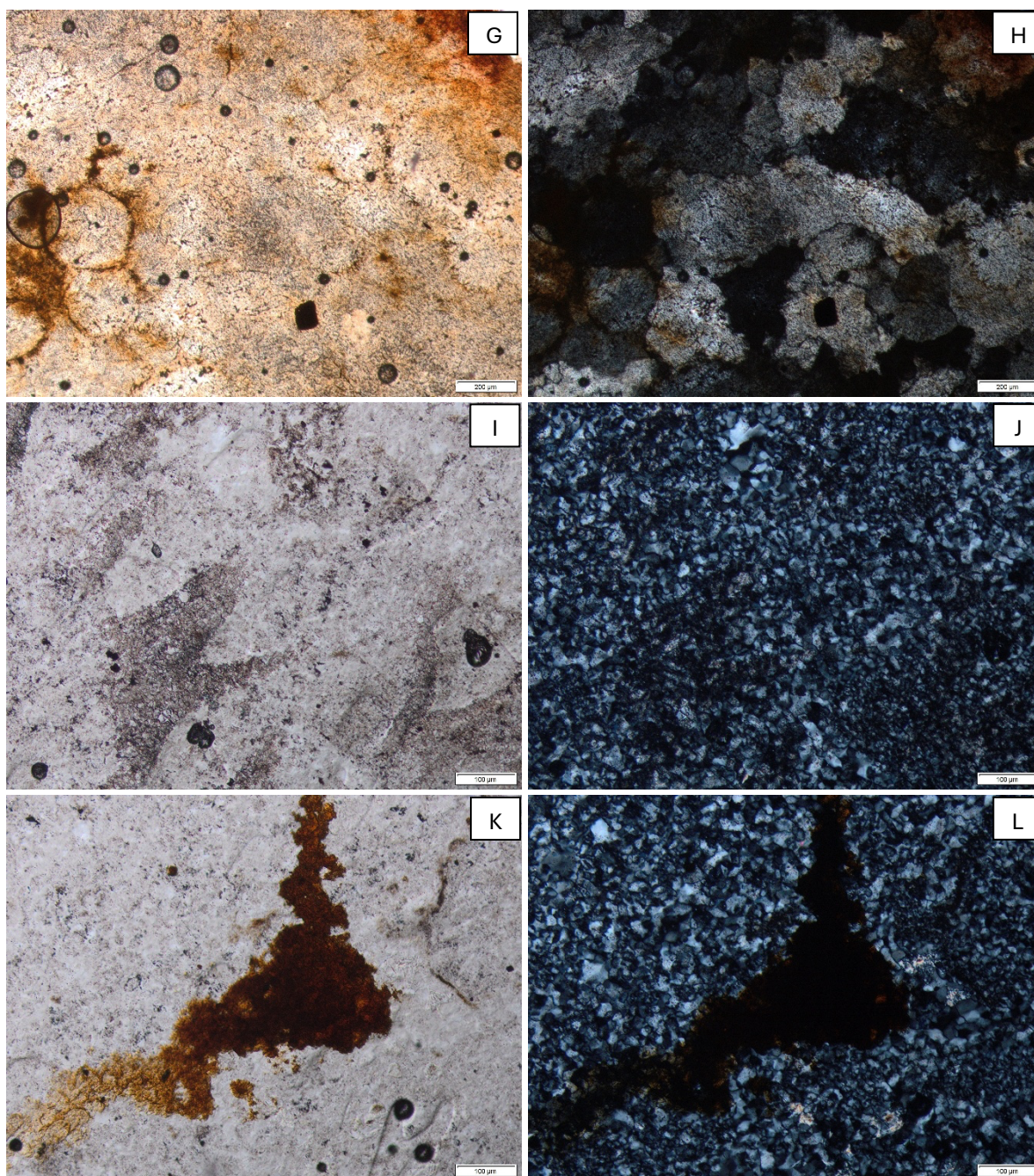


Figure 27: Photomicrographs of Kauroa Ash clasts in plane-polarised (left) and cross-polarised light (right). A/B) TR2. Groundmass has pinkish-orange clay-sized material when under plane-polarised light. C/D) TR2. In the centre of the image a large well-formed phenocryst is present surrounded by a light orange-pink clay-sized groundmass. E/F) TR1. Clay-sized dull pinkish-orange groundmass with yellow and brown material scattered throughout, a few opaques are seen but bubbles from glue are also present. In the upper centre there is an altered phenocryst. G/H) TA4. Groundmass clay-sized orangey-pink with darker brown and red material present, and opaques. I/J) TA2. Quartz rich with sizes varying. K/L) TA2. Large, weathered material with quartz rich groundmass.

Crystal Descriptions from Stereomicroscope

The sample C1 is very fine- to fine-grained and has a pale yellow to light tan colouration. The mineral grains are angular to subangular. The sample is dominated by fine material, with scattered elongate, translucent crystals that are visible from 7x magnification (Figure 28A, B). Under 20x magnification, very fine irregular wispy crystal habits can be observed (Figure 28D).

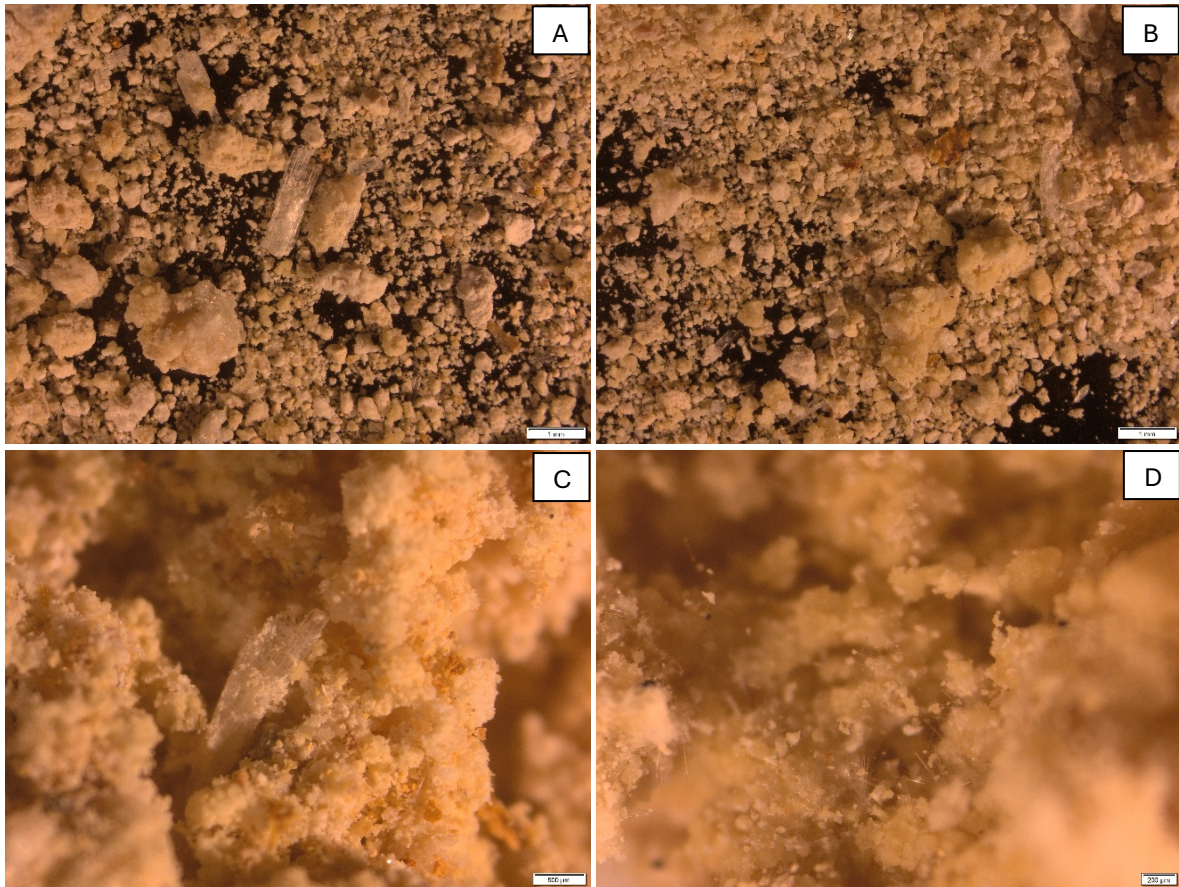


Figure 28: Stereomicroscopy of sample C1. A/B) 7x magnification. Elongate, translucent crystals within varying sizes of crystal material. C) 12.5x magnification. Long, elongate crystal which is in a fine matrix. D) 20x magnification. Wispy crystals in amongst larger crystals and material.

Sample C5 is fine- to medium-grained, crystals as small as 50 μm as well as crystals up to 5 mm. They have acicular and prismatic (Figure 29) as well as radiating crystal habits (Figure 29C). The crystals are set into a dark matrix of red, grey, and brown material as well as sections of a light yellow-cream matrix which the crystals are growing from.

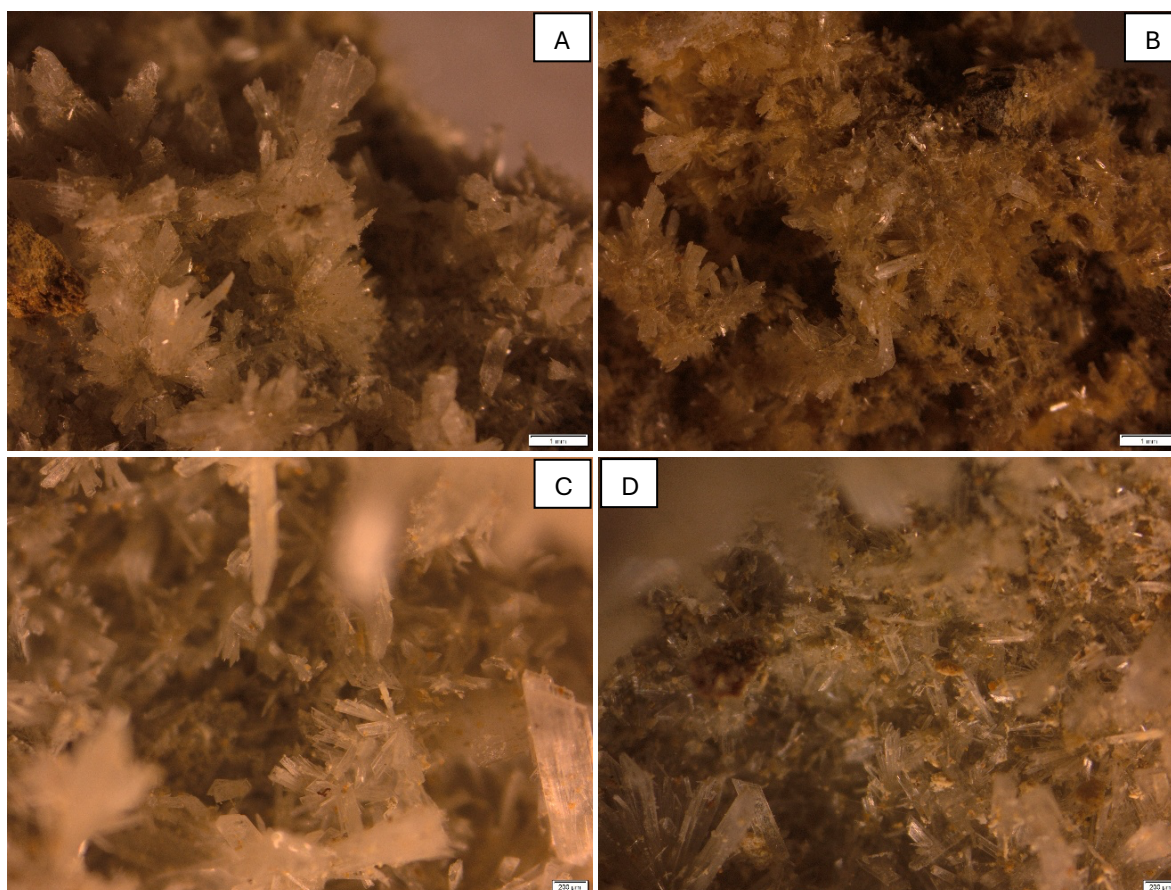


Figure 29: Stereomicroscopy of sample C5. A/B) 7x magnification. C/D) 20x magnification. A) Clustered, radiating crystals with yellowish brown material on the surface of the crystals and a ~2 mm clast on the side. B) Clustered, radiating crystals with a yellow hue to them due to material present on the surface. C) Clustered blade-like, prismatic crystals. D) Clustered acicular and prismatic crystals with yellowish brown material on the crystal surfaces.

In hand sample, sample C7 is hard to distinguish the crystals from the orangey-pink matrix due to the nature of said sample, however, under the microscope the crystal structures can be seen. Sample C7 has a wide range of crystal sizes ranging from 200 μm to ~1.5-2 mm. A large section of the sample shows fibrous crystals (Figure 30A, C) as well as prismatic crystals (Figure 30C, D) of variable abundance and sizes. There are small areas of grey/black aggregates present throughout the sample (Figure 30E).

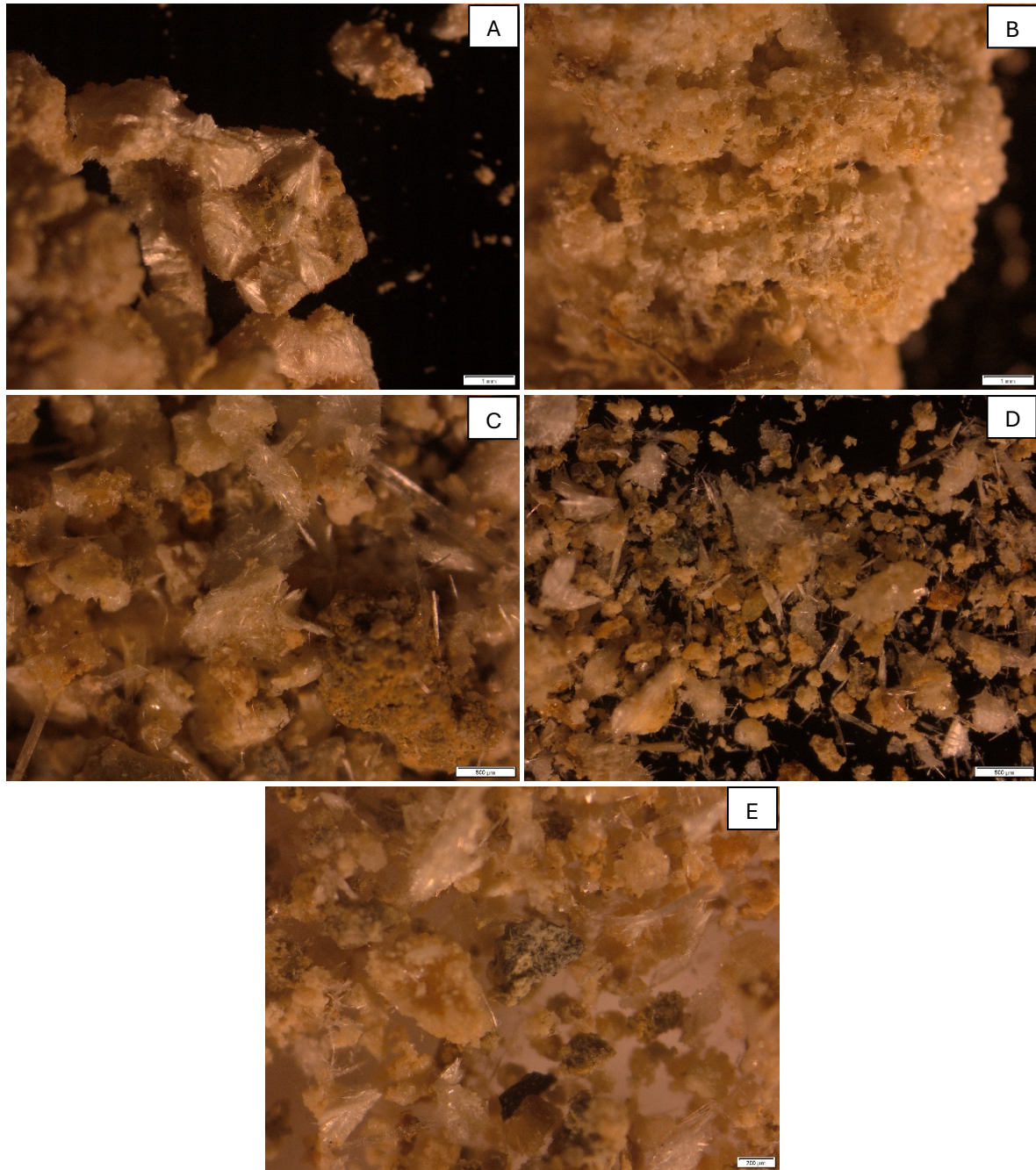


Figure 30: Stereomicroscopy of sample C7. A/B) 7x magnification. C/D) 16x magnification. E) 25x magnification. A) Pale yellow fibrous crystals with yellowish brown material present on the surface. B) The crystal arrangement is very irregular with the pale yellow crystals not having very identifiable textures. C) Fibrous crystals surrounded by yellowish grey material. D) Prismatic and fibrous crystals of varying sizes with loose pale yellow aggregates around sample. E) Pale yellow/black aggregates and fibrous crystals.

Clay and Hyaloclastite Descriptions from Stereomicroscope

Sample C2 is a pale yellow (5Y 8/3) clay with sizes varying amongst the sample as well as quite well-structured crystals within and around the clay with small black specks with some appearing to have a metallic lustre, which are likely to be magnetite (Figure 31A).

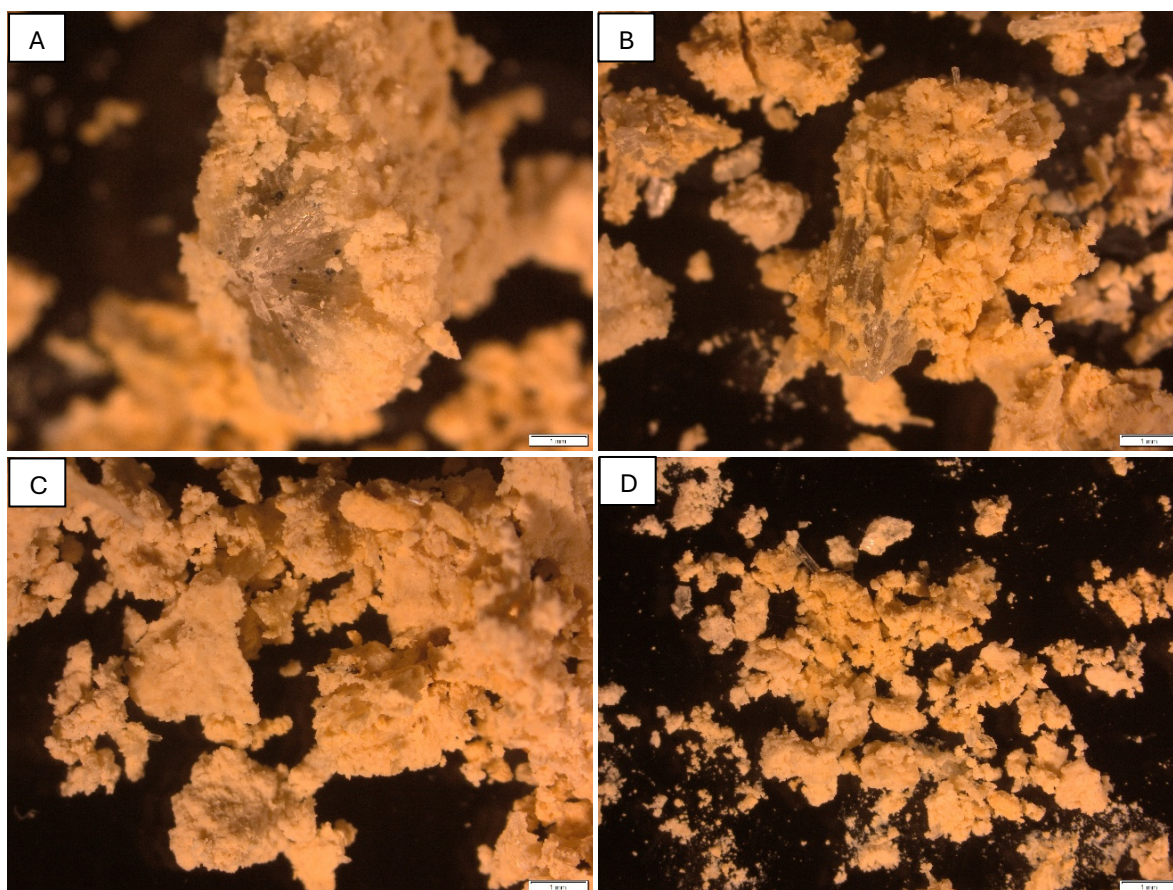
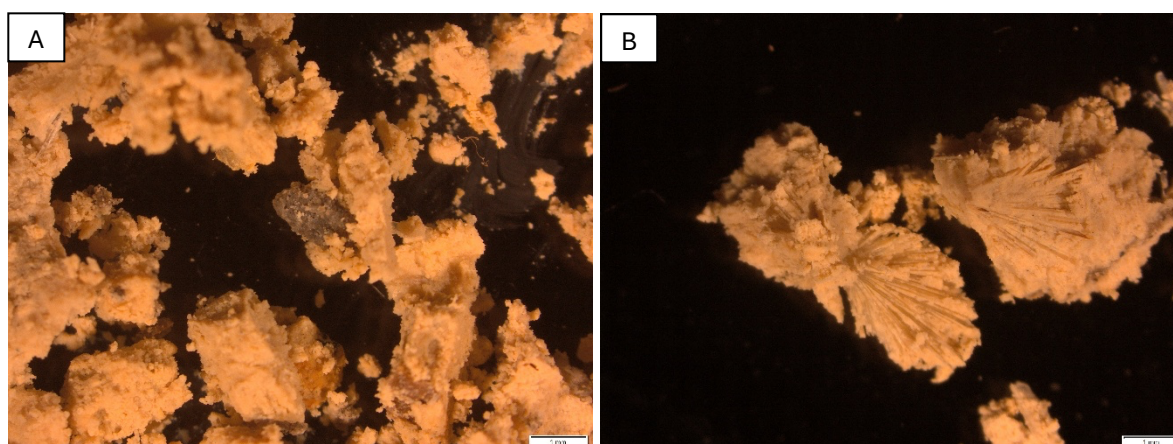


Figure 31: Stereomicroscopy of sample C2 at 7x magnification. A) The entire crystal piece surrounded by clay is ~20 mm. Within the crystal are small, potential, magnetite minerals. B) The clay is a pale yellow, encasing a large well-formed crystal with smaller crystals protruding from the clay. C) Pale yellow clay with prismatic crystals. D) The clay particles are all ~1 mm and range from a pale yellow to a brighter pale yellow, prismatic crystals are visible with small black specks scattered around.

Sample C4 has long fibrous crystals coated and enclosed within a light yellow (2.5Y 7/3) clay (Figure 32) with the occasional black speck (Figure 32C) as seen in sample C2, in addition to there being sections of basalt fragments.



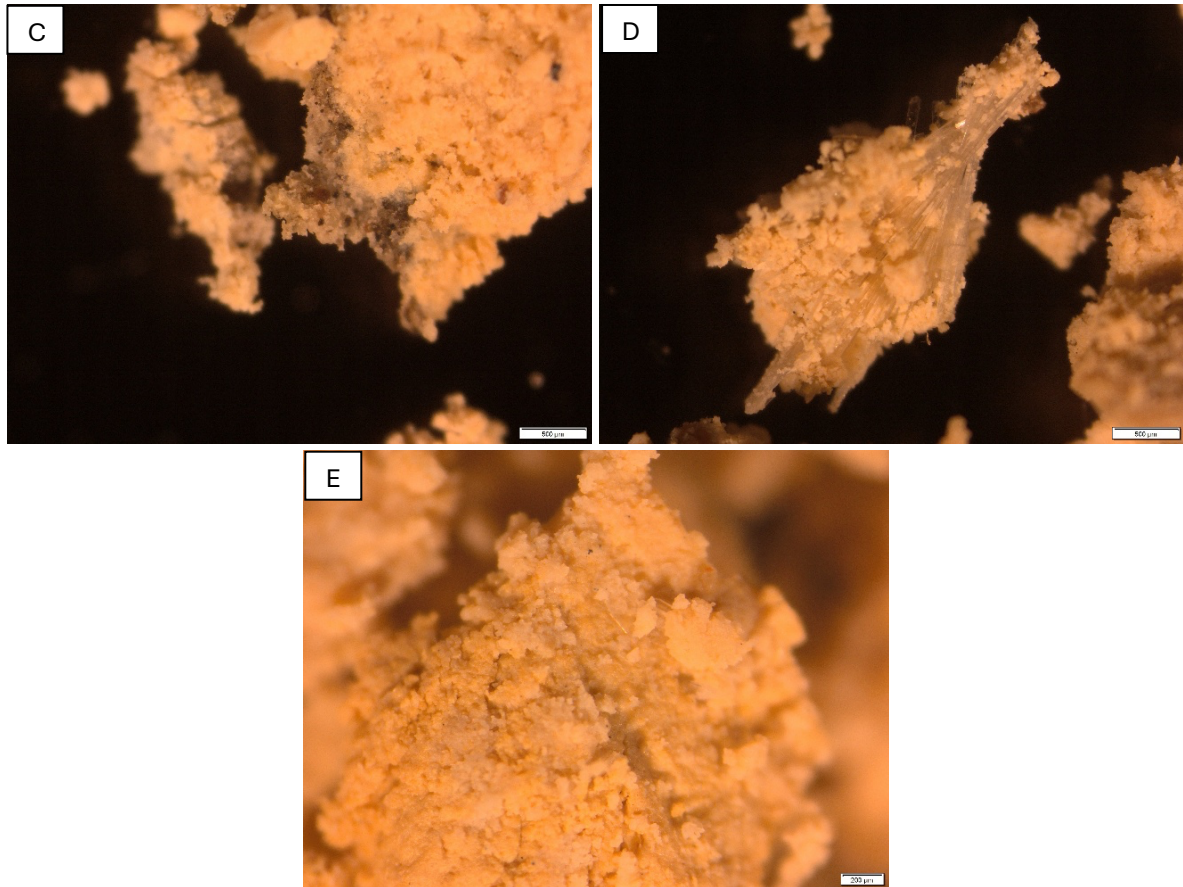


Figure 32: Stereomicroscopy of sample C4. A/B) 7x magnification. C/D) 16x magnification. E) 25x magnification. A) Pale to light yellow clay with small prismatic crystals and a 1 mm grey basalt fragment. B) Pale yellow clay encasing long fibrous crystals that fan out. C) Light yellow clay as well as a light grey mineral assemblage both having black specks scattered throughout, but a higher quantity in the grey. D) Long fibrous crystals interwoven with pale yellow clay collected on the surface. E) Pale to light yellow clay with small crystals present and a few small black specks.

The hyaloclastite, sample S9, was examined dry and shows alteration/differentiation of colour with defined white/pale yellow and grey patches (Figure 33), with black mottling occurring and ranging in size as well as red sections of oxidation and what appear to be shiny black organic material (Figure 33D). The grey sections show various levels of porosity.

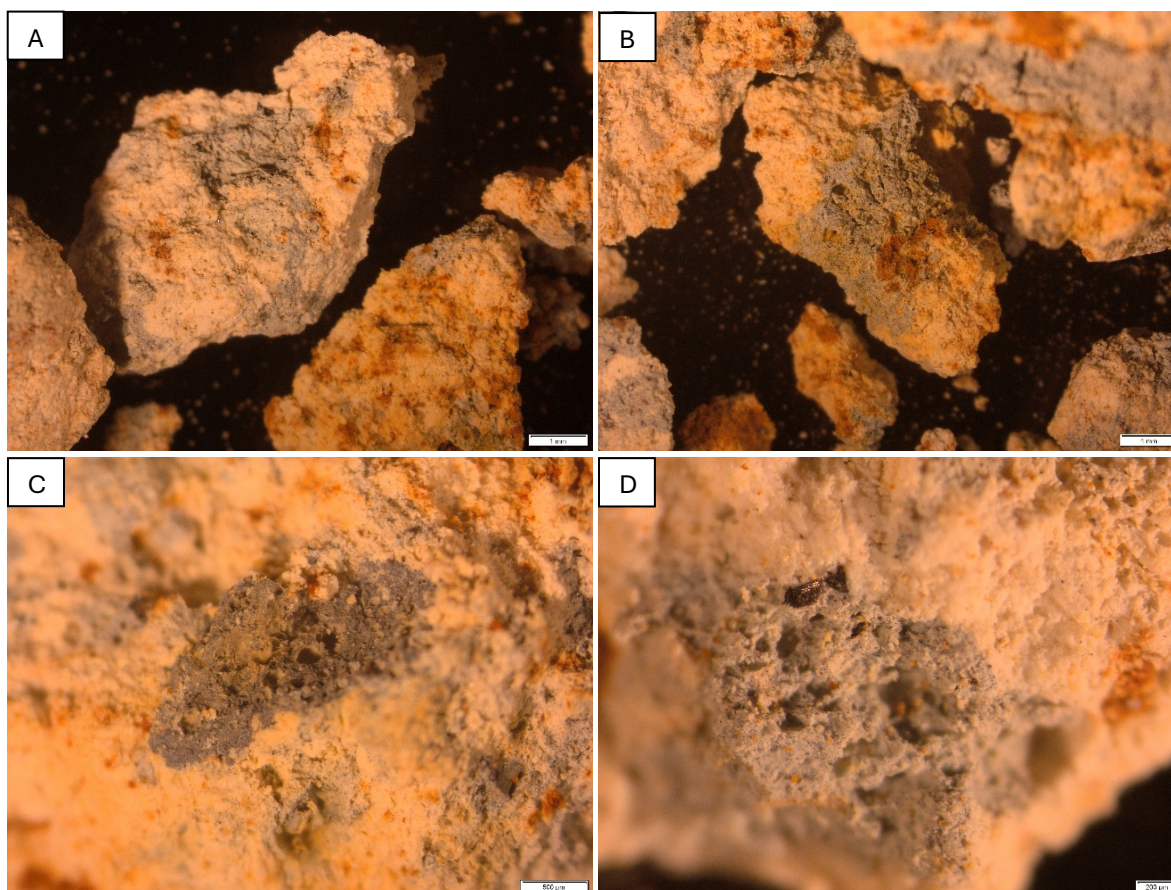


Figure 33: Stereomicroscopy of sample S9. A/B) 7x magnification. C) 16x magnification. D) 25x magnification. A) Combination of white, light grey, and light brown in the clays, small red and black material can be seen, as well as a piece of what appears to be a shiny metallic material. B) White/pale yellow and light grey with reddish brown mottles. C) Grey section of clay has visible porosity, and the white surrounding has light grey and red material scattered throughout. D) Pale grey clay with small black specks and a shiny metallic material $\sim 200 \mu\text{m}$. A white clay around the grey clay also has small black specks as well as yellow-orange particles.

Basalt Geochemistry (XRF)

For the whole rock geochemical analysis of samples B1-B6, the major elements were normalised to 100%, volatile free. Major and trace elements are displayed in Table 3.

All samples show chemical compositions consistent with those of mafic rocks, SiO_2 (42.60 wt.% to 43.92 wt.%), MgO (13.57-14.48 wt.%), Fe_2O_3 (12.97-13.18 wt.%), TiO_2 (2.62-2.90 wt.%), CaO (10.42-11.09 wt.%), and Al_2O_3 (11.97-12.47 wt.%). The LOI values range from 0.46 wt.% to 1.94 wt.%.

B6 has a higher total compared to the other five basalt samples this coincides with a high S content, but it should be acknowledged this may be caused by an instrumental error. Majority of the trace elements from the six basalt samples are very similar. There were, however, some differences in amounts found with S (12 ppm in B5 and 14467 ppm in B6 and not detected in the other four samples), and with Cr (1037 ppm in B1, 560 ppm in B2, 560 ppm in B3, 595 ppm in B4, 546 ppm in B5, and 601 ppm in B6).

Table 3: Whole rock geochemical analysis using XRF of the basalt (B1-B6) samples.

Sample Name	B1	B2	B3	B4	B5	B6
Major elements (XRF, wt.%)						
<i>(Normalized to 100% on LOI, volatile free; LOI and Total are original values; all Fe expressed as Fe₂O₃)</i>						
SiO ₂ (%)	43.34	43.39	43.33	43.92	43.61	42.60
Al ₂ O ₃ (%)	12.05	12.03	11.97	12.00	12.00	12.47
TiO ₂ (%)	2.73	2.69	2.73	2.62	2.71	2.90
MnO (%)	0.18	0.18	0.18	0.18	0.19	0.19
Fe ₂ O ₃ (%)	13.04	12.99	12.97	13.06	13.09	13.18
Na ₂ O (%)	2.65	2.65	2.70	2.16	2.40	1.68
MgO (%)	13.58	13.67	13.70	13.62	13.57	14.48
K ₂ O (%)	1.40	1.37	1.35	1.28	1.39	0.87
CaO (%)	10.42	10.46	10.48	10.56	10.45	11.09
P ₂ O ₅ (%)	0.59	0.58	0.58	0.60	0.59	0.55
LOI (%)	0.55	0.57	0.46	1.56	0.99	1.94
Total (%)	100.70	100.93	100.76	100.92	100.94	102.20
Trace elements (XRF, ppm)						
S (PPM)	-	-	-	-	12	14467
F (PPM)	428	346	410	314	523	358
Cl (PPM)	523	456	468	673	555	740
Sc (PPM)	18	17	18	19	19	19
V (PPM)	272	264	266	257	269	281
Cr (PPM)	1037	560	560	595	546	601
Co (PPM)	86	75	77	71	72	68
Ni (PPM)	329	325	333	307	323	332

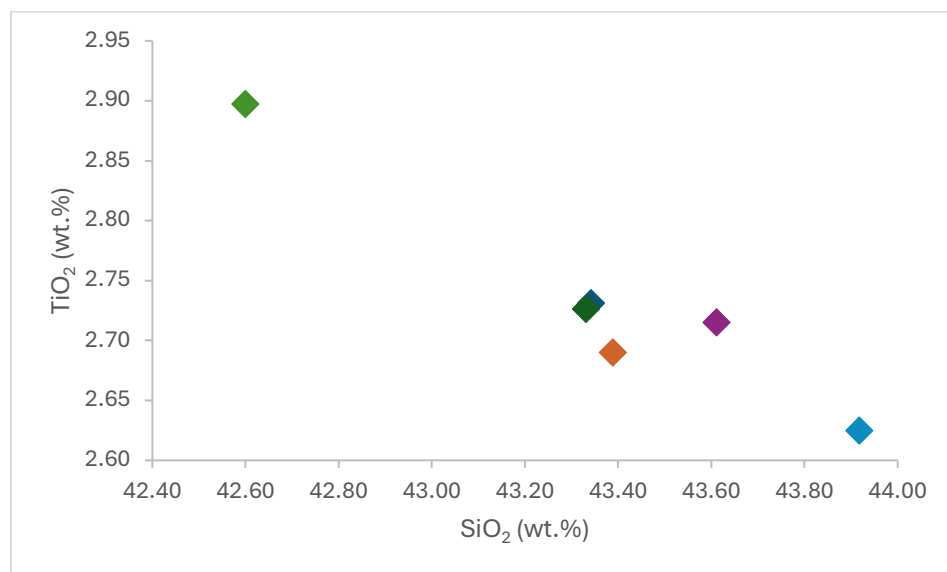
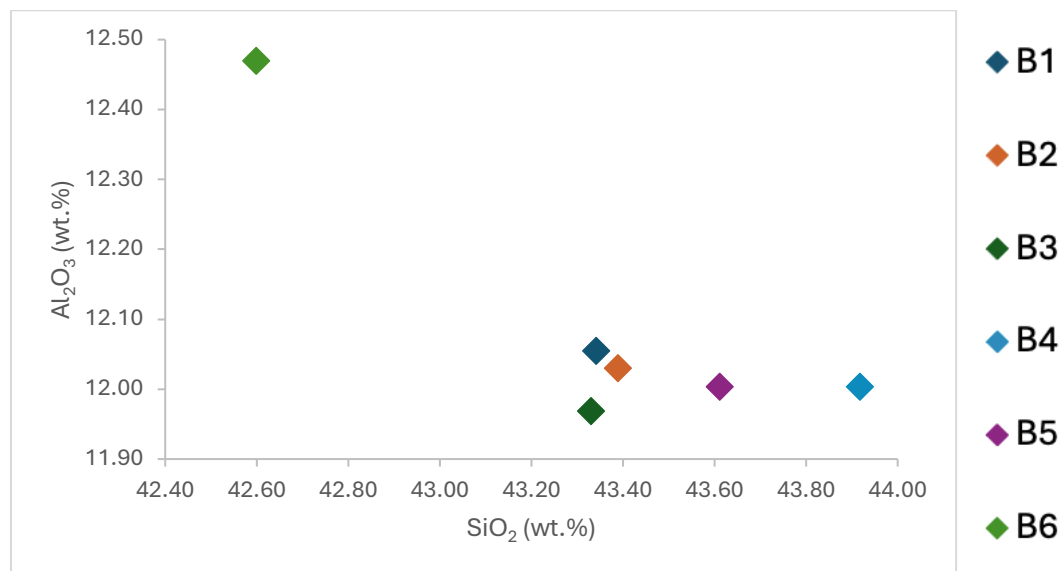
Cu (PPM)	69	69	68	68	69	70
Zn (PPM)	104	101	104	100	104	106
Ga (PPM)	21	21	20	22	20	22
As (PPM)	10	10	9	10	9	9
Rb (PPM)	28	28	27	26	27	20
Sr (PPM)	602	605	607	626	598	672
Y (PPM)	20	20	21	21	20	22
Zr (PPM)	211	213	212	214	209	218
Nb (PPM)	49	48	48	49	47	45
Mo (PPM)	5	5	5	5	5	5
Sn (PPM)	1	2	3	3	3	-
Sb (PPM)	-	-	3	1	-	-
Cs (PPM)	17	16	17	16	16	17
Ba (PPM)	278	273	280	279	263	345
La (PPM)	33	31	36	32	34	41
Ce (PPM)	85	78	79	79	83	84
Nd (PPM)	31	29	30	36	35	36
Tl (PPM)	-	-	-	-	-	-
Pb (PPM)	3	3	3	3	3	3
Th (PPM)	6	6	6	6	6	7
U (PPM)	3	3	3	3	3	3

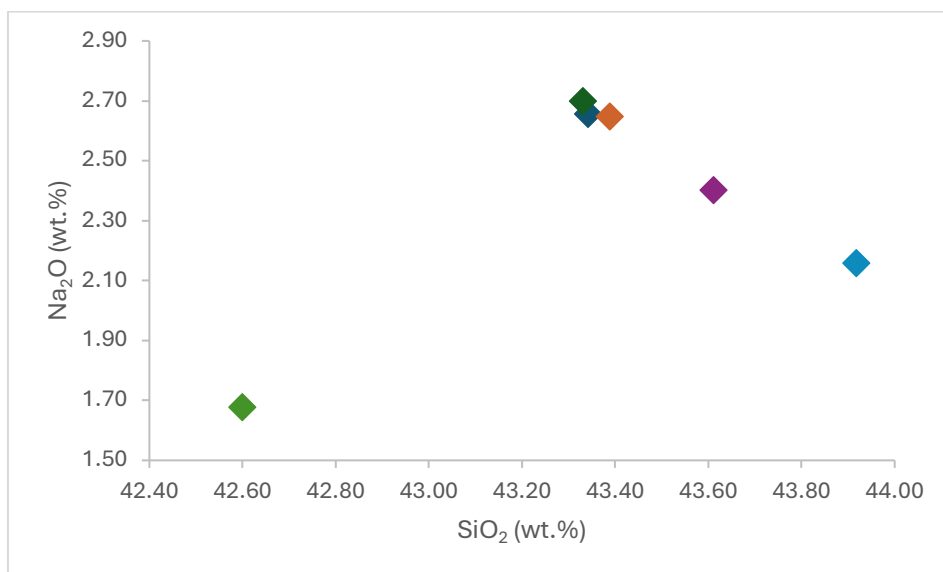
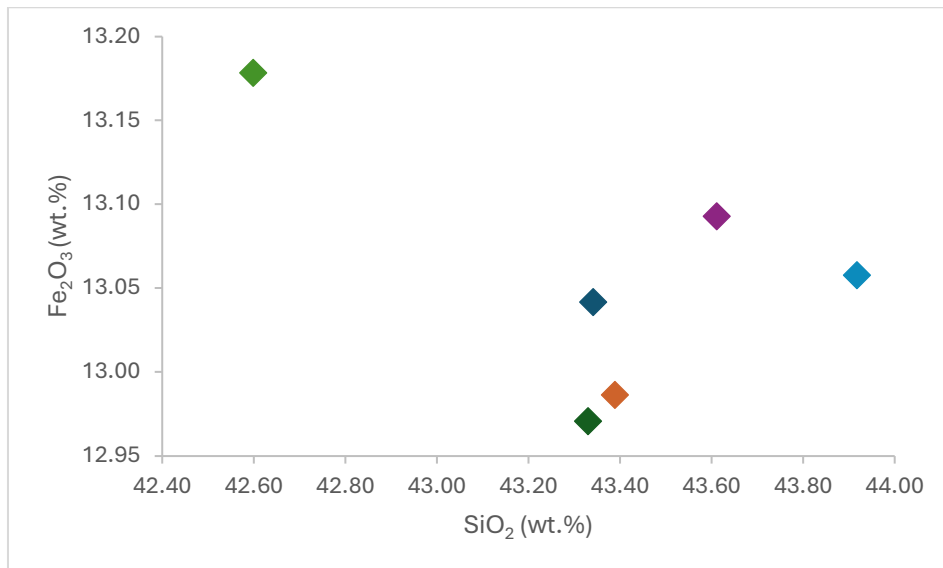
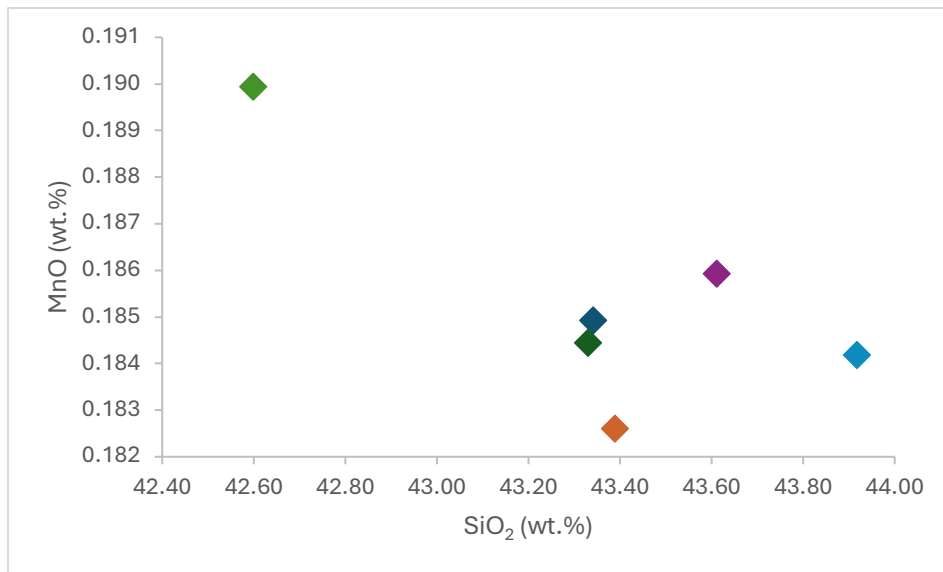
For the major element compositions, Harker variation diagrams for Al_2O_3 , TiO_2 , MnO , Fe_2O_3 , Na_2O , MgO , K_2O , CaO , and P_2O_5 versus SiO_2 are shown in Figure 34.

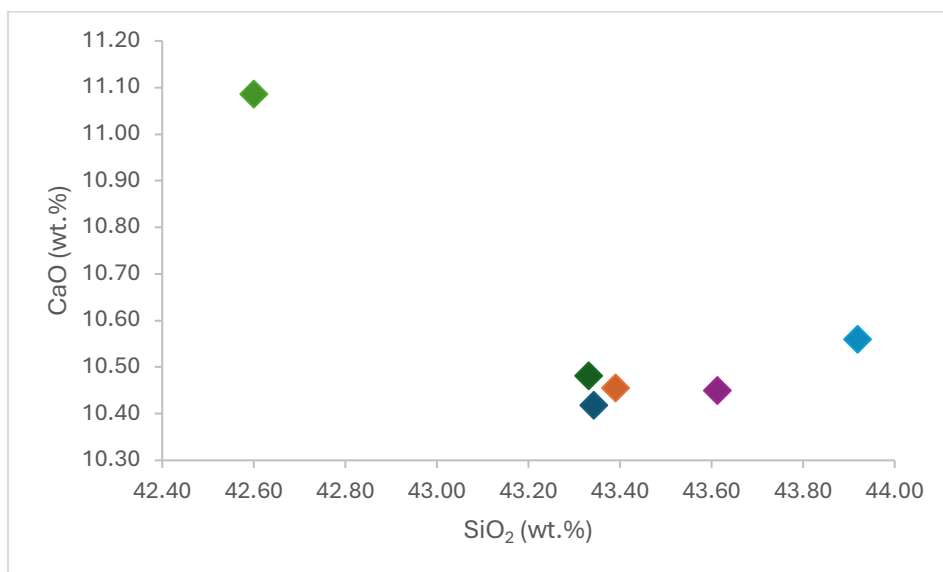
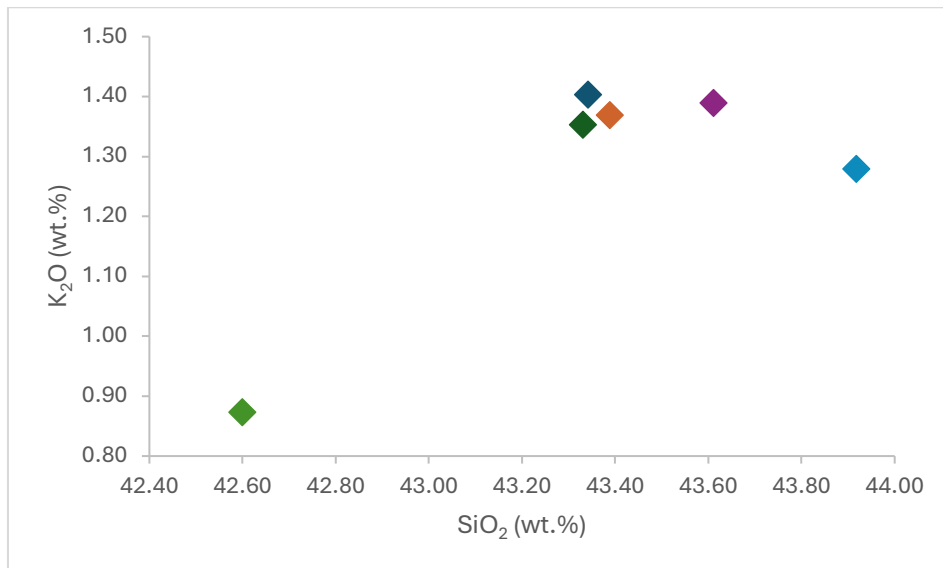
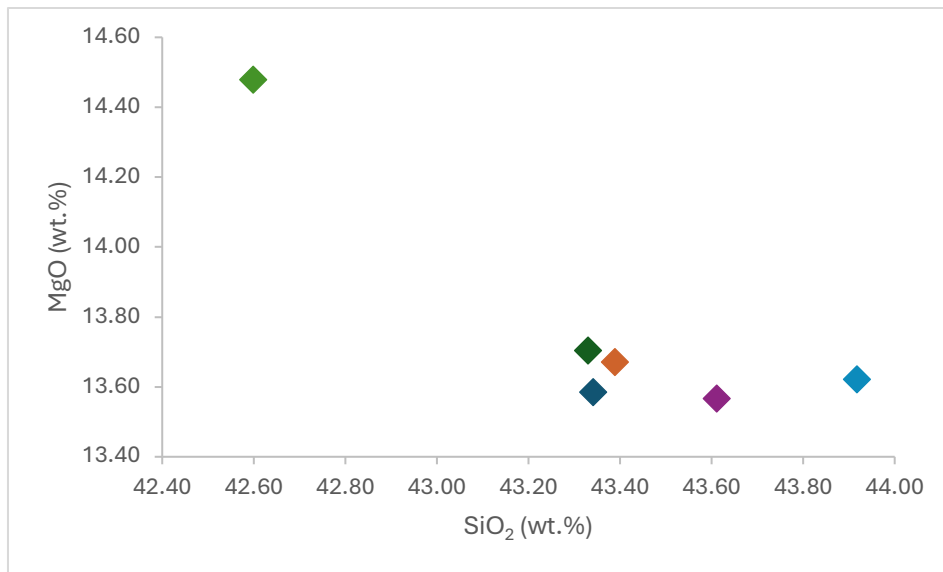
The basalt (B6) from within the cave (at the base of the lava) shows a slightly lower SiO_2 percentage compared to the other five samples when plotted, but all samples, elements, and the values are very similar to each other.

The samples B1, B2 and B3 are all relatively clumped together when plotted due to their SiO_2 percentages being within 0.06 wt.% of each other.

Due to the very minimal differences seen between the trace elements only Cr, Cl, and F were plotted against SiO_2 (Figure 35).







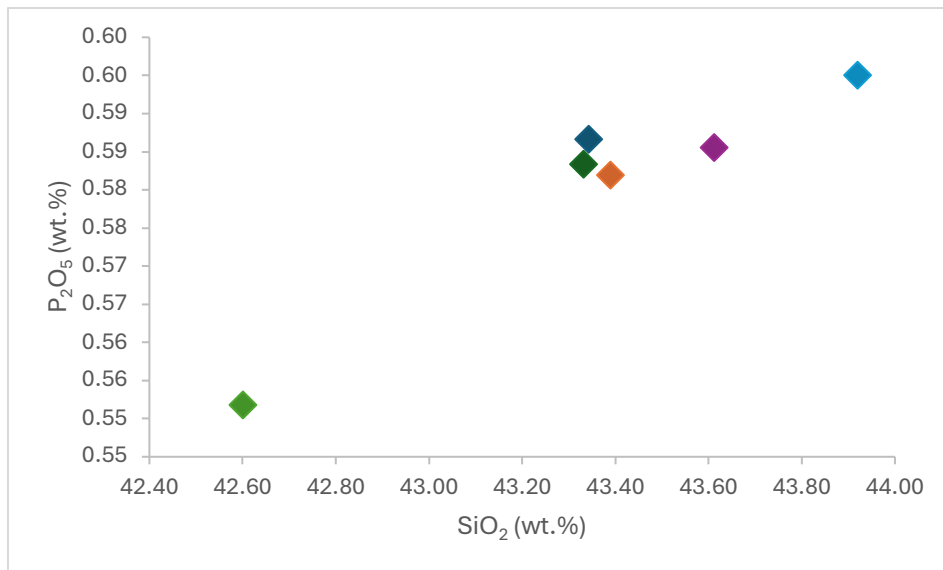
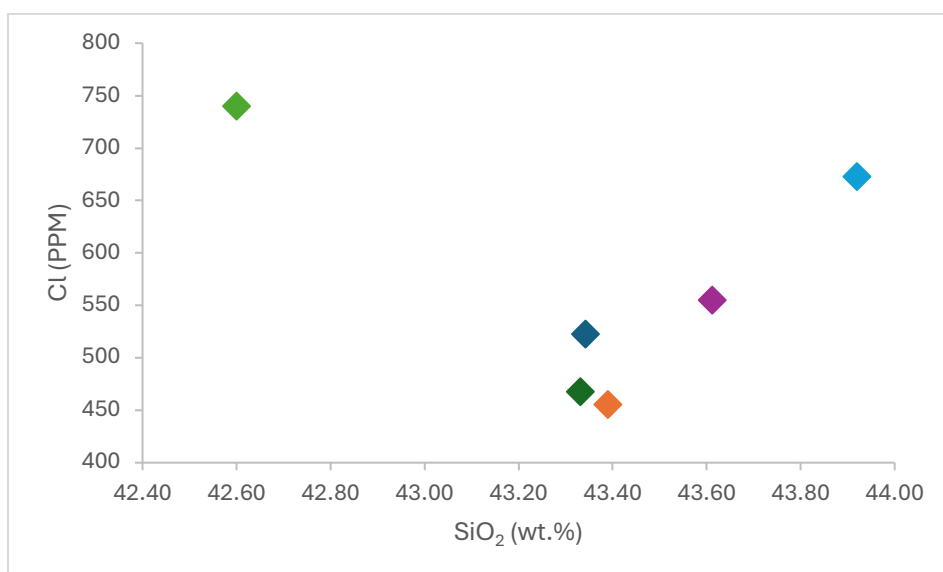
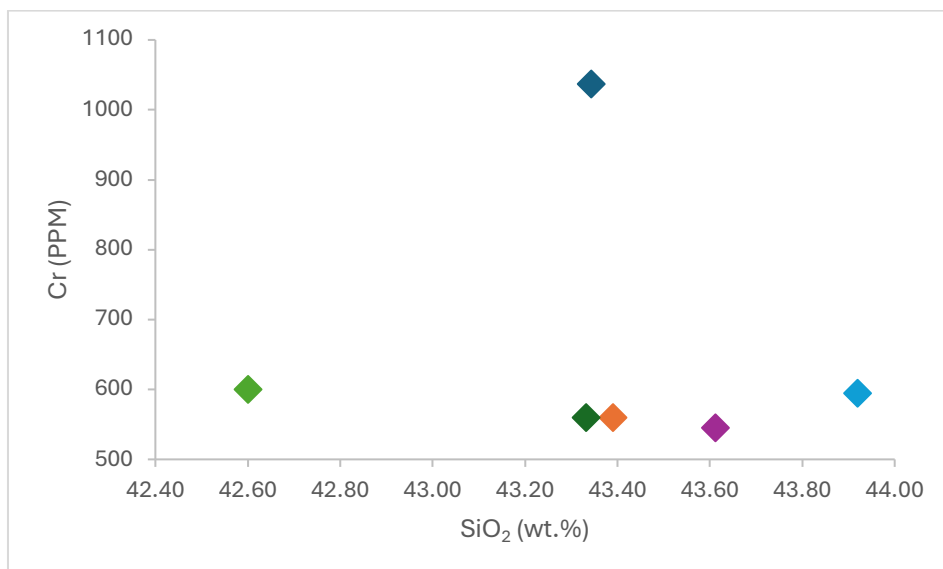


Figure 34: Harker Variation Diagram for major elements plotted against SiO₂ (wt. %).



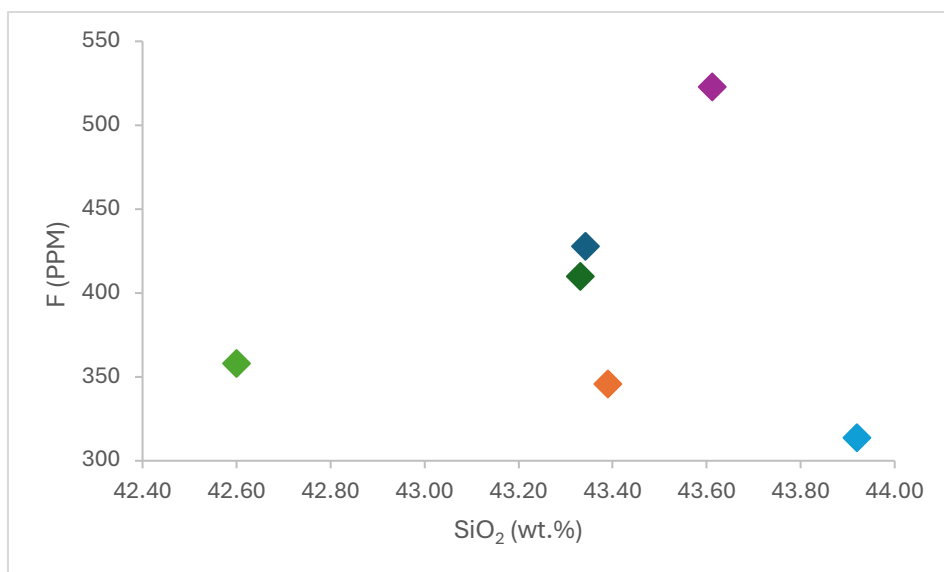


Figure 35: Harker Variation Diagram of trace elements (Cr, Cl, and F) in ppm against SiO₂ (wt. %).

Cave Minerals

pXRF

The raw data for samples C1, C5, and both sides of C7 are displayed in the Appendix.

Light elements (LE), calculated by instrument software to include O, C, Na, Mg as well as other low atomic number elements not directly measured, formed the majority of the identified composition of all samples (ranging from 69.93 wt.% to 87.42 wt.%). Samples showed S ranged from 6.67 wt.% to 12.08 wt.%; Fe from 2 wt.% to 6.53 wt.%; Si from 0.19 wt.% to 3.48 wt.%; Ca from 0.05 wt.% to 13.8 wt.%; and Al from 0 wt.% to 2.77 wt.%.

For C1 the four most abundant elements were LE at 81.85 wt.% (± 0.1 wt.%), S at 6.67 wt.% (± 0.03 wt.%), Fe at 6.54 wt.% (± 0.03 wt.%), and Si at 3.48 wt.% (± 0.03 wt.%). For C5 the most abundant were as follows: LE 69.93 wt.% (± 0.1 wt.%), Ca 13.8 wt.% (± 0.07 wt.%), S 10.86 wt.% (± 0.05 wt.%), and Fe 4.49 wt.% (± 0.03 wt.%). For the top of C7, the most abundant elements were LE 87.42 wt.% (± 0.12 wt.%), S 8.13% (± 0.05 wt.%), and Fe 2.56 wt.% (± 0.02 wt.%). The most abundant for the bottom of C7 were LE 82.74 wt.% (± 0.13 wt.%), S 12.08 wt.% (± 0.06 wt.%), Al 2.77 wt.% (± 0.11 wt.%), and Fe 2 wt.% (± 0.01 wt.%). The most common elements for each sample can be seen in Figure 36.

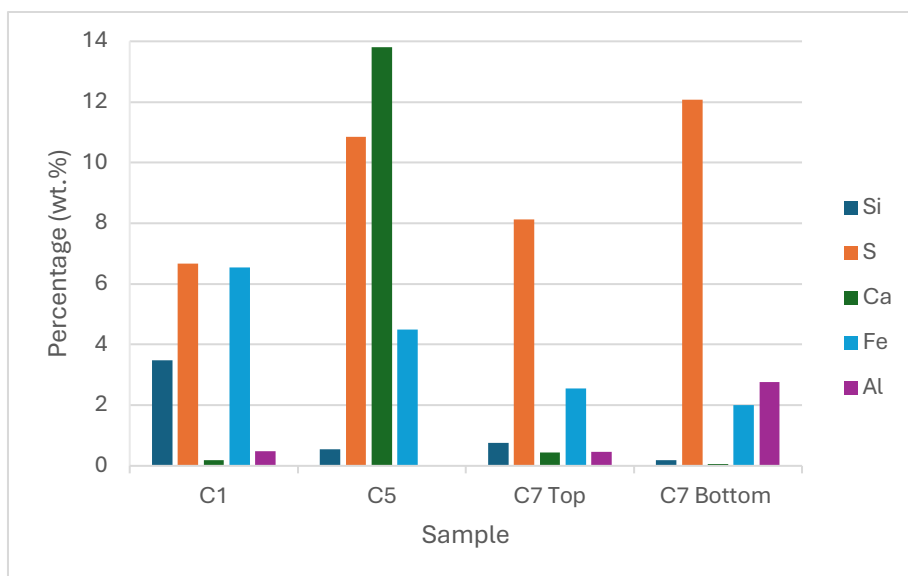


Figure 36: Weight percent (wt.%) of the most common elements present in the samples.

XRD

Sample C1 showed peaks to indicate the presence of alunogen as seen in Figure 37.

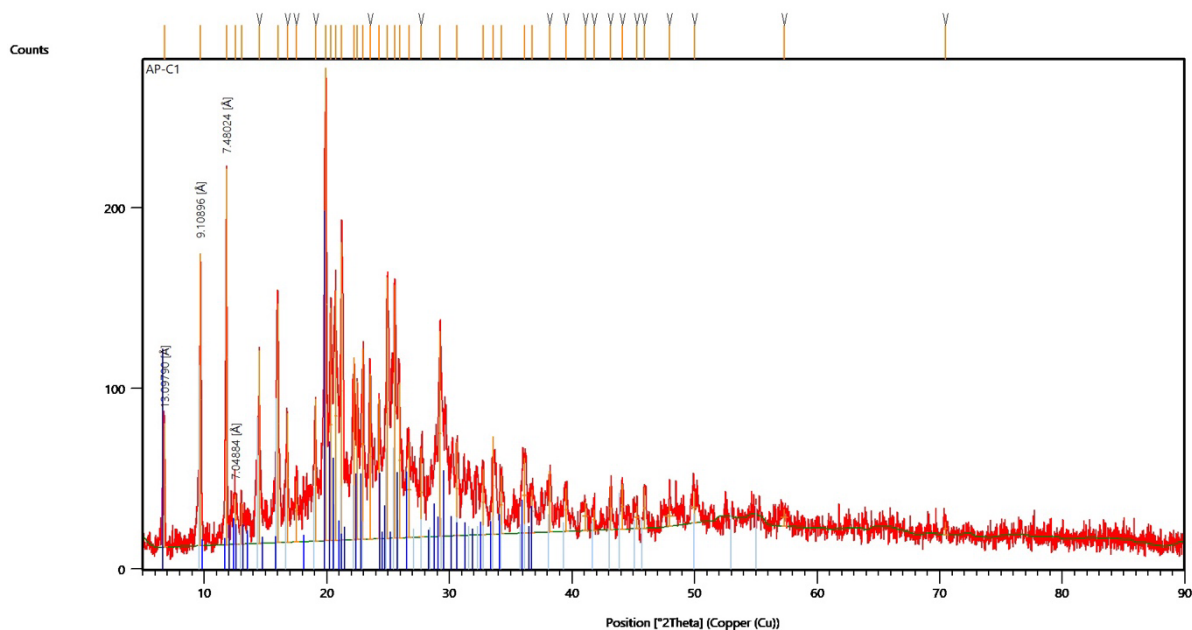


Figure 37: XRD analysis of sample C1 with alunogen peaks present.

Sample C5 showed peaks of both gypsum and natrojarosite as shown in Figure 38.

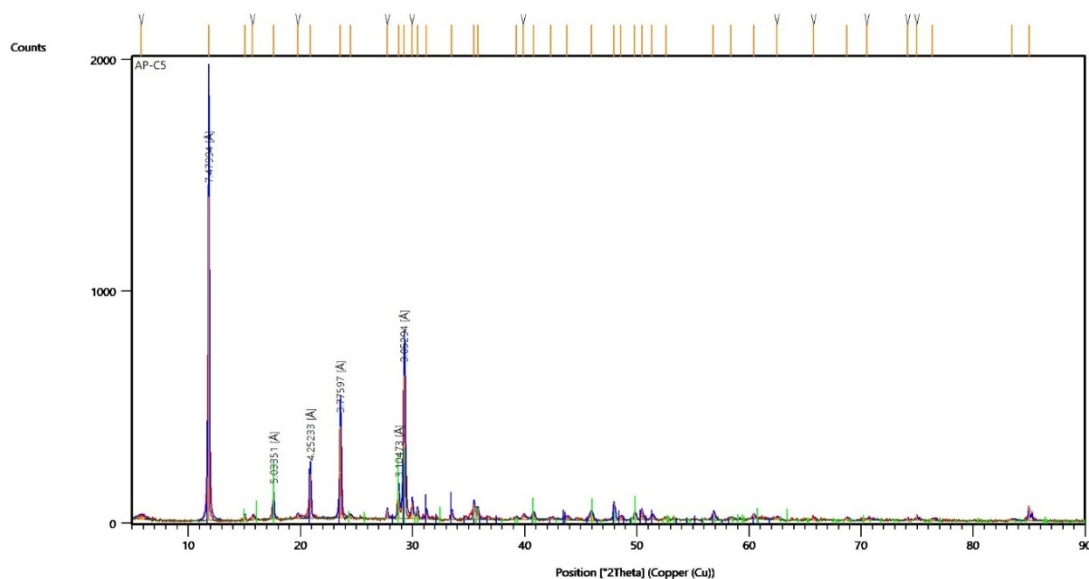


Figure 38: XRD analysis of sample C5 with peaks of gypsum (blue) and natrojarosite (green).

Sample C7 had inconclusive results and thus was not looked into further.

SEM

The SEM analysis of sample C1 (Figure 39) shows a predominantly fine-grained, matrix supported texture. The material is composed of very fine anhedral to subhedral particles forming a continuous groundmass, with occasional larger grains embedded within the matrix. The crystals commonly display irregular to platy morphologies, and only a few crystals with well-defined crystal faces are seen.

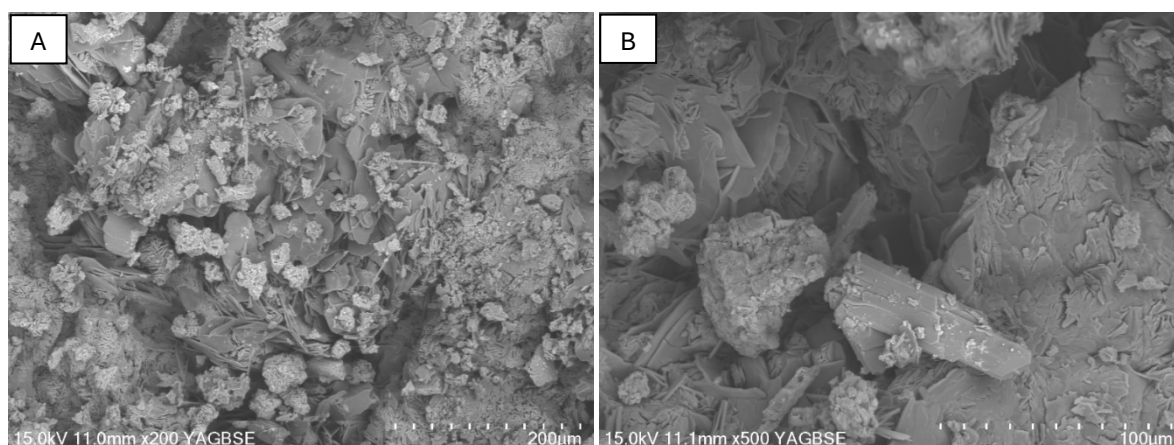


Figure 39: SEM imaging using YAGBSE of sample C1 at 15kV. A) 200x magnification. Large platy morphologies dominant with a fine-grained matrix. B) 500x magnification. Well-defined prismatic crystal face amongst a continuous groundmass.

The EDS point analysis results of sample C1 are displayed in Figures 40-42 and Tables 4-6. From the three chosen sites, the elements that were present in all sample points were S (2.7-29 wt.%), Fe (1.1-15.6 wt.%), and Si (1-46.6 wt.%). The measured O and C are considered uncertain.

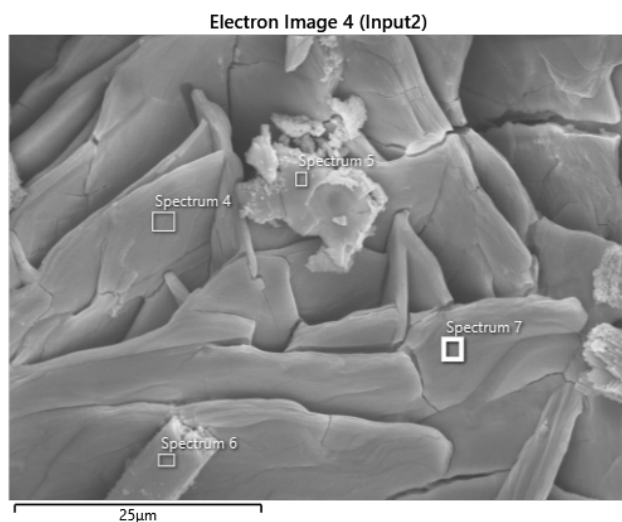


Figure 40: SEM image of C1 showing locations where Spectrum 4-7 were taken.

Table 4: Elemental composition (wt.%) of SEM-EDS of C1 site.

Element (wt.%)	Spectrum 4	Spectrum 5	Spectrum 6	Spectrum 7
O	35.5	50.4	58.8	53.7
S	29	7.3	12.4	16.7
C	20.5	19.9	14.4	14.1
Al	7.8	1.9	3.8	5.2
Fe	4.7	2.2	2.9	2.8
Si	2.4	17.1	7.2	6.5
Ti	N/A	1.1	N/A	0.7
Mg	N/A	N/A	0.6	N/A

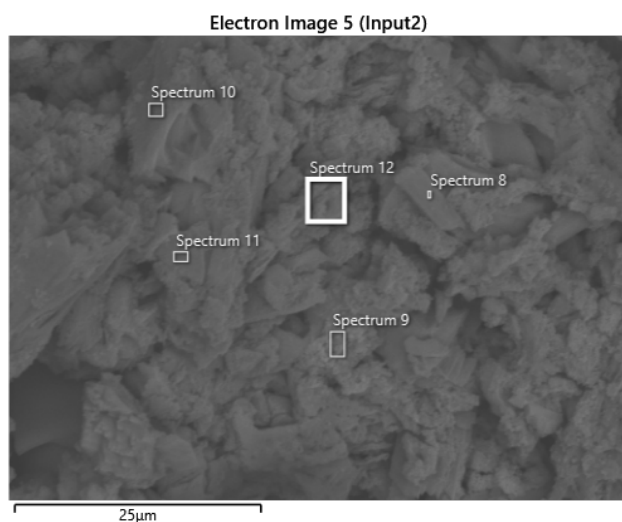


Figure 41: SEM image of C1 showing locations where Spectrum 8-12 were taken from.

Table 5: Elemental composition (wt.%) of SEM-EDS of C1 site.

Element (wt.%)	Spectrum 8	Spectrum 9	Spectrum 10	Spectrum 11	Spectrum 12
O	61.1	28.9	57.2	57.8	56
Si	30.3	46.6	28.7	28.8	24.8

S	4.7	6.9	3.1	2.7	4.2
Fe	1.8	5.1	1.1	1.2	1.9
Mg	1.4	1	0.8	0.9	1.1
Al	0.4	0.7	N/A	N/A	N/A
Ti	0.4	10.8	0.4	0.3	4.6
C	N/A	N/A	8.5	8.3	7.1

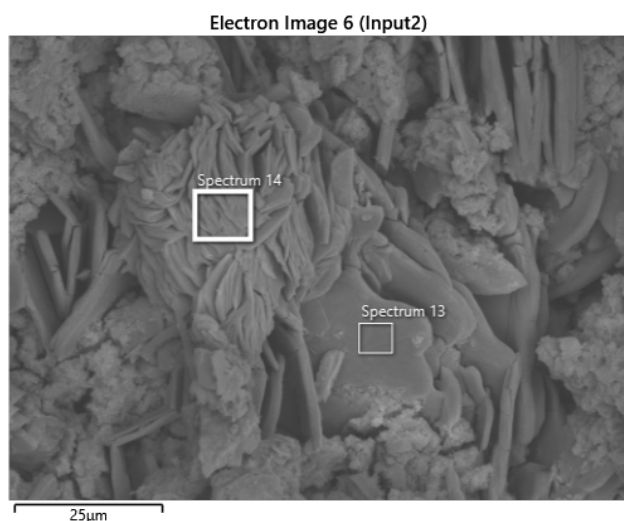


Figure 42: SEM image of C1 showing locations where Spectrum 13-14 were taken from.

Table 6: Elemental composition (wt.%) of SEM-EDS of C1 site.

Element (wt.%)	Spectrum 13	Spectrum 14
O	51	55.5
C	15.9	8.9
S	11.9	17
Si	7.8	1
Fe	6.8	15.6
Ti	3.7	N/A
Al	2.2	N/A
Mg	N/A	2.1
Zr	N/A	0

The SEM imaging of sample C5 shows very well-defined elongate prismatic crystal facies, with individual crystals up to several hundred μm long, as well as platy, sheet-like crystals with high aspect ratios (Figure 43). The surface of the crystals is coated with small clay-like particles with some particles being found in between the sheet-like plates (Figure 43C, D). From the straight prismatic crystals, radiating crystals can be seen (Figure 43B).

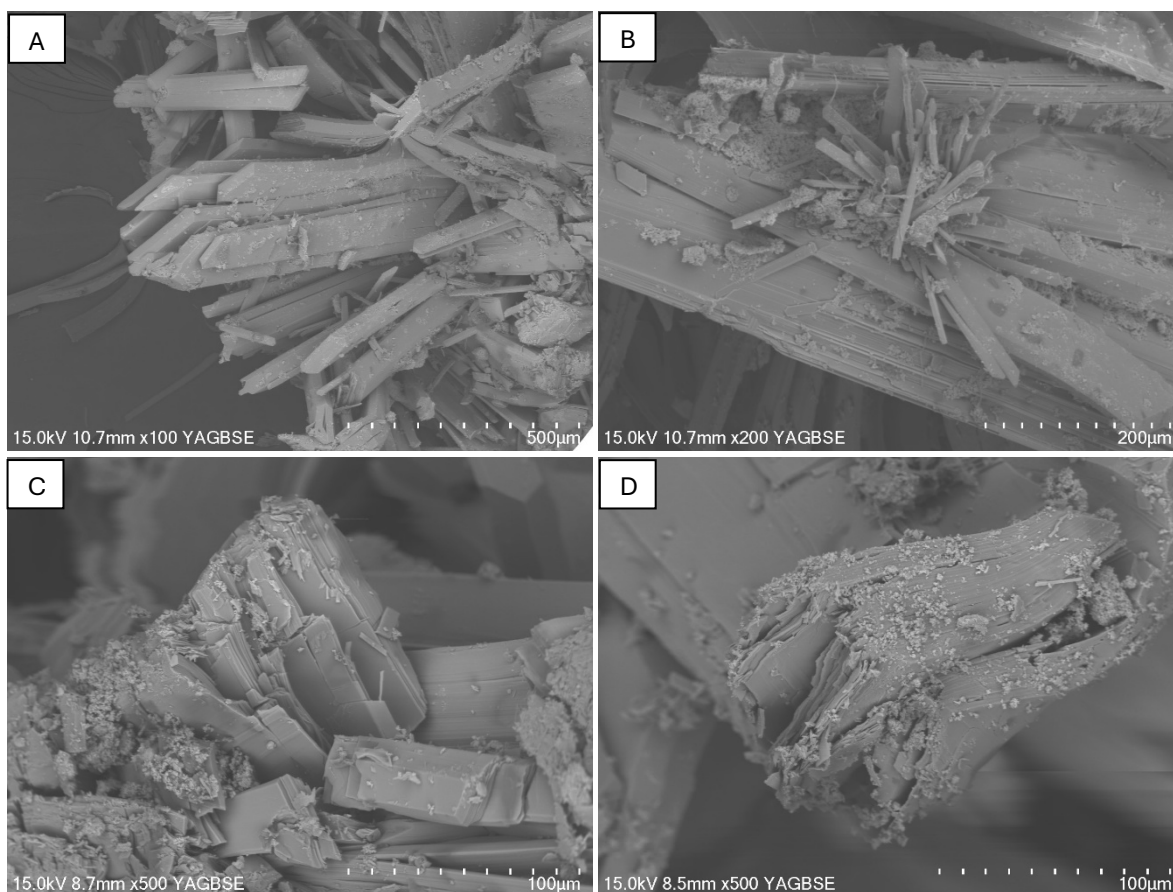


Figure 43: SEM imaging using YAGBSE for sample C5 at 15kV. A) 100x magnification. Well-defined prismatic crystals clustered together with some platy aspects and clay-like particles on the surface. B) 200x magnification. Long straight prismatic crystals with radiating crystals and clay-like particles. C) 500x magnification. Platy, sheet-like crystal habit coated with clay-like particles. D) 500x magnification. Platy crystal with particles on and in between the sheets.

The point analysis is displayed in Figures 44-46 and Tables 7-9. Not every site had the same elements present. Across all three sites for point analysis and the twelve spectra, there are concentrations of Ca (10.3-25.8 wt.%), and S (10-17.6 wt.%). Fe (0.5-12 wt.%) is present in all but three points, one from each site. The measured O and C are considered uncertain.

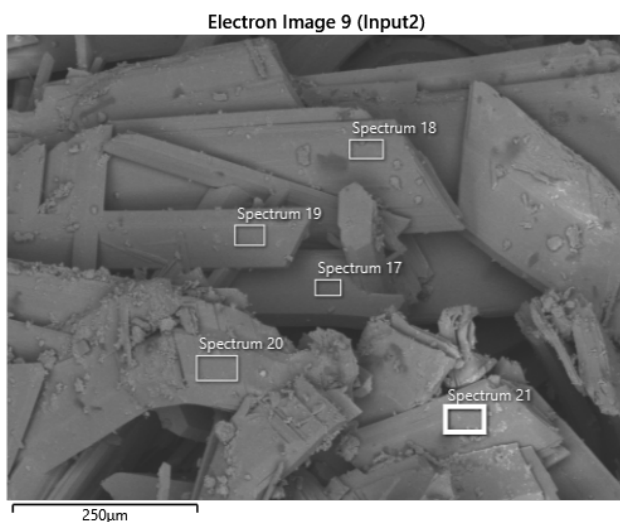


Figure 44: SEM image of C5 showing locations where Spectrum 17-21 were taken from.

Table 7: Elemental composition (wt.%) of SEM-EDS of C5 site.

Element (wt.%)	Spectrum 17	Spectrum 18	Spectrum 19	Spectrum 20	Spectrum 21
O	57.6	49.6	37	61.7	51.9
Ca	18	18.4	25.8	15.2	18.3
S	16.1	14.2	17.6	13.8	16.4
C	8.3	14.7	18.1	8.8	10.9
Fe	N/A	2.6	1.1	0.5	1.9
Si	N/A	0.5	0.3	N/A	0.6

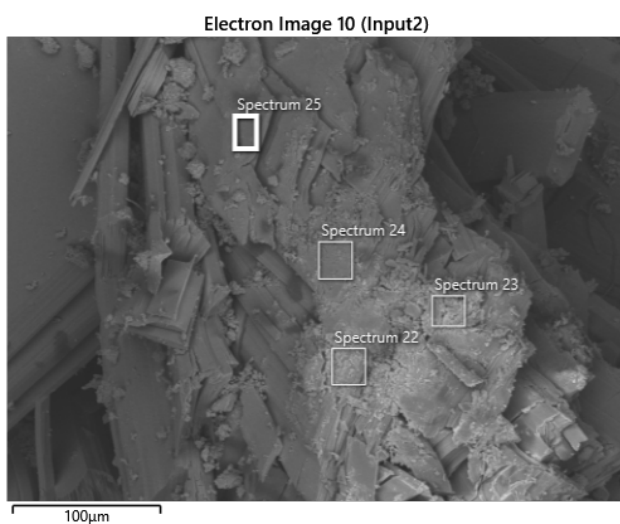


Figure 45: SEM image of C5 showing locations where Spectrum 22-25 were taken from.

Table 8: Elemental composition (wt.%) of SEM-EDS of C5 site.

Element (wt.%)	Spectrum 22	Spectrum 23	Spectrum 24	Spectrum 25
O	60.4	59.9	64.4	63.8
S	13.1	14.4	12.7	12.8
Ca	13	15.8	13.1	14
C	10.4	8.8	8.8	9.2

Fe	1.5	0.8	1	N/A
Si	1	0.3	N/A	N/A
Mg	0.3	N/A	N/A	N/A
Al	N/A	N/A	N/A	0.3

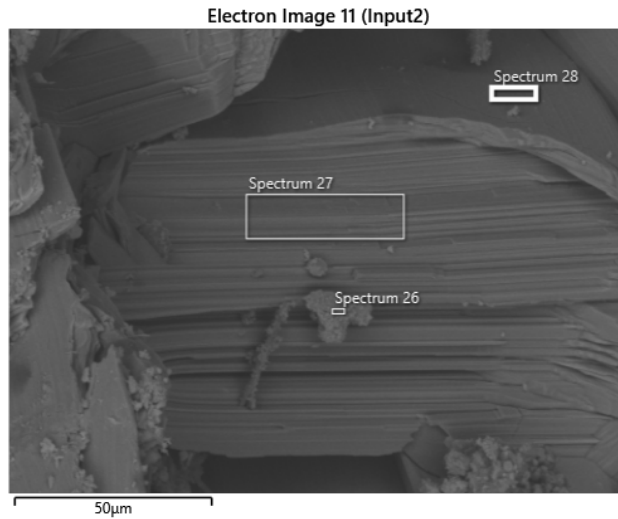


Figure 46: SEM image of C5 showing locations where Spectrum 26-28 were taken from.

Table 9: Elemental composition (wt.%) of SEM-EDS of C5 site.

Element (wt.%)	Spectrum 26	Spectrum 27	Spectrum 28
O	51.9	63.9	67.9
Fe	12	N/A	1.4
Ca	11.1	16	10.3
S	10	12.9	10.4
C	8.1	7.2	8
Si	5	N/A	N/A
Al	1	N/A	2

Sample C7 has a heterogeneous microtexture with size and shape of the grains non-uniform. There are sections of densely packed, clustered acicular crystal habits (Figure 47A, F) as well as prismatic crystals (Figure 47B-D) in amongst flaky and platy grains (Figure 47E). The well-formed crystals have, for the most part, high aspect ratios.

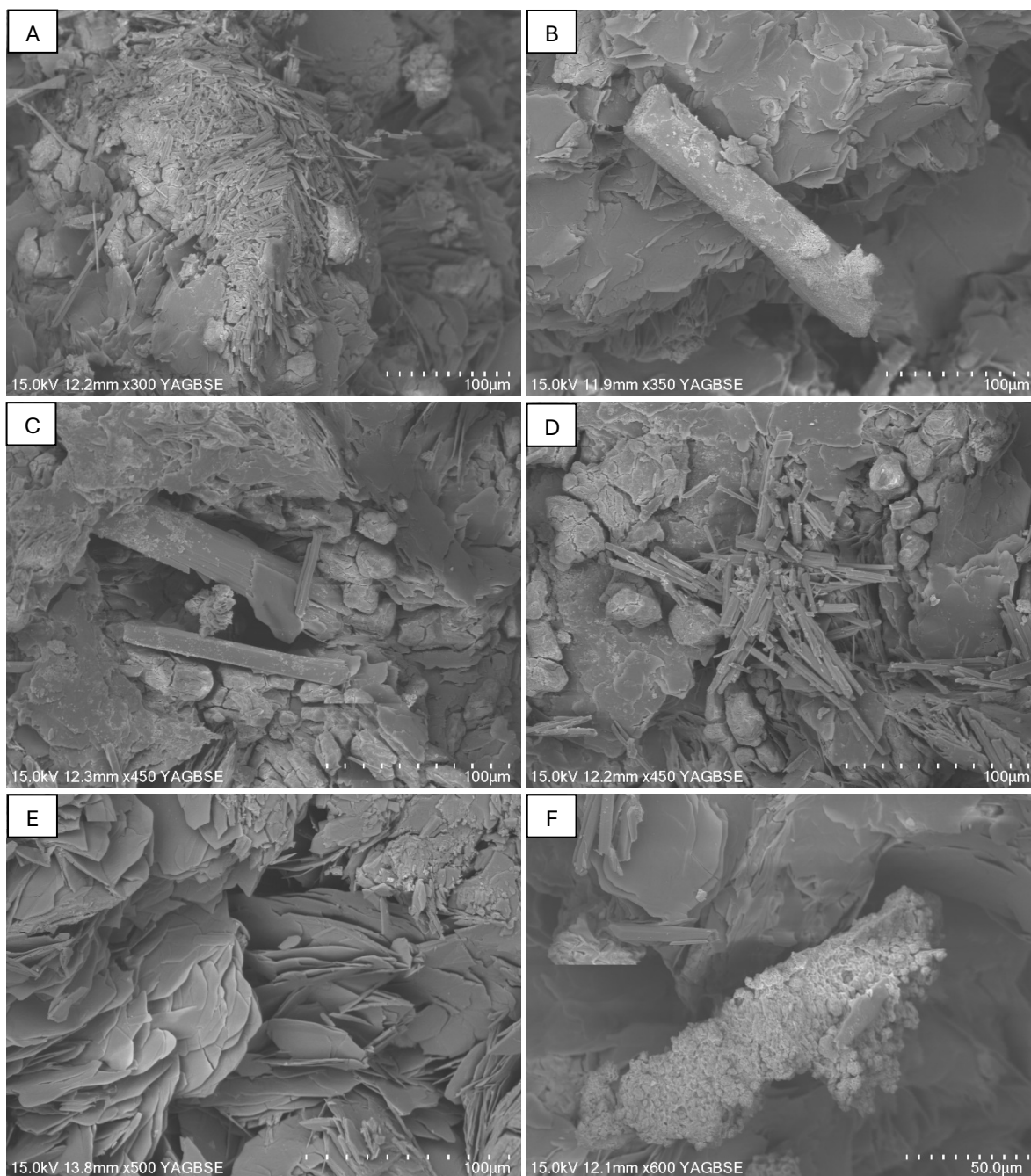


Figure 47: SEM imaging using YAGBSE of sample C7 at 15kV. A) 300x magnification. Densely packed cluster of acicular habits intertwined with platy grains. B) 350x magnification. Prismatic crystal surrounded by plates. C) 450x magnification. Prismatic and acicular crystals with flaky and platy grains. D) 450x magnification. Tight cluster of prismatic and acicular crystals that are surrounded by grains and sheets. E) 500x magnification. Densely clustered platy grains. F) 600x magnification. Cluster of tightly packed grains surrounded by plates.

Point analysis undertaken on the crystal minerals of sample C7 are shown in Figures 48-51 and Tables 10-13. The elements present in each point analysis are S (11.2-22.1 wt.%), and Al (0.4-8.3 wt.%). The measured O and C are considered uncertain.

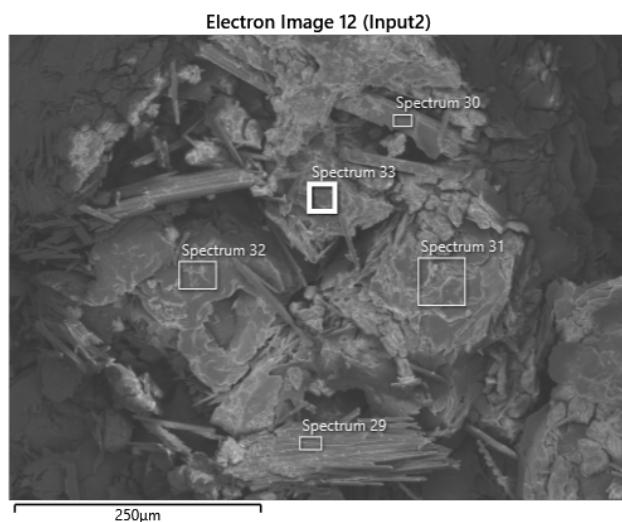


Figure 48: SEM image of C7 showing locations where Spectrum 29-33 were taken from.

Table 10: Elemental composition (wt. %) of SEM-EDS of C7 site.

Element (wt.%)	Spectrum 29	Spectrum 30	Spectrum 31	Spectrum 32	Spectrum 33
O	68.8	54	70.6	53.3	71.2
S	12.2	13.3	12.4	22.1	12.3
C	9.2	16.2	8	15	7.8
Al	6.1	0.4	7.8	8	8
Mg	2.7	N/A	1.2	1.6	N/A
Fe	0.9	N/A	N/A	N/A	0.8
Si	0.2	N/A	N/A	N/A	N/A
Zr	N/A	0	0	N/A	N/A

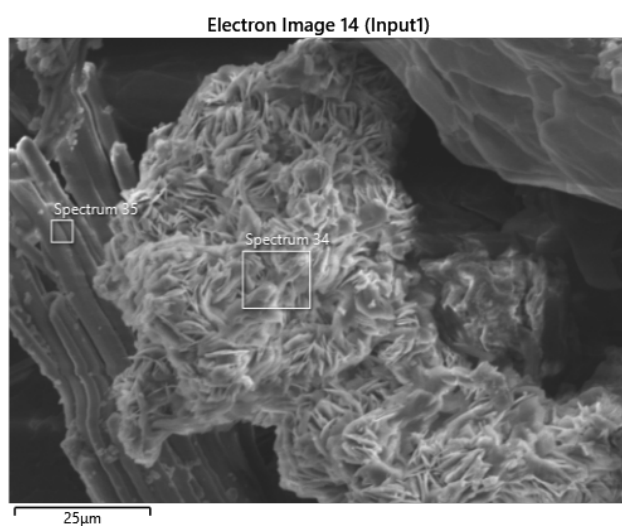


Figure 49: SEM image of C7 showing locations where Spectrum 34-35 were taken from.

Table 11: Elemental composition (wt. %) of SEM-EDS of C7 site.

Element (wt.%)	Spectrum 34	Spectrum 35
O	63	62.7
S	14	11.9
Fe	12.1	10.9
C	8.2	8.6
Mg	2.2	3.6
Al	0.6	0.5
Zr	0	N/A
Ti	N/A	1.5

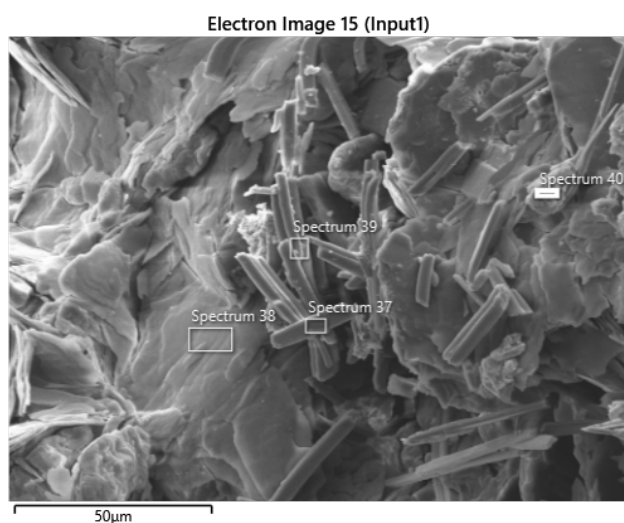


Figure 50: SEM image of C7 showing locations where Spectrum 37-40 were taken from.

Table 12: Elemental composition (wt. %) of SEM-EDS of C7 site.

Element (wt.%)	Spectrum 37	Spectrum 38	Spectrum 39	Spectrum 40
O	66	71.8	69.2	74.2
S	20.4	11.8	13.1	11.2
Mg	11.2	0.4	0.7	N/A
Al	2.4	8.3	7.4	7.4
C	N/A	7.6	9.5	7.1
Zr	N/A	0	N/A	N/A

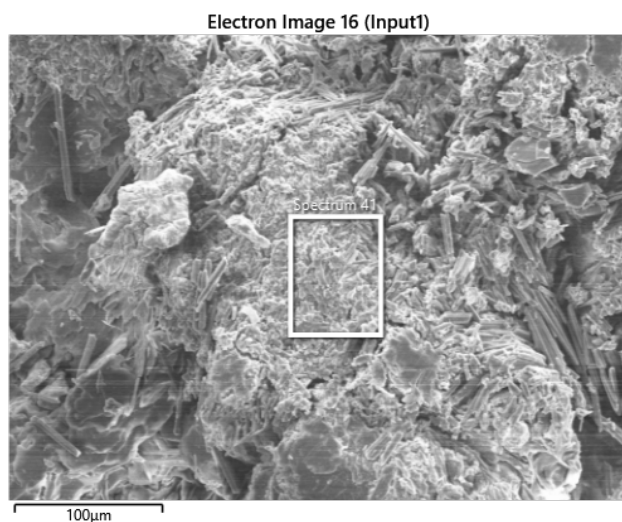


Figure 51: SEM image of C7 showing location where Spectrum 41 was taken from.

Table 13: Elemental composition (wt. %) of SEM-EDS of C7 site.

Element (wt.%)	Spectrum 41
O	65.8
S	13.1
C	10.6
Al	5.8
Mg	2.7
Fe	1.8
Si	0.2

Clay and Hyaloclastite

XRD

The XRD analysis of C2 shows that there is the presence of jarosite and gypsum (Figure 52).

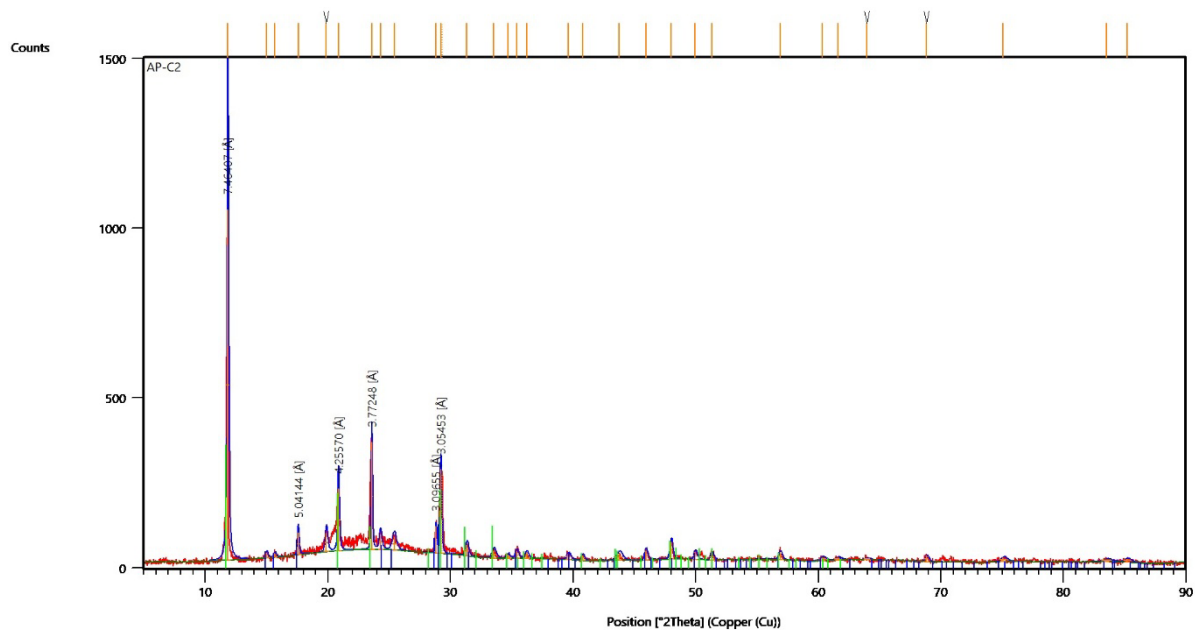


Figure 52: XRD of sample C2 showing jarosite (blue) and gypsum (green).

The sample C4 that was run showed anatase (Figure 53).

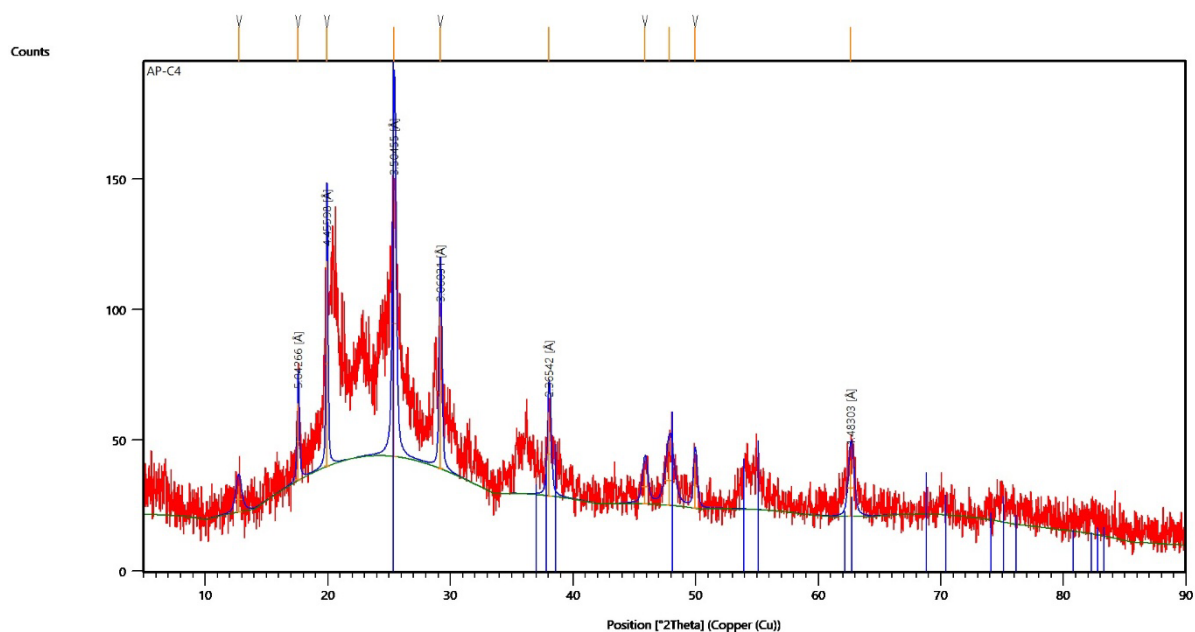


Figure 53: XRD of sample C4 displaying peaks consistent with anatase.

The grey subsample of S9 (Figure 54) showed magnetite with possible clay peaks at 9-10 Å.

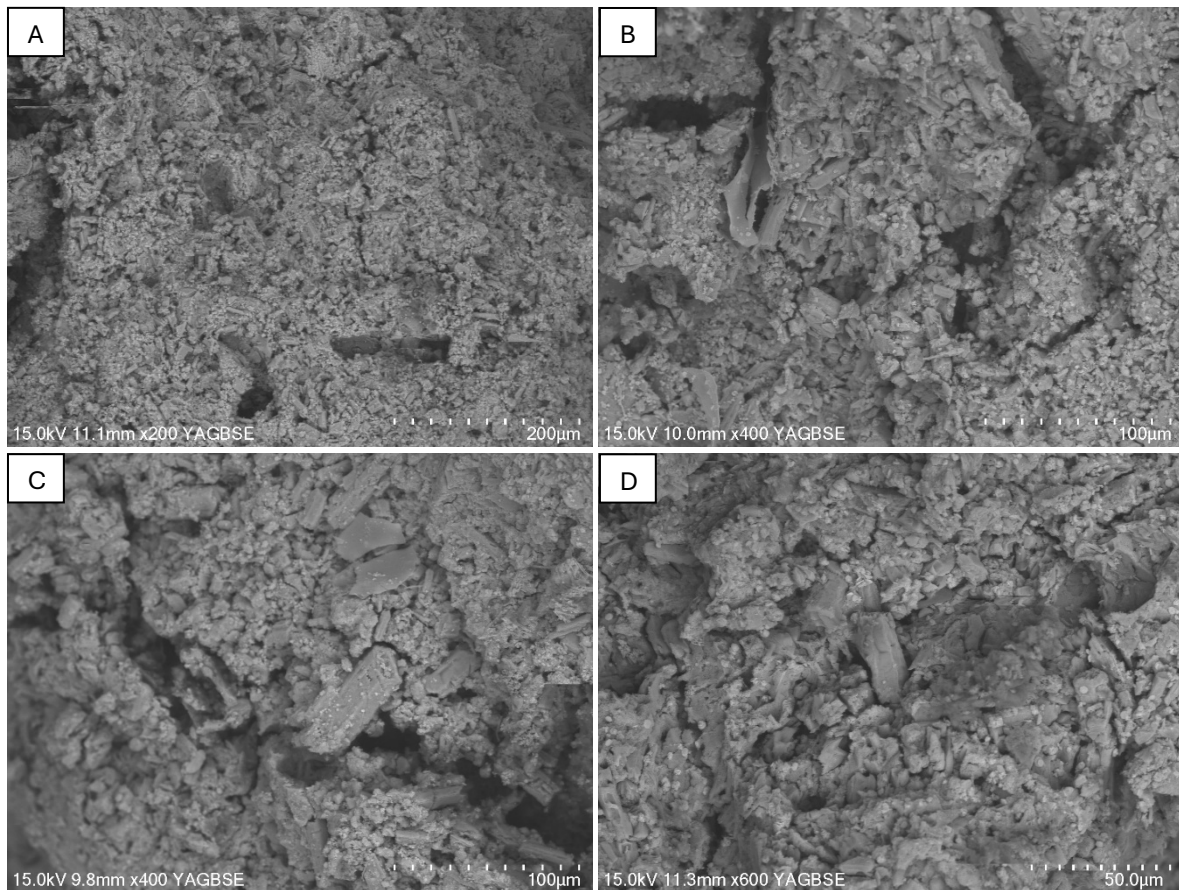
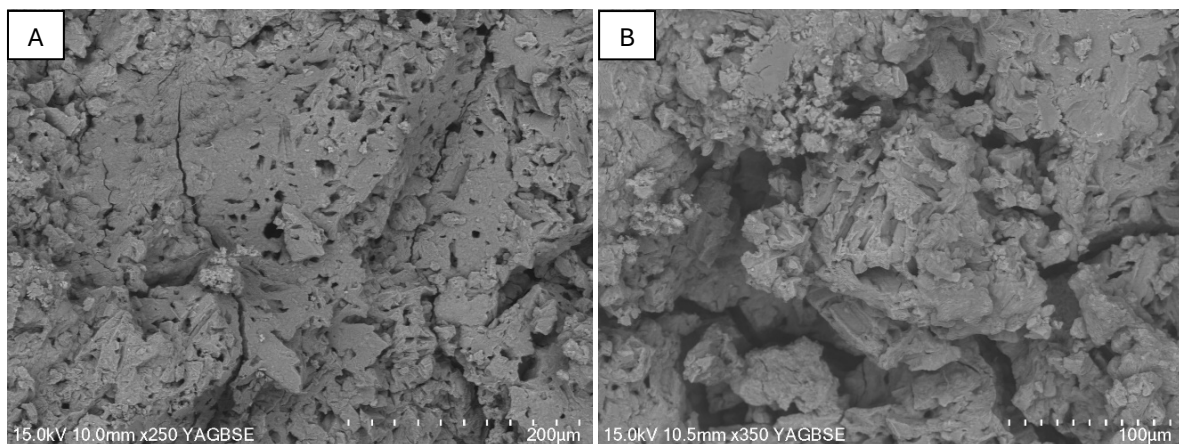


Figure 56: SEM imaging using YAGBSE of sample C2 at 15kV. A) 200x magnification. A fine-grained granular matrix with a rough surface and pits that could be the result of minerals that have fallen out. B) 400x magnification. Fine-grained granular matrix with well-formed prismatic crystals and platy structures. C) 400x magnification. Rough surface texture with platy and prismatic crystals. D) 600x magnification. Surface texture is rough with pits and platy, sheet-like structures as well as crystals present.

The SEM imaging of sample C4 (Figure 57) shows very fine-grained aggregates composed of irregular, blocky to platy particles with a rough surface. Throughout the sample cracks and pits can be seen as well as impressions where minerals could have once been.



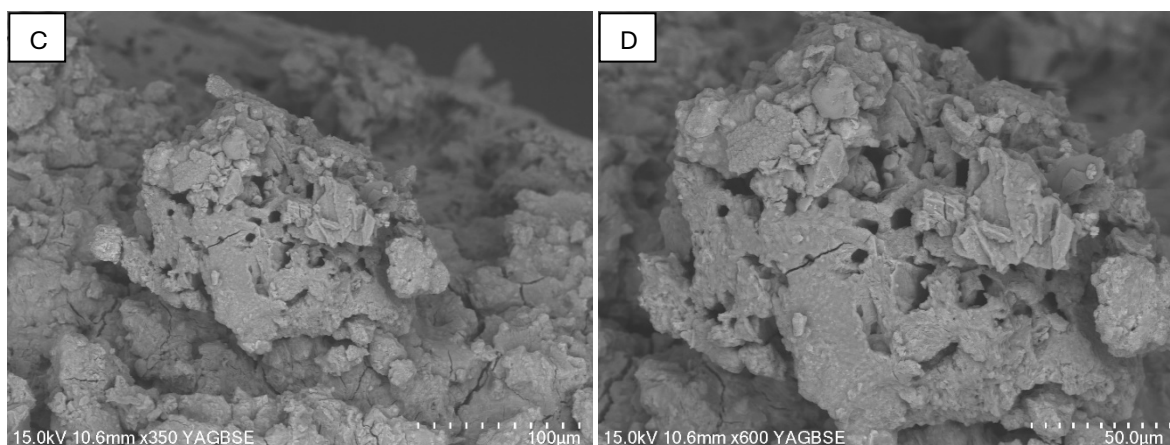


Figure 57: SEM imaging using YAGBSE of sample C4 at 15kV. A) 250x magnification. Aggregates that are irregular and blocky with the surface having cracks and pits. B) 350x magnification. Rough surface showing pits where minerals might have once been. C) 350x magnification. Cracks and pit can be seen on the surface of the aggregate. D) 600x magnification. Very fine-grained aggregates with blocky textures, pits and cracks can also be seen on the rough surface of the particles.

The SEM imaging of sample S9 (Figure 58) shows very fine-grained, crystal poor aggregation composed of irregular particles within a compact highly porous matrix. Many grains show smooth to slightly pitted internal surfaces, while others display scaly or plate-like textures. Further, SEM showed a crystalline poor matrix, composed of irregular, platy to blocky particles which formed dense but heterogeneous aggregates. The sample also shows a very smooth, rounded particle (Figure 58D).

At lower magnification, the individual grains are difficult to distinguish due to a very fine granular material that is covering the surface grains as well as most of the material, producing a large, aggregated mass. At higher magnification, the matrix is dominated by thin, sheet-like to lamellar particles with uneven edges and are commonly arranged in stacked and intergrown clusters. The platy particles display rough surfaces.

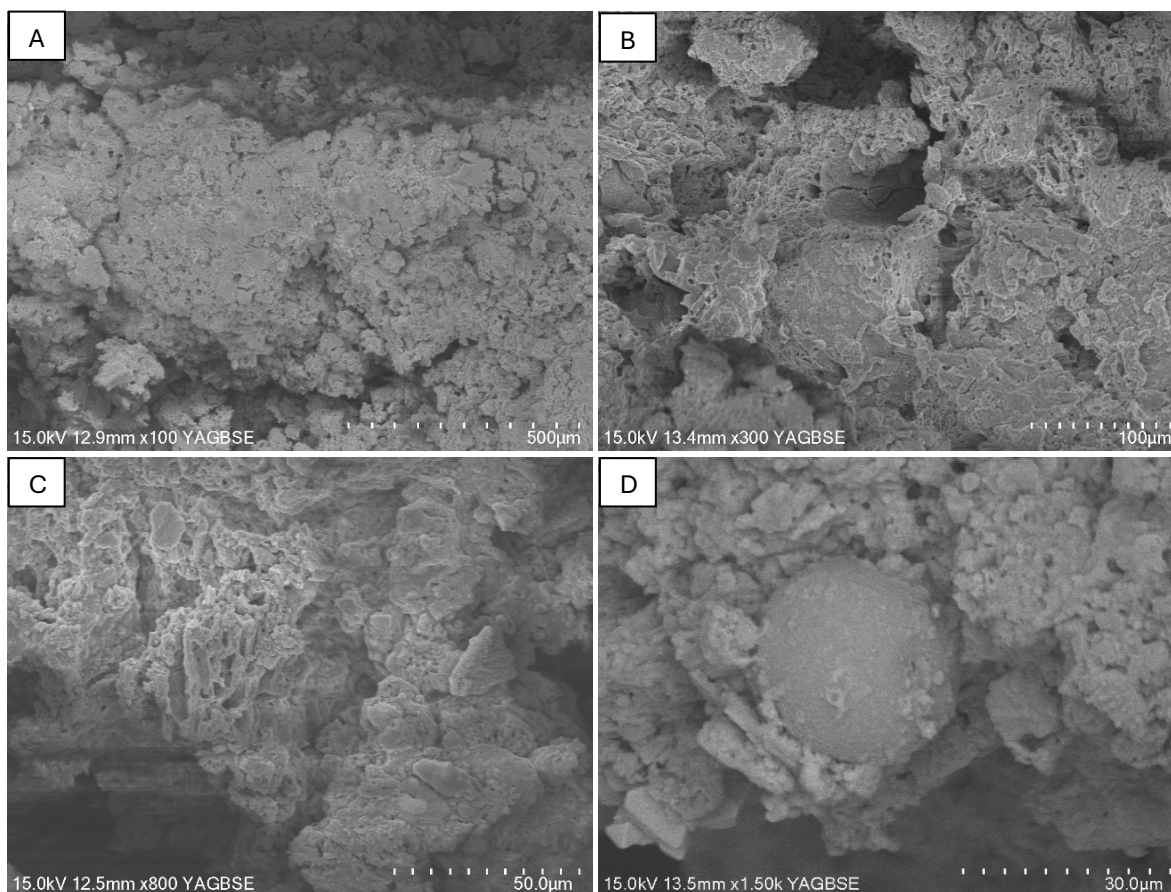


Figure 58: SEM imaging using YAGBSE of sample S9 under 15kV. A) 100x magnification. Smooth very fine-grained granular surface making a large, aggregated particle. B) 300x magnification. Highly porous, fine-grained matrix with pitted internal surfaces. C) 800x magnification. Surface textures are rough with pitting occurring alongside blocky and plate-like textures. D) 1.50k x magnification. The round particle is very smooth with small particles coating the outside. The aggregates around the spherical particle are rough.

Point analysis (Figures 59-60 and Tables 14-15) was undertaken on the round particle (Figure 58D). The point analysis showed concentrations of Si (6.6-7.7 wt.%), Fe (6.1-8.9 wt.%), Al (6.1-8.9 wt.%), and Ti (3.4-4.4 wt.%) in all sampling sites. The measured O and C are considered uncertain.

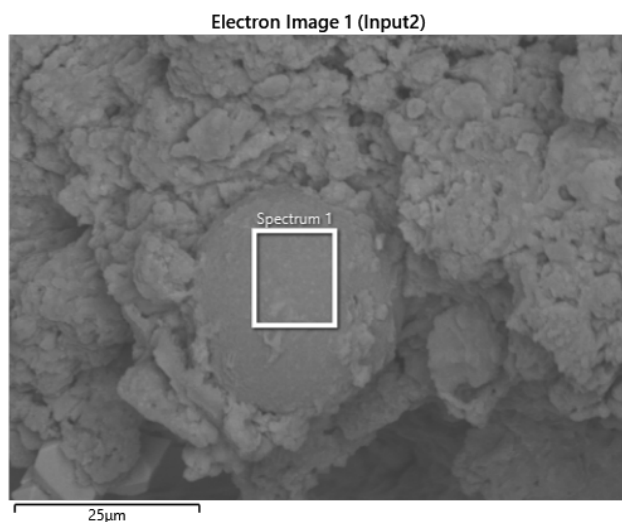


Figure 59: SEM image of S9 showing location where Spectrum 1 was taken from.

Table 14: Elemental composition (wt. %) of SEM-EDS of S9 site.

Element (wt.%)	Spectrum 1
O	42
C	34.2
Si	7
Fe	6.8
Al	6.1
Ti	3.8
Zr	0

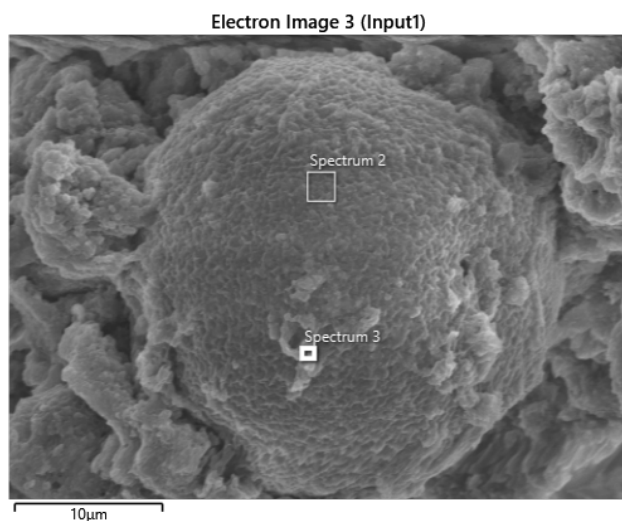


Figure 60: SEM image of S9 showing locations where Spectrum 2-3 were taken from.

Table 15: Elemental composition (wt.%) of SEM-EDS of S9 site.

Element (wt.%)	Spectrum 2	Spectrum 3
O	45.7	22.1
C	28.8	50.4
Si	7.7	6.6
Al	6.8	8.1
Fe	6.1	8.9
Ti	4.4	3.4
Ca	0.4	0.5

SEM Block

From the EDS element mapping of the S9 sample block, seven different sites were chosen for elemental mapping, only four are displayed with the rest in the Appendix. The elements chosen for detection were Al, Si, Ti, and Fe, however, this does not mean these are the most abundant elements that were detected for each sample.

From the element mapping (Figures 61-68 and Tables 16-19) the concentrations (where the brighter the colour, the higher the concentration) and distribution of each element across the sample can be observed.

From the EDS element maps, well-defined crystals can be observed and the difference in surface textures between the two colours (the grey (S9G) (Figure 63) and the white (S9W) (Figure 61)) can be easily distinguished with the white clay appearing as a smoother homogeneous surface compared to the grey which appears to hold more minerals and crystals within its matrix/on the surface.

Figure 61 shows one section of the white clay which is very smooth (excluding some saw marks that were left on the sample surface during preparation) across the entire surface and displays very minimal mineral assemblages. The element maps (Figure 62) show there is a lot of overlap with the elements over the surface of the sample, but particularly with Al and Si. There is a particularly high concentration of Si that is present in the upper lefthand corner of Figure 62.

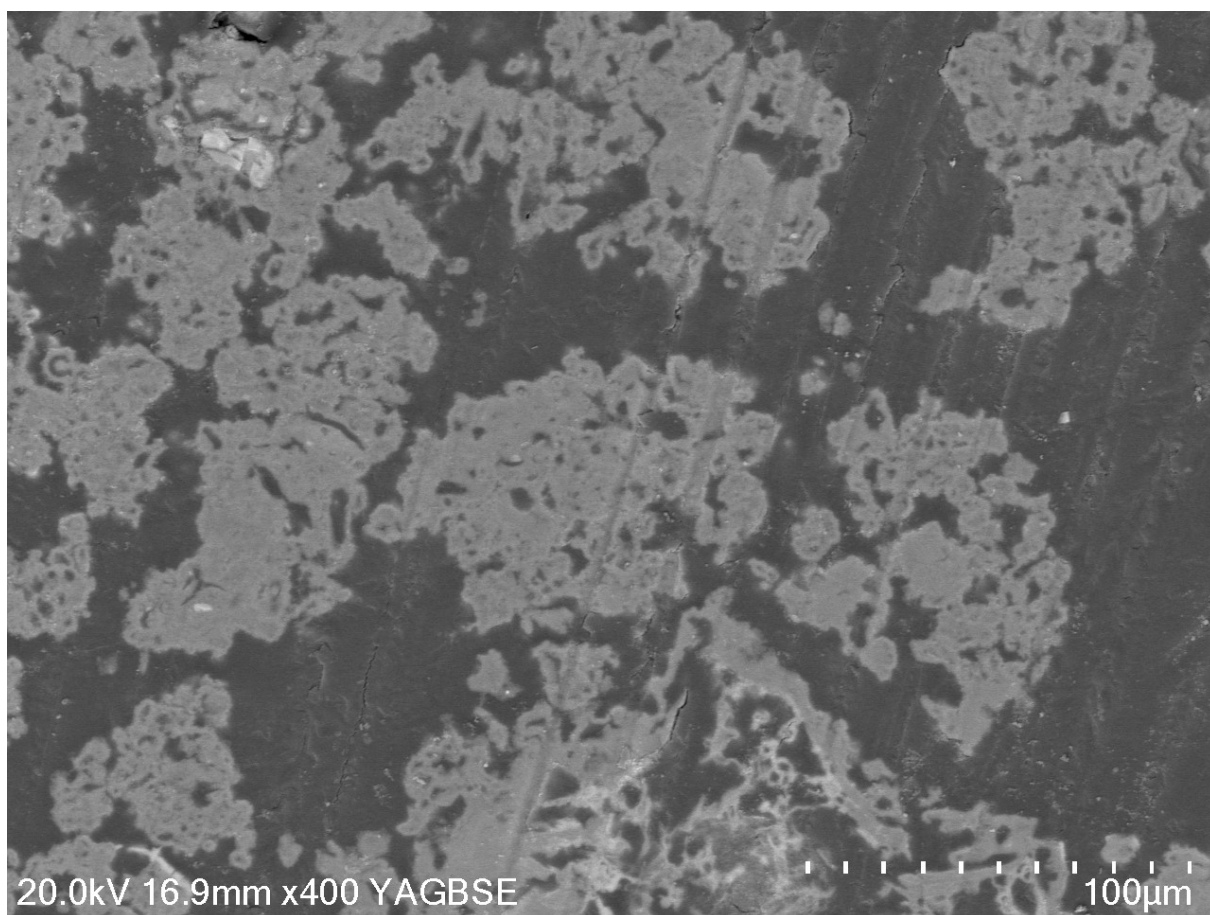
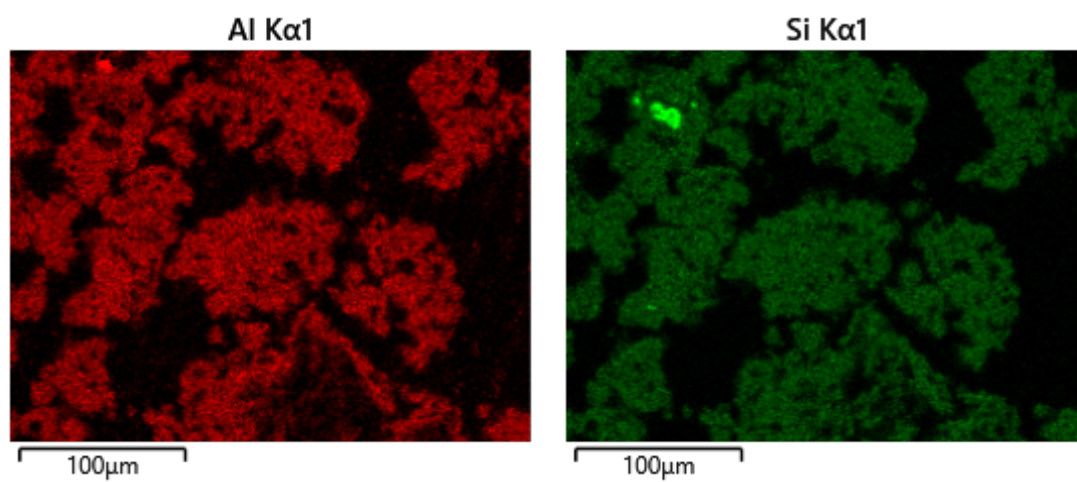


Figure 61: SEM imagery of the white section of the sample S9 block at 400x magnification under YAGBSE at 20kV. Very smooth surface that show minimal mineral assemblages.



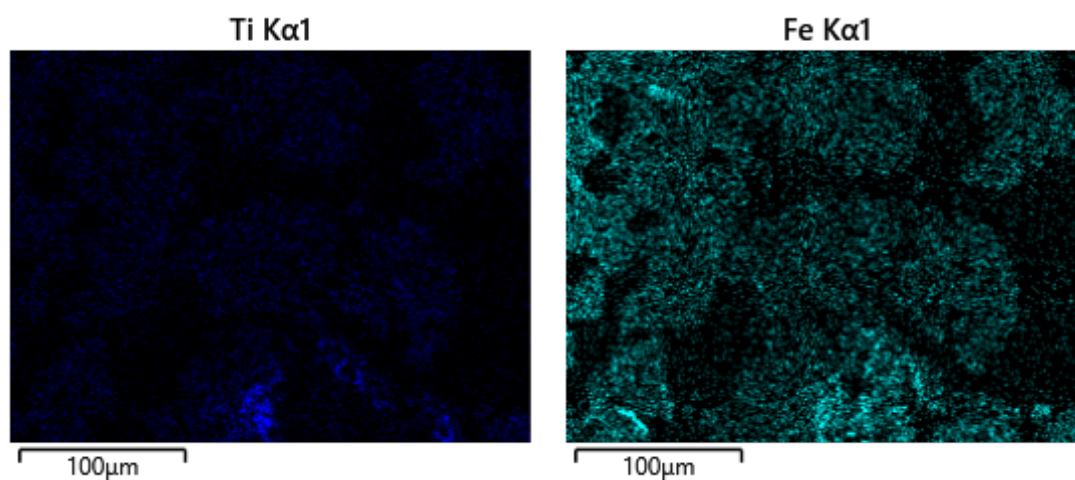


Figure 62: SEM imagery of the element maps from S9 block.

Table 16: Elemental composition (wt.%) of SEM-EDS from S9 block site with standard deviation.

Map Sum Spectrum S9-1		
Element	Weight %	σ
C	60.06	0.15
O	27.61	0.14
Si	5.12	0.02
Al	4.84	0.02
Fe	1.29	0.02
Ti	0.59	0.01
Cl	0.19	0.01
Ca	0.14	0.01
Mg	0.1	0.01
K	0.06	0.01

In contrast to Figure 61 (white), Figure 63 (grey) shows a mix of a rough and smooth surface covered with pits, representative of relict basalt textures found in a groundmass. Map S9-2 (Table 17) has the highest Fe concentration (5.33 wt.%) out of all the block sites chosen. There are disseminated Fe-rich and Al-rich minerals as well as areas of aluminium silicate where there is large overlap seen when comparing the maps (Al and Si) (Figure 64).

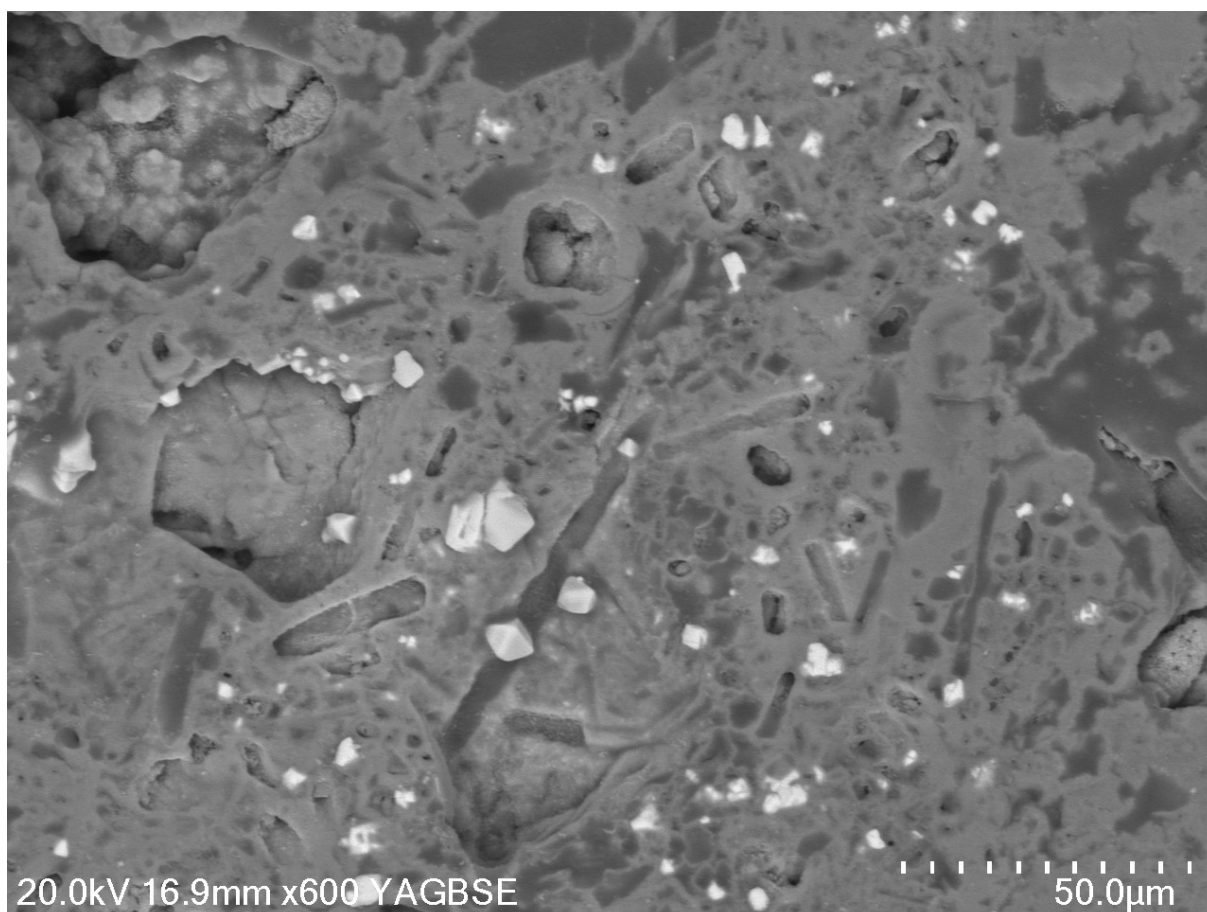


Figure 63: SEM imaging of grey section of sample S9 block at 600x magnification under YAGBSE at 20kV. The exterior is smooth with rough internal surfaces and edges. There are minerals on and in the surface of the block as well as pits.

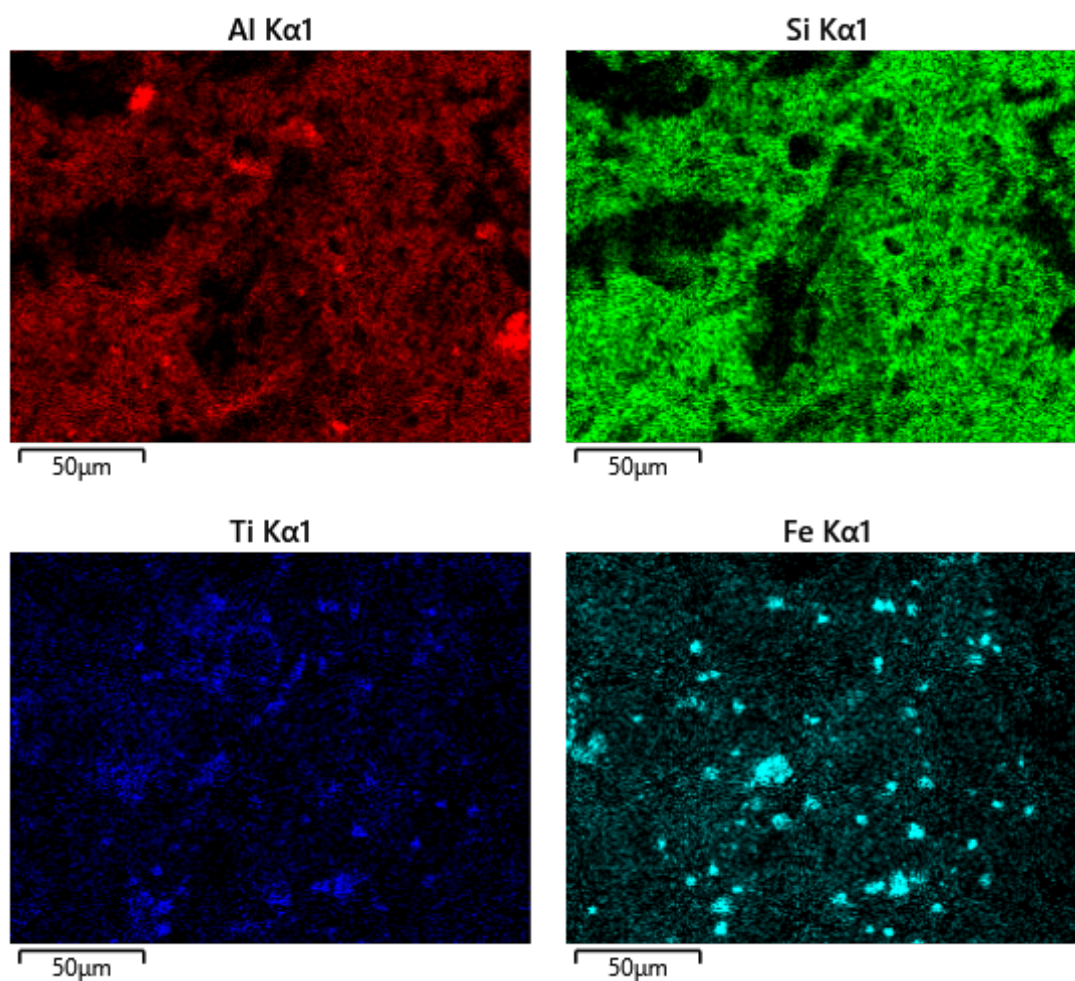


Figure 64: SEM imaging of element maps of sample S9 block.

Table 17: Elemental composition (wt. %) of SEM-EDS from S9 block site with standard deviation.

Map Sum Spectrum S9-2		
Element	Weight %	σ
C	42.91	0.3
O	33.88	0.23
Al	7.9	0.05
Si	7.79	0.05
Fe	5.33	0.06
Ti	1.35	0.02
Mg	0.21	0.02
Cr	0.2	0.02
Ca	0.2	0.01
Cl	0.14	0.01
K	0.09	0.01

Figure 65 and Figure 67 show the topographic contrast between the two clay types within the block of sample S9. In the element maps (Figure 66 and Figure 68) there is a distinct

difference when looking at the Fe and Ti element maps which helps to outline the boundaries of the clays. The disseminated Fe-rich areas show where the grey clay is present as well as relict textures that typically would be seen in a basaltic groundmass.

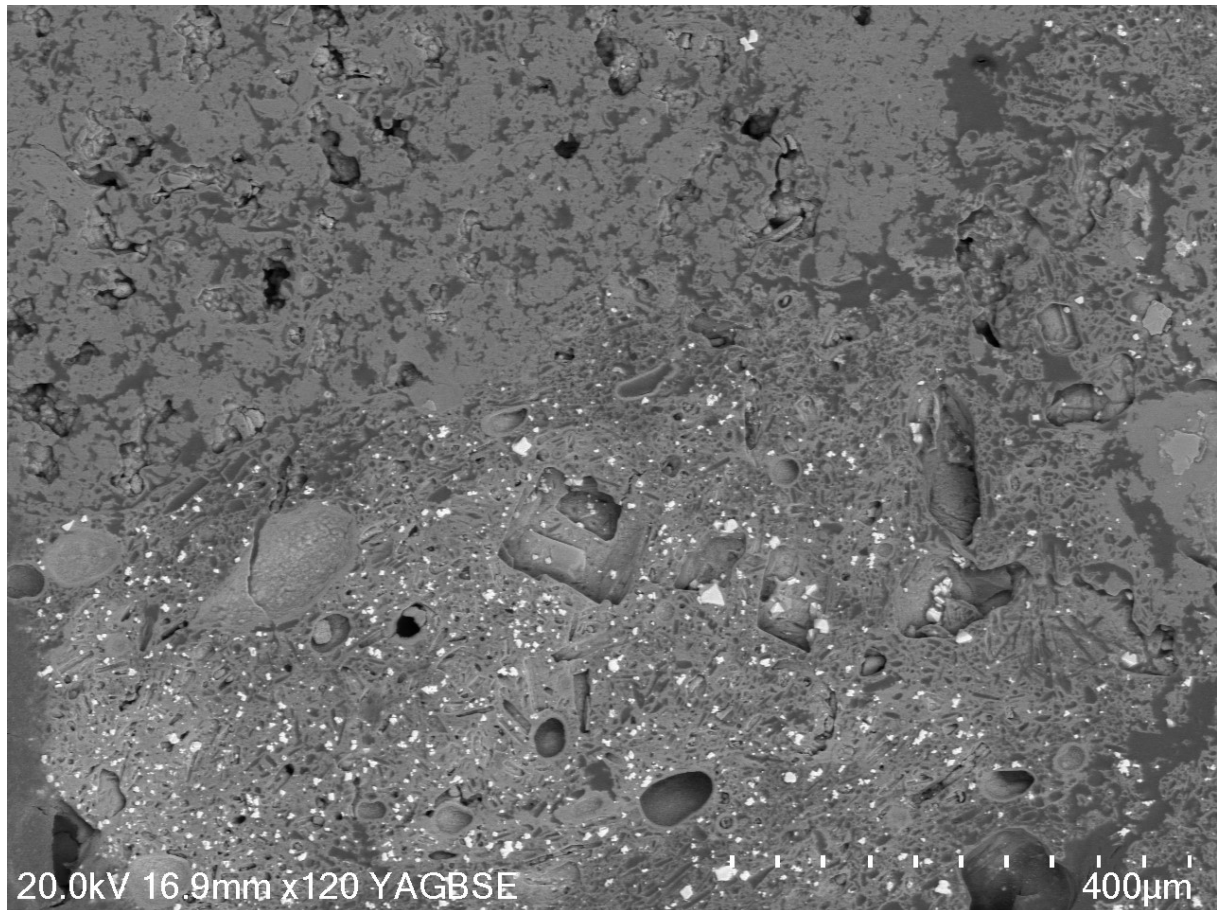


Figure 65: SEM imaging of the surface of the sample S9 block at 120x magnification under YAGBSE at 20kV. Lower half, grey clast of hyaloclastite with abundant Fe-rich minerals and relict textures of a typical intergranular groundmass of a basalt. Upper half, white clay matrix of hyaloclastite.

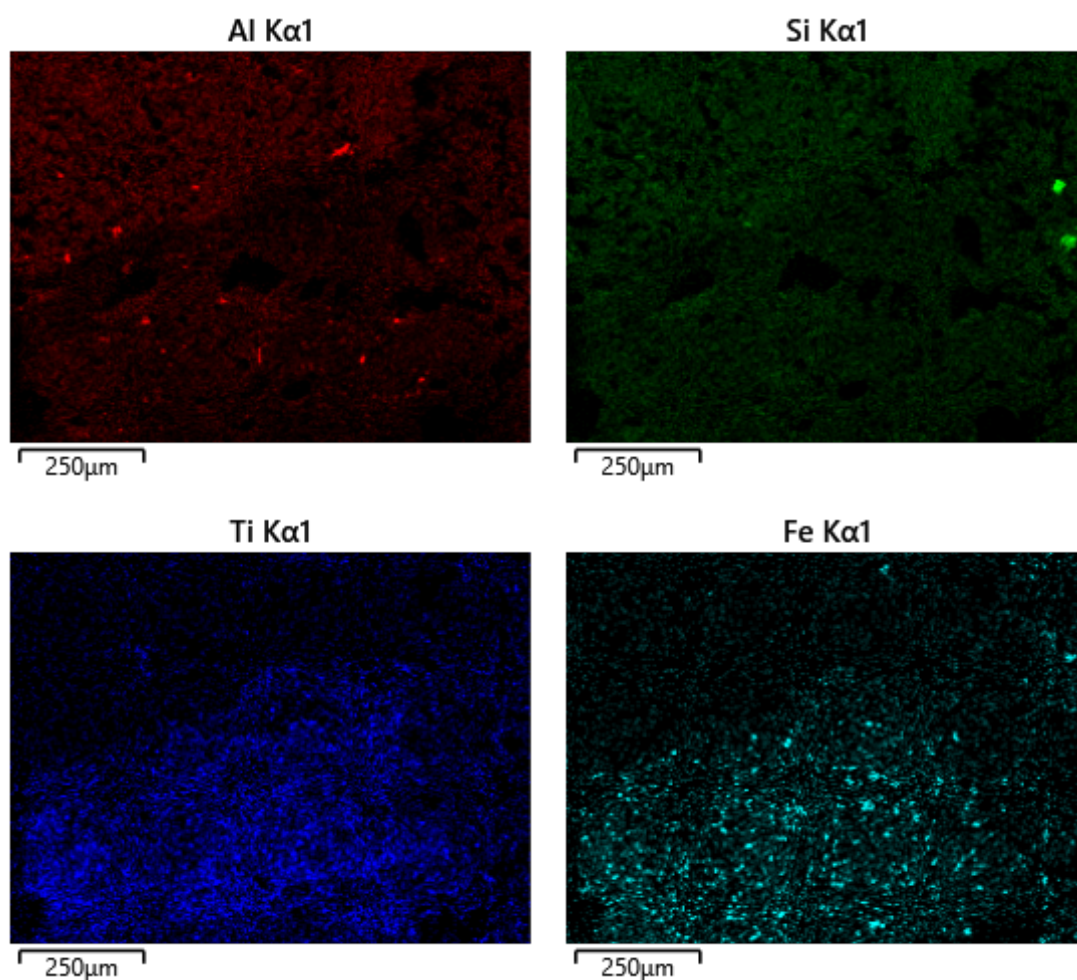


Figure 66: SEM imaging of element maps from Figure 65.

Table 18: Elemental composition (wt.%) of SEM-EDS from S9 block site with standard deviation.

Map Sum Spectrum S9-5		
Element	Weight %	σ
C	42.8	0.6
O	28.55	0.48
N	9.74	1.07
Si	6.36	0.09
Al	5.83	0.08
Fe	3.13	0.06
Ti	2.83	0.05
Mg	0.2	0.02
Ca	0.19	0.01
Cl	0.14	0.01
Cr	0.08	0.02
K	0.08	0.01
V	0.06	0.02

Over the entire sample are areas of overlap between Al and Si, suggesting aluminium silicates present throughout the sample.

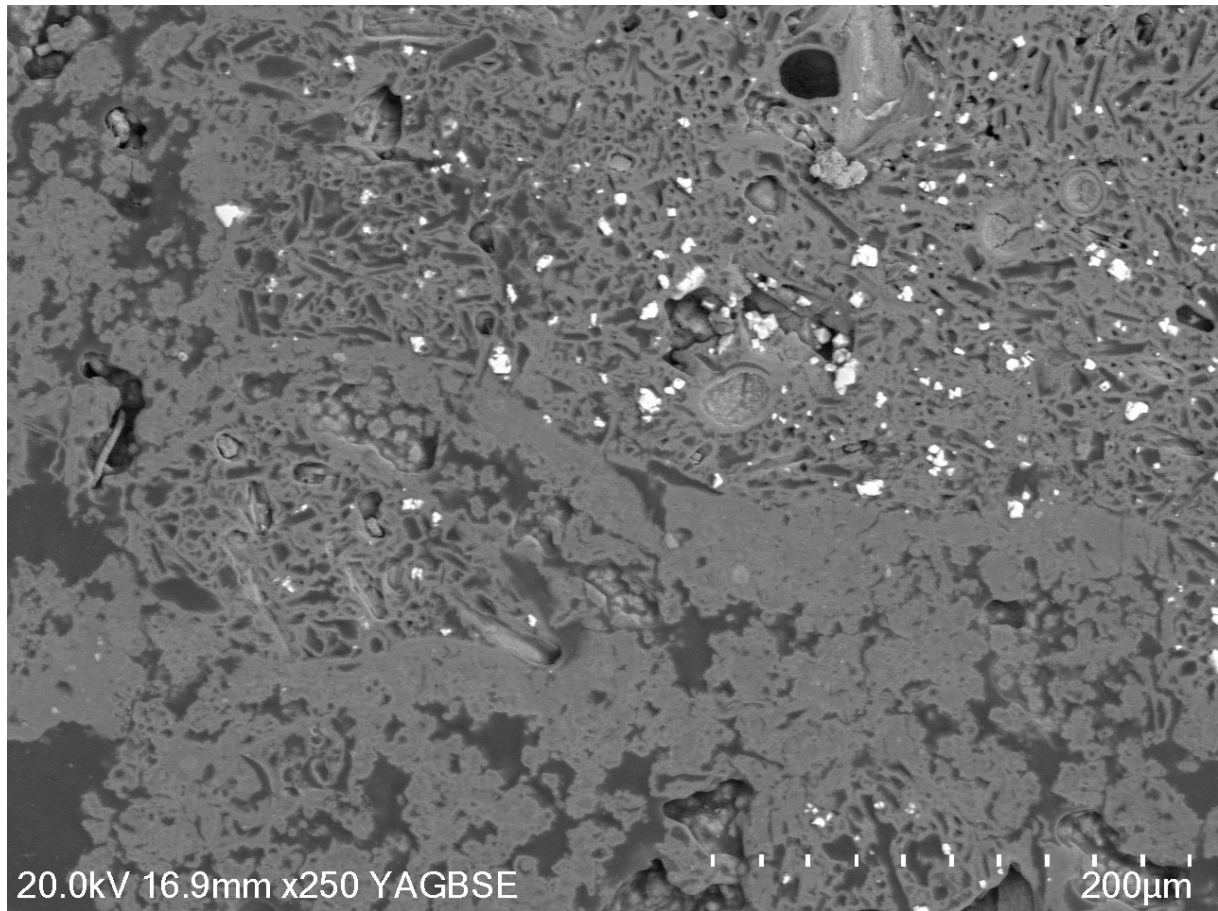


Figure 67: SEM imaging of sample S9 block for elemental mapping at 250x magnification under YAGBSE at 20kV.

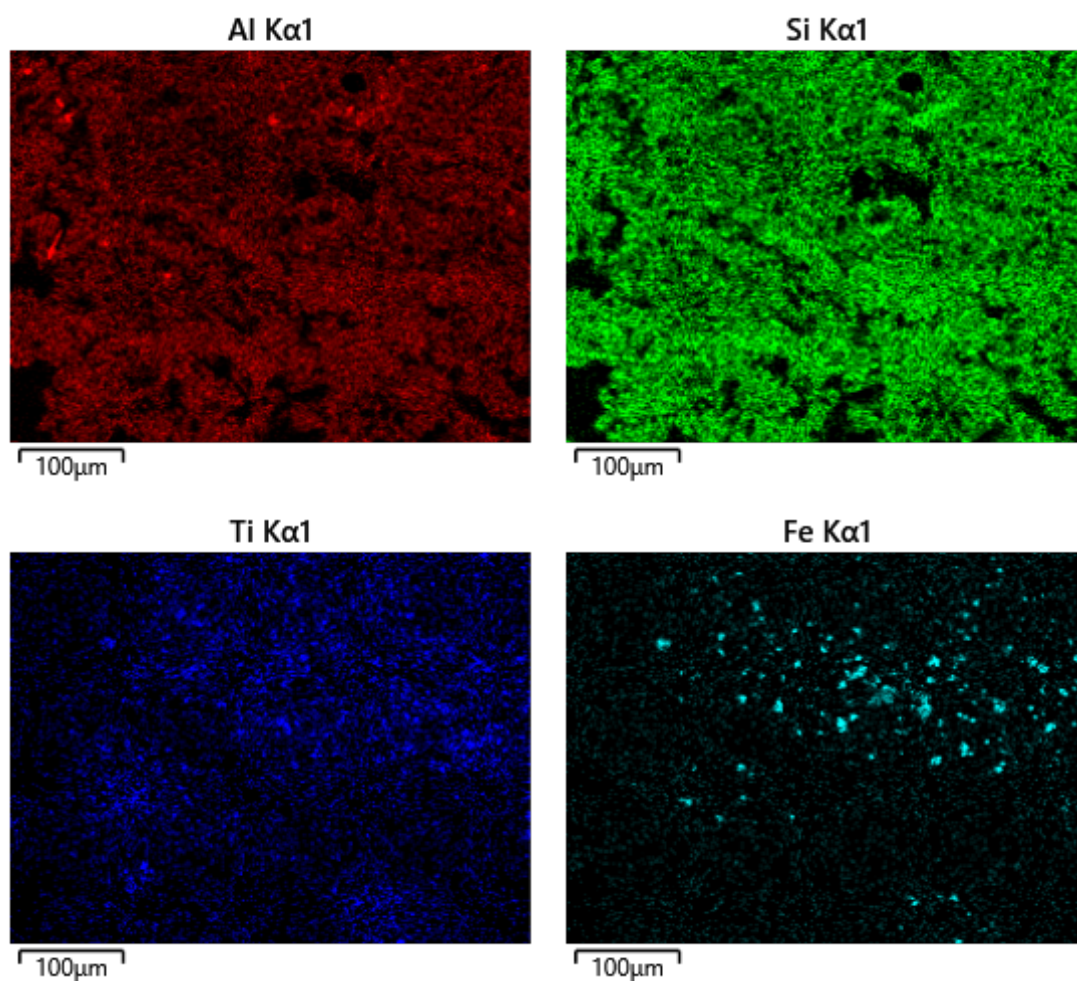


Figure 68: SEM element maps showing element distribution from Figure 67.

Table 19: Elemental composition (wt. %) of SEM-EDS from S9 block site with standard deviation.

Map Sum Spectrum S9-6		
Element	Weight %	σ
C	46.85	0.31
O	32.42	0.25
Si	8.32	0.06
Al	8.16	0.06
Fe	1.95	0.04
Ti	1.58	0.03
Ca	0.18	0.01
Mg	0.16	0.02
Cl	0.15	0.01
K	0.11	0.01
Cr	0.1	0.02

Chapter 4: Discussion and Conclusions

Discussion

The primary aim of this study was to characterise the Wairēinga (Bridal Veil) Falls lava flow, its emplacement, and the palaeoenvironment and volcanic history at Te Mata Quarry. To investigate this the stratigraphy and outcrop structures were examined and described in the field and samples were collected. Further, laboratory-based analyses were then conducted. To analyse the sandstones and siltstones, thin sections were made for microscopy and grain size distributions were determined; crystals sampled from the cave site were analysed using a combination of pXRF, XRD, SEM, and stereomicroscopy; clay samples and hyaloclastite beneath the basalt underwent XRD, SEM, and stereomicroscopy; hyaloclastite was also examined with thin sections; finally, basalt samples were investigated using thin sections and XRF. Clasts from a significant tephra layer in the cover beds were also examined by thin section microscopy.

The key findings from these investigations found that crystal precipitates collected from cave sites show consistent mineral assemblages, with clays also present, indicating secondary mineral formation within the cave environment. It was confirmed that the sandstones and siltstones underlying the basalts were of a marine origin, belonging to the Te Kuiti Group (Late Eocene–Oligocene to early Miocene). Their poor sorting, combined with the presence of glauconite, bioclasts, and calcite indicates deposition in a shallow marine setting with minimal sediment transport. Evidence suggests that prior to lava emplacement at ~2.57 Ma (Early Pleistocene), the environment was a wet terrestrial setting within a palaeovalley. This is indicated by the presence of buried wood and coal layers, suggesting vegetated and water-rich conditions. Hyaloclastite was found directly beneath the basalt, which provides evidence of lava–water interaction. Field textures, colour, and thin section observations indicate quenched, fragmented magma formed through rapid cooling from contact with external water. The basalt samples show minimal variation in mineralogy and geochemistry. However, jointing patterns indicate variability in cooling direction and flow orientation, including multiple flow directions, and patterns such as the presence of rosette structures. The rosette structures may relate to lava tube development. Furthermore, the Kauroa Ash stratigraphy overlying the basalt provides additional context for volcanic activity and sedimentation over the ~2.5 Ma following the basalt eruption.

Sandstones and Siltstones – Oligocene Bedrock

McLeod et al. (2024) states that the lower part of Aotea Formation, of the Te Kuiti Group, is well exposed beneath the lava at Te Mata Quarry. Based on the characteristics of the sand unit (S15) lower in the quarry it has been determined that this unit is part of the Hauturu Sandstone Member from the Aotea Formation (P. Kamp, pers. comm. May 20th, 2026.) The sandstones found at the bottom of the sequence are not characteristic of the member but display signs of weathering and the oxidation of iron leading to the colour variations that were observed. The stratigraphic position of these sandstones being the Hauturu Sandstone suggests that the overlying siltstone is the Patikirau Siltstone Member of the Aotea Formation.

The presence of glauconite and bioclastic material in both the sandstone and siltstone samples, indicates that during deposition of sediments in the Oligocene, prior to the lava flow at the start of the Pleistocene, Te Mata Quarry and the local area was a marine environment.

Glauconite is an iron potassium phyllosilicate, an iron-rich authigenic mineral, characterised by its green colouring. It forms during long-lasting contact between a pre-existing phyllosilicate and seawater (Tribovillard et al., 2023). Glauconite is formed in situ through a slow chemical process where faecal pellets, clay minerals or bioclasts are altered by the uptake of potassium and iron from seawater (Hesse & Schacht, 2011).

Bioclasts are skeletal fragments derived from organisms such as molluscs and brachiopods, commonly shells that have been preserved within sedimentary rocks (Kidwell & Holland, 1991). These bioclasts are typically made up of calcium carbonate (CaCO_3), most commonly of calcite or aragonite in polymorphic forms, and occasionally vaterite (Wheeler, 2020). Given shells are durable exoskeletons, they are more likely than soft tissues to survive following an organism's death, making them a dominant component in the fossil record of many sedimentary environments (Ray, 2014).

Shells are incorporated into rock through sedimentary processes of deposition, accumulation, and compaction. After the death of marine organisms, their skeletal remains settle on the seafloor, where they accumulate alongside other sediments. Over time, continued burial leads to compaction and lithification, forming biological sedimentary rocks (Haldar, 2020). Specifically, the presence of shells in limestone indicates the rock was formed in a shallow marine environment. First, the presence of shell material within rock layers not only reflects past biological activity consistent with a marine environment. Secondly, limestone typically forms in shallow marine environments (Spencer, 1988).

There is a significant unconformity that is present between the sandstones and siltstones and the overlying basalt, this is evident due to the ~20 million years between the age of the sandstones and siltstones (Oligocene) and the basalt (Early Pleistocene). The unconformity is due to erosion that occurred to form the palaeovalley through which the basalt flowed and filled. The palaeovalley had to have been at least 36 m deep, based on the stratigraphic log contact between the sediment, at its thickest, and basalt being placed up to ~36 m thick.

Environment Before Lava Flow – Early Pleistocene

The presence of the buried charred wood and the coal layers suggest there was a wet, terrestrial environment with abundant vegetation before the lava infilled the valley. If the environment was not wet in some capacity, then the wood most likely would have undergone complete combustion and turned to ash instead of the incomplete combustion that is seen with the charred material that was found at Te Mata Quarry (Bird, 2006; Scott, 2010). There is also the presence of hyaloclastite which indicates a wet environment.

Hyaloclastite

Hyaloclastite is a volcanic breccia formed by the sudden supercooling of magma/lava through contact with external water or ice leading to glassy debris fragments being formed (Cas et al., 2024).

The presence of hyaloclastite beneath the lava at Te Mata Quarry means that at some point there must have been water present in the valley for the basaltic lava to flow over/interact with, which also would explain the preservation of the woody material found in the basalt at Te Mata Quarry. Evidence for hyaloclastite include dark fragments, which are pieces of quenched, fragmented basalt lava indicative of the quench fragmentation that occurs when lava is supercooled when coming into contact with external water. The fragments of basalt set within a clay matrix were seen in the field, then confirmed using thin sections and SEM analysis. The SEM analysis of sample S9 was more revealing than the thin sections due to the relict textures that were evident from the SEM imaging.

The white clay matrix of the hyaloclastite could be altered glass where the finer material in the lava flow cooled and quenched much faster than the larger basalt fragments leading the formation of glass and over time the glass altered to clay.

The hyaloclastite of S9 was seen on the northern side of the quarry to the left of the siltstone outcrop. The clay C4 from within the cave, is most likely also hyaloclastite based on the evidence of basalt fragments. Leading to evidence that water was present on either side of the valley as the lava flowed through.

The extent of the water in the valley is unknown; however, a few fragmented logs collected and examined prior to the pilot study determined that beech was present at the quarry site prior to the lava flow (L. Donaldson, pers. comm. in University of Waikato, unpublished data.). Depending upon the species of beech and any other species that might be present, a lot of information could be inferred depending upon the preferred growing environment for species present in/under the basalt at the quarry.

There had to have been sufficient water for plant growth but not too abundant that water flooded and submerged the entire landscape constantly. Any soil present in the valley would have been saturated which is consistent with that of a swamp environment.

Eruption and Lava Flow

The olivine basalt lava that infills the palaeovalley includes at least two flow units with different columnar joint spacing, a rosette jointing pattern and a potential lava cave, these features show a multistage history of lava pulses and lava tube development.

The jointing patterns seen in the basalts show the cooling history and the direction of flow of lava as it moved across the landscape. As basalt cools it contracts and fractures, which then propagates from the top and bottom of the flows and grows inwards to the centre creating the prismatic columns. The lava flows at Te Mata Quarry are multidirectional and multifaceted. The jointing patterns shows that there was at least two lava flows with sharp contacts that moved through the valley as there are different patterns and angles of basaltic features seen around the quarry. The direction of flow can be assessed when looking at the joints and their position as some will curve in the direction the lava is advancing. From the geochemical analysis undertaken it showed that there was not any significant variation in the mineralogy and geochemistry between the two flow units.

The cave found in the side of the basalt is likely a lava tube. Lava tubes are volcanic conduits formed during effusive eruptions, generated either by the crusting over of flowing lava at the surface or through inflation associated with successive lava flows beneath earlier solidified units. They are widespread in volcanic regions, particularly in tectonically active

areas. Lava tubes typically form at shallow depths and are characterised by elongate geometries with relatively uniform diameters (Pipan & Culver, 2019; Sánchez et al., 2025).

Kauroa Ash Stratigraphy

The basalt was buried beneath ~10.7 m of the Kauroa Ash and Hamilton Ash formations. Identification of the tephra succession was beyond the focus of this study, however, the ~1 m of the pebble ash layer (T5) was partially examined.

The pebbles in the pebble layer (T5) seen in the Kauroa Ash could be pumice clasts that have undergone alteration to clay. Horrocks (2000) noted the presence of pumice as well as possible relict pumice clasts in their stratigraphy of the Kauroa Ash sequence; McLeod et al. (2024) also noted that the Kauroa Ash is “interbedded with a thick (1.5-2 m) pink alluvial deposit that hosts abundant pumice and chert pebbles”.

From the pebbles collected there was evidence of pumice or other clasts that had weathered to clays, while other clasts held most of their original structure.

Some of the pebbles collected from the layer are pumiceous and are highly vesicular and porous, with low density; whereas other pebbles are dense and have no porosity visible as well as white veins present in some.

The ash seen in T5 has a vertical grading that resembles that of an ignimbrite; with volcanic lithics found at the bottom and pumice concentrated at the top. Horrocks (2000), described within the Papakura Creek stratigraphy, dominant bed K12 as ‘Light grey (2.5Y 8/2) sandy clay at top, becoming pale orange (5YR 8/3) over 20 cm; very firm; abundant crystals, lithics (red, brown, grey), pumice; extensive Mn streaks’ (Horrocks, 2000, p. 23). The T5 layer from this study was describes as a pebble gravel with a pale yellow (2.5Y 8/3) clay matrix; with grey and red lithics; and white crystals.

Horrocks (2000) described the crystals at the Papakura Creek type-site as quartz; whereas in this study they were described as plagioclase; this could be an error due to the small nature of the crystals seen in T5 or human error, in T11 crystals were described as quartz.

Pain (1975) believed it is possible that the Oparau Tephra is the distal end of an ignimbrite (specifically the Ongatiti Ignimbrite) sheet that originated in the volcanic plateau of the Central North Island. Furthermore, data from Horrocks (2000) confirmed the correlation of K12 and Oparau Tephra with the Ongatiti Ignimbrite.

From the results of this study and the prior research mentioned above, I conclude that there is a correlation between the T5 layer and the K12/Oparau Tephra and thus with the Ongatiti Ignimbrite.

Cave Minerals

For the three cave samples collected, they showed similar mineralogy across the analyses they underwent. Sample C1 showed evidence from analysis of having alunogen present, C5 showed gypsum as a major mineral and has evidence for natrojarosite, and C7 from analysis indicates there is an aluminium sulphate mineral present, which could be alunogen.

Alunogen ($\text{Al}_2(\text{SO}_4)_3 \cdot 17\text{H}_2\text{O}$) is a hydrated aluminium sulphate mineral that is often found as a secondary mineral on the walls of mines and quarries as well as in relatively low temperature fumaroles. Its formation is due to a reaction of sulphates from sulphides with aluminous minerals (*Alunogen: Mineral Information, Data and Localities.*, n.d.).

Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is a soft sulphate mineral made of hydrated calcium sulphate. It is a common sulphate mineral found in association with sedimentary rocks. Gypsum is formed in oxidising sulphate deposits where a reaction occurs between sulfuric acid and carbonate rocks. It forms primarily as an evaporate mineral, depositing from saline waters in oceans, lakes, and sabkhas; in caves where the air is dry enough; at fumaroles; or from the dehydration of anhydrite (*Gypsum: Mineral Information, Data and Localities.*, n.d.).

Natrojarosite ($\text{NaFe}^{3+}_3(\text{SO}_4)_2(\text{OH})_6$), is an endmember of jarosite ($\text{KFe}^{3+}_3(\text{SO}_4)_2(\text{OH})_6$) which, is typically formed in oxidised zones of sulphide deposits in the presence of sodium (*Jarosite: Mineral Information, Data and Localities.*, n.d.).

A theory that came from this study is that the formation of these crystals could be the result of quarry activity leading to the exposure of deposits within the interior of the cave being exposed to atmospheric conditions and undergoing further reactions.

Implications

In addition to the main findings, this project had several key implications, both theoretical and practical.

The results provide more insight into the palaeoenvironment, and volcanic history represented by the geology at Te Mata Quarry. Previously, no extensive research has been done

focusing specifically on Te Mata Quarry. Whilst recent research in the local and regional area, such as McLeod et al. (2024) and Yousef Zadeh et al. (2023), focused on the basaltic lava flow and overlying tephra respectively, the underlying sedimentary layers beneath the basalt remain understudied.

This study confirms the marine origins for the sedimentary sequence beneath the basalt (Edbrooke, 2005; McLeod et al., 2024). This is backed up by the lithofacies (sandstone and siltstone), and the presence of glauconite, and bioclastic materials in this sequence.

The buried wood and coal layers signify a stable wet terrestrial environment with abundant vegetation and trees spread across the landscape. The presence of hyaloclastite also indicates that there was surface or near-surface water at the time of lava emplacement within the valley of the quarry.

Palaeoenvironmental reconstruction can provide insight into depositional processes and the interactions between volcanism and the environment it mantles, such as how the landscape morphology changes, the ecology that was once present and how they were altered/disrupted by volcanic processes such as lava flows and ash deposits.

Knowing the regional volcanic/geological history guides future geological investigations and regional mapping, whether that be more in-depth exploration or mapping of previously unmapped areas. This provides a more complete stratigraphic record in the Waikato area and allows for correlation between volcanic formations and deposits across geological time in the North Island.

Limitations and Direction for Future Research

This research project was not without limitations. Firstly, a significant limitation faced was, that during the study, some key analytical equipment malfunctioned. The XRD instrument at the University of Waikato was under repair so samples had to be sent away for analysis to the University of Auckland. This resulted in the decision to only do bulk XRD, and not clay separates as initially planned. The bulk XRD is used for mineral identification, whereas the clay separates provide clay identification. By not analysing clay separates, the clay minerals could not be determined, which may have provided some insight into the parent material to the matrix of the hyaloclastite (e.g. glass). Future research should focus on identifying the clay mineralogy that occur at the research site.

A further limitation arose during SEM preparation; this was due to samples not being dried enough prior to coating and then insertion into the SEM. This resulted in a significant amount of time being lost, due to the pressure in the specimen chambers not getting to level at which the samples could be run.

The XRF analysis gave a high total wt.% for sample B6 and corresponded to a high S content; the reason why was not resolved.

As a direct effect of the time restraints of the study, not all potential fieldwork or laboratory tests were run or considered. One such example that was not considered due to time was any analysis of the ash beds. Future research should examine the Kauroa and Hamilton ash beds, as investigating them could reveal key insights about the history of the quarry and surrounding areas and allow for correlation between the units described at Te Mata Quarry with those defined by Horrocks (2000) and Lowe et al. (2001).

In addition to the specific suggestions made above in response to limitations faced, future research should also aim to expand the scope of analysis to improve the overall understanding of the geological history of the quarry site. Specifically, future avenues for research should include point counting of thin sections, to quantify modal mineralogy and composition and microfossil analysis on the siltstones to correlate units and confirm the presence of Patikirau Siltstone in the quarry. Other valuable directions include analysing the preserved wood found around the quarry as well as the material found in the cave (C6) and the biological contact (S7) to better understand past environmental conditions and producing a comprehensive geological map of the site to capture its spatial complexity. Additionally, collecting and comparing basalt samples from different, more diverse, areas of the quarry, particularly the far eastern sides, would help assess variability and contribute to a complete interpretation of the site. Finally, the scope of the study being restricted to only the quarry has limited a full analysis of the lava flow and future work should include Wairēinga Falls and mapping of the wider area.

Conclusions

In this study, I set out to characterise the Wairēinga (Bridal Veil) Falls lava flow, with particular focus on its emplacement, and an aim to reconstruct the palaeoenvironmental conditions and volcanic history of Te Mata Quarry. Through a combination of field observations and laboratory analyses, I provide new insights into the geological evolution of the quarry site.

These findings point to the underlying sedimentary sequence having been deposited in a shallow marine environment, given the presence of glauconite and abundant bioclastic material characteristic of the Oligocene Te Kuiti Group. Furthermore, the preservation of buried wood and coal layers, suggest that in the early Pleistocene there was a valley with a wet, terrestrial environment existing prior to lava emplacement.

The emplacement of the Wairēinga Falls lava flow ~2.57 Ma occurred within this terrestrial valley system, where surface or near-surface water was present. Given the presence of hyaloclastite at flow margins, I can be confident a lava–water interaction occurred. This supports the idea that lava emplacement was into a water-influenced palaeovalley, where the wet conditions played an important role in controlling flow and cooling.

Petrographic and geochemical analyses of the basalt showed a homogeneous composition, consistent with previous literature focused on basalt in the region. However, during analysis, several key structural features, including variable columnar joint spacing, multidirectional joint orientations, and rosette jointing patterns, were noted. These hint towards a more complex emplacement history and indicate multiple lava flows as well as the development of lava tubes within the flow interior. Together, these findings show that while the magma source remained compositionally consistent, emplacement processes varied greatly.

Additionally, the Kauroa Ash sequence provides further regional context. Specifically, the characteristics of the T5 layer are consistent with the findings of studies focusing on volcanic activity in the central North Island, specifically on the Ongatiti Ignimbrite, helping to situate the Te Mata Quarry sequence within the broader evolution of the Alexandra Volcanic Group.

Overall, these findings show that the Wairēinga Falls lava flow was emplaced into a water-influenced valley, sometime after the environment transitioned from marine to terrestrial. The interaction between lava and water affected how the lava cooled, fragmented, and formed its internal structures. These findings help to improve understanding of the Te Mata Quarry region and provide insight into the volcanic processes and historic environmental change in the broader Waikato region.

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Appendices

Appendix A1.

Table A1: Raw pXRF data for C1, C5, and the top and bottom of C7.

	C1	C5	C7 Top	C7 Bottom
Mg	0	0	0	0
Mg +/-	0.49	0.65	1.47	1.25
Al	0.48	0	0.47	2.77
Al +/-	0.07	0.08	0.11	0.11
Si	3.4838	0.5525	0.7606	0.1929
Si +/-	0.0363	0.0209	0.0289	0.0185
P	0	0	0	0
P +/-	0.0071	0.0167	0.0196	0.017
S	6.6713	10.86	8.13	12.08
S +/-	0.0326	0.05	0.05	0.06
K	0	0	0	0
K +/-	0.0085	0.0118	0.0268	0.0211
Ca	0.1848	13.8	0.4448	0.0516
Ca +/-	0.0035	0.07	0.0068	0.005
Ti	0.6631	0.2507	0.0687	0.0416
Ti +/-	0.0109	0.0119	0.0082	0.0068
V	0.0028	0.0049	0	0
V +/-	0.0008	0.0011	0.0025	0.002
Cr	0.0134	0	0	0
Cr +/-	0.0015	0.0078	0.0064	0.0054
Mn	0.0357	0.0079	0.0346	0.0443
Mn +/-	0.0015	0.0016	0.0019	0.0018
Fe	6.5378	4.4853	2.5552	2.0037
Fe +/-	0.0303	0.0252	0.0176	0.0124
Co	0	0	0	0
Co +/-	0.0323	0.0368	0.0283	0.0224
Ni	0.0189	0	0.0819	0.0427
Ni +/-	0.001	0.005	0.0019	0.0013
Cu	0.0017	0	0	0
Cu +/-	0.0004	0.0027	0.0035	0.0027
Zn	0.0039	0.0012	0.008	0.006
Zn +/-	0.0003	0.0003	0.0004	0.0003
As	0.003	0.0018	0.0007	0.0005
As +/-	0.0001	0.0002	0.0001	0.0001
Se	0	0	0	0
Se +/-	0.0005	0.0008	0.0007	0.0006
Rb	0	0	0	0
Rb +/-	0.0011	0.0016	0.0015	0.0014

Sr	0.0107	0.0857	0.0038	0.0026
Sr +/-	0.0001	0.0006	0.0001	0.0001
Y	0.002	0.0008	0.0016	0.0018
Y +/-	0.0001	0.0001	0.0001	0.0001
Zr	0.0095	0.0066	0.0012	0.0014
Zr +/-	0.0002	0.0002	0.0001	0.0001
Nb	0.0055	0.0024	0.0014	0.0013
Nb +/-	0.0002	0.0002	0.0002	0.0001
Mo	0.0182	0.0054	0.0033	0.0032
Mo +/-	0.0003	0.0003	0.0003	0.0002
Ag	0	0	0.0053	0
Ag +/-	0.046	0.07	0.0015	0.06
Cd	0	0	0	0
Cd +/-	0.06	0.1	0.1	0.08
Sn	0	0	0	0
Sn +/-	0.06	0.09	0.09	0.08
Sb	0	0	0	0
Sb +/-	0.05	0.08	0.08	0.07
W	0	0	0	0
W +/-	0.0058	0.0096	0.0101	0.0085
Hg	0	0	0	0
Hg +/-	0.002	0.0035	0.0027	0.0024
Pb	0	0	0	0
Pb +/-	0.0041	0.0062	0.0054	0.0051
Bi	0	0	0	0
Bi +/-	0.013	0.0216	0.0205	0.0184
Th	0.001	0.0015	0.0028	0.003
Th +/-	0.0003	0.0004	0.0004	0.0003
U	0.0052	0	0.0023	0.003
U +/-	0.0002	0.0134	0.0002	0.0002
LE	81.85	69.93	87.42	82.74
LE +/-	0.1	0.14	0.12	0.12

Appendix A2.

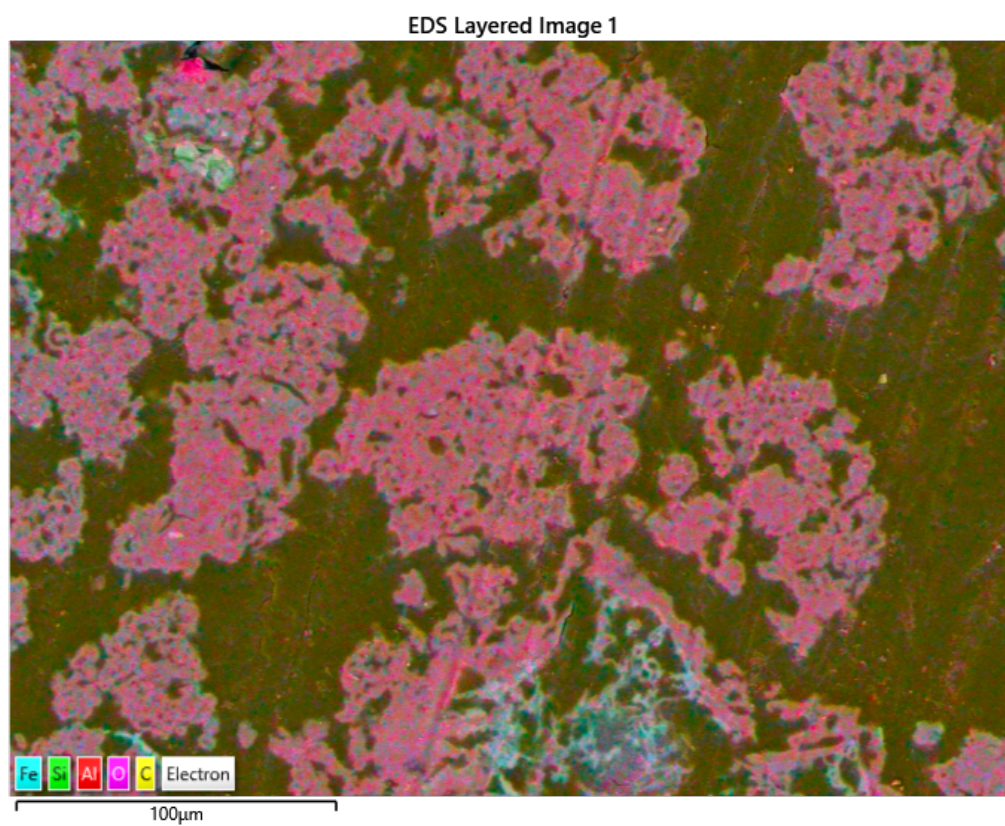


Figure A2.1: SEM-EDS layered image of S9 block (S9-1).

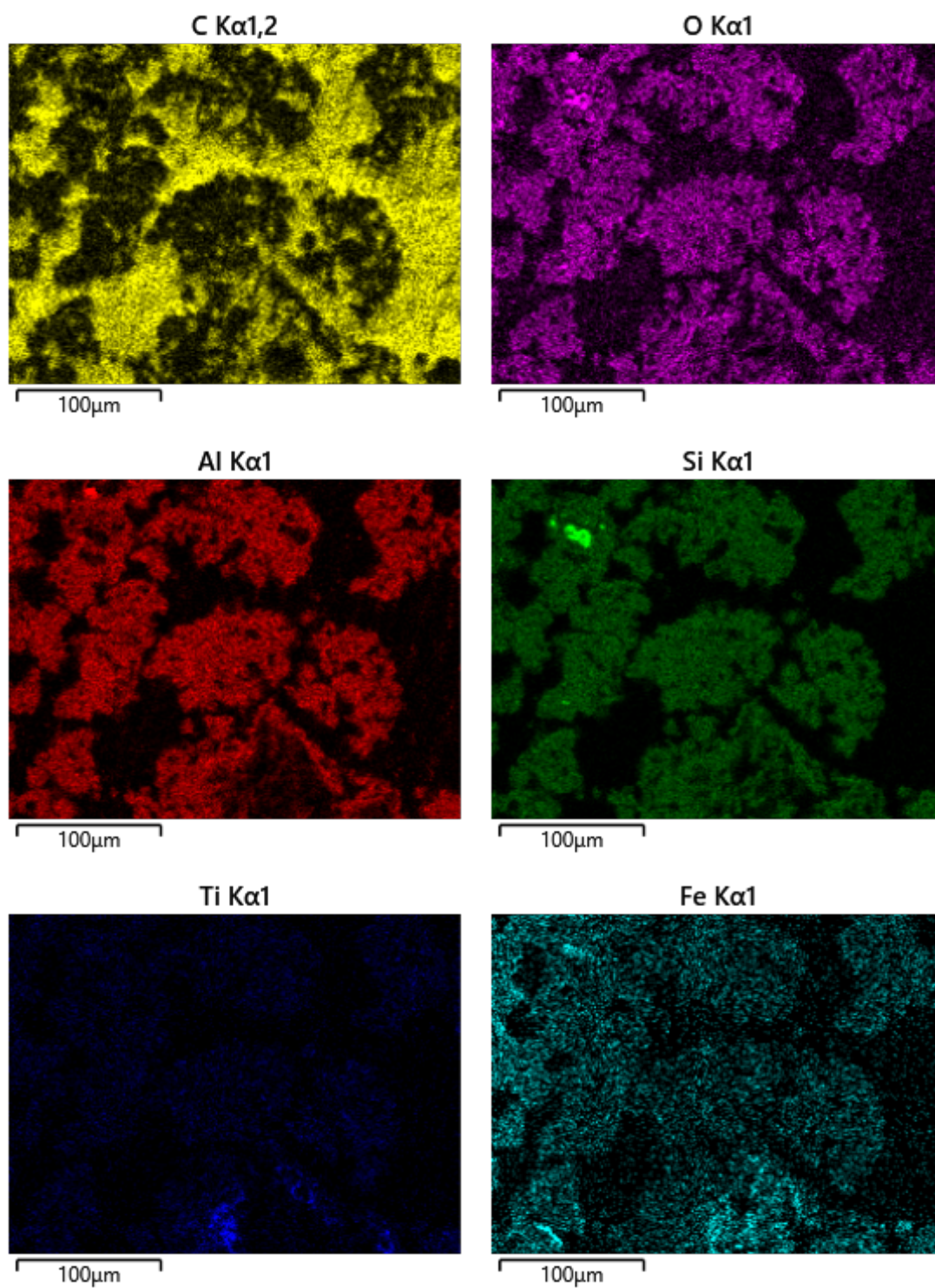


Figure A2.2: Element maps of S9 block (S9-1).

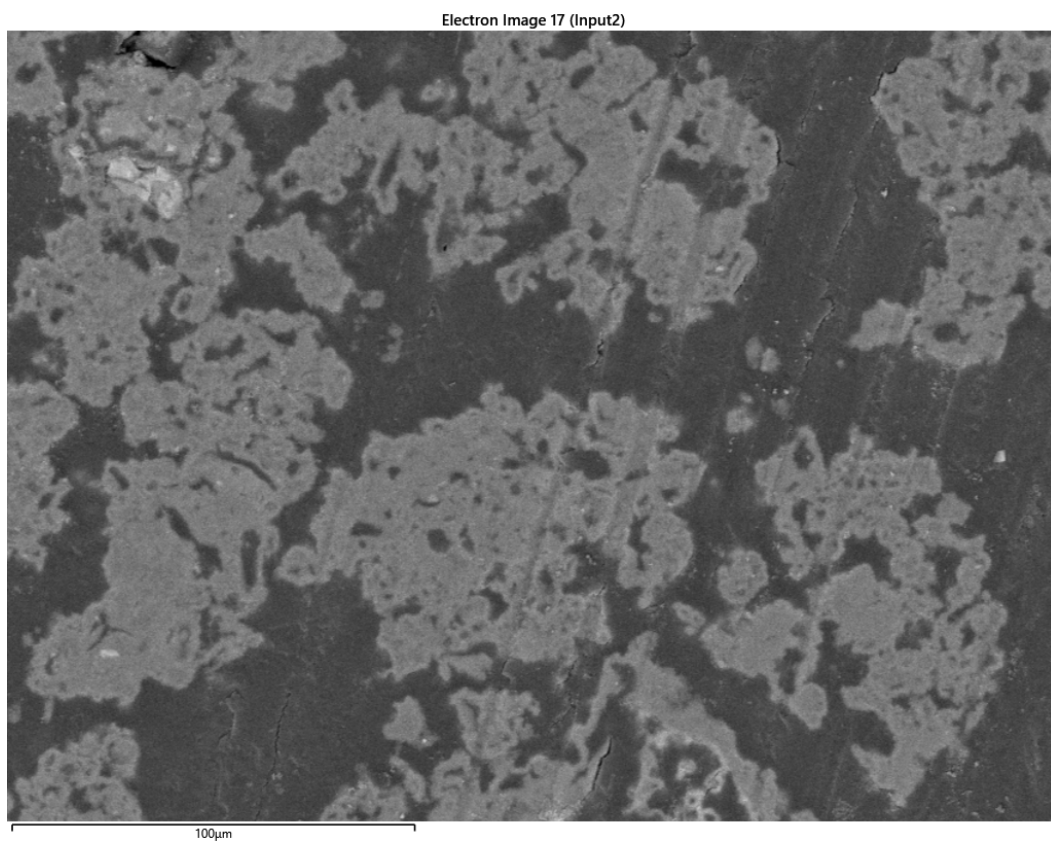


Figure A2.3: SEM-EDS map of S9 block (S9-1).

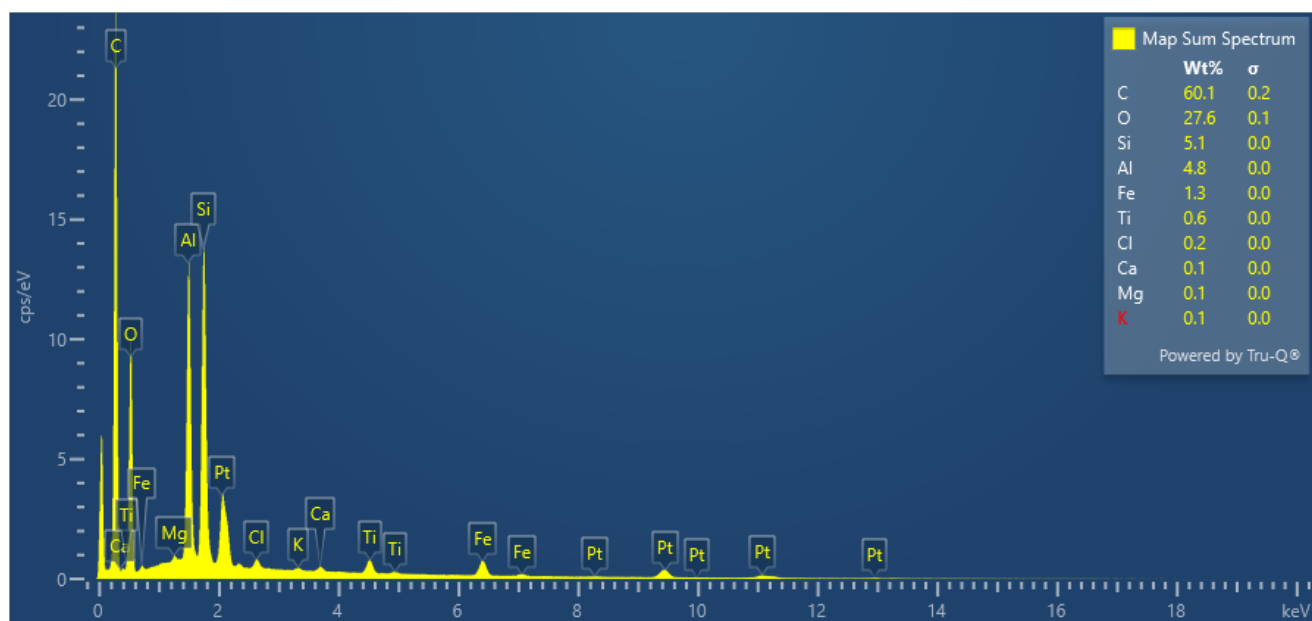


Figure A2.4: Element graph of S9 block (S9-1).

Table A2.1: Elemental composition (wt.%) of SEM-EDS from S9 block site (S9-1) with standard deviation.

Element	Weight %	σ
C	60.06	0.15
O	27.61	0.14
Si	5.12	0.02
Al	4.84	0.02
Fe	1.29	0.02
Ti	0.59	0.01
Cl	0.19	0.01
Ca	0.14	0.01
Mg	0.1	0.01
K	0.06	0.01

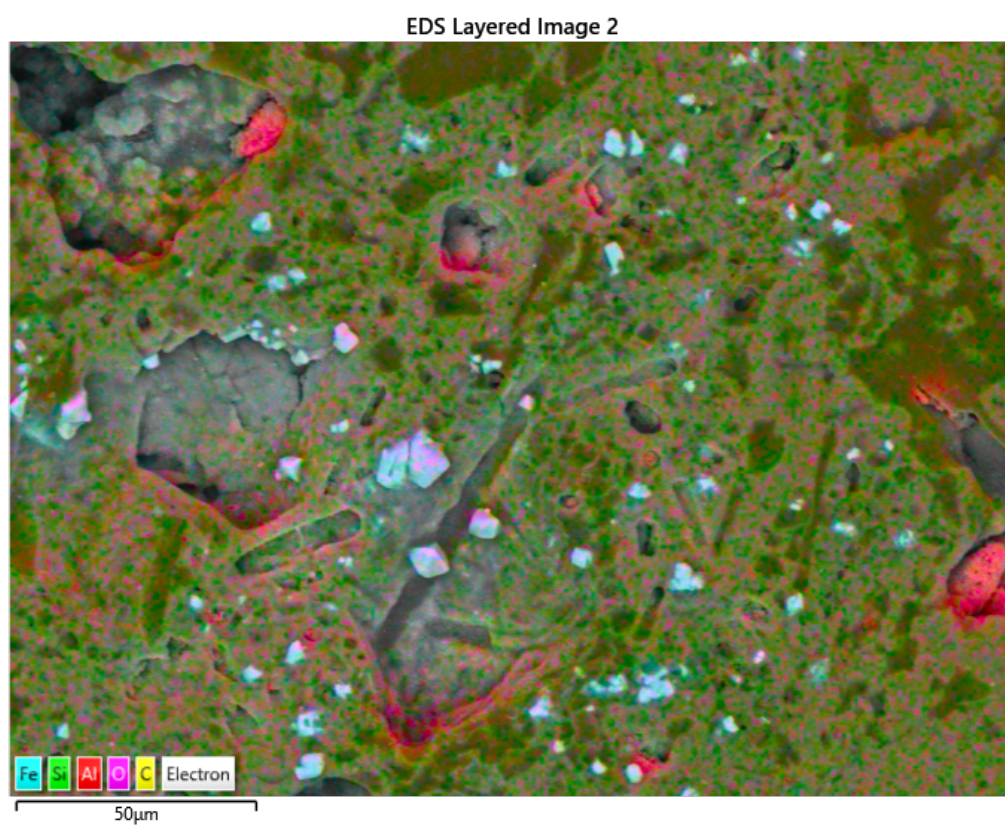


Figure A2.5: SEM-EDS layered image of S9 block (S9-2).

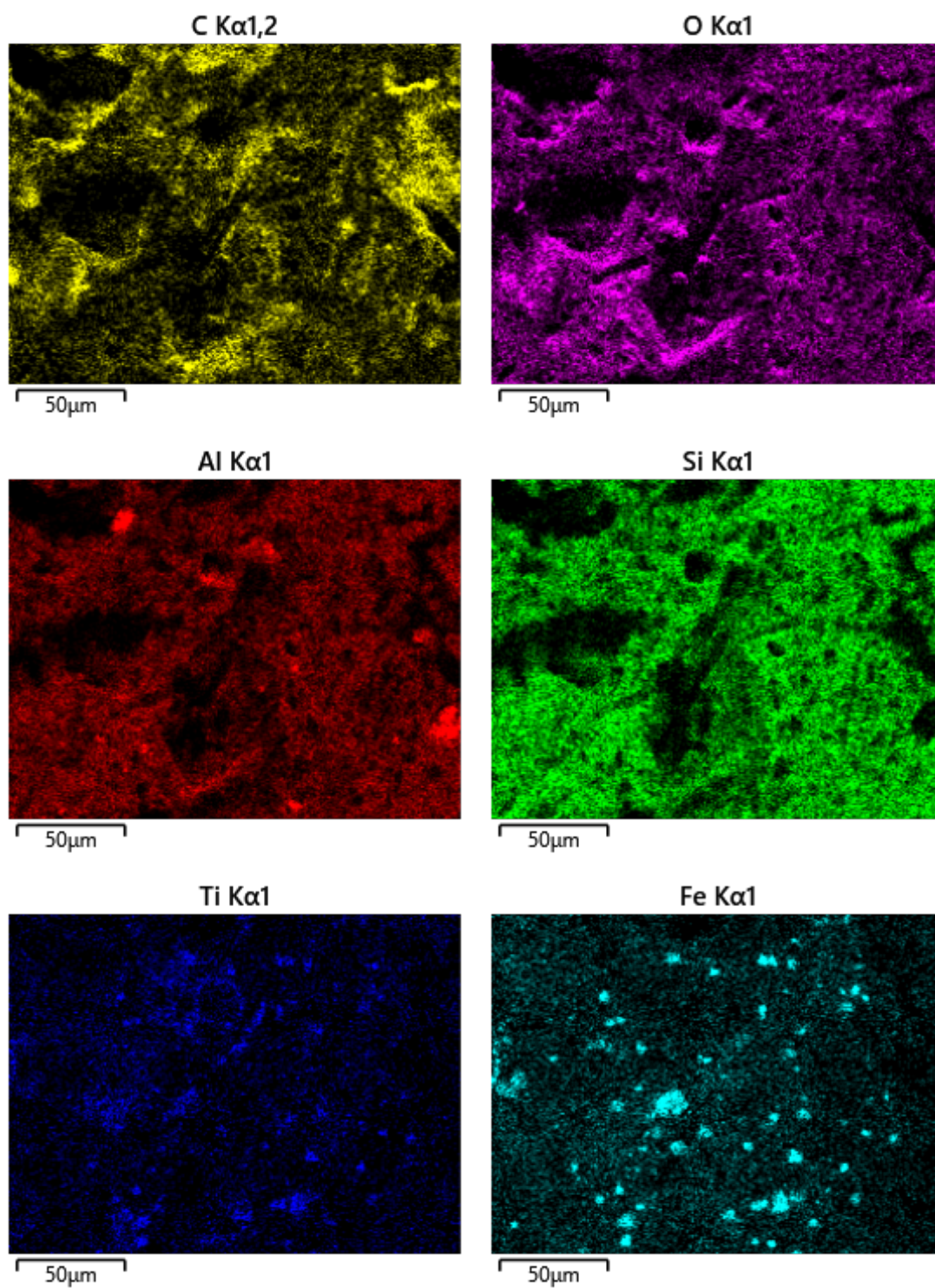


Figure A2.6: Element maps of S9 block (S9-2).

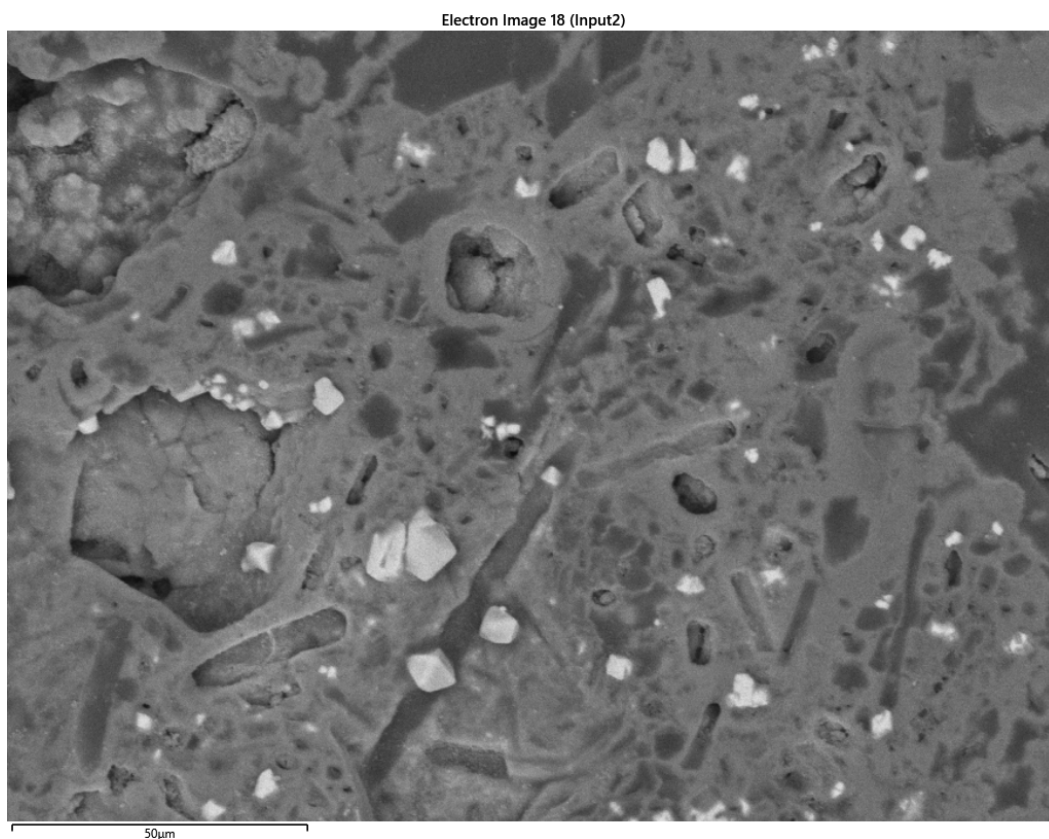


Figure A2.7: SEM-EDS map of S9 block (S9-2).

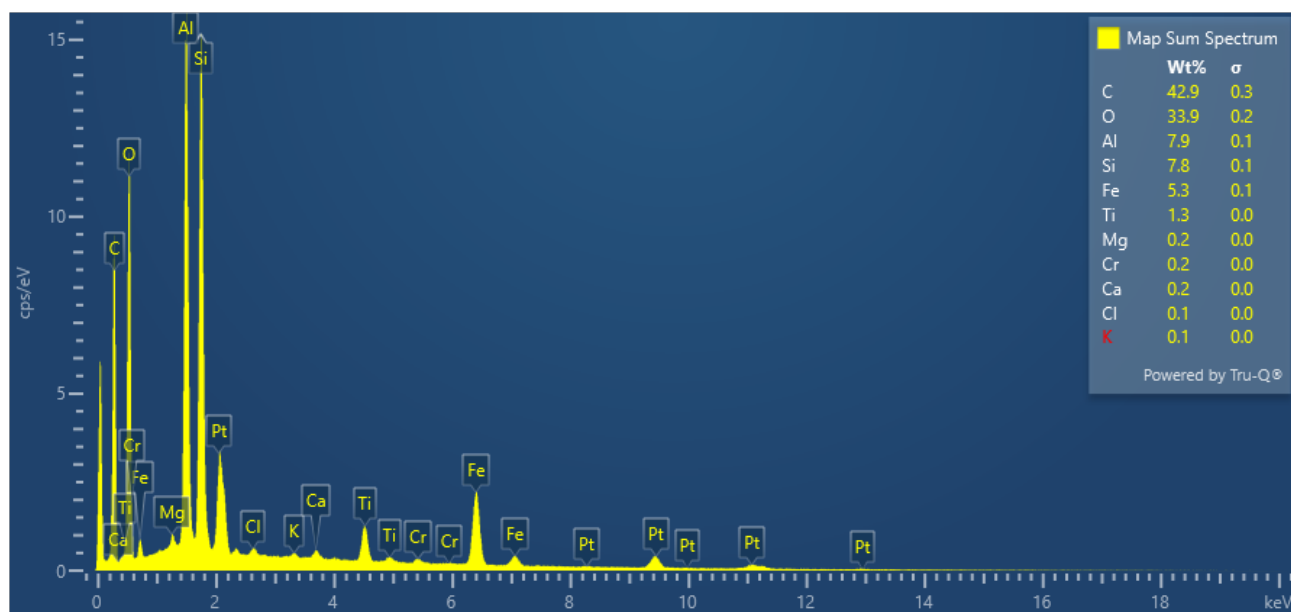


Figure A2.8: Element graph of S9 block (S9-2).

Table A2.2: Elemental composition (wt.%) of SEM-EDS from S9 block site (S9-2) with standard deviation.

Element	Weight %	σ
C	42.91	0.30
O	33.88	0.23
Al	7.90	0.05
Si	7.79	0.05
Fe	5.33	0.06
Ti	1.35	0.02
Mg	0.21	0.02
Cr	0.20	0.02
Ca	0.20	0.01
Cl	0.14	0.01
K	0.09	0.01

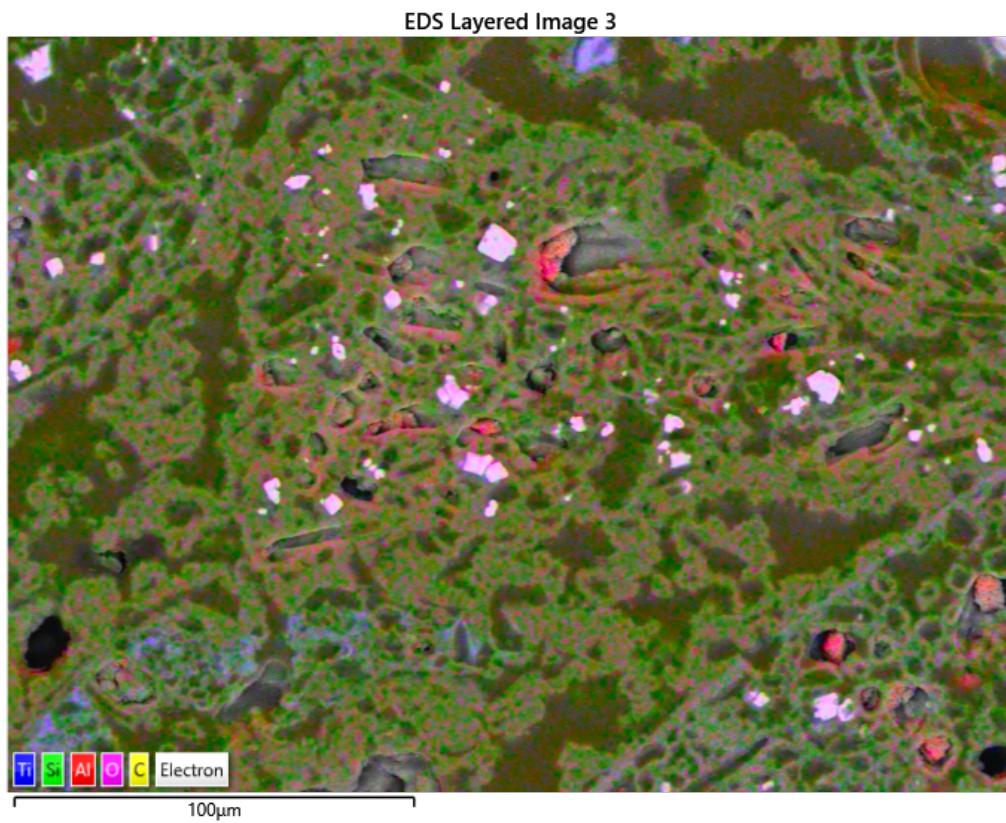


Figure A2.9: SEM-EDS layered image of S9 block (S9-3).

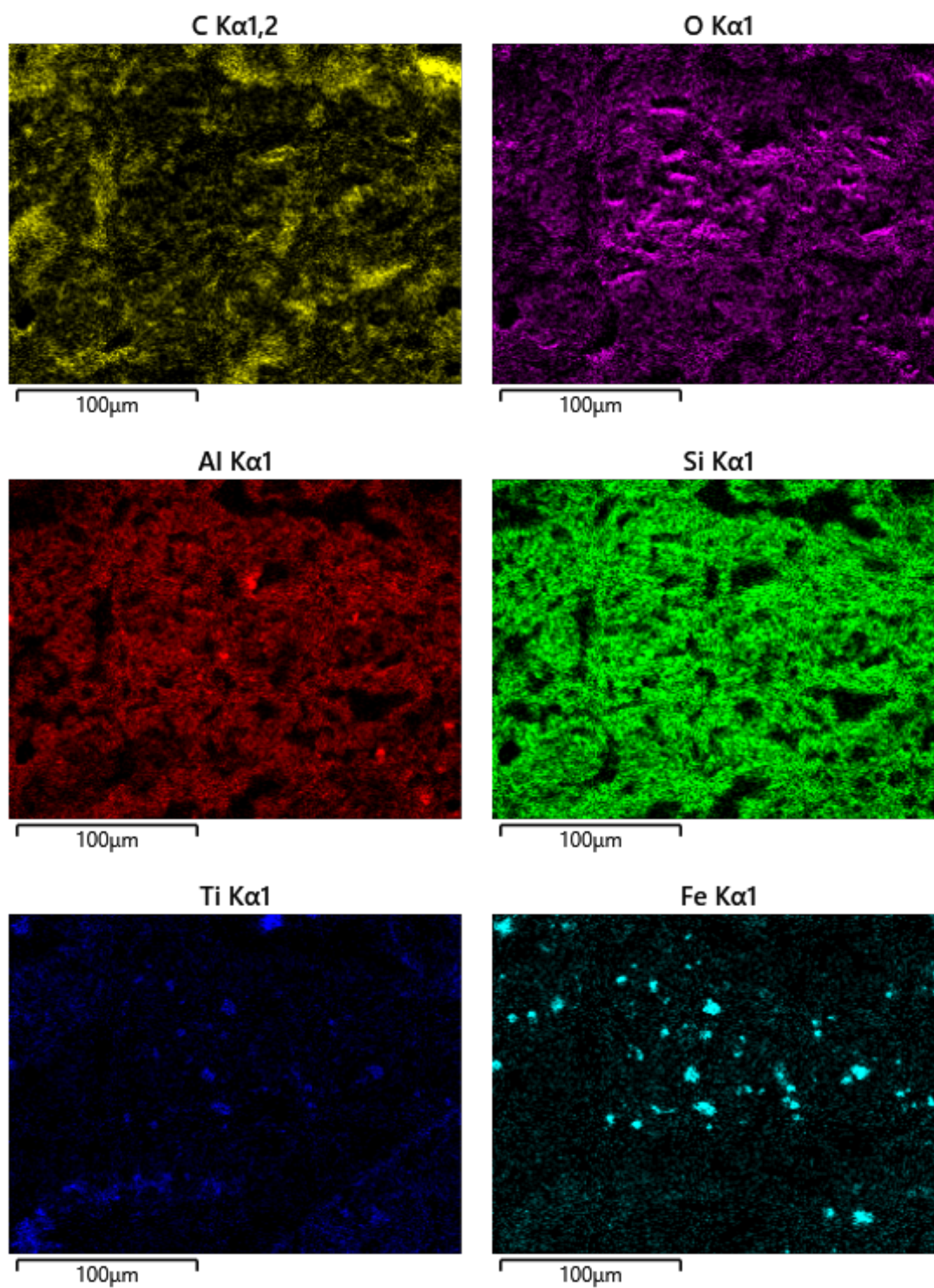


Figure A2.10: Element maps of S9 block (S9-3).

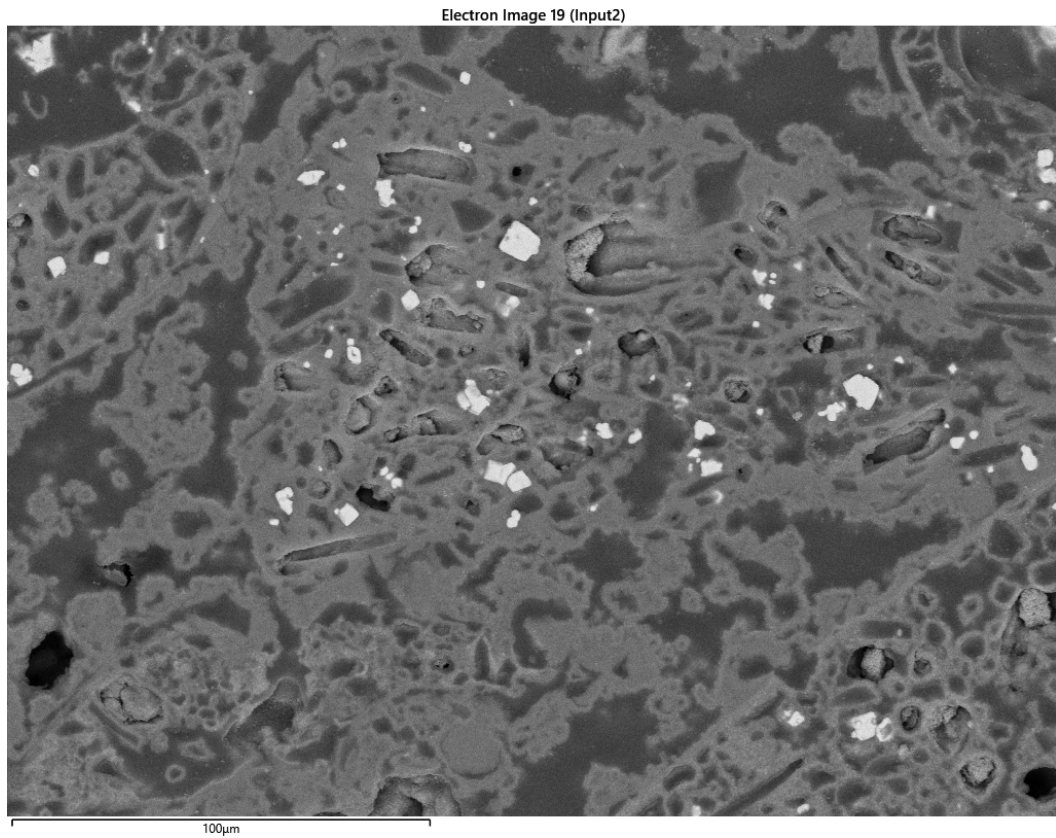


Figure A2.11: SEM-EDS map of S9 block (S9-3).

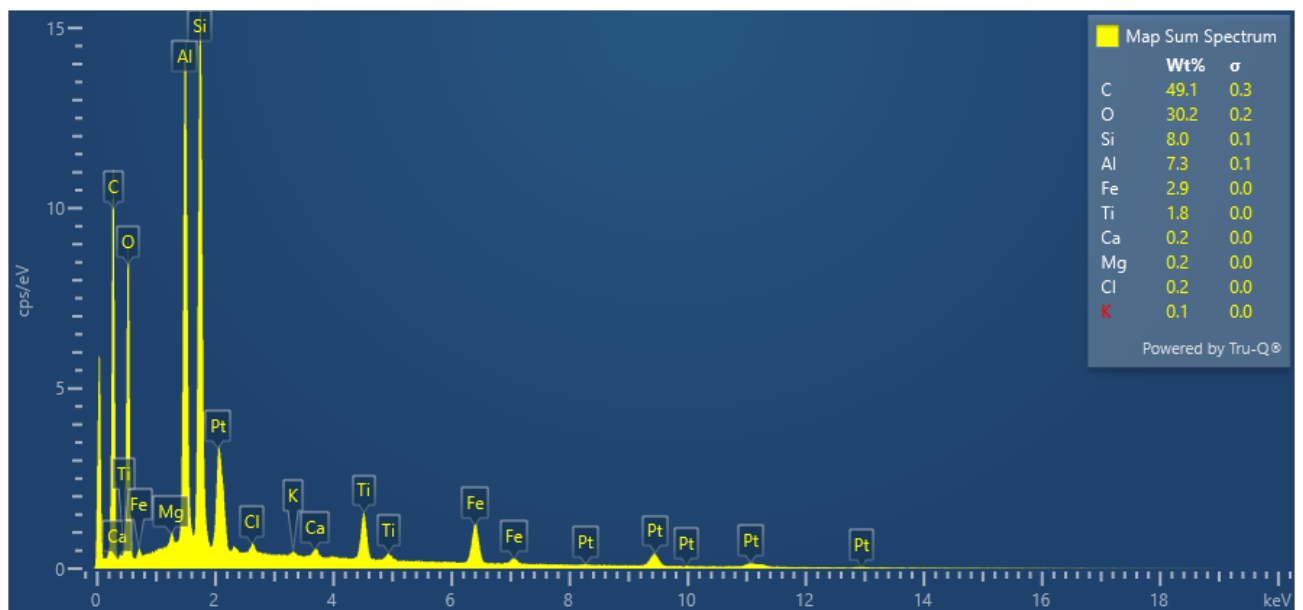


Figure A2.12: Element graph of S9 block (S9-3).

Table A2.3: Elemental composition (wt.%) of SEM-EDS from S9 block site (S9-3) with standard deviation.

Element	Weight %	σ
C	49.09	0.28
O	30.17	0.22
Si	7.99	0.06
Al	7.34	0.05
Fe	2.94	0.04
Ti	1.78	0.03
Ca	0.22	0.01
Mg	0.21	0.02
Cl	0.17	0.01
K	0.09	0.01

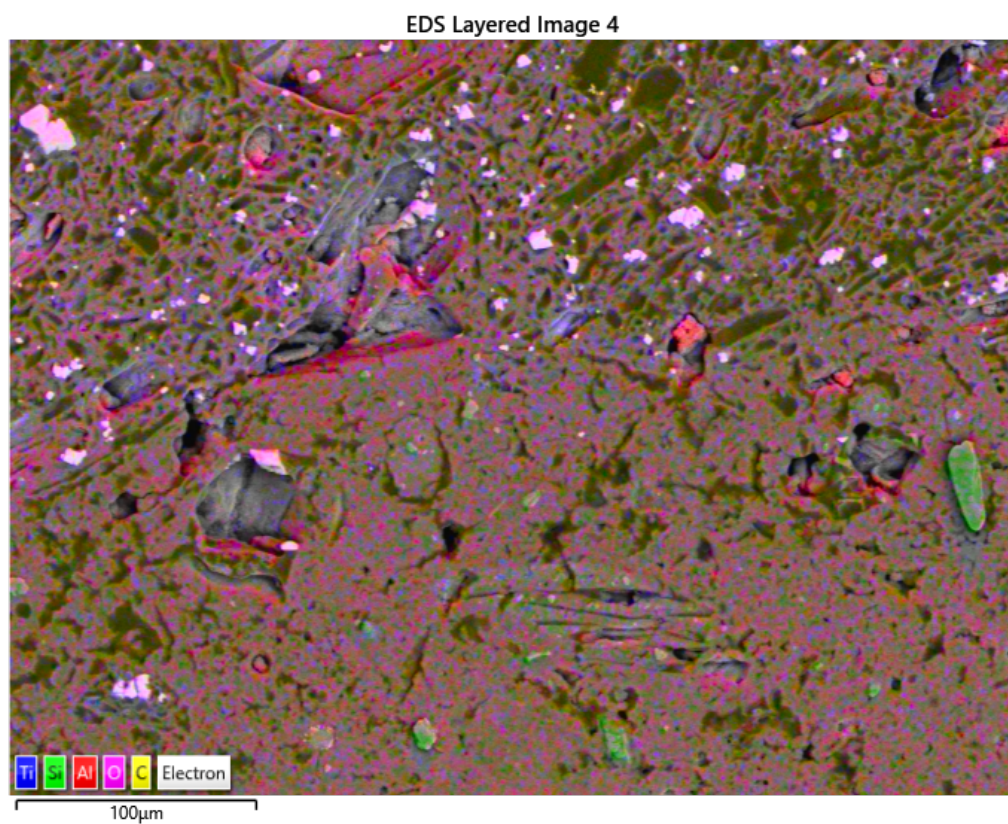


Figure A2.13: SEM-EDS layered image of S9 block (S9-4).

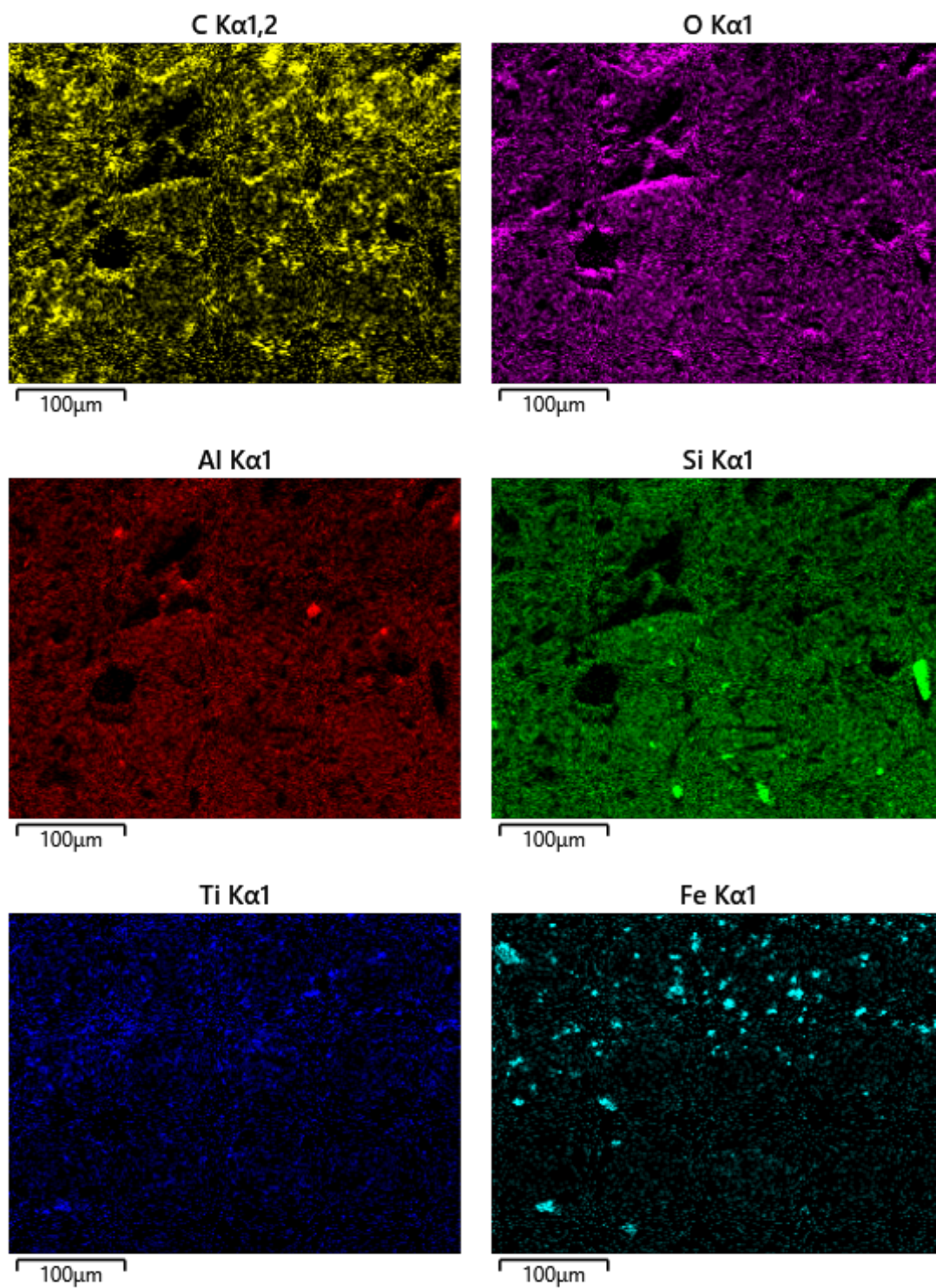


Figure A2.14: Element maps of S9 block (S9-4).

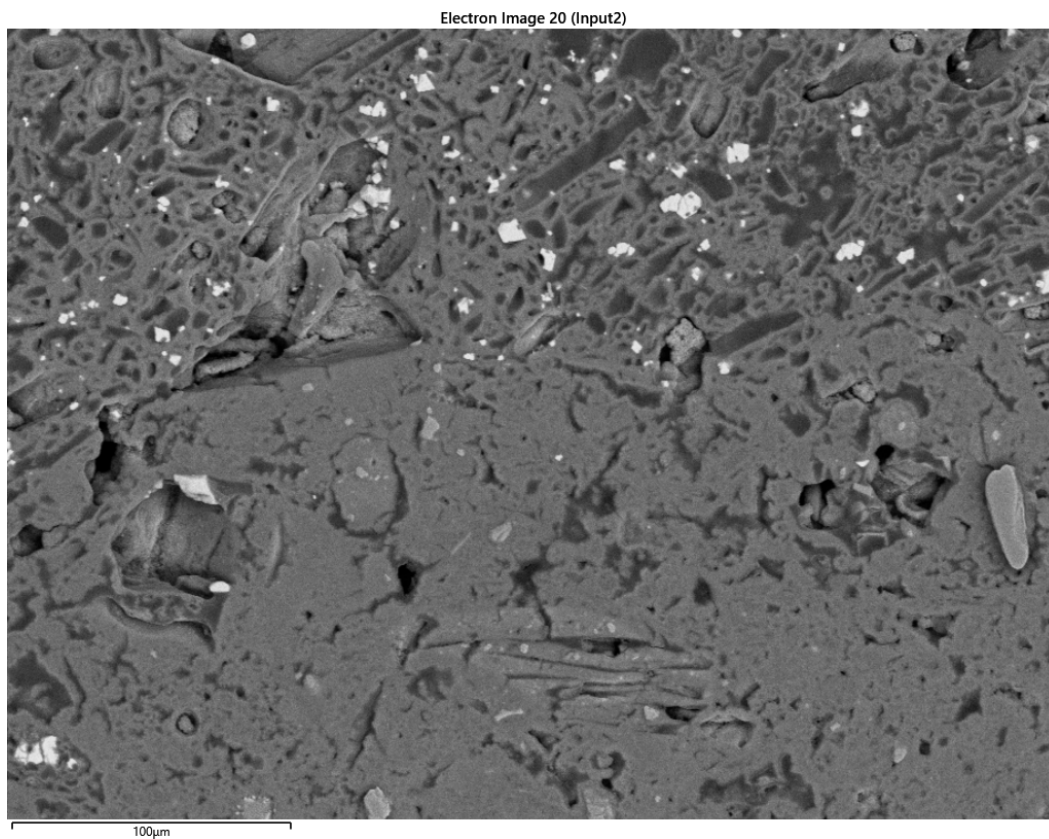


Figure A2.15: SEM-EDS map of S9 block (S9-4).

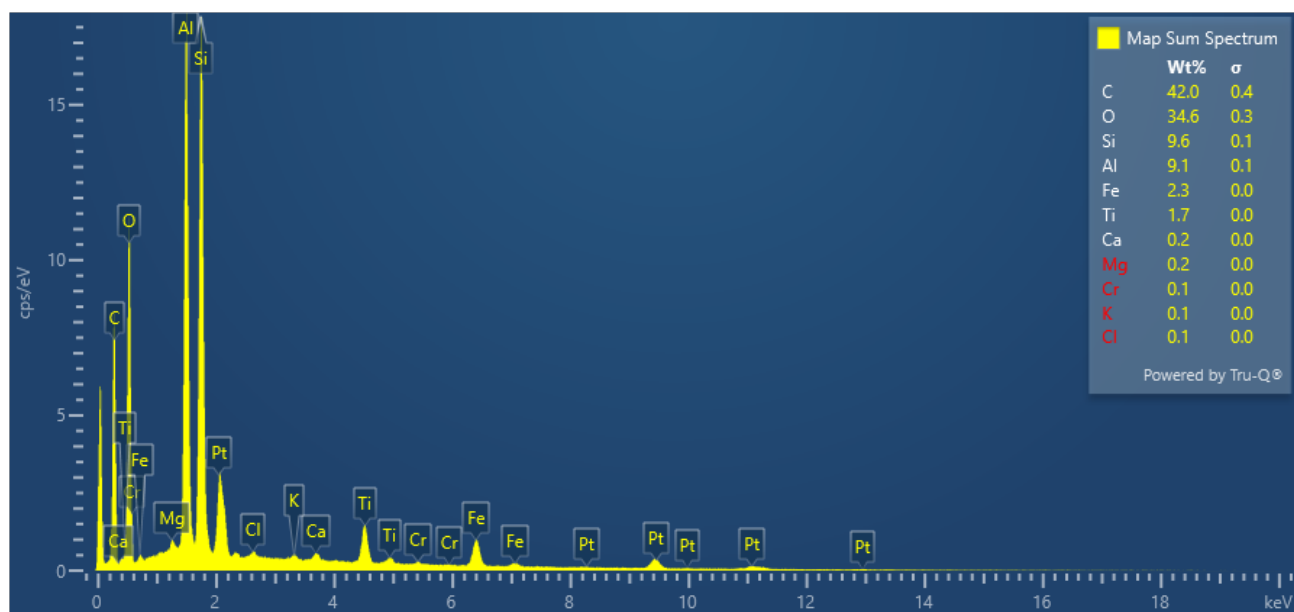


Figure A2.16: Element graph of S9 block (S9-4).

Table A2.4: Elemental composition (wt.%) of SEM-EDS from S9 block site (S9-4) with standard deviation.

Element	Weight %	σ
C	42.05	0.38
O	34.60	0.28
Si	9.57	0.08
Al	9.11	0.07
Fe	2.25	0.05
Ti	1.68	0.03
Ca	0.21	0.02
Mg	0.18	0.02
Cr	0.12	0.02
K	0.12	0.02
Cl	0.11	0.01

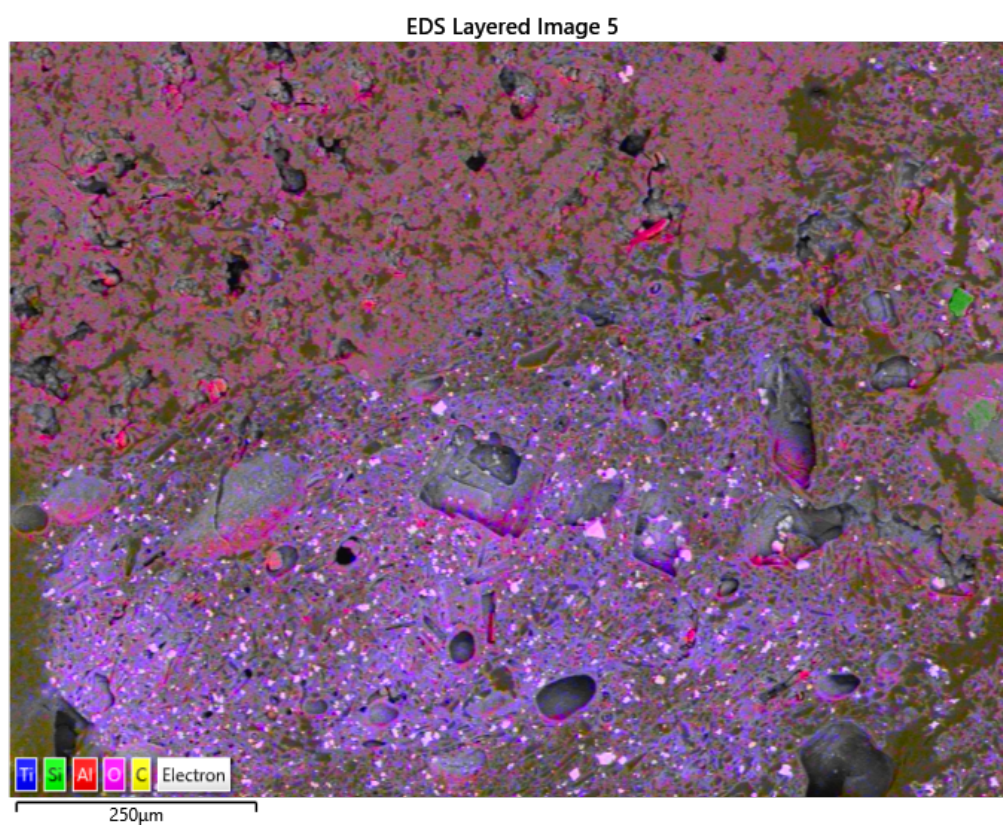


Figure A2.17: SEM-EDS layered image of S9 block (S9-5).

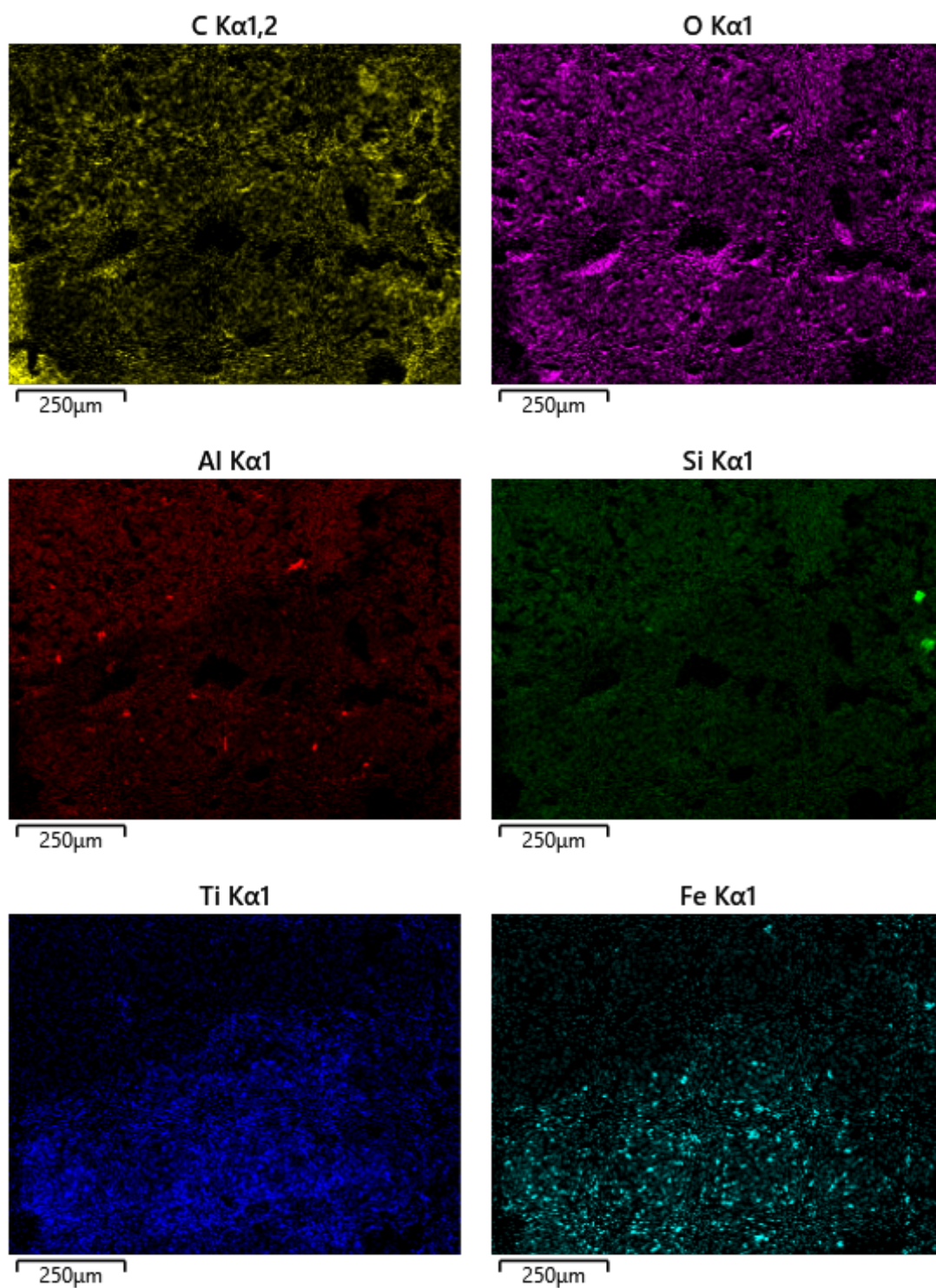


Figure A2.18: Element maps of S9 block (S9-5).

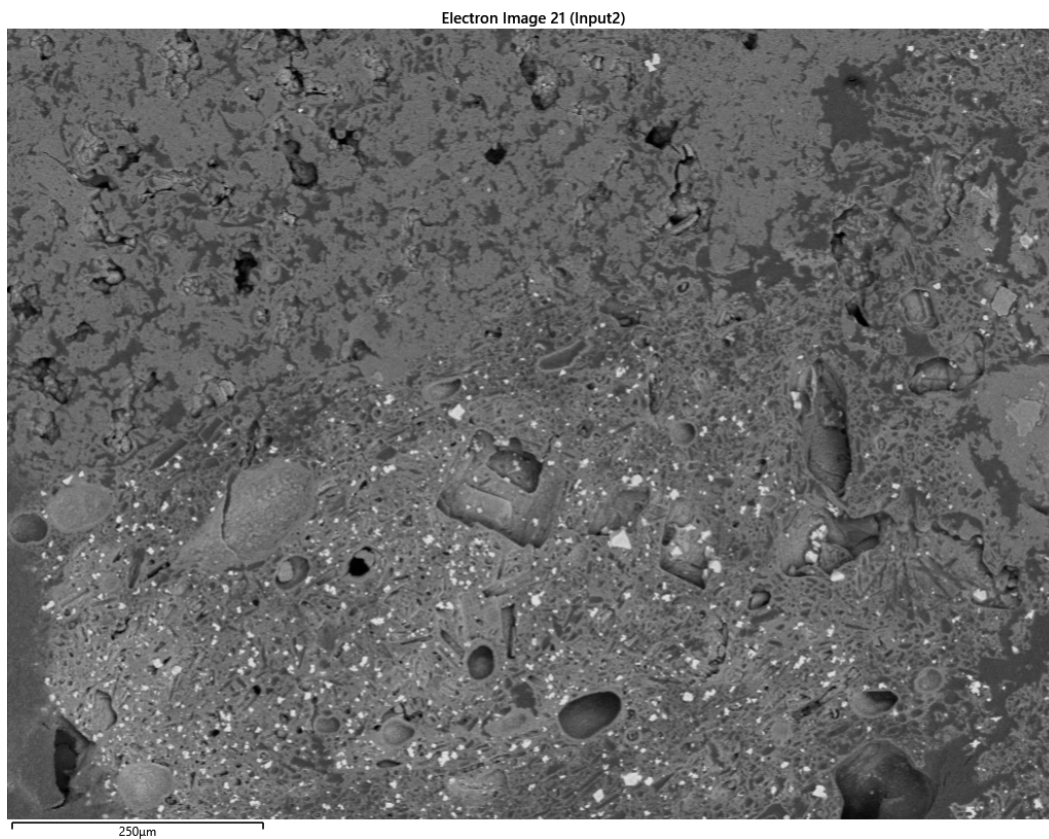


Figure A2.19: SEM-EDS map of S9 block (S9-5).

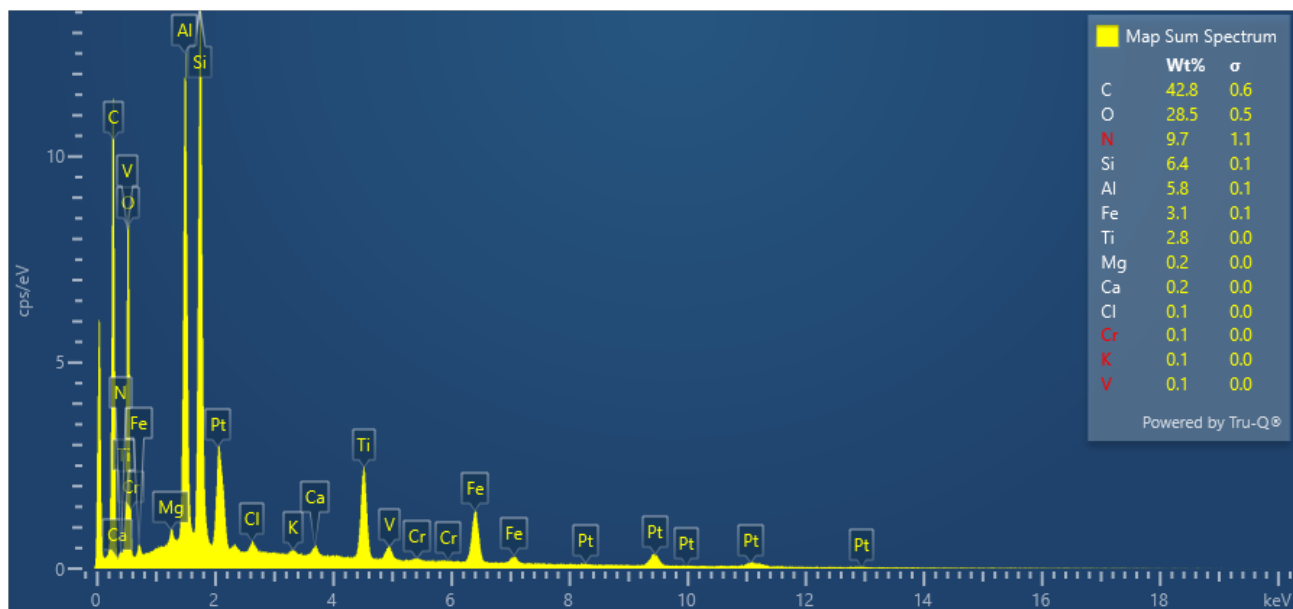


Figure A2.20: Element graph of S9 block (S9-5).

Table A2.5: Elemental composition (wt.%) of SEM-EDS from S9 block site (S9-5) with standard deviation.

Element	Weight %	σ
C	42.80	0.60
O	28.55	0.48
N	9.74	1.07
Si	6.36	0.09
Al	5.83	0.08
Fe	3.13	0.06
Ti	2.83	0.05
Mg	0.20	0.02
Ca	0.19	0.01
Cl	0.14	0.01
Cr	0.08	0.02
K	0.08	0.01
V	0.06	0.02

EDS Layered Image 6



Figure A2.21: SEM-EDS layered image of S9 block (S9-6).

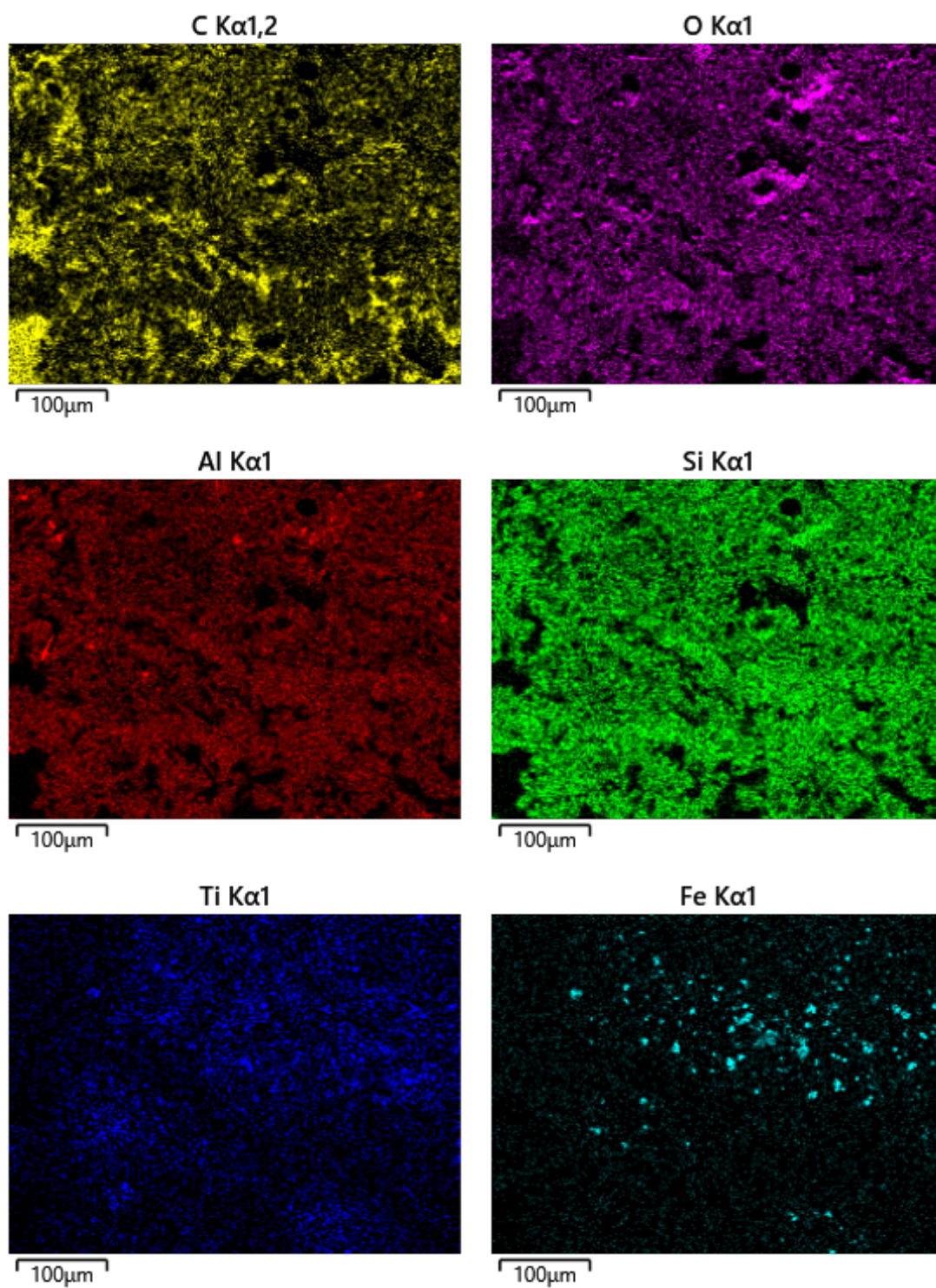


Figure A2.22: Element maps of S9 block (S9-6).

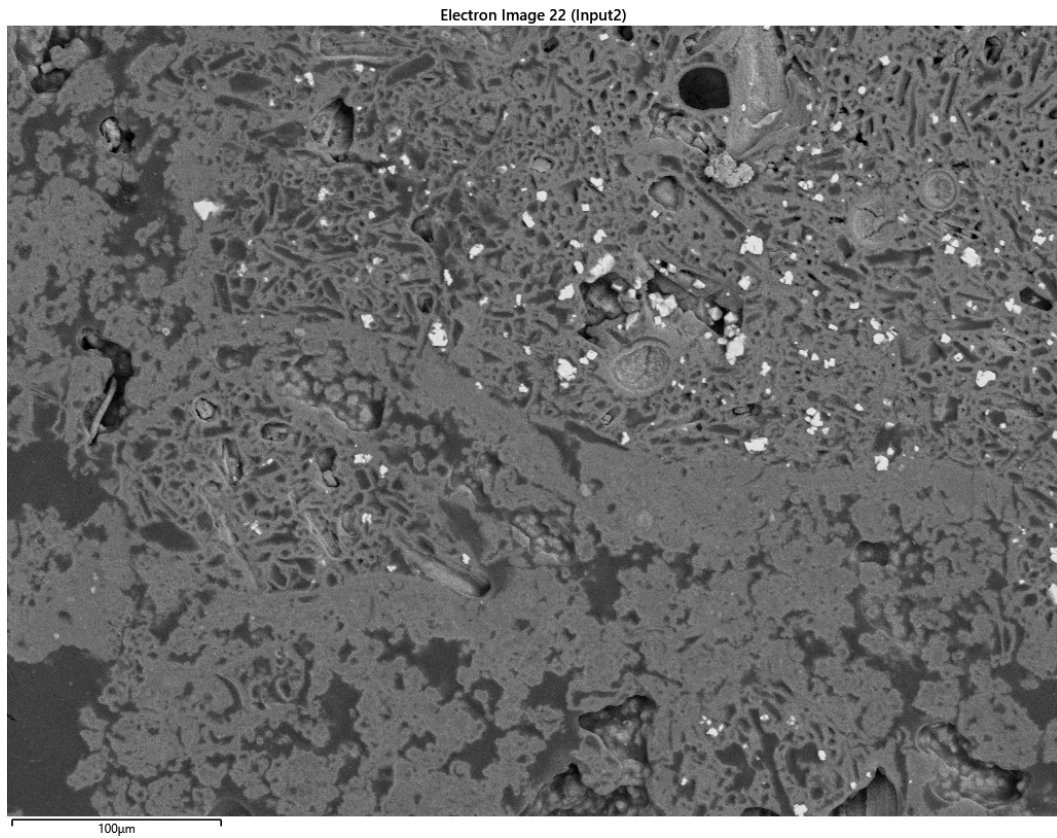


Figure A2.23: SEM-EDS map of S9 block (S9-6).

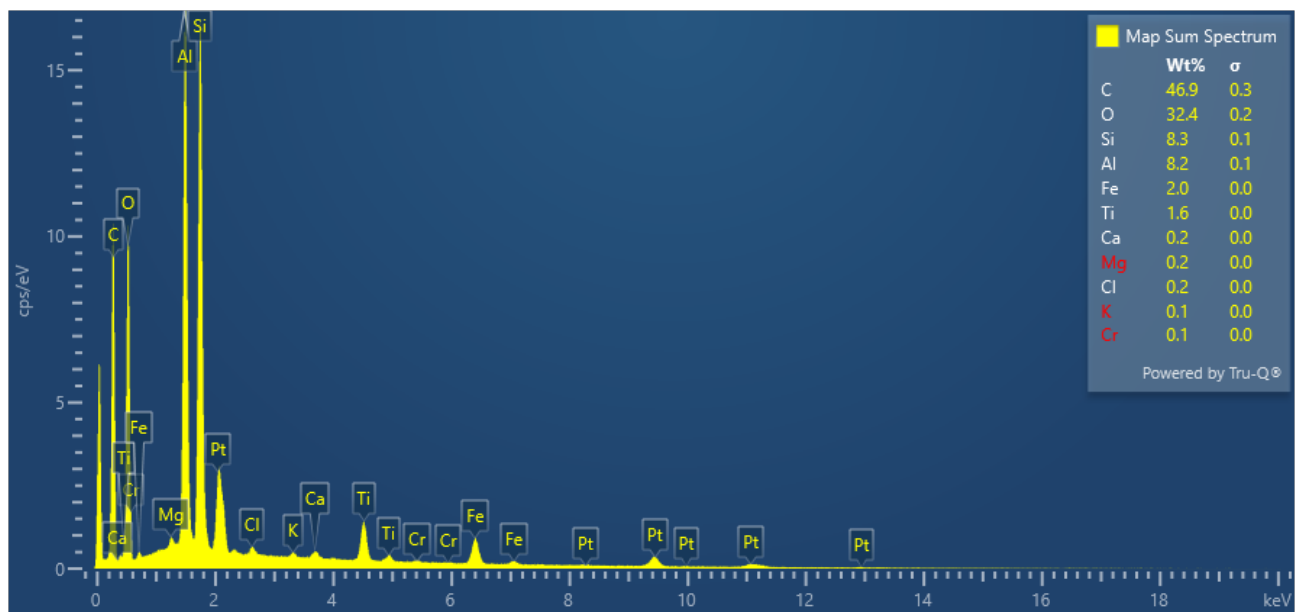


Figure A2.24: Element graph of S9 block (S9-6).

Table A2.6: Elemental composition (wt.%) of SEM-EDS from S9 block site (S9-6) with standard deviation.

Element	Weight %	σ
C	46.85	0.31
O	32.42	0.25
Si	8.32	0.06
Al	8.16	0.06
Fe	1.95	0.04
Ti	1.58	0.03
Ca	0.18	0.01
Mg	0.16	0.02
Cl	0.15	0.01
K	0.11	0.01
Cr	0.10	0.02

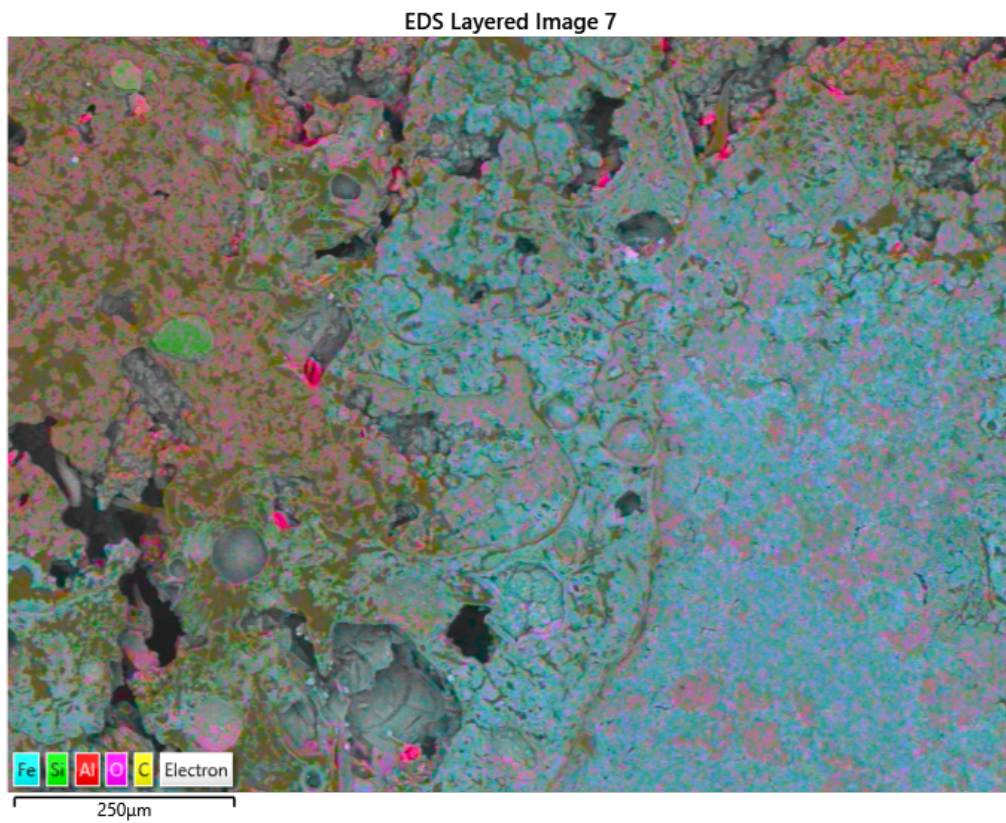
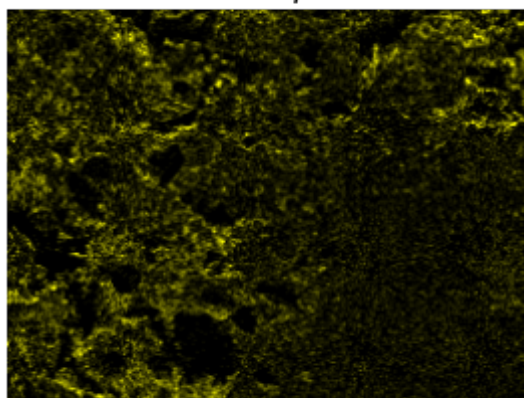
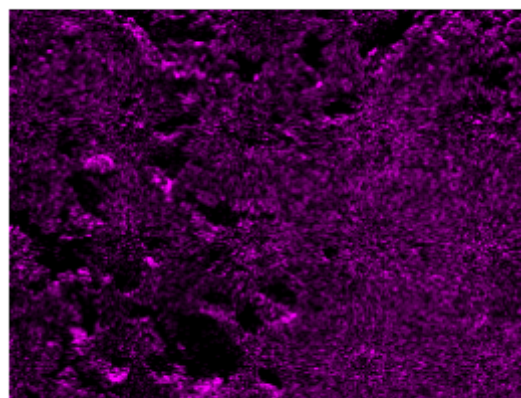


Figure A2.25: SEM-EDS layered image of S9 block (S9-7).

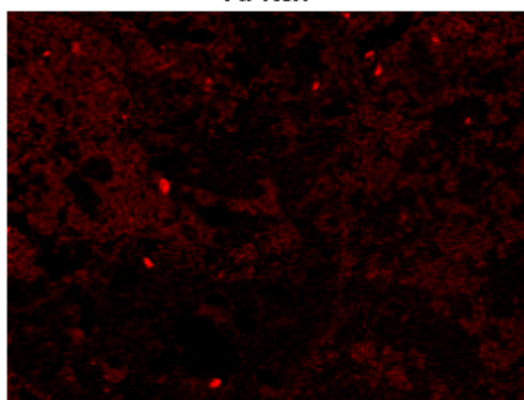
C K α 1,2



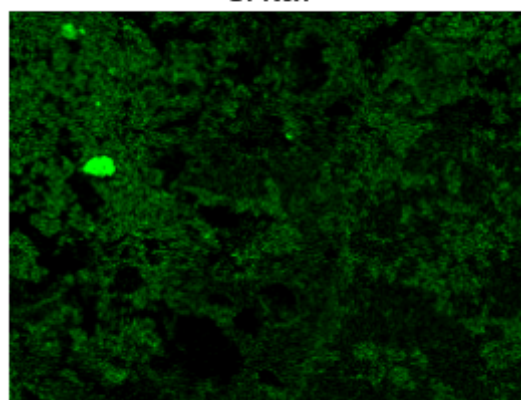
O K α 1



Al K α 1



Si K α 1



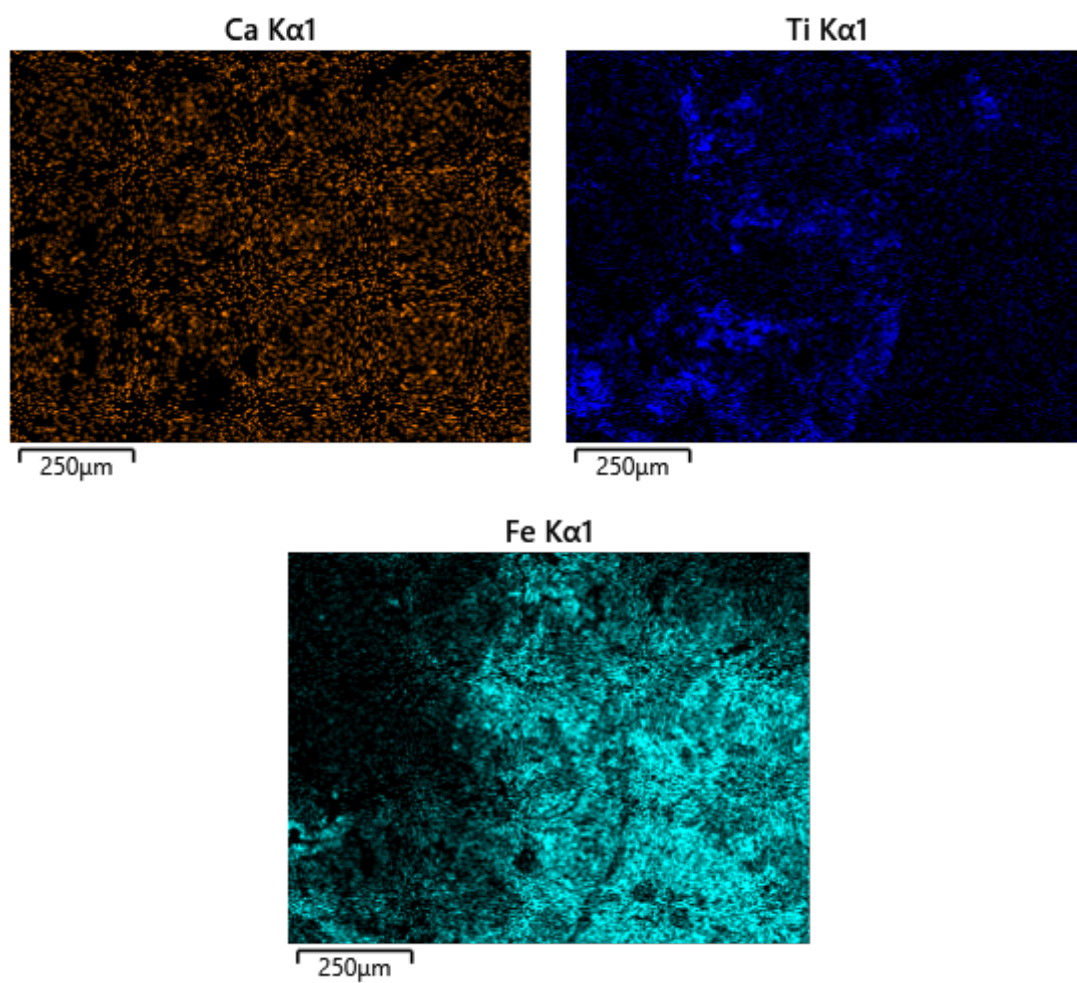


Figure A2.26: Element maps of S9 block (S9-7).

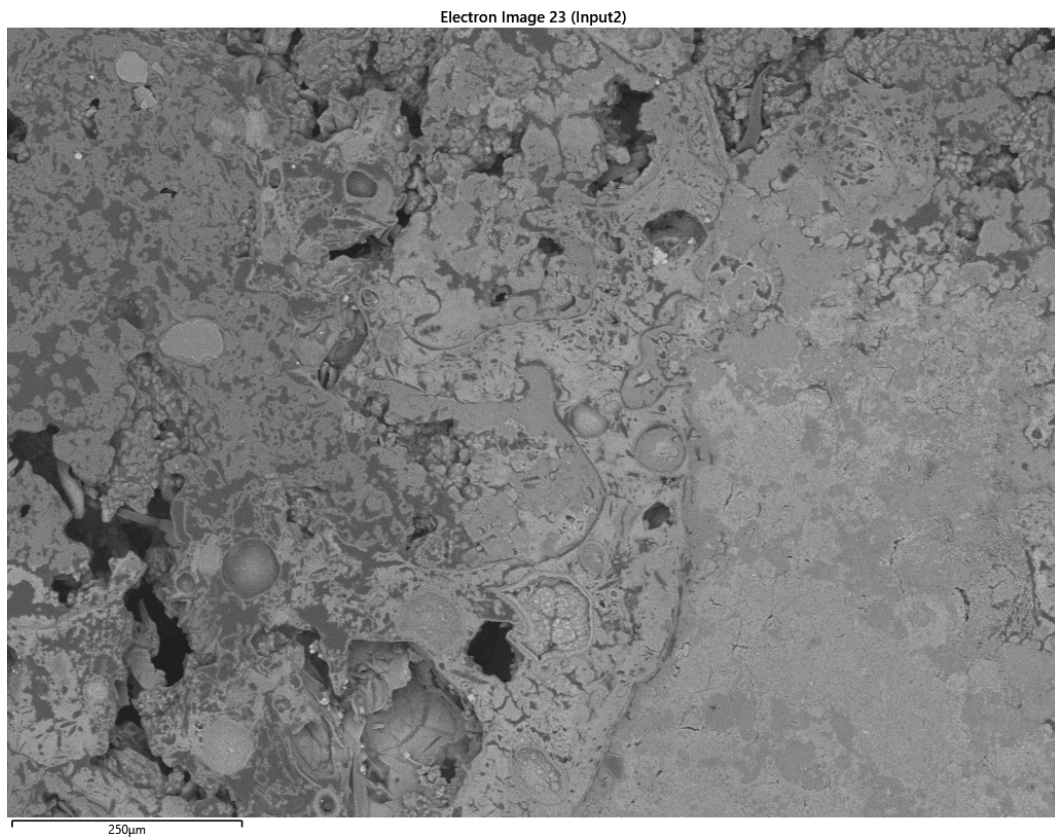


Figure A2.27: SEM-EDS map of S9 block (S9-7).

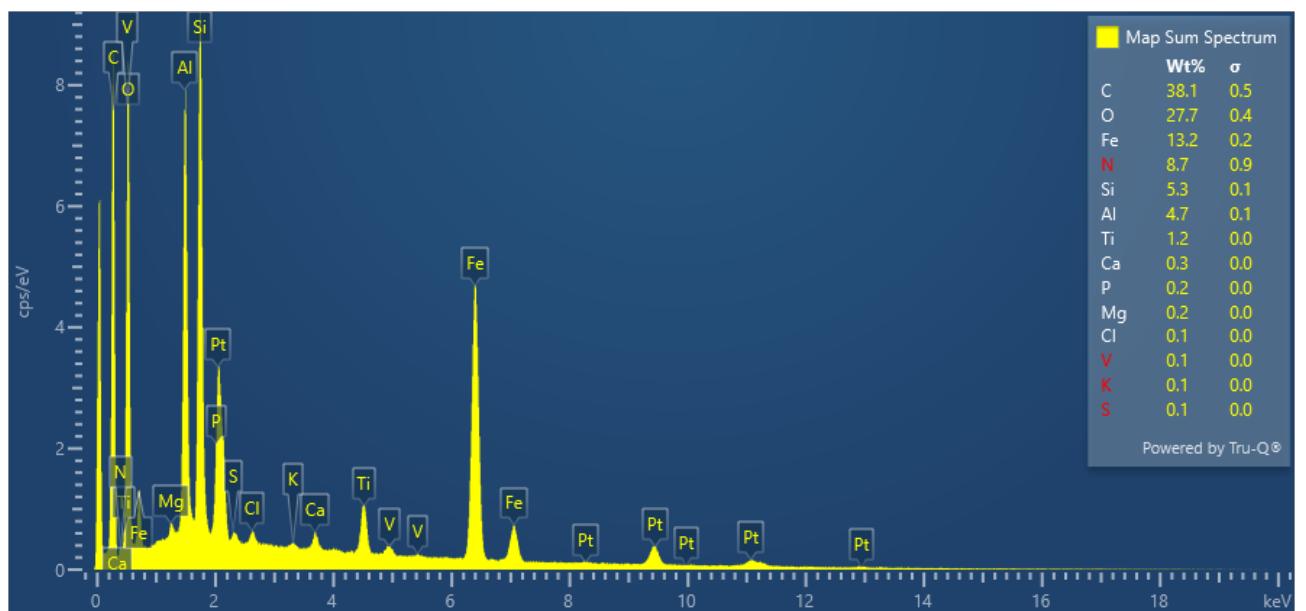


Figure A2.28: Element graph of S9 block (S9-7).

Table A2.7: Elemental composition (wt.%) of SEM-EDS from S9 block site (S9-7) with standard deviation.

Element	Weight %	σ
C	38.11	0.49
O	27.74	0.40
Fe	13.18	0.16
N	8.72	0.92
Si	5.29	0.07
Al	4.72	0.06
Ti	1.20	0.03
Ca	0.26	0.01
P	0.24	0.02
Mg	0.17	0.02
Cl	0.15	0.01
V	0.09	0.02
K	0.07	0.01
S	0.06	0.01